Typical Values of Energy Performance Indicators in Road Lighting

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Abstract. *Amongst many road lighting design criteria, energy performance plays an important role as it has a direct link to operational costs, potential reduction of carbon dioxide emissions, mitigation of obtrusive light, and its impact on the night-time environment in urban and conurban settlements. The energy performance of road lighting is conveniently described by the pair of normative numerical indicators PDI and AECI established in European standards. This article aims to present typical values of these indicators for different combinations of road arrangements, road widths, lighting classes and light source technologies to illustrate what benchmarks can be expected using this assessment system. Objectives of the article also comprise discussion on factors influencing the energy performance and conclusion whether it is appropriate to introduce limiting value requirements and/or ranking systems to label energy performance of road lighting systems.*

Keywords

Energy efficiency, energy performance, energy savings, lighting control, luminous efficacy, public lighting, road lighting.

1. Introduction and Background

Road lighting, also known as public lighting, is lighting provided for the purpose of illuminating public roads, cycle tracks, footways and pedestrian movement areas within public parks and gardens, as defined by the International Lighting Vocabulary ILV [9]. This public service provided to the residents and visitors of cities, towns, villages and other settlements has to simultaneously fulfil various functions, such as good visual conditions closely related to traffic safety, personal safety and assurance [10], safety to properties, visual performance at amenities other than those used for transportation, and not of less importance, is its contribution to increasing the attractiveness and enjoyment of the urban environment in the evenings.

Framework requirements for urban lighting should be settled in a well-prepared master plan; internationally approved guidelines for urban lighting master planning are provided in the CIE 234:2019 [11]. In line with the philosophy of this Technical Report, road lighting is constituting the "functional lighting" part of the general urban lighting scheme. Photometric requirements for road lighting are established in CIE 115:2010 [12], in European countries implemented in the standard EN 13201-2 [14] with a selection of lighting classes guided in the CEN/TR 13201-1 [13].

For the M lighting classes (M1 to M6) used for motorized traffic, the set of photometric parameters consists of maintained luminance, overall uniformity, longitudinal uniformity, Threshold Increment TI, and edge illuminance ratio EIR. For the P lighting classes (P1 to P7) intended predominantly for pedestrians and low-speed traffic, it is essential to assess the maintained average and minimum illuminance, and additionally, where applicable, requirements are specified for the maintained minimum vertical and semicylindrical illuminance. For collision sections or areas, the C classes (C0 to C5) based on the maintained horizontal illuminance and overall uniformity should be used. Auxiliary lighting classes HS (HS1 to HS4) accounting for the hemispherical illuminance (and its uniformity), EV (EV1 to EV6) for the vertical illuminance, and SC (SC1 to SC9) taking into account the semicylindrical illuminance can enhance the quality of lighting in some specific applications.

Careful determination of lighting classes in different periods of operation time is essential to ensure that only the necessary light level is provided at the right time, just when it is needed. Classification of road sections and similar structures should be carried out prior to (or as part of) the design stage considering all relevant circumstances as specified in the guidance CEN/TR 13201-1, like visual needs of the users, varying traffic volumes, weather conditions, traffic compositions, background brightness, etc. Then during the design stage, care should be taken to ensure that the criteria specified in EN 13201-2 for particular lighting classes are achieved without excessive overlighting and redundant spill light falling outside boundaries of the area to be lit. Luminous flux distribution can be nowadays quite well controlled by the selection of proper optics for luminaires, and overlighting can be reduced by continuously variable lighting control. The same principle is applicable to compensate the overlighting due to decay of luminous flux emitted from luminaires throughout the lifetime, e.g., by means of control gears with the CLO (Constant Light Output) function.

Photometric parameters are far not the sole criterion in designing the road lighting installation. The system must also be optimized to the lowest investment and operational costs, the least adverse impacts to the night-time environment, and the best energy performance. Environmental impacts cover a broad range of side effects of outdoor lighting, such as intrusive light, glare, sky glow or obtrusion to fauna and flora. In this complex scheme, the energy performance is centrally positioned, reflecting how the desired lighting parameters can be achieved with the minimum electricity consumption and CO_2 emissions, including the least amount of light losses in the form of unnecessary spill light, which can be potentially hazardous to the environment.

All the above-mentioned aspects must be carefully considered during the designing stage with a holistic approach. Road lighting quality versus energy efficiency benefiting from the mesopic design has been studied by Ylinen et al. [1] on concrete LED street lighting designs. A new simple method for the design of efficient public lighting has been proposed by Rabaza et al. [2] and is based on a new parameter relationship. Holistically and properly designed lighting is a powerful tool helping to reduce electricity consumption, as highlighted by Skoda & Baxant [3]. Besides accordingly designed new lighting installations, refurbishment of obsolete inefficient old lighting systems constitutes massive potential for energy savings, emphasized by Boyce et al. [4] as well as by Sokansky & Novak [5].

