UPWARD FLUX OF PUBLIC LIGHTING: TWO TOWNS IN NORTHERN ITALY

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ABSTRACT. A survey was carried out on public lighting installations in two towns in northern Italy, i.e. Turin (population 1 million) and Treviso (80.000). The distribution of the different types of luminaire was evaluated and the percentage of luminous flux emitted upwards was calculated.

The results of this survey are reported and compared with the relevant publications and with the draft standard under discussion by the Italian standardising body (UNI). The expected results on threshold magnitude due to sky luminance and on the cost/benefit ratio for different types of installation and luminaire are also discussed.

1. Introduction

No one questions the need for public lighting to ensure a safe environment by night for drivers and pedestrians and to serve the townspeople's needs by illuminating monuments, gardens, sport facilities and other such sites in every town. These benefits, however, are unfortunately countered by the unavoidable effects of the luminous flux that lighting installations emit upwards (the so-called spill light) and road surfaces reflect upwards, thus increasing sky luminance with a negative fallout on the visibility of the heavenly bodies.

To respond to complaints from both professional and amateur astronomers about what they call "luminous pollution", the CIE has studied this problem at international level with a view to offering guidance to lighting experts and standardising bodies for a more careful design of lighting installations and luminaires [1][2]. Two years ago, the Italian UNI appointed a working group to draft a standard in this field, taking the following issues into account:

- safety for drivers and pedestrians;
- protection of astronomical sites;
- optimisation of the cost/benefit ratio;

- impact on the market.

In the context of said standardising project, the Istituto Elettrotecnico Nazionale G. Ferraris (IEN), the Azienda Energetica Metropolitana (AEM) of Turin and the University of Padua (UNP) carried out a survey on existing lighting installations in two towns in northern Italy, i.e. Turin (population 1 million) and Treviso (80.000), with a view to verifying the feasibility of a city lighting plan in compliance with the draft standard.

The results of this survey are presented here, together with a preliminary discussion of the technical and scientific issues involved in the evaluation of the results.

2. Lighting and astronomy

In Italy, lighting experts and astronomers are discussing the correlation between sky luminance, which reduces the visibility of heavenly bodies, and spill light from public lighting installations, their aim being to draw up a national standard for restricting sky luminance. A number of issues have been examined, the results of which are summarised below.

2.1. Measurement units

For the benefit of lighting experts, it may be useful to recall that astronomers classify star luminosity according to its magnitude, i.e. the illuminance on the observer's entrance pupil, be it naked eye or telescope, evaluated on a logarithmic scale. Though the relationship between the units of magnitude and lux has never been formally established, for the purpose of this paper it can be assumed as:

$$M = -k\ log(E/E_o) \qquad (1)$$

where M is the magnitude, E the illuminance on the entrance pupil, E_o a reference illuminance and k a scale coefficient; though there is no consensus as yet on the values of E_o and k (the CIE is preparing to study this problem), k can be set at 2,5 magnitudes [1], while the value of E_o is irrelevant for the purposes of this paper. It is worth noting that M increases as E decreases, i.e. the fainter the star, the greater the magnitude.

2.2. Evaluating threshold magnitude

Several models have been proposed for evaluating sky luminance generated by public lighting and its effect on the absolute reduction in the visibility threshold for astronomical observations, but there is no international consensus on this evaluation at present. The CIE is proposing a campaign of measurements as a contribution to this problem, which depends not only on upward luminous flux, but also on local conditions such as orography and atmospheric pollution. Only comparative evaluations are made in this paper.

As mentioned before, the luminous flux coming to bear on the road surface is partially reflected upwards. The CIE reports a typical value of 10% for the ratio between the luminous flux reflected upwards and the total lumens emitted by the luminaire in space; measurements carried out in Turin by the IEN have confirmed this value.

