Limited nighttime visibility is one of the important parameters in traffic safety that requires attention. Although introducing road lighting can mitigate the amount and severity of accidents, the interaction between road lighting and car headlights are not complementary. In addition, energy consumption and related costs of road lighting are the driving forces for more efficient road lighting technologies. This dissertation seeks to answer how the current road lighting and car headlights interact and how road lighting could be adjusted so that it does not neutralize the effect of car headlights in varying conditions.

The effect of different road lighting levels on drivers’ visual performance under various conditions

Sanaz Bozorg
The effect of different road lighting levels on drivers’ visual performance under various conditions

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A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall F239a in Otakaari 3 on the 16th August 2019 at 12:00.

Aalto University
School of Engineering
Department of Built Environment
Spatial Planning and Transportation Engineering
Supervising professor
Professor Tapio Luttinen, Aalto University, Finland.

Thesis advisor
Dr. Isakki Kosonen, Aalto University, Finland.

Preliminary examiners
Professor John D. Bullough, Lighting Research Center, Rensselaer Polytechnic Institute, the United States of America.
Professor Steve Fotios, University of Sheffield, the United Kingdom.

Opponent
Professor Ronald B. Gibbons, Center for Infrastructure Based Safety Systems Virginia Tech Transportation Institute.
Traffic accidents are one of the leading causes of death globally. Accident rates are higher during darkness than during daylight. Some of the potential contributing factors in accidents are low visibility and impaired driving due to e.g. alcohol, drugs, distraction or fatigue. Introducing road lighting can mitigate the amount and severity of accidents that are due to low visual performance. However, at the same time, energy consumption and related costs of road lighting are the driving forces for more efficient road lighting technologies. Therefore, the transition of the road lighting to intelligent road lighting system that could tackle energy, cost, and safety challenges is inevitable. So far, not much research can been found about the combined effect of different road light intensities and car headlights on drivers’ visual performance. The aim of this dissertation is to provide such information under realistic conditions. The results can be used in the development of intelligent road lighting practices.

Several measures were executed in a stationary car with a constant distance to the targets. Drivers’ visual performance was investigated under various road surface conditions (dry, wet and snowy), different road lighting levels, and presence or absence of glare. Finally, detection distance study was designed to determine whether similar results can be found in a moving car. Various methods were applied to study driver’s visual performance such as contrast, Visibility Level, psycho-visual tests, and detection distance. All measures suggested similar conclusions.

The results of this study indicated that the current practice of road lighting levels for motorised traffic is not always necessary. In the presence of car headlights, with no glare from oncoming cars, headlights alone, or combined with a low lighting level, provided better visibility performance than when combined with full lighting intensity. In addition, the effect of different road lighting levels was not monotonic, because reducing road lighting shifted the contrast from positive to negative polarity or vice versa and made the contrast approach zero in some conditions. Therefore, road lighting should be lowered to a level that does not neutralize the effect of car headlights. This result supports the feasibility of reducing road lighting level under different road surface conditions. In the presence of glare from an oncoming car, higher road lighting level provided better visibility than lower lighting levels, but the effect of different road lighting intensities on visual performance was not statistically significant.
Preface

This doctoral dissertation is submitted for the degree of Doctor of Science (Technology) at Aalto University. The research described herein was conducted between 2013-2018 in the Department of Built Environment, School of Engineering, Aalto University, Finland. The study has been financially supported mainly by one of the Aalto Energy Efficiency research programmes named the Light Energy-Efficient and Safe Traffic Environments project. The work was also funded by Aalto University School of Engineering.

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I would like to express my gratitude to my parents for their continued trust in the decisions I made throughout my life. Special thanks, of course, are due to my sister and her husband for their everlasting encouragement. I want to take a moment to remember my late brother whose presence has been always empty by my side. He is truly missed. I would like to dedicate my doctoral thesis to my husband, Dr. Behrang Vand, who walked me through the ups and downs of doing a PhD, without his continued support and encouragement I could never have accomplished so much.

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Sanaz
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List of Abbreviations and Symbols

Abbreviations
AFS      Adaptive forward lighting
CEN     European Committee for Standardization
CIE    Commission International de l’Eclairage
HPS     High-Pressure Sodium
LED    Light Emitting Diode
TLS    Terrestrial Laser Scanning
VL     Visibility Level
RVP    Relative Visual Performance
HID    High-Intensity Discharge Headlights
RWVL   Relative Weighted Visibility Level
STV    Small Target Visibility

Symbols
E      illuminance [lx]
E_{gl}  illumination onto a vertical plane at the observers’ eye [lx]
L      luminance [cd/m²]
L_{ave} average luminance [cd/m²]
L_{b}  background luminance [cd/m²]
L_{t}  target luminance [cd/m²]
L_{v}  veiling luminance [cd/m²]
List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals


**Article II.** Bozorg Chenani, Sanaz; Vaaja, Matti. T; Kurkela, Matti; Kosonen, Iisakki; Luttinen, Tapio. 2017. Target detection distances under different road lighting intensities. Journal of European Transport Research Review. p. 9-17

Author’s Contribution

In **Article I**, the author conducted the field measurement and data collection together with M. Maksimainen, E. Tetri, I. Kosonen. As the main author, I was mainly responsible for evaluating, analysing and writing the results. The paper was improved by supervision and contributions from T. Luttinen.

In **Article II**, the first author was responsible for planning, analysing and writing the article. M.T. Vaaaja and M. Kurkela participated in data collection. They also provided road geometry measurement data based on Terrestrial Laser Scanning (TLS data). I. Kosonen participated in the field measurements. The paper was improved by contributions from Tapio Luttinen at various stages of the analysis and writing process.

In **Article III**, the author was responsible for collecting the data. E. Tetri participated in the field measurements. The main author was mainly responsible for evaluating and analysing the results and writing the article. Also, E. Tetri, I. Kosonen, and T. Luttinen helped to write and improve the article.
1. Introduction

1.1 Background

Traffic safety is one of the most prevalent transport problems (European Commission, 2008; AASHTO, 2014). Road accidents have been ranked as one of the top 10 causes of death, causing 1.3 million deaths in 2015 (WHO, 2017). AASHTO (2014) has estimated that 57% of traffic accidents are due solely to human, 3% by roadway factors and 3% by vehicular factors. The rest is due to their interactions. Some of the common human behaviour and performance factors which result in accidents are sleepiness (Sagberg, 1999; Horne and Reyner, 1999; Garbarino et al., 2001; Sallinen and Hublin, 2015), drunk driving (Elder et al., 2004; Reis et al., 2006), and distractions (McEvoy S., Stevenson M., 2007; Consiglio et al., 2003).

One counter-measure factor in the number and severity of road accidents caused by low visibility is road lighting. Several studies have indicated that accident risk is higher at night than during the day (CIE, 1993; Elvik, 1995; Elvik and Vaa, 2009). CIE (1993) overviewed 62 before-and-after road lighting studies from 15 different countries accounting for all road types (rural, urban and freeways, and intersections and interchanges) and concluded that road lighting reduced night-time accidents for all road types by 30% on average.

However, road lighting consumes a lot of energy. Road lighting alone is responsible for 8% of global use of electrical energy and accounts for about 6% of the total emissions of greenhouse gases (IEA, 2006). New lighting technologies such as utilization of LED luminaires1, as well as intelligent road lighting systems, that are capable of adjusting light output based on traffic on demand, can reduce energy consumption and costs of road-lighting without adversely affecting drivers’ visibility (Black sea Regional Energy Center, 2007).

Car headlights provide lighting in the field of view to allow a driver to respond to a hazard while minimizing the amount of light facing oncoming traffic (NHTSA, 2007), although car headlights alone provide sufficient illumination for visibility below certain critical driving speeds only (Perel et al., 1983; Janoff et al., 1986; Leibowitz et al., 1998). Previous findings suggest that adding road lighting might reduce the effectiveness of car headlights on drivers’ visibility performance (Akashi et al., 2003; Bacelar, 2004; Boyce, 2009; Bullough and

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1 Luminaires are apparatus which distributes, filters or transforms the light transmitted from one or more lamps and which includes, except the lamps themselves, all the parts necessary for fixing and protecting the lamps and, where necessary, circuit auxiliaries together with the means for connecting them to the electric supply.
Rea, 2010), except for visibility of peripherally located targets (Bullough and Rea, 2010). While road lighting illuminates road surface (horizontally), car headlights illuminate vertical objects on the road, and the combined effect of road lighting and car headlights may reduce the contrast of objects on the road. Such cumulative effects of headlights and road lighting tend to decrease the contrast between the target and the road surface (Bacelar, 2004; Ekrias et al., 2008). Consequently, due to the cost of road lighting and the combined effect of road lighting and car headlights, some governments have considered turning road lights off, for example, in the U.S. (Bullough and Rea, 2010).

However, and as previously noted, the presence of road lighting has been found to have a positive effect on traffic safety (CIE, 1992). There are several reasons why unlit roads can be unsafe. First, the effect of car headlights is limited to its distribution (beam distance and shape) and the speed of a car directly affects the effectiveness of headlights (Leibowitz et al., 1998). Second, glare from oncoming traffic can adversely affect visual comfort and performance, and road lighting reduces the effect of glare (Bacelar, 2004). Introducing road lighting offsets additional scattered light coming from oncoming cars in the eye. Third, road lighting illumination may be required for detection of roadway and targets beyond car headlights illumination.

Lower costs of new lighting technologies make road lighting more profitable, even with lower safety effects.

Reducing the power or output of the light source, or dimming, is a practice that is getting increasing attention. In dimming practices, energy savings depend on the use of energy prior to dimming, as well as on the level and the duration of dimming. It is important to consider the effect of different lighting levels on drivers’ visual performance in order to find out how to save energy without adversely affecting uniformity and traffic safety.

Steinbach et al. (2015) studied the effect of switching the luminaires off permanently, reducing the number of burning hours of the lights during the night (part-night lighting), reducing the power of lights (dimming) and replacing the lights from yellow to white during 2000–2013. Their results provided no evidence that dimming road lighting was associated with increased road traffic collisions. Unfortunately, they did not describe the dimming strategies in their study. However, they suggested that dimming practices can be a solution to reduce energy consumption without adversely affecting traffic safety.

The headlights of oncoming cars cause glare that adversely affects the visual performance of drivers. A study by Bacelar (2004) on the effect of glare on drivers’ visual performance under lit and unlit road indicated that road lighting reduces the effect of glare from the oncoming car due to the improvement in the driver’s visual adaptation. Unfortunately, the study only considered one lighting level (average illuminance 31.5 lx, the average luminance of 2.45 cd/m²).

The need for road lighting is different in various road surface conditions (Ekrias et al., 2007; Wanvik, 2009), and, it is possible to alter road lighting illumination when suitable controls are available. For instance, Ekrias et al. (2007) found that the luminance level of a snowy road was many times higher than under dry road conditions. Even when the road was only lightly covered by
snow or had been cleared, luminance levels still remained 50% higher than under dry conditions. The authors suggest that it is feasible to benefit from the prevailing weather conditions in intelligent road lighting practices.

The cost and energy saving concerns related to road lighting can be partly reduced by changing road lighting technology to more efficient ones assuming that the energy savings offset initial costs such as purchase prices and installation costs of intelligent road lighting (Tähkämö et al., 2016). In addition to the energy-saving advantages, the adjustment of light levels can contribute to the reduction of light pollution, and savings in maintenance (Brons et al., 2008; Tähkämö et al., 2016).

Currently, for energy saving reasons, intelligent road lighting control systems are increasingly practised. The dimming strategies are made on the basis of experiences of lighting designers. These designs are mainly based on traffic volume and weather conditions. In periods, when snow covers the road or when the traffic is low, the illumination level can be reduced (Black Sea Regional Energy Centre, 2007). For example, in Norway, dimming of the luminaires was carried out in response to traffic, climatic conditions, et cetera, so that, whenever the traffic was low or snow covered the streets, the need for light was lower than in normal conditions and the illumination could be reduced. This resulted in a 30% energy savings and a prolonged life expectancy of the lamps (Black Sea Regional Energy Centre, 2007). In Finland, 492 luminaires with 600 W HPS lamps on a 4-km, six-lane stretch of Ring Road III form an intelligent road lighting system. The dimming level is from 40% to 100% of the rated power, with continuous dimming steps of 5%, in response to traffic, weather, and luminance information. The minimum luminance is 0.75 cd/m² when the lamps are dimmed to 40% of rated power. Guo (2008) studied the energy saving based on this intelligent road lighting system. He found the energy saving of about 41% compared to traditional lighting systems installed with the same kind of lamps (Guo, 2008).

It is only beyond the range of low beam headlights that the role of road lighting on visual performance is important (Boyce, 2009; Federal Highway Administration Research and Technology, 2015). This suggests that, in very dense traffic, road lighting has little contribution to visibility, while in very light traffic road lighting is significant beyond the range of low-beam headlamps (Boyce et al. 2009). However, in the above-mentioned practices², an increase in traffic volumes demanded an increase in lighting level. This suggests that the effect of car headlights should be taken into account in intelligent road lighting systems. It is essential to determine the required lighting level when car headlights are available. Consequently, more research is needed to find out possibilities to dim the road lighting to lower lighting levels when and where possible, depending on real-time conditions.

Road lighting for motorized traffic should correspond to the variable needs of traffic throughout the night. The visual performance of drivers is influenced, for

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² Yet some practices consider car headlights. For example, in IES recommendations (ANSI/IES (2014)) busy freeways are lighted to lower light levels than major roadways.
example, by road surface conditions, the combined effect of road lighting and car headlights, and glare from oncoming traffic. So far, there have been few controlled studies which compare visibility performance differences considering the combined effect of car headlights and different road lighting levels in different conditions and there is a general agreement on considering the combined effect of car headlights and road lighting while designing both technologies. (i.e. Akashi et al., 2003; Rea et al., 2010; Bullough and Rea, 2010; Skinner and Bullough, 2011; and Fotios et al., 2017). For example, Akashi et al. (2003) studied the detection distances to small targets under three roadway lighting levels (2-20 lux) and three low beam headlight levels (100%, 30%, and 10%). Their results indicated that ambient illuminance, target position, headlights and the interaction between the target position and ambient illuminance had a significant effect in target visibility. The main results from their study suggest that recognition distance appears to increase as ambient road lighting increases. The effect of road lighting on recognition distance becomes smaller as the target eccentricity angle increases (eccentricity angle of 15° to the right). Finally, in lower eccentricities (eccentricity angle 0 to around ± 5 degrees) the effect of headlights intensity on recognition distance is smaller than that of ambient road lighting illuminance. Therefore, the results from their study indicate the non-complementary effect of road lighting and car headlights and support the importance of road lighting intensity for visibility of targets on the road by lowering the car headlights luminous intensity (city beam 100 cd) in lit roads.

Another example of visibility differences considering different road lighting levels is by Rea et al. (2010) which concentrated on driver’s visual performance in intersections. They assessed drivers’ visibility with three passenger cars in the virtual intersection simulations in different scenarios. The variables were (a) the presence or absence of fixed roadway lighting, (b) four different ambient light levels (illumination 20, 2, 0.2 and 0.02 lx), (c) the hazard (target 18 cm×18 cm with reflection factor of 50%), d) observer locations and speed (higher vs. lower than 40 mph or 64 km/h), and (e) the light levels provided by different light configuration (continuous lighting, single pole at and near the intersection and no road lighting). Their main conclusions were that both low and high-speed intersections should be illuminated to provide high illumination especially for older drivers. For low-speed roadways, there is a substantial gain in visibility by lighting the intersection only with a single pole, while continuous lighting had little incremental benefit. Their results suggest that the main visual performance concern was at very low ambient light levels (0.2 and 0.02 lx), but illuminance from the urban environment or extended lighting from the road can improve visual performance of the intersection. They also noted minimum visibility where there was a transition in target contrast from positive (target brighter than surround) to negative (target darker than surround) values.

Even for non-motorised traffic, high lighting levels above 2 lx may not be necessary. Fotios et al., (2017) investigated the relationship between various road lighting levels and cycle-mounted lamps. They found that the detection distance changes by cyclists under road lighting alone when reducing illuminance from 20 lux to 2.0 lux was negligible, but a significant decrease in detection was found
at illuminance levels below 2.0 lux. In addition, they found that the position of cycle-mounted lamps is important at low road illuminances, when hub mounted lamps provided better detection than the handlebar-mounted lamps. Possible reasons were given to explain why hub mounted lamps provided better detection than other heights. For road lighting of low illuminance (0.2 lux), hub mounted lamps improved detection compared with detection when mounted at the vertically higher and more common location of the handlebar, because it tended to increase contrast. Also, length of shadow cast by the obstacle may have affected obstacle detection. With the cycle light mounted in the hub the shadow was longer (approximately 150 mm from far edge of obstacle to tip of shadow) than with the helmet-mounted lamp (approximately 40 mm).

As could be seen from previous studies, the combination of headlights and different road lighting levels can result in contrast reversals and hence reductions in target visibility. Therefore, before applying different road lighting levels, factors affecting visual performance of drivers to detect obstacles on the road under different scenarios should be considered, including different road lighting levels, car headlights, weather conditions, and inclusion of glare from an oncoming car. As a result, the first step toward implementing any intelligent road lighting practices is to consider the effect of these factors on visual performance. This information would be essential to the development of intelligent road lighting practices.

1.2  Aim of the dissertation

The main aim of this dissertation is to provide information about the effect of different road lighting levels under varying traffic (presence/absence of oncoming glare) and road conditions, considering the effect of car headlights. These factors have a major effect on the visual performance of drivers. In order to obtain the goal, three research questions have been defined:

**Research question 1 (RQ1):** what are the combined effects of car headlights and different road lighting intensities on drivers’ visual performance under different road surface conditions (dry, wet, snowy), when no glare from oncoming car headlights is present?

**Research question 2 (RQ2):** what is the effect of glare from an oncoming car on drivers’ visual performance under different road lighting intensities?

**Research question 3 (RQ3):** what is the combined effect of car headlights and different road lighting intensities on detecting the targets from a moving car?

The application of the results in intelligent road lighting will be discussed in the final chapter.
1.3 Structure of the dissertation

The dissertation consists of a summary and three original publications. Following this introductory section, section 2 presents a literature review about the effect of light on vision and methods of measuring this effect, history of two artificial lights (road lighting and car headlights), the effect of glare from an oncoming car, the effect of road surface conditions, the combined effect of road lighting and car headlights, effect of different road lighting levels and intelligent road lighting systems. Section 3 describes the materials and methods used in this study to evaluate visual performance of drivers in different scenarios. Section 4 summarizes the results of the study. Section 5 discusses the importance and applicability of the results, compare the results with previous studies, discusses the limitations and presents suggestions for future research.
2. Literature review

Chapter 2 begins by laying out the theoretical dimensions of light, its effect on vision, and how to measure its effectiveness. The second and third sections of this chapter focus on the history of the two artificial lights used in night-time driving: road lighting and car headlights and their effects on traffic safety. The combined effect of road lighting and car headlights, and the effect of different road lighting levels are discussed in the fourth and fifth sections. The remaining sections review studies about the effects of glare from an oncoming car and different road surfaces on visual performance. The last section gives a summary of the most important findings in the literature review.

2.1 Light and vision

Previous studies have indicated that road traffic accident risk is 1.5 to 2 times higher at night than during the day (Elvik and Vaa, 2009; Elvik, 1995; CIE, 1992). The increased risk of night-time accidents is mainly attributed to fatigue and alcohol (Åkerstedt et al., 2001; Lee et al., 2016). Limited night-time visibility, which is the focus of this study is another potential factor in increased risk of night time accidents (Leibowitz et al., 1998; Elvik, 1995).

Visibility is important because drivers need to visually perceive the road and objects ahead, process the perceived information and decide the action accordingly. The limited level of light during the night can affect visual performance of drivers which in turn affects traffic safety (Bremond et al., 2013). Before proceeding to understand how artificial lights (road lighting and headlights) can affect driver’s visibility performance, it is first important to understand how vision works.

