Minimum semi-cylindrical illuminance and modelling in residential area lighting

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SUMMARY

The recognition of persons is extremely important in considering the safety aspects of residential area lighting. Semi-cylindrical illuminance is the appropriate descriptive parameter, as shown by experiments carried out under real outdoor conditions. The minimum level is used as a basic design criterion. On the other hand, values above 25 lux do not enhance recognition. Other experiments were set up to examine any correlation of modelling effects of the human face with the ratio of vertical to semi-cylindrical illuminance. It is shown that this ratio presents only a geometrical function relative to the object person position. Luminaire concepts are discussed in connection with guidelines for semi-cylindrical illuminance and glare.

KEYWORDS

Cylindrical illuminance, semi-cylindrical illuminance, residential area lighting, safety aspects, modelling

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1. Introduction

Public lighting design, as based upon car-driver oriented concepts, does require changes in perspective, especially within zones with a considerable presence of slow moving observers (pedestrians, cyclists and occasionally moped riders).

Lighting for motorways, with their high density and speed of cars, only considers observers from the driver's point of view; "personal" contact between them is obviously non-existent. These concepts have been extrapolated, more or less, to other applications in outdoor lighting where cars are still present, but in a minor role.

Recently however, the new architectural concept of the "*woonerf*" [1] has been introduced, as part of the tendency to accord the pedestrian a principal role with stress on quality of living conditions. This changed "*modus vivendi*" has undoubtedly affected other, more classically conceived residential areas and pedestrian zones (such as commercial centres, walkways, parks, etc.) as regards the design of the lighting installation.

In this paper the pedestrian remains the observer as an *individual*. All things considered, he is the most vulnerable subject on the scene. With regard to the *safety aspect*, which we may consider as a main theme, one ought to position the observer in the most unfavourable situation in order to deduce the measures to be taken to guarantee safety of persons and property.

Obviously, the fundamentals of residential area lighting can be recovered in the broader matter of public lighting. Analogous elements are being in the open, the configuration of streets and environment, the use of outdoor luminaires suspended from light-poles, etc.

There is undeniably a dialectic between the inside (interior) and the outside (outdoor) world, between the closed and the open space; as revealed by the French philosopher Gaston Bachelard in "*La poétique de l'espace*" [2]. Even so it may appear paradoxical that the basic design of outdoor area lighting involving pedestrians, as observed from pedestrian's point of view, correlates with fundamental criteria for interior lighting : it is evident that the ability of recognition of a human face and other patterns, and the estimation of a person's intentions play as well an extremely important role within residential areas. Interior lighting is considered here as more than aesthetics within private houses.

Residential areas involve human psychology in such a way that adequate lighting contributes substantially to a comfortable ambient atmosphere for residents moving outside their premises, and for non-residents entering unfamiliar surroundings after dark.

People are involved as individual human beings. The phenomenon of seeing in its totality is not translatable to a measurable quantity; the most we can attempt is to use descriptive parameters.

2. Summary of lighting criteria

Van Bommel and Caminada [3],[4] are the main contributors to a novel approach to the lighting of residential areas.

These criteria are mainly based upon concepts of illuminance, though one does not "see" in terms of illuminances. Exceptionally, with dedicated routes for mopeds and bicycles the luminance concept is used. But as here a description of an entire scene is needed, we do have to work with "easy-to-handle" parameters.

Clearly, this scene becomes more diverse in quality of materials (concrete, tiles, grass, gravel, bushes, etc. in different aspects) the more important the living and destination function is considered.

What is more, from pedestrian's point of view (or other slow moving observers), viewing directions are distributed over the entire space; the visual field cannot be determined in a singular way, and may cover several objectives of interest at the same time.

The lighting criteria can be summarised as follows :

(a) Perception of obstacles and objects, especially near ground level;

(b) Visual orientation, overall impression of environment, safety of properties;

(c) Recognition and identification of persons and their intentions, safety aspects;

(d) Glare restriction;

(e) Visual comfort (modelling effects, nature of the light source, light penetration into private houses, visual impact of the installation, etc.);

(f) Economical operation of luminaires and exploitation of installation from illuminating point of view, æsthetical outlook, maintenance aspects.

All this needs to be quantified in terms of descriptive lighting parameters, such as illuminances (horizontal, vertical, hemi-spherical, semi-cylindrical); luminances; intensities; ratios of illuminances; other parameters.

Particular stress is laid here on the three-dimensional forms of illuminances[2], which may be of some interest with regard to the recognition of a human face, and other objects with a spatial character or a definite shape.

