DIRECT VERSUS REFLECTED UPLIGHT IN CREATING LIGHT POLLUTION AND THE OPTIMIZATION OF EXTERIOR LIGHTING

Pierantonio Cinzano[1], Fabio Falchi[1], Diego Bonata[2]

1. ISTIL, Light Pollution Science and Technology Institute, Thiene, Italy
2. CieloBuio, Coordinamento per la protezione del cielo notturno, President

Light pollution is the alteration of the natural light levels in the night environment produced by introduction of artificial light. Due to the continuous growth of nighttime artificial lighting, this problem is every day more debated and fought with laws and regulations. Main prescriptions to limit the effects of light pollution on the night sky and the night environment are well known and applied:
1) avoid that fixtures of lighting installations send any light directly above the horizon, with particular care to cut the light emitted at low elevations (in the range °=90-135 degrees from the downward vertical, i.e. 0-45 degrees above the horizon plane). In facts this light propagates far and enhance the additive property of light pollution, an effects tremendously effective especially in densely populated territories.
2) avoid to waste downward light flux outside the area to be lit, because this is not only a main cause of increase of the installed flux per unit surface (and in turn a main cause of increase in the energy expense), but this light is also reflected upward from these surfaces. Even if lambertian diffusion from horizontal surfaces is less effective in sending light at low elevations than direct emission by fixtures, nevertheless when this last is eliminated, it remain a not negligible source of pollution.
3) avoid overlighting, i.e. avoid luminances or illuminances larger than those requested by security rules, or shut-off lights when the area is not in use or dim lights when the kind of use allows it.

These prescriptions must be implemented over large territories to be effective. In fact, light propagates at hundreds of kilometres. In diffusely urbanized areas the artificial sky brightness due to sources outside a certain radius decrease very slowly with the increasing of the radius (with $r^{-0.5}$). A typical case is given in fig. 1 where it is shown the contribution of all the sources outside a given distance from the observer. To cut in half the artificial sky brightness all the lights in the inner twenty kilometres should be shut off. In regions where the artificial sky brightness is 6 times the natural one this means that the total sky luminance remains 4 times the natural one (three times due to the artificial component and one due to the natural). This is still an heavy polluted sky! Things are still worse, because it is not possible to shut off all the lights. This implies that to protect the night sky it is mandatory to use effective regulation (such as specified on the three points above) over all the territory, not only in limited zones around observatories.

Contribution of direct light vs. reflected one

The effect of light pollution on the night sky depends on the emission direction of the light. Artificial sky brightness around zenith is greatly due to the sum of the contribution of light emitted at low angles above the horizon from sources in a large surrounding area. For example, at 20 km from a source, about 95% of zenith artificial sky luminance is due by light emitted at 0° to 45° above the horizon and about 50% is due to light emitted at 0° to 20°.

The upward light flux ratios, commonly used to compare these emissions, are quantities integrated on the upward hemisphere. They are not proper parameters to compare light pollution by roads, luminaries and other surfaces, and the effects on the night sky.
Given that roads pavements, other surfaces and luminaries have different intensity distributions, the integrated fluxes can be misleading, if the direction of emission is not in some way accounted.
In order to limit the artificial sky brightness it is necessary to limit the light intensity of the fixtures above the horizon plane in order it to be negligible in respect to the intensity of the lighted surfaces, and especially so at low angles above the horizon.
Using the software Roadpollution developed by Cinzano it is possible to obtain a precise evaluation of the intensity due to the fixtures and that due to the street, as seen in fig.2. It is immediately evident that the road emits primarily at high angles, producing light pollution at local level, while the emission of the luminarie is high at low angles, producing light pollution over large territories. In order to limit the unnecessary light pollution due

to the direct emission of the luminarie, their intensity should be limited to less than 10% of that emitted by the roads at the same angles.
Table 1 shows the mean intensity of 21 different roads at three angles above nadir (i.e. 95° means 5° above the horizon). The given intensity is the longitudinal one, the transversal one is far lower. This shows that in order to keep the intensity of the luminaries lower than 10% of that of the streets a limit of 0.2 cd/klm should be adopted.

Angle	95	100	110
Mean longitudinal light intensity (cd/klm)	2.0	4.0	7.8

Table 1

In fig.3 it is shown a comparison of the intensity due to the direct emission by the luminaries allowed by some laws (yellow) and the intensity of the road (cyan) at 90 to 110 degrees above nadir (0 to 20 above the horizon). Note that the fraction form the roads is the longitudinal one, so that averaging in all the direction the road contribute will be far lower. Our proposal of 10% of the intensity of the road is in the upper left graph while the intensity allowed by Lombardy law is the upper centre graph. Fig. 4 shows the same data as a ratio between the two intensities. It is self evident that it is not possible to allow for limits larger than the Lombardy law one, if the aim is to control light pollution. Fortunately today almost all the installation can satisfy the Lombardy limit, as shown in fig. 5.
Even with the very high demanding uniformity criteria in European technical rules today it is possible to install flat glass fixtures at pole spacing of 5 times the height. A new software was developed by Diego Bonata to help optimizing the design: Easy Light.

