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The effect of dimmed road lighting and car headlights on visibility in varying road surface conditions

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Abstract

This article evaluates the potential of dimming road lighting in order to save energy and lower costs while avoiding any adverse effects on the visibility of drivers. An experimental study under varying road surface conditions was conducted to examine the combined effect of car headlights and different road lighting intensities on the visibility level. The luminance levels of the road surface, contrast and visibility level of the objects were measured from a stationary car under three road surface conditions: a) dry, b) wet, and c) snowy conditions. The results support the feasibility of reducing road lighting intensity when car headlights are available. When within the range of car headlights, road lighting did not improve the visibility level. In the presence of car headlights, the average luminance providing a sufficient visibility level was found to be 0.19, 0.63 and 0.75 cd/m² under dry, wet and snow conditions, respectively. This would allow an energy savings of 317kWh/year/luminaire, representing savings of 80% luminaire/year for LED luminaires.

Keywords:

road lighting, car headlights, road surface conditions, dimming, visibility level, energy saving, cost saving

1. Introduction

Road lighting plays an important role in night-time traffic safety by reducing both the number and severity of accidents. For example, previous studies have indicated that the existence of road lighting reduces night-time accidents on average by 30% (CIE, 1993). Elvik (1995) estimated that introducing road lighting reduces night-time fatal accidents by 65 percent, injury accidents by 30 percent, and property damage accidents by 15 percent. A recent study by Donnell et al. (2010) proposed a framework to estimate the safety effects of road lighting at various intersection types and locations using Minnesota and California crash data. They found that the presence of roadway lighting at intersections. However, the electricity consumption and cost are the main concerns in many fields such as building (Alimohammadisagvand et al. 2015; 2016a; 2016b), and road lighting (IEA, 2006) applications. These concerns are factors hindering wider use of night-time road lighting. In 2005, 218 TWh of electricity was consumed by road lighting, accounting for about 8% of the total electricity consumption of lighting worldwide (IEA, 2006). Energy consumption and road-lighting costs could be reduced without adversely affecting drivers' visibility by developing intelligent road lighting capable of adjusting the light output based on the weather, roadway, and traffic conditions.

The transition from standard static road lighting practices to intelligent road lighting would be feasible because the luminance of road surface is dynamic and depends mainly on weather conditions. To date, road lighting intensity used in Europe has mostly been based on one static standardized lighting level ranging between 2.0 and 0.3 cd/m² (CEN, 2004). A recommendation for intelligent road lighting has been developed that covers external parameters, such as traffic volume, ambient light, road constructions, and weather circumstances (CIE, 2010). This recommendation is mainly based on the understanding that the luminance of a snow-covered road can be many times higher than that given by the standard for dry road conditions. Moreover, the need for a higher light level increases only when there is heavy traffic on the road. Indeed, the luminance level of a snowcovered 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, with the required luminance level being obtained when dimming the light flux to 20 percent of its full level (Wanvik, 2009). Ekrias et al. (2007) studied the quantity and quality of road lighting in five pilot locations; they found that the luminance level of a snowy road was many times higher than that under dry road conditions. Even when the road was lightly covered by snow or had been cleared, luminance levels still remained 50% higher than under dry conditions.

Several studies have indicated that even in the presence of car and pedestrian traffic, full road lighting intensity is unnecessary (Gibbons et al., 2014; Bacelar, 2005). For instance, Bacelar (2005) assessed observers' visibilities under three luminous flux reductions. The average illumination of each reduction was high, with an average illuminance of 31.5, 23.6, 15.7, and 8.7 lux being observed for 100%, 75%, 50%, and 25% reductions in luminous flux, respectively. His results indicated that dimming road lights by up to 50% (average illuminance 15.7 lux; average luminance 1.52 cd/m²; overall luminance uniformity 0.61; longitudinal luminance uniformity 0.67) did not reduce the observer's visibility based on appraisal ratings. However, Bacelar did not consider the effect of car headlights in his study. A study by Gibbons et al. (2014) focused on the relationship between the lighting level and roadway safety. Their results indicated that current road lighting practices result in over-lighting, and that this increased lighting level did not necessarily lead to a safer road. Thus, these studies indicate that road lighting levels could potentially be reduced by as much as 50 percent for the urban interstate functional class.

