Relevant parameters of luminaires, as regards light pollution and efficiency

Summary

Even if all man-made light entering outdoor environment is pollution per definition, it is important to distinguish such emissions which may serve their purpose, from those which may not.

The text below explains, why the emissions from luminaires should be divided into at least three zones as measured from nadir (giving them in degrees): 0–75, 75–90, 90–180. The zones below and above 75 degrees should never be merged into a single integral parameter. For an installed luminaire, the first zone is to be further divided into **useful flux** (onto the target) and wasted one. For some installations (small luminaire spacings), the division between the first and second zone should be below 75 degrees, typically at 65 degrees, sometimes even at 60 degrees. The last, upward zone might be reasonably further divided into 90–105 and 105–180.

Absolutely, the emissions into each zone should be expressed in lumens. Relatively, as fractions of total emissions, or much better, in units of useful flux (expressing **unneeded pollution *per* useful one**). Just for the useful flux, a reasonable relative measure is the fraction of the lamp flux, this measures the luminaire true light efficiency. In the EuP study, a similar quantity is is called **Utilisation Factor, UF** – the difference is, that it includes even the counterproductive light over 75 degrees; its non-glaring part might be called Really Useful Light Output Ratio (RULOR). For any luminaire alone (before it is installed) the relative parameter should concern whole first zone below 75 degrees: a suitable name for that would be **Potentially Useful Light Output Ratio** (PULOR or explicitly b75LOR).

A much better-established luminaire parameter (vital for reducing light pollution esp. as regards glare) are the maximum specific luminous intensities (per kilolumen of lamp flux) at 80 and 90 degrees from nadir. The proper upper limits are 30 cd/klm at 80 degrees and 0 cd/klm at 90 degrees; this follows from merging the two world's top standards (IESNA full-cutoff and CIE cutoff). The latter limit, **0 cd/klm at 90 degrees**, has been confirmed as the most important single parameter by a number of papers, and is demanded by a number of regional laws in Europe and United States. Maximum specific intensity is much easier to measure and verify than the integral quantities, and corresponds to a directly visible property (when multiplied by lamp flux) of the luminaire.

The above set of quantities can serve well for narrowing a choice of possible luminaires for any streetlighting task and should be a base of any eco-design criteria at product or system level. Of course, complete photometric data for such luminaires are needed for optimal final choice for any particular streetlighting task.

The basic parameters of non-installed luminaires can be ordered according to their significance:

1. maximal specific luminous intensity at 90 degrees and above
2. potentially useful light output ratio: potentially useful flux (= flux below 75 degrees) / lamp flux
3. maximal specific luminous intensity at 80 degrees
4. flux within 75 and 90 degrees / potentially useful flux
   (might be called Downward Glare Flux Ratio)
5. flux within 90 and 105 degrees / potentially useful flux
   (might be called Upward Glare Flux Ratio, should be below 0.1 per cent)
6. flux within 105 and 180 degrees / potentially useful flux
   (might be called Steep Upward Flux Ratio, should be below 0.3 per cent)

For an installed luminaire (with a concrete lamp, lamp position and mirror position), further 2 parameters are valid:

8. really useful flux (= onto the target, below 75 degrees or even lower depending on the spacing of a grid or row of luminaires, and **just that part of it which is recommended by standards**)

9. really useful light output ratio (the above flux / lamp flux)

Comparing the target-hitting flux with standards is important: if it is twice higher, or ten times higher (I know cases where it is 30 times the standard), it cannot be regarded useful as a whole, just its really needed part can. In cases of strong overkill, the RULOR may be as low as one to three per cent...

Geometry explanation

The only emissions from a luminaire, which may be useful for streetlighting, are those which are emitted not farther from the direction just down from the luminaire (called nadir) than 75 degrees.

Light emitted over these 75 degrees is too harmful for visibility to bring any benefit (this is a well known rule of lighting design, and a reason why emissions at 80 degrees from nadir are strictly regulated in all cases when visibility really matters [1]. In bidirectional or omnidirectional [2] lighting it causes too much glare. In technical words, veiling luminance [3] by such light may equal the ground luminance produced by the light of the same direction, resulting in threshold increment (TI) of horrible 65 per cent.

