Light pollution by luminaires in roadway lighting

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Abstract: We present the results of a comparison of light pollution produced by some light installations for roadway lighting as obtained with the software Roadpollution. Luminaires with an direct upward flux factor apparently as small as 0.2% and 2.2% produce increases of light pollution even of the order of 20% and 200% respectively. Reflection of downward light wasted outside of the road adds approximately another 50% – 100%, depending on the reflectivity of the surrounding surfaces and the fraction of wasted light flux, and should be minimized as much as possible.

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1. INTRODUCTION

An effective control of light pollution produced by roadway lighting requires that (a) the light necessarily re-emitted by the road pavements be limited as much as possible avoiding overlighting, (b) direct upward light emission by luminaires be negligible in respect to it, (c) the un-necessary light re-emitted by other surfaces be limited as much as possible minimizing the downward light wasted out of the road pavement. In facts, the first is required by the lighting process whereas the second can be in most cases completely eliminated using fully shielded fixtures and the third reduced as much as possible maximizing the utilance (i.e. the ratio between the flux sent on the road and the total flux emitted by the luminaire). Frequently the increase of light pollution due to direct upward emission by luminaires over the pollution produced by road pavements is underestimated in roadway lighting design and the minimization of the flux wasted out of the road is uncared for.

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, luminaires and other surfaces, and the effects on the night sky. They are related to the total quantity of light emitted in the atmosphere but not to the light pollution, i.e. on the alterations produced by this light (like e.g. the artificial night sky brightness). Cinzano and Diaz Castro (2000) showed that the direction of emission of the light is important in determining the quantity of light scattered in the atmosphere (related to the length and position of the light path) and the size of the area that is polluted because of the propagation of light pollution and its capability to add up to that produced by the other sources (both related to the geometry of the emission). Given that roads pavements, other surfaces and luminaires have different intensity distributions, the integrated fluxes can be misleading, if the direction of emission is not in some way accounted.

Here I present a comparison of light pollution produced by some light installations for roadway lighting as obtained with the software Roadpollution (Cinzano 2002). This software computes a full set of parameters useful to compare light pollution by roads and luminaires accounting for the direction of emission. Details on the parameters definitions and computational methods are described in Cinzano (2002). In section 2 the design parameters of the considered installations are described. In section 3 results are presented and discussed. Conclusions are in section 4.

2. METHOD

We compared 5 installations with different kinds of luminaires and upward flux factors UFF (also called UFR): the first uses prismatic glass luminaires with low UFF, the second uses convex transparent glass luminaires with high pole spacing ratio and very low UFF and the last three use the same flat glass luminaires with an average pole spacing ratio. All luminaires are available on the market. We evaluated the road design parameters for a single carriageway double lane road with these constraints:

Aver. maintained luminance $\approx$1 cd/m^2	Lumen depreciation factor 0.8
Overall uniformity $U_0 \geq 0.4$	C2 standard road surface
Lengthwise uniformity $U_l \geq 0.5$	Road width 7 m
Threshold index TI$\leq$ 15%	Overhang free

We assumed a pole height of 8 m in order to limit the quantity of downward light wasted out of the road pavement, but for comparison purposes we added two installations with flat glass luminaires at 10 m and 12 m. The design parameters were obtained choosing the lamp producing the luminance nearest to the requested one, then searching at our best for the minimum installed flux per unit length and the maximum pole spacing compatible with the constraints on the uniformities, and finally tuning the lamp flux in order to fit the required average maintained luminance. This is in agreement with other authors.

The parameters of the installations are shown in table 1.

Table 1

DESIGN PARAMETERS					
code number	09170114	09170102	09170043	09162356	09170209
luminaire kind	prismatic glass	convex transparent glass	flat glass	flat glass	flat glass
lamp flux (klm)	11	13	15	10.8	7.5
pole spacing (m)	36	41	42	35	28
luminaire height (m)	8	8	12	10	8
lamp	HQL	SON-T	NAV-T	NAV-T	NAV-T
ROAD PARAMETERS (luminaires at right/luminaires at left)					
average maintained luminance	1.0/1.0	1.0/1.0	1.0/1.0	1.0/1.0	1.0/1.0
overall uniformity U_0	0.4/0.5	0.4/0.4	0.5/0.4	0.5/0.4	0.5/0.4
lengthwise uniformity U_L	0.5/0.5	0.5/0.5	0.5/0.6	0.5/0.6	0.5/0.7
max threshold increment TI%	10.4/11.0	13.6/9.6	6.3/9.0	6.8/9.9	6.8/9.9
ENERGY SAVING PARAMETERS					
average luminance coefficient (luminance per unit illuminance) (10^-2 cd/lm)	89	68.2	93	91	87
used fraction of the lamp flux %	35.4	40.7	28.6	33.5	40.9
wasted fraction of the downward flux %	51.0	51.9	61.6	54.9	45.0
light output ratio of the luminaire LORL %	71	84.9	74	74	74
luminaires per km	27.7	24.4	23.8	28.6	35.7
installed lamp flux per unit length (lm/m)	306	317	357	309	268
installed lamp flux per unit area (lm/m^2)	44	45	51	44	38