Easy Light- Save the Sky

Easy Light- Save the Sky is a design optimizing software (fig.6). Given certain design parameters (say mean luminance and uniformity criteria, dimensions of the road) it optimizes the height and distance of the poles, overhang of the fixture in order to obtain the better designs possible for a given fixture. The results are displayed in a spreadsheet form where they can be ordered choosing several parameters (like: pole height, pole spacing, pole spacing/pole height, installed power per unit length, area, annual consumption per km and several others). See fig. 7. In the latest version of Easy Light it is possible to optimize the parameter with several different fixtures (even hundreds) at a time. Given a number of fixtures Easy Light can chose the best for a particular purpose comparing thousands of design, while a human designer stops after tens!
An example of the results obtainable is shown in table 2. The calculus was made for a 7 m wide road with two lanes, fixtures on one side only of the road, mean luminance 1 cd/m^2, general Uniformity 0.4 and longitudinal Uniformity 0.5.

Altezza Sostegno [m]	Sbraccio [m]	Lm [cd/m^2]	Ul	Uo	Interdistanza [m]	I/A	Pmin [W/km]	Pali x km [N°]
Pippo 70W								
5	0.5	1.02	0.4	0.57	18	3.6	3.9	56
Pippo 100W								
7	1	1.01	0.46	0.65	30.5	4.36	3.28	33
8	0.5	1.01	0.46	0.76	28	3.5	3.57	36
Pippo 150W								
7.5	0	1.01	0.4	0.53	41.5	5.47	3.66	25
7.5	0.5	1.04	0.41	0.51	41	5.53	3.61	25
Pluto 150W								
7.5	0	1.01	0.43	0.53	44.5	5.93	3.37	23
Pluto 250W								
11	0.5	1.06	0.54	0.5	56	5.09	4.46	18
Pluto 400W								
15.5	0.5	1.01	0.55	0.5	71.5	4.51	5.59	14

Table 2

The name of the fixtures are fantasy ones, but behind there are real luminaries with real photometric data. All the fixtures are fully shielded one (they complain to the 0.49 cd/klm at 90° and above of some Italian regional laws). There is no single best fixture. The 'best' depends on what is the aim of our designer. If one seeks for the fewer poles 'Pluto 400W' wins with only 14 poles per road km, with a pole spacing (interdistanza) of more than 70 m. If one seeks for the lowest possible installed power 'Pippo 100W' wins with 3.28 kW/km. The highest ratio between pole spacing and pole height (I/A) is an outstanding 5.93 value of 'Pluto 150W'.
Sometimes I hear that prismatic glass type fixtures allow for more pole spacing that the flat glass one (by the way, note that Italian laws do not force to use a flat glass, they give only an intensity limit at and above the horizon). In Italy I've never seen new installation with prismatic glass with a so high spacing. It is frequent to see pole spacing under 3 times the pole height. To be honest, all fixtures are installed with short pole spacing, even if it is possible to put them far apart one from the other (design error? Need to sell more fixtures?).

