



International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

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DOI 10.25039/x051.2025/g3u6hj

This article is also published as part of:

Proceedings of the CIE 2025 Midterm Meeting Vienna, Austria, July 4-11, 2025:
Scientific Conference (July 7-9, 2025)

DOI 10.25039/x051.2025

in

Proceedings of the CIE (International Commission on Illumination)

ISSN no. 3061-015X (print), 3061-0168 (online)

The paper has undergone double-blind peer review and its final version has been presented at the CIE 2025 Midterm Meeting, Vienna, Austria, July 4–11, 2025.

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SPECIFYING LUMINAIRE CUTOFF IN LIGHT POLLUTION REGULATIONS

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Abstract

This paper examines different approaches used to specify the cutoff, or shielding, properties of luminaires in light pollution regulations, with a focus on the G^* classification defined in the European road lighting standard, and the CIE flux code FC3, used in the French regulation. To compare the G^* and FC3 rating schemes, a simple parametric model is introduced to generate typical luminous intensity distributions used in road lighting. In addition, these rating schemes are applied to a dataset of 145 measured luminous intensity distributions of outdoor luminaires with different characteristics. The results show that the G^* classification yields more robust ratings than requirements based on FC3. However, neither FC3 nor G^* can correctly predict the cutoff angle of the luminous intensity distributions, a parameter linked to the visibility of a luminaire at long distance.

Keywords: Light Pollution, Road Lighting, Regulation, Standard, Visibility, Glare, Luminaire, Cutoff, Shielding, Luminous Intensity Distribution, G^* class, BUG rating, CIE Flux Code, ULR

1 Introduction

Light pollution is caused by electric light emitted towards the sky and potentially contributing to nighttime sky glow (Morgan-Taylor, 2023). Light pollution also encompasses adverse effects produced at closer distances from the source, such as the spurious illumination of residential buildings or natural areas which should remain dark at night (Jägerbrand et al., 2022). The visibility of the source from a distance is also a major contributor to the attraction of insects (Dieterberger et al., 2024).

Pedestrians and drivers may also experience glare from light sources seen from a distance farther away from their useful illumination area. This case of glare is also considered as a form of light pollution. Together with spill light, it can be reduced by limiting light emissions in directions below the horizontal plane (CIE, 2017).

Several methods can be used to specify the cutoff properties of luminaires. The upward light ratio (ULR) is the most widely used parameter to assess the fraction of the luminous flux emitted in the upper hemisphere. By definition, the ULR does not specify the amount of light emitted in directions slightly below the horizontal plane, responsible for glare and useless illumination of areas that should be kept in the darkness. Other rating methods are applicable to assess these light components.

In order to compare the outputs of these rating schemes, a simple parametric model is introduced to generate typical luminous intensity distributions used in road lighting. In addition, the different ratings are applied to a sample of 145 measured luminous intensity distributions of outdoor luminaires with different characteristics.

2 Methods to specify luminaire cutoff

2.1 The upward light ratio (ULR)

The light directly emitted towards the sky can be assessed using the ULR of the luminaire mounted with an orientation given by its in-situ tilt angle. So far, the direct measurement of ULR has never been demonstrated on site. However, ULR is reliably assessed by a calculation based on the measured luminous intensity distribution, as provided by test laboratories equipped with

a goniophotometer. The ULR = 0 condition is associated with the notion of “full cutoff” luminaires, entirely devoid of upward light. In France, the 2018 light pollution decree (JORF, 2018) introduced a “relaxed” full cut-off requirement for outdoor lighting luminaires by allowing a tolerance margin: the nominal ULR value should be less than 1% when measured in the lab, and less than 4% when assessed in situ. These limit values reflect several difficulties in the assessment of ULR: the uncertainties in goniophotometric measurements, the difficulty of achieving a full cut-off with some designer fixtures, and the tolerance on the mounting conditions granted to the installer. As a consequence of the 4% limit to the “in situ ULR”, full cutoff luminaires can be legally mounted with a tilt angle to extend the illuminated area, increasing the visibility of the luminaire at long distances.

2.2 The G* class

The G* luminous intensity classes are defined in the EN 13201-2 European road lighting standard (CEN, 2016). This system was originally designed to better control glare and upward light, while providing more stringent requirements to limit the emission of light in unwanted directions. The G* classes are determined using relative luminous intensity values, expressed in unit of cd/klm, in directions above 70°, 80°, 90° and 95° measured from the vertical. Table 1 shows the requirements of the G* classes.