The energy efficiency of lighting products is subject to European directives specifying ecodesign requirements [19] and energy labelling [20]. Assessment of the energy performance of lighting systems is already well established in indoor applications in specific building categories, based on the LENI numerical indicator according to the EN 15193-1:2017 [17] (the first standard on this subject EN 15193 [18] was published in 2007). In the field of public lighting, this has been introduced by EN 13201-5:2015 [16], where the performance is described by means of two compound indicators PDI and AECI. Because the lighting energy performance in buildings is summed up with other energy-consuming services to form the total energy performance indicator, LENI cannot intrinsically comprise photometric parameters in order to normalize the energy consumption to the actual lighting needs. But this is not the case for road lighting, and thus, the indicators are related to illuminance as a universal quantity regardless of what is the target photometric parameter, i.e., also for luminance-based lighting classes. Yet before the publication of the standard EN 13201-5, Pracki [6] dealt with the problems of energy efficiency in road lighting and proposed a particular classification method.

The problem with proper assessment of the energy performance of lighting systems taking into account the efficiency of the technologies implemented and the performance of the lighting controls is that the two compensate for each other. It means that systems with energy-efficient luminaires operated at full power with no dimming can have a similar energy performance rating as some inefficient systems with aggressive dimming strategies. To make the evaluation fair, two key aspects of the energy performance are split, and thus, there are two mutually dependant indicators that should be always evaluated and presented together (side by side): PDI (symbol D_P, in $\mathrm{W\cdot lx^{-1}\cdot m^{-2}}$) stands for Power Density Indicator and accounts for the efficiency of the implemented lighting products as well as how well the lighting system is designed to fulfil the bunch of criteria; generally speaking, this indicator is describing the quality of the lighting design from a static perspective. AECI (symbol D_E, in $\mathrm{kWh\cdot m^{-2}}$) is the Annual Energy Consumption Indicator accounting for factors influencing the electricity consumption, which is the input power and the operation time, both varying in the course of operation; this indicator is describing the behaviour of lighting systems in response to lighting controls from a dynamic perspective. It is obvious that the PDI should be calculated and presented for all discrete light levels considered, while the AECI is only a single number.

Although PDI and AECI is the only normative system of energy performance indicators for road lighting applications, EN 13201-5 is presenting two alternative approaches having informative status, used in some countries: one based on luminous efficacy of a lighting installation η_{inst} and the other based on lighting factor of a lighting installation q_{inst}. However, these are out of the scope and will not be discussed further in this article.

2. Motivation and Objectives

Massive development of advanced LED technology during the last decade in diverse areas of lighting, including road lighting, is the driving force behind the need for more frequent update of technical standards specifying even more stringent requirements to both the quality of light and its energy performance. LED technology already brought to urban lighting a number of benefits: high luminous efficacy, tailored optics, free choice of colours, dynamic control. The efficiency of lighting equipment is still being improved.

However, LEDisation is just the first step towards sophisticated, efficient, sustainable, tailored and integrative (human-centric) lighting. In the time being, we are witnessing that adaptive lighting control is taking over the relay for the middle lap of the development. By implementation of the so-called "smart lighting" elements, systems and technologies, the lighting becomes part of a superior smart city network and tends to integrate with other infrastructural subsystems, such as traffic monitoring and control, telecommunication, utility services and others. Interactions that have a direct influence on setting up the target lighting parameters are especially significant: weather conditions, visibility level, traffic conditions (density, volume, speed), user presence or movement, the composition of users, etc. Adaptive lighting is the technical precondition to provide lighting on demand – where, when and how much it is needed.

The structure of the tables in EN 13201-5 can be improved as well. First of all, light sources other than LEDs are not assumed anymore for new or refurbished lighting installations; thus, it is worthless to provide data for different older types of obsolete light sources like sodium lamps (tubular and elliptical), metal halide lamps and even mercury vapour lamps. However, it is worth illustrating how development in lighting affects the value of the indicators when presented in a simplified form. In this respect, it is interesting to show the difference in energy performance between LED technologies in the span of 7 years (Q1/2014 versus Q4/2020). Note that comparisons between different technologies arising for public lighting have been experimentally investigated by Rodrigues et al. [7]. The tables can be additionally simplified to present values of PDI and AECI only for typical combinations of road widths and lighting classes.

For the purpose of this article, the calculation results are to be presented graphically rather than in tabular form. Further objectives of the article comprise analysis of the results, discussion about sensitivity of the typical values on influencing factors, and finally a recommendation to establish or not limiting values and/or ranking system for energy performance of road lighting. A kind of classification system for energy efficiency of road lighting has been proposed by Pracki [6], and such a system based on normative indicators PDI and AECI would be beneficial, if feasible.

3. Methodology

3.1. Energy Performance Indicators

Assuming that only a certain finite number of lighting levels is used for road lighting, annual lighting energy consumption can be calculated as follows:

$$W = \sum_{i=1}^{365} \sum_{j=1}^{M} (P_{ij} \cdot t_{ij}), \qquad (1)$$

where P_{ij} is the lighting system power associated with the given lighting level, W; t_{ij} is the daily operational time of the given lighting level, h; j, M is the index and number of different preset or considered lighting levels.

System power (of a lighting installation in a given state of operation) P is the total power of the road lighting installation needed to fulfil the required lighting classes as specified in EN 13201-2 in all the relevant sub-areas and to operate and control the lighting installation.

