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LED (Light-Emitting Diode) Road Lighting in Practice: An Evaluation of Compliance with Regulations and Improvements for Further Energy Savings

Annika K. Jägerbrand

The Swedish National Road and Transport Research Institute, Box 55685, SE-102 15 Stockholm, Sweden; annika.jagerbrand@vti.se; Tel.: +46-13-204219

Academic Editor: Enrico Sciubba
Received: 21 March 2016; Accepted: 4 May 2016; Published: 11 May 2016

Abstract: Light-emitting diode (LED) road lighting has been widely implemented in recent years, but few studies have evaluated its performance after installation. This study investigated whether LED road lighting complies with minimum regulations in terms of traffic safety and whether improvements for energy efficiency are possible. Average road surface luminance (L), overall luminance uniformity (U_o), longitudinal luminance uniformity (U_I), power density (P_D) and normalised power density (P_N) were evaluated for 14 roads (seven designed for vehicular traffic and seven for pedestrians and bicycles). Energy savings were calculated as the percentage reduction to the minimum level of the existing lighting class or a lower lighting class and by applying a dimming schedule. The results showed that LED road lighting for vehicular traffic roads generally fulfilled the requirements, whereas that for pedestrian and bicycle roads generally corresponded to the lowest lighting class for L, and often did not meet the statutory requirements for U_o and U_I. By adapting lighting levels to the minimum requirement of the existing lighting class or by dropping to a lower lighting class, vehicular traffic roads could save 6%–35% on L to lighting class M5 and 23%–61% on L to lighting class M6. A dimming schedule could lead to energy savings of 49%. There is little potential for savings on pedestrian and bicycle roads, except by implementing a dimming schedule. Thus, in general, for vehicular, pedestrian and bicycle roads, a dimming schedule can save more energy than can be achieved in general by reducing lighting class. Furthermore, since a dimming schedule can be adjusted to traffic intensity, any potential risk of compromising traffic safety is minimised.

Keywords: roads; pedestrian and bicycle paths; luminance; energy efficiency; uniformity

1. Introduction

The widespread trend of using light-emitting diodes (LEDs) for outdoor lighting in order to decrease energy consumption has led to interest in evaluating installed LED lighting systems from the perspectives of traffic safety and energy efficiency. Such evaluations are highly relevant, since traffic safety regulations often require a minimum light level and since energy consumption by outdoor lighting can be very high due to the long operating hours. In fact, street lighting can account for 60%–80% of total electricity consumption by a municipality [1,2], leading to a high financial burden for maintaining public lighting [3]. To reduce these energy costs and to comply with the mandatory changes in the lighting market caused by the European Union Ecodesign regulations, municipal authorities are highly interested in changing to new lighting technologies, particularly if these pose no risk of compromising light quality.

LED technology offers high efficiency, good physical robustness, long life expectancy and low power consumption [4]. Thus, a switch to LED lighting can result in energy savings and lower costs in coming decades (e.g., [4,5]). Furthermore, LED lighting is easy dimmable and has a rapid on/off time, which is very appropriate for application of dimming schemes to further reduce energy consumption [4,6]. However, while many studies have evaluated the performance of LED lighting in scenarios and calculations in various software programmes, evaluations based on the field performance of LED road lighting after installation are rare [7].

Evaluations of outdoor lighting from various light sources based on field performance have shown that the systems can be both over-lit and not very energy efficient [8,9]. For example, initial over-lighting can be up to 40%, depending on the light source and luminaire [10]. This is in order to compensate for the decline in lumen output over time due to decreases in light emission and changing surface properties with age, which forces designers to set higher levels than recommended at the start so that lighting installations still meet the requirements at the end of their life cycle [11]. The lamp lumen depreciation factor for LED lighting is reported to be 0.7–1, suggesting that there is no reduction in lumen output during its lifetime [12] or that it is 0.7 [13] but can be higher when shortening the lifetime in the calculation from 100,000 h to e.g., 50,000 h [14]. Furthermore, LED lighting can be programmed to increase lumen output, and it would therefore be technically possible to compensate for any light losses at later stages in its lifetime. Thus, in theory, LED road lighting installations should not show signs of initial overlighting.

The road lighting in Sweden is owned by the Swedish Transport Administration (public roads), municipal authorities and, in some cases, smaller organisations or associations. Only road lighting owned by the Swedish Transport Administration is legally obliged to fulfil the regulations set by the Swedish standard, whereas compliance by road lighting owned by others is recommended, but there are no sanctions if the regulations are violated. The Swedish standard was originally based on "common sense" for visual performance, but has been refined over the years.

In practice, it seems common for municipal officials to choose road lighting based on suggestions from software programmes such as DIALux, with input data based on, e.g., an assumed lighting class, the difficulty of the road environment and forecast traffic intensity [15]. Thus, lighting classes are rather freely selected by municipal officials based on road environment conditions, municipal policies and the official's personal experience. Due to these circumstances, it is possible that the implemented lighting class could be further reduced to save energy without affecting visual performance or traffic safety.

Since LED is a new technology for road lighting use and its implementation is strongly based on calculated energy and cost savings, it is highly important to study whether LED road lighting conforms with the requirements stipulated by the European standard [16] or the Swedish standard [17]. This study therefore investigated the following questions:

I. Does LED road lighting complies with minimum regulations when evaluations are based on field performance?
II. If so, is there room for further improvement of the energy efficiency of LED lighting without violating the stipulated regulations?

These questions were examined by measuring and calculating the field performance of LED road lighting in terms of road surface luminance (L), overall luminance uniformity (U_o), longitudinal luminance uniformity (U_l), power density (P_D) and normalised power density (P_N) on roads designed for vehicular traffic and roads for pedestrians and bicycles. To evaluate improvements in energy efficiency, the energy consumption and savings achieved by reducing lighting class or by implementing a dimming schedule were calculated. Energy efficiency was also evaluated by Road Lighting Energy Efficiency Class (RLEEC) [18].

2. Methodology

2.1. Road Sites

Roads with LED lighting were located by contacting street lighting departments in municipal authorities and performing field visits to ensure that potential sites were not excessively influenced by the surrounding outdoor lighting and that the roads were level, to ensure that multiple measurements could be made at the same location. A total of 14 roads were selected for the study, seven roads for vehicular traffic and seven intended for pedestrians and bicycles (Table 1). Road width, luminaire spacing and correlated colour temperature (CCT) were measured in the field on dry road surfaces. The number of measurements varied between two to five, depending on the location (Table 1). Road lighting owners were contacted and asked for information on the installed power for each luminaire at the 14 study locations.

