Light Pollution has become a major concern in the recent years. Many studies try to quantify this phenomenon as accurately as possible. This article presents the results of a study that enables the rigorous calculation of upward flux coming both directly from outdoor lighting luminaires but also from illuminated surfaces by reflection.

Precise Evaluation of Upward Flux from Outdoor Lighting Installations (applied in the case of roadway lighting).

by

Marc Gillet (Schréder Group), Prof. P. Rombauts (University of Brussels - VUB)

Summary

Many authors have already conducted studies including the quantity of reflected flux from illuminated surfaces in order to quantify the total upward flux that is emitted. This paper uses interior lighting calculation technique in order to quantify with a fixed and high level of accuracy this flux by integrating all the light coming from illuminated surfaces outdoor. Compared with the recent contributions on this matter, it brings a further precision on the reflected flux and therefore enables an improved knowledge of the phenomenon.

Due to the relatively large discrepancies existing among the assumptions taken in all the different models taking into account the impact of the reflected flux on the outdoor illuminated surfaces, it appeared clearly that a refined analysis of the reflectance to incorporate in the calculations could be suggested. From model to model, average road reflectance is once considered as equal to 7 %, 10 %, or 18 % to give some examples.

Even if it is true that there is a large variation of reflection behavior among the variety of road surfaces existing around the world, the ‘average’ assumption cannot at least be considered as agreed among the experts who have already investigated this question in their works. Furthermore, the conclusions deduced from the models using an average reflectance in their assumptions may vary greatly from one to another due to the large impact - that has already been demonstrated - of the reflection of the illuminated surface on the global flux quantity that is emitted upward. In simple words, we may consider from the existing researches (see ref. 5, 6, 7, 8, 9) that the assumption on reflectance's figures is not consensual and therefore may lead to large discrepancies in the conclusions.

The first part of this study has been made in close cooperation with the University of Berlin (prof. H. Kaase) in order to measure the reflectance curve as a function of the γ -

angle for different kinds of road samples. This is an aspect of importance in this study. Indeed the majority of the studies existing on the matter do simply consider the reflectance as a constant whatever the incidence of the light beam. In the present approach, we included the variation of this reflectance as a function of the incidence of light. The process to quantify the quantity of light that is upward emitted is well known and has been widely used for inter-reflection calculation in indoor lighting applications. By definition, directional reflection is given for an intensity having a well defined γ incidence :

$$\rho = \phi_r / \phi_i \qquad [1]$$

In roadway lighting applications, the luminance is provided by the following formulation in the majority of calculation softwares that are available on the market:

$$\mathbf{L_p = q(\beta, \gamma) \cdot E_p} \qquad [2]$$

A very similar (computer seen) formulation can provide the total quantity of upward flux which is reflected by the road surface. This is in fact

$$\phi_r = \int \rho(\gamma, \text{nature of road}).E.dS \qquad [3]$$

This formulae signifies that the total quantity of light upward reflected is nothing else than the integration of all the sub-patches fluxes representing small parts of the illuminated surface (in this case, the road) that may be considered as individual indirect lighting sources. By essence as reflectance is variable as a function of γ as E is, the integral can only be computed as a finite sum of the varying terms **ρ.E.dS.** Finally the integration can very easily be written as

$$\phi_r = \sum (\rho_i.dS).E_i \qquad [4]$$

When looking at [2] and [4]**,** the analogy appears clearly. A punctual luminance as computed by a calculation software may very easily be translated into the punctual upward reflected flux by simply changing **q (β, γ)** term of equation [2] by **(ρi.dS)** term of equation [4]. “dS” quantity is the area of an elementary patch subdividing the zone of interest (illuminated area) into a finite number of them. ρ has now to be accurately measured in order to calculate rigorously the value of each term of the sum in equation 4.

Measurement of reflectance is a well documented field of photometry. In the present case, it was imperative to have a system being able to vary the incidence angle in order to build up the **ρ = f (**γ,surface**)** curve needed in the calculation process.

The reflectance – measurement sphere (see figure 1) has an intrinsic diameter of 1.5m and the reflectance of the interior of the sphere is non-selective and diffuse with a ρ=0.8

The aperture diameter is max.50cm and changeable to 30,20,15 and 10cm. Detector is a photo element with V(λ)-,cos- evaluation and shutter. Regarding light incidence, the incidence of the beam varies following the sequence of angles : 8°, 20°, 30°, 40°, 50°, 60°, 70°.