The light emitted upwards by lighting installations is diffused by the atmosphere, leading to an increase in the luminance of the sky, with a consequent reduction both in the contrast of the heavenly bodies against the background of the sky and in the threshold magnitude, i.e. the greatest magnitude still visible by a naked or assisted eye. Lighting experts will certainly compare this effect with the veiling luminance created by car headlamps in foggy weather, but no mathematical evaluations are possible in this case because the bidirectional reflectance distribution function of the atmosphere and the luminous intensity distribution of spill light are generally not known.

It is nonetheless possible to assess the drop in threshold magnitude DM with reference to a known, or supposedly known, condition. The "sky glow formula", developed by the CIE [1] and illustrated here in eq. (2), enables an evaluation of the decrease in threshold magnitude which equates to the contrast between star and background in actual and reference conditions:

$$M = -2,5\ log(1 + a) \tag{2}$$

where a is the relative increase in the upwards luminous flux between the actual and the reference condition. In this paper, the reference condition is the unavoidable luminous flux reflected by the road (10% of the total luminous flux emitted), while a is the luminous flux emitted upwards directly by the luminaire in relation to the reflected luminous flux.

2.3. Characterisation of lighting installations

As far as the sky luminance generated by public lighting is concerned, lighting installations are classified according to the suggestions of the CIE [1] on the basis of their "upward waste light ratio" (UWLR), i.e. the proportion of the luminaire's luminous flux that is emitted above the horizontal when the luminaire is in its installed position.

2.4. Energy saving

Though there is no unanimous consent on this issue, reducing sky luminance does not seem to coincide with any energy saving [3]. On the matter of the luminaires, good public lighting benefits from the reflecting characteristics of road surfaces and requires a high luminous intensity at angles 70-75° from the vertical. A reduction in UWLR could suggest a luminaire with a flat glass window, but the reflection factor of the air-glass interface is very high at such angles, as shown in fig. 1, with a consequent drop in efficiency and poor light control. A reduction in aperture angles, as in the so-called cut-off luminaires, calls for the installation of a greater number of luminaires with a consequent increase in the luminous flux reflected by the road, which outweighs the reduction in UWLR: the CIE reports an increase of about 1,5% for semi-cut-off luminaires [2]. The cost of both installation and energy would also increase.

Table I compares a number of conditions (though not complete, it is certainly sufficiently representative of what is available on the market) for luminaire windows and lamps for similar road lighting installations with an average road luminance of 1 cd/m^2 [3].

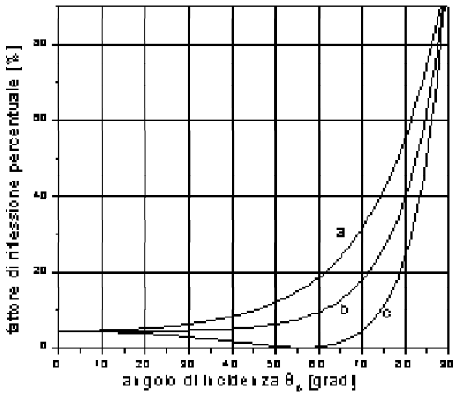

Fig. 1. Reflection factor for the air-glass interface. Curves a and c are for polarised light, b for unpolarised light.

The best energy-saving condition is achieved with luminaires using prismatic bowl windows and fitted with high-pressure sodium lamps (No. 3 in table I), with a UWLR of about 3%. Table I shows the increase in energy consumption for the other windows by comparison with this condition. The lower efficiency of luminaires with low-pressure sodium lamps (No. 6 in table I) is hardly surprising: in fact, the large size of these lamps prevents a valid control of the luminous intensity distribution.