In order to see, light rays should enter the eye passing through different tissues including cornea, lens, vitreous, onto the retina. The cornea is the outer transparent structure at the front of the eye, the lens is a transparent structure that helps to focus light on the retina. Vitreous is a clear jelly-like substance that fills the eye from the lens to the back of the eye, and finally, the retina is the light-sensitive layer of the eye. Figure 1a, shows the basic anatomy of an eye and Figure 1b, shows the structure of the retina.
After light reaches the retina it is converted into electrical signals. The complex structure of retina consists of three layers (Fig 1b): photoreceptors, bipolar cells (or collector cells), and ganglion cells. There are four photoreceptors each containing different photo-pigments and spectral sensitivity. These four photoreceptors are grouped into two main groups, rods and cones (Van Bommel, 2015; Eloholma, 2004). There is just one type of rod photoreceptor that contains the same photo-pigment. Rods are more numerous and sensitive than cones. However, they are achromatic and not sensitive to colour. There are three different cone photoreceptors with three photo-pigments that allow colour vision to occur. Each of the cones is sensitive to a range of wavelengths and colours. That is why they are also referred to as short (S), medium (M), and long (L) wavelength cones. Medium (M), and long (L) wavelength cones are mainly concentrated around the 2-degree visual field where there are no rods (fovea line of sight, central vision). The S cones have the highest sensitivity and are mostly found outside the fovea. Outside this 2-degree visual field, both rods and cones are responsible for peripheral vision. The three cone types are also not distributed equally across the retina. The L- and M-cones are concentrated in the fovea, their density declining gradually with increasing eccentricity. The S-cones are largely absent from the fovea, reach a maximum concentration just outside the fovea and then decline gradually in density with increasing eccentricity.


Figure 1: structure of a) an eye, b) Retina, c) spectral sensitivity of retinal rod and cone cells, and d) spectral sensitivity of eye for peripheral visual performance
Photoreceptor layer translates the absorption of light from the outside world into an electrical impulse. Bipolar and other collector cells pass these signals on to the ganglion cells. Ganglion cells collect the signals and transmit them into the optic nerves which pass them to the brain for processing. The output from the cones is subject to subsequent neural processing. Colour vision is the ability to perceive differences in the wavelength content of a light source. Human vision is trichromatic because there are only three classes of cone photoreceptor in the eye, each of which responds univariantly to the rate of photon absorption. CIE developed a set of three hypothetical or imaginary primaries X, Y, and Z in order to be able to match any colour by mixing these primaries with positive weights. The three fundamental primaries are the three imaginary primary lights that would uniquely stimulate each of the three cones to yield L-, M- and S-cone spectral sensitivity functions. Figure 1c shows absorption spectra of the three types of cones, short (S), middle (M) and long (L) wavelength and rods. All perceived colours can be obtained by mixing the outputs of three primaries (Wördenweber et al., 2007).

Activity of rods and cones depends on the adaptation luminance. Three different human vision ranges are classified on the basis of light level known as photopic vision, scotopic vision, and mesopic vision. Photopic vision refers to human vision at high ambient light level when vision is dependent on the cones. An obvious example of this is vision during daylight. The spectral sensitivity with photopic vision is characterized by the V(λ) curve and reaches its maximum sensitivity at a wavelength (λ) of around 555 nm, corresponding to a green-yellow colour (Figure 1d). The photopic vision system applies to luminance levels around > 3 cd/m². Scotopic vision refers to human vision at low ambient light levels when vision is mediated by rods, vision during the night is an example of this vision system. At low light levels, objects lose their colours and only appear to have different grey levels. The scotopic vision regime applies to luminance levels around < 0.003 cd/m². The spectral sensitivity with scotopic vision is characterized by the V′(λ) curve (Figure 1d). It reaches its maximum sensitivity at a wavelength of around 505 nm, corresponding to the colours blue-green. Finally, the term mesopic vision has been applied to situations where light levels are between photopic and scotopic vision regime (approximately 0.003 cd/m² < mesopic luminance < 3 cd/m²) as a result, the spectral sensitivity gradually shifts into the direction of short wavelengths—that is to say in the direction of blue (DiLaura et al., 2011).

During the night, due to low lighting level and mesopic vision, recognition of colour varies with the amount of light available and viewing conditions in the road. Also, the effect of colour contrast measurements on overall visibility under differing ambient lighting and vision conditions differs. Therefore, due to the dynamic lighting conditions (i.e. road lighting, car headlights, ambient lights

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4 Reference to the image: https://commons.m.wikimedia.org/wiki/File:1416_Color_Sensitivity.jpg
5 Reference to the image Figure 1 d) (Van Bommel, 2015)
6 Luminance is the measure of the luminous intensity per unit area of light travelling in a given direction, unit (cd/m²).
etc.) during night-time driving, most researchers measure luminance contrast, not colour contrast, in night-driving studies (FHWA, 2015). The ability to see differences in brightness, i.e. contrast, is a fundamental function of the visual system. Luminance contrast ($C$) is expressed as:

$$C = \frac{L_t - L_b}{L_b},$$  \hspace{1cm} (1)

in which $C$ is contrast, $L_t$ is the luminance of the target, and $L_b$ is the background luminance. The higher the absolute value of the contrast, the more visible the target becomes.

Targets on the road can have a positive or negative contrast due to their polarity differences from their backgrounds: negative contrast occurs when the target appears darker than the background (negative polarity), and when the target is lighter than the background, the luminance contrast is positive (positive polarity) (Ekrias, A. et al., 2008). According to Equation (1), negative contrast ranges from -1 to 0 and positive contrast ranges from 0 to infinity. Consequently, contrasts of equal absolute value but with opposite signs (positive or negative) do not lead to equal visual performance. To find equal visual performance, the contrast can be obtained from a reconsidered equation (2), in which contrast equals the absolute value of the difference between target and background luminance divided by the larger of the two luminances (Janoff, 1992), i.e.

$$C = \frac{|L_t - L_b|}{\max(L_b, L_t)}. \hspace{1cm} (2)$$

Contrast describes the amount of the difference in the luminance between an object and its immediate background, and it does not take into account objects size, drivers’ age, observation time, etc., which have an effect on lighting quality. Several visibility metrics, that are correlated with night-time traffic accidents, are available, including visibility level (VL), Relative Visual Performance (RVP), small target visibility (STV), psycho-visual tests (subjective assessment of visibility), and detection distance. Some of the most used metrics in literature, VL (Mayeur et al., 2010; Bacelar, 2004) and RVP (Freyssinier et al., 2008; Bullough and Skinner, 2009), psycho-visual tests, and detection distance are explained here.

Visibility Level (VL) by the Adrian model (Adrian 1987, Adrian, 2005) which is used in this dissertation, is a model to assess one aspect of road lighting quality (Mayeur et al., 2010). The amount of visibility calculated by the Adrian model is the ratio between the difference of luminance between target and its background and the threshold contrast needed for 99.99% detection. Contrast threshold is the function of size, contrast polarity (positive or negative), background luminance, age, possible disability glare, and observation time (Mayeur, 2010). When VL of an object is less than one, it is invisible; when is greater than one it is visible. A higher VL indicates higher visibility but it is important to keep in mind that VL is not linearly proportional to visibility, visibility of an object negligibly increase after certain VLs. For example, a visibility level, VL, of 10
Literature review

does not correspond to a situation that is twice as visible as one with a visibility level of 5. The level of visibility often becomes saturated at VL higher than 10 to 15 (Van Bommel, 2015). Visibility level (Adrian 1987) is calculated as

\[ VL = \frac{\Delta L_{\text{actual}}}{\Delta L_{\text{threshold}}} \]  

(3)

\( \Delta L_{\text{actual}} \) is the luminance difference between the target and its background in the real condition, i.e.

\[ \Delta L_{\text{actual}} = |L_t - L_b| \]  

(4)

where

- \( L_t \): target luminance
- \( L_b \): background luminance

\( \Delta L_{\text{threshold}} \) is the luminance difference needed for minimal visibility, between a target of certain angular size and its background.

\[ \Delta L_{\text{threshold}} = k \left( \frac{\sqrt{g}}{a} + \sqrt{L} \right)^2 \frac{a(aL_f + t_g)}{t_g} F_{cp} AF \]  

(5)

The details of equation 5 (Adrian 1987) are provided in Appendix A.

**Relative Visual Performance (RVP)** is yet another measure of visual system, representing speed and accuracy of processing visual information. Rea and Ouellette (1991) developed the measure based on two experiments. One experiment measured response times to flashed targets that are different in size and luminance contrast to their background. The second experiment was performed under a range of lighting and luminance contrast conditions. It measured the speed and accuracy with which people could perform a numerical verification task consisting of pages printed with two matching columns each containing twenty five-digit numbers, and on each page subjects were instructed to identify mismatches digits. RVP model is shown in Appendix B.

RVP value is a function of background luminance, luminance contrast and visual size. Relative visual performance is compared to speed and accuracy of a reference condition corresponding to high light levels, high luminance contrast and large size (e.g., reading black 10-point type on white paper under typical office light levels), which is defined to have an RVP value of 1.0. RVP values close to 1.0 are expected to result in similar speed and accuracy as the reference visual task. RVP values of zero correspond to the threshold for legibility or recognition, and negative RVP values correspond to visual targets that can be detected but not recognized. Also, it is found that the RVP value of 0.8 corresponds to the point at which a driver would start to react in response to a potential roadway hazard (Bullough, 2015).

Research has shown that RVP model matches well with night-time driving conditions (Freyssinier et al., 2008; Bullough and Skinner, 2009). Bullough and Radetsky (2014) reviewed the literature to investigate the correlation between
RVP model and various tasks associated with night-time driving (i.e. pedestrian identification, sign legibility, detection distance, night-time safety). They concluded that the RVP model correlated well with detection distances, response/identification times and traffic safety related to intersection road lighting.

One advantage of RVP over VL is its characteristic that under saturation of visibility further improvements in contrast or background luminance have hardly any effect on improvements in visibility (RVP values higher than about 0.9 which correspond to the plateau of the RVP body). Also, RVP values lower than 0.7 correspond to the area on the steep downwards slope (escarpment). Only for low RVP values (<0.7) small reductions in contrast and/or background luminance have a strong negative effect on RVP and, thus, on the speed and accuracy of visual processing (Van Bommel, 2015).

Parallel to the models above, psycho-visual tests have been used. Such tests focus on observer’s subjective impression of their visual performance. Participants use a subjective scale (Table 1) to grade how well they can see the target in different scenarios. Normally, a scale from 1 to 5, as shown in Table 1, is used to rate the visibility of targets. These are subjective evaluations of how well participants think they can see the target under each test condition, not how well they actually see it.

### Table 1: Psycho-visual scale

<table>
<thead>
<tr>
<th>Invisible</th>
<th>Poor</th>
<th>Satisfactory</th>
<th>Good</th>
<th>Very good</th>
<th>Excellent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Several studies have used this method (e.g. Janoff, 1992; Menard and Cariou, 1994; Bacelar et al., 1999; Bacelar, 2005; Guler and Onygil, 2003). For example, in a study by Janoff (1992) subjects had to rate visibility on a 0-5 scale under different test conditions. He planned twenty-four conditions using a combination of two road lighting systems, two target positions, and six different targets. His findings support the possibility of only exploring contrast and VL to estimate visibility performance of drivers.

Psycho-visual tests are typically used for discomfort glare evaluation using the deBoer Scale. It is a nine-point scale where the participants rate the glare impression with qualifiers for the odd points as follows: 1 (unbearable), 2, 3 (disturbing), 4, 5 (just acceptable), 6, 7 (satisfactory), 8, 9 (just noticeable). Sivak et al. (2005) studied the effect of blue content of headlamps on discomfort glare on participants. Subjects seated in a stationary car rated discomfort (1-unbearable to 9-just noticeable) from brief presentations of stimuli produced by illuminances of 0.25, 0.5, and 1 lux from three LED headlamps, as well as tungsten-halogen headlights and HID headlights. They found that LED headlights produced more discomfort glare because they had bluer content than tungsten-halogen or HID headlamps.

Another method of evaluating visibility performance is detection distance (Brémond et al., 2012). Because for traffic safety, sight distance should be of a sufficient length so that drivers can control the operation of their cars to avoid striking an unexpected object. Some studies have evaluated VL at the time of
target detection (Brémond et al., 2010). In detection distance studies, the dis-
tances at which the drivers were able to detect and recognize different objects
were evaluated. For instance, Blanco et al. (2005) assessed visual performance
during night-time driving by detection and recognition of different objects as
well as subjective performance ratings at the time of detection. They studied
how different vision enhancement systems (i.e. halogen low beam, halogen high
beam, ultraviolet A, etc.), age, and type of object (pedestrian, cyclist, etc.) can
affect the detection and recognition of different types of objects. Their results
suggest that although halogen headlights (low-beam configuration) consistently
provided the longest detection and recognition distances, they were not signifi-
cantly different from other vision enhancement systems. Janoff et al. (1986)
studied the detection distance of a small target (3D shape, 0.15 m in size with
reflection factor of 18%) with the speed of 89 km/h under different road lighting
conditions, including no lighting, every other luminaire extinguished, lumina-
naires on one-side of the roadway extinguished, and different kind of dimming
levels. Their results indicated significant differences between full road lighting
and other road lighting intensities. The best detection distance was achieved
under full road lighting conditions, with orderly decrements in performance
noted for uniform dimming to 75% power, 50% power, every other luminance
extinguished, one side extinguished, and no lighting condition, respectively.

2.2 Road lighting for motorised traffic

The origin of road lighting can be traced back to the fifteenth century, with the
goal of crime reduction (Hargroves, 1983). In Paris, a lantern had to be hung
out under the level of the first-floor window sills in such a position that the street
receives sufficient light during the night (Boyce, 2009). In the seventeenth cen-
tury, lanterns were mounted on suspended cables fifteen feet above streets. Pul-
leys at each side allowed for servicing from adjoining buildings (Landmarks
Preservation Commission, 1997). The demand for road lighting at night has in-
creased with urban growth, especially with the introduction of gas lighting by
1805 when the roads were permanently lighted by gas. For instance, by 1823,
215 miles of London streets were lighted with over 39,000 gas lamps. Gas road
lighting maintained a considerable presence well into the twentieth century, and
long after the introduction of electric street lighting (Landmarks Preservation
Commission, 1997). Electric road lighting technologies have developed from in-
candescent lamps to fluorescent, mercury vapour, low-pressure sodium, high-
pressure sodium, and metal halide. Currently, LED technology is known as an
energy-efficient light source technology (Li et al., 2009) in regard to improved
efficiency, cost saving as well as lifespan, colour properties, dimming ability,
and run-up and re-ignition times of road lighting (Tetri et al., 2017).

Currently, it is becoming difficult to ignore the energy consumption, electricity
costs and environmental pollution related to road lighting. The International
Energy Agency has evaluated that in 2005, 19% of the total global electricity
consumption was used for lighting of which road lighting used 218 TWh
amounting to about 8% of lighting electricity consumption (IEA, 2006).
In addition to energy consumption and costs, light pollution originating from road lighting can be considered an environmental problem. This issue is mainly considered as obtrusive light (e.g. impact on human and on the environment, skyglow\textsuperscript{7} and trespass\textsuperscript{8}) (Gaston et al., 2012; Luginbuhl et al., 2014). To minimize these impacts, the International Dark Sky Association and Illuminating Engineering Society of North America (IES) have developed road lighting ordinances based on the environmental sensitivity of the areas. The goal of this zoning is to reduce glare, light trespass and skyglow (IES, 2011).

Tähkämö and Halonen (2015) conducted comparative life cycle assessment studies of LED and HPS luminaires. The results indicated that, excluding impacts of obtrusive light, the total environmental impacts caused by the production, use, and disposal of the energy and materials of both technologies are at a similar level. Considering a kilometre of a lit road as the functional unit, the environmental impacts of HPS luminaires were on average 3% lower than those of LED luminaires. The main environmental impacts in both technologies were generated in the use-phase of the luminaires, 96% in case of HPS and 87% in case of LED luminaires. Manufacturing and end-of-life entail much smaller impacts, 4% and 13% in manufacturing and less than 1% in the end-of-life phase, for HPS and LED luminaires respectively. Although environmental issues are not within the scope of this research, lower lighting intensities, based on the prevailing need for artificial light, can reduce the environmental impacts of road lighting.

In respect to the cost analysis for the high-pressure sodium and light-emitting diode luminaires, Tähkämö et al. (2016) conducted a life-cycle cost analysis. The analysis took investment costs (including the purchase prices of all parts, freight and installation costs), operating costs (the energy and maintenance costs), and residual value over a 30-year time frame into consideration. The study excluded the previous installations, poles, wiring and other infrastructure. Their results indicated that LED luminaire had greater life-cycle costs compared to the HPS luminaire. The total life-cycle costs of HPS luminaires was 45 % lower than those of LED luminaires per kilometre. But their sensitivity analysis indicated that there were circumstances where the cost-efficiency of the LED luminaire was particularly improved, circumstances such as increased electricity price, exclusion of spot replacements, reduced purchase price and modularity of the LED luminaire. Thus, they expected that LED technology will become more economical in the future due to the development in luminous efficacy, improved product quality, reduction in the purchase price and the enhanced competition in the LED segment.

A range of guidelines exists for appropriate lighting levels for different types of users, modes of traffic, speeds, etc. Since the focus of this thesis is motorised traffic, only recommendations for motorised traffic are provided. The International Commission on Illumination (CIE), provides the basis for many of the national and regional recommendations in the world. In CIE recommendations,\textsuperscript{7} Skyglow refers to the increased brightness of the night sky.

\textsuperscript{8} Light trespass refers to unintentionally lit areas.
the lighting quality parameters for road lighting design are lighting level (average road-surface luminance), uniformity (overall and longitudinal uniformity) surround lighting (surround ratio), and glare restriction (threshold increment). **Average road-surface luminance** ($L_{ave}$) is luminance averaged over the specified surface. **Overall luminance uniformity** refers to the ratio of the minimum luminance at a point to the average road surface luminance over an evaluation area. **Longitudinal uniformity** refers to the ratio of the minimum to the maximum luminance along a line parallel to the length of the roadway. **Surround ratio** detects if the road luminaire distribution pattern is too sharp. Surround ratio is the average illuminance on strips, which are adjacent to the edges of both sides of the carriageway to the average illuminance on the adjacent strips in the carriageway. **Threshold Increment** (TI) is a measure of disability glare expressed as the percentage increase in contrast required for equal visibility when a source of glare is introduced. Higher values of TI correspond to greater disability glare (De Boer and Schreuder, 1967).

In the European Committee for Standardization (CEN) the criteria for selecting the lighting class are similar to the CIE recommendations. Thus, similar to the CIE recommendations, they correspond to six lighting classes for motorised traffic (M1-M6). In Europe, the recommended average road surface luminance ($L_{ave}$) is between 0.3 – 2 cd/m² (CEN, 2003). Illuminating Engineering Society of North America (IESNA) provides basis for road lighting design for roadways, streets, adjacent bikeways, and pedestrian ways. As far as motorised traffic is concerned, the standard recommends the luminance design for the straight roadways and streets, and horizontal illuminance design for intersections and interchanges. The criteria used for luminance and illuminance are largely the same as those of CIE. There are a few differences between the Illuminating Engineering Society of North America (IESNA) and CIE recommendations. For instance, IES does not include surrounded ratio or threshold increment, instead, they provide upper limits values for veiling luminance. In IES, the recommended average road surface luminance ($L_{ave}$) is between 0.3 – 1.2 cd/m² (Van Bommel, 2015).

Reduction of night-time accidents has become the main justification for installing lighting (Hargroves, 1983). To measure the effect of road lighting on accidents, accident data has been compared either as cross-section studies between lit and unlit conditions, or as before-after studies on the roads where lighting did not previously exist and was then introduced or where improvements have been made to road lighting. Two common metrics to quantify the effect of road lighting on accidents are crash-rate ratio and odds ratio.

Crash-rate ratio compares the number of crashes within a certain period of time in lighted and unlighted conditions per vehicle-miles driven. If there are no other confounding factors related to the accidents and the ratio is lower in lit conditions than in unlit conditions then a reduction in nighttime crash risk may exists (Rea et al., 2009).

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9 Luminance refers to luminous intensity, per unit projected area. The unit of luminance is cd/m²
Another method is odds ratio. Odds ratio determines the risk of a particular outcome if a certain treatment is present. In terms of traffic safety, considering the effect of road lighting, the odds ratio is based on the number of crashes and it does not refer to any data regarding the distribution of traffic between lit and unlit. It can be calculated using equation (6) below:

\[
\text{Odds ratio} = \frac{\text{No. accidents in darkness on lit roads}}{\text{No. accidents in darkness on unlit roads}} + \frac{\text{No. accidents in daylight on lit roads}}{\text{No. accidents in daylight on unlit roads}}
\]

If there are no confounding factors involved in the accidents odds ratios equal to 1 suggest that road lighting has no effect in number of night-time accidents. If the ratio is less than 1, lighting may reduce the number of night-time accidents, otherwise (odds ratios greater than 1) lighting may increase the number of night-time accidents. Table 2 summarizes some of the previous research on the effect of road lighting on traffic accidents.