3. Semi-cylindrical illuminance E_{SC}

Gutorov [5] defined the mean cylindrical illuminance (E_{Cyl}) as a new concept and Epaneshnikov *et al.* [6] related it to the lighting of places with a high density of pedestrians and with an "open" character, such as railway and underground entrance halls, exhibition rooms, congress meeting halls, etc.

The concept of E_{SC} was only recently introduced in design of sports lighting for colour television capture [7] and in the design of interior lighting where people should be able to communicate with each other and where "spatial restoration" of objects is a necessity.

Briefly, E_{SC} is defined as the averaged illuminance on the curved surface A_{SC} of an upright half cylinder. (See Figure 1) :

$$E_{SC} = \lim_{A_{SC} \to 0} \frac{\Phi}{A_{SC}}$$

$$\Rightarrow \; E_{SC} = \frac{1}{\pi} \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} E_V(\varphi)\, d\varphi$$

where Φ is the luminous flux on the half cylinder, A_{SC} is the curved surface, and $E_V(\varphi)$ is the vertical illuminance as a function of φ.

2 During the last CIE Session in Venice (1987) the new Technical Committee on "Three-dimensional forms of illuminance" (CIE TC 3-14) was inaugurated, under the chairmanship of Kit Cuttle (NZ).

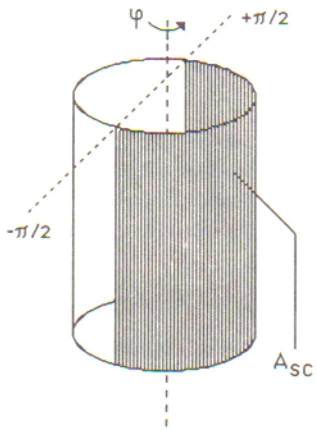

Figure 1 : Definition of semi-cylindrical illuminance

As the light flux collected by the (infinitely small) half cylinder has an integral character one has to bear in mind that E_{SC} cannot represent the distribution of light completely. When the proper "flow of light" needs to be characterised, the vector/scalar concept of illuminance is appropriate here.

4. Field research on E_{SC}

In view of the criterion of the recognition of a human, a series of experiments has been carried out to examine the relationship between facial recognition and identification on one hand and lighting parameters on the other hand, in this case confined to E_{SC}.

Facial recognition turns out to be the first and leading element of interest when two people meet in the street. For this reason, we shall consider E_{SC} at 1,5 m above ground level, mainly according to longitudinal and transversal road axes. One can regard the form of the face as well as the human body itself at a greater distance away, as a half cylinder, even with oblique viewing directions. From there, hemispherical illuminance with normal to basis horizontally, is less obvious here.

A preliminary series of experiments was set up to examine the way in which an assembly of luminaires in the field contributes to recognition capability. This was done by switching on and off combinations of the luminaires in the street. The test conditions are largely as in section 4.2.

It appears that the impact can be limited to individual lamp-posts for what concerns facial recognition and glare effect, as undoubtedly in residential areas the ratio of interdistance to mounting height is relatively high and is indeed emphasized by economical objectives. In some cases this corresponds to the "unacceptable" situation where some of the light sources are broken down or obstructed by trees. This also represents the worst case.

So, throughout the experiments, the lighting installation was taken as consisting of only one luminaire at 4 m height.

A real environment was taken as the location for the experimental set-up. So, "being there" within a real residential area did not have to be imitated.

4.1 Luminaire characteristics

The luminaire is of small size, with a particular directional distribution of the reflector controlled light flux, mainly into the lower hemisphere. The bottom cover is in transparent glass or polycarbonate (see Figure 2).

This luminaire rather acts as a source for sparkle and not as a diffuser as opaline globes do. It is termed "semi~cut-off" and was initially inspired by public lighting luminaire design (principally according to the luminance concept).

In fact, classical opaline-type luminaires (see Figure 3) are translucent and spread out the luminance of the source over a relatively large surface of the envelope (with a diameter of about 50 cm) into the lower as well as into the upper hemisphere, so that the utilisation of the lamp flux is often very poor. Their distribution of light intensity is nearly constant. They favour attainment of the minimum level of E_{SC}, with a real installation geometry (e.g. poles of 4 m of height at distances of about 24 m) and with a certain average road luminance level. See also section 6.

The light source is a 70 W High Pressure sodium lamp.

