Sustainable environmental compatibility of road lighting assured through the minimization of energy consumptions
An instrumented drone measures the upward spill light
A report of the Italian NC to CIE Divisions 4 and 5 - Paris, 2013

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0 Summary

This document reports the results of an experimental research carried out in Italy, aimed at the reduction of the negative effects of road lighting on the environment, about both the obstacles to astronomy (luminous flux emitted/reflected upward) and the energy consumptions (costs for the citizens and emissions of greenhouse gases by the power plants).

The results of the measurements with flat and shallow glass luminaires equipped with HID lamps and LEDs (see table 0.1), show that the upward emissions of the luminaires (ULOR) are much lower than the reflections of the illuminated surfaces, which practically behave like uniform diffusers. The results, which are in full agreement with the previous measurements carried out on lit towns, are valid for all types of luminaire in all types of installation and confirm, the higher consumptions of the cut-off luminaires, due to the Brewster's inside reflections of the flat glass, and the role of the installation luminance factor $q_{inst} = L / (Q_0 \cdot E)$ is demonstrated in the evaluation of the environmental compatibility, both during the design stage and at the verification on realized installations.

Road lighting installations - Upward emissions and reflections								
Elevation range [°]	**ULOR and total upward flux / flux of the source [%]**							
	Metal halide				**LED**			
	Flat glass		**Shallow glass**		**Flat glass**		**Shallow glass**	
	ULOR	**Total**	**ULOR**	**Total**	**ULOR**	**Total**	**ULOR**	**Total**
0-20	0,07	1,60	0,10	1,70	0,15	1,50	0,40	1,70
20-90	0,06	13,2	0,10	13,3	0,16	11,9	0,20	11,5
0-90	**0,13**	**14,8**	**0,20**	**15,2**	**0,31**	**13,2**	**0,60**	**13,2**
ULOR/Total	**0,8%**		**1,3%**		**2,3%**		**4,5%**	
Cuitoff Cons.	**+16%**		**-**		**+26%**		**-**	
q_{inst}	**0,95**		**1,12**		**1,04**		**1,19**	

Table 0.2 reports effects of some lighting arrangements/luminaires on the limiting magnitude ΔM_{TH} and on installed power.:

Table 0.2 **Increment of limiting magnitude vs ULOR and energy consumptions**			
Characteristics of the installation	$\Delta\Phi / \Phi$ **[%]**		**Limit. nag.**
	ULOR	**Energy**	ΔM_{TH} **[ma]**
Shallow glass lumin.*ULOR*=3%, q_{inst} = 1,0	Reference		
Flat glass luminaires	-3	20	-0,17
Reduction of 1 class in CIE 115	-	-25	0,25
Reduction of 2 classes in CIE 115		-50	0,44
q_{inst} = 0,85 (typical of cutoffs)		18	-0,18
q_{inst} = 1,10 (typical of shallow glass)		-9,1	0,09
q_{inst} = 1,20 (typical of good shallow glass)		-17	0,17

Conclusions and proposals are summarized below.

- In road lighting, the value of *ULOR* is much lower than the reflection factor of the illuminated surfaces and cannot contribute significantly to the artificial sky luminance.
- It is thus useless and even detrimental for the environment to prescribe *ULOR*=0, like in CIE publication 150: the prescription *ULOR*≤0,03 of the European regulation 245 permits the lowest energy consumption without impairing the astronomic observations.
- The only way for improving the astronomic observations is to reduce the prescription of road luminance in CIE 115 in the zones close to the observatories (see table 0.2), assuring the safety of road users through alternative subsidiary means, like higher lighting levels at the intersections and on the pedestrian crossings, while moreover calling the attention of the drivers with conspicuous internally illuminated signs, which in some case, e.g. when conflict traffic does not exist like in the highways (see figure 9.1), could replace completely the lighting installations, with a considerable advantage in foggy weather because of the absence of the veiling luminance generated by the luminaires.

Consequently, the draft of the new CIE 150 should be completely revised, together with CIE 115, introducing special prescriptions at low distances from international observatories.