<table>
<thead>
<tr>
<th>Research</th>
<th>Database and method</th>
<th>Results (reduction in night time accidents)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIE, 1992</td>
<td>62 before and after studies</td>
<td>-30% all type of accidents</td>
</tr>
<tr>
<td>Elvik and Vaa (2004)</td>
<td>meta-analysis of 38 studies</td>
<td>-64% fatal accidents</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-28% injury accidents,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-17% property-damage-only</td>
</tr>
<tr>
<td>Wanvik (2009)</td>
<td>traffic collision database</td>
<td>-49% on fatal crashes</td>
</tr>
<tr>
<td></td>
<td>1987–2006</td>
<td>-46% on injury crashes</td>
</tr>
<tr>
<td>Jackett and Frith (2013)</td>
<td>traffic collision database</td>
<td>-19% in all type of crashes by each 0.5 cd/m² increase in Lave</td>
</tr>
<tr>
<td></td>
<td>2006-2010</td>
<td></td>
</tr>
</tbody>
</table>

As demonstrated in Table 2, road lighting can reduce the night-time accidents. However, the findings have been inconsistent. An overview of 62 before and after studies in 15 countries indicated that the average effect of road lighting installation on the reduction of accidents was 30% (CIE, 1992). In a meta-analysis of 38 studies, Elvik and Vaa (2004) found that the use of road lighting on previously unlit roads led to a 64% reduction in fatal accidents, a 28% reduction in injury accidents, and a 17% reduction in property-damage-only accidents. Wanvik (2009) estimated the effect of road lighting based upon the Dutch database of traffic collisions in the Netherlands covering the period 1987–2006 on motorways with a speed limit of 120 km/h. British and Swedish data were also used. Odds ratio was used as estimator of effect. He found a reduction of 49% on fatal crashes and 46% on injury crashes. A more recent study by Jackett and Frith (2013) used night/day crash ratios to study the impact of road lighting on road safety based on the total crash number of 79,444 during 2006 to 2010 in New Zealand. They found that for each 0.5 cd/m² increase in average luminance a reduction of 19% in all type of crashes can be expected.
The differences in the results of previous studies can be explained by a number of aspects. One important factor is the noise in studying the relationship between road lighting and accidents. For instance, in odds-ratio studies only the number of accidents are being used and traffic distribution, drivers’ behaviour, road conditions etc. are not considered (Wanwik, 2009). For instance, Assum, et al. (1999) investigated speed-behaviour before and after the introduction of road lighting. He concluded that drivers increase their speeds in the lit roads. He also noted that the increase in speed does not reduce the effectiveness of road lighting during darkness.

Overall, it is hard to estimate the effect of road lighting on accidents because there are many other factors that can influence the risk of accidents. Donnell et al. (2010) who proposed a framework to estimate the safety effects of fixed lighting at a variety of intersection types and locations, reminded that (intersection) safety is influenced by a number of factors, not only lighting. Therefore, omitting these variables from analysis leads to biased findings, particularly if these features are correlated with lighting presence. A safety assessment of lighting should include the expected crash frequencies conditioned on the values of other safety influencing features (Donnell et al., 2010).

2.3 Car headlights

The origin of car headlights can be traced back to the nineteenth century with the use of candles and oil burning lanterns on the horse-drawn carriages. At the advent of cars at the end of the 1880s, no lighting was associated with them. Thus, night-time driving was forbidden. The first car headlights were oil burning lanterns that allowed people to start driving at night. Such headlights were used until 1900 as signals to drivers of other vehicles, carriages and to pedestrians, and improving the visibility of the road. The first car headlights using a carbon filament were used in the U.S. in 1908 as optional equipment. First electric headlights were installed as standard equipment on U.S. passenger cars in 1911 and in 1913 on European passenger cars. Before 1924 there was only one beam pattern resembling today’s high beam headlights. It was not until mid-twenties that two-beam patterns were developed (Moore, 1998).

The first lighting regulation was adopted in the state of Massachusetts in 1915 (Devine, 1921): “This regulation provided that wherever there was not sufficient light on the highway to make all substantial objects visible for a distance of at least 150 feet (45.7 m), the lamps which a motor vehicle was required to display, should throw sufficient light ahead to make clearly visible any such object within the specified distance. They provided further that any light thrown ahead or sidewise should be so directed that no dazzling rays should at any time be more than 3.5 ft (1.1 m) above the ground 50 ft (15 m) or more ahead of the vehicle, and that such light should be sufficient to show any substantial object 10 ft (3 m) on each side 10 ft (3 m) ahead of the vehicle.”

Light distributions and placement of car headlights are regulated. They should follow either the recommendations of the Economic Commission for Europe (ECE, 2003) or the US Federal Motor Vehicle Safety Standard (FMVV, 2004).
Comparison between these standards indicate some similarities and some differences. The maximum luminous intensity values allowed for high beam headlights are higher in the ECE regulations than in the regulations used in North America. Although low beams regulations for both North American and ECE regulations beam pattern are similar (they both emphasize the near side of the road and a limit luminous intensity directed towards vehicles approaching in the opposing lane), they differ in the luminous intensity distribution towards the approaching driver. The ECE low beam has a much sharper cut-off than the North American low beam, indicating the greater emphasis given to controlling disability glare (Boyce, 2009).

In addition, it is important for headlights to be properly aimed\textsuperscript{10}, because misaimed headlights can result in discomfort glare and reduce the visibility of drivers. The effect of misaimed headlight can be minor or dramatic, depending on the amount of misaim, but the effect of horizontal misaim is not as large as that of vertical misaim (Mace et al., 2001). Sivak et al. (1993) found that horizontal misaim of 1.5 degrees in either direction had no practical significance with the U.S., European, or Japanese headlights. However, vertical misaim of 1.5 degrees had practical significance for U.S. headlights and even 1 degree miscalculation resulted in significant effects for U.S. and European headlights. As Skinner et al. (2010) demonstrated, misaimed headlights can be commonly found in the U.S. because in some states aim status of the headlights is not part of annual safety inspections. Misaimed headlights can result from a number of factors such as duration of service, ageing of the lamp and optical system, vehicle body condition, vehicle loading and tire condition (Skinner et al. 2010). Skinner et al. (2010) assessed headlights aim of 120 new and old headlights (102 privately owned cars and 20 new cars). They considered a misaim headlight to have a vertical orientation that is 0.76\degree or more from a horizontal reference (Society of Automotive Engineers, 2002). Their results show that on average, headlights of used cars were aimed slightly downward, while new cars were aimed correctly. Also, 60\% of used cars had at least one misaimed headlight. Approximately 45\% of the new cars had at least one headlamp misaimed. However, there were not any statistically reliable relationships between vertical misaim and vehicle age, vehicle type, headlamp optical systems or headlamp source (i.e., halogen versus high-intensity discharge). They encouraged regular assessment of car headlight aim because having downward aimed headlights results in reductions in forward visibility and upward aimed headlights results in discomfort glare.

The technology of headlights is also shifting from halogen headlamps to High-intensity Discharge (HID) headlamps and LED headlights. The three important visibility factors in headlamps are the amount of light they produce, the luminous intensity distribution and the spectral power distribution of the emitted light (Boyce, 2009). HID headlights generate more light than halogen headlights. As regulations specify minimum and maximum values of luminous intensities at central axis of the beam, the extra light provided by HID headlights is directed to the peripheral angles of the beam. Therefore, HID headlights allow

\textsuperscript{10} Misaiming shifts the beam pattern horizontally or vertically.
longer detection distances and over a wider range of angles than Halogen headlights (Boyce, 2009).

Bullough and Rea (2010) compared visibility performance under different headlight-types, and ambient luminance (from private or public electric lighting). The headlights studied were halogen low-beam, HID low-beam, and halogen high-beam. Four levels of ambient illumination were from private or public electric lighting of the road and ranged from high-urban to rural lighting levels, specifically 20, 2, 0.2 and 0.02 lx. The car was located 150 ft (=46 metres) from the centre of the intersection while a target of 7 x 7-inch (=18 cm x 18 cm) with a reflectance of 0.5 was placed in 60 and 120 ft (=18.3 metres and 37 metres) ahead of the driver along the passenger side of the road. Studied scenarios were developed on lighting calculation and simulation software (AGi32, Lighting Analysts). They indicated that at 60 ft from the car, the highest vertical illuminance on targets was provided by low beam HID, then by high beam halogen and low beam halogen headlights, respectively. At 120 ft from the car, the highest vertical illuminance on targets was provided by high beam halogen, then by low beam HID, and low beam halogen headlights, respectively. Apart from vertical illuminance by headlights, they used RVP model to study visibility performances at different scenarios. The results from RVP reveal that with no road lighting, the low beam HID headlamp beam pattern resulted in the best visual performance, with little difference between the halogen low beam and the high beam headlamp beam patterns. The reason is the broader beam pattern produced by HID headlights relative to halogen headlamps as well as higher vertical illuminances than the other options. They argued that when there is no road lighting or when ambient light is low (i.e. rural areas) higher peripheral illuminance provided by HID headlights in comparison to other headlights gives better possibility to see hazards.

Aside from greater light efficiency (lumens per watt) and longer life of HID headlights over halogen headlights, higher illumination of HID headlights over halogen headlights appears to be the primary appealing factor from driver’s point of view. Sivak et al. (2002) studied the benefit of a wider beam pattern by HID versus halogen headlights by conducting two experiments. First, they assumed that the wider pattern of HID should decrease the workload required for road-tracking, thus should make the steering task less demanding. To measure workload, they used frequency band between 0.3 to 0.6 Hz as an index of steering task difficulty. Two similar sedan cars, one equipped with HID low beams and the other with tungsten-halogen low beams were used. Sixteen subjects drove 20 km long route (including rural, urban, and limited-access) twice with different headlights. The instructions of the first experiment did not prime the subjects that the focus was on headlights. From the total route of 20 km, they selected 7 km from three relatively dark and straight segments for their analysis, their results indicated that statistically significant difference between headlights and steering performance. The HID headlights yielded a lower percentage of steering effort in the 0.3 to 0.6 Hz range than the tungsten-halogen headlights. Second, they assessed drivers' preference for HID versus tungsten-halogen low
beams via a rating scale (range from 1 = very good to 5 = very poor). Eight drivers from their first experimental study had driven the cars (once with HID headlights and then with halogen headlights, no randomisation) on a 5-km long route, the subjects were asked to rate several performance aspects (i.e. making objects stand out, performance on curves, the general appearance of colours, evenness of light distribution, etc.) of each lamp type using a five-point rating scale. The subjects were primed to pay attention to the headlights. This time, however, they were asked to concentrate on the headlights of the cars and to make some ratings of those lamps. The results indicated that the effect of lamp type on workload was statistically significant, and HID headlights yielded a lower percentage of steering effort in the 0.3 to 0.6 Hz range than did the tungsten-halogen headlights. Surprisingly, their second study indicated that both HID and halogen headlights got good grades for all studied aspects. But when the driver’s attention was primed to different headlight types, they overwhelmingly preferred HID lamps (Sivak et al., 2002). Their argument relies mainly on the evaluation of headlights by eight drivers. The authors did not use other methods, such as distance detection or other visibility performance studies, to confirm their questionnaire evaluation.

LED headlamps have many advantages compared to other traditional headlamps. They have longer lifetimes, produce less pollution and consume less energy than conventional headlamps (Hamm 2009). Hamm (2009) compared LED headlights with other conventional headlights based on energy use. He noted that LED headlights save 92 watts/km in comparison with other conventional technologies. Also, for average cars and speeds, LED headlights resulted in 2.4g/km CO2 less pollution than other conventional headlights. Furthermore, typical LED headlamp uses about 80% of the energy consumption of a halogen headlamp (Kang et al., 2010). Kang et al. (2010) compared Halogen (H7 lamp type, luminous intensity at distance of 25 m 19.97 cd, main wavelength 588 nm, distribution of main wavelength 62.5%, luminance 1210 cd/m²), HID (D2R lamp type, luminous intensity at distance of 25 m 21.16 cd, main wavelength 580 nm, distribution of main wavelength 53.1%, luminance 1470 cd/m²) and LED headlights (S-model LED, luminous intensity at distance of 25 m 37.73 cd and M-model LED, luminous intensity at distance of 25 m 26.42 cd, main wavelength 466 nm, distribution of main wavelength 28.9%, luminance 3071 cd/m²) in relation to photometric performance, discomfort glare, sensitivity glare, and visibility by simulation and experimental studies. They studied photometric performance using luminous intensity from a distance of 25 m and chromaticity at a distance of 4.25 m in a dark room undisturbed by other light sources. Their results indicated that LED headlights have better luminance intensity than halogen and HID headlights. However, in respect to the illumination length and width, HID provided the highest performance, followed by LED and halogen headlights. Chromaticity results revealed that the white light from LED headlights fell in close proximity to the blue-green area, and that LEDs did not satisfy the chromaticity requirements of Korean Motor Vehicle Safety Standard. Kang et al. (2010) also studied discomfort glare (using De Boer
comfort glare rating by applying illuminance at the driver's eye point, adaptation luminance, and the angle between the glare source and the observer's fixation point) and sensitivity glare (subjective visibility test while driving in presence of glare from oncoming headlights). For discomfort glare study, they placed an illuminance meter on the driver's seat at the eye level, about 1.2 m above ground, in a subject car. Then the illuminance of the oncoming car for every 10 m, starting from a distance of 100 m, was measured. The oncoming car had different headlights (halogen, HID and LED headlights). They calculated the representative De Boer subjective (De Boer, 1967) rating based on measured illuminances under different headlights (halogen, HID and LED headlights), adaptation luminance of 1 cd/m², and the angle between the glare source and the observer’s fixation point. The De Boer rating is graded by nine levels, with the lowest acceptable value of 5. A higher rating means less glare. All the studied headlight sources by Kang et al. (2010) provided acceptable rating value (5 De Boer rating). Since the light sources delivered different light colours, they also studied sensitivity glare. In that experiment, subjects were driving toward other cars with different headlights 100 m distance apart from each other. They had to rate how their vision was affected by different headlights (discomfort glare). The results indicated that subjects were more sensitive to LED headlamps than that of halogen and HID headlamps due to the colour coordinate of LED light, which is more concentrated in the blue zone. To explain, human eyes become very sensitive to short wavelengths (450 nm to 500 nm) at night (Flannagan et al., 1994; Bullough et al., 2003). They analysed the spectrum of white LED light sources and found the maximum energy to occur at a primary wavelength of 466 nm. Halogen and HID lamps have main wavelengths of 588 nm and 580 nm, respectively. The primary wavelengths of halogen and HID lamps are outside the sensitive band. Thus, the light from LED headlamps results in higher discomfort glare than from conventional headlights. This analysis reveals that discomfort glare experimented by subjects is significantly affected by both colour and wavelength of light. The study of visibility was conducted only for LED and halogen headlights and carried out by measuring recognition of road signs or road studs11 at short and long distances (evaluation rating ranged between 5 to 1: 5 represented excellent visibility and 1 represented very poor visibility). The results indicated that at both distances drivers could see more road studs and signs with LED headlights due to the wider beam than halogen headlights. (Kang et al., 2010). Flannagan et al. (1994) studied discomfort glare and brightness as a function of wavelength. A combination of wavelengths (480, 505, 550, 577, 600, and 650 nm) with different illuminances (with average levels of 4.2, 0.6, and 0.1 lux), and visual eccentricity (0 and 10 degrees) were presented to sixteen subjects. Subjects were divided into two groups, some had to rate how much discomfort they felt due to glare from each stimulus and the other group had to rate how bright each stimulus looked to them. Average background luminance was 0.10 cd/m². Their results indicated that both discomfort glare and brightness are a u-shaped function of wavelength. The least discomfort glare and brightness were experienced at 577 nm (yellow) and the greatest discomfort

11 raised pavement marker
glare and brightness was at 480 nm (blue), followed by 650 nm (red). Also, they noted that discomfort glare was highly correlated with the brightness (r = 0.98).

Similar results have been found by Sivak et al. (2005) who studied discomfort glare produced by LED headlights and compared it with HID and Halogen headlights. They evaluated the effect of blue content of headlamps on discomfort glare. In their experimental study, twelve subjects rated discomfort glare from 3 seconds presentations of stimuli based on the De Boer ratings. In each trial, two subjects were seated in a stationary sedan. Forty meters in front of the car there was five different headlights. The lamps were spaced laterally with their centers 42.5 cm (0.6° at 40 m) apart. The LED lamps were presented only at the three middle locations. The tungsten-halogen and HID lamps were presented only at the outermost locations. A large blackboard including five apertures was used to mask the lamps, through which individual lamps were shown when corresponding shutters were lifted. Each aperture was 15 cm wide and 7 cm tall. On each trial, one lamp was presented for three seconds. The presentation order was randomized within each block. The first block of 15 trials served as practice to allow subjects to familiarize themselves with the task. For each trial, the subjects were instructed to look at one of the fixation points. Each fixation point was positioned 0.5° (at the viewing distance of 40 m) below the center of the lamp to be presented on that trial. Thus, in each trial subjects saw only a large, blackboard with small white fixation dots illuminated by the subject vehicle low beams. The variables were five lamp types (tungsten-halogen, HID, and three LED types). The three LED headlights had correlated-colour-temperatures (CCT)\(^\text{12}\) of 4000, 4800, and 6600 K. Three levels of illuminance produced by headlights were of 0.25, 0.5, and 1 lux. Their results indicated that the effect of lamp type was statistically significant. Discomfort glare was lowest for the tungsten-halogen lamp, followed by the HID lamp, LED-4000, LED-4800, and LED-6600. LED headlights appear bluer than tungsten-halogen or HID headlights and generate more discomfort glare. The effect of illuminance was statistically significant, with the amount of discomfort monotonically related to the amount of illuminance. However, there was no statistically significant interaction of lamp type and illuminance. Regarding stimulus size, they noted that the effective stimulus size is related to stimulus uniformity. Giving the example of a stimulus for which 99% of the intensity is emitted through the central 50% of the nominal area. In such a case, the effective size of the stimulus is likely to be only 50% of what it would be if the stimulus was completely homogenous. Therefore, they evaluated the uniformity of the five lamps by masking each lamp down to 25% of the area centered on the center of the lamp. Meaning that the outer part of the nominal size of the lamp (15 cm × 7cm) was covered to get the light output from the central part of the lamp (7.5 cm × 3.5 cm). They then measured the resulting light output. If the lamps were perfectly uniform, masking down the area to 25% of the full area would have produced 25% of the full light output.

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\(^{12}\) The correlated colour temperature (CCT) is a specification of the colour appearance of the light emitted by a lamp, relating its colour to the colour of light from a reference source when heated to a particular temperature, measured in degrees Kelvin (K). The CCT rating for a lamp is a general "warmth" or "coolness" measure of its appearance. For example, a "warm light" is around 2700K, moving to "neutral white" at around 4000K, and to "cool white", at 5000K or more.
output. The results indicate that for both the tungsten halogen and HID lamps, less than 25% of the output (5%) was due to the central 25% of the area. On the other hand, for all three LED lamps, more than 25% (50% to 58%, depending on the lamp) was due to the central 25% of the area. They conclude that the LED lamps might have been perceived as somewhat smaller than the tungsten-halogen and HID lamps. Consequently, a small part of the difference in discomfort between the tungsten-halogen and HID lamps on one hand and the LEDs on the other could be due to the effective stimulus size. Therefore, they noted that the effective stimulus size should have had no effect on either the differences in discomfort ratings between the tungsten-halogen and HID lamps, or the differences among the three LED lamps. They suggested minimizing discomfort glare by reducing the blue content of LED headlights as low as practicable.

