Piotr PRACKI

Warsaw University of Technology, Institute of Electrical Power Engineering, Lighting Division

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The use of different metrics for the evaluation of road lighting energy efficiency

***Abstract**. This paper tackles the issue of the road lighting energy efficiency. The levels of the normalised power density, the normalised power per road length, the normalised energy density and the normalised energy per road length for road lighting situations were calculated. Levels of these parameters represent the potential ranges of typical road lighting situations. The use of different metrics for the accurate evaluation of road lighting energy efficiency is essential and only the evaluation based on different metrics gives the opportunity to select rational lighting solutions for roads.*

Streszczenie.** Artykuł porusza problematykę efektywności energetycznej oświetlenia drogowego. Wyznaczono poziomy różnych miar efektywności energetycznej oświetlenia drogowego: moc jednostkową, moc jednostkową na jednostkę długości jezdni, energię jednostkową i energię jednostkową na jednostkę długości jezdni. Poziomy tych parametrów reprezentują typowe zakresy dla sytuacji oświetlenia drogowego. Wykorzystanie różnych miar do dokładnej oceny efektywności energetycznej oświetlenia drogowego jest koniecznością i tylko w takim przypadku prowadzi do wyboru racjonalnych rozwiązań oświetlenia drogowego. **(Wykorzystanie różnych miar do oceny efektywności energetycznej oświetlenia drogowego)

Keywords: road lighting, energy efficiency
Słowa kluczowe: oświetlenie dróg, efektywność energetyczna

Introduction

The main objective of road lighting is to ensure the safety of road users. Achieving this goal is possible thanks to making people, vehicles and objects on the road visible, and avoiding discomfort to the road users. It is believed that meeting lighting recommendations given in the standards supports safe, fast and comfortable traffic. The criteria used for the evaluation of road lighting, vary in detail from country to country, but are well recognised and have common features [1-2]. In the EU the lighting recommendations for roads are given in the EN 13201-2 [3] that was established on the basis of CIE TR 132 [4]. In 2010, CIE TR 115 [5] was published and on the basis of it the work to update the standard was undertaken and it has been on progress.

The criteria used for roads where vehicular traffic is dominant include the average road surface luminance, the overall and longitudinal road surface luminance uniformities, the threshold increment and the surround ratio [3]. In practice, many lighting solutions, correct from the point of view of the luminous environment, can be offered and the final choice can be made on the other criteria, energy efficiency being one of high importance.

The energy efficiency analysis and evaluation of road lighting solutions should be obvious today. Surprisingly, there is no wide open discussion on a lighting energy efficiency evaluation system for road lighting that would be generally accepted. The need for such system was noticed quite long time ago [6-7] and the effort to prepare recommendations for road lighting energy efficiency evaluation was undertaken (work on EN 13201-5 at the level of the European Union). It seems, however, that this issue does not arouse proper interest.

In the course of research, the author introduced an idea of unified system of lighting energy efficiency evaluation for roads and interiors [8] and a proposal to classify road lighting energy efficiency [9] that later was finalised [10-11]. The use of the system in practice was demonstrated [12].

The evaluation of lighting solutions regarding their energy efficiency may be conducted on the base of different criteria, e.g. [13-18]. In practice, it is often evaluated on the base of lighting power and energy demand. It is important to understand the correlation between different metrics and have proven requirements assuring the energy efficiency evaluation including the best, up to date lighting solutions. This paper discusses the use of different metrics for the evaluation of road lighting energy efficiency.

Metrics of road lighting energy efficiency

A starting point for analysing and evaluating the road lighting energy efficiency is to state the installed power demand required to provide the recommended luminance level in the road, time and degree of the power use. The installed power demand of the road lighting P can be given as:

$$P = \frac{L \cdot A}{Q \cdot LE \cdot UF \cdot MF} \qquad (1)$$

where: L – the average road surface luminance; A – the road surface area; Q – the road surface luminance coefficient; LE – the luminous efficacy of the lighting system; UF – the utilisation factor of the lighting system; MF – the maintenance factor of the lighting system.