The outcome of this research can be expressed in a short sentence:

The necessary and sufficient condition for assuring the sustainable compatibility of road lighting with the environment is the minimization of the consumption of energy and of the installed luminous flux, the only condition being the compatibility with the safety of the road users.

1 Environmental compatibility of road lighting - Laws and CIE publications

In order to reduce the negative side effects of road lighting for astronomy on one side and energy consumptions on the other, some laws (e.g. [1]), regulations (e.g. [2] and technical publications (e.g. [3, 4]) issued in the last decade limited the luminous flux, sometime the luminous intensity, emitted upward by the luminaires (ULOR), considered the sole cause of the artificial sky luminance. The reason is probably more psychological than technical: at far distance, the luminaires, being small, are perceived according to the illuminance they generate on the pupil and appear brighter and more disturbing than the roads, dark but larger (figure 1.1), perceived according to their luminance, even if the reflections of the roads are higher than the emissions of the luminaires.

In order to reduce the negative side effects of road lighting for astronomy on one side and energy consumptions on the other, some laws (e.g. [1]), regulations (e.g. [2] and technical publications (e.g. [3, 4]) issued in the last decade limited the luminous flux, sometime the luminous intensity, emitted upward by the luminaires (ULOR), considered the sole cause of the artificial sky luminance. The reason is probably more psychological than technical: at far distance, the luminaires, being small, are perceived according to the illuminance they generate on the pupil and appear brighter and more disturbing than the roads, dark but larger (figure 1.1), perceived according to their luminance, even if the luminous flux reflected by road surfaces is higher than the upward emissions of the luminaires.

This is the real point: looking at a light source, attention should be paid not at its visibility but at its effects on sky luminance.

Figure 1.1 Road reflections much higher than the emissions of the luminaires

This was actually the approach of CIE Divisions 4 and 5 in publication 126 [3] and 150 [4], which in critical zones prescribe 0 upward emissions (actually, cutoff luminaires), with no attention for the higher upward reflections and energy consumptions of cutoffs.

2 Objectives

The measurements recently carried out in Italy by INRIM [5], the National Metrological Laboratory, and AIDI [6], the Italian Lighting Association, are coherent with the measurements on lit towns [7, 8], clarifying the influence of the factors relevant to the negative effects of road lighting.

The objectives of the research were:

- to measure the influence of the components of road lighting installations on the environmental compatibility, for both the obstacles to astronomy and the consumption of energy;
- to identify the parameter(s) for evaluating the compliance of a lighting installation, at the design stage and for the photometric verification of a realized installation, with both the safety of road users and the environment;
- to verify the agreement of calculations with measurements;
- to aim at general results valid for any luminaire installed in any arrangement.

3 Measurement setup

Some measurements of both the upward spill light of the road lighting and of the reflections of the lit surfaces were carried out on 4 pilot installations, with cutoff and shallow glass luminaires and with metal halide lamps and LEDs.

Each luminaire was used in four pilot installations in a two lane road in Mercallo con Casone, close to Milan, with the aim of measuring the average road illuminances and luminances (figure 3.1): the CIE 115 class was M3, the height of the luminaires 8 m and the spacing was optimized for the lowest energy consumption. The measurements were carried out through normal luxmeters and luminancemeters, according to EN 13201-4.

Then, one luminaire for each type described above was installed at the premises of INRIM in Turin, again on a stretch of a two lane road with some grass on each side (figure 3.2). In this way, the measurements can be easily extended to installations composed by any number of that luminaire placed in any position. A small helicopter equipped with a visual luminancemeter, flew repeatedly over the installations performing measurements at different heights.