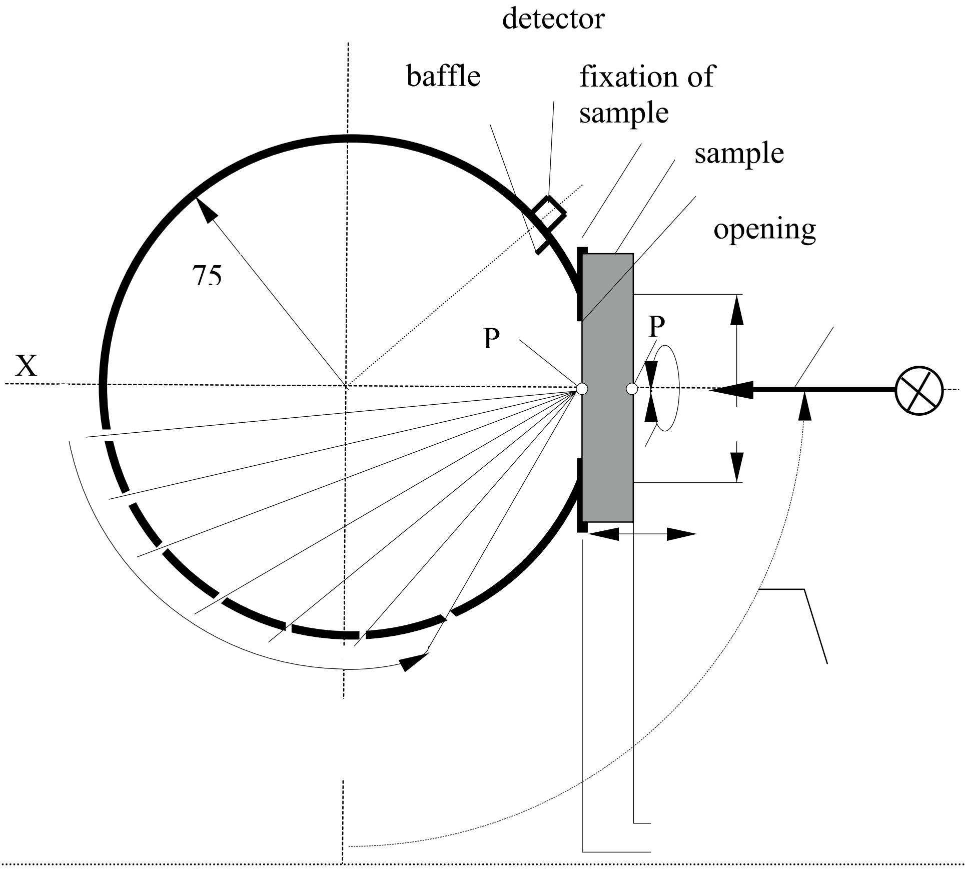


Figure 1 : Integrating sphere for the measurement of light reflectance dependant on light incidence

Light source consists in a CIE standard illuminant D65, analog to natural light. The adjustment of the light incidence is done manually.

This apparatus enabled the measurement of several families of representative road surfaces such as bituminous asphalts, porous asphalts and concretes. Hereafter, the curves of the most representative of them are presented. Figure 2 shows the **ρ = f (**γ,surface**)** function in the case of a representative bituminous asphalt. The main observation of this curve is that reflectance is highly variable (supra linear) and the increase in reflectance is +53% between 8° (6.3%) and 70° (9.7%) incidences.

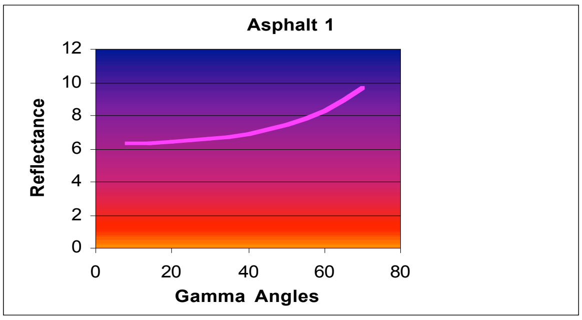


Figure 2 : ρ = **f(**γ) for a bituminous asphalt

Figures 3 and 4 show respectively the **ρ = f(**γ,surface**)** functions in the case of representative porous asphalt and concrete.