In addition, Bozorg Chenani et al. (2016) showed that the correlation between road lighting and car headlights is not complementary. The study was conducted on a road lit by high-pressure sodium (HPS) lamps. Their study showed that in the presence of car headlights, road lighting dimmed to 49% of the luminous flux (average illuminance 4.1 lux) provided a better visibility level (VL) than full road lighting (average illuminance 8.3 lux). However, the effect was not monotonic, since road lighting at 71% of the full road lighting (average illuminance of 5.9 lux) provided the worst visibility level. Thus, reducing road lighting to a certain level allowed the effect of car headlights to become more apparent, especially in the range of car headlights, as the interaction between vertical (car headlights) and horizontal (road) light sources affect the contrast between the background and the object to be viewed (Bozorg Chenani et al. 2016; Bozorg Chenani et al. 2017). However, these latter two studies only considered one weather condition.

Currently, HPS lamps have a long lifespan and high luminous efficacy, which explains the dominance of HPS lamps as street light sources (Guo, 2008). However, the introduction of LED light sources with higher efficacies than HPS luminaires will provide a promising solution for road lighting in the near future (Tetri et al., 2017). Although both HPS and LED luminaires can be dimmed to reduce energy consumption, LEDs are more suitable for dimming than HPS luminaires (Tetri et al., 2017).

Although the effect of road lighting or car headlights on drivers' visibility has been extensively investigated, no work has yet examined the combined effect of different road lighting levels and car headlights under varying road surface conditions. Therefore, the aim of this paper is to determine the effects on driver's visibility of dimming road lighting with a combination of road lighting and car headlights under varying road surface conditions (dry, wet, and snowy).

2. Material and methods

Measurements were conducted to determine the best road lighting level for drivers' visibility in the presence of car headlights. In the measurements, different road lighting levels, object sizes, reflections, and car

headlights (low beam) were considered in varying road surface conditions. 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). Thus, low-beam car headlights are studied because they are the most used car headlights in urban areas (Boyce, 2008).

Instead of focusing on weather conditions, this study chose three road surface conditions, due to the difficulty in maintaining consistent weather conditions throughout the whole measurement. Moreover, measurements and visibility level calculations could also be affected by changes in the precipitation pattern. Therefore, the measurements used three road surface conditions: dry, completely wet and snowy.

The experiment were conducted in Munkkiniemenranta, Helsinki, Finland. This location was selected because of its quiet environment and the capability of dimming the road light to different intensities in order to perform the measurements. The experimental site used for the test was approximately 150 meters long and 6 meters wide. The road did not have road markings. The lighting was one-sided with five LED luminaires whose light output level could be altered. When dimming the road, all five luminaires were dimmed. On full lighting intensity, the power of each luminaire was 100 W, with a luminaire luminous flux of 8450 lm. The spacing between luminaires was 30 meter and the height 8 meters. The road lighting class for the selected road was ME4b according to the classification system in CEN/TR 13201-1. The ME4b road lighting class has the following standard requirements:

- Average luminance level (Lave) 0.75 cd/m²
- Overall uniformity (U₀) 0.4
- Longitudinal uniformity 0.5
- Overall uniformity for wet conditions (U_{o, wet}) 0.15

The road lighting photometry is shown in Figure 1 a). Road pavement is classified as road class R3 with a reflective characteristic of $Q_0 = 0.07$.

The car used was a Volkswagen Polo 1999. The headlights were halogen H7, 50 W, and luminous flux of lamp was 1500 lm. The photometry of the car headlights is given in Figure 1 b). Luminance measurements were conducted from inside the Volkswagen Polo using an imaging luminance photometer TechnoTeam LMK Mobile Advanced. 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.



Figure 1: a) Road lighting photometry b) car headlight photometry

The experiment used two objects (a target and a pedestrian). A Critical or standard target ($20 \text{cm} \times 20 \text{cm}$ target) was selected because it is considered to be geometrically small and difficult to perceive in a normal-sized vehicle (Bacelar, 2005; Ekrias et al, 2008; Mayeur, 2010). The reflectance of the target was 50%. In addition, a pedestrian was selected, as this is a familiar object for road users. The 185-cm tall pedestrian was dressed in navy-blue clothing with a reflectance of 3.3%.

The experimental setup chosen for this study focused on the effect of road lighting and car headlights on the driver's visibility at different distances to the objects. According to Bommel (2015), the area of the road up to 160 meters in front of a car comprises the background area against which the objects must be detected at most driving speeds. Car headlights have a strong effect on the visibility of the object until a distance of only 60 meters, while the effect of road lighting can be noted at distances between 60 and 160 meters (Bommel, 2015). To determine the location where the car headlight would have a low vertical illumination impact on a standard target, a pilot measurement was conducted. In the pilot measurement, the target was placed between two poles on the centre line of the road, and the car was placed 100 meters away facing the target. Measurements were taken at 20-metre increments as the car approached from an initial distance of 100 from the target, with the final measurement occurring at 20 meters. The results of these pilot measurements are shown in Figure 2.