Figure 3.1 A pilot installation at Mercallo con Casone

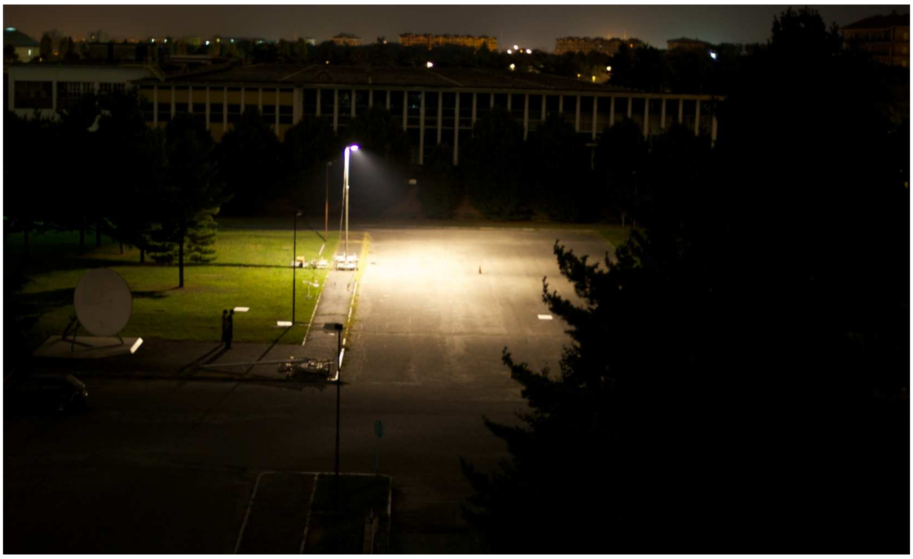

Figure 3.2 A single luminaire installation at INRIM in Turin

4 Measurement results and evaluations - Installed luminance factor

The characteristics of the pilot installations are shown in table 4.1, together with the average luminance/illuminance, the installed power, the spacing and the installation luminance factor $q_{inst}=L/(E \cdot Q_0)$, a parameter described at point 6, i.e. what should be measured at the ground level according to the standard EN 13201-4 and perceived by drivers and pedestrians at the ground level.

Table 4.1 shows the results of the measurements: the data on the lighting installations were calculated extending the measures to an indefinite number of the same luminaires, all installed on the edge of the road at the reported spacing with the height of 8 m and the spacing reported in table 4.1.

5 Measurement results and evaluations

The spill luminous flux emitted upward by the luminaires and reflected upward by the illuminated surfaces was measured from above for each single luminaire installation in Turin. Each installation was then evaluated like a virtual light source with the axis oriented upward placed on the road surface at the foot of the luminaire. It was thus possible to calculate the luminous intensity distribution, i.e. the distribution matrix, of the virtual source in the CIE (C,γ) space, simulating completely the spill light for all emission and reflection angle: figure 5.1 shows the luminous intensity distribution on a C plane, which shows a clear diffusing character with a reflection factor of 0,12-0,15.

Due to this diffusing property, from the installed flux and the average reflectance of the lit surfaces, the upward reflections in the range (β_1, β_{20}) are:

$$\Phi_{1,2} = \rho\, \Phi_{inst} \left[\sin^2 \beta_2 - \sin^2 \beta_1\right] \qquad (5.1)$$

for verifying the influence of an installation in the actual orography.

Table 4.1 - Measurement results

Lighting installation with a single luminaire
Upward emissions and reflections

Elevation range [°]	ULOR and total upward flux / flux of the source [%]							
	ULOR	Total	ULOR	Total	ULOR	Total	ULOR	Total
0-20	0,07	1,6,0	0,10	1,70	0,15	1,50	0,40	1,70
20-90	0,06	13,2	0,10	13,3	0,16	11,9	0,20	11,5
0-90	**0,13**	**14,9**	**0,20**	**15,2**	**0,60**	**13,2**	**0,60**	**13,2**
ULOR/Total	**0,8%**		**1,3%**		**2,4%**		**4,5%**	

Installation with an indefinite number of luminaires

Installation data				
Source	**Metal halide**		**LED**	
Glass	piano	curvo	piano	curvo
Spacing [m]	**33**	**37**	**33**	**37**
Luminaires/km	30,3	37,0	30,3	37,0

Measurements and calculations

Light source	Glass	Illumin. [lx]		Lumin. [cd/m²]		Fatt. lumin. q_R		Costs cutoff
		means.	calcul.	means.	calcul.	means.	calcul.	
metal halide	flat	15,0	16,0	1,22	1,06	1,10	**0,95**	**+16 %**
	shallow	13,7	14,0	1,10	1,10	1,19	**1,12**	**-**
LED	flat	15,8	15,9	1,46	1,16	1,27	**1,04**	**+26 %**
	shallow	14,7	15,8	1,47	1,31	1,43	**1,19**	**-**

Some comments are in order.