Table 1 is worth some comments. For the same pole height the installation with flat glass fixtures results the less consuming (only 268 lm/m) due to his minor wasting of light out of the road. This likely depends on the more concentrated emission of these specific fixtures on the plane perpendicular to the road axis. However the smaller installed light flux per unit length requires the larger number of luminaires per unit road length. Using 1/3 less luminaires we would spend 1/3 more light flux. The number of luminaires per unit length and the installed flux per unit length appear to act in opposite way for any kind of luminaires. It seems always better minimizing the installed light flux per unit road length because the saved energy can pay back the larger installation cost. The number of luminaires per km of the flat glass installation is only 3% larger than that of the prismatic glass installation, when comparing installations with the same flux per km. Note that the five installation in this paper appear reasonably good from the point of view of energy saving because the average installed light flux per unit road length obtained by a sample of 12 typical installations with prismatic and curved glasses from an example-book is 390±76 lm/m.

The Threshold Index TI of the first two installations exceed the limits given in standard rules for some kind of roads (e.g. according to UNI10439 must be TI<10% for flowing urban roads, suburban roads and motorways). TI seems increase when pole height decrease. If for some fixtures the pole height cannot be decreased because TI grows over the limits, it could result very difficult designing low wasting light installations with these fixtures.

The average luminance coefficient of these installations depends more on the design than on the kind of glass.

3. RESULTS

Result for the two installations with ULOR≠0 are resumed in table 2.

Table 2

upward light output ratio ULOR (calc) %	1.6	0.17
upward flux ratio $UFR_{luminaire}$ %	2.2	0.2
road upward flux ratio UFR_{road} %	3.7	3.8
increase of upflux ratio due to direct emission %	60	5.3
increase of scattered light due to direct emission %	85	NA
increase of low-angles upward flux due to direct emission %	167	16
increase of low-angles scattered light due to direct emission %	212	21

Table 2 shows that luminaires with upward flux factors apparently as small as 0.2% and 2.2% produces increases scattered light at low elevations of the order of 20% and 200%. This give an insight on the increase of light pollution contributed by these luminaires at a distance greater than 20 km where the artificial night sky brightness near the zenith is produced almost completely by low angle emission (e.g. Cinzano and Diaz Castro 2000).

If the increase of light pollution due to directly spilled light should be limited under 5%-10% both these luminaires are ruled out, even taking in account the contribution by "out-of-road reflection" discussed. In fact, even if we double the scattered light due to road reflection to account for "reflection by surfaces out-of-road", so that the increases in table 2 halves, they still are respectively of 10.5% and 106%.

The road upward flux ratio can be misleading. The three flat glass installations (rightmost in table 3) show apparently an increasing road upward flux ratio but the installed lamp flux per unit road length decreases, so that the upward flux actually changes little. Note that these flat glass luminaires produces slightly less upward flux by road reflection than the other two kinds (even 10-15% at the same pole height), just the opposite of what has been frequently claimed.

Table 3

installed lamp flux per unit length (lm/m)	306	317	357	309	268
road upward flux ratio UFR_{road} %	3.7	3.8	2.9	3.4	4.2
road upward flux (lm/m)	11.32	12.04	10.35	10.50	11.25

Table 4 and table 5 (last row) show the increase of the scattered flux produced by reflection of the light wasted out of road over that produced by the road reflection.

Table 4 is computed for a reflectance of 7% and lambertian emission. Green vegetation could have a reflectance of this order, or even smaller, due to chlorophyll absorption at visible wavelength. The reflectance depends on the spectra of the source and the photometric band in which it is measured, therefore it should be always measured in the CIE Photopic photometric band and using as light source a typical lamp for road lighting (e.g. a standard HPS lamp). The use of visual albedo measured for solar light could be source of large errors.

Table 4

wasted fraction of the downward flux %	49.0	51.9	61.6	54.9	45.0
out-of-road upward flux ratio%	3.2	3.5	4.1	3.7	3.0
increase of scattered light due to out-of-road emission %	66	--	110	83	55
increase of low angles scattered light due to out-of-road emission %	68	74	113	86	57

Table 5 assumes an average reflectance of 13.5% by a mix of out-of-road surfaces and Lambertian emission. This reflectance is obtained averaging the visual reflectance of some common surfaces (from grass to brick, concrete and plaster) and assuming that vertical surfaces send upward approximately one half of the reflected light. Due to the range of reflectance of existing materials, this table give only a magnitude order for comparison purposes.