Table 1. Road name, location, number of measurements on each road (No.), road width (m), luminaire spacing (m), correlated colour temperature (CCT, K), installed power (W) and road type. GC = pedestrian and bicycle roads.

Road	Location	No.	Road Width (m)	Luminaire Spacing (m)	CCT (K)	Power (W)	Road Type
Ösbydalsvägen	Gustavsberg	5	8.3	28.9	4272	56	2 non-separated lanes
Ösby	Gustavsberg	4	3.1	30.9	3161	29	2 non-separated lanes
Kryddgårdsvägen GC	Botkyrka	5	3.0	20.5	3870	28	Pedestrian & bicycle
Vreta Gårds väg	Botkyrka	5	5.0	32.3	4222	58	2 non-separated lanes
Vreta GC	Botkyrka	2	4.0	26.2	4196	28	Pedestrian & bicycle
Solskensvägen GC	Botkyrka	5	3.0	25.6	3768	28	Pedestrian & bicycle
Solskensvägen	Botkyrka	5	7.0	34.9	3984	58	2 lanes with markings
Hallunda gårdsgata	Botkyrka	5	7.5	25.0	4142	58	2 non-separated lanes
Tullingeberg GC	Botkyrka	5	3.0	23.6	3689	28	Pedestrian & bicycle
Skogshemsvägen	Botkyrka	5	7.3	21.6	4114	42	2 non-separated lanes
Timotejvägen	Botkyrka	2	6.0	22.4	3901	58	2 non-separated lanes
Fredsgatan	Nynäshamn	5	6.0	12.0	5788	17 × 2	2 non-separated lanes
Folketshus GC	Nynäshamn	4	3.5	22.2	3873	28	Pedestrian & bicycle
Nickstahöjden GC	Nynäshamn	5	3.0	24.0	3683	28	Pedestrian & bicycle

2.2. Measurements

Luminance was measured using an LMK Mobile Advanced imaging luminance photometer (based on a Canon EOS 550D) and the associated computer software LMK labsoft ver. 12.7.23 (Techno Team Bildverarbeitung GmbH, Ilmenau, Germany). The LMK Mobile Advance is designed to convert images directly into luminance values with assistance of a software programme. Photos were taken at 10 m distance from the road lighting in the driving direction and at a height of 150 cm. Two sets of photos were taken, with and without flashlights on the ground to mark the corners of the road so that the exact locations of the road surface could be found in the software programme. LMK labsoft was used to extract the measured data. A Jeti Specbos 1201 spectroradiometer (JETI Technische Instrumente GmbH, Jena, Germany) was used to measure CCT. Equipment was pre-calibrated by the manufacturer before purchase in 2012. The LMK Mobile Advanced luminance measurements were calibrated against Jeti Specbos 1201 luminance measurements taken against a white surface below the road light for matching to the spectral lamp type. All measurements were taken during dark (night-time) and dry conditions on the road surface, while the temperature varied somewhat during the measurement occasions (but less than <10 °C difference). Canon EOS 550D is a digital single-lens reflex camera with a CMOS sensor with 18.0 effective megapixels resolution and has a working temperature range of 0–40 °C and working humidity of 85% or less. The Jeti Specbos 1201 measuring spectral range is 380–780 nm with a wavelength resolution of 5 nm, measuring range luminance is from 2 to 7×10^{14} cd/m^2 (candela per square metre), luminance accuracy is ±2%, while the wavelength accuracy is ±0.5 nm. Operating conditions for the Jeti specbos 1201 are temperatures between 10 and 40 °C and working humidity up to 85% (relative humidity at 35 °C).

Then L, U_l and U_o were calculated based on the European and Swedish standards [16,17], which use the same calculation methods for this purpose. The main differences between using a photometer and a conventional luminance meter are that the distance when taking photos can be reduced from the standard 60 m with a luminance meter and that the number of photometer measurements needed is smaller, since the camera only needs to take three photos to create a luminance picture for the whole road area analysed. A previous study has shown that it may be difficult to zoom in correctly during darkness when using a camera due to the low visibility, making it preferable to use a shorter distance to the measurement area [8]. Another study found no significant difference in luminance results when using the LMK Mobile Advanced at heights of 1, 3, 4 and 5 m or at differing distances (20, 60, 80 m) [19]. Furthermore, it is safer and faster to work at a closer distance when measuring road width and placing flashlights. LMK Mobile Advance has a measurement error in repeatability for luminance (ΔL) of 0.5%–2% according to the manufacturer [20].

For pedestrian and bicycle roads, the standards state that S-series and CE-series lighting classes can be applied, but the European Standard (EN 13201-2) also states that "*The CE classes are mainly intended for use when conventions of road surface luminance calculations do not apply or are impracticable. This can occur when the viewing distances are less than 60 m and when several observer positions are relevant*" ([16], note 3, page 9). CE-series lighting classes are mainly intended for conflict areas, but can be used for both vehicular traffic roads and for other road uses. S-series lighting classes are intended for pedestrians or bicyclists on roads separated from roads with motorized traffic or other areas, for example roads along parking spaces or pedestrian streets. EN 13201-1 [21] identifies lighting classes of comparable lighting levels to avoid large differences between adjacent areas. In this study, luminance measurements were used to evaluate the performance of LED road lighting on pedestrian and bicycle roads and the comparable lighting levels identified by the European Standard [21] were used to find the correct classification in the CE-series and S-series (Table 2).

Table 2. European and Swedish lighting classes M1–M6, comparable European Standard CE-series and S-series classes [21], average road surface luminance (L, cd/m^2) and minimum (min) values of U_o (overall luminance uniformity) and U_l (longitudinal luminance uniformity) according to European and Swedish Standards [16,17].

Lighting Class	Comparable CE-Series Class	Comparable S-Series Class	L (cd/m^2)	U_o (min)	European U_l (min)	Swedish U_l (min)
M1	CE1	-	2.0	0.40	0.70	0.60
M2	CE2	-	1.5	0.40	0.70	0.60
M3	CE3	S1	1.0	0.40	0.60	0.60
M4	CE4	S2	0.75	0.40	0.60	0.50
M5	CE5	S3	0.50	0.35	0.40	0.40
M6	-	S4	0.30	0.35	0.40	0.35

The luminance measurement points were distributed by the LMK labsoft programme across the road surface and each measurement field encompassed two luminaires. The distribution of luminance measurement points for roads with two lanes and painted road markings is shown in Figure 1A, that for roads with two lanes without road markings in Figure 1B and that for pedestrian and bicycle pathways/roads in Figure 1C. One location included the road section between four hanging luminaires (Fredsgatan) since there were two luminaires on the same wire crossing the street perpendicularly.