- Measured and calculated illuminances are in good agreement, authorizing the extension of the results to all installations according to the calculations.
- ULOR of cutoff luminaires (table 5.1) is due to the reflections of the columns.
- The relative upward luminous flux (ULO) emitted by the luminaires is very low, 5-10% of the total luminous flux emitted and reflected upward: actually, the reflections always prevail.
- The differences between calculated and measured luminance are probably due to the great sensitivity of the luminaires to the orientation during the installation and/or to the difference between the reflection matrix of the road surface used in the calculations and in the measurements. For this reason, the evaluation of the costs was based on the calculated luminances.
- Installations with cutoff luminaires need more columns than the curved glass luminaires and require a higher installed power, with higher energy management costs.
- The comparison of the costs for installation and energy is referred to a road luminance of 1 cd/m^2.
- Light pollution is higher with cutoff luminaires, which emit and reflect upward a higher luminous flux.

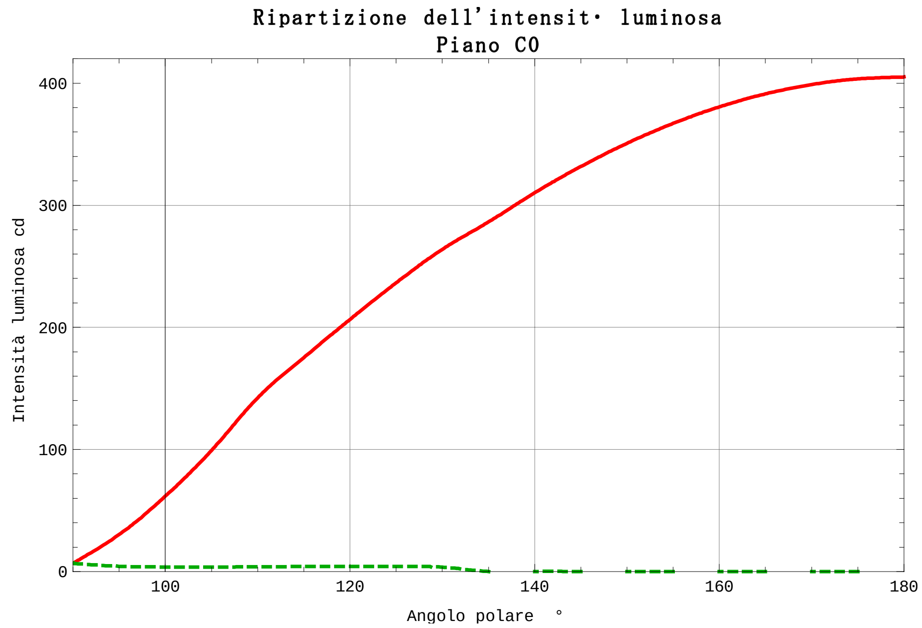

Figure 5.1 A C-meridian of a virtual luminaire for the simulation of the total luminous flux emitted and reflected upward by a luminaire

6 Installed luminance factor

The importance of the installation luminance factor q_{inst} can be understood considering that a high value for this factor involves a road luminance generated with a low illuminance, which means low values of both energy consumptions and which means lower energy consumptions and low light reflected upward, the main cause of the artificial sky luminance.

The "effectiveness" of q_{inst} as an indicator of the compatibility with the environment, energy included, is demonstrated in figure 7.1, where the correlation of this factor with the luminous flux emitted and reflected upward and the installed power of a number of road lighting installations is shown.

For good environmental compatibility q_{inst} should be higher than 1,10.