Figure 2: Vertical illuminance on the target located between two poles along the central axis under different road lighting conditions in presence of car headlight on dry road surface

As can be seen from the figure, vertical illumination is high until 40 meters from the headlights, indicating the dominant effect of car headlights. The effect of car headlights gradually decreases at distances between 40 to 80 meters. At distances greater than 80 metres from the car headlights, the dominant effect of road lighting became apparent. As also indicated by Ekrias et al. (2008), the effect of low-beam car headlights on target contrast was evident up to a distance of 80 meters; at distances greater than 80 meters, low-beam car headlights had little effect. Therefore, the distance of 80 meters can be considered as the upper limit for the effect of car headlights, with this effect becoming negligible at distances greater than 80 meters and progressively higher with diminishing distance to the headlights. Based on these results, the distance of 80 meters was chosen for evaluating the visibility of objects on the road, since this distance to the target not only enables target detection but also provides sufficient distance for safely stopping the vehicle.

In order to ensure a static distance between the measurement car and the objects, the car was moved after each measurement to maintain a constant distance of 80 meters between the objects and car headlights. The objects were positioned in two different locations: the standard target was always placed in the middle of the road (central axis) and the pedestrian stood near the sidewalk on the road (right axis). Both objects were located in five different positions at a distance of 7.5 meters between two luminaires. Figure 3 represents the measurement area and positioning of the objects. The figure shows that there were no oncoming car headlights.



Figure 3: Configuration of the experiments

Table 1 lists the horizontal illuminances of the road in target and pedestrian positions. The horizontal illuminance of each measurement point was measured using the LMT (Lichtmesstechnik GMBH) Pocket Lux 2 2 which was calibrated in the autumn of 2014. The lux meter was placed at each measurement point, and the lux reading was displayed on the monitor. Illumination of the road on the unlit road (off-road lighting) is caused by the surroundings. The measurements were done during the autumn and winter of 2015.

	Road lighting	1	2	3	4	5	Average illuminance (lux)	
	100%	34.3	16.4	7.4	17.4	33.7	21.8	
Target position	70%	24.9	13.2	4.7	12.4	25.3	16.1	
	50%	18.7	9.9	3.8	9.4	19.1	12.2	
	20%	8.1	4.5	1.8	4.2	8.5	5.4	
	0	0.3	0.2	0.1	0.1	0.2	0.2	
Pedestrian position	100%	34.2	15.1	7.8	14.9	39.9	22.4	
	70%	24.5	11.2	5.5	11.3	25.2	15.5	
	50%	18.4	8.2	4.2	8.4	19.0	11.6	
	20%	7.9	3.7	1.9	3.9	8.2	5.1	
	0	0.2	0.2	0.1	0.0	0.0	0.1	

Table 1: Horizontal illumination (lux) on different road lighting intensities in different target and pedestrian positions on the road surface. Percentages in road lighting range between full road lighting (100%) and no lighting (0%) conditions.

Figure 4a, illustrates the target and pedestrian eccentricity (in degrees) relative to the line of sight. The target was positioned at 0° eccentricity (straight-ahead line of sight to the target onto which the driver's eyes focused); the pedestrian, however, was positioned at 0.52°, which is close to the line of vision. As can be seen in Figure 4b, both the target and pedestrian were positioned in the 2-degree visual field associated with foveal vision. Therefore, due to this very small eccentricity, it was chosen to exclude the effect of eccentricity from these measurements.



Figure 4: a) orientation and eccentricity of objects in relation to the car, b) two-degree visual field c) Pedestrian size, as well as d) object and background luminance of the pedestrian

This study calculates luminance, contrast, and visibility levels. Luminance measurement provides us with information on how the lighting changes when it is reduced under different weather conditions.

Contrast measurement provides information about polarity shifts as road lighting is dimmed. Targets on the road can have a positive or negative contrast due to their polarity differences against 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 et al., 2008). Contrast equals the value of the difference between target and background luminance divided by the background luminance. Contrasts of equal absolute value but with opposite signs (positive or negative) do not lead to an equal visual performance. To get equal visual performance from negative and positive contrast, contrast can be calculated from equation (1) (Janoff, 1992).

$$C = \frac{|L_t - L_b|}{\max(L_b, L_t)} \tag{1}$$

in which C is contrast, L_t is the luminance of the target, and L_b is the background luminance.