Table 1. Definition of the G* classes of EN 13201-2 according to relative luminous intensity values at elevation angles above 70°, 80°, 90° and 95°.

Class \ Angle	Maximum relative luminous intensity (cd/klm)			
	≥ 70°	≥ 80°	≥ 90°	≥ 95°
G*1	unrestricted	200	50	unrestricted
G*2	unrestricted	150	30	unrestricted
G*3	unrestricted	100	20	unrestricted
G*4	500	100	10	0
G*5	350	100	10	0
G*6	350	100	0	0

2.3 The CIE flux code FC3

The CIE flux code FC3 is used by the French regulation which sets limits applicable to lighting installations with the goal of reducing different forms of light pollution (JORF, 2018). Originally, the flux code classification was defined by the CIE (CIE, 1978) to classify indoor luminaires according to the width of their light distribution. The system relies on relative partial fluxes assessed in different angular sections of the space surrounding the luminaire. The partial flux code FC3 is the luminous flux emitted downward in a solid angle of $3\pi/2$ sr centred on the vertical axis, divided by the luminous flux emitted in the downward hemisphere. The solid angle corresponds to a half angle of 75.5° from the vertical. The French regulation requires FC3 to be greater than 0.95. It means that the luminous flux emitted in a cone defined by elevation angles between 75.5° and 90° must be less or equal to 5% of the downward luminous flux.

2.4 The BUG rating

The BUG luminaire classification system was developed by the IES and the International Dark Sky Association, now DarkSky International. The acronym stands for Backlight, Upward light and Glare. It is mainly used in North America (IES, 2020). The BUG rating assesses a set of partial luminous fluxes, each being defined in a specific section of the full space surrounding the luminaire. The partial fluxes related to glare are assessed in 4 different angular sections covering different ranges of elevation angles. The partial flux between 60° and 90°, with respect to the vertical, is the most restrictive to determine the glare rating, which can have 6 values from G0 to G5, G0 being the best rating (least glaring). Unlike the ULR, the BUG rating is based on absolute limits (in unit of lumen) of the partial luminous fluxes. For instance, the most restrictive glare rating G0 corresponds to less than 10 lm in the forward sector between 80° and 90° of elevation, and less than 10 lm in the backward sector between 80° and 90°. This partial

luminous flux value would correspond to a mean luminous intensity less than 10 cd in these sectors.

3 Comparison of the different ratings using a mathematical model

In this section, an equation is introduced to model the luminous intensity distribution along the direction of the road (longitudinal direction C0-C180). Using this formula, it is possible to directly calculate the CIE FC3 flux code and determine the G* class. As the BUG rating uses absolute light levels, it is not possible to compare it with the G* system or with the CIE partial flux code classification, both relying on relative light levels.

3.1 Modelling longitudinal light intensity distributions used in road lighting

The model is based on a cosine distribution with a power exponent, as described by Equation (1):

$$I(\gamma) = I_0 \cos^\alpha(\gamma) \tag{1}$$

where:

γ is the elevation angle, measured from the downward vertical direction;

$I(\gamma)$ is the luminous intensity in the direction defined by γ ;

α is the power exponent of the model;

I_0 is the intensity at $\gamma = 0$.

A physical cutoff angle γ_{lim} can be introduced in this model. Above this angle, the intensity values are supposed to be zero. Full cutoff luminaires are modelled with values of γ_{lim} less than 90°. The numerical integration of Equation (1) between 0 and γ_{lim} allows us to compute the luminous flux and normalize the luminous intensity by a fixed luminous flux of 1000 lm, resulting in an expression for the relative luminous intensity in unit of cd/klm, shown in Equation (2):

$$[I(\gamma)]_{cd/klm} = \frac{500}{\pi} (\alpha + 1) \frac{\cos^\alpha(\gamma)}{1 - \cos^{\alpha+1}(\gamma_{lim})} \tag{2}$$

Using different values of the power exponent α , luminous intensity distributions can be generated, from the most intensive (narrow distributions) to the most extensive (wide distributions). Increasingly positive values of α correspond to increasingly narrow distributions. Negative values of α correspond to extensive distributions for which the luminous intensity increases with the elevation angle. This type of distribution is commonly used by road lighting luminaires to produce an elongated illuminance pattern with a good uniformity. A value of $\alpha = -3$ corresponds to a pattern with uniform horizontal illuminance.