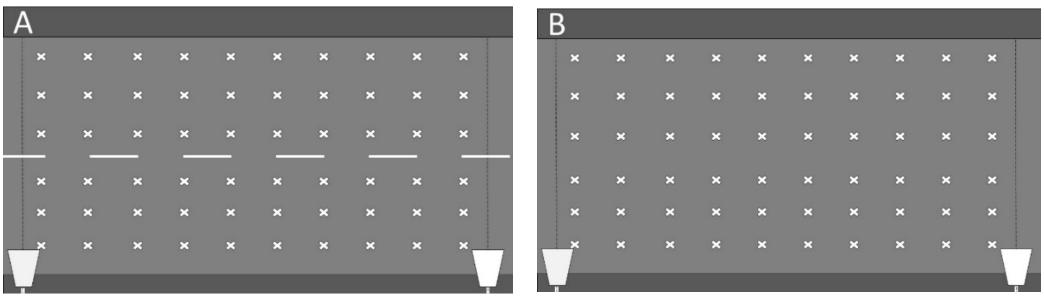

Figure 1. *Cont.*

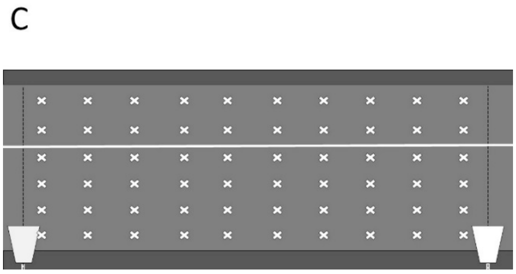

Figure 1. Locations of luminaires (white cones) and points (white x) for average road surface luminance and luminance uniformity measurements. (**A**) Road with two lanes with painted road markings; (**B**) road with two non-separated lanes; and (**C**) pedestrian and bicycle road. Dotted lines show the start and end of the measurement area. Darker areas are outside the road surface. The diagrams are sketches, not scale drawings.

2.3. Calculations

Road surface luminance (L) was calculated as the average luminance of the grid points in the field of calculation, as seen in Figure 1. Longitudinal luminance uniformity (U_I) was calculated as the ratio of the highest luminance in the longitudinal direction along the centre of each lane and overall luminance uniformity (U_o) as the ratio of the lowest luminance occurring at any grid point in the field of calculation to the average luminance [22].

A linear relationship between the power (W or radiant flux) and the measured and calculated variables (luminance, P_D, P_N) was assumed, based on the fact that for each measurement/road section, the radiometric and photometric quantities were constant, at least at the point in time when the measurement was performed. Thus spectral flux, reflectance (reflection coefficient) and distance to the light source were all assumed to be constant for each case when calculating energy savings. In reality, however, reflectance is dependent upon a range of conditions, making comparable measurements of e.g., decreases in radiant flux and the corresponding luminance, difficult to perform, since they have to be made at the same time-point. Since U_I and U_o were restricted by minimum levels, they were only used to exclude measurements and calculations that were at or below the recommended standard. The following parameters were calculated:

- Power demand per year (kWh/year)
- Power demand per kilometre road (W/km)
- Power demand per kilometre road and year (kWh/km/year)
- Power density (W/m^2)
- Normalised power density ($W/m^2 \mid cd/m^2$)

Potential energy saving was calculated based on both dropping down a lighting class and the percentage reduction required in luminance, U_o, U_I and P_D to meet the minimum (lower) requirement of the existing lighting class. Normalised power density (P_N) was used to evaluate the energy efficiency of the road lighting by RLEEC classification [18]. Effects of ballasts were not included.

2.4. Case Study of Dimming Schedule

The case study of a dimming schedule consisted of 8 m high poles equipped with 58 W Iridium^2 LEDs, situated approximately 32.3 m apart and installed in 2011/2012 at Vreta Gårds väg, Botkyrka (Table 1). The road lighting operates with an automatic dimming schedule, which is applied everywhere except at intersections. The road lighting automatically turns off at sunrise and on at sunset and is regulated by a timer. The lighting is on at 100% effect except between 07:00 p.m. to midnight and 05:00–07:00 a.m., when the effect is 80%, and between midnight to 05:00 a.m., when the effect is 50%.

3. Results

The quality and uniformity of the LED road lighting varied between roads. Examples of road sections that were overlit or had good or adequate lighting conditions are shown in Figure 2. Fredsgatan (Figure 2A,C,E) had double hanging 17 W lamps and the road section had an average L value of 0.96 cd/m^2, with U_o = 0.68 and U_l = 0.84 and 0.73 (on different sides of the road). Vreta Gårds väg (Figure 2B,D,F) had 58 W lamps and the road section had an L value of 0.81 cd/m^2, with U_o = 0.74 and U_l = 0.53 and 0.63.