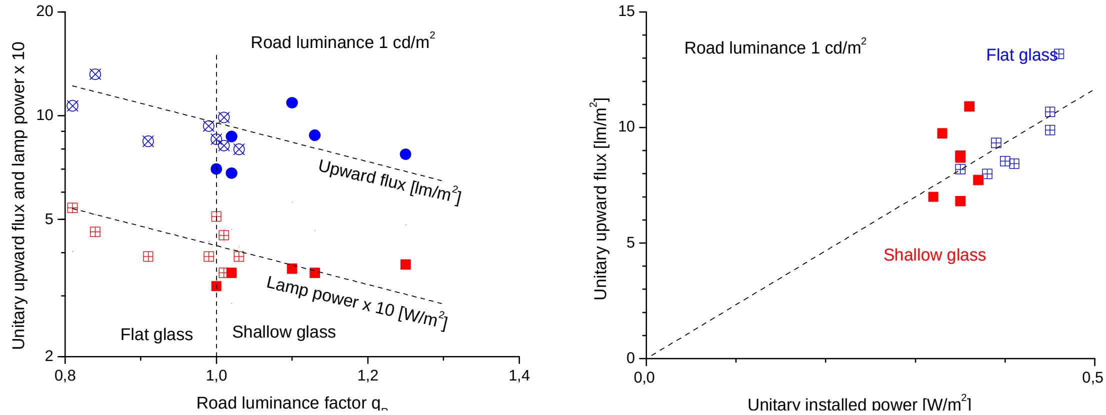

Figure 6.1 UPF_L versus q_{inst} and lamp power: the shallow glass luminaires adsorb less energy. The open crossed symbols refer to horizontal flat glass luminaires, the full symbols to shallow glass ones.

7 Validity of the results for all road lighting installations

The four installations submitted to measurements in the research should be considered only non limiting examples. Actually, the conclusions reported at section 5 are valid for all road lighting installations independently of the characteristics of the luminaires, of their positions, their height and spacing, etc., for the following reasons.

Uniform diffusion of the lit surfaces. If a surface is found to behave like a uniform diffuser, it behaves in the same way for all light source and for any direction of incidence of the light. It is thus possible to calculate the emissions for different elevation ranges from the installed flux and the reflection factor

Values of ULOR much lower than the reflection factor of the illuminated surfaces. According to the state of the art technology, the lamp is deeply recessed into the reflector in order to maximize the luminous flux collected and reduce consequently the energy consumptions. Figure 7.1 shows that shallow glasses avoid the internal reflections of flat glasses, increasing in this way the efficiency. The lamp is not visible at low elevations: there is no direct upward emission by the lamp, but only a diffusion when the light beams cross the glass. This research shows that ULOR plays no practical role in the generation of the artificial luminance of the sky, since, for all state of the art luminaires, its value for both flat and shallow glass luminaires is negligible with reference to the reflection factors of the lit surfaces, which on the contrary are quite high.

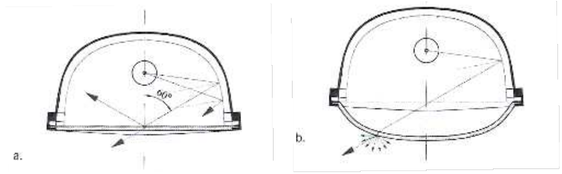

Figure 7.1 The internal reflections of flat glass luminaires (cut-off) and the upward light of shallow glass luminaires due to the diffusion of the light crossing the glass with no direct upward emission

Higher consumptions and upward emissions and reflections for flat glass luminaires. The internal reflections of the flat glass at the grazing incidence necessary for obtaining the highest efficiency reflections from the road surfaces, reduce the efficiency of a flat glass luminaires and require a higher number of columns. This is a problem for all flat glass luminaires.

Lower consumptions and upward reflections with higher values of q_{inst}. This is due to the correlation of illuminance with the installed power and with the upward reflections, which gives to q_{inst} a general valence for all installations.

8 Concluding remarks

This research confirms the measurements carried out on lit towns form a hill by a number of scientists [8, 9, 10] and the evaluations reported in 1973 by Waldrum [7] on the diffusing character of a lit village. Two main points emerge clearly form the measurements:

- the environmental compatibility involves each road lighting installation and not only the luminaires;
- the installation of cut-off luminaires is not only more expensive, but also detrimental, for both astronomy and energy saving.