A set of 18 particular points was marked on the road surface, over which the persons to be observed are positioned. These points are according to values of E_{SC} of 0,1 to 18,2 lux and values of E_V/E_{SC} from 0,18 to 1,57 ($= \pi/2$). See footnote[3]. The illumination originating from the sky by night is taken into account ($E_{SC} = E_{Cyl} = 0,1$ lux when all artificial light sources are switched off).

Figure 2 : View on the test site by day. The compact luminaires have reflector controlled light flux and transparent cover.

[3] The vertical to semi-cylindrical illuminance ratio is a measure of modelling effect.

Figure 3 : Opaline-type luminaire with translucent envelope. The lamp-posts are at distances of 22 m maximum. Despite an average road illuminance or luminance level (0,5 to 1 cd/m^2), recognition is hardly feasible.

4.2 Test conditions

Consider two separate groups : the "observer" group and the "object" group (or "observed" one). The groups are composed miscellaneously, including men and women, older and younger people, experts and non-experts, persons acquainted with persons from the other group and those who are not.
All arrangements are coordinated by a conductor.

The experiment is set up as follows. An *observed person* is standing still in one of the 18 positions and is viewing in directions parallel to the road axis, facing the luminaire (see Figure 4).
An *observer* is asked to come from behind a wall and to walk longitudinally towards the object person, starting from a separation of more than 30 m.

At certain distances *d* to the object, the observer is asked to evaluate his view according to the gradation scheme of Table 1 until no. 9 on the scale is reached.

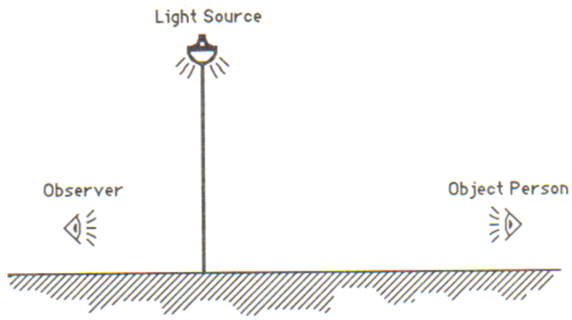

Figure 4 : Sketch of experimental set-up

Gradation on scale	Condition
1	One is not able to see anybody.
2	One surmises a presence.
3	One can see a silhouette.
4	One can distinguish certain details, such as a beard.
5	One can say whether it is a man or a woman. More details become clear, such as glasses.
6	One can distinguish a laughing person from a non-laughing one. Intentions are becoming visible.
7	One has a suspicion of whom it might be, or of whom it might *not* be.
8	One is almost sure of distinguishing identity.
9	One is completely sure.

Table 1 : Degrees of facial recognition

It should be noticed, that only thanks to the experiments, a diversity of perceived details as beard and glasses is attributed to a certain degree.

Elements of prerecognition or predetermination were excluded from the evaluation by separating the groups from the very beginning. Furthermore, an observer could not discover unconsciously any underlying systematics, or determine an object person by "eliminating", as the combination of *observer*, *object person* and *object person position* was organised randomly. The relative position of the object was not known by referring to a tree or other poles in the scene.

No association that could be made through a certain way of moving by the object persons, who all wear a neutral dark overcoat.

Altogether over 100 tests were carried out.

4.3 Experimental results

As we consider absolute recognition as a prerequisite for personal safety, gradation no. 9 was isolated out of the tests. The data were then treated statistically, giving the curve of Figure 5.

This reveals a relationship between the semi-cylindrical illuminance at face level (1,5 m) and the distance *d* between observer and object, for facial recognition.

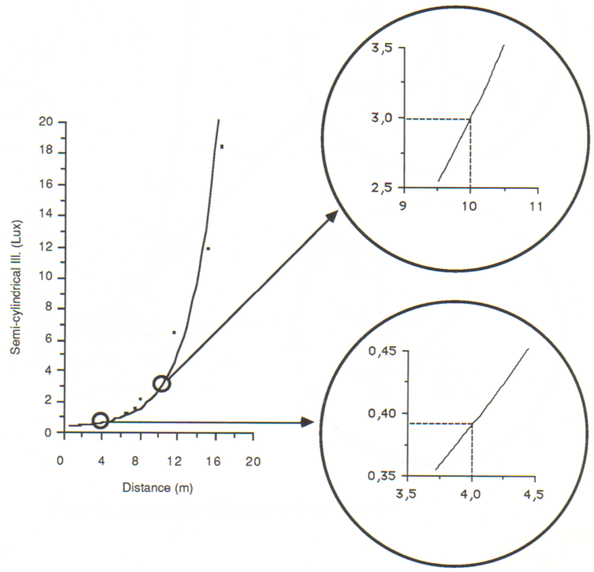

Figure 5 : E_{SC} as a function of distance, for facial recognition

4.4 Discussion

One can ascertain a very good correlation between the facial recognition distance and the value of E_{SC}.