Figure 1 shows an example of an intensive distribution corresponding to $\alpha = 3$ and two extensive distributions respectively corresponding to $\alpha = -0.5$ and $\alpha = -1.5$. In Figure 1, these distributions have a cutoff angle arbitrarily fixed at 77°.

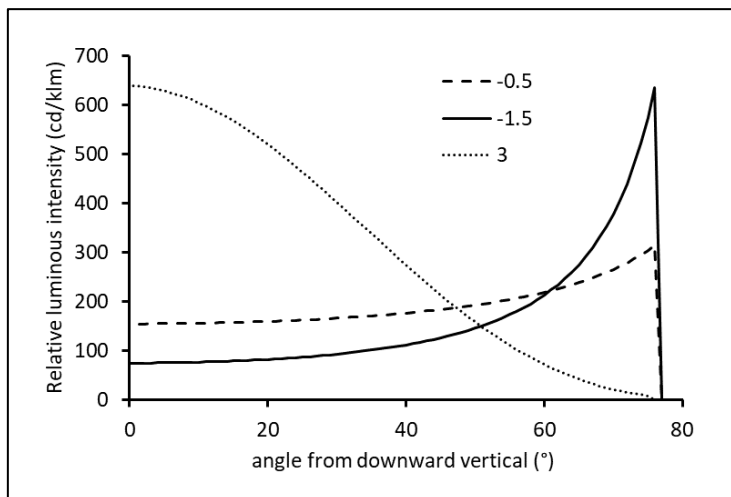


Figure 1. Examples of longitudinal luminous intensity distributions generated by Equation (2)

3.2 Calculating the theoretical values of FC3 and G*

The calculation of the CIE flux code FC3 and the G* class can be applied to a set of wide luminous distributions corresponding to negative values of α between -0.1 and -3. Figure 2 confirms that the physical cutoff of 75° ensures the condition FC3 = 1, which is consistent with the definition of this parameter. Figure 2 also shows that physical cutoffs can be defined at slightly higher angles, up to 77°. In this case, however, the compliance with the French regulation (FC3 ≥ 0.95) is ensured only for a limited range of distributions corresponding to values of α between -0.6 and 0.

Intensive luminous intensity distributions, defined by positive value of α , are not shown in Figure 2. They comply with the FC3 ≥ 0.95 requirement when $\alpha \geq 1.17$, which corresponds to distributions slightly narrower than the Lambertian distribution ($\alpha = 1$).

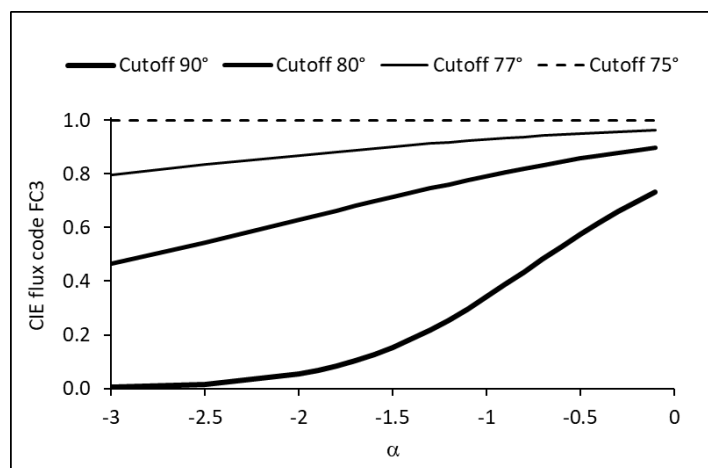


Figure 2. Flux code FC3 calculated for wide luminous intensity distributions and different physical cutoff angles ≤ 90°

Figure 3 illustrates the variation of the G* rating across the set of wide luminous intensity distributions, for different values of the physical cutoff angle. With cutoff angles less than 80°, the G* rating increases when the luminous intensity distribution gets narrower (α varying from -3 to 0). When the cutoff angle is between 70° and 80°, G* classes of 3, 4 and 5 are obtained according to the width of the luminous intensity distribution. Since the physical cutoff angle is less than 90°, the G*5 and G*6 rating have identical requirements (see Table 1). Figure 3 does not show results for positive values of α (intensive distributions). In this case, all distributions with $\alpha \geq 0.5$ are G*6.

