LIGHTING POLLUTION AND INTRUSIVE LIGHT EVALUATION IN RESIDENTIAL AND RURAL AREAS

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Introduction

The study of Lighting Pollution (LP) demands of reliable indicators to estimate the effects on different social sectors, climates and environments. This work describes part of a larger study carried out on urban and rural areas of the Northwestern area of Argentina including cities, towns, villages and scattered houses. The aim is to study LP not only from the photometric and energetic point of view but also recording people's perception of the phenomenon. This paper informs about three cases including photometric surveys, lighting design approaches and environmental considerations. The reference for the photometric analysis are the parameters recommended by the International Commission of Lighting (CIE) in order to limit the disturbing light in installations of public lighting[1]. Preliminary results about human assessments in a urban residential area are reported in other work[12]. Some basics optical characteristics of the urban environment studied were reported in a former paper[13].

Characterization and regulation of the lighting pollution

The regulation of the environmental impact associate to LP which produces disturbances to diverse groups of the community, astronomers, citizens, environmentalists, etc., has been proposed by the CIE in Publications Nr 126 and CIE TC - 12[1, 2].

The CIE publication Nr 126[1] introduces the foundations of Lighting Pollution and proposes recommendations with respect to the maximums values allowed for lighting installations. In the Publication CIE TC 5-12[2], other aspects are covered such as the disturbance or interference of the light, in particular the effects on the residents of houses, citizens in general and on users of transports and signaling systems.

In both publications are used the following definitions:

a) ULOR (Upward Light Output Radio).
b) $ULOR_{INST}$ (upward light output ratio installed).
c) System of Division in Zones: For zones E1, E2, E3 and E4, the $ULOR_{INST}$ ratio is 0%, 0-5%, 0-15% and 0-25% respectively.

Besides, Publication [2], considers the vertical illuminance in windows, the intensity of the luminous points outside of the illuminated area, the average luminance of the surfaces of vertical facades in the buildings and the disturbing glare in the street and road lighting systems.

Equipment

The photometric studies of the lighting installations were performed with a LMT luxmeter B360, a Minolta luminance meter LS-110. The evaluation of luminaries were carried out in laboratory tests with a mirror LMT goniophotometer GO-DS 1600.

Evaluation in a residential zone

The public lighting system in residential areas facilitates the displacement of vehicles and pedestrians. In the case of automotive traffic it must improve the nocturnal visibility of the drivers in the detection of obstacles, other vehicles and pedestrians. On the footpaths it must make possible the visual orientation of pedestrians, to detect obstacles, to identify names of streets, numeration of houses and fundamentally to allow the pedestrians to recognize attitudes and characteristics of other people who circulate. Also, is important for the visual appearance of the environment and may intrude in the houses. This approach is considered in the lighting design since the 80´s[3] in several countries[4]. In Argentina these proposals have not yet been considered in national recommendations although, since several years, it is studied in the Department of Lighting, Light and Vision of the University of Tucumán[5, 6], and some Municipalities have produced their own recommendations[14] .

The following sections summarize a retrofitting of the public lighting in a quarter of San Miguel de Tucumán city. The Neighbors Association of the quarter asked assistance to the local university in order to evaluate the public lighting conditions. The request was the start point of a project involving the Neighbors Association, the University and the Municipality[7, 12]. .

Description of the district

The city (27° latitude South, 65° longitude West), 400 m above see level, wet subtropical climate and 500 000 inhabitants. The quarter is displayed on 14000m^2, with 800 inhabitants living in individual houses and 6 buildings of 10 floors each distributed along 8 streets and 5 alleys. The streets are 6 - 9 m width and 120 m of longitude with footpaths 2.7-4m width. The surfaces of the majority of the streets are of concrete and the footpaths are of concrete, stones or tiles with adjacent zones of soil and grass. The urban design includes roads of access and exit to the zone with secondary streets and alleys. The transit of vehicles is low, involving mainly the vehicles of the residents and services. Like most of these areas the public space of footpaths and streets are utilized in an important proportion by pedestrians.