The results of these experiments are somewhat consonant with those of Van Bommel and Caminada [3],[4] obtained under completely different circumstances.

Examination of Figure 5 readily shows the existence of some "vertical asymptote", which corresponds in fact to a physiological limit at 17 m. At levels of 20 to 25 lux, increasing E_{SC} will *not* lead to a further increase in the recognition distance. So, values for E_{SC} over 25 lux make no sense ! Even with daylight such a limit does exist : physiologically we are not able to recognise someone at very great distances.

Recommendations for semi-cylindrical illuminance should not exceed this value, either absolutely or on average.

When thinking in terms of personal safety and, in this connection, counting the ability of recognition and identification as the major lighting objectives, one ought to consider the "worst case"; this occurs within dark zones. Hence, directives concerning the *minimum* level of E_{SC} are relevant, averaged quantities are not.

Figure 5 shows the minimum level to be maintained over the entire visual scene for a certain distance of proximity. For instance, at a distance of 4 m, $\{E_{SC}\}_{Min}$ = 0,4 lux, after expanding the curve.

The experiments were carried out without taking glare effects into account. However, when taking into account a TI-index up to 15 % as disability glare, as realised by an appropriate configuration of luminaires, a shift of 0,2 lux in E_{SC} is found. We can state from this that for a recognition distance of 4 m

$$\{E_{SC}\}_{Min} = 0{,}6 \text{ lux} \qquad (1)$$

at 1,5 m of height; principally longitudinally as this is the main walking direction. This represents in fact the absolute minimum over the entire field.

One has to bear in mind the existence of "dynamic aspects", since people are moving observers : a dark zone can be allowed on condition that E_{SC} in the nearby zone is a lot higher than the minimum level [3],[4].

Consider a realistic set-up with luminaires in a staggered configuration at 4 m height, an interdistance of 24 m, and with 8 m between rows. When moving away from a luminaire, according to the longitudinal direction facing it, the value of $_{ESC}$ decreases.

At a distance of about 18 to 20 m this value has become lower than 0,5 lux, although the luminous flux in terms of horizontal illuminance will be very important in this region, because of the influence of another luminaire. In spite of low E_{SC} under the luminaire (theoretically $E_{SC} = 0$ right under it), for the same viewing direction, facial recognition can take place over the nearby zone, as generally dark zones are followed up by zones with higher levels.

So, a zone of about 3 m in both directions with E_{SC} below its minimum level is allowed on condition that recognition over the adjacent zones is realised at a distance of about 10 m, which corresponds to a $\{E_{SC}\}_{Min}$ of 3,4 lux (3 + 0,4 from shifting for glare). See Figure 5.

E_{SC} is a rather new concept and such low values of illuminance are unfamiliar.

When much higher absolute minima of, for instance, 2 to 3 lux are recommended, the consequences on installation geometry are abundantly clear.
With current commercially available luminaires (e.g. with a High Pressure sodium lamp of 70 W, and at a height of 4 m), interdistances should be set at about 10 m !

To keep the scene vivid however, a certain unbalance or asymmetry in the illuminance distribution should be built in. Higher levels for E_{SC} are also required in the neighbourhood of important spots as telephone booths, benches, playgrounds, etc.
Thus averaging over an area in longitudinal/transversal directions is more significant than averaging over all directions at a given point.

Uniformity of illuminances is a less important criterion : accommodation capability is strongly improved, since observers are moving slowly.

So, a more extensive dynamic range of light levels can be allowed, carefully chosen to limit glare effects.

When people are asked to express their overall impression of an area, they seem to remain thinking in terms of light coming from *above* (as they are used to the sunlight by day); and thus mainly relating it to horizontal illuminances. In [8] it is showed that overall impression is best described by *average horizontal illuminance* (over semi-cylindrical or hemispherical).

Hence, in this context, when talking of *average* values, there is no need to introduce either E_{SC} or E_{HS} (hemispherical illuminance) over bidimensional vertical or horizontal illuminances.

The observers were asked to abstract the effect of *glare*. When they were unable to do so, because of a certain degree of disability or discomfort, a physical obstruction such as a piece of paper or one's hand was brought into the eye-line to the source. We appeal to the tendency, when observing a object of interest, to overcome some discomfort from the surroundings.