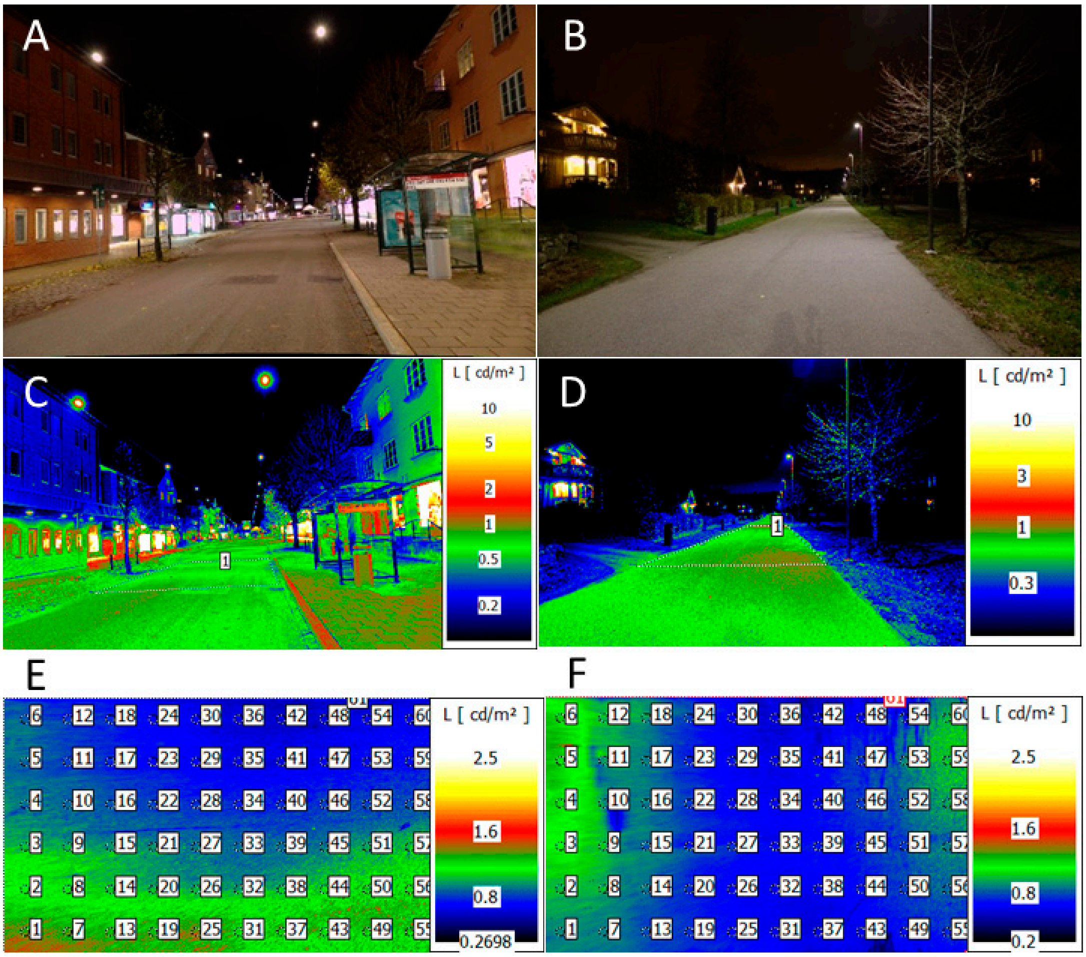

Figure 2. Photos and luminance photos and evaluations of (**left**) Fredsgatan (**A**,**C**,**E**) and (**right**) Vreta Gårds väg (**B**,**D**,**F**). Luminance photos and evaluations have false colours. The luminance scale is individual and is therefore shown in each photo and evaluation. Photos were taken with a Canon EOS 550D (zoom 17–50 mm, F2.8; F4, ISO100) set 150 cm above the ground on a tripod.

Examples of road sections that had inadequate road lighting, especially low U_o values, are shown in Figure 3. Vreta Gårds väg (Figure 3A,C,E) had 58 W lamps and the section shown had an average *L* value of 0.70 cd/m^2, U_o = 0.32 and U_l = 0.41 and 0.53, whereas Tullingeberg GC (pedestrian and bicycle road) (Figure 3B,D,F) had 28 W lamps and this section had an *L* value of 0.39 cd/m^2, U_o = 0.33 and U_l = 0.15 and 0.22.

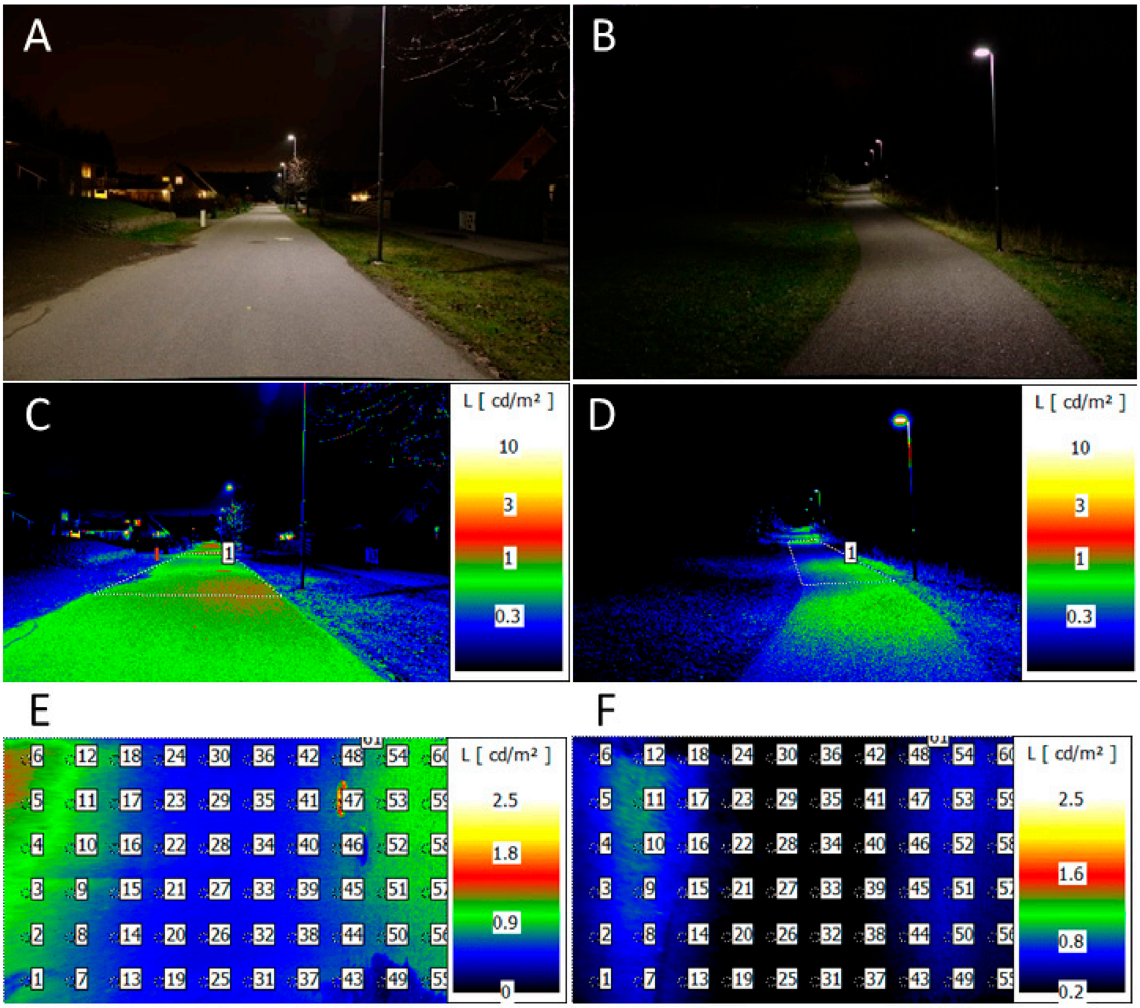

Figure 3. Photos and luminance photos and evaluations of (**left**) Vreta Gårds väg (**A**,**C**,**E**) and (**right**) Tullingeberg GC (**B**,**D**,**F**) (pedestrian and bicycle road). Luminance photos and evaluations have false colours. The luminance scale is individual and is therefore shown in each photo and evaluation. Photos were taken with a Canon EOS 550D (zoom 17–50 mm, F2.8; F4, ISO 100) set 150 cm above the ground on a tripod.