Residual light pollution

After having enforced the three prescription given earlier (fully shielding fixtures, avoiding outside of target and of time light, avoiding overlighting) some upward light emission remain, due to the reflection from the properly lighted surface.
This is a necessary by-product of the lighting operation: lighting is made just to produce a reflection of light. However, after having carried out its tasks the lights is dispersed into the environment. Due to its Lambertian behaviour, this reflection is frequently less effective at low elevations than at large elevations, so that the effect on the night sky tends to be confined in the nearby of the source. In any case, the environmental impact of this light, that we call "residual light pollution", cannot be neglected.
The limitation of this residual pollution requires to limit not only "how" nighttime lightings is made, but also "how much" nighttime lighting is made. Typically it has been proposed to limit the growth rates of the installed flux in each city or to limit the average density of the installed light flux (e.g. the installed flux per acre). However there is another way to limit this residual pollution: the use of those light sources which spectral emission has the smaller impact on the star visibility and the greater one
on the visibility in areas with artificial lighting. This would allow to reduce the negative effects on the first without limiting the useful flux for lighting purposes.
The possibility of limiting the residual light pollution, avoiding the need to limit nigh time outdoor lighting itself, is based on the different response with wavelength of the two main classes of eye receptors. In a schematic way we can distinguish the photopic response of cones and the scotopic response of rods. The eye response is fully photopic, i.e. cones fully determine it, for luminances over 3 cd/m^2 whereas the eye response is fully scotopic, i.e. rods fully determine it, under about 0.01 cd/m^2. In the range between these two limits, called mesopic, the eye response goes from scotopic to photopic in depending on the relative contribution of the two classes of receptors which in turn depends on the luminance (fig.8). Standard rules, e.g those on road safety lighting, usually requires from 0.3 to 2 cd/m^2 but, even where laws against light pollution require not to use lighting levels larger than prescribed by security rules, in practice new installations rarely have an average maintained luminance under 1 cd/m^2. Even due to the logarithmic dependence of the eye response with the intensity of the stimulus, at these luminances the response is predominantly photopic (see discussion below). In fact when we look to artificially lighted outdoor areas our eye recognizes colours, which is a property of cones. Otherwise, we could use everywhere monochromatic lamps like Low Pressure Sodium lamps and there will be no reason to use white light.
In the observation of the starry sky, at natural luminances of the order of 2 x10^{-4} cd/m^2, the response is scotopic (excluding when looking to few luminous stars). So this difference give us the fundamental key to spectrally separate the primary polluting effects of the light from its lighting capabilities. Unfortunately the scotopic and photopic response curves overlay in part. This prevent us to fully separate these two effects. This means that we cannot use the spectra of lamps to limit light pollution in place of fully-screened fixtures and the other prescriptions.
Even monochromatic lamps emitting at the maximum of photopic response, like e.g. LPS lamps, contribute consistently to the scotopic response pass band. So the prescriptions previously given are not avoidable. However we can use this different response to diminish the polluting effect of the residual pollution, after that we already applied at best all the possible cares to limit the effects of light pollution.
Our proposal to limit the effect of residual light pollution on the sky (and to prevent the strong growth of artificial night sky brightness which would be produced by a migration from the actual population of HPS lamps to MH or LED lamps, which white light is really necessary only in a limited number of cases) is:

The wavelength range of the visible light spectrum between 440 and 540 nanometres, corresponding to the maximum sensitivity of the scotopic vision of the human eye, is a protected range. It is forbidden any use for outdoor nighttime lighting of lamps (a) emitting in this wavelength range an energy flux larger than 15 per cent of the energy flux emitted in the photopic response passband, measured in watt, or, in any case, (b) emitting in the scotopic response pass band a luminous flux larger than two thirds of that emitted in the photopic response passband, measured in lumens.

REFERENCES

Bonata, D. 2003, Save the Sky: un nuovo modo per affrontare la progettazione illuminotecnica stradale, ControLuce, http://www.cielobuio.org/supporto/luce/luce.htm

Cinzano, P. Diaz Castro, F.J. 2000, in Measuring and Modelling Light Pollution, ed. P. Cinzano, Mem. Soc. Astron. Ita., 71, 1, 251-256.

Cinzano, P, Roadpollution: a software to evaluate and understand light pollution from road lighting installations, in prep.

Falchi, F. Cinzano, P., Limiting the impact of residual light pollution on stellar visibility, in prep.