The visibility level using the Adrian model was applied in this experimental study. For visibility-level computation, two photometric values are needed: the luminance of the target and the luminance of its near background (Bremond, et al., 2011). Adrian's visibility level can be calculated using the following equation (2):

$$VL = \frac{\Delta L_{actual}}{\Delta L_{threshold}},\tag{2}$$

where:

 ΔL_{actual} is the difference of luminance between a target and its background

 $\Delta L_{threshold}$ is the luminance difference needed for minimal visibility. It depends on several factors, including the angular size of the target, the observation time, age factor, as well as target and background luminance. A higher value for visibility level implies better visibility. One of the shortcomings of visibility level is that despite having a unique field factor, the same VL can lead to different performance levels depending on the context (e.g. speed, traffic, task demand) (Rea, 1986).

Details of visibility level calculations using the Adrian model are given in the Appendix. The object and background luminance needed to calculate the visibility level using the Adrian model were extracted from the luminance map. For the target, the average luminance of the right and left sides of the target was obtained for background luminance. In addition, the middle point of the target was selected as the target luminance. The Adrian formula was developed for targets comprising small uniform squares or discs. Therefore, for a pedestrian target, a small circle was selected around the center of the pedestrian body. The luminance values of the pedestrian is extracted from images taken from an imaging luminance photometer. The average luminance values within the dots contribute to background luminance (Figure 4 d)." As can be seen from Figure 4 c, the pedestrian size was 75 minutes. The background of the target is the road surface, while the pedestrian background is the environment (i.e., trees) behind the pedestrian.

The first set of measurements was designed to test the relative effects of different road lighting levels in the presence of low-beam car headlights on the visibility of objects (small target and pedestrian) under dry road conditions. The second and third sets of measurements were designed to test the same variables on either a completely wet road surface or snow-covered road, respectively. Analysis of the data was performed using TechnoTeam LabSoft and Matlab.

3. Results

3.1. Luminance measurements

Luminance measurements were conducted under three different weather conditions with the same set-ups. Figure 5 shows the road section with average luminance (L_{ave}), overall uniformity (U_0) and longitudinal uniformities (U_L) for each undimmed (full road lighting) condition. Average luminance refers to the luminance averaged between two poles. Overall uniformity refers to the ratio of the minimum luminance at a point to the average road surface luminance over an evaluation area, and longitudinal uniformities refer to the ratio of the minimum to maximum luminance in a longitudinal direction along the center line of each lane. Table 2 lists the average luminance, overall luminance uniformity, and longitudinal luminance uniformities in all road lighting intensities under varying weather conditions with the effect of car headlights.

The L_{ave} , U_0 , and U_L required for ME4b are 0.75 cd/m², 0.4, and 0.5 and the minimum overall luminance uniformity required for wet road surface is 0.15 (CEN/TR 13201-1). As depicted in Table 2, under full road lighting conditions, the dry road surface was able to meet the luminance requirements of the CEN/TR 13201-1.

In wet conditions, the luminance level was higher than in dry conditions, as can be seen from Figure 5 and Table 2. Furthermore, due to non-uniform specular reflections 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. Due to some very high luminance measurements, the calculated average was higher in wet conditions than in dry conditions; nonetheless, the road surface appears darker in wet than in dry conditions. On a wet road surface, the minimum overall luminance uniformity required was fulfilled for all dimming levels except for that of the unlit road. Under full road lighting conditions, the average luminance level on a wet road surface was 2.5 times higher than the required luminance level; similarly, the average luminance level of the snowy road surface was 3 times higher than the required luminance level. The overall and longitudinal luminance uniformities of the snowy road surface were lower than under dry conditions but still met the requirements.



Snow road surface: $L_{ave} = 3.12 \text{ cd/m}^2$ Uo = 0.54

 $U_{L,left} = 0.36$

U_{L,right} = 0.48

Figure 5: Luminance measurements using an imaging luminance photometer (full road lighting and low-beam car headlights), including average luminance Lave, overall luminance uniformity Uo and longitudinal luminance uniformities Ul in full road lighting under varying weather conditions, UL, left is from the left and Ul, right from the right lane. Note: Uniformity is a plain figure.