In addition, a study by Bullough et al. (2003) investigated the impact of glare illuminance, glare spectral power distribution (SPD), and glare source size on peripheral detection of small targets in the field. They studied visual performance and discomfort glare for: 1) a constant SPD glare source with different illuminances at the eye, 2) a constant glare illuminance at the eye with three different glare source SPDs: HID, halogen, and blue-filtered halogen, and 3) a constant illuminance at the eye and a constant SPD, for different light source size/luminance combinations. The variables were: The different glare illuminance were 0.2, 1 and 5 lx corresponding to luminous intensities of 500, 2500 and 12,500 cd, respectively from HID headlamps having a luminous area of 26 cm². SPD of 1 lx (2500 cd from 50 m) for halogen, HID and blue-filtered halogen headlights had a luminous area of 26 cm². The glare size was 1 lx (2500 cd from 50 m) from HID headlamps having luminous areas of 9, 26 and 77 cm² on peripheral detection of small targets in the field. Different sizes were produced by placing masks with holes over the headlamp lens. They used sample of subset of conditions from the 3 x 3 x 3 matrix of all possibilities they could use. The order of conditions was randomized to reduce learning effects. Thirty-one individuals participated in the study. They ran six sets of trials to ensure familiarity with the procedure. Five small square-shaped targets (approximately 20 × 20 cm, reflectances of 0.2 and 0.4) were positioned on the roadway 60 m in front of the subject, the angular distance between the line of sight and the targets’ locations, were in -2.5, +2.5, +7.5, 12.5 and 17.5 degrees. They used reaction time to study the effect of disability glare. Participants had 20 trials before doing the final experiment. The results indicated that the detection of peripheral targets worsened as the glare illuminance increased from 0.2 to 5 lx. The effects of glare illuminance on target detection were dependent upon the characteristics of the objects that had to be detected. Compared to headlight glare of 0.2 lx at the eye, detection of high-reflectance (40%) targets was not significantly affected by headlight glare up to 5 lux, while even 1 lx greatly impaired detection of the low reflectance (20%) targets. However, even a relatively low amount of headlamp glare, providing 0.2 lx at the eye, significantly impacted detection of the target located closest to the glare source, regardless of its reflectance. Neither the spec-
tral power distribution (halogen, high-intensity discharge or blue filtered halogen) nor glare source size (from 9 to 77 cm$^2$ in area) affected peripheral detection.

The effectiveness of car headlights is limited by their distribution (beam distance and shape) and the speed of the car (Leibowitz et al., 1998). The sufficiency of low beam headlights was reported by Perel et al. (1983) by comparing car stopping distance with driver’s detection distance. Twenty-five headlight studies of detection distance (using standard U.S. and European headlamps) were compared where different targets with different reflective factors (either small 0.5-meter square a reflection of 7% or man-size with dark-coloured fabric) were used. Drivers drove at a set speed on a straight, flat road and detected targets by pressing a button. Mean visibility distance to a pedestrian target with U.S. low beams ranged from about 30 metres to 120 metres. With an opposing glare source, detection distances were reduced significantly compared to no glare. Detection distances ranged from about 25 to 80 metres. Comparisons between detection distances and stopping distances suggested that the maximum safe speed when using low beams was 20 mph to 55 mph (32-88 km/h) under normal conditions, without glare from an oncoming car. The range of speed is due to the various detection distances and stopping distances in the previous studies. The great difference in the range of headlights is due to the differences between studies, such as the difference in targets, tests, alert/unalert subjects, etc. (Perel et al., 1983). Boyce (2009) used the bottom range of the detection distance by Perel et al. (1983) and suggested the safe speed for driving with only low beam headlights to be 48 km/h (30 mph).

Drivers’ ability to detect approaching hazards in the dark is often not based on either road lighting or car headlights but on their combined effect, therefore, it is important to assess the interaction of these two sources in the visual performance of drivers. Next section reviews previous literature on the combined effect of road lighting and car headlights.

2.4 The combined effect of road lighting and car headlights

Illumination from car headlights and, when present, road lighting combine to provide visibility for drivers. Both technologies were developed separately. Road lighting was designed to promote visibility without reference to vehicle lighting, and car headlights were designed to provide visibility in the absence of road lighting.

Headlights and road lighting can be described as forming three zones of visibility for object detection on the road: near, intermediate and far zone (Boyce, 2009; Federal Highway Administration Research and Technology, 2015). In near zone visibility is dominated by headlights, while in intermediate zone car headlights and road lighting have a combined effect. In far-zone road lighting alone contributes to visibility. Three different ranges of the zones could be found in the literature, as listed in Table 3 below. To determine zones of visibility Boyce (2009) used the study by Bacelar (2004), discussed above, by comparing
vertical illuminance (lx) on the target at different distances from headlights between two poles under different conditions, with only road lighting, only low beam, and only high beam. Bacelar used a target of 20 cm × 20 cm with the reflection of 20%, while Federal Highway Administration Research and Technology (2015) used a target of 18 cm × 18 cm with the reflectance of 20% and a pedestrian.

Table 3: Visibility zones due to the combined effect of road lighting and car headlights

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Near</td>
<td>0 to 40 m</td>
<td>0-30 m</td>
</tr>
<tr>
<td>Intermediate</td>
<td>40 to 60 m</td>
<td>30 to 76.2 m</td>
</tr>
<tr>
<td>Far</td>
<td>60 to beyond</td>
<td>76.2 and beyond</td>
</tr>
</tbody>
</table>

Although different number of factors were used in their studies, both studies suggest that there is a decline in the effect of car headlights as distance between objects and headlights increase. The largest effect of road lighting on visual performance can be seen on the far zone. Finally, there is a conflicting effect between car headlights and road lighting in the intermediate zone. Consequently, one could conclude that the visibility zone distances depend on object characteristics (i.e. reflectance, size, etc.), headlight characteristics, and road lighting characteristics.

Due to the conflicting combined effect of road lighting and car headlights in the intermediate zone, several research tended to focus on the visibility performance of drivers considering both technologies. For instance, Oya et al. (2000) studied the visibility with only road lighting and under a combination of car headlights and road lighting. The average luminance was set at 0.7 cd/m². Eight subjects were sat in a stationary car and had to observe a target (20 × 20 cm with a reflectance of 20%) located 75 m away from the car. Each subject in a stationary car was instructed to observe sight marks that were presented for 0.2 seconds and located at the distance equivalent to the sight distance from the car. They studied target visibility levels for transverse directions of the road. The goal was to determine conditions under which visibility performance declined under road lighting only and under a combination of car headlights and road lighting. Their results indicate that the combination of road lighting and low beam headlight illumination can reduce the visibility of objects. With only road lighting, objects with a reflectance of 20% are mainly seen in silhouette vision (object darker than background) while under a combination of car headlights and road lighting, they could be seen in silhouette vision or reversed silhouette vision (object lighter than background). Therefore, they chose to improve silhouette vision by improving the lighting system. Their improved system was achieved by counter beam lighting (turning optical axes toward the drivers to improve the road surface luminance and obstacle visibility). Their results indicated that VL values of the improved system were greater than the correspond-
ing value of the ordinary system at many points. This improved system had several problems, first, the new system provides asymmetric light distribution due to turning the optical axes toward the drivers, thus the spacing between luminaires should be examined before making any decisions on using this system. Also, in the case of face-to-face traffic, if luminaires are arranged on one side only, there is no effect on the lanes of the other side. If luminaires are arranged on both sides, it is necessary to examine the light distribution and spacing of luminaires in order to eliminate the influence on the lanes of the other side (Oya et al., 2000).

Similar conclusions could be found in the study by Ekrias et al. (2008). They used contrast measurements to investigate the contribution of headlights to target visibility on a lit road. The results indicated that the combined effect of car headlights and road lighting did not improve the visibility of various targets on the road because when road lighting and car headlights were on, luminance contrast was lower compared to the situation when only road lighting was on. In addition, low beam headlights had little effect on target contrast when the distance between the target and the car was more than 80 metres. At shorter distances, the effect of car headlights became more apparent. They suggested using parking lights instead of low beam headlights in presence of road lighting. This would reduce the negative combined effect of road lighting and low beam headlights. It might, however, result in other unwanted effects concerning traffic safety, such as reducing the visibility of other cars in traffic and low illumination of the surrounding that only depends on road lighting (Ekrias et al., 2008).

Bacelar (2004) calculated the visibility level (VL) of standard 20 cm square targets with a reflectance of 20% at different distances from the vehicle (a constant distance of 40 m from the vehicle for low-beam headlights and 90 m for high-beam headlights) along the axis of the road using the Adrian model (Adrian, 1989). His results indicated a variation in visibility level in (1) car headlights only, (2) road lighting only, and (3) the joint effect of headlights and road lighting conditions. VL with only headlights was constant at constant distances from the car. VL was lower at far distances using high-beam headlights than near distances using only low-beam headlights because of the lower illuminance on the target and its smaller angular size at the greater distance. VL with only road lighting was different at different locations due to light distribution. Finally, he noted that using road lighting and low-beam car headlights separately results in better visibility than when they were used together.

A clear conclusion can be found from these studies and previous section (2.3. car headlights): a) the effect of car headlights are limited to its distribution and the speed of the car, b) the joint effect of car headlights and road lighting is not complementary until intermediate zone, and c) the effect of road lighting is important in detecting the targets in the far zone. Consequently, the evidence from the previous studies consistently emphasizes the importance of considering the combined effect of road lighting and car headlights in the design of road lighting. However, road lighting should not be considered as a digital variable (on/off). It is important to estimate the effect of different road lighting levels in
the presence of car headlights on the visual performance of drivers as well as on traffic safety. The next section provides this information.

2.5 The effect of different road lighting levels

As discussed in the previous section (2.4), the combined effects of road lighting and car headlights are not always complementary. Some studies suggest reducing the effect of car headlights (city beam) (Schreuder, 1975; Akashi et al., 2003; Ekrias et al., 2008) and others suggest to reduce the road lighting level (Bacelar, 2005).

Bacelar (2005) studied the influence of different road lighting levels on the visual performance of observers. The average illuminations were 31.5, 23.6, 15.7, and 8.7 lux and the average luminances were 2.45, 2.24, 1.52, and 0.75 cd/m². Two methods were used, psycho-visual test and Visibility level. In the first test participant had to stand 83 metres away from target in the centerline of the road (size 20cm ×20 cm with a reflection factor of 20%). They heard two beeps. On the first beep they had to turn toward the target, and on the second beep they had to face back and grade how well they had seen the target. His results indicated that reducing road lighting levels from 31.5 lux (average luminance 2.45 cd/m², overall luminance uniformity 0.6, longitudinal luminance uniformity 0.7) to 15.7 lux (average luminance 1.52 cd/m², overall luminance uniformity 0.61, longitudinal luminance uniformity 0.67) didn’t have great influence on the amount of VL and appraisal rating. While at road lighting level 8.7 lux (average luminance 0.75 cd/m², overall luminance uniformity 0.56, longitudinal luminance uniformity 0.67) 43% of VL and appraisal rating were under 2 (appraisal rating of 2 corresponded to Visible), which he considered not safe and comfortable for drivers. He also noted that the visibility of the target was more affected by its position than by lighting level. Although he did not consider the effect of car headlights, he concluded that current road lighting practices result in over-lighting (Bacelar, 2005).

Table 4 summarizes previous studies on road lighting and car headlights. As can be seen from the Table 4, different studies using various methods concluded that the combined effect of road lighting and car headlights are not complementary.

<table>
<thead>
<tr>
<th>Reference</th>
<th>the combined effect of car headlights and road lighting</th>
<th>methodology</th>
<th>non-complementary effect</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akashi et al. (2003)</td>
<td>√</td>
<td>recognition distances</td>
<td>√</td>
<td>city beam</td>
</tr>
<tr>
<td>Bullough and Rea (2010)</td>
<td>√</td>
<td>RVP</td>
<td></td>
<td>use car headlights only</td>
</tr>
<tr>
<td>Skinner and Bullough (2011)</td>
<td>√</td>
<td>RVP</td>
<td></td>
<td>use car headlights only</td>
</tr>
<tr>
<td>Bullough et al. (2012)</td>
<td>√</td>
<td>RVP</td>
<td></td>
<td>use car headlights only</td>
</tr>
<tr>
<td>Fotios et al. (2017)</td>
<td>√ (cycle lighting)</td>
<td>detection distance</td>
<td>√</td>
<td>reduced road lighting</td>
</tr>
</tbody>
</table>
A detection distance study by Akashi et al. (2003) was done under three road-way lighting levels (2–20 lux) and three headlight dimming levels (100%, 30%, and 10%). Five targets (18 × 18 cm² with a reflectance of 20%) were placed in five directions (eccentricity, -15°, -5°, 0°, 5°, and 15°) from the location of stationary car. All main effects and interactions (3 headlight conditions × 9 lighting conditions × 5 target positions) were statistically significant. The main results from their study suggest that recognition distance increased as road lighting increased. The effect of road lighting on recognition distance becomes smaller as the target eccentricity angle increases (eccentricity angle of 15° to the right). Finally, in lower eccentricities (eccentricity angle 0° to around ± 5°) the effect of headlights intensity on recognition distance is smaller than that of road lighting illuminance. They support the use of city beam, i.e. dimmed headlights in lit areas. The city beam should have wider luminous intensity distribution than the normal distribution to make peripheral targets visible.

A study by Bullough and Rea (2010), compared visibility conditions provided by different headlights, road lighting conditions, and ambient luminance provided to the road from private or public electric lighting. The headlights studied were halogen low-beam, HID low-beam, and halogen high-beam. Road lighting conditions were a) no road lighting, b) a single road luminaire that was installed at the intersection providing an average horizontal illuminance of 15 lx in the conflict area of the intersection and c) continuous road lighting provided by a series of road luminaires spaced 150 ft apart so that the average horizontal illuminance was 15 lx in the conflict area of the intersection and 9 lx on the surface of the major road. Four levels of ambient illumination selected were from private or public electric lighting of the road and ranged from high-urban to rural lighting levels, specifically 20, 2, 0.2 and 0.02 lx. The car was located 150 ft from the centre of the intersection while a target of 18 cm × 18 cm (7 × 7 sq-inch) with a reflectance of 50% was placed in 60 and 120 ft ahead of the driver along the passenger side of the road. Studied scenarios were developed on lighting calculation and simulation software (AGi32, Lighting Analysts). They indicated that at 20 m (60 ft) from the car, the highest vertical illuminance on targets was provided by low beam HID, then high beam halogen and lastly by low beam halogen headlights. At 40 m (120 ft) from the car, the highest vertical illuminance on targets was provided by high beam halogen, then by low beam HID, and low beam halogen headlights, respectively. In addition to the vertical illuminance by headlights, they used RVP model to study visibility performances at different scenarios. The results from RVP reveal that with no road lighting, the low beam HID headlamp beam pattern results in the best visual performance, with little difference between the halogen low beam and the high beam headlamp beam patterns, which is due to the broader beam pattern produced by HID headlights relative to halogen headlamps as well as having higher vertical illuminances than the other options. With single road luminaire, the differences among the headlights beam patterns reduce greatly, although there is still an advantage of the HID headlamp beam pattern. With continuous road lighting, the differences among the headlamp beam patterns were negligible. They also
found that under highest ambient illuminances (2 or 20 lx) and independent of car head lighting beam pattern, visual performance is high with RVP values of about 0.9 or higher. For targets located 40 m ahead and no road lighting, the highest RVP was provided by high beam halogen, then by low beam HID, and low beam halogen headlights, respectively. Adding single road luminaire or continuous road lighting, visual performance of targets located in 40 m was still high independent from the effect of road lighting. Because of the costs of road lighting, most motorways in the U.S. are not illuminated and some government agencies have also considered turning off existing road lighting (Bullough and Rea, 2010).

Other examples of the research on the combined effect of road lighting and different car headlights can be found on roundabouts. For example, Skinner and Bullough (2011) studied the ability of drivers to see pedestrian under three different headlights (halogen, HID and Adaptive forward lighting, AFS) and different levels of ambient illumination from fixed road lighting systems. In their simulation analysis, they used RVP model based on photometric simulation of the headlights with different ambient illumination from road lighting. Their results indicated that the combination of road lighting and static headlights sometimes results in lower visibility performance than with headlights alone. However new headlight technologies (HID and AFS) provided better visibility performance regardless of the presence of road lighting. Based on their results, they suggested the importance of considering the effect of car headlights as a significant factor in designing road lighting in roundabouts. Bullough et al. (2012) conducted a field study on participant’s visibility performance in an outdoor roundabout intersection to compare driver’s ability to detect and identify pedestrian activity with different car headlights under different road lighting conditions. They used Relative Visual Performance (RVP) model. The characteristics of the experiments were: asphalt pavement of 10%-15% reflectance; a child-sized silhouette target (1-meter height with 5% reflectance); two low beam headlights (a halogen and a high-intensity discharge, i.e. HID, set equipped with swivelling functionality), six angular positions and distances, and road lighting illumination (2 lx corresponding to maximum ambient illumination on positions on the road and negligible illuminance on peripheral locations). Participants had to identify the walking direction (left or right) of the target as quickly as possible. Participants were seated behind the headlight system with a laptop that could record their reaction times. In the experiment, after setting a randomized arrangement, participants could look up for a pedestrian target and press the left or right arrow, corresponding to the walking direction of the pedestrian target. Their results suggest that car headlights have a significant role in pedestrian detection along roundabout intersections. Identification times were longer for the distant targets or when they were in the peripheral field of view. Systems such as HID headlamps, which produce greater amounts of peripheral illumination can result in shorter identification times for pedestrians, including when the location of the pedestrian is not known in advance. (Bullough et al., 2012).

Apart from car headlights, studies on the combined effect of different road lighting levels and bicycle-mounted lighting give similar conclusions, although
road lighting requirements in pedestrian and cyclist areas are different from motorized traffic areas. Fotios et al. (2017) investigated the ability of cyclists to detect obstacles located ahead but in peripheral vision using different scenarios of road lighting and bicycle-mounted lighting. The experiment was done on a floor which was made from medium density fibre-board painted in Munsell N5 grey paint (reflectance 20%). The test area was lit from above by two identical arrays of LEDs. Different road lighting levels provided horizontal illuminances of 0.2 lx, 2 lx and 20 lx and no road lighting. They also considered three mounting heights (565 mm, 1830 mm and 1370 mm, i.e. the hub, helmet and handlebar) and three luminances (off, 0.1 cd/m², 0.32 cd/m², and 1 cd/m²) of cycle mounted light. The obstacle was raised at seven heights (0.5 mm, 2.8mm, 4.5 mm 7.1 mm, 11.3 mm 17.9 mm, and 28.4 mm) at two rising speeds (1 mm/s and 2 mm/s). The participants sat and cycled on the bicycle that was mounted on a roller. They had to detect the randomized obstacles by pressing a hand-held response button. Three experiments were conducted each using 10 participants. The first experiment investigated the combined effect of different road lighting levels and cycle lighting, when the cycle-mounted lighting was positioned in the handlebar. The second experiment investigated the effect of various heights of cycle-mounted light with the luminance of 0.32 cd/m² and four road lighting levels. Finally, in the third experiment, the combined effect of different road lighting levels and cycle lighting was studied when the cycle-mounted lighting was positioned in the wheel hub. Their results indicated that cycle-mounted lighting on the handlebar in the presence of any road lighting levels either reduced detection of obstacles or did not have any effect. While cycle-mounted lighting on the hub led to an increase in the detection of obstacles when road lighting was at a low level (0.2 lx), this was not the case in higher road lighting levels (2 lx or 20 lx). Although the vertical illumination properties of bicycle lights and car headlights are different, they display a similar conflicting effect with road lighting (horizontal illumination).

Comparing traffic accidents under different road lighting levels reflects the relative magnitude of night-time crash risk. Gibbons et al. (2014) focused on the relationship between the lighting level and roadway safety based on five criteria: 1) horizontal illuminance, 2) vertical illuminance, 3) vertical-to-horizontal illuminance ratio (effect of glare), 4) lighting uniformity measure, and 5) luminance. The lighting conditions studied could include ambient illumination from other roads, parking lots, advertising signs, etc. and not just from the designed road lighting for the roads on which they were measuring. Their findings indicated that current road lighting practices result in over-lighting and the increased lighting level does not necessarily lead to safer roads. They stated that the current lighting levels may be higher than required for roadway safety. For interstates and freeways, there is a potential to reduce the lighting level by as much as 50% from the current recommended practices. They suggested following values for the above-mentioned criteria: 1) the minimum required average horizontal illuminance of 5 lux, 2) the minimum average vertical illuminance of 3 lux, 3) vertical-to-horizontal ratios of 0.6, 4) the minimum uniformity of 0.3, and 5) luminance level of 0.15 cd/m².
Gibbons et al. (2014) also explored the impact of lighting levels on different roadway types. To determine the impact of the lighting and the functional class, they analyzed the relationship between horizontal illuminance and weighted night-to-day crash rate ratio by roadway functional class. They suggested minimum horizontal limits for urban interstate, urban principal arterial, other principal arterial and minor arterial to be 5, 7.5, 13, and 16 lux, respectively. Beyond these minimum values, an increase in illuminance did not have an effect on the overall traffic safety. The difference in lighting level requirements for different roadway types was explained by traffic volume and potential conflict with other cars and driveways. For instance, minor arterials with lighting are safer during night-time than during daytime due to lower traffic volumes and fewer conflicts with other cars at night-time. Combined, the results of Gibbons et al. (2014) suggest that without compromising traffic safety, there is a potential to use low lighting levels when the traffic densities of driveways and potential conflicts between cars are low. This interpretation from Gibbons et al. (2014) is already recognized in existing recommendations for road lighting that allow light levels to be reduced when there is lower traffic or pedestrian volume.