According to the European standard EN 13201-5:2015, the energy performance of road lighting systems is expressed by means of two numerical indicators – Power Density Indicator (PDI) and Annual Energy Consumption Indicator (AECI). While PDI indicates the performance of a lighting installation in steady-state operation, AECI incorporates lighting control, and thus, it can be used to characterize the performance of dynamic lighting operation.

Power Density Indicator PDI (of a lighting installation in a given state of operation, for an area divided into sub-areas) D_P, in W·lx^{-1}·m^{-2}, is the value of the system power divided by the value of the product of the surface area to be lit and the calculated maintained average illuminance value on this area according to EN 13201-3 [15]:

$$D_P = \frac{P}{\sum_{i=1}^{n} \left(\overline{E_i} \cdot A_i\right)}, \quad (2)$$

where D_P is the power density indicator, W·lx^{-1}·m^{-2}; P is the system power of the lighting installation used to light the relevant areas, in W; $\overline{E_i}$ is the maintained average horizontal illuminance of the sub-area i, in lx; A_i is the size of the sub-area i lit by the lighting installation, in m^2; n is the number of sub-areas to be lit. The PDI indicator should be calculated for each lighting level of the operational profile with associated input power of the luminaires and calculated illuminances of the sub-areas.

Annual Energy Consumption Indicator AECI (of a lighting installation in a specific year) D_E, in Wh·m^{-2}, is total electrical energy consumed by a lighting installation day and night throughout a specific year in proportion to the total area to be illuminated by the lighting installation, calculated by the formula:

$$D_E = \frac{\sum_{j=1}^{m} (P_j \cdot t_j)}{A}, \quad (3)$$

where D_E is the annual energy consumption indicator for a road lighting installation, Wh·m^{-2}; P_j is the operational power associated with the j-th period of operation, W; t_j is the duration of j-th period of operation profile when P_j is consumed, over a year, h; A is the size of the area lit by the same lighting arrangement, m^2; m is the number of periods with different operational power P_j.

For the calculation of AECI, it is necessary to assume some lighting control profile. Operation hours of road lighting systems are dealt, e.g., in [8]. Full power operational profile is typical for many existing lighting installations with simple switching devices like time switchers or photosensors where luminaires operate constantly at full power throughout the nighttime each day. For the full power operational profile, it is common to take the annual operation time 4,000 hours. In regulated and sensing systems, tri-power or even quadri-power detector-driven operational profile, like the example shown in Fig. 1 (daily course), can be used to control lighting levels. Lighting levels must be associated with particular lighting classes specified for a road and given conditions. In off-peak hours with lower traffic density, one or more reduced lighting levels can be defined. It is recommended that in case of no traffic, at least a minimum lighting level is maintained throughout the night time. In addition, if a vehicle and/or presence detectors are used to control the lighting system, actual lighting levels can be truncated, and the output of luminaires can be reduced in time periods when no traffic is sensed by the associate detectors.

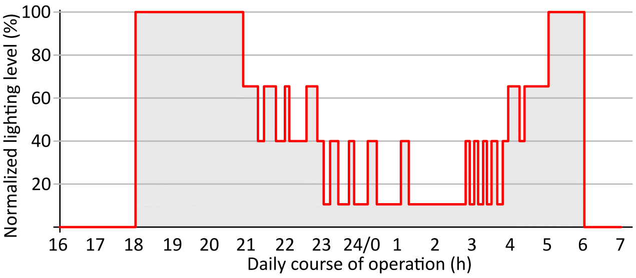


Fig. 1: Example of a quadri-power detector-driven operational profile.

For the calculation of AECI, it is also necessary to assume for annual detection probability parameter for each of the lighting levels. Estimation of the probability can be a hard task, particularly for new installations where no historical data are available; the value can be established by comparison with similar and neighbouring installations and/or derivation from higher class major roads. In systems with flat lighting levels without dropdowns, the probability is 100 % by default.

3.2. Typical Values of Energy Performance Indicators

Values of energy performance indicators PDI and AECI depend on many factors like the actual lighting class, road profile arrangement, width of carriageway and concurrent footpaths, type of the light source and luminaire implemented, the spatial distribution of luminous flux from luminaires, etc. In the case of AECI, switching and control profile may strongly affect the value of this indicator. Assuming that the lighting system is optimized according to the target photometric parameters, lighting designs may still differ in energy performance. The lower is the value of PDI and/or AECI, the better is energy performance.

Indicative values of energy performance indicators PDI and AECI presented in this article are based on numerous calculations of lighting systems for different combinations of road profiles, road widths, lighting classes, and luminaires (having luminous flux and type of optics appropriate for particular arrangements) that are common in practice.

Additional input data and boundary conditions for seeking the optimum geometry of the lighting system are listed below:

- six typical road profile arrangements considered,
- width of footpaths and grass strips, where applicable, equals to 2 m,
- maintenance factor is set to 0.8 for all types of luminaires and road profiles,

- for road reflection properties, the R3 table is considered,
- mounting height is optimized within the range 6 m to 12 m (step: whole numbers),
- spacing of lighting poles is optimized and sought between 20 m to 60 m (step: 1 m),
- arm overhang is ranged from 0 m to 2 m (step: 0.5 m),
- luminaires are not tilted,
- annual operation time 4,000 h at full power.