When plotting the FC3 flux code with respect to the G^* rating, as shown in Figure 4, it appears that the range of possible FC3 values is greater for the G^*3 class than for the G^*4 and G^*5 classes. In all these G^* classes, it is possible to find compliant and non-compliant luminous intensity distributions with the $FC3 \geq 0.95$ requirement of the French regulation. The minimum FC3 value in class G^*5 is 0.84. The minimum FC3 value in class G^*4 is 0.81. The minimum FC3 value in class G^*3 is 0.46.

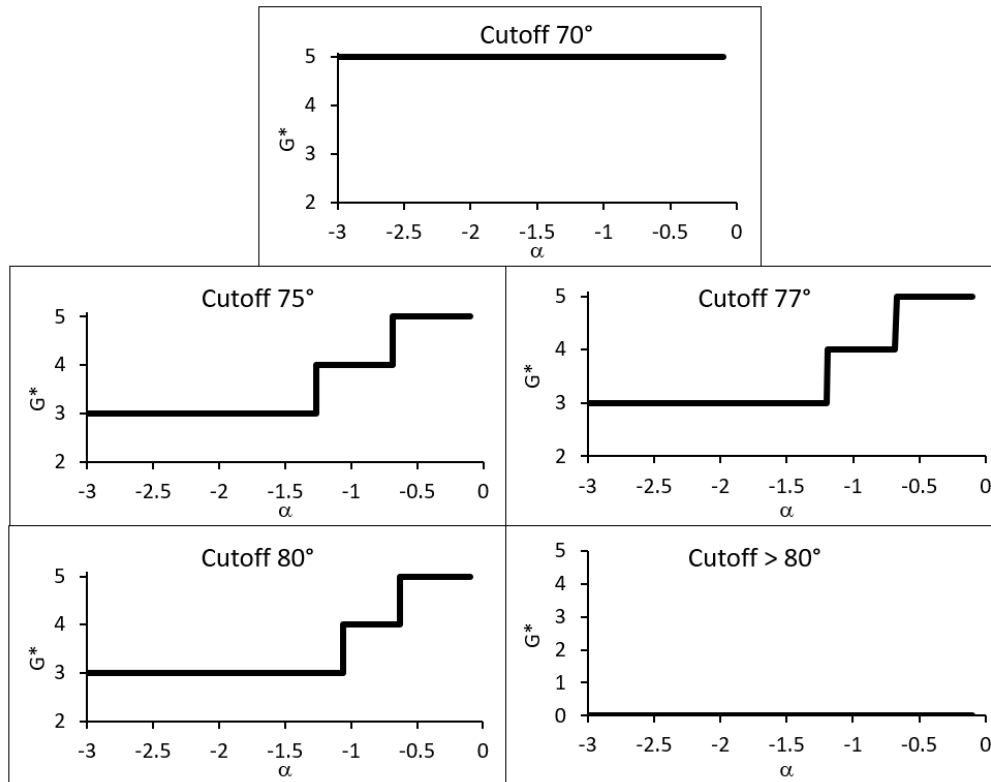


Figure 3. Class G^* calculated for wide luminous intensity distributions and different physical cutoff angles. A rating of G^*0 means that the luminous intensity distribution does not meet the G^*1 requirements (lowest rating). The cutoff angles being less than 90° , the G^*5 rating also corresponds to G^*6 .

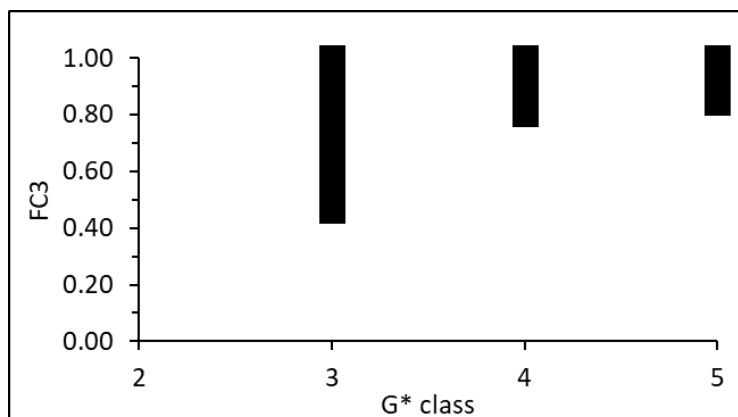


Figure 4. Graph showing the range of variation of FC3 as a function of the G^* rating, for non-zero G^* values. This range of variation was obtained using values of α between -3 and 0, corresponding to extensive luminous intensity distributions. The cutoff angles being less than 90° , the G^*5 rating also corresponds to G^*6 .