Table 8.1 (Source: Regulation 245/2008)
Energy and environment conservation for European directive 32/2005

Table 25 of Regultion 245/09	
Indicative maximum Upward Light Output Ratio (ULOR) values per road class for street lighting luminaires (at benchmark level)	
Luminous flux	***ULOR***
Road classes ME1 to ME6 and MEW1 to MEW6, all lumen outputs	
Lumen outputs	*3%*
Road classes CE0 to CE5, S1 to S6, ES, EV and A	
12 000 lm ≤ light source	*5%*
8 500 lm ≤ light source < 12 000 lm	*10%*
3 300 lm ≤ light source < 8 500 lm	*15%*
light source < 3 300 lm	*20%*

In areas where light pollution is of concern, the maximum proportion of the light going above the horizon is not more than 1 % for all road classes and lumen outputs.
Luminaires are designed so that they avoid emitting obtrusive light to the maximum extent.
However, any improvement of the luminaire aiming at reducing the emission of obtrusive light is not to the detriment of the overall energy efficiency of the installation for which it is designed.

This means that the minimization of the consumption of energy assures itself the best environmental compatibility of road lighting: in other words, energy and environment should be approached with the same actions, with the only limit of the safety of the road users and, in the centre of the towns, with a particular attention to the visual comfort and the city beautification.

Consequently, ULOR should be limited only for reducing the energy consumptions: adopting the European Regulation 245 reported in table 8.1, ULOR≤3% is less than 1/5th of the reflection of a single road and about 1/8th of the upward emissions of a lit town.

The only useful action for improving the environmental compatibility is the reduction of the lighting levels, where necessary. However, since the safety of road users should be assured, alternative initiatives should be adopted, like the use of internally illuminated conspicuous signs, an ad hoc illumination of the crossing paths for pedestrians, the reduction of the speed limits, the identification of sidewalks through small lights installed on the walls, etc. keeping the safety levels.

Consequently, the draft of the new CIE 150 should be completely revised, together with CIE 115, introducing special prescriptions at low distances from international observatories.

Table 8.2 reports effects of some lighting arrangements/luminaires on the limiting magnitude ΔM_{TH} and on installed power according to eqn. (8.1):

$$\Delta M_{TH} = -2,5 \cdot \log \left(1 + \frac{\Delta\Phi}{\Phi} \right) \tag{8.1}$$

where Φ is the reference upward luminous flux and $\Delta\Phi$ the increase of the upward reflections, proportional to road illuminance and to the installed power, correlated with energy consumptions through the operating time.

Table 8.2 shows that flat glass luminaires are detrimental for both energy consumptions, 20% more, and for the limiting magnitude of the astronomic observatories, -0,17 mag, even if compared with a shallow glass with *ULOR*=3%, i.e. complying with the European regulation 245 in table 8.1.

Table 8.2 Increment of limiting magnitude vs ULOR and energy consumptions			
Characteristics of the installation	$\Delta\Phi/\Phi$ **[%]**		**Limit.nag.**
	ULOR	**Energy**	**ΔM_{TH} [ma]**
Shallow glass lumin.*ULOR*=3%, q_{inst} = 1,0	Reference		
Flat glass luminaires	-3	20	-0,17
Reduction of 1 class in CIE 115		-25	0,25
Reduction of 2 classes in CIE 115		-50	0,44
q_{inst} = 0,85 (typical of cutoffs)	-	18	-0,18
q_{inst} = 1,10 (typical of shallow glass)		-9,1	0,09
q_{inst} = 1,20 (typical of good shallow glass)		-17	0,17

9 Suggestions for actions

Point 8 leads to some consideration and suggestions as it follows.

- In road lighting, the value of *ULOR* is much lower than the reflection factor of the illuminated surfaces and cannot contribute significantly to the artificial sky luminance.
- It is thus useless and even detrimental for the environment to prescribe *ULOR*=0,like in CIE publication 150: the prescription *ULOR*≤0,03 of the European regulation 245 permit to the lowest energy consumption without impairing the astronomic observations.
- The only way for improving the astronomic observations is to reduce the prescription of road luminance in CIE 115 in the zones close to the observatories (see table 8.2), assuring the safety of road users through alternative subsidiary means, like e.g. higher levels at the intersections and on the pedestrian crossings, and moreover calling the attention of the drivers with conspicuous internally illuminated signs, which in some case, e.g. when conflict traffic does not exist like in the highways (see figure 9.1), could replace completely the lighting installations, with a considerable advantage in foggy weather because of the absence of the veiling luminance generated by the luminaires.