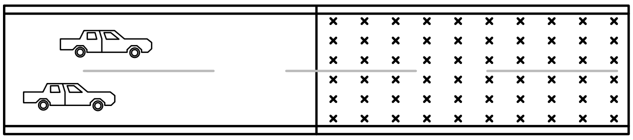
The arrangement of the lighting system is single-sided in all cases. In the framework of the investigated road widths, application of the opposite (or other double-sided) arrangement was not necessary. Within each calculation, the lighting system geometry has been optimized with preference given to the spacing in order to enlarge the illuminated area as much as possible and to have thus the energy performance indicators as low as possible. Mounting height and arm length affect the indicators only indirectly. However, accounting for the lowest possible installation costs, the mounting height has been sought as minimum as possible in addition to the previously mentioned criteria.

Calculations are based on generic lighting products (luminaires) available in Q4/2020. The average luminous efficacy of LED luminaires is 125 $\text{lm}\cdot\text{W}^{-1}$ with very small deviations within the product range (-4 %/$+0.8$ %). Exclusively warm white light sources with $T_c = 3,000$ K have been used.

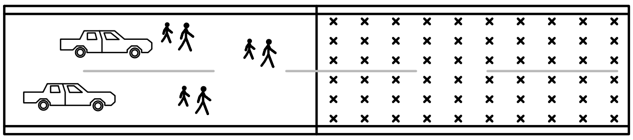
Road profile arrangements are depicted in Fig. 2 and denoted as follows:

- Road profile A: Two-lane road for motorized traffic,
- Road profile B: Road with mixed motorized and pedestrian traffic without footpaths,
- Road profile C: Road with a footpath on the side of the lighting installation,
- Road profile D: Road with footpath opposite to the lighting installation,
- Road profile E: Road with two footpaths on both sides,
- Road profile F: Road with two footpaths on both sides, separated from the carriageway by grass strips.

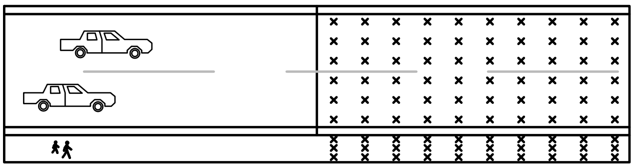
The range of values for the AECI indicator is presented only in a descriptive way and apply to full-power operational profile with an annual operation time of 4,000 h. To consider different operational profiles, it is usually sufficient to combine the annual operation times of individual lighting levels with the associated system power and the detection probability (in systems with detectors) into a single lighting operation coefficient c_{op}. This coefficient can be used to multiply the AECI for full power operation to obtain the value of AECI for an actual operational profile. It can also



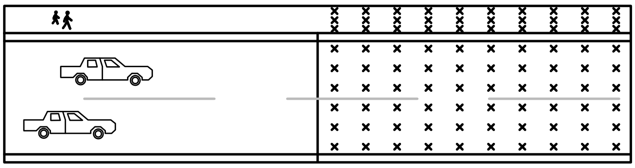
(a) Road profile A.



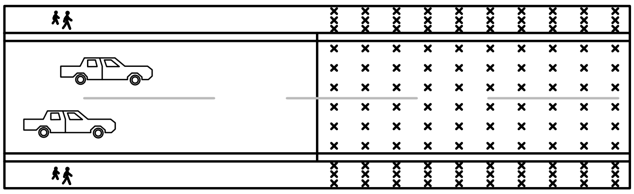
(b) Road profile B.



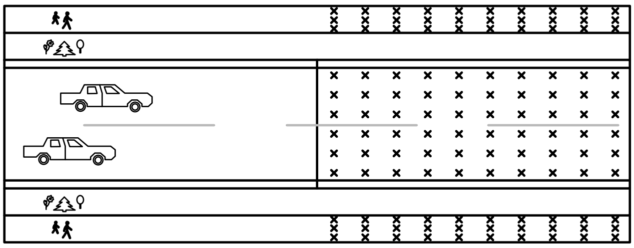
(c) Road profile C.



(d) Road profile D.



(e) Road profile E.



(f) Road profile F.

Fig. 2: Road profiles for calculation and comparison of typical values of energy performance indicators.

be used as a self-standing indicator of energy-saving potential of a lighting control system. In-depth presentation and analysis of the AECI values are beyond the objectives of this article.

3.3. Comparison of Energy Performance Indicators for Different Light Sources

High-pressure mercury vapour lamps, metal halide lamps, elliptical and tubular sodium lamps, LEDs on the technology level of 2014, and currently available LED products (2020) are included in the comparison. Values of energy performance indicators are determined for the selected (assumingly most typical) boundary conditions described as follows:

- width of the carriageway 7 m,
- lighting class M4,
- annual operation time $4,000$ h at full power.