The experimental set-up was conceived to minimise this need : the eye-line to the luminaire is only tending to the eye-line to the object person for positions of the object with a great amount of light flux. In this way, "counter lighting", i.e. a dark silhouette against a brighter background, is not considered.
Physiological glare was thus easy to eliminate. The luminaire however, was chosen to yield high luminance contrast with the background.

Concerning psychological glare on the other hand, the boundary values of the glare figures as introduced in [3],[4] were upgraded recently to meet current practice.

Further research is necessary and should be integrated in a comprehensive glare approach over the entire field of application (geometry of installation, light source, luminaire, road/background luminance, etc.).

5. Modelling experiments

The recognition experiments were linked with the research into the "modelling" effects of the human face and their correlation with E_V/E_{SC} as descriptive parameter.

The observer and object person are now positioned face to face at an interdistance of about 4 m so that recognition has taken place. The particular positions correspond with values for E_V/E_{SC} from 0,18 to 1,57 (= π/2), while E_{SC} varies from 0,4 to 10 lux (all at face height).

Here too, a gradation scheme is introduced (see Table 2). The observer has to make an evaluation of the spatial resolution of the human face and the ability of the lighting installation to reveal the characteristics of it (e.g. the facial expression as laughing).

Gradation on scale	Condition
1	Too sombre, too dramatically, too much cast shadow; practically no features are recognisable, frowning is a lot more emphasized than laughing.
3	Some features are becoming recognisable, but still too dramatic.
5	Facial expression and mimicry can be recognised clearly. Features are well balanced with "natural resolution".
7	The lighting is too diffuse; resolution is too flat; the features are not clearly recognisable.
9	Total frontal illumination, i.e. without depth of visibility. Because of the flat resolution one can hardly recognise facial features.

Table 2 : Degrees of modelling

The two extreme gradations 1 and 9 stand for the theoretical extremes of the ratio E_V/E_{SC} of 0 and π/2. The obtained relation is represented in Figure 6.

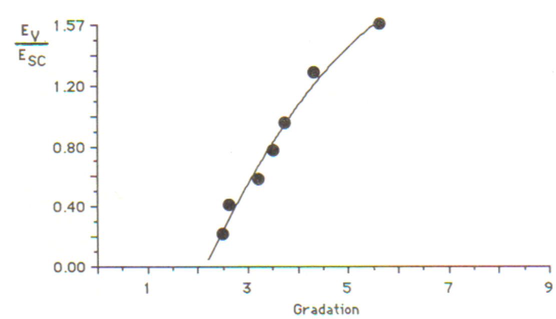

Figure 6 : Evaluation of modelling

Features are well balanced (gradation 4 to 6) when

$$1{,}1 \leq E_V/E_{SC} \leq 1{,}5 \qquad (2)$$

In contrast with applications with interior lighting, relative high frontal, diffuse illumination can be applied in night outdoor conditions.

Modelling again is mainly determined by the influence of one luminaire, within a practical set-up where luminaires are at distances of 5 to 6 times the installation height.
Therefore, the use of E_{SC} is to be preferred to the use of E_{Cyl} in the ratio with E_V. With much higher background luminance levels, this situation would change anyhow.

It remains to be pointed out whether the "flow of light" and the absolute level of illumination have an influence on modelling evaluation with the same value of E_V/E_{SC}.

Anyway, from modelling point of view, only a small degree of asymmetry is needed in this light distribution, since "natural balancing" is not strictly interpreted within residential area lighting.

Mathematically, the ratio of E_V to E_{SC} can be written (Figure 7) as

$$E_V/E_{SC} = \frac{\pi}{1 + \left(1 + \cot^2(\beta)\right)^{\frac{1}{2}}}$$

This is in the longitudinal direction and originating from one luminaire (taken as a point source).

It appears that this ratio is independent of the type and the installation height of the luminaire and the luminous flux; and gives only a *geometrical function* of the angle β, defined as the relative position in the horizontal plane of the observed person (or object) with respect to the transversal plane.

Hence, E_V/E_{SC} can be plotted as a function of β (Figure 8). Here the eye-line of the observed person is parallel to the (longitudinal) road axis.