3.1. Energy Efficiency

Energy efficiency of the roads was calculated based on installed power and road length, on a yearly basis and on a P_N basis, and classified in accordance with energy classification system of RLEEC (see Table 3). RLEEC [18] is based on the following P_N classes: A $\leqslant$ 0.2 (most energy efficient); B = 0.2–0.4; C = 0.4–0.6; D = 0.6–0.8; E = 0.8–1.0; F = 1.0–1.2; and G > 1.2 (least energy efficient), *i.e.*, low P_N values indicate high energy efficiency. The P_N values obtained for pedestrian and bicycle roads resulted in RLEEC between B and H, while the vehicular traffic roads had RLEEC between B and D, but generally a higher class than pedestrian and bicycle roads. Thus, roads for vehicular traffic had higher power demand, but also higher energy efficiency and lower P_N values, than pedestrian and bicycle roads.

Table 3. Energy efficiency variables for road lighting (mean values): installed power for each road section (W); power demand per year (kWh/year), per kilometre road (W/km) and per kilometre road per year (kWh/km/year); normalised power density (P_N); and classification in Road Lighting Energy Efficiency Class (RLEEC, where A the most energy efficient and G the least). Bold letters indicate pedestrian and bicycle roads. Mean values. * = calculated for 4200 burning hours per year.

Road	Power (W)	Power Demand * per Year (kWh/Year)	Power Demand per Kilometre (W/km)	Power Demand * per Kilometre per Year (kWh/km/Year)	Normalised Power Density, P_N	RLEEC
Ösbydalsvägen	56	235	1938	8138	0.60	C
Ösby	**29**	**122**	**937**	**3937**	**0.83**	**E**
Kryddgårdsvägen GC	**28**	**118**	**1367**	**5742**	**1.16**	**F**
Vreta Gårds väg	58	244	1796	7542	0.55	C
Vreta GC	**28**	**118**	**1071**	**4497**	**0.36**	**B**
Solskensvägen GC	**28**	**118**	**1094**	**4594**	**1.13**	**F**
Solskensvägen	58	244	1664	6988	0.32	B
Hallunda gårdsgata	58	244	2324	9760	0.56	C
Tullingeberg GC	**28**	**118**	**1185**	**4979**	**0.97**	**E**
Skogshemsvägen	42	176	1944	8167	0.34	B
Timotejvägen	58	244	2589	10,875	0.76	D
Fredsgatan	17 × 2	143	2833	11,900	0.60	C
Folketshus GC	**28**	**118**	**1261**	**5297**	**0.63**	**D**
Nickstahöjden GC	**28**	**118**	**1167**	**4900**	**0.90**	**E**
Mean value cycle/ped.	**28**	**118**	**1155**	**4849**	**0.85**	-
Mean value vehicular	54	218	2155	9053	0.53	-

GC, pedestrian and bicycle roads; ped., pedestrian.

3.2. Measurements of Luminance

In terms of average L values, all roads met the minimum levels for the lowest lighting classes and a few road sections had L values matching the higher lighting classes M3, CE3 and S1 (Figure 4). Most pedestrian and bicycle roads (e.g., Folketshus GC and Kryddgårdsvägen GC) fulfilled the requirements for the lowest lighting classes M6/S4 and M5/CE5/S3, while vehicular traffic roads (e.g., Fredsgatan, Solskensvägen and Vreta Gårds väg) generally fulfilled for requirements for similar or higher classes (Figure 4).

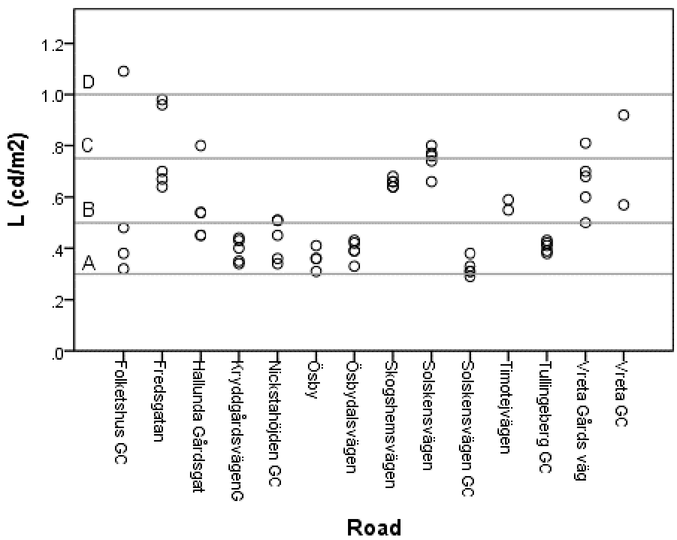

Figure 4. Average road surface luminance values (L, cd/m^2) measured for the 14 roads studied, relative to lighting class boundaries A–D (horizontal lines). A = M6/S4; B = M5/CE5/S3; C = M4/CE4/S2; D = M3/CE3/S1, where M3–M6 are lighting classes with their comparable European Standard CE-series and S-series classes according to [21].

Overall, the U_o and U_l values (Figures 5 and 6 respectively) were both consistently lower for pedestrian and bicycle roads, but some sections of roads for vehicular traffic also had low values. For example, both U_o and U_l were found to be below the minimum level at e.g., Solskensvägen GC and Nickstahöjden GC, whereas high values were found at e.g., Fredsgatan, Hallunda Gårdsgata and Ösbydalsvägen (Figures 5 and 6).