LED products available in 2014 used for derivation of typical values published in the standard EN 13201-5:2015 have had luminous efficacy 100–105 lm·W^{-1} and correlated colour temperature $T_c = 3,000$ K. Overall luminous efficacy of luminaires with HID lamp types strongly varies with wattage of the lamps and quality of optics as it is common for this traditional lighting equipment. In the case of high-pressure sodium lamps, the overall luminous efficacy was 70–120 lm·W^{-1}; for metal halide lamps, it was 70–75 lm·W^{-1}, for mercury lamps below 45 lm·W^{-1}.

4. Results and Discussion

Road profile A is the simplest arrangement consisting of a single carriageway. Relation between PDI on one side and road width and lighting class on the other side is, therefore, more straightforward. The lighting is designed to luminance according to the corresponding lighting class M. Besides luminance, the requirements differ in all other parameters so that lower lighting classes are less demanding in many aspects. Typical values of the PDI indicator are lying around 20 mW·lx^{-1}·m^{-2} with small deviations, as presented in Fig. 3 with cross-section for the 7 m road in Fig. 4.

The only exception is the M6 lighting class and, in particular, the 4 m road, which is quite narrow to efficiently direct the light beam and, at the same time to create the required luminance for an observer in his standard position 60 m in front of the calculation field.

The values of AECI (in kWh·m^{-2}) for the 7 m road range from 0.32 for M6 up to 2.70 for M1. Because

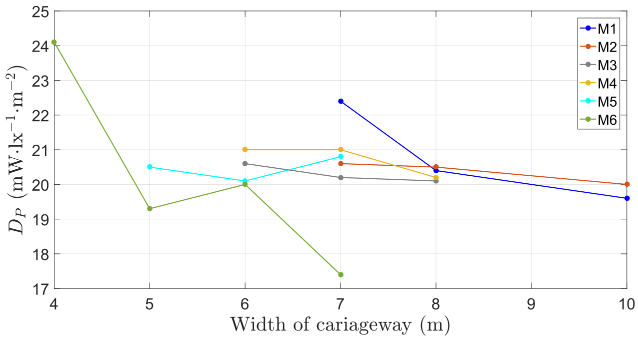


Fig. 3: Typical values of the Power Density Indicator D_P in mW·lx^{-1}·m^{-2} for road profile A.

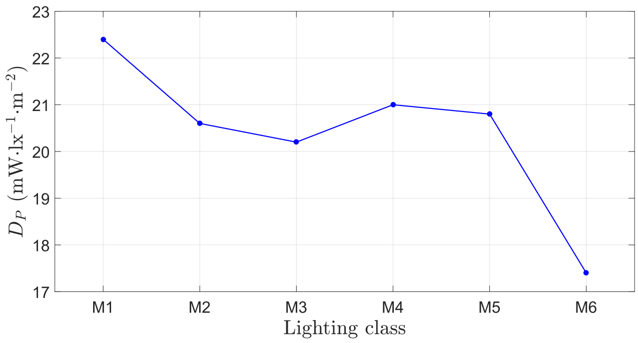


Fig. 4: Typical values of the Power Density Indicator D_P in mW·lx^{-1}·m^{-2} for road profile A with road width 7 m.

AECI is free of reference luminous parameter, the value will be strongly dependant on lighting class and this is true for all luminance-based road profiles. AECI is decreasing with smaller road widths to 0.45 for 4 m road classified to M6. But for wider roads and higher lighting classes, the value is also decreasing, for example, to 2.35 for 10 m road and the M1 class and similarly for other situations.

Road profile B is somewhat unusual compared to the other profiles in that the lighting design is fully based on illuminance, and the photometric requirements are associated with C lighting classes. The absence of an observer means that complex road surface reflection properties (the R-tables) are not applied what makes the design process and the results more predictable. PDI values are presented in Fig. 5, which shows that depending on road width, the curve is exponentially descending for wider roads where the luminous flux is better used up, and losses are smaller (nearby edges). There is almost no or neglectable difference in values across lighting classes what can be seen explicitly in Fig. 6 for the average 7 m road, where the span of the values makes less than 3 %, and this is indeed the worst case. For this reason, it is worth presenting only common values for all lighting classes C0 to C5.

Road profiles C (Fig. 7 and Fig. 11), D (Fig. 8 and Fig. 11) and E (Fig. 9 and Fig. 11) can be analyzed together and confronted mutually. As it follows from

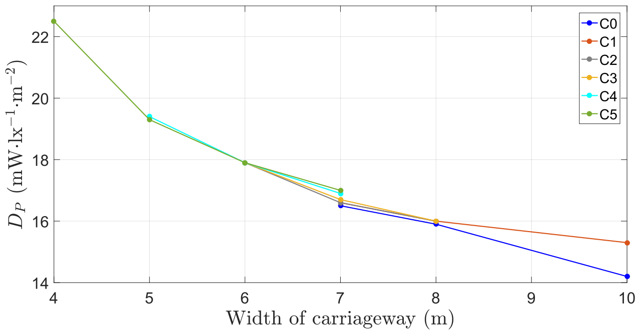


Fig. 5: Typical values of the Power Density Indicator D_P in mW·lx^{-1}·m^{-2} for road profile B.