Tab. I - Comparison between road lighting installations
Average road luminance 1 cd/m^2 Road reflection 10%

No.	Lamp	Window	Effic. %	UWLR %	Total upward flux	Power cons. $W/cd\ m^{-2}$	Energy %	Magnitude loss
1	Hp sodium	flat glass	73	0	10	141	+34	0 (*)
2	Hp sodium	curved glass	85	0,1	10,1	123	+17	0,01
3	Hp sodium	prism. bowl	80	2,8	13,5	105	0 (°)	0,3
4	Hp sodium	smooth bowl	82	1,8	12,2	118	+12	0,2
5	Mercury	smooth bowl	68	1,5	12,2	195	+86	0,2
6	Lp Sodium	prism. bowl	67	3,9	15,8	108	+3	0,5

(*) Best case for magnitude loss
(°) Best case for energy consumption

Table I also illustrates the reduction in the visibility threshold (in magnitudes) calculated using eq. (2): the flat window (No. 1 in table I) is naturally the best, but at the expense of a 34% greater energy consumption. The loss of star visibility in magnitudes for the other lamp/window combinations, referring to the high-pressure sodium/flat window, is shown in the last column of table I.

2.5. Structure of the UNI standard

The Italian standard on the reduction of sky luminance, which is still being developed, deserves some comment. This draft standard is based on a 3-zone system (the CIE recommended 4 [1]) for the Italian territory. The first zone is for international observatories, the second surrounds the first and protects national and amateur observatories and the third is for the rest of Italy. The draft does not consider single installations, but specifies the average UWLR value for each town, the general requirement being: to protect zones 1 and 2 and to improve the quality of luminaires and lighting installations in all zones; to avoid any increase in the cost of luminaires, installations and energy consumption except for zone 1, which will include only the three Italian international observatories; and to ensure a soft impact on the market. Even if the UWLR values are under debate, the drafting work group has prepared a proposal for an overall 1% in zone 1, 5% in zone 2 and 10% in zone 3 (including luminaires, installation geometry, tolerances, etc.). This means that flat window luminaires should be installed only in zone 1, whose radius should be at least 5 km, while the more economical prismatic bowl luminaires should be installed in the other zones.

3. Lighting installations in Turin

Turin is a heavily industrialised town with a population of about 1 million, which should be included in zone 3 of the draft UNI standard. The local electrical energy distributor AEM decided to prepare a public lighting plan that, for each type of road, specifies luminance and illuminance levels, the type of lamp and colour of the emitted light (for use as visual guidance and for illuminating monuments), the type of luminaire and also the maximum UWLR for each type of lighting (motorised roads, pedestrian streets, gardens, monuments, etc.).

In preparation for said plan, the AEM has carried out a survey with the co-operation of the IEN on the different types of luminaires and lamps currently installed in Turin. The results of the survey are summarised in Table II: to simplify matters, the luminaires are divided into 6 types and the typical appearance of each type of luminaire is shown in figs. 2 to 7. For a comparison with table I, it is to be noted that the UWLR values in table II include the spill light due not only to the luminaires, but also to their design inclinations and mounting tolerances.

The following comments relate to table II, which refers to the present situation of lighting installations.

- Turin comes very close to the UNI draft standard requirements for zone 3 because many road installations are recent. The average UWLR could even be further reduced, were it not for a considerable number of traditional luminaires that cannot be changed because they are an important feature of the historical city centre by night.

- The contribution of the freely-emitting spheres to the UWLR is very low because

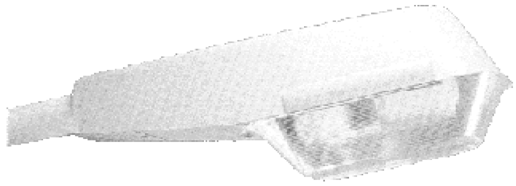

Fig. 2 Typical luminaire for street lighting on pole (n. 1 in table II)

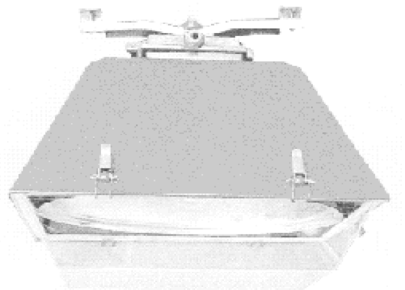

Fig. 3 Typical luminaire for street lighting on suspension (n. 2 in table II)