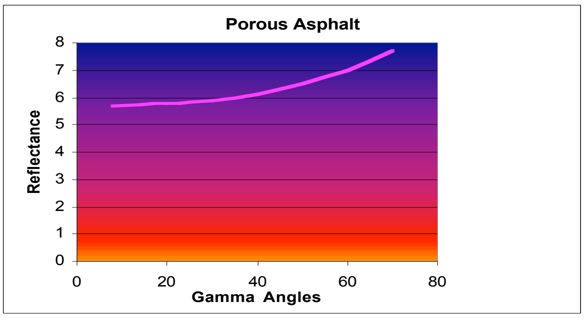


Figure 3 : ρ = **f(**γ) for a porous asphalt

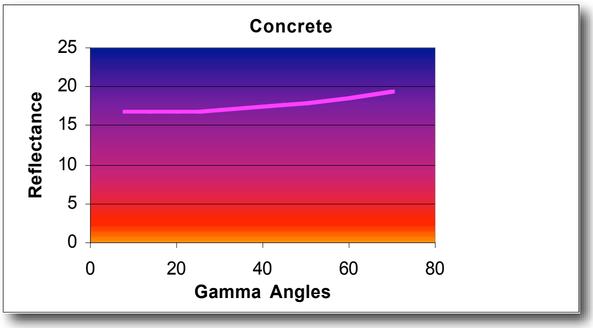
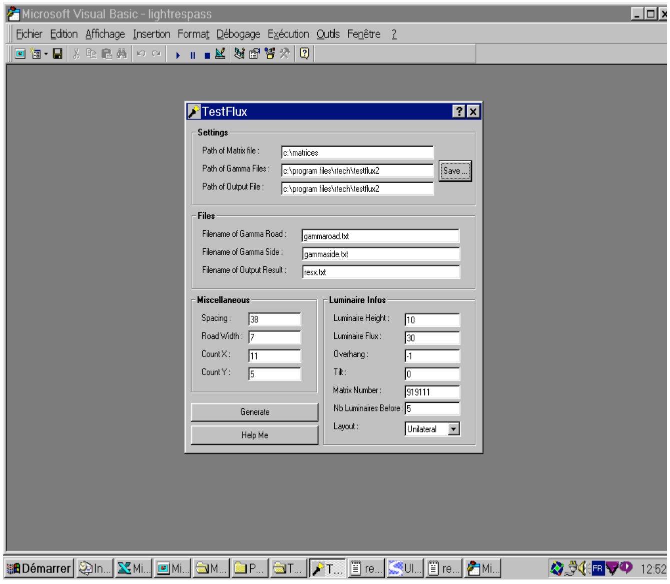


Figure 4 : ρ = f(γ) for a concrete

The general trend of the presented and other measurements may be synthesized as follows :

- ρ is highly variable and always grows up from rather perpendicular beams to larger incidence angles. This increase is always supra linear.
- Figures that were measured are in many cases (at least in the case of representative bituminous and porous asphalt) lower than assumptions taking into account light pollution modeling in some countries.
- Gain is lower in the case of concrete (flatter); this latest road surface remaining obviously brighter than other bituminous or porous asphalt surface for equivalent incidence angles.

The algorithm coupled with the set of data's presented here above –in the case of the 3 representative road measurements on 6 road samples totally- has then been translated in a calculation routine based on an existing road luminance calculation software to deduce the total upward flux. Figure 5 presents the screen of input data's needed to calculate the total upward flux. This calculation tool has been used in the scope of the present paper for a roadway lighting application but its use can obviously be extended to other outdoor lighting applications. Main data's needed for a roadway lighting calculation are: set of reflectance for road and surroundings, light distribution intensity-table, spacing between poles, road-width, size of the patches (X and Y-dimension), luminaire height and lamp flux, overhang, tilt, arrangement and the number of luminaires to incorporate in the calculation.



Settings

Path of Matrix file : c:\matrices

Path of Gamma Files : c:\program files\rtech\testflux2

Path of Output File : c:\program files\rtech\testflux2

Files

Filename of Gamma Road : gammaroad.txt

Filename of Gamma Side : gammaside.txt

Filename of Output Result : resx.txt

Miscellaneous

Spacing : 38

Road Width : 7

Count X : 11

Count Y : 5

Luminaire Infos

Luminaire Height : 10

Luminaire Flux : 30

Overhang : -1

Tilt : 0

Matrix Number : 919111

Nb Luminaires Before : 5

Layout : Unilateral

Figure 5 : screen for the collection of data's needed for a total upward calculation

The third part of this study consists in the utilization of both the set of data's collected from the measurements in the University of Berlin and the investigation of a typical case of roadway lighting. The case is treated as a representative example but can surely not be considered as representative of a majority of lighting situations. It simply helps in comprehending the contribution of the methodology in the case of a realistic and widely encountered lighting situation.