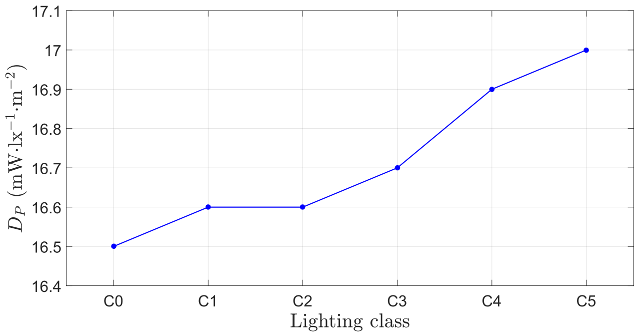


Fig. 6: Typical values of the Power Density Indicator D_P in mW·lx^{-1}·m^{-2} for road profile B with road width 7 m.

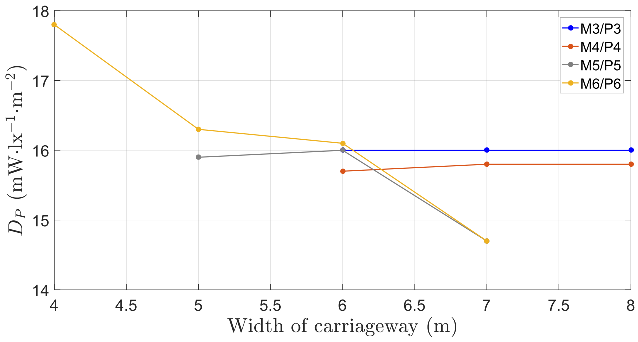


Fig. 7: Typical values of the Power Density Indicator D_P in mW·lx^{-1}·m^{-2} for road profile C.

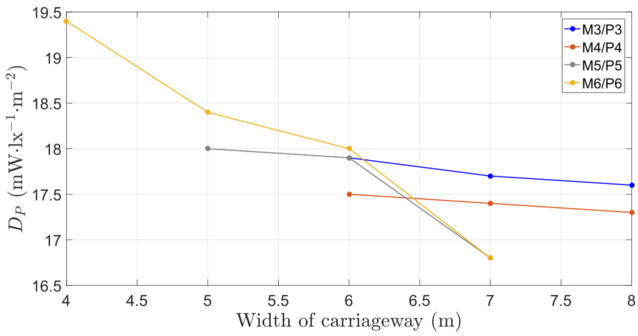


Fig. 8: Typical values of the Power Density Indicator D_P in mW·lx^{-1}·m^{-2} for road profile D.

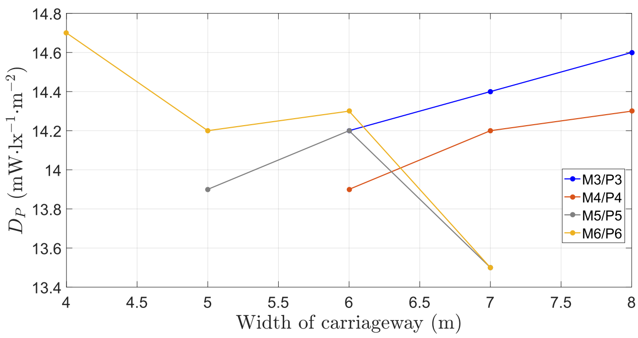


Fig. 9: Typical values of the Power Density Indicator D_P in mW·lx^{-1}·m^{-2} for road profile E.

the figures, the curves are very similar for the three cases. The average value of PDI is, however, biased between each other, being around 16 mW·lx^{-1}·m^{-2} for the C profile, slightly higher 17.5 mW·lx^{-1}·m^{-2} for the D profile and only about 14.2 mW·lx^{-1}·m^{-2} for the E profile. In these cases, it is essential to choose a luminaire with luminous flux distribution that suits the actual road profile arrangement, i.e., emitting some light to the nadir and behind (away from the carriageway) in case of the C profile, directing the light beam under higher angles of the asymmetrical light distribution curve in the C90-270 plane to reach the footpath opposite to the row of light points in case of the D profile and balancing these two in case of the E profile. It is always easier to illuminate the footpath on the side of the lighting installation than on the other side due to higher distance (inverse square law) and angles of incidence (cosine law), hence higher (ca 10 %) PDI numbers for the D profile. The principles similarly apply to the E profile, but because here the total target area is a sum of two sub-areas, the resulting indicator values are shifted downwards (ca 12.5 %) as can be expected.

The behaviour of typical AECI numbers for road profiles C, D and E reflects principles discussed above. Taking the 7 m road as the reference, then the AECI values (in kWh·m^{-2}) for lighting classes M6/P6 to M3/P3 span from about 0.30 to 1.00 identically for the C and D profiles (the same target area), and from 0.24 to 0.82 for the E profile (the same area of the carriageway and double area of the footpaths). Variation of the values over widths of carriageways is neglectable; only in the case of the E profile, small changes can be identified, with performance improving (smaller numbers) for narrower roads and vice versa for wider roads.

It is important to emphasize that the results presented and discussed in the previous paragraphs are closely bound with the assumed road profile parameters. In real situations, however, the width of footpaths can be different from the assumed, even differing between each other on both sides of the carriageway, and the lighting class assigned to the footpaths can also be different (in many cases lower, typically P5 and P6 even for carriageways classified to M4 or M3). It is then obvious to expect different values of the PDI and

Tab. 1: Typical values of the Power Density Indicator D_P in mW·lx^{-1}·m^{-2} for different light sources.