Road lighting	Weather conditions	Lave	Uo	UL,left	UL,right
Intensity					
	Dry	0.79	0.64	0.60	0.52
100%	Wet	2.62	0.17	0.14	0.12
	Snow	3.12	0.54	0.36	0.48
	Dry	0.63	0.67	0.56	0.58
70%	Wet	2.09	0.18	0.13	0.13
	Snow	2.49	0.56	0.34	0.41
	Dry	0.46	0.58	0.45	0.58
50%	Wet	1.52	0.15	0.11	0.13
	Snow	1.82	0.49	0.27	0.41
	Dry	0.19	0.62	0.39	0.44
20%	Wet	0.63	0.17	0.09	0.10
	Snow	0.75	0.52	0.23	0.41
	Dry	0.04	0.23	0.013	0.11
Off	Wet	0.13	0.06	0.003	0.03
	Snow	0.16	0.19	0,08	0.10

Table 2: Average luminance (cd/m²), overall luminance uniformity and longitudinal luminance uniformities in all road lighting intensities under varying weather conditions

3.2. Contrast

The first set of measurements was conducted on a dry road surface and used as a reference condition for comparison with wet and snowy road surfaces. In all measurements, the car used its low-beam headlights. Figure 6 illustrates the contrast polarity data for the target and pedestrian in each position.

The transition between polarity is apparent in Figure 6. For instance, in the case of the target (Fig 6 a), reducing road lighting levels changed the polarity from negative to positive in most positions. Conversely, in the case of the pedestrian (Fig 6 b), reducing road lighting levels changed the polarity from positive to negative. Thus, shifting from positive to negative polarity or vice-versa makes the contrast become zero in some positions (almost the same for background and target luminance).







Figure 6: contrast for different road lighting levels in presence of car headlights a) target and b) pedestrian

3.3. Visibility level measurements

Figure 7 shows the mean visibility levels of the 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. The smaller standard error, the more likely that any sample mean is close to the population mean.



Figure 7: Mean visibility levels for all positions under different road lighting intensities and low-beam car headlights for target and pedestrian. The bars represent standard error

Error bars in Figure 7 indicate that the visibility levels of the 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, the position of the target and pedestrian on the unlit road with only car headlights did not have any effect on sample mean.

As shown in Figure 7, the visibility level of the pedestrian is higher than that of the target, except in the case of the unlit road. The higher reflection factor of the target does not compensate for its smaller size relative to the pedestrian. The target is small in size and its reflection factor is higher than that of the pedestrian. In addition, the pedestrian forms a 3-D shape.

In dry road surface conditions, the average visibility of the target at all positions was 1.9, 1.9, 1.7, 2.6, and 3.9 under light intensities of 100%, 70%, 50%, 20%, and off, respectively. In contrast, the average visibility of the pedestrian was 3.6, 2.7, 2.4, 3.9, 4.4 under light intensities of 100%, 70%, 50%, 20%, and off, respectively. The visibility levels of the 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. In all positions, the "off " road lighting provided the best visibility followed in declining order of visibility by light intensities of 20%, 100%, 70%, and 50%. For both the target and pedestrian, the best average visibility levels over all positions were achieved with only car headlights (no road lighting). A road lighting intensity of 20% provided better visibility levels than at higher intensities. The average visibility levels become slightly worse, followed in declining order of visibility by light intensities of 100%, 70%, and 50%, though these differences were only slight.

Under wet road surface conditions, some fluctuations in visibility performance were observed at different 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, indicating that low-beam car headlights were adequate for the visibility performance of drivers. The second-best condition after unlit road conditions was observed for the visibility level obtained under 20% road lighting combined with low-beam headlights, although some fluctuations were apparent across the positions. In such cases, other road lighting intensities from 100% to 50% yielded similar results. The average visibility of the target at all positions was 1.5, 2.0, 1.5, 2.5, and 4.8 under light intensities of 100%, 70%, 50%, 20%, and off, respectively. The visibility level of the pedestrian under wet road surface conditions indicates that unlit and low road lighting (20%) resulted in almost the same visibility levels, which were higher than those obtained using other road lighting levels. The average visibility of the pedestrian at all positions was 5.0, 3.7, 2.4, 3.8, and 4.2 under light intensities of 100%, 70%, 50%, 20%, and off, respectively.

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 standard. The VL graph of the target indicated that in snowy conditions, the visibility of a highly reflective target (50%) did not require road lighting, since car headlights provided better contrast against a darker rather than a well-lit road surface. After unlit conditions, the lowest lighting level (20%) provided the best visibility, while other lighting levels between 100% to 50% yielded lower visibility levels. Average visibility of the target at all positions was 1.7, 1.6, 1.4, 2.6, and 5.7 under light intensities of 100%, 70%, 50%, 20%, and off, respectively. For the dark pedestrian, a well-lit snowy background provided the best contrast. Although visibility levels dropped 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 under light intensities of 100%, 70%, 50%, 20%, and off, respectively.