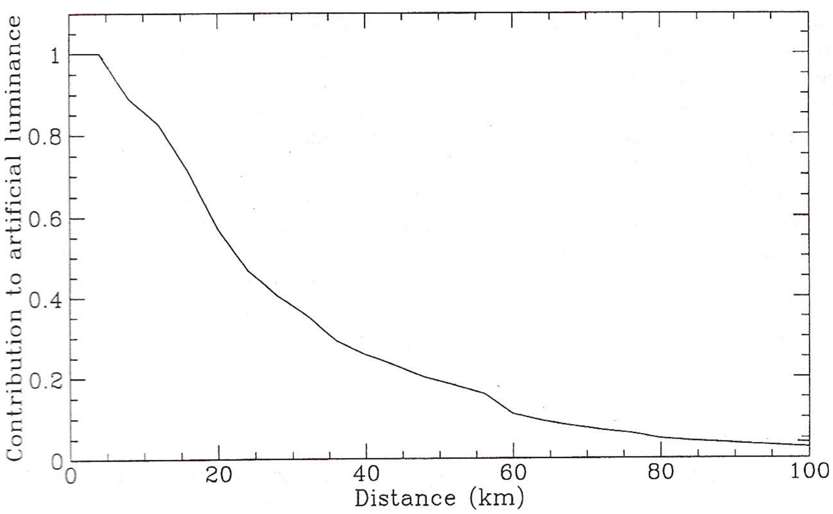
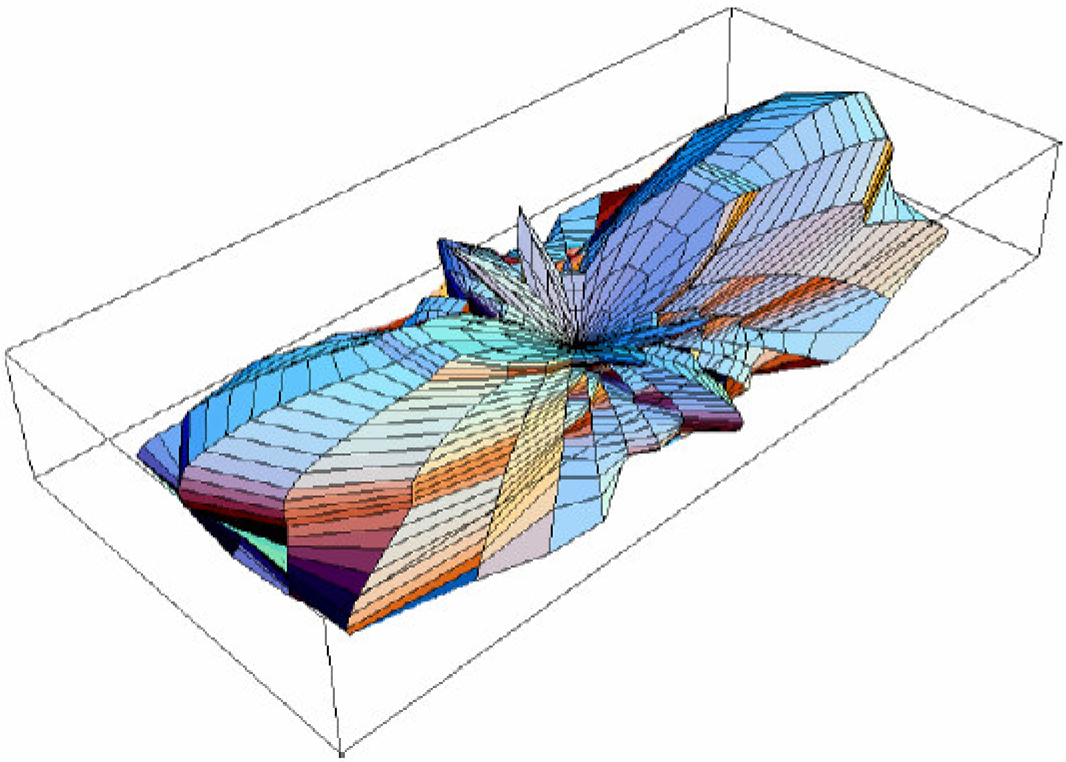
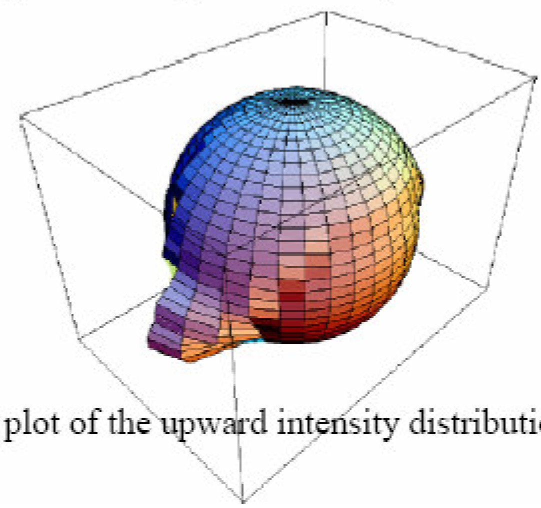


Fig.1



Example of 3D polar plot of the upward intensity distribution of a luminaire.



Example of 3D polar plot of the upward intensity distribution of a road.