The lighting situation treated as an example consists in a 7 meter width road with luminaires installed with 1 meter negative overhang on a single-sided arrangement. Height of installations of luminaires is 10m and the spacing is optimized in order to obtain standard lighting levels of :

$$Lave = 0.75\ cd/m^2$$

$$U0>40\%$$

$$Ul>60\%$$

TI<15%

Several families of light distributions (fitted with High Pressure Sodium Lamps) have been optimized one by one in order to reach for each of them the highest possible spacing (this approach is usual in many new installations). Families of luminaire's light distributions are : spherical luminaire without optics, and the following types with a reflector: sphere type with low-efficiency reflector, flat glass high-efficiency type, curved glass h-e, smooth polycarbonate (dished bowl) h-e and refractor h-e.

Luminance results obtained with the various light distributions do not always allow to reach strictly the requirements that are pre-defined. ***In order to compare all the various light distributions on an equal basis***, fluxes of the lamps in each of the various cases shall be dimmed to reach 0.75 cd/m^2 strictly at any time. Furthermore, the optimization in spacing shall be proceeded on the 3 most representative road samples i.e. one bituminous and one porous asphalt as well as one concrete. For all the installations optimized by following this process, the total quantity of upward flux was computed by using the developed calculation routine presented earlier. It is also important to note that in this roadway lighting situation analysis, surroundings were considered as having a constant (as a function of γ) reflectance equal to 5% representing a grass surface. Further investigation about surrounding surfaces with specific measurements should in a near future complete ideally the present approach.

Figure 6 presents the total upward flux (direct + reflected) for the considered families of light distributions in the case of the representative bituminous asphalt.

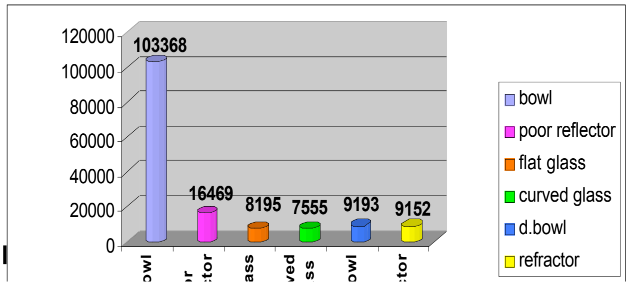


Figure 6 : Total upward flux (direct + reflected) in the case of a bituminous asphalt

Main observations from previous diagram are:

- A factor of 10 may exist between high performance and low performance lighting systems when considering the total upward flux emitted by roadway lighting installations.

same amount of upward flux.

- When considering high-efficiency lighting systems (whatever the type of light distribution), differences appear more subtly. A case by case (refined) analysis is needed. In the present case, curved glass and flat glass appear as the less-upward-light-emitting systems.

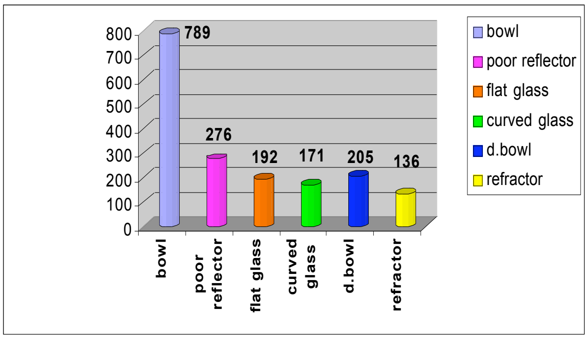


Figure 7 : installed lamp klm/km

Figure 7 presents for the same analysis (bituminous asphalt) the results of installed lamp lumen per kilometer. ***This parameter is an interesting indicator of light pollution reduction as the big trends are similar even if for some cases it is not exactly corroborative*** (e.g. flat glass vs. refractor ; see the inversion of trend between total upward flux and lamplm/km).

The following figure 8 presents the repartition between directly emitted and reflected flux for each of the various solutions.

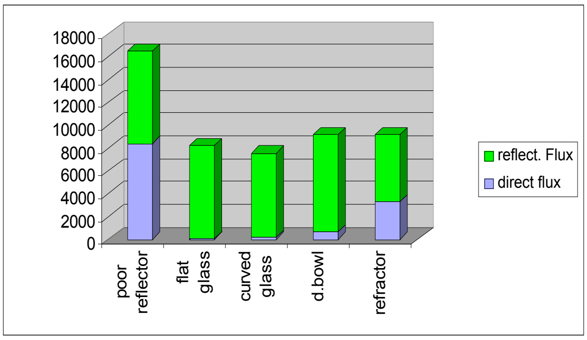


Figure 8 : repartition between direct and reflected flux between solutions

We can learn from the previous diagram that:

- A low-efficiency lighting system emits as much light directly as by reflection.
- The quasi total amount of light from flat glass and curved glass high-efficiency light distributions is obtained by reflection while
- Polycarbonate (dished bowl) and refractor's h-e distributions present a much bigger proportion of direct flux than more cut-off distributions such as flat glass and curved glass but sometimes do present (in the case of refractor for instance) a lower portion of reflected flux.