There are two groups of the road lighting energy efficiency metrics: one connected with the road surface area and the second connected with the road surface length.

In the first group there are two energy efficiency measures. The installed power density of the road lighting P_D can be given as:

$$P_D = \frac{P}{A} = \frac{L}{Q \cdot LE \cdot UF \cdot MF} \qquad (2)$$

The normalised power density of the road lighting P_N can be given as:

$$P_N = P_D \cdot \frac{1}{L} = \frac{1}{Q \cdot LE \cdot UF \cdot MF} \qquad (3)$$

In the second group there are two energy efficiency measures too. The installed power per road length P_L can be given as:

$$P_L = \frac{P}{RL} = \frac{L \cdot RW}{Q \cdot LE \cdot UF \cdot MF} \qquad (4)$$

The normalised power per road length P_M can be given as:

$$P_M = P_L \cdot \frac{1}{L} = \frac{RW}{Q \cdot LE \cdot UF \cdot MF} \qquad (5)$$

where: RL – the road surface length; RW – the road surface width.

The similar equations can be given for the energy of road lighting. The energy demand of the road lighting per year *W* can be given as:

$$W = \frac{L \cdot A \cdot t}{1000 \cdot Q \cdot LE \cdot UF \cdot MF} \qquad (6)$$

where: t – the time of the lighting system use per year.

The energy density of the road lighting per year W_D can be given as:

$$W_D = \frac{W}{A} = \frac{L \cdot t}{1000 \cdot Q \cdot LE \cdot UF \cdot MF} \qquad (7)$$

The normalised energy density of the road lighting per year W_N can be given as:

$$W_N = W_D \cdot \frac{1}{L} = \frac{t}{1000 \cdot Q \cdot LE \cdot UF \cdot MF} \qquad (8)$$

The energy per road length, per year W_L can be given as:

$$W_L = \frac{W}{RL} = \frac{L \cdot RW \cdot t}{1000 \cdot Q \cdot LE \cdot UF \cdot MF} \qquad (9)$$

The normalised energy per road length, per year W_M can be given as:

$$W_M = W_L \cdot \frac{1}{L} = \frac{RW \cdot t}{1000 \cdot Q \cdot LE \cdot UF \cdot MF} \qquad (10)$$

As it can be seen from the above equations, the correlations between these parameters are straightforward and the concern is to determine the ranges of these parameters for road lighting situations.

The utilisation factor levels for the road lighting

The road utilisation factor depends on the luminaire lighting intensity distribution, its light output ratio, the luminaires' layout and road geometry. The theoretical analysis was proposed to state typical levels of the road utilisation factor for different road widths. In practice, the luminous flux of the luminaires reaches not only the road surface but also the immediate surrounding and is sent out of it. The minimum luminous flux of luminaires to fulfil the lighting requirements is determined by the average maintained luminance level of the road surface and by the surround ratio level. The road utilisation factor in this investigation was defined as the ratio of the luminous flux reaching the road surface and the luminous flux of the lamps of lighting installation. The luminous flux of the luminaires (of the lighting installations) can be separated into two components: the luminous flux reaching the road surface and the lost luminous flux, sent outside the road surface. The lost luminous flux can be additionally separated into two components: the luminous flux reaching the immediate surrounding of the road and the luminous flux falling outside the immediate surrounding of the road. According to the standard [3] the immediate surrounding of the road needs to be illuminated and the surround ratio level determines the level of required illumination. In perfect (theoretical) situation the total luminous flux of the luminaires should reach the road surface and the immediate surrounding only.