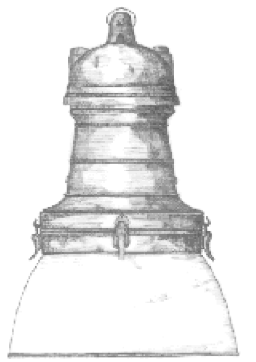

Fig. 4 Typical luminaire with diffusing photometric characteristics (n. 3 in table II)

Fig. 5 Typical lantern (n. 4 in table II)

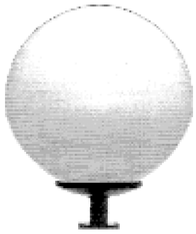

Fig. 6 Typical sphere (n. 5 in table II)

Fig. 7 Typical luminaire for garden lighting
(n. 6 in table II)

they account for only 1% of the total luminous flux generated in Turin. Nonetheless, each sphere will be equipped in the near future with a sort of internal reflector that will reduce their UWLR by half. The reduction in the town's average UWLR to be gained from this modification is only 0,2%, however, which corresponds - according to eq. (2) - to a very limited increase in sky visibility (about 0,02 magnitudes).

- The contribution of road lighting installations (luminaires Nos. 1 and 2 in table II) to both total luminous flux and total power is about 72%: this means that a better potential energy saving can be obtained by improving the quality of their lighting design, using prismatic bowl luminaires (No. 3 in table I) wherever possible. Something can also be done for the type 3 diffusing luminaires (which contribute 11,4%). It is worth noting that in Turin the traditional luminaires (types 4, 5 and 6), that it would be difficult to modify, only contribute 9%.

- Monument lighting is switched off at night, at a time decided by the local authority, so - though its contribution to the total luminous flux is not very high - it has not been included in table II.

Tab. II Public lighting installations in Turin

No.	Luminaire	Quantity	Power MW	Flux Mlm	Rel. Flux %	UWLR %
1	Road (on post)	42593	8,3	635	68,8	6
2	Road (suspended)	2113	0,4	33,8	3,7	6
3	Diffuser	9761	1,6	105	11,4	20
4	Lantern	2952	0,6	33,5	3,6	33
5	Sphere	1101	0,1	10,1	1,1	50
6	Garden	5027	0,9	50,4	5,5	33
7	Others	3888	0,8	54,5	5,9	6
	Total	67435	12,7	922	100 (∘)	10,5

(∘) This value is the average UWLR weighted according to the relative luminous flux established for the whole town by the draft UNI standard.

As far as the improvement schemes of the Turin lighting plan are concerned, the objective for the town's average UWLR in the near future can be around 9,6%, thus complying with the zone 3 UWLR of the UNI draft standard. This value will be achieved when certain obsolete road lighting installations have been replaced with prismatic bowl luminaires over the next few years: this solution will assure the best use of energy. According to eq. (2), the threshold magnitude is thus expected to increase by about 0,1 magnitudes.

It should be noted, however, that an increase is also expected in the luminous flux installed because the towns people are constantly asking the local authority to install new luminaires and increase lighting levels for public safety reasons. Using eq. (2), it is easy to see that a 10% increase in the luminous flux installed, due only to the light reflected from the roads, which can easily be expected simply from the modernising of luminaires, will counterbalance the expected reduction of UWLR.