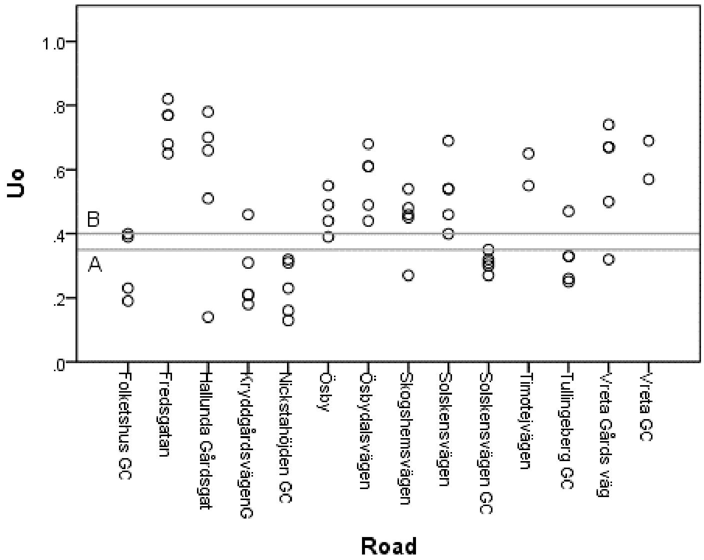

Figure 5. Overall luminance uniformity (U_o) measured for the 14 roads studied, relative to lighting class boundaries A–B (horizontal lines). A = M6-M5/CE5/S4-S3; B = M4-M1/CE4-CE1/S2-S1, where M1–M6 are lighting classes with their comparable European Standard CE-series and S-series classes according to [21].

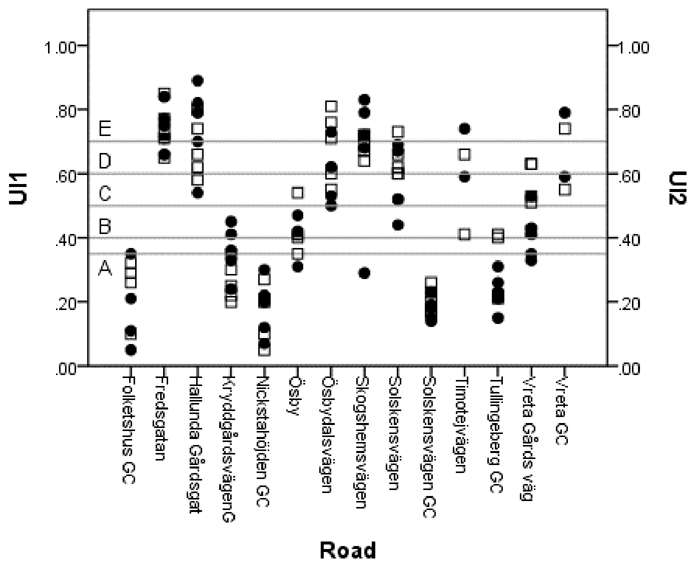

Figure 6. Longitudinal luminance uniformity (U_l) measured for the 14 roads studied, relative to lighting class boundaries A–E (horizontal lines) in accordance with EN 13201-2 [16]: B = M6-M5/CE5/S4-S3; D = M4-M3/CE4-CE3/S2-S1; E = M2-M1/CE2-CE1 and in accordance with Swedish standards [17]: A = M6/S4; B = M5/CE5/S3; C = M4/CE4;/S2. D = M3-M1/CE3-CE1/S1, where M1–M6 are lighting classes with their comparable European Standard CE-series and S-series classes according to [21]. U_l1 (squares) and U_l2 (filled circles) are based on luminance measurements on different sides of the road.

3.3. Energy Savings

Calculations of savings based on L, U_o and U_l showed that roads designed for vehicular traffic could save energy by changing to the minimum requirement of the existing lighting class or by dropping to a lower class, which would save 6%–35% in L for M5 and 23%–61% in L for M6 (Table 4). This was confirmed by analysis of P_D (W/m^2) for the vehicular traffic roads (Table 5), since it is technically possible to lower the M-class with LED lighting. The potential energy savings based on mean values of L, U_o and U_l also showed that the vehicular traffic roads studied had scope to meet the standards for M6 (Table 6). Some of the vehicular traffic roads studied could lower M-class to M5 (Swedish and European standards) and gain a potential energy saving of between 38 and 73 kWh/year without violating the minimum regulations. Pedestrian and bicycle roads could in some cases save energy by lowering M-class based solely on L values (7%–57% savings between M5 and M6), while the mean values of U_o and U_l obtained showed that, in most cases, it would be impossible to lower the lighting levels without creating inadequate road lighting (Table 4). The P_D data also showed that few pedestrian and bicycle roads could save energy, because most of them did not fulfil any other requirements than for class M6 and they also had low energy efficiency classifications in RLEEC (Table 5). Thus pedestrian and bicycle roads had little potential for energy savings based on mean values of L, U_o and U_l. Only two roads, Vreta GC and Ösby, showed room for energy savings by lowering class (Table 6). However, for Ösby, the savings were very small, only 16 kWh/year.

Table 4. Calculated saving (mean value in %) based on the limit for M-classes of average road surface luminance (L, cd/m^2), overall luminance uniformity (U_o) and longitudinal luminance uniformity (U_l). The M-classes for U_l differ between European and Swedish standards and are therefore not shown (but see Table 2). Negative values would have indicated road lighting below the limit of the class and are therefore not shown. "GC" and bold letters indicate pedestrian and bicycle roads.

Variable	*L* Saving (%)			U_o Saving (%)		U_l Saving (%)			
Minimum value (M-class)	0.30 (M6)	0.50 (M5)	0.75 (M4)	0.35 (M6, M5)	0.4 (M4–M1)	0.35	0.4	0.5	0.6
Road	-	-	-	-	-	-	-	-	-
Ösbydalsvägen	23	-	-	37	28	40	32	15	-
Ösby	**16**	-	-	**24**	**13**	**7**	-	-	-
Kryddgårdsvägen GC	**23**	-	-	-	-	-	-	-	-
Vreta Gårds väg	53	22	-	33	24	12	-	-	-
Vreta GC	**57**	**29**	**-**	**44**	**36**	**42**	**37**	**21**	**6**
Solskensvägen GC	**7**	-	-	-	-	-	-	-	-
Solskensvägen	60	33	-	31	22	35	26	8	-
Hallunda gårdsgata	44	6	-	6	-	42	39	24	9
Tullingeberg GC	**26**	-	-	-	-	-	-	-	-
Skogshemsvägen	54	24	-	15	3	32	26	7	-
Timotejvägen	47	12	-	41	33	26	20	1	-
Fredsgatan	61	35	2	52	45	46	42	28	13
Folketshus GC	**34**	-	-	-	-	-	-	-	-
Nickstahöjden GC	**29**	-	-	-	-	-	-	-	-

Table 5. Classification in accordance with the Road Lighting Energy Efficiency Classification (RLEEC) [18] for different M-classes (M4–M6), based on P_D, installed power density (W/m^2). M-classes shown are restricted by the minimum class for which the requirements were fulfilled (based on fulfilment of classes shown in Table 4). A = the most energy efficient, G = the least energy efficient. "GC" and bold letters indicate pedestrian and bicycle roads.