For the purpose of the broader luminous flux analysis the following situations were assumed. Two levels of the immediate surrounding illumination were considered:

- the illuminance of the immediate surrounding equals 50% (SR=0,50) of the illuminance in the zone of the road that has the same width as the immediate surrounding zone (the minimum required illumination of the immediate surrounding);
- the illuminance of the immediate surrounding equals 75% (SR=0,75) of the illuminance in the zone of the road that has the same width as the immediate surrounding zone (higher surround ratio is often gained when a road is illuminated according to standard requirements at relatively long spacings).

For each level of the immediate surrounding illuminance, three different situations regarding the luminous flux falling outside both the road surface and the immediate surrounding were considered:

- the luminous flux of the luminaires reaches the road surface and the immediate surrounding only (theoretical case) (LFO=0,0);
- 50% of the luminous flux that reaches the immediate surrounding is sent outside the road surface and the immediate surrounding (in practice, luminous flux from luminaires is always sent outside the immediate surrounding too) (LFO=0,5);
- 100% of the luminous flux that reaches the immediate surrounding is sent outside the road surface and the immediate surrounding (LFO=1,0).

For each situation and road width between 7 and 28 m the utilisation factor levels were calculated. In Fig. 1 the utilisation factor levels for luminaire output ratio 80% are presented.

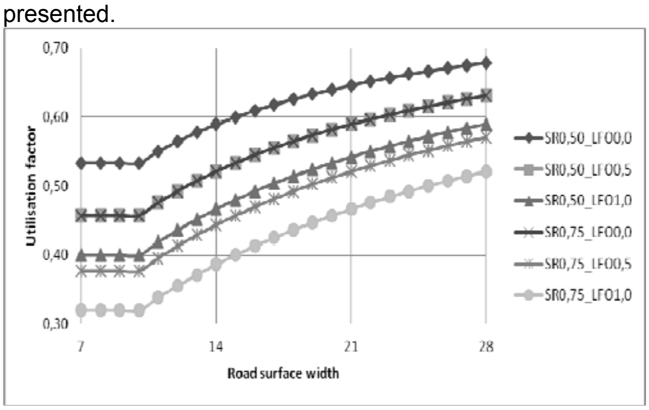

Fig. 1. Road utilisation factor levels for the analysed cases.

The six curves in Fig. 1 represent the combination of situations resulting from the two illuminance levels of the immediate surrounding and the three luminous flux levels falling outside the road surface and the immediate surrounding. The impact of road surface width on the utilisation factor level is shown.

The upper curve represents cases where the luminous flux of the luminaires reaches the road surface and the immediate surrounding only and the immediate surrounding is illuminated to the minimum required level. The lower curve represents cases where 100% of the luminous flux that reaches the immediate surrounding is sent outside the road surface and the illuminance of the immediate surrounding equals 75% of the illuminance in the corresponding zone of the road.

Two curves overlap: one representing situation where 50% of the luminous flux that reaches the immediate surrounding is sent outside the road, and the immediate surrounding is illuminated to the minimum required level, and one representing situation where the luminous flux of the luminaires reaches the road surface and the immediate surrounding only, and the illuminance of the immediate surrounding equals 75% of the illuminance in the corresponding zone of the road. The constant level of utilisation factor up to 10 m results in theoretical assumptions. In practice, it is always easier to gain higher utilisation factor for wider road.

On the ground of the results presented in Fig. 1, the following levels of the utilisations factors were proposed for further calculations:
- for the roads width 7 m: 0,30 – 0,55;
- for the roads width 14 m: 0,40 – 0,60;
- for the roads width 21 m: 0,45 – 0,65;
- for the roads width 28 m: 0,50 – 0,70.

The levels of road lighting power and energy – theoretical approach

The road lighting power and energy levels, out of the utilisation factor, depend on the road surface luminance coefficient, the luminous efficacy and the maintenance factor of lighting systems. Levels of these parameters representing broad range of typical road situations were assumed as follows:
- the road surface luminance coefficient: 0,05 – 0,075 – 0,1;
- the luminous efficacy of the lighting system: 50 – 100 – 150 – 200;
- the maintenance factor of the lighting system: 0,70 – 0,80.