Road profile	Mercury	Metal halide	Sodium elliptical	Sodium tubular	LED (2014)	LED (2020)
A	90	60	41–47	34–42	23	21
C	73	50	35–38	30–34	20	16
D	78	48	35–40	27–35	19	17
E	65	41	33–34	26–28	17	14
F	71	45	34–36	28–32	23	22

Tab. 2: Typical values of the Annual Energy Consumption Indicator DE in kWh·m^{-2} for different light sources.

Road profile	Mercury	Metal halide	Sodium elliptical	Sodium tubular	LED (2014)	LED (2020)
A	5.0	3.1	2.3–2.5	1.8–2.4	1.1	0.9
C	4.0	2.4	1.8–1.9	1.5–1.8	0.9	0.7
D	4.0	2.4	1.8–1.9	1.4–1.8	0.9	0.7
E	3.2	2.0	1.5	1.2–1.5	0.7	0.6
F	3.2	2.0	1.5	1.2–1.5	1.0	0.7

AECI indicators at any deviations. The overall scheme becomes more complex. It would be beneficial to study these relations further.

Road profile F is even more complicated because grass strips separating footpaths from the carriageways can be almost arbitrary wide. In this case, with currently available lighting equipment, it is impossible to avoid light losses on the grass strips if all sub-areas are to be illuminated by one lighting installation. It can be noted that in practice, widths of grass strips up to 3 m can be acceptable, at 4–5 m, illumination of concurrent footpaths is inefficient and sometimes also hard to satisfy the lighting requirements; above 5 m, it has no sense to consider shared lighting installation and if the lighting of footpaths is inevitable or requested then it should be satisfied by a dedicated lighting installation.

Typical values for the road profile F should be deemed as very illustrative due to many assumptions specified for this case. Results are shown in Fig. 10 and the cross-section of this graph for the 7 m road is unfolded in Fig. 11. Values of the PDI indicator are spread around 22 mW·lx^{-1}·m^{-2} what is almost 60 % higher than in the case of unseparated footpaths (road profile E).

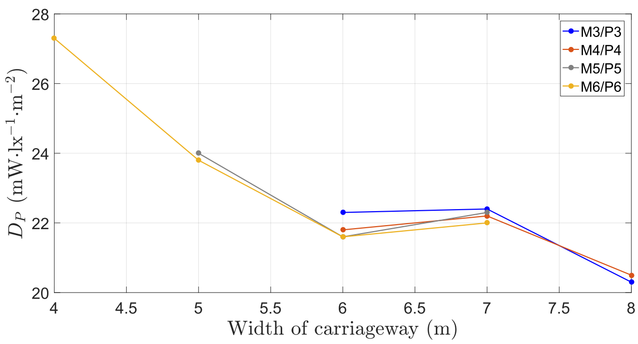


Fig. 10: Typical values of the Power Density Indicator D_P in mW·lx^{-1}·m^{-2} for road profile F.

The drop in performance is significant. The impact of the width of the carriageway must be treated with respect to the width of parallel footpaths and grass strips; the narrower carriageway, the more the indicators are influenced, and, in general, the worse the energy performance. Typical values of AECI for the 7 m road are ranging from 0.29 (M6/P6) to 0.93 (M3/P3) with only small variations for other widths of the carriageway.

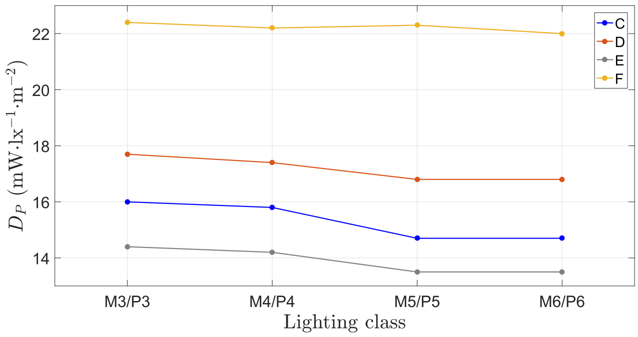


Fig. 11: Typical values of the Power Density Indicator D_P in mW·lx^{-1}·m^{-2} for road profiles C, D, E, F with road width 7 m.

Table 1 and Tab. 2 show results of the comparison of energy performance indicators for different light sources. The values of PDI are graphically presented also in Fig. 12. From the tables, it can be seen that advances in the LED technology gained about 10 % (referring to the PDI values, AECI is improved as much as by 20 %). LED lighting is performing twice better than its sodium technology predecessor and 4.5 times better than the obsolete mercury-based technology. It must be noted that not only higher luminous efficacy of the lamps (or luminaires) is responsible for this benefit, but to much extent, it is due to significantly different quality of optics – from modest diffusers in combination with bulky elliptical mercury bulbs through faceted reflectors combined with compact-size sodium lamp burners up to precise Fresnel lens optics attached to tiny LED chips.