4. Discussion

In this study, three methods were used to assess the combined effect of car headlights with different road lighting intensities under varying road surface conditions: luminance measurement, contrast, and visibility level. This study employed two different objects: a small standard target ($20\text{cm} \times 20\text{cm}$) with a reflection factor of 50% and a pedestrian 185 cm in height of wearing navy-blue clothing with a lower reflectance of 3.3%. Unlike many previous studies (Bacelar, 2005; Ekrias et al, 2008; Mayeur, 2010) focusing only on full-power road lighting, our study used road lighting at 100% (0.75 cd/m^2), 70% (0.53 cd/m^2), 50% (0.38 cd/m^2), 20% (0.15 cd/m^2) and 0% lighting levels. The experiments were carried out in the same location during different road surface conditions.

The luminance measurements conducted under different road surface conditions indicate that the luminance levels (average luminance level, overall uniformity, and longitudinal uniformity) were different. The luminance level was higher in wet and snowy conditions than in dry conditions. Under wet conditions, due to non-uniform specular reflections, the luminance of some positions was higher or lower than under dry conditions. In contrast, during the winter, when the road was covered with snow, the luminance level exceeded (between 2 to 2.5 times or more) the luminance standard requirements. This also accords with earlier observations by Ekrias et al. (2007), who found that the luminance level of a snow-covered road was 50% higher than that observed during dry conditions.

The results for contrast measurement indicate a clear trend in changing polarity obtained by altering road lighting levels. For a target with a reflection factor of 50%, reducing road lighting changes contrast polarity from negative to positive. Conversely, in the case of a pedestrian, dimming road lighting alters the polarity from negative to positive. However, some dimming levels resulted in zero contrast. Therefore, it can be concluded that road lighting should be dimmed to a level that does not interfere with the effect of car headlights or should be at its full level when no car headlights are in use.

Visibility calculations were designed for a standard target, since background luminance is not uniform when the target is large, such as in the case of a pedestrian. While the background of the target was the road surface, the background of the pedestrian was the scenery behind the pedestrian. The results of the VL study also indicate that in the presence of car headlights, the need for full road lighting is unnecessary, as car headlights can suffice to ensure the visibility of objects when road lighting is unavailable. Furthermore, the vertical illuminance provided by car headlights is more important for the visibility of objects on the road, as they mainly highlight the vertical surfaces of objects on the road. Therefore, turning off road lighting would be feasible within the range of car headlights (Fig 2). This finding is in agreement with the experimental study of Janoff et al.'s (1986), which investigated drivers' performance under full and unlit lighting conditions on straight ramps using car headlights. Their results indicated a slight decrease in drivers' performance on the unlit road in mainline sections. Therefore, lighting could potentially be reduced on mainline sections. Although our results indicate that unlit road lighting is adequate for ensuring the visibility of objects, there are various counterarguments underscoring the adverse effects of unlit roads on traffic safety. Firstly, and most importantly, VL does not actually correlate with traffic safety. As reported previously, turning off the road lighting adversely affects traffic safety by 30% on average (CIE, 1993; Wanvik 2009). Secondly, objects on the road seldom exhibit a high reflection factor and normally appear with a reflectance of only 20% or less (Hansen et al., 1979; Narisada, et al., 2001). Since these targets are usually seen in negative contrast (the object has less luminance than the background), switching off-road lighting reduces the chances of seeing such targets while driving (as can be seen by comparing the average pedestrian visibility level against the VL of the target in unlit road conditions. Thirdly, drivers in urban areas can commonly experience disability glare from the headlights of oncoming cars. The effect of this glare can be reduced through the use of road lighting (Bacelar, 2004; Boyce, 2008). A fourth counterargument is that unlit road lighting does not generally provide safe driving conditions, especially for those who are unfamiliar with potentially adverse features of the road (i.e., curves, geometry, surroundings and intersections). Finally, since road lighting is just as important for pedestrians, turning off-road lighting is not recommended. As can be seen from Figure 10, reducing road lighting from full to 50% (Table 1: average illuminance of 22 to 15 lux) gradually reduces the visibility level. Nonetheless, reducing it to 20% (Table 1: average illuminance of 5 lux) increases the visibility, because the effect of car headlights is likely to be more noticeable in lower road lighting conditions. Twenty percent of full road lighting provided the best road lighting in all three weather conditions. This also saves energy while simultaneously having no adverse effect on visibility performance.