For the combination of the assumed parameters, the ranges of the normalised power density of the road lighting P_N, the normalised power per road length P_M, the normalised energy density of the road lighting W_N, and the normalised energy per road length W_M were calculated. The results are given in tables 1 and 2.

Table 1. The road lighting power levels.

LE [lm/W]	RW [m]	P_N [W/m^2 per cd/m^2]	P_M [W/m per cd/m^2]
50	7	0,47-**1,79**	3,28-12,50
100		0,23-0,89	1,64-6,25
150		0,16-0,60	1,09-4,17
200		0,12-0,45	**0,82**-3,13
50	14	0,42-1,48	5,94-20,71
100		0,21-0,74	2,97-10,36
150		0,14-0,49	1,98-6,90
200		0,11-0,37	1,48-5,18
50	21	0,39-1,22	8,13-25,71
100		0,19-0,61	4,06-12,86
150		0,13-0,41	2,71-8,57
200		0,10-0,31	2,03-6,43
50	28	0,37-1,10	10,31-**30,71**
100		0,18-0,55	5,16-15,36
150		0,12-0,37	3,44-10,24
200		**0,09**-0,27	2,58-7,68

Table 2. The road lighting energy levels.

LE [lm/W]	RW [m]	W_N [kWh/m^{2}y per cd/m^2]	W_M [kWh/my per cd/m^2]
50	7	1,97-**7,50**	13,78-52,50
100		0,98-3,71	6,89-26,25
150		0,66-2,50	4,59-17,50
200		0,49-1,88	**3,45**-13,13
50	14	1,78-6,21	24,94-87,00
100		0,89-3,11	12,47-43,50
150		0,59-2,07	8,31-29,00
200		0,45-1,55	6,23-21,75
50	21	1,63-5,14	34,13-108,00
100		0,81-2,57	17,06-54,00
150		0,54-1,71	11,38-36,00
200		0,41-1,29	8,53-27,00
50	28	1,55-4,61	43,31-**129,00**
100		0,77-2,30	21,66-64,50
150		0,52-1,54	14,44-43,00
200		**0,39**-1,15	10,83-32,25

The calculated ranges of P_N, P_M, W_N and W_M represent most of typical road lighting cases. The bolded values represent the minimum and maximum levels achievable for each parameter.

The levels of road lighting power and energy – practical cases

In the next stage of investigation the aim was to calculate the road lighting power and energy levels for some practical situations. Twelve LED road luminaire types were selected. They were differentiated by luminous intensity distribution (LID) and power. Four LIDs (A, B, C and D) were randomly chosen and three power and luminous efficacy levels (80 W and 119,25 lm/W, 155 W and 123,10 lm/W, 257 W and 133,54 lm/W) for each LID were available. Designation, LIDs and power of selected luminaires are shown in Fig. 2.