4 Comparison of the different ratings using measured luminous intensity distributions

Street and road lighting LED luminaires manufactured by the Eclatec company were measured in the manufacturer's laboratory using a goniophotometer. These luminaires are sold in France and more than 30 other countries. Special types of luminaires used with unusual mounting conditions such as luminaires for pedestrian crossings were excluded from the study, resulting in a dataset of 145 individual luminous intensity distributions. They correspond to the following types of illuminance pattern: asymmetric forward throw pattern (7 tested distributions), symmetrical circular pattern (18 tested distributions), and road lighting pattern (120 tested distributions), the latter being characterized by a wide symmetrical longitudinal range and different transversal width (narrow, normal, or wide).

Each distribution was individually rated with the different methods presented above. Table 2 presents the breakdown of the tested distributions by type of pattern and by G* rating. The first number in each cell of Table 2 correspond to the number of distributions in compliance with the requirement $FC3 \geq 95\%$ of the French regulation. The second number, in parenthesis, shows the total number of distributions for the given pattern type and G* class.

Table 2. Breakdown of luminous intensity distributions in the dataset, by type and G* rating. The first number is the number of tested luminous intensity distributions with $FC3 \geq 95\%$ (compliant with the French regulation). The second number, in parenthesis, is the total number of tested distributions by type and by G* rating.

	G*0 (unrated)	G*1	G*2	G*3	G*4	G*5	G*6	Total
Asym. forw.	0	0 (1)	2 (2)	3 (3)	1 (1)	0	0	6 (7)
Circular	0 (1)	0	0 (1)	5 (6)	2 (2)	3 (3)	4 (5)	14 (18)
Road lighting	0 (15)	12 (18)	19 (19)	45 (45)	11 (11)	2 (2)	10 (10)	99 (120)
Total	0 (16)	12 (19)	21 (22)	53 (54)	14 (14)	5 (5)	14 (15)	119 (145)

The histogram of Figure 5 shows the number of tested distributions for each G* class, and the number of tested distributions compliant with the French regulation. The highest proportions of intensity distributions (37%) fall in the G*3 class. In the G*3 class, 53 intensity distributions out of 54 (98%) comply with the $FC3 \geq 95\%$ requirement of the French regulation.

Table 1 shows that 119 out of 129 (92%) of the tested distributions rated G*1 or higher comply with the $FC3 \geq 0.95$ requirement of the French regulation. Similarly, 107 out of 110 (97%) of the tested distributions rated G*2 or higher comply with the French regulation.

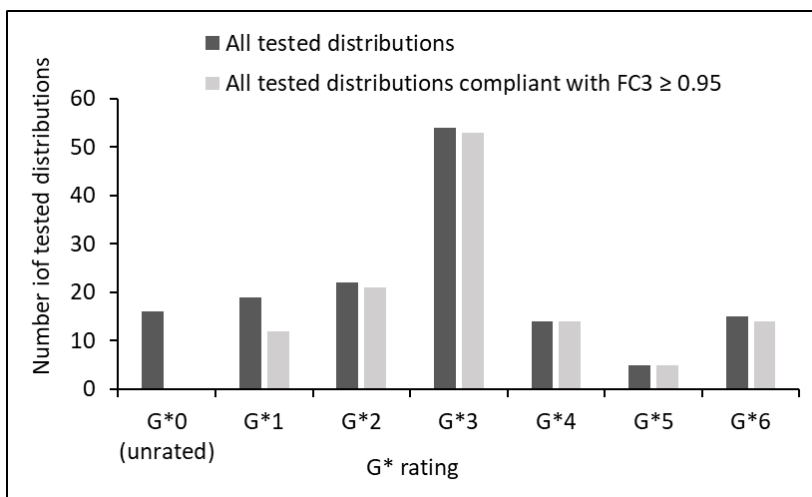


Figure 5. Histogram showing the number of tested luminous intensity distributions for each G* rating (dark grey bars) and the number of distributions complying with the requirement of FC3 ≥ 0.95 (light grey bars)