Road	P_D (W/m^2)	M4	M5	M6
Ösbydalsvägen	0.233	-	-	D
Ösby	**0.299**	-	-	**E**
Kryddgårdsvägen GC	**0.456**	-	-	**G**
Vreta Gårds väg	0.359	-	C	F
Vreta GC	**0.268**	-	**C**	**E**

Table 5. *Cont.*

Road	P_D (W/m^2)	M4	M5	M6
Solskensvägen GC	**0.365**	-	-	**G**
Solskensvägen	0.238	-	C	D
Hallunda gårdsgata	0.310	-	D	F
Tullingeberg GC	**0.395**	-	-	**G**
Skogshemsvägen	0.266	-	C	E
Timotejvägen	0.432	-	E	G
Fredsgatan	0.472	D	E	G
Folketshus GC	**0.360**	-	-	**G**
Nickstahöjden GC	**0.389**	-	-	**G**

Table 6. Calculated energy savings as power per year (kWh/year), power per kilometre road (W/km) and power per year per kilometre road following adaptation to the minimum requirements of different lighting classes based on percentages shown in Table 4. Mean values based on percentage savings in L, U_o and U_l; values not shown when minimum regulations for any of L, U_o or U_l were violated. SWE = in accordance with Swedish regulations [17], EU = in accordance with European regulations [16]. M5 = in accordance with both Swedish and European regulations. Other M classes are not included, since no savings were found. * = calculated for 4200 burning hours per year.

	Power Demand per Year (kWh/Year)				**Power Demand per Kilometre (W/km)**				**Power Demand per Kilometre per Year * (kWh/km/Year)**			
Road	M6 SWE	M6 EU	M5	M4 SWE	M6 SWE	M6 EU	M5	M4 SWE	M6 SWE	M6 EU	M5	M4 SWE
Ösbydalsvägen	78	72	-	-	645	590	-	-	2709	2480	-	-
Ösby	**19**	-	-	-	**146**	-	-	-	**612**	-	-	-
Kryddgårdsvägen GC	-	-	-	-	-	-	-	-	-	-	-	-
Vreta Gårds väg	80	-	-	-	592	-	-	-	2485	-	-	-
Vreta GC	**56**	**54**	**43**	-	**511**	**493**	**392**	-	**2146**	**2072**	**1646**	-
Solskensvägen GC	-	-	-	-	-	-	-	-	-	-	-	-
Solskensvägen	102	102	73	-	696	695	500	-	2922	2921	2099	-
Hallunda gårdsgata	74	72	41	-	707	685	393	-	2967	2876	1653	-
Tullingeberg GC	-	-	-	-	-	-	-	-	-	-	-	-
Skogshemsvägen	59	56	38	-	657	616	420	-	2759	2589	1764	-
Timotejvägen	93	88	60	-	984	939	636	-	4132	3944	2672	-
Fredsgatan	76	74	61	36	1500	1463	1216	705	6299	6144	5105	2959
Folketshus GC	-	-	-	-	-	-	-	-	-	-	-	-
Nickstahöjden GC	-	-	-	-	-	-	-	-	-	-	-	-

3.4. Dimming Schedule Case Study

The case study of Vreta Gårds väg showed that a dimming schedule decreased the average road surface luminance during the dimming period, that M5 was maintained even when an 80% dimming schedule was applied and that a 50% dimming schedule generally did not fulfil M6 (Table 7). The traffic flow on the road exceeded 200 vehicles/h from 12:00 a.m. to 10:00 p.m., while during midnight to 07:00 a.m. it was below 100 vehicles/h (Figure 7). Since the dimming schedule applied involved a 50% decrease midnight to 05:00 a.m. and 80% decrease 07:00 p.m. to midnight and 05:00–07:00 a.m., the dimming schedule was not adapted to the real traffic flow variation during the period of traffic flow measurements in this study.

Table 7. Average road surface luminance (L, cd/m^2) of different road sections (1–5) during the dimming schedule (100%, 80% and 50% power) applied for Vreta Gårds väg. The values for 100% were measured and those for 80% and 50% calculated assuming a linear relationship.

Road Section	L		
	100%	80%	50%
1	0.68	0.54	0.27
2	0.81	0.65	0.32
3	0.60	0.48	0.24
4	0.50	0.40	0.20
5	0.70	0.56	0.28
Mean	0.66	0.53	0.26

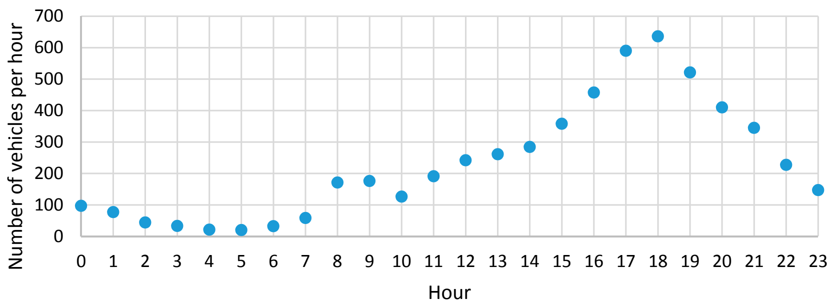

Figure 7. Number of vehicles per hour along Vreta Gårds väg, a residential road in Botkyrka. Total vehicle flow 4–10 November 2014 was 5524.

3.5. Calculated Dimming Schedules

The dimming schedule of the case study was applied to data for all roads designed for vehicular traffic included in the study in order to evaluate potential energy savings in comparison with lowering the lighting class. The potential energy saving was 49%, or a decrease in power demand of 70–120 kWh/year, 820–1397 W/km and 3445–5867 kWh/km/year (Table 8).

Table 8. Calculated total energy consumption and percentage energy savings for light-emitting diode (LED) lighting on vehicular traffic roads with a dimming schedule applying a 50% reduction between 00:00 and 05:00 a.m., 80% between 05:00 and 07:00 a.m. and 07:00 p.m. to midnight, and 100% for rest of the time between sunset and sunrise. Calculated for Stockholm, Sweden. * = calculated for 4200 burning hours per year.