Unfortunately, no lighting design programme will enable a good view of the stars in Turin because the luminous flux reflected from the roads is already enormous, about 100 Mlm (assuming 10% of the emitted luminous flux) and, as mentioned above, it is constantly increasing. Even if there is no commonly-accepted model for calculating the reduction in the star visibility threshold due to the reflected light, this reduction is certainly quite high, partly because there is a virtually permanent inversion layer over Turin at about 300 m above the town which diffuses light on the sky. This is sadly a typical situation for many industrialised towns in Italy, especially in the north of the country. As for energy savings, in Turin this mainly depends on the replacement of the street lighting installations and has almost nothing to do with any reduction in the UWLR. The data in table I show that at lower UWLR (Nos. 1 and 2 in table I) a higher energy consumption is to be expected: for instance, adopting flat window luminaires for the street lighting installations in Turin (Nos. 1 and 2 in table II) instead of the foreseen prismatic bowl luminaires (No. 3 in table I) could eventually lead to an increase in energy consumption of about 22% for the whole town as opposed to an improvement in threshold visibility of only 0,1 magnitudes, making the cost/benefit ratio unacceptable. Again, experience in Turin demonstrates that there is no useful correlation between energy savings and a reduction in spill light.

4. Lighting installations in Treviso

Treviso is a town in the relatively well-developed north-east of Italy, characterised by the presence of numerous small manufacturing industries and businesses distributed over a territory that still retains the features of intensive agriculture. Unlike Turin, Treviso is a rather typical, medium-sized Italian town with a population of about 80.000. It is situated in the Veneto region, where a local law issued in July 1997 establishes certain restrictions on the use of public lighting with a view to containing upward luminous flux [4]. That is why the Department of Electrical Engineering at the University of Padua chose Treviso for a "sample" assessment of present-day luminous pollution levels. The first step in this direction was taken as part of a thesis [5], which enabled the amount of luminous flux dispersed upwards to be calculated for the different kinds of luminaire currently used in the town and in the surrounding territory. The results of this work are summarised in table III, which refers separately to the historical town centre, its suburbs, and the municipality as a whole.

The main types of lighting installation in Treviso are illustrated in Figs. 8 - 12. The mathematical methods involved are the same as were used for the city of Turin, as specified by the UNI draft standard. The data emerging on the two situations are therefore reported in the same way and are suitable for comparison.

The Treviso study actually included a great deal of other information for a more thorough assessment of the luminous pollution phenomenon. Some interesting results emerged from evaluating not only the flux emitted upwards by the luminaires, but also the flux reflected by road surfaces and vertical surfaces surrounding the lighting installation. In the case of Treviso, the proportion between direct and reflected fluxes is

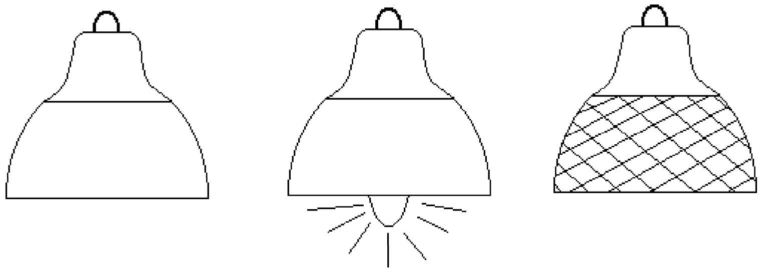

Fig. 8 - Typical luminaire for street lighting (open type) in Treviso

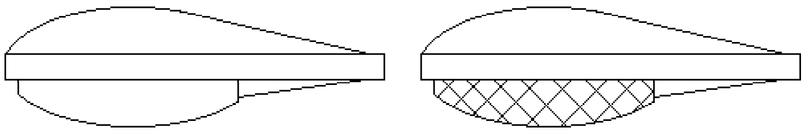

Fig. 9 - Typical luminaire for street lighting (diffuser type) in Treviso

around 1:2, so the reflected flux has the greatest weight in the total level.

Finally, several simulations were performed to assess how the reflecting features of the road surfaces affect the quantity of flux reflected upwards, always assuming that the requirements of the UNI standard 10439 for levels of horizontal illuminance and luminance are satisfied in all cases: preliminary results demonstrate that the type of road surface has relatively little bearing on the situation. Intuitively, this might be explained basically by the fact that a paler surface reduces the quantity of flux needed to obtain the required illuminance level (thus ensuring an undeniable advantage in energy terms), but simultaneously increases the reflection factor and thus the relative quantity of flux directed towards the sky - so these two factors tend to compensate for each other.