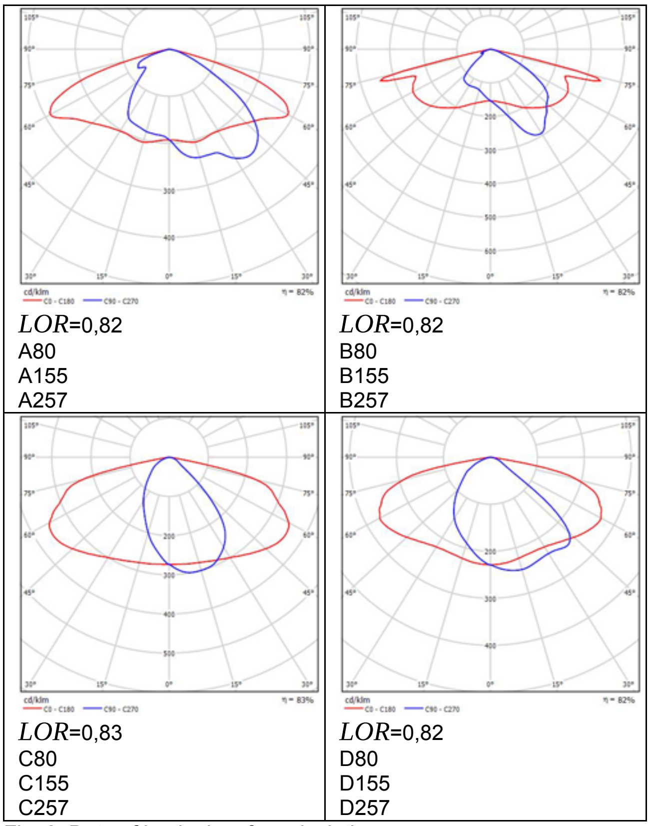

Fig. 2. Data of luminaires for calculations.

A single carriageway roads with two, four and six lanes were considered. The width of each lane was 3,5 m that corresponds to road width 7 m, 14 m and 21 m respectively. Road surface class R3 and maintenance factor 0,74 were assumed for the calculations. For each road three road lighting classes were considered: ME5, ME3a and ME1. For class ME5 – 80 W, for class ME3a – 155 W and for class ME1 – 257 W luminaires were applied.

The 7 m road was illuminated by a single sided system, and the 14 m and 21 m roads were illuminated by a dual sided opposite system. The luminaire's tilt was assumed to be 0° and the overhang within the range -3,5 and 3,5 m was analysed. The calculation results for the longest spacings are presented in tables: table 3 for road width 7 m, table 4 for road width 14 m and table 5 for road width 21 m.

Table 3. The calculation results of lighting parameters for road width 7 m.

Luminaire type	H [m]	M [m]	L [cd/m^2]	P_N [W/m^2 per cd/m^2]	P_M [W/m per cd/m^2]	W_N [kWh/m^{2}y per cd/m^2]	W_M [kWh/my per cd/m^2]
A80	9	51	0,50	0,45	3,14	1,88	13,18
B80	9	49	0,51	0,46	3,20	1,92	13,45
C80	10	58	0,50	0,39	2,76	1,66	11,59
D80	9	51	0,50	0,45	3,14	1,88	13,18
A155	10	44	1,05	0,48	3,35	2,01	14,09
B155	10	43	1,04	0,50	3,47	2,08	14,56
C155	11	49	1,03	0,44	3,07	1,84	12,90
D155	10	44	1,00	0,50	3,52	2,11	14,80
A257	11	40	2,00	0,46	3,21	1,93	13,49
B257	11	37	2,04	0,49	3,40	2,04	14,30
C257	11	46	2,10	0,38	2,66	1,60	11,17
D257	10	42	2,00	0,44	3,06	1,84	12,85

Table 4. The calculation results of lighting parameters for road width 14 m.

Luminaire type	H [m]	M [m]	L [cd/m^2]	P_N [W/m^2 per cd/m^2]	P_M [W/m per cd/m^2]	W_N [kWh/m^{2}y per cd/m^2]	W_M [kWh/my per cd/m^2]
A80	12	66	0,50	0,35	4,85	1,45	20,36
B80	11	65	0,50	0,35	4,92	1,48	20,68
C80	12	71	0,52	0,31	4,33	1,30	18,20
D80	11	68	0,50	0,34	4,71	1,41	19,76
A155	13	60	1,06	0,35	4,87	1,46	20,47
B155	13	60	1,02	0,36	5,07	1,52	21,27
C155	13	60	1,10	0,34	4,70	1,41	19,73
D155	13	59	1,09	0,34	4,82	1,45	20,25
A257	14	51	2,03	0,35	4,96	1,49	20,85
B257	14	50	2,04	0,36	5,04	1,51	21,16
C257	14	62	2,04	0,29	4,06	1,22	17,07
D257	14	53	2,01	0,34	4,82	1,45	20,26

Table 5. The calculation results of lighting parameters for road width 21 m.