The measurement of reaction times has been used to characterize visual performance under different road lighting conditions and spectrums. A study by Rea et al., (1997) using a road lighting simulation with Metal Halide (MH) lamps (S/P ratio = 1.63) and HPS lamps (S/P ratio = 0.64) found that, for foveal-target detection, participants had similar reaction times with the two lighting types of road lightings. However, in the case of off-axis detection, reaction times with HPS lighting were slower than those for MH lighting, especially at lower light levels. To obtain similar reaction times, the HPS lighting had to be about 10 times as bright as the MH lighting, a ratio far greater than the ratio of S/P ratios of the lighting types (1.63:0.64 \(\approx\) 2.5:1) would predict. Therefore, a comparison of the \(V(\lambda)\) and \(V'(\lambda)\) functions (section 2.1), on which S/P ratios are based, does not describe visual performance for off-axis detection in the mesopic range.

Bullough and Rea (2004) reviewed previous studies on the effect of Spectral Power Distributions (SPD) on visual performance. They concluded that SPD has no effect on on-axis (foveal) visual tasks at any light level. None of the studies they reviewed has ever demonstrated that a source with a low S/P ratio is visually more effective than one with a higher S/P ratio. Another main conclusion was that the effects of SPD on peripheral detection tasks tend to increase as (photopic) luminances are reduced, especially below 1 cd/m², with sources having high S/P ratios providing improved performance over sources having lower S/P ratios at the same (photopic) luminance. These studies suggest that reaction times of on-axis targets are similar under different light spectrum and varies in the case of off-axis detection.

Unfortunately, most studies on the effect of road lighting on traffic safety have used road lighting as a binary variable: lighting was either present or absent. So far only limited research could be found to consider the effect of different road lighting levels on traffic safety. Monsere et al. (2007) examined the relationship between lighting level and crash rates in the Pacific Northwest, and Oregon. A reduction in power consumption by 10% during October 2001 and April 2002
at interchanges and along linear highway sections occurred. The reductions fit into three categories, (1) interchanges where lighting was reduced from full to partial lighting design\(^{13}\); (2) interchanges where lighting was reduced from a partial plus\(^{14}\) design to a partial design; and 3) highway sections where mainline lighting was reduced or removed. Their results indicated that when lighting was reduced from full to partial, night-time crashes increased by less than 4%. When full mainline lighting was changed to all or some luminaires turned off, crashes increased by nearly 30%, and fatal and injury crashes increased by nearly 40%. When lighting was reduced from partial-plus to partial, crashes decreased by 35%. However, Monsere et al. do not suggest that reducing roadway lighting leads to a definitive safety benefit. Gibbons et al. (2014) argue that the results provided by Monsere et al. (2007) are not robust because the sample size was small and the roadways where lighting was reduced were selected based on their history of safety, which might affect the results.

Bullough et al. (2013) studied the linkage between roadway lighting, visual performance and traffic safety for different intersection types in Minnesota. They used RVP analysis jointly with the statistical models. Their findings indicated a strong positive correlation (\(r^2 = 0.93\)) between the night-to-day crash ratio and RVP score values. Therefore, improvements in RVP from road lighting are correlated with nighttime reductions in crashes at roadway intersections, which supports the role of improved visibility in safety.

Steinbach and others (2015) focused on the effect of reduced road lighting on traffic safety and crime prevention. The effect of four road lighting strategies (switch off, part-night lighting, dimming and white light) on casualties and crime in England and Wales was studied. The study was based on the analysis of police data on road traffic collisions and crime in 62 local authorities during 2000-2013, and crime within census Middle Super Output Areas during 2010-2013. Interestingly, the results provide no evidence that switching off, part-night light, and dimming adaptations to road lighting were associated with night-time traffic accidents. They did not find any evidence for an association between the aggregate count of crime and switch off or part-night lighting. There was weak evidence for a reduction in the aggregate amount of crime with dimming and white light. They suggest that when local authorities carefully study the risk associated with using switch off, part-night lighting, dimming, and white light strategies, they can safely reduce road lighting levels to save both costs and energy without negatively impacting road traffic collisions and crime.

### 2.6 The effect of glare from an oncoming car

Disability glare from the headlights of oncoming cars, which is usually experienced during night time driving, reduces visibility. Disability glare refers to the loss of retinal image contrast as a result of intraocular light scatter or stray light.

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\(^{13}\) Full lighting describes interchange lighting where all critical points such as gore areas, terminal on surface streets, merge points, curbs, piers, and abutments are lit as well as points in between.

\(^{14}\) Partial plus is design that has more lighting than partial lighting design but less than full lighting.
This causes extra light to fall on the image of the object and will lead to veiling luminance (Aslam et al., 2007).

In road traffic, disability glare is caused by the headlights of an oncoming car on drivers’ vision at night. The sensation depends on the luminance of the glare source (e.g. an oncoming car’s headlights), reflection of the road surface (e.g. from snow or ice) as well as background luminance, which all have an effect on the adaptation level of the driver, not to mention other variables on the driver’s part such as age and fatigue level. The contrast in the presence of glare can be calculated by modifying equation 1 (section 2.1.). In presence of a veiling luminance due to a glare source, extra light is added to the retina at a location that corresponds to both the target and background luminance, resulting in a reduction of contrast. Thus contrast in the presence of glare can be obtained by equation 7:

\[ C = \frac{(L_t + L_v) - (L_b + L_v)}{L_b + L_v} = \frac{L_t - L_b}{L_b + L_v} , \]  

where \( L_v \) is the veiling luminance. Contrast is reduced when \( L_v \) increases (Adrian and Benji, 1991). \( L_v \) can be obtained from Equation 8:

\[ L_v = \frac{k \times E_{glare}}{\theta^n} , \]

where

\[ k = 9.05 \left[ 1 + \left( \frac{age}{66.4} \right)^4 \right] \]

\[ n = \begin{cases} 2.3 - 0.7 \log \theta, & \theta < 2^\circ \\ 0.2^\circ < \theta < 2^\circ \\ 2^\circ \end{cases} \]

Here, \( E_{glare} \) is the illumination of glare source in lux at the eye; \( \theta \) (in degrees) is the angle of glare source and the fixation line valid for \( 1^\circ < \theta < 30^\circ \) from the line of sight of young drivers; and \( k \) is an age-dependent factor (CIE, 2002). The higher the contrast, the more visible the target becomes.

To evaluate the visibility level (VL) in the presence of glare (Adrian 1987), adaptation luminance is used instead of background luminance. Adaptation luminance can be obtained as

\[ L_A = L_b + L_v . \]

Thus, VL can be obtained from equation (3); however, instead of background luminance, we use adaptation luminance.

Bacelar (2004) studied the amount of disability glare from an oncoming car falling into luminance meter and influence of glare from an oncoming car on driver’s visibility with and without road lighting based on the VL. The measurement car had low-beam headlights, road lights were either switched on or off, and the car producing glare was at different distances from the measurement car. He used a flat target (20 cm x 20 cm targets with a reflection of 0.2, as described in the section mentioned 2.4) and considered two glare measuring
directions: 1) luminance meter was parallel to the axis of the car, and 2) luminance meter was toward the left optic of the opposing car. The results indicate that when the luminance meter was aimed straight ahead (resembling a driver looking straight forward) maximum contribution of the car headlights was between 0.1–0.25 cd/m² depending on the distance from headlights. Thus, the average contribution of 0.15 cd/m² when a driver looks straightforward can be expected with the maximum effect at a distance of 30 m. The results show almost ten times higher effect when the luminance meter was in the direction of opposing headlights.

Bacelar (2004) also studied the VL of a flat target with and without road lighting when influencing with one or three opposing cars. The results of VL in lit road indicate that, when the driver’s eyes were directed to the oncoming’s car’s headlights, visibility was reduced by at least 30% for a single opposing car and up to 50% for three oncoming cars. He also indicated that a lit environment reduces the impact of glare from the oncoming car due to eye adaptation of driver to higher luminance. When the driver’s eye was straightforward, the VL reduction was between 15% in the case of one car and 20% in the case of three cars. VL in presence of glare from an oncoming car was more effected under unlit road than under lit road. When there was no road lighting and driver looked straight ahead, VL was reduced by 40–50%. His results indicated that in the presence of glare from an oncoming car, drivers’ visual performance was more affected on unlit roads than on lit roads. Lighting improved the visual adaptation of the driver. However, he didn’t consider the effect of dimmed road lighting in his study.

To sum up, disability glare from oncoming traffic can adversely affect visibility comfort and performance, and road lighting reduces the effect of disability glare from oncoming cars. Road lighting offsets the adverse effect of scattered light from oncoming cars in the driver’s eye.

This raises questions about how different road surface conditions can influence visibility performance considering the combined effect of road lighting and car headlights in presence or absence of glare from an oncoming car. Next section surveys the literature on this issue.

2.7 The effect of road surface conditions

In addition to road lighting, different weather conditions have an effect on the background luminance due to different reflectance of road surface. The luminance level of a snow-covered road surface has been shown to increase by a factor of 4 or 5 compared to the luminance level required for a dry or standard road (Wanvik, 2009).

Ekrias et al. (2007) studied the road lighting by monitoring the road surface luminance levels in different road surface conditions (dry, wet, and snowy). They found that the luminance level of a snowy road was many times higher than under dry road conditions. Even when the road was only lightly covered by snow or had been cleared, luminance levels still remained 50% higher than under dry conditions. Even in wet conditions, the average luminance was higher
than in dry conditions. Since wet surface had specular reflection, the uniformity is lower than in dry conditions which might cause discomfort glare for drivers.

The authors suggested that it is feasible to benefit from the prevailing weather conditions in intelligent road lighting practices by real-time measurements of luminance. Luminance meter can monitor the luminance level on the road surface and compare it to the required level. The location of the luminance meter and the measurement area is important and has to be selected and calculated specifically for different cases. They noted that the meter should be placed as close to the driver’s position as possible. Also, the meter should measure the road surface between one luminaire spacing, and in the transverse direction the area should be defined by borders of a carriageway.

No research has been found that surveyed the combined effect of car headlights and different road lighting intensities on contrast or visibility level under varying road surface conditions.

2.8 Overview

Road lighting technology has been in transition with the goal of providing efficient lighting, mitigating energy consumption, costs and environmental pollution related to them without compromising traffic safety. Current static road lighting design provides mostly constant full design illumination during the entire night which leads to unnecessary energy use, cost and other light pollution.

Intelligent road lighting practices strive to reduce energy consumption where and when possible. However, in the design of intelligent road lighting practices, it is important to identify factors affecting drivers’ visual performance during darkness.

The literature review presented above provided information about the interactions among car headlights, road lighting, road surface conditions and glare from oncoming traffic on drivers’ visual performance during darkness. The following conclusions can be drawn:

1) The presence of road lighting has been found to have a positive effect on traffic safety. 2) The effect of car headlights is being underestimated in current road lighting systems. However, the effect of car headlights is limited to their distribution (beam distance and shape) and the speed of a car. 3) The combined effect of car headlights and road lighting is not complementary. 4) There is a possibility to reduce road lighting level in presence of car headlights without adversely affecting visual performance. 5) Disability glare from oncoming traffic can adversely affect visibility comfort and performance, and road lighting reduces the effect of disability glare from oncoming cars. 6) Different road surface conditions can have an effect on road surface luminance, which can be used as a factor to alter lighting level based on demand.

However, several questions remain unanswered at present. For instance, it is essential to determine the required lighting level under different conditions when car headlights are available. In order to be able to study what lighting level is needed under different conditions, different visual performance criteria should be studied. As explained in the literature review, during darkness and at
the relatively low lighting levels, colour vision is poor and visual detection is mainly due to luminance contrast. Apart from contrast measurement which only considers luminance of target and its immediate background, several other visibility performance metrics are available that consider other factors. Among them, Visibility Level by Adrian model is an approach to study visual performance considering factors such as object’s size, driver’s age, observation time, etc. This method is also being used in a concept called “Small-Target Visibility (STV)”, which uses Adrian model to calculate visibility performance according to strictly-defined conditions by the American National Standards Institute. STV has been used as a design metric for good-quality road lighting installations (ANSI 2000). Visibility level is not linearly proportional to visibility. For instance, visibility performance at VL=10 does not correspond to a situation that is twice as visible as one with a VL=5. Also, similar VL can lead to different visual performance due to different light levels, different sizes, etc. Nonetheless, visibility under most roadway lighting conditions is close enough to the threshold (Buyukkinaci et al., 2017) where deviations between Visibility Levels and actual performance are relatively small. Also, previous studies indicate a good relationship between detection distance of an object under dynamic conditions and the calculated VL (Janoff, 1990), and between VL and subjective rating of visibility (Janoff 1992; Ménard and Cariou 1994; Bacelar et al. 2000). Detection distance and psycho-visual tests are two other approaches that associate with actual drivers.
3. Material and methods

3.1 Research questions

The aim of the research is to provide information about the effect of different levels of road lighting under varying traffic (presence/absence of oncoming glare) and road surface conditions, considering the effect of car headlights. The three research questions, presented in the Introduction, and the methods used to study them are explained here.

In all measurements low beam headlights were used, because they are the most used car headlights in urban areas (Boyce, 2009). Although high-beam headlights can provide better illumination for long distances than low-beam headlights (Helmers and Rumar, 1975; Schoettle et al. 2002; Wordenweber, 2007), drivers underuse high beams, even in rural areas (Sullivan et al., 2004). Furthermore, in some countries, such as Finland it is illegal (Road Traffic Act, 36§) to use high beams on adequately lit roads.

Research question 1 (RQ1): What are the combined effects of car headlights and different road lighting intensities on driver’s visual performance under different road surface conditions (dry, wet, snowy) when no glare from an oncoming car is present?

Multiple parameters can affect the visibility of objects on the road, which makes the study of drivers’ visual performance complex. In this study, we have considered the combined effect of different road lighting intensities with car headlights, different road surface conditions, different road lighting technologies (HPS and LED) and positions of objects. The luminance of road surface forms the background to possible objects on a road. Therefore, different road conditions can influence the luminance of road surface due to different reflectances. To answer RQ1, a set of measurements was planned in a stationary car to study the visual performance of drivers under various road surface conditions both under LED and HPS lamp luminaires. First, a standard target was used to evaluate the contrast and visibility level, and to perform psycho-visual tests. The results were also used to find optimal standard target positions for measurements in various weather conditions. Based on these results, similar measurements were performed on different road surface conditions (dry, wet and snowy). A pedestrian was used as an additional object.

Research question 2 (RQ2): What is the effect of glare from an oncoming car on driver’s visual performance under different road lighting intensities?
Vertically mounted standard targets were used to study how contrast, VL and the results of psycho-visual tests from a stationary car vary when dimming road lighting with glare from an oncoming car. The results of contrast can provide us with information about the polarity changes. VL measurements indicate the effect of glare from oncoming cars on the visual performance of drivers. Finally, psycho-visual tests indicate if the theoretical calculations of contrast and VL provide similar results as the subjective evaluations of test drivers.

**Research question 3 (RQ3): What is the combined effect of car headlights and different road lighting intensities on detecting the targets from a moving car?**

Since previous measurements were designed in a stationary car, extra measurements were designed to confirm if similar results could be expected in a moving car. Test drivers drove a car with low beam headlights at a certain speed while an opposing stationary car with low beam headlights was and was not present. The participants had to press a button immediately after they had detected the standard target.

### 3.2 Road characteristics

Two different roads in the Uusimaa region, Finland, were selected having low traffic volumes and the ability to dim the road lighting to perform the measurements: Otaranta measurement area and Munkkiniemenranta measurement area. A series of measurements were planned on both roads. Measurements on Munkkiniemenranta area considered the effect of different road surface conditions (dry, wet and snowy) and measurements on Otaranta road considered the effect of glare/no glare and the study of moving car.

**Otaranta road section** was approximately 165 metres long and 6 metres wide with road markings. The road surface was slightly wet during the experiment. The surface was darker than a dry surface, however, there were no pools of water that could affect driver’s vision (i.e. reflections). The surface reflection properties of the road were R2 (Q0 = 0.07) for dry and W3 (Q0 = 0.21) for wet road\(^{15}\), as given by road lighting designer Kari Sola (CIE 1982). Road lighting consisted of five 100 W HPS lamp luminaires with luminous flux of 7252 lm and a one-sided arrangement on a two-lane road. The spacing between the poles was 32 metres, and the height of the luminaires was 10 metres. The intensity of the light source could be adjusted by changing the supply voltage. Visibility was measured with 100%, 71% and 49% light source intensities, which are equal to 230V, 210V, and 190V supply voltages, respectively. The measurements were conducted during autumn 2013 and the results have been published in articles I and II. Figure 2 a shows Otaranta road, also the measurement plan for this road is shown in figure 7 in section 3.6.

**Munkkiniemenranta road** was approximately 150 metres long and 6 metres wide with no road markings. This road was selected for the second set of experiments, because it had more dimming options. The lighting was one-sided

\(^{15}\) A roadway’s reflective characteristics are defined by its physical surface properties. Several typical roadway pavements are provided in Appendix C
with five LED luminaires. When dimming the road, all five luminaires were
dimmed by the same amount. On full lighting intensity, the power of a luminaire
was 100 W and the luminous flux 8450 lm. The spacing between luminaires was
30 metres and height 8 metres. The road lighting class for the selected road was
ME4b in the classification system in CEN/TR 13201-1. Road pavement was clas-
sified as road class R3 with a reflective characteristic of Q0 = 0.07, for dry and
W3 (Q0 = 0.21) for wet road given by road lighting designer Mirja Kaitila. The
measurements were conducted during autumn and winter 2015 and the results
have been published in Article III. Figure 2 b shows Munkkiniemnrannta road.
The measurement plan for this road is shown in figure 8 in section 3.6. The re-
sults of Otaranta road section with HPS lamp luminaires and Munkkinie-
menranta road with LED luminaires could not be directly compared, because of
different road surface conditions (slightly wet versus dry).

Figure 2: Measurement locations a) Otaranre road b) Munkkinie-
menranta road

Average luminance was measured using an LMK Mobile Advanced and analysed
with technoteam LabSoft. This software converts images directly into lumi-
nance values. Photos were taken at 80 m distance from the target inside the car
in the driving direction and at a height of 120 cm. No adjustments on luminance
values were considered for the windshield transmittance. The luminance meas-
urement points were distributed by the LMK labsoft programme across the road
surface. $L_{ave}$ was calculated from the grid points (60 points between two lum-
naires) in the field of calculations. The characteristics of the roads are listed be-
low (Table 5):
Table 5: characteristics of the lighting classes

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Otaranta road</th>
<th>Munkkinienmenranta road</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting class</td>
<td>M5</td>
<td>ME4b</td>
</tr>
<tr>
<td>Average luminance (Lave)</td>
<td>0.50</td>
<td>0.75</td>
</tr>
<tr>
<td>Overall uniformity (Uo)</td>
<td>0.35</td>
<td>0.4</td>
</tr>
<tr>
<td>Longitudinal uniformity</td>
<td>0.40</td>
<td>0.5</td>
</tr>
<tr>
<td>Road pavement</td>
<td>R2</td>
<td>R3</td>
</tr>
<tr>
<td>Road lighting technology</td>
<td>HPS</td>
<td>LED</td>
</tr>
<tr>
<td>Measured</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road lighting intensities (cd/m²)</td>
<td>0.56, 0.40, 0.27</td>
<td>0.75, 0.53, 0.38, 0.19, 0</td>
</tr>
<tr>
<td>Overall uniformity (Uo)</td>
<td>0.35, 0.35, 0.31</td>
<td>0.64, 0.67, 0.58, 0.62, 0.23</td>
</tr>
</tbody>
</table>

As can be seen in table 5, Otaranta road is designed to have an average luminance of 0.50 cd/m², while the measurements indicated 0.56 cd/m². The slightly wet surface could affect this extra amount of luminance on the road. In addition, uniformity was calculated by the ratio of minimum luminance to average road surface luminance over the evaluation area.