Based on the previous integration in order to deduce with accuracy the total upward emitted flux, it is now possible to deduce an 'average' reflectance from the following equation :

$$\rho_{ave} = \phi_r / (E.S) \qquad [5]$$

where :

- **ρ_{ave} is the average reflection factor to be determined after the integration calculation**
- **ϕ_r is the reflected upward flux provided by the calculation routine**
- **E is the average illuminance provided by a classical photometrical evaluation**
- **S is the total area (in the present case the road) that may be considered as having a "constant" reflectance**

This calculation will provide a representative figure for the reflection factor that may serve as a rather good approximation when working on a pre-defined type of road surface.

In the present analysis of a bituminous asphalt, it leads to the following results :

- refractor and curved glass : **ρ_{ave}=7.4% (i.e γ=50°)**
- flat glass : **ρ_{ave}=7.2% (i.e γ=46°)**

The logical interpretation of the existence of different reflectances for the same road surface but for different types of light distribution is obviously that a flat glass distribution is by essence a more cut-off distribution and therefore light beams "fall closer" to the poles so that in average γ angles are in average a bit smaller.

Hereunder, the reader will find an analogous total upward flux evaluation but in the case of representative porous asphalt and concrete which shows the same general trend.

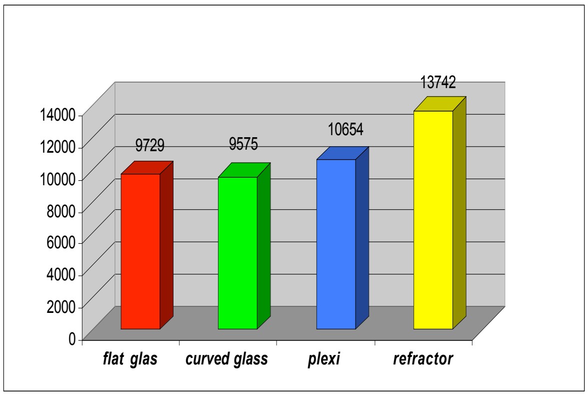


Figure 9 : Total upward flux (direct + reflected) in the case of a porous asphalt

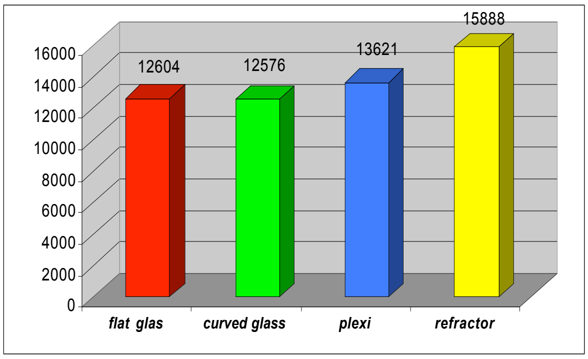


Figure 10 : Total upward flux (direct + reflected) in the case of a concrete

Conclusions:

- A rigorous and systematical approach for the evaluation of outdoor lighting upward flux leading to light pollution has been elaborated for practical use. Both simple measurement and calculations systems provide a powerful tool to the lighting designer who intends to optimize carefully his installation in respect with light pollution reduction.
- Reduction of light pollution is first a question of performance i.e. the capacity that an installation has to minimize the quantity of installed lamplm/km to reach a reference set of lighting criteria's. Large differences may exist between different lighting systems.
- Such an approach of dimming is clearly a powerful way to minimize sky glow by providing the quantity of flux which is just needed to reach the pre-defined level of (il.)luminance.
- There is also therefore a clear interest to measure accurately and systematically the reflection properties of illuminated surfaces in the case of luminance design.

Finally and to conclude, further investigation is needed in a near future to extend the present analysis to a "surrounding" analysis in the case of roadway lighting installations. Other fields of outdoor lighting applications can also be investigated through the present process.

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R-Tech (Schréder Group)
rue de Mons, 3B
B-4000 Liège
Tél.: + 32 (0)4.224.71.48
Fax: + 32 (0)4.224.00.73

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