Fig.2

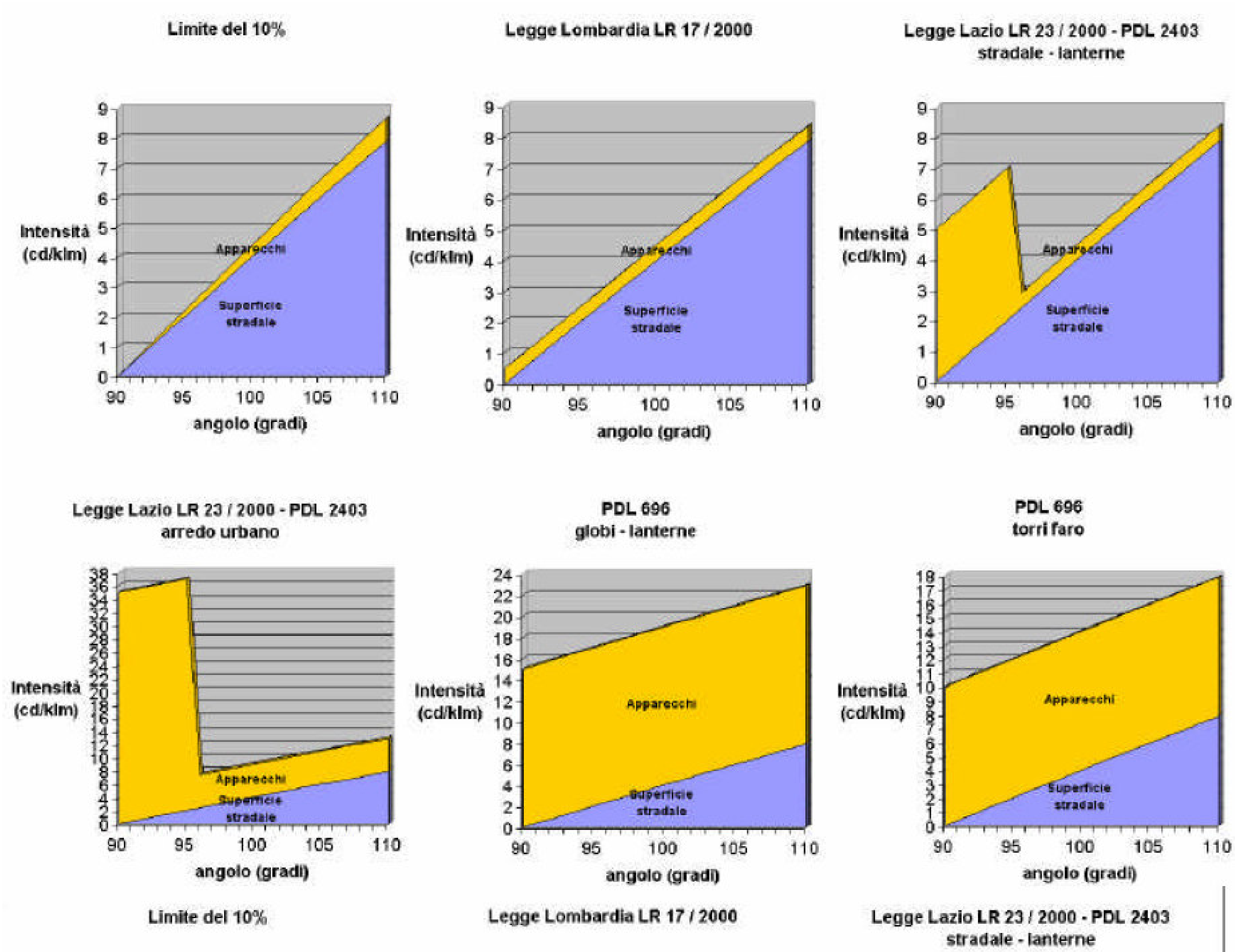

Limite del 10%
Legge Lombardia LR 17 / 2000
Legge Lazio LR 23 / 2000 - PDL 2403
stradale - lanterne
Legge Lazio LR 23 / 2000 - PDL 2403
arredo urbano
PDL 696
globi - lanterne
PDL 696
torri faro
Intensità (cd/klm)
angolo (gradi)
Apparecchi
Superficie stradale
Limite del 10%
Legge Lombardia LR 17 / 2000
Legge Lazio LR 23 / 2000 - PDL 2403
stradale - lanterne