Road	Power Demand * per Year (kWh/Year)	Power Demand per km (W/km)	Power Demand * per km per Year (kWh/km/Year)	% Saving
Ösbydalsvägen	116	955	4012	49
Vreta Gårds väg	120	885	3718	49
Solskensvägen	120	820	3445	49
Hallunda gårdsgata	120	1146	4811	49
Skogshemsvägen	87	958	4026	49
Timotejvägen	120	1277	5361	49
Fredsgatan	70	1397	5867	49

4. Discussion and Conclusions

The LED road lighting for roads with vehicular traffic generally fulfilled the requirements stipulated by European and Swedish regulations for L, U_o and U_l, but there were some exceptions for specific road sections. The road lighting in these sections had perhaps been inadequately planned or installed, e.g., with too long spacings between luminaires. The LED lighting on pedestrian and bicycle roads generally fulfilled the requirements for the lowest lighting class in terms of L (M6/S4), but most often these roads did not fulfil the lowest class requirements for U_o and U_l, with some exceptions. For example, Vreta GC had high values of L, U_o and U_l, but also had substantial surrounding lighting from nearby houses. Light emissions from nearby buildings may result in higher luminance values when road lighting is evaluated by field measurements. This was also demonstrated at Fredsgatan, a road located in the city centre, where many shop windows are illuminated around the clock.

The results showed that there is room for further improvement of the energy efficiency of LED road lighting for roads carrying vehicular traffic without violating either the Swedish or European regulations. Energy savings can be achieved by adapting to the minimum levels of the current M class or dropping down to a lower M class on vehicular traffic roads and by implementing a dimmable schedule adapted to the traffic intensity. Furthermore, the luminance and uniformity measurements suggest that if uniformity were to be improved in LED road lighting, it would be possible to decrease energy consumption also for pedestrian and bicycle roads, because uniformity is often the limiting variable when choosing a lower M class.

The data obtained in this study showed that average surface road luminance on some vehicular traffic roads with LED lighting could be reduced by between 6% and 35% or 23% and 61% by adapting to the minimum levels of the nearest lighting class or a lower lighting class for M5 or M6, respectively. This was exemplified by reductions of 56–102 kWh/year, 592–1500 W/km or 2485–6299 kWh/km/year for these roads. However, a dimming schedule on the same road lighting could lead to energy savings of 49%, resulting in savings of 70–120 kWh/year, 820–1397 W/km and 3445–5867 kWh/km/year. Thus, a dimming schedule has the potential to save more energy than dropping down a class or adapting to the minimum limit of the existing road lighting class. However, while adapting to the minimum level for the lighting class would probably not affect traffic safety, dropping down a road lighting class or two could potentially increase the risk of traffic accidents due to reduced visibility. In contrast, a dimming schedule could be adapted to traffic intensity and thus minimise the risk of affecting traffic safety. For pedestrian and bicycle roads there seems to be little room for energy reductions, since the LED road lighting was found to be less energy efficient. However, a dimming schedule could still be implemented for periods when these roads are infrequently used, for example during night-time. In such cases, it is important that the dimming schedule is based on user preferences.

In comparison with previous studies, the power demand for the road lighting in this study was significantly lower. The power demand per kilometre was between 1664 and 2589 W/m for vehicular traffic roads and between 937 and 1367 W/m for pedestrian and bicycle roads. In comparison, 2400–3600 W/m and 2000–4000 W/m seems to be normal for other light sources such as high pressure sodium, low pressure sodium and ceramic metal halide for non-highway roads, according to the existing literature [8,10]. Regarding power density (P_D), a previous study reported higher values, with mean value 0.64 W/m^2 for six roads with high pressure sodium and ceramic metal halide light sources [9], while the road lighting in this study had a P_D mean value of 0.33 W/m^2 for vehicular traffic roads and 0.36 W/m^2 for pedestrian and bicycle roads. The normalised power density (P_N) for vehicular traffic roads in this study (mean value of 0.53) was in line with previous values, for example 0.38–0.50 [23], but the P_N for pedestrian and bicycle roads was somewhat higher, 0.85 (mean value). This, together with the low energy efficiency classification in RLEEC, indicates that even though these roads have LED lighting it is not especially energy efficient and also has low luminance and uniformity. This is probably because the LED road lighting on these roads is of an early type and there are better products on the market nowadays.

Pedestrian and bicycle roads were included in this study, but such roads are normally evaluated by illuminance measurements and not luminance and luminance-based variables of uniformity. However, because evaluations of energy efficiency and improvement potential based on several other parameters such as P_N and P_D were also included in this study, the results seem to be robust enough to be valid. Sources of errors influencing the results presented in this study are primarily the impact of the lighting qualities of the pavement, because the luminance is a function of the illuminance on, and the reflection properties, of the road surface. In this study, the reflection properties of the road surface were unknown. However, the influence of the road surface on luminance values was minimised by performing field measurements during dry weather conditions and by choosing roads that had been in use a few years.

In order to evaluate payback periods and environmental impacts, such as CO_2 emissions, it would be possible to perform calculations of different energy optimisations as has been shown for road tunnels [24,25]. It would also be possible to use these results to forecast LED energy savings for larger areas such as multiple streets or entire cities by applying newly developed heuristic models or large-scale photometric computations [26,27]. Such use of the results may give a better estimate of the costs and environmental impact of energy optimisation for whole cities or regions to use for planning purposes.

In conclusion, by adapting LED road lighting to the lowest permissible lighting M class and combining it with a dimming schedule, great energy savings could be made on roads for vehicular traffic. For pedestrian and bicycle road lighting, however, there is little potential for energy savings except by implementing a dimming schedule.

Acknowledgments: This study was funded by the Swedish Energy Agency through its research programme on energy-efficient lighting, part II (2012-003200), project number 36232-1. The work took place with the kind cooperation of Thomas Dottman, Botkyrka municipality, Christian Hedlund, Värmdö municipality, Dick Åkerberg, Nynäshamn municipality, and Anton Nilsson, Ösbydalens samfällighet, who are gratefully acknowledged for their support. Staffan Dahlberg helped with practical support.

Conflicts of Interest: The author declares no conflict of interest.

Nomenclature

CCT	Correlated colour temperature (K)
CRI	Colour rendering index
L	Average road surface luminance (cd/m^2)
LED	Light-emitting diode
P_D	Power density (W/m^2)
P_N	Normalised power density (W/m^2 ∣ cd/m^2)
RLEEC	Road lighting energy efficiency class
U_l	Longitudinal luminance uniformity
U_o	Overall luminance uniformity

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