On the Munkkinienmenranta road with LED luminaires, three different road surface conditions were considered: a) dry, b) wet, and c) snowy. The effects of different road surface conditions were measured with the setup of Figure 8 using the contrast and visibility level of both the standard target and a pedestrian. To investigate the difference in luminance values during various road surface conditions, the average luminance level of the road surface was measured (Table 6).

Table 6: Average luminance (cd/m²), overall luminance uniformity and longitudinal luminance uniformities in all road lighting intensities under varying weather conditions on Munkkinienmenranta (Article III)

<table>
<thead>
<tr>
<th>Road lighting Intensity</th>
<th>Weather conditions</th>
<th>Lave</th>
<th>Uo</th>
<th>U_L, left</th>
<th>U_L, right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>0.79</td>
<td>0.64</td>
<td>0.60</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>2.62</td>
<td>0.17</td>
<td>0.14</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Snow</td>
<td>3.12</td>
<td>0.54</td>
<td>0.36</td>
<td>0.48</td>
</tr>
<tr>
<td>Lave = 0.75 (100%)</td>
<td>Dry</td>
<td>0.63</td>
<td>0.67</td>
<td>0.56</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>2.09</td>
<td>0.18</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Snow</td>
<td>2.49</td>
<td>0.56</td>
<td>0.34</td>
<td>0.41</td>
</tr>
<tr>
<td>Lave = 0.53 70%</td>
<td>Dry</td>
<td>0.46</td>
<td>0.58</td>
<td>0.45</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>1.52</td>
<td>0.15</td>
<td>0.11</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Snow</td>
<td>1.82</td>
<td>0.49</td>
<td>0.27</td>
<td>0.41</td>
</tr>
<tr>
<td>Lave = 0.38 50%</td>
<td>Dry</td>
<td>0.19</td>
<td>0.62</td>
<td>0.39</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>0.63</td>
<td>0.17</td>
<td>0.09</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>Snow</td>
<td>0.75</td>
<td>0.52</td>
<td>0.23</td>
<td>0.41</td>
</tr>
<tr>
<td>Lave = 0.19 20%</td>
<td>Dry</td>
<td>0.04</td>
<td>0.23</td>
<td>0.013</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>0.13</td>
<td>0.06</td>
<td>0.003</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Snow</td>
<td>0.16</td>
<td>0.19</td>
<td>0.08</td>
<td>0.10</td>
</tr>
</tbody>
</table>
As could be expected, full road lighting under dry road surface closely followed road lighting requirements (class ME4b). In full road lighting under dry condition, the average luminance level required by ME4b is 0.75 cd/m² and the measured average luminance level on Munkkiniemenranta road was 0.79 cd/m². In wet conditions, the luminance level was higher than in dry conditions. The higher average luminance level in wet condition was mainly due to the non-specular reflection in the wet road surface. The luminance of some points was much higher while the luminance of other points was lower than the luminance under dry conditions. Under full road lighting conditions, the average luminance level on a wet road surface was 2.5 times higher than the required luminance level (dry conditions) and 0.2 times less than the snowy condition. The average luminance level of the snowy road surface was 3 times higher than the required luminance level.

3.3 Objects characteristics

Two objects were used: a standard target and a pedestrian. A standard (20cm × 20cm) target was selected, because it is small and difficult to perceive, but can pass underneath a normal-sized car (Bacelar, 2005; Ekrias et al, 2008; Mayeur, 2010). Being small in size and having no motion, colour and internal contrast, it is difficult to perceive by drivers (Narisada, Karasawa, & Shirao, 2003). The reflectance of the standard target was 50%.

In addition, a pedestrian was used as a more familiar object to road users. A 185-cm tall pedestrian wore navy-blue clothing with a reflectance of 3.3%. Figure 3 provides a picture of objects standing vertically on the road. The white strip on the pedestrian clothing is a reflective tape. Visibility measurements of the pedestrian were only based on luminance measurement and thus the luminance of the tape was not considered. If visual performance would have been performed by psychovisual tests, the reflective tape could have had an influence on the visibility of the pedestrian. The pedestrian was a real person wearing a uniform cloth. The reflection of the pedestrian was found by equation (10) for diffuse reflection surfaces

\[ L = \rho \times \frac{E}{\pi}, \]

in which L is luminance (cd/m²), \( \rho \) is reflectance, E is illuminance (lx). E and L were measured with illuminance meter and luminance meter from five different points and then the reflectance was found from equation (10) above. The used reflectance was the mean of calculated reflectances.
3.4 Car characteristics

The two cars used for the measurements were a Volkswagen Golf (model 1990) and Volkswagen Polo (model 1999). Volkswagen Polo was used as the main car (measurement car) and Volkswagen Golf was used to produce glare. Only one type of low-beam headlights was used. Both cars had Halogen headlights, Volkswagen Polo had H7 lamps, 50 W and 1500 lm, and Volkswagen Golf had H4 lamps 55 W and 1000 lm. Both car headlights followed the European car headlight regulation (Economic Commission for Europe (ECE), 1971, 1995). The illumination of car headlights at several distances from the car was measured. Volkswagen Polo headlights photometry of H7 (main car) is shown in Figure 4. The photometry of the headlights is provided by headlight manufactures, however, the illumination on 18 points at different distances on the target in front of the headlights was checked (center, right and left, 0° and ±4° eccentricity). The results corresponded with headlights photometry provided by the manufacturers.

The imaging luminance photometer was placed in the measurement car with a measuring height of 1.20 metres, which is the average height of a driver’s eyes (Ekrias et al., 2008; Mayeur et al., 2010; Bacelar, 2004). The luminance of the standard target and pedestrian and their background was measured with the luminance photometer. With the information collected from measurements, the contrast and visibility level by the Adrian model were calculated.

![Figure 4: Car headlights photometry (Volkswagen Polo)](image)

In the presence of glare, the vertical illuminance ($E_{\text{glare}}$) that comes to the eyes was measured by illuminance meter. The illuminance was measured by placing the illuminance meter on the forehead of the driver seating in the driver seat of the car. Illuminances coming to the eye decreased from 1.4 to 1.05 and to 0.89 lux in different road lighting levels from 0.56, 0.40, and 0.27 cd/m², respectively. Since the distances of the measurement car and the glare car to each lateral position of targets were constant, the theta angle had three different values (right, centre, and left directions). Theta angle to evaluate veiling luminance, which then is used to evaluate VL can be found by two lines. One is the line to
the glare source and the other is towards the target. Figure 5 illustrates the theta angle in the measurements, and Table 7 displays the theta values for each direction.

Figure 5. Theta angle for positions of the standard target on the road

Table 7. Theta values for different positions of the standard target

<table>
<thead>
<tr>
<th></th>
<th>Theta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>2.46°</td>
</tr>
<tr>
<td>Centre</td>
<td>1.83°</td>
</tr>
<tr>
<td>Left</td>
<td>1.2°</td>
</tr>
</tbody>
</table>

As Figure 5 and Table 7 illustrate the theta values for different lateral positions varied, but it was constant across longitudinal positions due to constant distances.

3.5 Participants

The participants had valid driver’s licenses. Among the participants, one 30-year-old male had myopia (near-sightedness) with -0.5 power on both of his eyes. He wore eyeglasses to satisfy the visual requirement for driving. Other participants had normal colour vision and visual acuity.

In the measurement car, psycho-visual tests were performed in the Otaranta road section. In the stationary car measurements, five participants were selected: four males (two were 30 years old, one was 25, and one was 50) and one female (30 years old) performed a psycho-visual tests evaluation. The results of psycho-visual tests can be compared with previous studies that conducted similar tests, including Menard, Cariou (1994), Guler and Onygil (2003), and Baccelar (2005).

In the psycho-visual tests measurement, participants sat in the car resembling the driving condition. They all received one sheet of paper including the psycho-visual scale (Table 1) in which they had to grade. Participants had to look down while the experimenter positioned the targets on measurement points (Fig. 7). Three standard targets (section 3.3) with the same characteristics were placed on the measurement points at a distance of 80 m away from the measurement car (i.e., positions 1, 2 and 3 simultaneously). After positioning, participants could look up, see the standard targets, and grade. When they moved to the next column, both cars were moved to keep the distance constant. Having three standard targets at the time allowed participants to compare the visibility of
Material and methods

them and to provide a more precise grade based on their comparison. All participants had to grade all standard targets in all positions and different lighting levels under low beam car headlights in the presence or absence of glare from an oncoming car. The order of longitudinal locations (columns) of the standard targets was different for each driver. The order of dimming was 0.56 cd/m², 0.27 cd/m², and 0.40 cd/m², respectively. As indicated in previous studies (Bullough et al., 2003; Bacelar, 2005) orderly testing conditions may adversely influence the results by affecting the behavior of the subjects, although changing the order of test conditions may help to reduce learning effects for participants. If the lighting level was changed step by step, participants’ performance might either improve or worsen due to the order of the test conditions. For each lighting level, the measurements were done in two parts. First, each driver graded the visibility of the standard target without the presence of glare using the subjective graded visibility scale. Then oncoming car headlights were turned on, and the grading was repeated with the effect of disability glare.

In the moving car measurements (detection distance study), five drivers participated in the experiments: three males (2 of them 30 years old, with the heights of 175 cm and 189 cm, and one 50 years old, height 176 cm) and two females (one 30 years old, height 158 cm and one 50 years old, height 183 cm). Participants were instructed equally about the procedure of the experiment. Each driver had to detect one standard target in each round. Drivers were changed in each round to avoid order effect.

The main methods were contrast and Adrian model measurements. Psycho-visual tests and detection distance tests were used for comparison with the contrast measurements and the Adrian model (as discussed in section 2.8. overview). Because the measurements were dependent to several external factors, such as using a real, trafficked road, finding proper conditions and having permissions from local authorities (reducing light levels, etc.), we performed small sample experiments with only five test drivers. The results indicated that no further or larger scale psycho-visual experiments were necessary.

3.6 Instruments

The luminance measurements were conducted using imaging luminance photometer TechnoTeamLMK Mobile Advanced with 55 mm focal length lens and analysed with TechnoTeamLabSoft and Matlab. The camera was installed in the driver’s seat position at a height of 1.2 m above the road surface corresponding to the average height of a driver’s eyes (Bacelar, 2004; Ekrias et al., 2008; Maiveur et al., 2010), inside the Volkswagen Polo.

The roads were lit by either HPS or LED luminaires. The luminaires were pole-mounted on the right side of the road from the observer’s point of view. Depending on the measurement point, three or four luminaires were present in the visual scene.

Overall, four methods were used: contrast, Visibility Level, psycho-visual test, and detection distance. The psycho-visual and detection distance tests were only
run on the Otaranta road. The small-sample experiments indicated good correlation with contrast and VL measurements. Accordingly, there was no need for larger scale psycho-visual test with test drivers, but further studies could be based on contrast and VL measurements. Therefore, on Munkkiniemenranta road only contrast and VL measurements were studied.

The luminance of the target and its background was measured with photos taken from the luminance photometer. With the information collected from measurements, the contrast and visibility level by the Adrian model could be calculated. The analyses in the present dissertation use the VL by Adrian model, since night time visibility with car headlights and most road lighting conditions is close to the threshold, resulting in small deviations between visibility level and actual visibility performance (Bremond et al., 2013). Luminance contrast and VL in the absence of glare from the oncoming car was assessed using Eqs. (2) and (3). In the presence of glare, the luminance contrast was determined by Eqs. (7) and (8), in which the theta angle was computed based on two lines. One was the line to the glare source and the other was towards the target. The observation time of 0.2 seconds, based on the results of eye movements studies (Adrian 1987), was selected in VL calculations.

To measure horizontal illuminances LMT (Lichtmesstechnik GMBH) Pocket Lux 2 2 lux meter was used. The illuminance meter was placed on the road surface at different grid positions (Figure 6 and 7) and the result was read from the luxmeter screen. To measure vertical illuminance, the lux meter was placed vertically at the centre of the standard target.

Detection distances were measured using a Nikon D700 camera with a wired remote control and a measuring tape mounted on the road surface. ISO speed 200 and the aperture f/5.6 were used. Camera movement was avoided by using a flash with a short exposure time (1/3200 sec). The shutter lag was 40 milliseconds. The camera was pointed towards the measuring tape, which was placed on the road surface. The camera was located outside of the car, approximately at the same distance from the standard target as the driver’s head. The camera was connected to a remote switch button that was handed to the driver. The measurement error due to the camera remote control delay is estimated to be at most 10 cm, the distance that might have been travelled after pressing the remote switch button when the driver observed the standard target on the road surface. When the button was pressed, the camera took a picture of the measuring tape, which displayed the distance to the standard target. Also, the position of the camera was fixed and the delay related to the remote (maximum time that might took the shutter to close after the remote was pressed) would apply to all drivers. Possible sources of random inaccurac y might be possible noise in the camera orientation and the in the camera remote control delay.

Driver’s reaction time may vary depending on the situation (alerted or surprise situation). Wortman and Mathias (1983) found 0.9 seconds and 1.3 sec-

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16 In the article II, the mentioned estimated uncertainly was approximately ±10 cm which is incorrect. Because the delay might be due to pressing the camera remote control, which results in at most 10 cm car movement before the picture was shot.
onds’ perception-reaction time for alerted and surprising situations, respectively. The reaction time of each participant was assumed to be similar in all lighting conditions. The main goal of this experiment was to assess and determine what level of road lighting could provide better visibility for the drivers, regardless of the recognition and reaction times. As explained in section 2.5, variation in reaction time would be expected to have only a minor effect on differences in detection distances under different lighting levels for targets on on-axis position. However, considering reaction times would lead to systematically slightly longer detection distances than the ones presented here.

3.7 Measurement setups

To make the measurement set up as close as possible to real conditions, several parameters were considered. Two different road lighting technologies with different dimming options were selected. Low beam car headlights in the presence and absence of glare from an oncoming car were used. Visibilities of two objects (i.e. standard target and a pedestrian) were measured.

According to the literature, under both road lighting and car headlights, the main impact of car headlights can be recognized on the Near and Intermediate zone, while the effect is negligible on the Far zone (Boyce, 2009; Ekrias, 2008; Federal Highway Administration Research and Technology, 2015). Previous literature was used to determine the upper bound location of the Intermediate zone. Boyce (2009) used a target of 20 cm × 20 cm with reflection of 20%, and Federal Highway Administration Research and Technology (2015) used a target of 18 cm × 18 cm with reflection of 20% and a pedestrian which were different than the one used in these investigations (as shown in Table 3, section 2.4).

In Europe, a standard object is defined in the CIE report (CIE, 1979) as a flat square of size 18 cm × 18 cm with the reflectance of 20%. In American standards (ANSI/IESNA, 2000), a standard object is a flat square size 20 cm × 20 cm with the reflectance of 50%. As discussed by Fotios and Gibbons (2018), detection is affected by size and reflectance of the selected target. It is important to choose a target that is suitable for the test conditions. A low-reflectance target to be detected on a lit road, especially against a light road surface (e.g. snowy) results in negative contrast (silhouette) against the light background. Objects of low reflectance are easily perceptible. Conversely, car headlights illuminate vertical surfaces and an object is typically revealed in positive contrast against dark background, so that objects of high reflectance are easily visible but those of low reflectance are not. Since the current study considers the effects of both different road lighting levels and car headlights under various road surface conditions (dry, wet and snowy), we decided to use as a standard object a flat square of size 20 cm × 20 cm with the reflectance of 50%. In addition, an experimental study was conducted to find out the upper limit for the intermediate zone. To determine the location where the car headlight would have a low vertical illumination impact on a standard target, an experiment was conducted. The standard target was placed at a fixed location between two poles on the central axis of the lane (target position 3 in Figure 8), and the car was placed 100 metres away, facing
the target. Illuminance meter was placed on the target, measuring the amount of light hitting the target. The measurements were made at 20-metre increments as the car approached the standard target from the initial distance (100 m) with the final measurement occurring at 20 metres. The measurements were repeated for five different illumination levels. The results are provided in Figure 6.

For RQ1, two sets of measurements were performed. The first set was on Otaranta road with HPS lamp luminaires and the second set on Munkkiniemennranta road with LED luminaires.
On Otaranta road, only a slightly wet road surface was studied. The measurements considered several parameters: the combined effect of road lighting and car headlights, the effect of dimming and different locations of standard targets. The measurement location was selected between two poles. One lane of this road section was divided into five lateral columns and three longitudinal rows. Each column had three arrangements (left, centre and right), and each row consisted of five arrangements. The schematic diagram in Figure 7 represents the standard target positions in the measurement area. Each column had three arrangements (left, centre and right), and each row consisted of five arrangements. The longitudinal distance between measurement points was 8 m, and the lateral distance between measurement points was 0.75 m.

For each lateral position of the standard targets, the measurement car remained stationary in the central axis at a distance of 80 m to the standard targets. The car was moved after each measurement to maintain a constant distance of 80 m between the targets and car headlights.

Contrast, VL and psycho-visual tests were studied. Although these tests were performed for all the positions displayed in Figure 7, the results of location 13, 14, 15 were not used to avoid double counting. (The average between similar positions were not used because the road geometry was slightly different. We used position 1, 2, 3 in our calculations because they had lower VLs than positions 13, 14, and 15.) Overall, 360 gradings were collected. The results of these measurements were also used to find out which positions were critical for the visibility of the target. Those positions were then used for follow-up measurements on the Munkkiniemenranta road and in the moving car study.

On Munkkiniemenranta road, varying road surface conditions (dry, wet and snowy), more dimming options (0.75, 0.53, 0.38, 0.19, 0 cd/m²) and two objects and reflection levels (standard target and pedestrian) were used. Figure 8 represents the object positions in the measurement area.

The distance between objects and the car headlights was constant. Thus, the car and the objects were moved after each measurement to maintain a constant distance of 80 metres between the objects and car headlights. The objects were positioned in two different longitudinal locations: the standard target was always placed in the middle of the lane (central axis), because the results of previous measurements on the Otaranta road indicated that standard targets on the central axis had the lowest visibility.
The pedestrian stood near the sidewalk on the road (right axis) because pedestrian can be expected to be seen in this position during driving conditions. The pedestrian had a very low reflection factor and, for safety reasons, he was able to step on the sidewalk when necessary. Both objects were located in five different positions at a distance of 7.5 metres between two luminaires. Average luminance level on the road surface as well as contrast and visibility levels were studied. Figure 8 represents the measurement area and positioning of the objects.

Figure 8: Measurement setup for RQ1 (Article III) conducted on Munkkiniemenranta road

Because the psycho-visual tests conducted on Otaranta road indicated that psycho-visual tests had a high correlation with contrast and VL, in Munkkiniemenranta road, only luminance, contrast and VL were measured. The average VL of positions 1 and 5 was used to avoid double counting the positions under poles. (In Article I, we omitted positions 13, 14 and 15, but in Article III, we found that average of positions 1 and 5 could give better results than using only one position.)

For RQ2 (the effect of glare), a set of measurements were conducted in a stationary car on a slightly wet road surface on Otaranta road. The similar measurement set up as described in Figure 7 was used. The only difference was the presence of glare from an oncoming car. The distance from the source of the glare to the measurement car was 70 m (10 m in front of the standard target in order to slightly obscure the standard target, thus rendering lower visibility for drivers). Although contrast, VL and psycho-visual tests were performed for all the positions showed in Figure 7, the results of location 13, 14, 15 were not used to avoid double counting the visibility under the poles. Positions 1, 2, 3 were used, because they provided lower VLs than positions 13, 14, and 15.

For RQ 3, measurements were made on Otaranta road in a moving car. The effects of both no glare and glare were studied. The drivers drove at the speed of 30 km/h (inner city speed and the speed limit of the street), and they pressed a button immediately when they detected the standard target. Each driver had to detect one standard target in each round. Changing the order of road lighting intensity for each driver to randomize the test was not possible, because changing the lighting level took 10-15 minutes. Drivers were changed in each round to avoid order effect. Three lighting intensities were used in the order of 0.56, 0.27 and 0.40, cd/m². The schematic diagram in Figure 9 represents the standard target position, car positioning and car circuit in the measurement area.
The drivers had to detect the standard target in both glare and no glare condition (low beam car headlights and glare from the oncoming car). Participants were instructed equally about the procedure of the experiment, in which each had a trial run to get familiar with the road and the standard target. Overall 30 detection distances were collected (5 participants × 3 road lighting levels × 2 two oncoming headlight conditions, off and low beam). Table 8 summarizes all the variables that were used in the measurements. The details of them are described below.