Fig.3

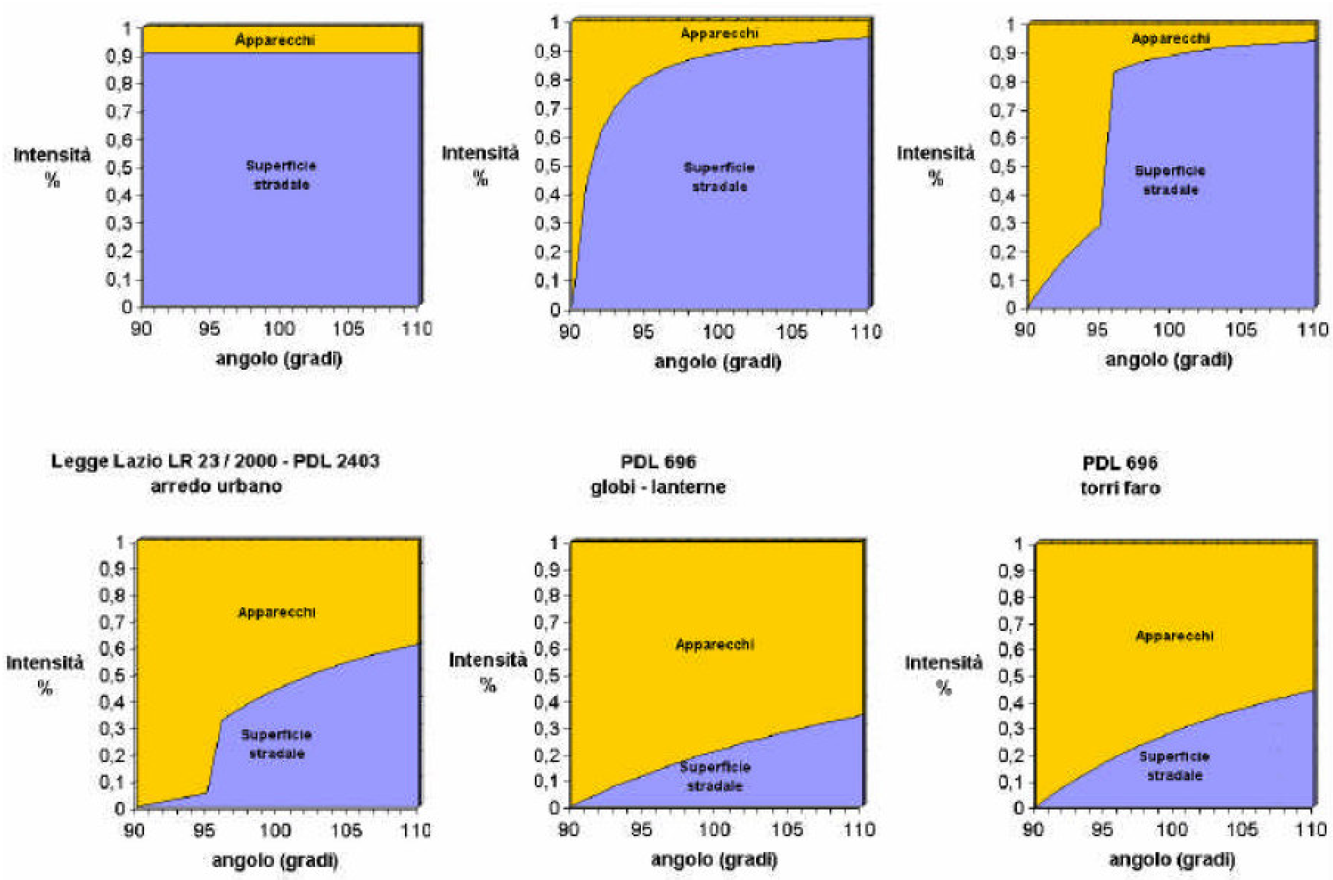

Apparecchi
Superficie stradale
Intensità %
angolo (gradi)
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
90
95
100
105
110
Legge Lazio LR 23 / 2000 - PDL 2403
arredo urbano
PDL 696
globi - lanterne
PDL 696
torri faro