5 Analysis of the measured cutoff angles

The longitudinal cutoff angle was determined for each measured luminous intensity distribution. This angle was defined using a 1/10 criterion: when the elevation angle is at the cutoff, the luminous intensity falls to 1/10th of its maximum value in the longitudinal plane (C0-C180). Figure 6 shows the repartition of the cutoff angle of the 145 tested distributions. The values range from about 70° to 92°. The most common range of cutoff angles is 78° to 80°, corresponding to a proportion of about 28% of the tested distributions.

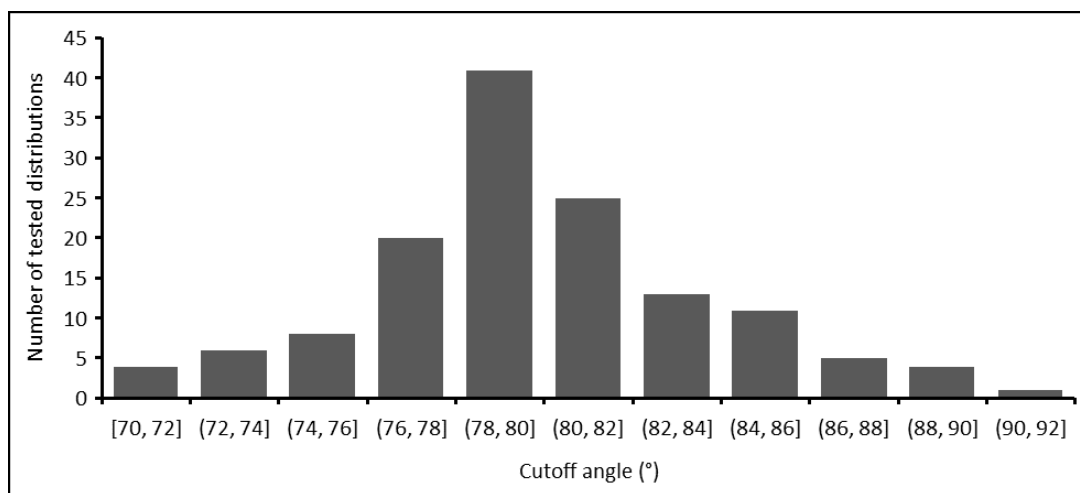


Figure 6. Histogram showing the repartition of cutoff angles for the tested luminous intensity distributions

Figure 7 shows how the cutoff angle varies with the G* rating and with the FC3 flux code. The trends in these plots are generally decreasing. On average, high G* classes and high FC3 values have lower cutoff angle. However, there is a wide scatter of the cutoff angle values in each G* class and for each FC3 value. As a result, it is not possible to make a reliable correspondence between the cutoff angle, FC3 and the G* rating. Neither FC3 nor G* is a good predictor of the cutoff angle.

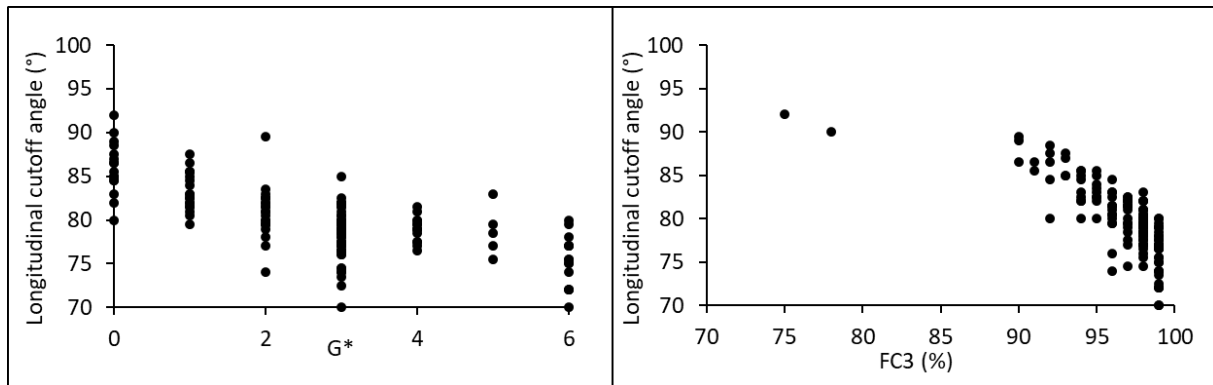


Figure 7. Left graph: cutoff angles of the tested distributions plotted as a function of the G^* rating. Right graph: cutoff angles plotted as a function of the flux code FC3.