**Table 8: Variables used in the measurements**

<table>
<thead>
<tr>
<th>Variable Type</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Independent variables</strong></td>
<td></td>
</tr>
<tr>
<td>Road lighting</td>
<td>• HPS (0.56, 0.40, 0.27 cd/m²)</td>
</tr>
<tr>
<td></td>
<td>• LED (0.75, 0.53, 0.38, 0.19, 0 cd/m²)</td>
</tr>
<tr>
<td>Car headlights</td>
<td>• Measurement car with low beam and no glare</td>
</tr>
<tr>
<td></td>
<td>• Measurement car with low beam and glare from oncoming headlights.</td>
</tr>
<tr>
<td></td>
<td>Illuminance of glare source was 1.4, 1.05 and 0.89 lux for 0.56, 0.40, 0.27 cd/m².</td>
</tr>
<tr>
<td><strong>Experimental designs</strong></td>
<td></td>
</tr>
<tr>
<td>Roads</td>
<td>• Otaranta</td>
</tr>
<tr>
<td></td>
<td>• Munkkiniemenranta</td>
</tr>
<tr>
<td>Test driver’s</td>
<td>• Five</td>
</tr>
<tr>
<td>Objects</td>
<td>• Standard target (20cm×20cm, reflection 50%)</td>
</tr>
<tr>
<td></td>
<td>• Pedestrian (185 cm, reflectance 3.3%)</td>
</tr>
<tr>
<td>Methods</td>
<td>• Contrast</td>
</tr>
<tr>
<td></td>
<td>• Visibility Level</td>
</tr>
<tr>
<td></td>
<td>• Psycho-visual test</td>
</tr>
<tr>
<td></td>
<td>• Detection distance</td>
</tr>
</tbody>
</table>

Regression analysis was used to estimate the coefficients of determination ($R^2$) of (small sample) psycho-visual tests with both contrast measurements and the Adrian model. Statistical tests were used to find out, if similar results could be found with the psycho-visual tests as with contrast measurements and the Adrian model. Based on these comparisons it was determined that no further psycho-visual tests were necessary.
4. Results and interpretation

The combined effect of different road lighting intensities and car headlights have been studied in different scenarios. The results are described below, following the research questions.

4.1 The effect of different road lighting levels under different road surface conditions

As mentioned in the measurement set up section (section 3.6), two sets of measurements were designed with both HPS and LED luminaires. The results are elaborated here:

4.1.1 High-Pressure Sodium (HPS) lamp luminaires

The first set of measurements were conducted under HPS lamp luminaries on Otaranta road on a slightly wet road surface. The test car had low beam headlights. Illuminance, contrast, VL and psycho-visual tests were studied under three dimming levels (0.27, 0.40 and 0.50 cd/m²). Figure 10 illustrates the average horizontal and vertical illuminances (lux) on the standard target as a result of the combined effect of road lighting and car headlights. The targets were located on the left, central and right axis of the road between two poles.

![Figure 10: a) Average horizontal and b) vertical illuminances (lux) on the standard target in different positions on the left, central and right axis](image)

Obviously, at lower road lighting levels the average horizontal illuminance (Fig 10.a) on the road is reduced. (The illuminance value of each point are given in Appendix D and Article I.) Vertical illuminance (Fig 10.b) is mainly provided by
car headlights, and it is almost constant at constant distances from car head-
lights. In these measurements, the distance between car headlights and the
standard target was constant, 80 metres. The effect of road lighting on vertical
illuminance can be found by comparing the differences between lighting levels.
Figures 10 a and b, display an overview of the effects of different lighting levels
and car headlights on vertical and horizontal surfaces. These results provide in-
formation for contrast studies.

Figure 11 displays the average contrast values of the standard target on each
axis on the Otaranta road. The results have been published in Article I. Negative
values are displayed to demonstrate the differences in polarity.

Figure 11: Contrast in no glare condition a) amount of contrast value for
each measurement points b) Average contrast of the standard target on
the standard target in different positions on the left, central and right
axis (negative values just indicate polarity)

The results indicate a change in the amount of contrast when reducing road
lighting intensity (gradually decreasing and then increasing, Figure 11 a). Lower
road lighting levels usually moved contrast toward higher positive values but
did not always improve the (absolute) contrast. Also, contrast is not a monotonic
function of road lighting level. The average luminance ($L_{ave}$) of right and left axes
under 0.40 resulted in a lower contrast than full road lighting level ($L_{ave}= 0.56$) and the lowest level of lighting in this study ($L_{ave}= 0.27$). The lowest level was similar or better than the other levels.

Due to the pattern of car headlights on the right axis, the contrast on the right axis was always positive. On the central axis, the values of contrast under full road lighting with an average luminance of 0.56 and 0.27 were similar with different polarity. At $L_{ave}= 0.40$ and 0.27, the contrast was positive and the change, in contrast, was similar as in the right axis. In the case of the left axis, which received the highest horizontal illumination and the lowest vertical illuminance (Fig 10), the contrast values were the lowest. The combination of light distributions from the car headlight and road lighting and the reflections of the standard target and the road surface led to either positive or negative contrasts.

Participants’ psycho-visual tests (as shown in Table 1) were measured under the same lighting levels ($= 0.27, 0.40, 0.56 \text{ cd/m}^2$) as contrast and VL measurements. Figure 12 demonstrates the correlation between contrast and average subjective visibility as graded by the test drivers. Crosses represent participants’ subjective-graded visibility with glare and circles without glare from the oncoming car.

As can be seen in Figure 12, there is a strong linear relationship between contrast and subjective graded visibility ($R^2= 0.93$). Indicating that the detection of the standard targets depended mainly on the contrast between the standard target and its background. The linear function was the best-fitting curve between contrast and subjective target visibility. This is consistent with previous studies. Canon (1997) used magnitude estimation to study the relationship between stimulus contrast and contrast sensation. He used one high contrast grating (50%) and one low contrast grating (5%), subjects had to assign a number that they thought was proportional to the contrast of the stimulus to each grating that would be presented. He found a linear relationship between stimulus contrast and contrast sensation. Also, in the study by Rea (1989) subjects were pre-
Results and interpretation

Presented with lists of printed numbers having different contrast created by variations in the ink pigment density and the lighting geometry. In the first experiment, they had to read the numbers as quickly and accurately as possible. In another experiment, they were asked to rate, from 0 (threshold) to 10 (very black on white), the apparent contrast of the numbers; background luminance was held constant at 20 cd/m². He also found linear function of contrast and visual performance.

Figure 13 illustrates the relationship between average visibility levels and average subjective graded visibility. The relationship between average visibility levels and average subjective visibility indicates a strong relationship ($R^2 = 0.88$). In this data, contrast predicts graded visibility even better than VL. A linear relationship between VL and average subjective visibility gave $R^2 = 0.85$, as shown in Figure 13. Previous research also found a high correlation between Visibility Level by Adrian model and subjective visibility measurements (psycho-visual tests). Janoff (1992) conducted a measurement using thirty subjects to grade visibility on a 0-5 scale and orientation of target (facing left or right). Six targets were used. Five of them were referred to as notched targets being 17.8 cm² (7 in²) with a 8.9 cm² protruding from one side with reflectances of 5, 20, 30, 50, and 80 percent. The other target referred to as a pointed target was 17.8 cm² (7 in²) with a point on one side with 20 percent reflectance. Two lighting systems were used in which had poles in every 220 ft in an opposite arrangement. (One system used one 200-W HPS luminaire per pole and the other used two 200-W HPS luminaires per pole.) Similar to our study, he found a non-linear relationship between VL and subjective visibility measurement, however, unlike the polynomial curve fit ($R^2 = 0.88$) found in our study, they found the best fitting curve to be of an exponential form ($R^2 = 0.98$). The range of VL studied by Janoff (1992) was rather wide and between 1.23 to 14.11 with mean subjective rating ranging between 0.61 to 3.95. While in our study, the VL and

![Figure 13: Relationship between average visibility levels calculated by the Adrian model and average subjective graded visibility (Article 1)](image_url)
subjective rating could be categorized into two groups: no glare from an oncoming car and glare from an oncoming car. VL and subjective visibility rating from the first group (no glare scenario) ranged from \(0.11 < VL < 9\) and \(0.4 < \) subjective rating \(< 3\). VL. While subjective visibility rating from the second group (with the presence of glare from the oncoming car) ranged from \(0.09 < VL < 2.9\) and \(0.2 < \) subjective rating \(< 1\).

To find out if there is any significant difference between each lighting level, a non-parametric two-tailed Friedman test was used due to the ordinal scale of the subjective graded visibility. The significance level of 0.05 was applied. The statistical analyses were run to find out the significance in mean graded visibilities under \(L_{ave} = 0.56 \text{ cd/m}^2\) (Mean = 1.72, Std. Deviation = 0.78), \(L_{ave} = 0.40 \text{ cd/m}^2\) (Mean = 1.6, Std. Deviation = 0.89) and \(L_{ave} = 0.27 \text{ cd/m}^2\) (Mean = 1.97, Std. Deviation = 0.80) lighting intensities in the absence of glare. The result was significant (\(P < 0.05\)). The Wilcoxon Signed-rank test was used for pairwise comparison of lighting levels. The results indicated a significant difference between mean graded visibilities under \(L_{ave} = 0.40 \text{ cd/m}^2\) vs. \(L_{ave} = 0.27 \text{ cd/m}^2\) road lighting levels and between \(L_{ave} = 0.56 \text{ cd/m}^2\) and \(L_{ave} = 0.27 \text{ cd/m}^2\) intensities. There was no significant difference between \(L_{ave} = 0.56 \text{ cd/m}^2\) and \(L_{ave} = 0.40 \text{ cd/m}^2\) road lighting levels. The results are provided in Table 9, and the details of statistical tests can be found in article I.

### Table 9: Statistical analysis

<table>
<thead>
<tr>
<th>Road lighting levels (cd/m²)</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full (0.56 cd/m²) - Medium (0.40 cd/m²)</td>
<td>(P &gt; 0.05)</td>
</tr>
<tr>
<td>Full (0.56 cd/m²) - Low (0.27 cd/m²)</td>
<td>(P &lt; 0.05)</td>
</tr>
<tr>
<td>Medium (0.40 cd/m²) - Low (0.27 cd/m²)</td>
<td>(P &lt; 0.05)</td>
</tr>
</tbody>
</table>

Although an increase in sample size could increase statistical power, the results were consistent.

A Kruskal-Wallis test indicated that there was no statistically significant (\(p=0.29\)) difference between subjective graded visibility by participants between different conditions. The difference between mean and median subjective graded visibility distributions was not significant. Also, there were no outliers in the collected data (Appendix F).

#### 4.1.2 LED luminaires

Because subjective graded visibility is well explained by contrast (Fig. 12) as well as by the VL of the Adrian model (Fig. 13), contrast and VL measurements can be assumed to give adequate information about visibility conditions without a need for subjective visibility studies. Also, the results of target positions on Otaranta road indicate that central axis can provide the average overview of the other positions, thus central axis was used to study the contrast and VL of the standard target. In addition to the standard target, contrast and VL of a pedestrian were investigated, as explained in sections 3.3 and 3.5.

Figure 14 indicates average contrasts for different road lighting levels in presence of car headlights for standard target and the pedestrian. Figure 15 displays...
the mean visibility levels for all positions under different road lighting intensities and low-beam car headlight for the standard target and a pedestrian. The x-axes of Figures 14 and 15 represents average road surface luminance in dry conditions, as a reference. The actual average road surface luminances for other conditions are provided in Table 6.

Figure 14 illustrates the polarity transition in the average contrast of the standard target and pedestrian over all positions (Figure 8).

As can be seen from Figure 14 a, target contrast is zero at lighting level 0.38 cd/m² regardless of road condition which is due to the reflection factor of the target (50%). In dry (contrast +0.04) and wet (contrast +0.011) road surface condition the polarity was positive and in snowy road surface (contrast -0.03) the polarity was negative. For instance, reducing road lighting levels changed...
the polarity of the standard target from negative to positive in most positions. Shifting from positive to negative polarity or vice-versa makes the contrast become zero in some positions (almost the same luminance on background and standard target). In the case of a pedestrian, the contrast was mainly negative due to the low reflection of pedestrian clothing. As one could expect, the snowy road surface provided better (absolute) contrast values for the pedestrian.

Figure 15 shows the mean visibility levels (VL) of the standard target and pedestrian across all positions in different road lighting intensities and different road surface conditions in the presence of low-beam car headlights. The average VL for positions 1 and 5 was used to avoid double counting of a position below the luminaire. Error bars represent standard error of the mean, which provides an indication of the reliability of the mean estimate. The smaller standard error, the more likely sample mean is close to the population mean.

![Figure 15](image)

**Figure 15: Mean visibility levels for all positions under different road lighting intensities and low-beam car headlights for a standard target and a pedestrian. Error bars represent standard error** *(The x-axis represents average road surface luminance in dry conditions, as a reference)* (Article III)

Error bars in Figure 15 indicate that the visibility levels of the standard target and pedestrian were highly dependent on the longitudinal position between luminaires, especially in the case of the pedestrian on the snowy road surface. As could be expected, on the unlit road with car headlights, the position of the standard target or the pedestrian did not have any effect on sample mean.

As shown in Figure 15, the visibility level of the pedestrian is higher than that of the standard target, except in the case of the unlit road. The higher reflection factor of the standard target does not compensate for its smaller size relative to the pedestrian.

In dry road surface conditions, standard target had highest visibility under unlit road. Increasing road lighting level gradually reduced the VL until $L_{ave} = 0.38$, and then slightly increased. Similar, and even stronger, pattern can be seen in the case of the pedestrian. The visibility levels of the standard target and
pedestrian in unlit conditions were constant in different positions. Overall, under dry road surface conditions, the effect of road lighting levels was not monotonic. For both the standard target and pedestrian, the best average visibility levels over all positions were achieved with car headlights only (road lighting off). Average road lighting level of 0.19 cd/m² provided better visibility levels than higher intensities. The average visibility levels became slightly worse, in declining order of visibility by average road lighting levels of 0.75, 0.53, and 0.38 cd/m², though these differences were only slight.

Under wet road surface conditions, some fluctuations in visual performance were observed at different standard target positions, due to reflections in the wet road surface. The visibility level of the standard target on the unlit road was the highest in all positions. The second-best condition after the unlit road was 0.19 cd/m² average road lighting level combined with low-beam headlights, although some fluctuations were apparent across the positions. In such cases, other road lighting levels from 0.75 to 0.38 cd/m² yielded similar results. The visibility level of the pedestrian under wet road surface conditions reduced from unlit road until $L_{ave}=0.38$ and then increased.

When there was snow on the road, the overall brightness of the road and surroundings increased. Under such conditions, the luminance distribution was moderately uniform and was found to give road surface luminance approximately 2 - 2.5 times higher than that in dry conditions, thereby exceeding the requirements of the road lighting standard (in this case class ME4b). The VL graph (Fig. 15) of the standard target indicated that in snowy conditions, the visibility of a standard target (50%) did not require road lighting since car headlights provided better contrast against a darker background rather than against a lighter road surface (i.e. higher road lighting levels). After unlit conditions, the lowest lighting level (with the average luminance level of 0.19 cd/m²) provided the best visibility, while other lighting levels between full until half road lighting intensity (with the average luminance level of 0.75 to 0.38 cd/m²) yielded lower visibility levels. For the dark pedestrian, a well-lit snowy background provided the best contrast. Although visibility levels dropped with decreasing road lighting, they were still sufficiently high to detect the low-reflective, 3D shape of the pedestrian. The average visibility of the pedestrian was 10.8, 9.6, 9.8, 8.5 and 4.5 over average road lighting levels of 0.75, 0.53, and 0.38 cd/m², 0.19 and off respectively.

Overall, it can be concluded that VL was not a monotonic function of road lighting. In case of standard target, over all surface conditions, unlit road had the best VL. The second best was road lighting with $L_{ave}=0.19$. In case of the pedestrian, the same pattern could be seen in dry condition. In wet and snowy conditions $L_{ave}=0.75$ provided the best visibility. For other lighting levels visibility reduced in the order $L_{ave}=0.53$, 0, 0.19 and 0.38 and $L_{ave}=0.38$, 0.53, 0.19 and 0 respectively for the wet and snowy road surface.
4.2 Influence of glare from an oncoming car

To answer RQ 2, the influence of glare from an oncoming car was measured with contrast, VL and psycho-visual tests on Otaranta road. The measurements are described in Figure 9. The results are provided in Article I. Figure 16 below illustrates the average contrast on different axes of the Otaranta road in presence of glare from an oncoming car with HPS lamp luminaires. In presence of glare, contrast depends on the driver’s age and the illumination of glare source to the eye (angle of the line of sight to the glare source).

The results indicate that where the angle of standard target and the glare source is higher, better contrast can be expected. This means that the contrast of standard targets was reduced when the eye moved from right axis to centre axis and left axis, because standard targets located in left axis were closest to the glare source.

In a no-glare condition, when background luminance (road lighting) was reduced, polarity changed from negative to positive. In presence of glare from an oncoming car, an extra light is added to the background luminance. Thus, contrast is always negative. Also, the amount of contrast is lower than contrast in no glare situation (Figure 11).
Figure 17 plots the effect of road lighting and glare on means of grading (average response of participants for each conditions). The figure suggests a possible effect of lighting intensities.

The statistical significance of the effect of road lighting intensities and car headlights (glare, no glare) on visibility gradings was tested using non-parametric tests. Subjective graded visibility in glare condition was significantly lower in glare condition than in no glare (Figure 12 and 13), they also overlap well with contrast and VL. The Wilcoxon test was used to see if there was any difference between glare and no glare condition. All pairwise comparisons under all three road lighting levels using signed Wilcoxon tests indicate statistically significant (P < 0.001) differences in subjective graded visibilities in glare vs. no-glare conditions.

Friedman statistical analyses were run to find out if there was a statistically significant effect in subjective graded visibilities due to different road lighting levels with glare. The test indicates that the differences were not statistically significantly (P = 0.078). The slightly non-significant result may be due to the low number of participants, but the contrast was low for all lighting levels.
4.3 Target detection distances

To answer RQ3, target detection distance studies were conducted on the Otaranta road both with and without the effect of glare from an oncoming car. Normality test was run to determine if the population is normally distributed. To test normality Shapiro-Wilk test was used on distance detection under glare and no glare condition under different road lighting levels. The null hypothesis was that the sample data were drawn from a normally distributed population. The test results indicate that the null hypothesis of normal distribution cannot be rejected (p = 0.78) (Appendix E). Figure 18 represents the mean detection distance under different road lighting levels. The horizontal bars represent standard deviation.

The results in Figure 18 indicate that, in no glare condition, full road lighting intensity (Lave = 0.56 cd/m²) and lowest road lighting level (Lave = 0.27 cd/m²) provided similar detection distances, while under medium (Lave = 0.40 cd/m²) road lighting intensity visibility was lower.

Statistical tests were run to determine the significance of the differences in detection distances under different road lighting intensities with glare and no glare. A two-way ANOVA with repeated measures test was used to analyse the effect of the road lighting intensities and the glare on detection distances. The results indicated that there was a significant difference in the detection distance under different road lighting intensities (P = 0.009). There was no significant difference in detection distances in presence or absence of glare from an oncoming car (P = 0.095). But the interaction between car headlights (glare vs. no glare) and road lighting was significant (P = 0.048).

A further analysis was conducted due to the significant difference in the effect of road lighting and the interaction between car headlights (glare vs. no glare) and road lighting. First, the effect of glare/no glare was studied so that in each

![Figure 18: The mean detection distance of all drivers under different road lighting intensities under glare and no glare (Article II)](image-url)
statistical tests one road lighting level was considered. The results indicated significant differences (P < 0.05) in detection distances due to the presence or absence of glare under full (L_{ave} = 0.56, p = 0.000) and low (L_{ave} = 0.27, P = 0.010) lighting levels.

Second test was run to determine the difference in the effect of various lighting levels on detection distance in the no-glare scenario. The results indicated a significance difference between different road lighting intensities (P = 0.008). The further pairwise analysis indicated that the significant main effect was between L_{ave} = 0.40 cd/m² and L_{ave} =0.27 cd/m² (P = 0.019), but not between full road lighting (L_{ave} =0.56) and medium lighting level (L_{ave} = 0.40)(P = 0.087). Also there was a near significant difference between full (L_{ave} =0.56) and low (L_{ave} =0.27) road lightings (P = 0.056). This result indicates that in no glare condition the low lighting level (L_{ave} = 0.27) provided better visibility than medium road lighting (L_{ave} = 0.40) and the effect of dimming appears not to be monotonic.