Table 1 and Tab. 2 are intended only for illustrative purposes to demonstrate how development in light

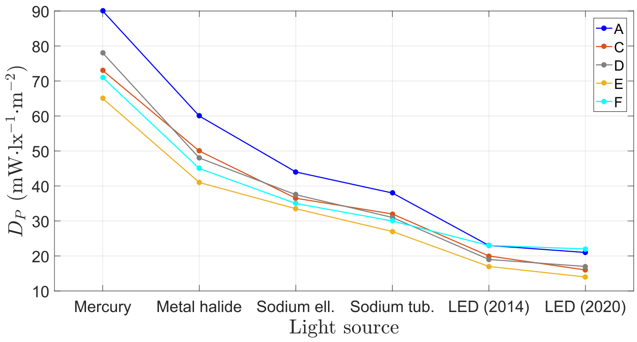


Fig. 12: Typical values of the Power Density Indicator D_P in mW·lx^{-1}·m^{-2} for different light sources.

source technology over past decades affects the energy performance of road lighting installations. Thus, older lamp types presented in the tables are referring to previous lighting techniques and, of course, cannot be recommended for new or refurbished lighting systems.

5. Conclusions

Typical values of the road lighting energy performance indicators have been updated to reflect the current level of technology referred to the end of 2020, in a simplified and streamlined structure. The results showed that in the span of the last seven years, the performance is biased to slightly better figures, although the gain is not that significant for PDI. However, AECI values are improved by approximately 20 % in the case of the flat full-power operational profile what is not neglectable. It can be assumed that advances in lighting controls in recent years will boost the performance mile steps forward.

Graphs composed of typical values well illustrate the behaviour of the PDI indicator depending on the main influencing parameters, which are the road width and the lighting class. A deeper understanding of these relations has been, however, acquired by optimization of road lighting designs in the framework of numerous model calculations, attempting to vary the spacing of lighting poles, mounting height and wattage of luminaires, amongst others. It has been proved that the utilance of the installation is what matters indeed, and similar numbers of the performance indicators can be obtained for various lighting system arrangements. It also means that the energy performance expressed through Power Density (PDI) is appropriate for the purpose in the steady-state operation regime. Hence, to maximize the utilance, proper selection of the luminous flux distribution and adjustment of the absolute value of luminous flux are key points of the lighting design.

Comparison of the indicators for different types of light sources showed significant improvement of the performance with upraise of the LED technology, which is twice better than the preceding sodium lamp technology and yet little better than metal halide lamps. Heavily obsolete mercury lamps (that still can be found operating in some aged systems) perform 4.5 times worse than modern lighting products.

Assuming that for new installations, all parameters of the lighting system geometry are free to choose and the road profile consists only of a single element which can be carriageway, cycle track or footpath, then it is possible to agree on certain limit values of PDI to be required as an additional criterion for individual lighting classes. However, this fails when it comes to refurbishment of the system where, e.g., replacement of lighting poles is not desired. Moreover, any other road profile arrangement than that used for calculation of typical values can strongly affect the indicator's value – namely width of concurrent footpaths in road profiles C to F (in general, the width can be different on both sides of the road) as well as the width of grass strips in road profile F. The situations can be so complex that it is impossible to find a correlation between so many variables, and this makes any attempts to define fair limit values and even more a ranking system not feasible at the moment. Thus the indicators should be used only in accordance with the original intention, i.e., to compare different (e.g., alternative, competing in public tenders, etc.) lighting designs for the same lighting task – the same road profile and the same boundary conditions.

6. Outlook

Typical values of the lighting operation coefficient c_{op} have been calculated for different typical lighting control profiles under standard assumptions, though not specifically presented in this article. Right the lighting control is promising a huge amount of energy savings, but this potential is unfortunately still exploited to a very little extent. Technological advances in the field of road lighting controls are very rapid, but their implementation lacks a solid scientific background. Research should be focused on adaptive road lighting, intensifying the investigation of conditions that can be utilized to optimize the lighting according to various criteria and their combinations. The new Technical Committee CIE/TC4-62 has been established to study and report the state-of-the-art adaptive road lighting.

The standard EN 13201-5 is currently undergoing revision, and the updated typical values of PDI and AECI, in tabular form, are proposed for the revised document. The draft is in the final stage of revision, and hopefully, the proposed amendments will be approved in CEN. However, since the introduction of the indicators, their acceptance in practice is insufficient, in some countries fully neglected and this problem is still persisting. Initially, the standardization work item has been mandated by the European Commission, but at the end of the day, no European directive has been published in the field, unlike for the buildings. Nevertheless, the PDI/AECI system is a useful tool to the benefit of road lighting operators. Typical values are, in particular, intended to support and enhance the usage of this standard in practice.

The possibility to define limiting values and to build up a ranking system is questionable. For the reasons explained above in conclusions, this activity is halted for the current revision. Continuing analyses might bring more light to the problem what can possibly lead to finding an alternative solution.

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Author Contributions

D.G. specified motivations and objectives of the study, selected suitable methods and prepared framework for their implementation, carried out model calculations and supervised the study. P.J. performed calculations and analyzed results for different road profiles. J.R. performed calculations and analyzed results for different light sources. All authors discussed the results and contributed to writing the manuscript.

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