The minimization of energy consumption is the necessary and sufficient condition for the environmental compatibility of road lighting.

Figure 9.1 A light guide can replace illumination without any conflict traffic (courtesy of Autostrade per l'Italia)

Appendix A

Confrontation with previous measurements and evaluations

A.1 Lit towns: single uniform diffusers

As already pointed out some 30 years ago by Waldrum [7] and confirmed by recent measurements [8, 9, 10], illuminated towns behave like single uniformly diffusing sources. Table A.1 reports the luminances of four towns observed at low elevations from far hills, which are in very good agreement with the luminances calculated from the installed luminous fluxes, a condition verified only for uniform diffusers. The reflection factor is in all cases ρ_C=0,23, including a 5th town, where this factor was evaluated by an astronomer. This factor is higher than the value measured in this research, because of the multiple reflections between the buildings (see figure A.1), including the walls of the houses, normally made of clear materials with high reflection factors (table A.2).

Table A.1
Measured and estimated luminances of a lit town seen from a hill

Town	Popul. x 10^{-3}	Distance from hill [km]	Reflected lumin. flux [lm/m^2]	Luminance [cd/m^2] Calc. with ρ_C=0,23	Luminance [cd/m^2] measured at the hill	Refl. fact. calc. from measures
Padova	100	15	2,2	0,26	**0,25**	**0,222**
Abano	20	6,8	1,8	0,36	**0,36**	**0,23,4**
Montegrotto		7,3	2,0	0,40	**0,39**	**0,228**
Torino	1000	15	2,1	0,26	**0,28**	**0,248**
Treviso	80	-				**0,234**

Rel. differ. of meas. and calcul. luminan.	**Mean**	**-0,003**
	Std. deviation σ	**0,051**
Reflection factor of the cavities ρ_C	**Mean**	**0,233**
	Std. deviation σ	**0,010**

Table A.2 - Typical reflection factors ρ (Source IES)

Material	ρ [%]
Bluestone, sandstone	18
Brick	30-48
Cement	27
Concrete	40
Earth	7
Grass (dark green)	6
Grass (clear)	18
Gravel	13
Marble	45
Paint (white)	55-75
Snow	64-74
Vegetation	25

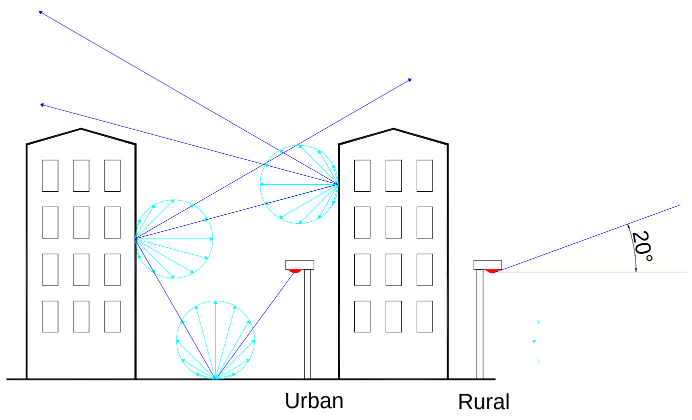

Figure A.1 A town can be assimilated with a set of light sources, with most luminaires hidden into the cavities between the buildings (urban sources) and some other not screened by buildings (rural sources)

A.2 Luminaires hidden in city cavity

The measurement carried out show that all lighting installations are uniform diffusers as far as the luminous flux emitted and reflected upward. Formerly, this characteristics was only for the luminaires hidden into the city cavities (figure A.2), the majority of all towns, a limitation, however rare, that according to this research is no longer necessary.

Figure A.2 On the left Milan by night from Madonnina on top of the Cathedral: very few luminaires are visible out of at least 15000 installed in this sector of Milan, since they are deeply hidden into urban cavities. On the right Florence with the well known steeple and cathedral by Giotto and Brunelleschi. Again, practically all the 39000 installed luminaires are hidden into the urban cavities, whose upward diffusing openings are shown by the many small bluish spots

References

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