The last statistical analysis tested the effect of various lighting levels on detection distance in the presence of glare. Under glare, standard targets were detected at shorter distances compared to the no-glare scenarios. Detection distances were highest at full road lighting (L_{ave} = 0.56 cd/m²), but the differences were not statistically significant (P=0.26). The details are provided in Article II.

### 4.4. The effect of high beam headlights

High beam headlights provide illumination for longer distances and have centre-weighted light distribution. Such headlights are mainly used in rural areas and where there are no opposing vehicles. They are not normally used in urban areas and areas that have road lighting. Since the technology of switching between low-beam and high-beam depending on the presence of approaching cars is now available in some cars (Boyce, 2009), we also collected data with high beam headlights under different road lighting levels in order to gather information for the potential to save road lighting energy. However, the results of this section were not published in any of the published articles.

The measurements were conducted in Otaranta road with HPS lamp luminaires, the measurements were the same as explained in Figure 6, the only difference was high beam headlights instead of low beam headlights. There was no oncoming glare because it is illegal to have high beam headlights when there is an oncoming car. Contrast, VL and psycho-visual tests were studied.

Average subjective graded visibility with high beam car headlights and different road lighting levels are displayed in Figure 19. The green colour in the Figure represents the subjective graded scale of satisfactory or above, and red represents poor visibility or invisibility (see Table 1).

The results indicate that standard target visibility varied due to the target positions. Medium lighting level (L_{ave} = 0.40) appears to provide the worst visibility. The lowest (L_{ave} = 0.27) and highest (L_{ave} = 0.56) lighting levels provide better visibility of the target in almost all positions.

The visibility level (VL) of the Adrian model also supports this finding. With high beam headlights, medium (L_{ave} =0.40) road lighting intensity provided the
worst visibility. A two-way analysis of variance with replication was used to test the subjective graded visibility under different road lighting intensities with either low or high beam headlights was conducted. The main effect of road lighting intensities on subjective graded visibilities was significant (p = 0.000). The main effect of low and high beam car headlights was not significant (P = 0.727). Moreover, the interaction effect was not significant (P = 0.467).
5. Discussion and Conclusions

5.1. Main results

Besides other frequent causes of accidents (e.g. alcohol, drug, fatigue, etc.), visibility is one of the important parameters in traffic safety during night-time driving. The two sources of artificial light that aid drivers’ visual performance during night-time, are car headlights and road lighting. Drivers must have car headlights when driving at night even when there is road lighting. Cars have two light distributions; low beam as the main headlights and high beam headlights when there are no oncoming cars.

In addition to headlights, road lighting assists drivers to see far distances. Previous studies indicate that traffic safety is benefiting from the presence of road lighting (CIE, 1992; Elvik and Vaa, 2004; Wanvik, 2009; Jackett and Frith, 2013; Gibbons et al., 2014; Steinbach et al., 2015). However, in most studies (CIE, 1992; Elvik and Vaa, 2004; Wanvik, 2009; Jackett and Frith, 2013) the presence of lighting has been used as a binary variable: lighting was either present or absent.

There is some evidence that the combined effect of car headlights and road lighting may reduce the contrast of objects (standard targets) on the road (Bace-lar, 2004; Ekrias et al., 2008; Akashi et al., 2003; Rea et al., 2010; Schreuder, 1975; Skinner and Bullough, 2011; Bullough et al., 2012). While road lighting illuminates road surface (horizontally), car headlights illuminate vertical objects on the road, leading to a possible combined effect of reduced contrast. This results in lower visibility which can, in turn, negatively affect traffic safety. So far, however, there has been little research about the effect of low-intensity road lighting on driver’s visual performance and little is known about the combined effect of low-intensity road lighting and car headlights. Consequently, more research is needed to better understand the combined effect of car headlights and different road lighting levels on driver’s visual performance.

This dissertation examined the combined effect of dimmed road lighting and car headlights on drivers’ visual performance in different scenarios to find possibilities to reduce road lighting output to a level that does not reduce/eliminate the effect of car headlights in creating contrast, or even improves it. The main questions addressed in this dissertation were RQ1) what are the combined effects of different road lighting intensities and car headlights on drivers’ visual performance under different road surface conditions (dry, wet, snowy), RQ2) what is the effect of glare from an oncoming car on drivers’ visual performance under different road lighting intensities, and RQ3) what is the combined effect
Discussion and Conclusions

of different road lighting intensities and car headlights on detecting standard targets from a moving car. The findings have potentially important implications e.g. for the development of intelligent road lighting.

To answer the research questions and find preliminary optimal intensities for road lighting, several methods were used to provide some insights toward answering the research questions. Perhaps the most basic approach to understand the combined effect of car headlights and different road lighting levels is contrast. Contrast data indicates the main impact of road lighting. One problem with this approach is that it only considers the luminance data. Visibility Level (VL) considers also factors such as targets’ size, drivers’ age, possible disability glare, and observation time. In addition, we considered psycho-visual tests and detection distances.

In order to evaluate visual performance, the study employed two objects: a standard target (20 cm × 20 cm with reflection factor of 50%), which has the critical size for a normal car, and a pedestrian (185 cm in height wearing navy blue clothing with a reflectance of 3.3%), which is a more realistic target on the roads. Two road lighting technologies with dimming possibilities studied in this dissertation were HPS lamp luminaires and LED luminaires. The Otaranta road with HPS lamp luminaires was studied only on a slightly wet road surface with three light intensity levels and the Munkkiniemenranta road with LED luminaires was studied under a) dry, b) wet, and c) snowy road surface with five light intensity levels. The effect of low beam car headlights at a distance of 80 meters from the targets combined with abovementioned factors was included in the analysis. The distance of 80 meters was used because it corresponded to the upper limit of the intermediate zone considering the standard target of 20 cm × 20 cm with reflection factor of 50%. In addition, the effect of glare from an oncoming car was studied.

To answer RQ1, first we assessed contrast, visibility level, and psycho-visual tests on 15 positions in right, centre and left axis of the lane on the Otaranta road. Based on the contrast measurements on Otaranta road (Figure 11), we found that positions of target in relation to the road lighting are important in creating sufficiently high contrast for visibility, specially in full road lighting. The reason is that in some positions (position 7, 8, 9 and 10, 11 and 12 Figure 11) targets received more light from road lighting than other positions, resulting in higher contrast values in these positions. At lower road lighting levels, the effect of target positions in creating sufficiently high contrast for visibility is reduced.

The study on Otaranta road with HPS lamp luminaires indicated that there was a strong linear relationship between psycho-visual tests and contrast (Fig 12: R²= 0.93). A strong linear relationship has also been found by Rea (1989). In addition, a strong nonlinear relationship between the psycho-visual tests and VL (Fig 13: R²= 0.88 was found. Janoff (1992) also found a non-linear relationship between VL and subjective visibility measurement, however his best fitting curve was of exponential from (R² = 0.98). The findings from this study suggest that contrast and VL measurements correspond well with psycho-visual tests, therefore, this study along with some previous studies (Rea, 1989;
Janoff, 1992, Menard and Cariou, 1994; and Bacelar et al., 1999) support the possibility of only exploring contrast and VL to estimate driver’s visual performance, as we did.

The results indicate that when the target is in the range of car headlights, car headlights alone resulted in better visual performance than when combined with road lighting in all studied road surface conditions. However, the distance from car headlights to the target was held constant.

In addition, another main result of these experiments was that the combined effect of road lighting and car headlights on visual performance is neither complementary nor monotonic. Non-complementarity suggests a potential for lower road lighting levels when car headlights are available. The non-monotonic combined effect of road lighting and car headlights should be considered in determining the lighting levels. Since we cannot neglect the positive effect of road lighting in traffic safety and eye adaptation regarding the glare from an oncoming car, it is important to find the minimum road lighting level where standard target and pedestrian visibility was not compromised. The results found that in road lighting levels below about 0.3 cd/m² (0.19 cd/m² in case of LED study under all road surface conditions and 0.27 cd/m² in case of HPS study under slightly wet road surface) the interaction between road lighting and car headlights provided the best contrast and VL for a standard target in all road surface conditions tested. For the pedestrian in wet and snowy road surface conditions high road lighting level provided the highest VL. However, average luminance level of 0.19 cd/m² provided acceptable visibility level. In the case of other road lighting levels (from 0.3 cd/m² up to full road lighting), objects on the road might undergo a change in polarity as contrast is passing through zero. This makes an object difficult to be detected. For example, in Munkkinie menranta road, target contrast was approximately zero at average lighting level of 0.38 cd/m² in all road surface conditions, while pedestrian contrast was close to zero at average lighting level of 0.53 cd/m² in wet and dry conditions (see Fig.14). The findings of the current study are similar and consistent with those of Gibbons et al. (2015) who found that the best combination of headlights and road lighting was when road lighting was dimmed to provide 3 lux or 0.3 cd/m² in the intermediate zone. They also acknowledged the positive effect of road lighting in detecting standard targets at far distances (the Far zone) and off-axis, i.e. beyond the effective reach of the vehicle’s headlights.

The combined effect of different road lighting intensities and car headlights under various road surface conditions was only measured on Munkkinie menranta road. These results are similar to the results under dry and slightly wet road surface conditions, supporting the possibility to reduce road lighting under various road surface conditions. Although contrast and VL under wet road surface condition were lower than under dry condition, 0.19 cd/m² provided the best results. Moreover, as one could expect, a pedestrian with a negatively contrast could be easily detected against a snowy background. Yet, due to the high road surface luminance (luminance level was between 2 to 2.5 times or
more higher than under dry condition) even road lighting level 0.19 cd/m² enabled good visual performance.

Clearly, glare from an oncoming car reduces visual performance. Seeking to answer RQ2 on the combined effect of different road lighting levels and car headlights in the presence of glare from an oncoming car (disability glare), psycho-visual test, contrast and VL studies were conducted on the Otaranta road. The results indicate that **target visibility in presence of glare was much lower than without glare, and the position of the target in relation to glare source was important.** When the angle between the line of sight and glare source was large, the visibility level was higher than with a smaller angle. In addition, higher road lighting intensities appeared to provide slightly better visibility when there was glare from an oncoming car. However, the **combined effect of car headlights and different road lighting levels in presence of glare from an oncoming car on visual performance was not statistically significant.**

Research questions 1 and 2 were studied in a stationary car. A detection distance study was conducted (RQ3) regarding the effect of different lighting levels on detection distances from a moving car. The results supported our previous results of a non-monotonic effect of lighting intensity on visibility. The results also indicated that an average illumination of 4.28 lux provided detection distances comparable to those provided by full road lighting (average illumination of 8.3 lux) when driving at 30 km/h.

Janoff et al. (1986) studied the detection distance of a small hemisphere target (3D shape, 0.15 m in size with reflection factor of 18%) at high speed (89 km/h) in different road lighting conditions. After detecting the target, drivers were asked to grade how well they saw the target visibility (1 = very poor; 10 = very good) The road lighting conditions studied were 100% (L ave: 0.58 cd/m²), 75% (L ave: 0.29 cd/m²), 50% (L ave: 0.15 cd/m²) of road lighting power, as well as with every other luminaire extinguished (L ave: 0.27 cd/m²), one side extinguished (L ave: 0.049 cd/m²), and no light (L ave: 0.016 cd/m²). Their results indicated significant differences between full road lighting and other road lighting intensities. The best detection distance was achieved under full road lighting conditions (mean detection distance = 88 m, subjective graded visibility = 8 ), with orderly decrements in performance noted for uniform dimming to 75% power (mean detection distance = 71 m, subjective graded visibility = 7), 50% power (mean detection distance = 68 m, subjective graded visibility = 7), every other luminance extinguished (mean detection distance = 62 m, subjective graded visibility = 7), one side extinguished (mean detection distance = 50 m, subjective graded visibility = 6), and no lighting condition (mean detection distance = 50 m, subjective graded visibility = 7), respectively. Their study also suggested that there was a minimal difference between different lighting intensity levels. They recommended that during periods of low traffic density, lower road lighting intensities can be applied to save energy and cost with a minimal adverse effect.
on driver performance. Our results, however, suggest to lower road lighting intensities in slow speed limit roads when stopping distance is in the intermediate zone).

The results of this study have several practical implications. The cost and energy saving concerns related to road lighting can be partly reduced by using an intelligent road lighting system. In such system factors, such as car headlights and weather conditions, and possible glare from an oncoming car should be taken into account.

5.2. Limitations and Future Research

Although this study provides new important information about the effects of different road lighting intensities, our study leaves much room and need for further research.

The number of participants in psycho-visual and detection-distance studies was relatively small. The results were consistent. Although an increase in sample size could increase statistical power, the results were consistent. Also, there were no outliers in the collected data. The main results were supported by several tests and measurements, as well as by some earlier studies. Although statistically more significant results could be obtained with a larger number of participants, our results indicate that contrast and VL measurements may be sufficient. The most important result of these tests was, however, that the psycho-visual tests had a strong correlation with both contrast and VL measurements, indicating that the latter could be considered sufficient. The methods are post-installation measurements to increase understanding of the combined effect of car headlights and road lighting. These methods have limited applicability for pre-installation design.

For the studies about the effect of glare on visual performance and detections distances the use of participants would still be necessary especially on the effect of discomfort glare on visual performance. Further studies are needed, for example, about the effect of disability and discomfort glare on visual performance under various weather and roadway conditions. The measurements only applied to static targets, and visibility of dynamic objects (moving pedestrian) was not investigated. In addition, the visibility on only one lane (closer to the luminaires) was studied.

The test drivers were a sample from the population of Finnish drivers, with permission to drive a car. No additional selection criteria, e.g. based on eyesight, was used. However, eyesight tests could have given additional information for the interpretation of the results.

The pavement reflectance data was provided by road lighting designer. Another limitation in this study was the effect of speed. Our measurements were conducted with one-speed (30 km/h). In addition, in our distance detection study, reaction times of drivers were not considered. Also there was slight crest vertical curvature on the road. Due to the curvature the drivers had to wait until they actually saw the target (Profile view of the Otaranta road is shown in the article II).
The target became visible gradually according to the height of drivers. Because the same drivers were used in all scenarios, the height difference didn’t have an effect between different lighting levels. We assume that we obtained reliable estimates about the effects of different road lighting levels on detection distances, but more reliable estimates about the actual detection distances could be obtained on a road with precisely straight vertical and horizontal geometry.

Only one set of headlights was studied (both for measurement car and the glare source). Regarding the shift in headlights technology (i.e. LED, HID headlights), and their illuminance distributions (as explained in section 2.3 Car headlights), it is important to conduct further studies with different headlights as well as headlight outputs (Schreuder, 1975; Akashi et al., 2003; Ekrias et al., 2008).

Each set of measurements were made in one location during one night. Measurements in several locations during several days could give more information about the effects of e.g. clouds, moonlight and a larger variety of road surface conditions.

The measurements were made in the dark. Road lighting is also needed in the late twilight time, when a little ambient light is available. In some areas, as in Finland, this time may be rather long.

Although our study was conducted to find out possibilities to save energy by reducing road lighting levels, it would be interesting to find out the effect of increased road lighting and compare it with current results. In this study, it was not possible to increase road lighting levels.

The current study only used a single type of HPS and a single type of LED luminaire with their own unique distributions that may differ substantially from luminaires used on other roads. The study was also limited to only one road lighting arrangement (one-sided layout of luminaires with a particular spacing and mounting height on each road). Staggered layouts of luminaires and those with higher or lower wattages and lateral/longitudinal distributions differing from the road lights used in this study could also result in different findings. Further studies and investigations are needed before more generalized conclusion can be drawn.

The effects of dimming were estimated using different measures related to visibility. Further work needs to be done to establish whether different intelligent road lighting strategies have a negative or positive effect on traffic safety.
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Appendix

Appendix A
If the target luminance is higher than the background, it is called positive contrast. However, if the target luminance is lower than the background then it is called negative contrast. For both cases, minimum luminance difference for the perception of the target with a certain probability level has to be evaluated.

$$\Delta L_{\text{threshold}} = k \left( \sqrt{\frac{\varphi}{\alpha}} + \sqrt{L} \right)^2 \cdot \frac{a(L_f) + t_g}{t_g} \cdot F_{cp} \cdot AF$$

(7)

where

- \(k\): factor for probability of perception (K=2,6 for 100% probability),
- \(\varphi\): Luminance flux function (lm),
- \(L\): luminance function (cd/m²),
- \(F_{cp}\): contrast polarity factor,
- \(AF\): age factor.

For \(L_b \geq 0.6 \text{ cd} / \text{m}^2\):

\[m^2 \left( \log \sqrt{\varphi} = 0.028 + 0.173 \log L_b \right) \]

For \(0.00418 < L_b < 0.6 \text{ cd} / \text{m}^2\):

\[m^2 \left( \log \sqrt{L} = -0.891 + 0.5275 \log L_b + 0.0227 (\log L_b)^2 \right)

\(a\): target angular size in minute:

\[a = 2 \cdot \tan^{-1} \left( \frac{r}{d} \right) \cdot 60\]

\(F_{cp}(a, L_f) = 1 - \frac{m \cdot a^{-\beta}}{2A \Delta t_{pos}}\).

Contrast is 1 for positive contrast and less than 1 for negative contrast as targets are more visible. Where \(m\) comes from:

\[log m = -10^{-\left(0.125 \cdot \log L_b + 1\right)^2 + 0.0245}\],
\[k = 0.125 \text{ for } L_b > 0.1 \text{ cd} / \text{m}^2\],
\[k = 0.075 \text{ for } L_b > 0.004 \text{ cd} / \text{m}^2\],
\[\beta = 0.6 \cdot L_b^{-0.1488} \text{ for any } L_b\],

Exposure time influence:

\[\alpha(a, L_f) = \frac{\left[a^2 + a(L_b)^2\right]^{1/2}}{2} \]
Appendix

\[
a(\alpha) = 0.36 - 0.0972 \times \left( \frac{1}{(\log\alpha+0.523)^2 - 2.513(\log\alpha+0.523) + 2.7195} \right)
\]

\[
a(L_b) = 0.355 - 0.1217 \times \left( \frac{1}{(\log L_b+6)^2 - 10.4(\log L_b+6)^2 + 52.28} \right)
\]

AF: influence of age

\[
AF = \frac{(age-19)^2}{2160} + 0.99,
\]

\[
AF = \frac{(age-56.6)^2}{1163} + 1.43
\]

Appendix B

Relative visual performance as a function of luminance and contrast for a small target as viewed from a distance of 46 meters (Rea and Ouellette, 1991)

Appendix C

Roadway's reflective characteristic with their reflectance

<table>
<thead>
<tr>
<th>Pavement</th>
<th>overall reflectance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>0.10</td>
<td>IES RP-8 - Mostly diffuse reflectance properties characteristic of Portland cement or asphalt surface with a minimum of 15% of the aggregates composed of artificial brightener aggregates.</td>
</tr>
<tr>
<td>R2</td>
<td>0.07</td>
<td>IES RP-8 - A combination of diffuse and specular reflectance's characteristic of asphalt surfaces with aggregate composed of a minimum of 60% gravel of size greater than 10 mm. Also asphalt surfaces composed of 10% - 15% artificial brightener in aggregate mix.</td>
</tr>
</tbody>
</table>
Appendix

R3 0.07  IES RP-8 - Slightly specular reflectance typical of asphalt surfaces with dark aggregates, rough texture and some months of use. This surface is common in the United States.

R4 0.08  IES RP-8 - Mostly specular surface typical of very smooth asphalt texture.

W1 0.11  CIE W1 - Wet Road Surface

W2 0.15  CIE W2 - Wet Road Surface

W3 0.21  CIE W3 - Wet Road Surface

W4 0.25  CIE W4 - Wet Road Surface

Ref: https://docs.agi32.com/AGi32/Content/references/R-Tables%20for%20Roadway%20Lighting.htm

Appendix D

Horizontal and vertical illuminance of the measurement points in the measurement field a) Horizontal Illuminance of the measurement points without car headlights, b) Vertical Illuminance on the target, unit lux (lumen per square meter). The intensity of the yellow indicates the intensity of the illumination.
Appendix E

Histogram

Normality test

Appendix F

Box Plot Diagram to Identify Outliers
Limited nighttime visibility is one of the important parameters in traffic safety that requires attention. Although introducing road lighting can mitigate the amount and severity of accidents, the interaction between road lighting and car headlights are not complementary. In addition, energy consumption and related costs of road lighting are the driving forces for more efficient road lighting technologies. This dissertation seeks to answer how the current road lighting and car headlights interact and how road lighting could be adjusted so that it does not neutralize the effect of car headlights in varying conditions.

The effect of different road lighting levels on drivers’ visual performance under various conditions

Sanaz Bozorg