Adding these two components of downward light, the potentially useful one and the harmful one into one compound parameter (all light below 90 degrees), and trying to maximising this compound parameter, is a mistake which belongs among barriers to replacement of bad lighting by good one (and to simultaneous power savings). It is like adding gains and losses in bookkeeping; even if such parameter can be used (how much money went through a cash desk), for an evaluation of a trade success, losses are to be subtracted from gains.

So, the simplest relevant parameter of a luminaire (total rate of emissions, in lumens), describing its polluting capacity, is to be further divided into at least three, not just two sub-parameters: light flux below 75 degrees (potentially useful, can be called "steep down light"), between 75 and 90 degrees (most harmful as glare is regarded, to be minimised [4]) and above 90 degrees (easy to avoid completely). All these three sub-parameters are easy to compute from the luminaire photometric data (should be available for each luminaire, the availability is obligatory in at least six Italian regions), this is done e.g. by ies2tab, available at `http://amper.ped.muni.cz/light/ies2`.

Even the "steep down light" is not the parameter to be maximised for most cases of streetlighting, as the area to be lit is typically **a long narrow rectangle**. Along the long axis of this rectangle, all light up to 75 degrees can be part of the **useful flux**. This holds if the spacing/height ratio of the row of luminaires is over 3.5. Otherwise the visibility is maximised by avoiding emissions over 65 degrees – just those below this angle should be called useful flux. If the relative spacing is below 2, the maximum useful angle can drop even below 50 degrees (to suppress glare when people are looking upwards). Perpendicularly to the rectangle axis, 75 degrees is never a limit for useful light; to the "house side" from the luminaire it may be as low as 5 degrees, to the "street side" it's mostly below 50 degrees. All light falling outside the proper target (street) is not only wasted, but also an unnecessary pollution. As evident, this usually concerns even part of the potentially useful flux: to make the full potential true, the luminaire would have to be at least four times its height from any side of the area to be lit.

So, at a system level (installed luminaires), the total emissions should be further split, subdividing the "steep down light" into the useful and wasted parts (how much this wasted part is harmful, depends on the site, and can differ very much from case to case – can be extremely harmful if there are bedroom windows in the ground floor along the street).

Even the upward emissions have two components with very differing polluting potential: the closer to 90 degrees the larger. If the street goes down a steep slope, even the emissions over 90 degrees cause glare for pedestrians and drivers. Upward emissions close to 90 degrees change the urbanised areas in valleys to a sea of light points, when viewed from above (preventing visibility of a true landscape). They disturb sleep of people having their bedroom windows even hundreds metres from such luminaires. They attract insects from surrounding hills down to the settlement. When the light emitted close to 90 degrees does not hit any terrestrial objects, it travels so long through the atmosphere, that it is completely dispersed. In clear sky conditions, half of that dispersed fraction escapes to the universe, half of it hits the ground in distance (up to 200 km far from the source luminaire). In overcast conditions, even distant clouds are illuminated and shine down even to those areas, which should be kept in a state near to a natural one (including the cycle of day and night with its common range of illuminance of $1{:}10^8$). Therefore, the upward flux should be further subdivided into "steep up light" (less harmful) and "shallow up light". A reasonable limit may be again 15 degrees from horizontal direction, i.e. at 105 degrees from nadir (unlike for downward flux, this is still a matter of discussion; however, instead of arguing about this limit, finer subdivisions are possible, like 95, 105 and 120 degrees).

Relative amounts

The basic quantities as regards illumination by some luminaire are luminous fluxes expressed in lumens. However, on a system level, it is not so important how much light is emitted from a single luminaire, but rather the total emissions of each kind are relevant. The most reasonable way is to state the useful flux (keeping in mind that even to the target area, just those light should be included, which is steep enough), and then express the relative amounts of light in another zones: below 75, but outside the target, to the 75–90 zone, 90–105 zone and 105–180 zone, all **compared to the useful flux**.