Fig.4

Fig.5

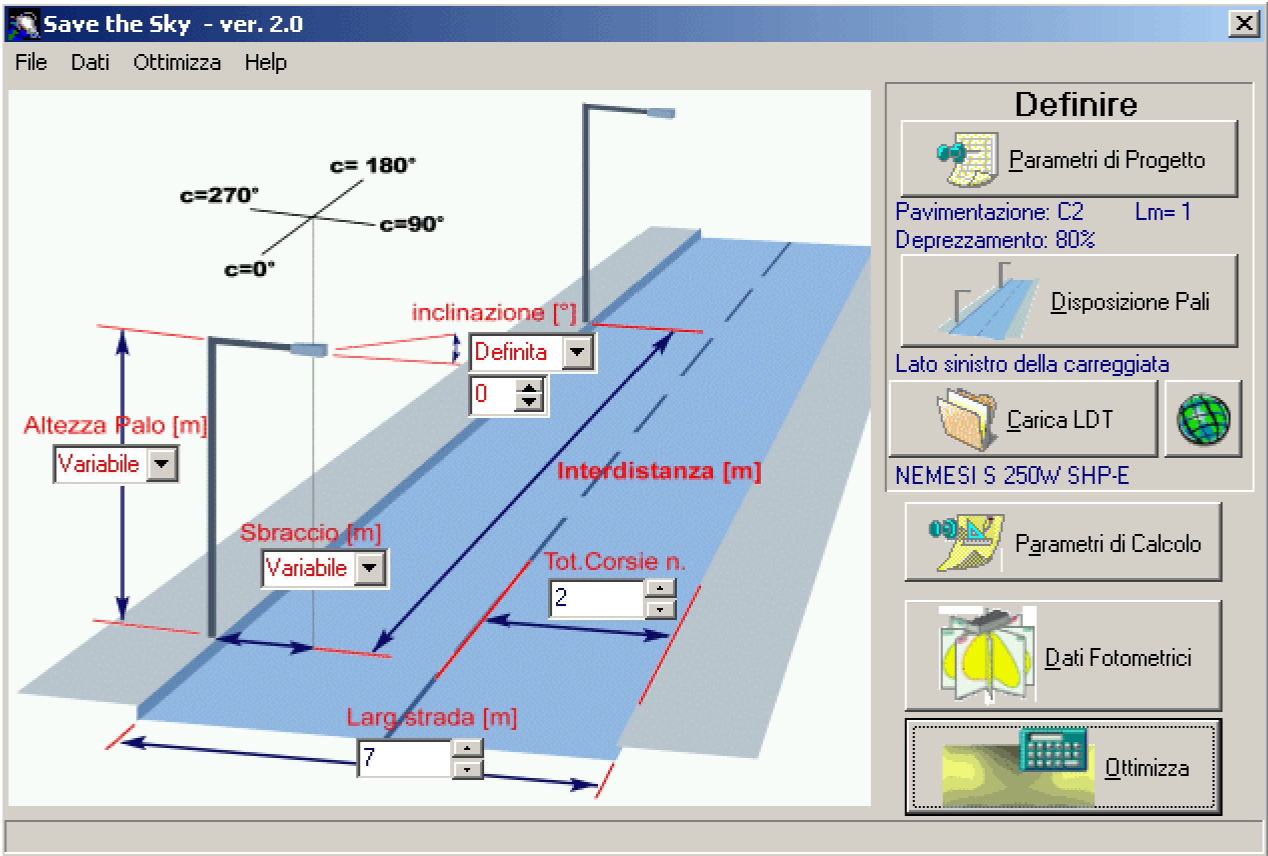
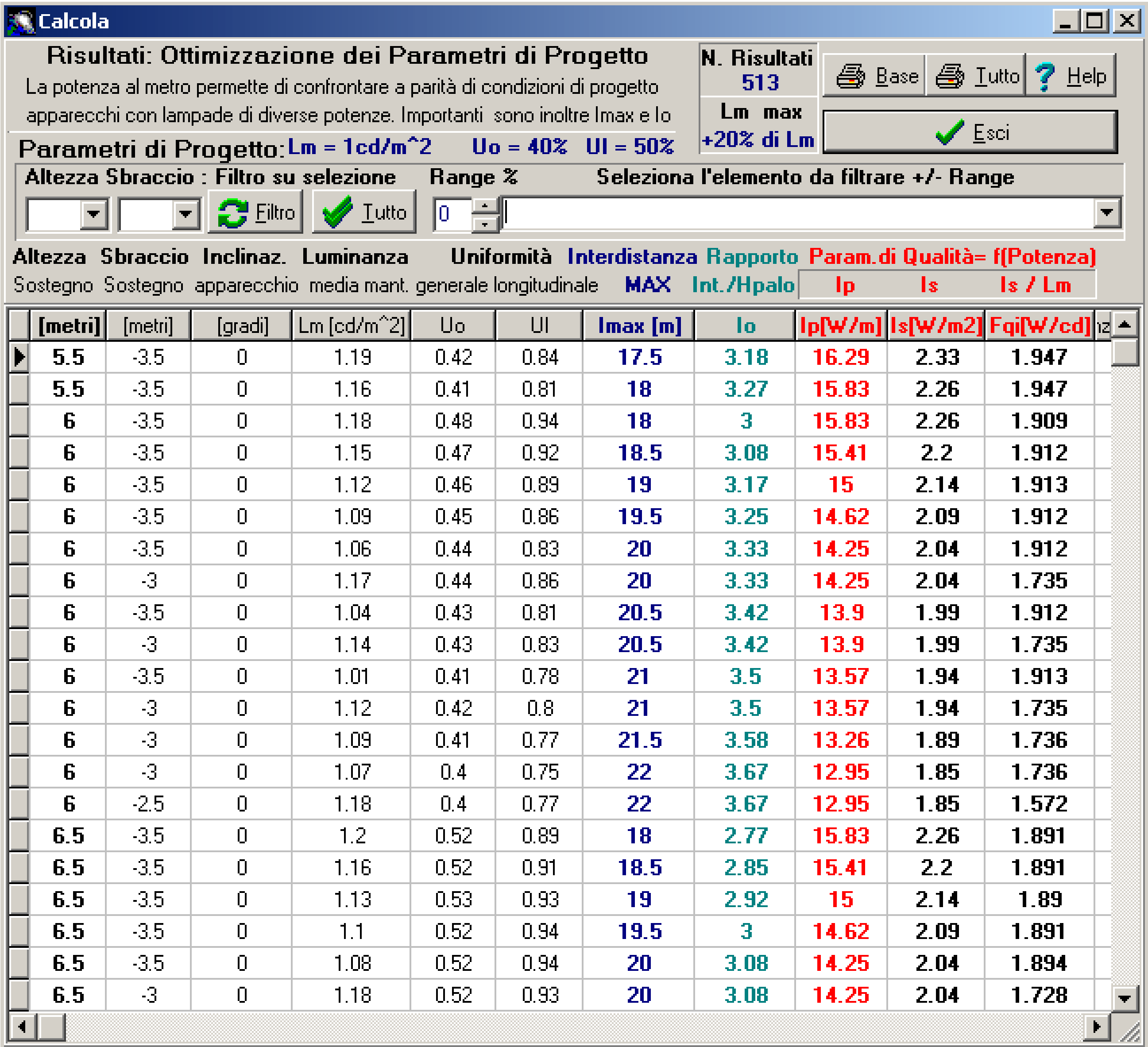