Luminaire type	H [m]	M [m]	L [cd/m^2]	P_N [W/m^2 per cd/m^2]	P_M [W/m per cd/m^2]	W_N [kWh/m^{2}y per cd/m^2]	W_M [kWh/my per cd/m^2]
A80	11	50	0,50	0,30	6,40	1,28	26,88
B80	11	50	0,50	0,30	6,40	1,28	26,88
C80	12	54	0,50	0,28	5,93	1,19	24,89
D80	12	51	0,50	0,30	6,27	1,25	26,35
A155	13	48	1,01	0,30	6,39	1,28	26,86
B155	13	44	1,10	0,30	6,40	1,28	26,90
C155	12	51	1,03	0,28	5,90	1,18	24,79
D155	13	51	1,04	0,28	5,84	1,17	24,55
A257	12	44	2,00	0,28	5,84	1,17	24,53
B257	13	41	2,08	0,29	6,03	1,21	25,31
C257	12	48	2,02	0,25	5,30	1,06	22,26
D257	12	43	2,03	0,28	5,89	1,18	24,73

For the road width 7 m the utilisation factor levels are between 0,30 and 0,41 and being in agreement with the assumed values. The normalised power density P_N is between 0,38 and 0,50 W/m^2 per cd/m^2, the normalised power per road length P_M is between 2,66 and 3,52 W/m per cd/m^2, the normalised energy density W_N is between 1,60 and 2,11 kWh/m^{2}y per cd/m^2 and the normalised energy per road length W_M is between 11,17 and 14,80 kWh/my per cd/m^2, all being in ranges presented in tables 1 and 2.

For the road width 14 m the utilisation factor levels are between 0,40 and 0,52 and being in agreement with the assumed values. The normalised power density P_N is between 0,29 and 0,36 W/m^2 per cd/m^2, the normalised power per road length P_M is between 4,06 and 5,07 W/m per cd/m^2, the normalised energy density W_N is between 1,22 and 1,52 kWh/m^{2}y per cd/m^2 and the normalised energy per road length W_M is between 17,07 and 21,27 kWh/my per cd/m^2, all being in ranges presented in tables 1 and 2.

For the road width 21 m the utilisation factor levels are between 0,50 and 0,57 and being in agreement with the assumed values. The normalised power density P_N is between 0,25 and 0,30 W/m^2 per cd/m^2, the normalised power per road length P_M is between 5,30 and 6,40 W/m per cd/m^2, the normalised energy density W_N is between 1,06 and 1,28 kWh/m^{2}y per cd/m^2 and the normalised energy per road length W_M is between 22,26 and 26,90 kWh/my per cd/m^2, all being in ranges presented in tables 1 and 2.

All the calculated values of road lighting energy efficiency parameters stated for practical cases are in agreement with the values of these parameters resulting from the theoretical approach.

Conclusions

In this paper the four metrics for the evaluation of road lighting energy efficiency were characterised. The values of P_N, P_M, W_N and W_M were calculated (tables 1 and 2) for a wide range of the luminous efficacy, utilisation factor, maintenance factor and road surface coefficient levels, and representing most of typical road lighting cases. The influence of road surface width and luminous efficacy of lighting system on the power and energy of road lighting (tables 1 and 2) was demonstrated too. The values of P_N, P_M, W_N and W_M for some practical road lighting situations (tables 3÷5) were calculated as well. The theoretical and practical values of these parameters are in agreement.

The presented results can serve the basis for the elaboration of the classification and recommendation of road lighting energy efficiency, including the road surface width influence.

The presented results can serve the road lighting practitioners and scientists in their work and investigations as road lighting energy efficiency targets.

***Author**: dr hab. inż. Piotr Pracki,* Warsaw University of Technology, Institute of Electrical Power Engineering, Lighting Division*; Koszykowa street 75, 00-662 Warsaw, E-mail:* *piotr.pracki@ien.pw.edu.pl*

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