Table 5

wasted fraction of the downward flux %	49.0	51.9	61.6	54.9	45.0
out-of-road upward flux ratio%	6.5	7.0	8.3	7.4	6.1
increase of scattered light due to out-of-road emission %	132	--	220	166	110
increase of low angles scattered light due to out-of-road emission %	136	149	227	172	114

Tables 4 and 5 show that the upward flux produced by reflection of the light wasted out of road as percent of the total flux emitted by the luminaire (out-of-road upward flux ratio) strictly depends on the wasted fraction of the downward light flux, which must be minimized as much as possible. With an accurate design the wasted light flux can be reduced to less than half of the downward flux. They also show that for accurately designed installations, the increase of low angles scattered flux produced by reflection of light wasted outside the road can be limited approximately to 60% - 110%, for a reflectivity of the surrounding surfaces in the range 0.07 – 0.12. For the same pole height, the installation using prismatic glass luminaires of our sample produces an increase 20% larger than flat glass luminaires. Note that the upward intensity distributions of the road, the surrounding surfaces and the luminaires are different so a comparison of their intensities in the more polluting directions, rather than their fluxes, would be more appropriate.

Table 6 resume the results.

Table 6

upward flux ratio $UFR_{luminaire}$ %	2.2	0.2	0	0	0
road upward flux (lm/m)	11.32	12.04	10.35	10.50	11.25
increase of low angles scattered light due to direct + out-of-road emission % (reflectivity=13.5%)	348	170	227	172	114
increase of low angles scattered light due to direct + out-of-road emission % (reflectivity=7%)	280	95	113	86	57

The increase of scattered light at low angles produced by both the luminaires and by out-of-road surfaces, over the scattered light due to the pure road reflection, goes from 348% for prismatic glass installation (UFR=2%) to 170% for convex transparent glass (UFR=0.2%), to 114% for the flat glass installation (fully shielded) with the same pole height for the adopted surface mix with reflectance 13.5%. It goes from 280% for prismatic glass installation to 95% for convex transparent glass, to 57% for the flat glass installation for green vegetation with 7% reflectance. Note that installation 4 apparently produces an increase of the same order that installation 2 but its road upward flux per unit length is 15% smaller. Results for installation 3 demonstrates that the control of downward light wasted out of the road, i.e. the control of the wasted flux ratio cannot be neglected, even in fully shielded installations.

4. CONCLUSIONS

We resume here our conclusion for the considered lighting installations.

1) Luminaires with upward flux factors apparently as small as 0.2% and 2.2% produces increases scattered light at low elevations of the order of 20% and 200%. This give an insight on the increase of light pollution contributed by these luminaires at a distance greater than 20 km where the artificial night sky brightness near the zenith is produced almost completely by low angle emission. If the increase should be limited under 5%-10% both these luminaires are ruled out, even taking in account the contribution by “out-of-road reflection”.
2) The upward flux due to reflection by out-of-road surfaces is strictly depending on the wasted fraction of the downward flux which must be minimized as much as possible. With an accurate design the wasted light flux can be reduced to less than half of the downward flux. The control of downward light wasted out of the road, i.e. the control of the wasted flux ratio cannot be neglected, in particular in fully shielded installations.
3) For accurate installations, reflection of downward light wasted outside the road can add to the low angles scattered flux approximately another 60% - 110%, depending on the reflectivity of the surrounding surfaces.
4) The number of luminaires per unit length and the installed flux per unit length appear to be conflicting quantities. In any case it is better to minimizing the installed light flux per unit road length because the cost of the saved energy can pay back the installation cost.
5) The *road upward flux ratio* can be misleading. Installations could show an increasing road upward flux ratio but a decreasing installed lamp flux

per unit road length, so that the upward flux actually does not changes much.

6) For the same pole height the installation with flat glass fixtures results the less consuming (only 268 lm/m) due to his minor wasting of light out of the road. This likely depends on the more concentrated emission of these specific fixtures on the plane perpendicular to the road axis. However the number of luminaires per unit road length is the larger one. Using 1/3 less luminaires we would spend 1/3 more light flux.
7) The number of luminaires per km of the flat glass installation is only 3% larger than that of the prismatic glass installation, when comparing installations with the same installed flux per km.
8) These flat glass luminaires produces slightly less road upward flux than the other two kinds (even 10-15% at the same pole height), just the opposite of what has been frequently claimed.
9) For the same pole height, flat glass luminaires produces 20% less scattered light due to out-of-road wasted light than the installation with prismatic glass luminaires.
10) The increase of scattered light at low angles produced by both the luminaires and by out-of-road surfaces, over the scattered light due to the pure road reflection, goes from 348% for prismatic glass installation (UFR=2%) to 170% for convex transparent glass (UFR=0.2%), to 114% for the flat glass installation (fully shielded) with the same pole height for 13.5% reflectance. It goes from 280% for prismatic glass installation to 95% for convex transparent glass, to 57% for the flat glass installation for 7% reflectance.

5. REFERENCES

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