Save the Sky - ver. 2.0
File
Dati
Ottimizza
Help
c= 180°
c=270°
c=90°
c=0°
inclinazione [°]
Definita
0
Altezza Palo [m]
Variabile
Interdistanza [m]
Sbraccio [m]
Variabile
Tot.Corsie n.
2
Larg.strada [m]
7
Definire
Parametri di Progetto
Pavimentazione: C2
Lm= 1
Deprezzamento: 80%
Disposizione Pali
Lato sinistro della carreggiata
Carica LDT
NEMESI S 250W SHP-E
Parametri di Calcolo
Dati Fotometrici
Ottimizza

Fig.6



Altezza Sostegno [metri]	Sbraccio Sostegno [metri]	Inclinaz. apparecchio [gradi]	Luminanza media mant. Lm [cd/m^2]	Uniformità generale Uo	Uniformità longitudinale Ul	Interdistanza MAX Imax [m]	Rapporto Int./Hpalo Io	Param. di Qualità= f(Potenza) Ip Ip[W/m]	Is Is[W/m2]	Is / Lm Fqi[W/cd]
5.5	-3.5	0	1.19	0.42	0.84	17.5	3.18	16.29	2.33	1.947
5.5	-3.5	0	1.16	0.41	0.81	18	3.27	15.83	2.26	1.947
6	-3.5	0	1.18	0.48	0.94	18	3	15.83	2.26	1.909
6	-3.5	0	1.15	0.47	0.92	18.5	3.08	15.41	2.2	1.912
6	-3.5	0	1.12	0.46	0.89	19	3.17	15	2.14	1.913
6	-3.5	0	1.09	0.45	0.86	19.5	3.25	14.62	2.09	1.912
6	-3.5	0	1.06	0.44	0.83	20	3.33	14.25	2.04	1.912
6	-3	0	1.17	0.44	0.86	20	3.33	14.25	2.04	1.735
6	-3.5	0	1.04	0.43	0.81	20.5	3.42	13.9	1.99	1.912
6	-3	0	1.14	0.43	0.83	20.5	3.42	13.9	1.99	1.735
6	-3.5	0	1.01	0.41	0.78	21	3.5	13.57	1.94	1.913
6	-3	0	1.12	0.42	0.8	21	3.5	13.57	1.94	1.735
6	-3	0	1.09	0.41	0.77	21.5	3.58	13.26	1.89	1.736
6	-3	0	1.07	0.4	0.75	22	3.67	12.95	1.85	1.736
6	-2.5	0	1.18	0.4	0.77	22	3.67	12.95	1.85	1.572
6.5	-3.5	0	1.2	0.52	0.89	18	2.77	15.83	2.26	1.891
6.5	-3.5	0	1.16	0.52	0.91	18.5	2.85	15.41	2.2	1.891
6.5	-3.5	0	1.13	0.53	0.93	19	2.92	15	2.14	1.89
6.5	-3.5	0	1.1	0.52	0.94	19.5	3	14.62	2.09	1.891
6.5	-3.5	0	1.08	0.52	0.94	20	3.08	14.25	2.04	1.894
6.5	-3	0	1.18	0.52	0.93	20	3.08	14.25	2.04	1.728

Fig.7

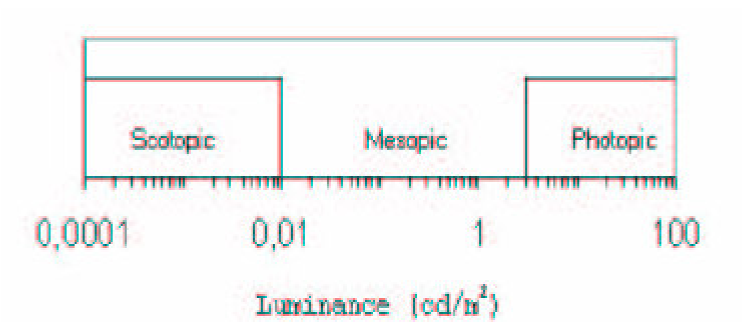


Fig.8