6 Conclusion

This paper examines different rating methods used to assess light emitted just below the horizontal plane by street and road lighting luminaires. Limiting these light components is an important specification to limit glare, spill light, and luminaire visibility at long distances.

The BUG rating is a standard method based on limiting absolute light emissions in certain angular sectors below the horizontal. The G^* classification is based on the assessment of relative luminous intensity values assessed in several directions, slightly below and above the horizontal plane. The CIE flux code FC3 is used in the French regulation to limit the partial luminous flux emitted below the horizontal, but in another angular range. Relying on relative photometric quantities, the G^* and flux code systems can be compared together, but they cannot be directly compared with the BUG rating.

A practical model of longitudinal light distribution was introduced to perform theoretical assessments of the CIE flux code FC3 and the G^* class. These results reveal that FC3 is very sensitive to small variations of the physical cutoff angle, of an order of about 1° . This sensitivity may be detrimental to the reliability of the assessment of FC3 which is influenced by the measurement uncertainties of the luminous intensity and by the angular resolution of the intensity distribution around the value of 75.5° used in the definition of FC3. With cutoff angles less than 80° , the G^* rating increases when the luminous intensity distribution becomes narrower. When the cutoff angle is between 70° and 80° , G^* classes of 3, 4, 5 or 6 are obtained according to the width of the luminous intensity distribution. In all the G^* classes, it is possible to find compliant and non-compliant luminous intensity distributions with the $FC3 \geq 0.95$ requirement of the French regulation. However, the range of possible FC3 values is wider for the G^*3 class than for the G^*4 and G^*5 classes.

A more comprehensive assessment of these rating schemes was performed on a set of 145 luminous intensity distributions measured on currently available street and road lighting luminaires manufactured by a leading manufacturer. These distributions covered the whole range of G^* classes. However, the highest proportions of intensity distributions fell in the G^*3 class. In this class, 98% of the distributions complied with the $FC3 \geq 95\%$ criterion of the French regulation. Considering lower G^* classes, 92% of the distributions rated G^*1 or higher complied with the $FC3 \geq 0.95$ requirement of the French regulation.

The theoretical and experimental results presented in this study indicate that the FC3 is not the best parameter to use for regulatory purposes because it is very sensitive to angular errors in the luminous intensity distribution from which it is derived. Furthermore, FC3 cannot be checked on site. The G^* rating is a more reliable predictor of unwanted luminous intensities between 70° and 90° of elevation. It is not as sensitive to angular uncertainties. Furthermore, the G^* class has the advantage of being verifiable on site through intensity measurements (made with luminance or illuminance meters), normalized by the value of the luminous flux of the tested luminaire at the time of the measurements. The luminous flux cannot be measured on site, but it can be estimated using the operating conditions of the luminaire such as input voltage, electrical power and dimming level.

The cutoff angles of the tested distributions covered a range between 70° and 92°, with the most likely values falling between 78° and 80°, correspond to visibility distances between 4 to 6 times the mounting height on either side of the luminaire.

The respective correlations of the cutoff angle with the G* rating and with the FC3 parameter are very poor. Neither FC3 nor G* is a good predictor of the cutoff angle. Therefore, FC3 and G* are not suited to predict the visibility of the luminaire at long distance.

When updating existing light pollution regulations or devising new ones, it would be useful to introduce separate requirements to limit the luminous flux in a critical angular sector on one hand, and on the other hand, to limit the visibility distance of luminaires. The first requirement could rely on an extension of the ULR slightly below the horizontal plane. A so-called USLR parameter (Upward and Sub-horizontal Light Ratio) could be defined with a specified angle of 10° or 15° below the horizontal in addition to the upper hemisphere (USLR 10 or USLR 15). The second requirement could be based on the cutoff angle of the luminous intensity distribution with a precise specification of the cutoff criterion. A relevant criterion could be based on absolute luminous intensity values (i.e. 1 cd or 10 cd), rather than relative values in cd/klm.

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