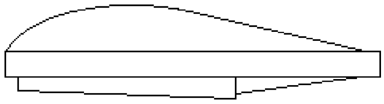

Fig. 10 - Typical luminaire for street lighting
(flat diffuser type) in Treviso

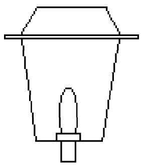

Fig. 11 - Tipycal luminaire for historical
centre in Treviso (lantern)

5. Conclusions

The surveys carried out in Turin and Treviso show that a good-quality lighting is essential for compliance with the draft UNI standard on the reduction of sky luminance in zone 3. In both towns, the upward luminous flux limit for zone 3 can be satisfied by modernising the road lighting installations, which account for the vast majority of all public lighting installations. The use of luminaires with a prismatic bowl window and, wherever possible, with high-pressure sodium lamps ensures the most efficient use of energy.

The results reported in this paper demonstrate that, in order to ensure both good sky visibility and low energy consumption, the astronomical observatories should be surrounded by dark zones (the so-called "star parks"), where lighting installations should not be allowed. The very high luminous flux reflected from the road surfaces in towns

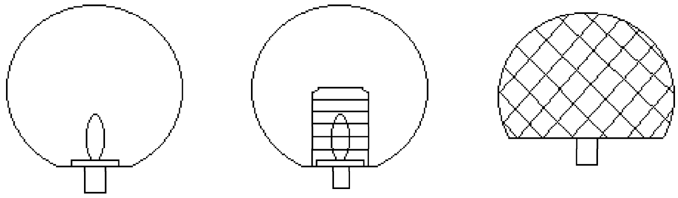

Fig. 12 - Typical luminaire for garden and pedestrian areas
in Treviso (sphere)

prevents a good view of the celestial bodies and simply reducing spill light does not pay off. Considering the distribution of the different types of lighting installation in towns, even the use of flat-window luminaires instead of the prismatic bowl luminaires for street lighting installations, leaving as they are now the other types of lighting installations (monuments, pedestrian streets, garden, etc.), would improve the visibility threshold in the UNI standard's zone 3 by less than 0,15 magnitudes. It is easy to verify that, extending the results on the distribution of lighting installations given in table II to a town in zone 2 (for which the UWLR should be 5% according to the draft UNI standard), the use of flat window luminaires in the conditions reported above would lead to about the same improvement in the visibility threshold. In both zones, the increase in energy consumption would between 20% and 30%, so the cost/benefit ratio is distinctly unfavourable.

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Tab. III - Public lighting installations in Treviso

Luminaire	number	Power kW	Flux Mlm	Relative flux %	UWLR %
historical town centre					
Road (open type)	456	59,8	2,6	53,2	15,7
Road (with diffuser)	137	19,8	1,0	20,5	3,5
Road (flat diffuser)	10	1,8	0,08	1,7	5,4
Lantern	117	12,6	0,60	12,3	39,7
Sphere	160	16,2	0,60	12,3	38,8
TOTAL	880	110,2	4,88	100	19,13
suburbs					
Road (open type)	3497	264,0	7,8	28,6	8,5
Road (with diffuser)	1376	158,1	7,6	27,8	2,9
Road (flat diffuser)	1399	178,4	10,5	38,5	1,2
Lantern	0	0	0	0	-
Sphere	326	35,9	1,4	5,1	43,3
TOTAL	6598	636,4	27,3	100	5,94
global values					
Road (open type)	3953	323,7	10,4	32,4	10,3
Road (with diffuser)	1513	177,9	8,5	26,5	2,9
Road (flat diffuser)	1409	180,2	10,6	32,9	1,2
Lantern	117	12,6	0,6	1,9	39,7
Sphere	486	52,1	2,0	6,3	42,0
TOTAL	7478	746,5	32,1	100	7,94
Unclassified	35(*)	?	0,4 (*)	-	-

(*) Not considered in computations