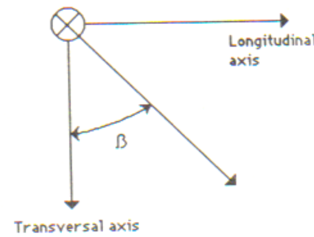

Figure 7 : Definition of β

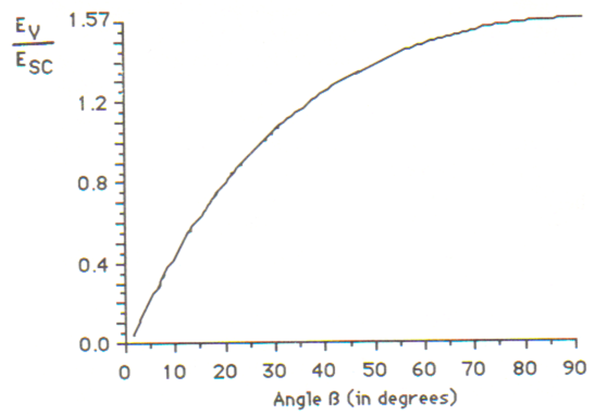

Figure 8 : E_V/E_{SC} as a function of β

A zone on the pavement can be defined where relation (2) is satisfied (shaded area in Figure 9). Calculations confirm these conclusions too.

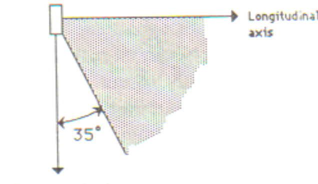

Figure 9 : The zone around the luminaire, according to equation 2, only considering the road side (shaded area)

While designing, one can choose important meeting places, walkways, benches or telephone booths to be in this zone, bearing in mind well be aware of the fact that only one particular viewing direction (longitudinal axis) has been considered. Combination with an additional nearby luminaire is possible.

6. What about the luminaires ?

A certain distribution of light (in terms of illuminances, etc.) must be realised. This distribution is produced by means of some configuration of luminaires.
The market offers a huge choice in lighting apparatus within which some differentiation can be made :

- Luminaires with or without internal reflector, or refractor (e.g. acrylate disks);
- The light distribution is so-called *cut-off*, *semi~cut-off* or *non~cut-off*;
- Transparent (e.g. clear glass, acrylate, polycarbonate) or translucent (e.g. opaline globe) cover or refractor.

Luminaires originating from public lighting are mainly designed according to luminance concepts, and to limit glare, their light distribution is made cut-off or semi~cut-off.
Others are more designed as decorative lanterns, in some cases even more or less as the bare lamp covered by an envelope.

Efficient installation design should embody the concept of the luminaire itself as well as the installation geometry (height of the light source, distance between poles, etc.).

An important factor is the interdistance of luminaires.

Modern luminaires, with internal reflector and extended light distribution (e.g. I_{max} at 70° to 75° in C = 0°-180° plane) allow considerable greater distances with the same installation height. Attention should be paid however to disturbing glare, which is then not easy to control.

Glare effect clearly occurs with opaline spheres and globes (see Figure 3), obviously even more when mercury lamps are used, which give a harsh contrast with the background. It acts in such a way one is only able to see the light source itself, while the environment looks completely black; just as well because the luminant surface of the source is rather extensive and the observer's eye is attracted by the brightest spot. Orientation only occurs towards the light source (as in a room with a lamp in the centre of the ceiling) and not within the entire surroundings.

Nevertheless, these globes are well suited to illuminance design concepts. Besides, with interdistances of 5 to 6 times the installation height (e.g. d = 30 m, H = 6,3 m, single-sided configuration) the minimum level of E_{SC} is relatively easy to achieve, but with the inconvenience of high power consumption.
What is more, to obtain an average road luminance of 1 cd/m^2, public lighting type luminaires with extended distribution require 4 to 5 times less luminous flux than opaline globes do.

Hence, one can state that, in order to fulfil the criteria involving semi-cylindrical illuminance, new (compact) luminaires need to be developed, since resolving great interdistances (i.e. maximising the ratio of distance to installation height), the E_{SC} concept and thence minimum E_{SC}, and glare control, remain problematic.

7. Conclusion

Semi-cylindrical illuminance has become a principal design element within residential area lighting. With personal safety in mind, the minimum value of E_{SC} should not fall below 0,6 lux, whereas maximum values above 25 lux are of no concern.

Uniformity of illuminances (E_H, E_V, E_{SC}), although important, is only a secondary parameter. On the other hand, some references as DIN 5044 *Teil* 1 [9], recommend very stringent conditions on ratios of minimum to maximum illuminance, with typical values of 0,1. With currently available luminaires, this has serious implications for installation design : agreement with this standard is only feasible with relatively short distances between light-poles !

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