Accordingly, the second-best road lighting level found in this study was provided by a dimmed road lighting intensity level of only 1690 lumens, corresponding to 20% of the undimmed LED luminaire. At a road lighting level of 20%, average luminance was found to be 0.19, 0.63 and 0.75 cd/m² under dry, wet and snow conditions, respectively. The results of the current study (under LED luminaires) corroborate well the findings of previous work implemented using high-pressure sodium (HPS) luminaires (Bozorg Chenani et al., 2016). The findings of the current study are also consistent with those of Gibbons et al., (2014), who 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. Their findings indicated that current road lighting practices result in over-lighting, though the increased lighting level does not necessarily lead to a safer road. Thus, their study confirms the potential to reduce road lighting levels. As a minimum requirement, they proposed an average horizontal illuminance of 5 lux, since increasing the average illuminance had no significant effect on the night-to-day crash rate ratio, though average illuminance values below this level (average illuminance levels of 0 to 3) were found to have a significant effect on the crash rate ratio. Additionally, Gibbons and his co-workers also suggested a minimum average vertical illuminance of 3 lux, a desired ratio of 0.6 for vertical-to-horizontal ratios, a minimum uniformity of 0.3 and a luminance level of 0.15 cd/m^2 .

However, because the current study was conducted in a stationary car, we may have underestimated the effect of speed and driving conditions. A study by Perel et al. (1983), focusing on driving with low beam car headlights alone, provided enough visibility at speeds up to 48 km/h. Furthermore, a study by Bozorg Chenani et al (2017) 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) while driving at 30 km/h. in contrast, a study by Janoff et al. (1986) studied the detection distance of a small target at high speed (89 km/h) car in different road lighting intensities. The road lighting conditions studied were 100% (Lave: 0.58 cd/m²), 75% (Lave: 0.29 cd/m²), 50% (Lave: 0.15 cd/m²) of road lighting power, with every other luminaire extinguished (Lave: 0.27 cd/m²), one side extinguished (Lave: 0.049 cd/m²), and no light (Lave: 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, 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. The varying interpretations of Janoff et al. (1986), Perel et al. (1983) and Bozorg Chenani et al (2017) emphasise the importance of the Assured Clear Distance Ahead (ACDA) rule. The ACDA rule is based on the basic speed law, which stipulates that the drivers should maintain a speed low enough to enable them to stop within the range of vision, thus avoiding accidents with any obstacles that might appear in the car's path (Leibowitz et al., 1998). Accordingly, it can be concluded that the effect of car headlights are limited to the speed.

In addition, user experience is also important. A questionnaire-based study by Viikari et al. (2012) from over 105 drivers on different aspects of road lighting (i.e., quality, visual performance, and safety) indicated that drivers valued road lighting in terms of traffic safety and that they would not relinquish road lighting for energy savings. Nonetheless, they were willing to have the amount of light reduced to save energy.

Reducing road lighting to 20% of its power in different weather conditions (dry, wet, and snowy conditions), could under some circumstances result in good visibility levels and provide the possibility of reducing road lighting as well as saving energy and costs. It also increases the lifespan of luminaires and reduces carbon dioxide emissions depending on the source used to generate the electricity. Our visibility level measurements show that the combination of car headlights can reduce the necessity of employing full road lighting in varying weather conditions. However, since weather conditions can greatly affect luminance and visibility, the road luminance should be monitored and dimming should be dynamic, taking into account the environmental circumstances. The current measurements were conducted after rain and snow precipitation (road surface conditions). Since visibility might be reduced during precipitation, the dimming should be applied after precipitation. In addition, it is suggested that future studies should investigate the potential association between weather conditions and drivers' visibility.

On average, the annual burning hours of one luminaire in Finland is 3965 hours, which corresponds to an electricity consumption of 396.5 kWh. Based on our findings, there is no need for full road lighting when car

headlights are available. For instance, reducing road lighting output to 20% could reduce energy consumption to 79.3 kWh/year/luminaire, yielding an energy saving of 317 kWh/year/luminaire. The average price for electricity in 2016 has been 8 cents/kWh (includes energy, distribution and taxes). Thus, the total energy cost for one luminaire without dimming would be 31.72 euros/year. Reducing road lighting to 20% would give an energy cost of 6.35 euros/luminaire/year, and a savings for each luminaire of 25.36 euros/luminaire/year.

One limitation of this study is that it ignored the effect of glare in different weather conditions (e.g., rain and snow). Similarly, the drivers' experience was not taken into account, and the measurements were carried out in a stationary car. Therefore, future research could benefit by examining these parameters.

5. Conclusion

The present study was designed to measure the combined effect of different road lighting intensities and lowbeam headlights under different road surface conditions with the goal of determining the feasibility of reducing road lighting. The study has given an account of reducing road lighting levels in different road surface conditions. The visibility level results indicate that for better visibility, road lighting should be full (100%) or to a level that does not counteract the effect of car headlights (average luminance of 0.19 cd/m²). Finally, the average visibility of the pedestrian was higher than that of the target, even though the target possessed a higher reflection factor. This is due to the size and 3-D shape of the pedestrian.