For installations with spacings below 3.5 (they are very common), even a part of light going below 75 degrees and onto the target should be expressed separately, if not steep enough (i.e., if the spot could be illuminated just by luminaires which are closer to it): the unneeded glare due to that light compromises the purpose of lighting at this particular site and in bookkeeping it should written on the "pure pollution side", not on the "useful pollution" one.

As regards efficiency of a lighting system, just the **useful flux** per consumed power should be maximised. Staying in the photometry domain, it is logical to express it as a fraction of the lamp flux. There is no justification to express the remaining light (emitted into the other zones) as a fraction of lamp flux, it would be just confusing. For luminaires which are not installed yet, the base quantity may be the potentially useful flux (emissions below 75 degrees). The 75–90 zone emissions should be always minimised. And those over 90 avoided (with an emphasis on the 90–105 zone) – avoiding them is an easy task, as it is sufficient that all optical parts of the luminaire are contained within its opaque body, i.e. not protruding downward from the bottom opening of that body.

The single most harmful feature of luminaire market is a tendency to treat those luminaires, whose emissions are the largest proportion of lamp flux, as "very efficient". No, they are just very polluting, when employed outdoors. Even the "DLOR" (emissions below 90 degrees divided by lamp flux) is a misleading number, as efficiency is concerned. Its use should be abandoned. "**SDLOR**" (steep down light output ratio) could be a name of its correct product-related replacement as streetlighting is regarded, or, as proposed in the summary, **PULOR**, potentially useful light output ratio (the purpose of this ratio is more evident from this name).

Footnotes

1. 30 cd/klm at 80 degrees at most and 10 cd/klm at 90 degrees seem to be the basic demands of Deutsche Bahn (German Railways) for quality (low-glare) lighting. In practice, most employed luminaires have 0 cd/klm at 90 degrees. Some other railways (Swiss for sure) as institutions which light some of its areas (stations) for **their own** employees and customers, behave with this degree of common sense and responsibility. The goal is not "to have a plenty of light", but **good visibility for real safety**.

2. Unidirectional lighting, where even emissions over 75 degrees from nadir may be beneficial, can be applied in cases where nobody looks backwards, all people move in the same direction. Such lighting can be made without any glaring surfaces being visible. Light cones from luminaires (reflectors) can go far before they hit the ground, similarly as light from car headlamps. This option is however not used even on one-way motorways, as road surface is partly glossy and much larger road luminances are obtained when the light is directed against the observer (then it reflects from the road in his direction predominantly). The only widespread example of unidirectional lighting is the illumination of ski slopes (no advantage from specular reflection can be obtained there and glare prevention is critical).

3. veiling luminance is produced by dispersion of light inside eyes; the proportion of dispersed light increases with age. For 66 years old people it is usually taken as

   $$18 \times L \, / \, \textit{viewing angle}^2,$$

   if we consider just one prominent source of glare which produces luminous flux density L and is *viewing angle* far from the direction where the eye looks at. If there are more such sources, a sum is applied, generally it is an integral of luminance over space angle. Threshold increment, TI can be computed as

   $$65\ \% \times \textit{veiling luminance} \, / \, \textit{road luminance}^{0.8}.$$

   (Road luminance is computed for driver looking far ahead, at grazing angle to the road, just 1 degree below horizon.)

4. Optical guidance is sometime mentioned as a reason why some light should be emitted even between 80 and 90 degrees – the driver is informed by seeing distant luminaires, how the road proceeds. However, even from luminaires which have 0 cd/klm horizontally and upwards, there is always a plenty of light below 90 degrees to keep the luminaires visible. For example, from over one thousand of such possibilities from Siteco (of photometry files concerning a lot of luminaires and their settings), no has less than 2 cd/klm at 80 degrees, and almost one half has more than 30 cd/klm (see here). At the bottom limit, this translates to 20 cd for a 100W lamp, a very conspicuous light signal indeed. Optical guidance works well only with luminaires whose emissions tend to zero toward 90 degrees – it becomes very apparent which luminaire is far away and which is close. This is not the case with luminaires producing over 0 cd/klm horizontally, some very distant ones may be much brighter than near ones (this is called clutter sometimes). Physics offers no way to minimise light emissions between 75 and 90 degrees so much that optical guidance would cease to exist (for cars, not for airplanes).