Further, road lighting levels can be reduced within the range of car headlights, especially in roads with low-speed limits.

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Appendix

Adrian model visibility level can be calculated by equation (1):

$$VL = \frac{\Delta L_{actual}}{\Delta L_{threshold}},$$
(1)

where.

 ΔL_{actual} is the difference of luminance between a target and its background

$$\Delta L_{actual} = L_t - L_b \left(\frac{ca}{m^2}\right),\tag{2}$$

L_t is target luminance,

L_b is background luminance

 $\Delta L_{threshold}$ is the difference of luminance necessary for obtaining minimum visibility between the target of the given angular measurements and its background.

$$\Delta L_{threshold} = k \cdot \left(\frac{\phi^{1/2}}{\alpha} + L^{1/2}\right)^2 \cdot F_{CP} \cdot \frac{a(\alpha, L_b) + t}{t} \cdot AF, \tag{3}$$

where:

k is target perception probability coefficient (k=2.6 for the probability equalling 99.9%),

 ϕ , L are background luminance functions,

 α is angular size of the object,

 F_{CP} is the contrast polarisation factor,

 $a(\alpha, L_b)$ is parameter dependent on the angular size of the object and background luminance,

T is target observation time,

AF is the age factor.

 $\phi^{1/2}$ and $L^{1/2}$ can be calculated from the equations above:

If background luminance $L_b \ge 0.6 \ (cd/m^2)$ then: $\phi^{1/2} = \log(4.1925L_b^{0.1556}) + 0.1684L_b^{0.5867}$ $L^{1/2} = 0.05946L_b^{0.466}$ If background luminance $0.00418 < L_b < 0.6 \ (cd/m^2)$ then: $log\phi^{1/2} = -0.072 + 0.3372logL_b + 0.0866(L_b)^2$ $logL^{1/2} = -1.256 + 0.319logL_b$ If background luminance $0.00418 < L_b \ (cd/m^2)$ then:

 $log\phi^{1/2} = 0.028 + 0.173 logL_{b}$

$$logL^{1/2} = -0.891 + 0.5275 logL_b + 0.0227 (logL_b)^2$$

The angle (α) is the angular size of the object. The object of radius r seen from the distance d has the measurement of observation angle can be found by:

$$\alpha = 2. \tan^{-1}\left(\frac{r}{d}\right). 60, (minutes)$$

The influence of exposure time can be calculated by: $a(\alpha, L_b) + t$

$$\frac{u(u, L_b) + u}{t}$$

in which α is a function of target size and luminance level L_b. The following equations are used to calculate $a(\alpha, L_b)$:

$$a(\alpha) = 0.36 - 0.0972. \frac{(log\alpha + 0.523)^2}{(log\alpha + 0.523)^2 - 2.513(log\alpha + 0.523) + 2.7895}$$

$$a(L_b) = 0.355 - 0.1217. \frac{(logL_b+6)^2}{(logL_b+6)^2 - 10.4(logL_b+6) + 52.28},$$

For target sizes with $\alpha < 60'$ the value of $a(\alpha, L_b)$ can be found by:

$$a(\alpha, L_b) = \frac{(a(\alpha)^2 + a(L_b)^2)^{1/2}}{2.1}$$

For target observation of 2sec, the exposure time can be found by:

$$\Delta L_t = \Delta L_{t=2 sec} = \frac{a(\alpha, L_b) + t}{t}$$

Contrast polarisation factor can be determined by F_{CP}, the value of that can be calculated from:

$$\Delta L_{neg} = \Delta L_{pos}.F_{CP}$$
,

where ΔL_{pos} is the value for perception time for t=2sec. contrast polarization factor F_{CP} is calculated according to the following equation:

$$\begin{split} F_{CP}(\alpha, L_b) &= 1 - \frac{m\alpha^{-\beta}}{2.4 \,\Delta L_{pos,t=2sec}},\\ \text{in the equation for } L_b \geq 0.1 \,cd/m^2\\ m &= 10^{-10^{-(0.125(logL_b+1)^2+0.0245}}\\ \text{for } L_b \geq 0.004 \,cd/m^2\\ m &= 10^{-10^{-(0.075(logL_b+1)^2+0.0245}}\\ \text{for all } L_b: \end{split}$$

 $\beta = 0.6L^{-0.1488}$ age factor (AF) can be calculated from:

$$23 < \text{age} < 64: AF = \frac{(age - 19)}{2160} + 0.99$$

$$64 < \text{age} < 75: AF = \frac{(age - 56.6)^2}{116.3} + 1.43$$