Public lighting previous to the retrofitting

The lighting installation consisted of luminaries of symmetric distribution luminous around the axis vertical with a cover of polycarbonate with reduced optical control of the luminous flux distribution (*Figure 1*). The luminaries, equipped with 150W clear HPS lamps, were mounted in one sided installations, 6.5-7 m high on streets with dense vegetation, specially orange trees on both footpaths. The geometry and heights of the luminaries generated intense shadows on footpaths. The level of illumination in the area was insufficient. The correction to this problem consisted of increasing the efficiency and control of the luminous emission of the luminaries, adding to them simple controls of the luminous flux distribution, for example shields -*Figure 2*-. The criterion adopted in this project was to use accessories and simple procedures of low cost, to facilitate a process of improvement of the optical operation of the devices, promoting the adoption and reproduction to municipal administrations with limited financing.

Figure 1.- Luminarie before the retrofitting.

Figure 2.- Luminarie after retrofitting.

New Public Lighting System

The new lighting system was composed by a two sided alternated posts distribution with shielded luminaries with 100W HPS lamp (similar to *Figure 2*), 5 m high, aimed on the streets, with a separation of 40 m in each footpath (20 m between consecutive posts).

The illumination before and after the retrofitting

The calculated levels of average horizontal illuminance on streets and footpaths are compared in *Table 1*. The results show an improvement of the average values, being the retrofitting efficient also with respect to the energy consumption, since the power installed by block has been reduced in a 20%, whereas the average levels are practically duplicated. Paradoxically, the increase of the levels of road illuminance could be counter-productive to the effects of the LP reduction, because the higher the illuminance,

Table 1. Illuminance Levels before and after retrofitting.

Place	**Average horizontal, vertical Iluminances and uniformities - [lux]**					
	Before			*After*		
	Eh	Min/Avg	Min/max	Eh	Min/Avg	Min/max
Street	11.6	0.33	0.16	21.9	0.36	0.1
Footpath left	11.9	0.34	0.17	14.2	0.34	0.11
Footpath right	5.7	0.49	0.23	13.1	0.33	0.1
Ev window at 7m high. Pos.1	13.2	0.94	0.89	0.57	0.52	0.33
Ev window at 7m high. Pos.2	5.6	0.97	0.94	0.87	0.45	0.20

the larger is the road reflected component towards the atmosphere; but this increase is compensated with the screening of the reflected flux by the dense vegetation existing on the streets[8, 9].

Facade luminance before and after the retrofitting

Table 2 shows the variation of facade luminance measured at different heights, before and after the retrofitting on a 10 floor building. *Figures 3* and *4* show the facade before and after the retrofitting.

Table 2. Luminance in building facade [cd/m^2]

Distance to ground [m]	4	6.5	9	11.5	14	16.5	19	21.5	24
Before Retrofitting [cd/m^2]	2.6	4.4	1.8	0.65	0.5	0.42	0.38	0.35	0.28
Alter Retrofitting [cd/m^2]	2.5	0.6	0.5	0.41	0.34	0.32	0.31	0.3	0.24

Figure 3. Facade before retrofitting

*Figure 4. F*acade after retrofitting

Evaluation of results

Table 3 shows both types of luminaries used before and after the retrofitting and its corresponding percentage of $ULOR_{INST}$ emitted from their mounting position.

Analyzing the upward light emission for both luminaries, is evident that luminarie Nº2 not only fulfills the E3 zone requirements indicated in [1], but that also can be used in zones of the E2 type, that is in rural areas. In summary, the retrofitting was successful not only from the point of view of the improvement of the efficiency of electrical energy consumption, but also on outlook, security and visual guidance of the public space.

Table 3. Main characteristics of the analyzed luminaries

Nº	**Luminarie**	**closing**	**lamp**	**Efficiency [%]**			**Glare control**
				Inf. emission (0-90º)	*Sup. emission (90-180º)*	*Total*	
1		Clear polycarbonate	HPS 150W	51%	31%	82%	Non-cutoff
2		Clear polycarbonate	HPS 100W	75%	5%	80%	cutoff

In addition to this photometric evaluation, a neighbors assessments evaluation were performed about visual aspects of the zone. The results, commented in another work[12], suggest that the sensitivity of the neighbors to the potentially offensive effects of the public illumination is low. This data indicates a subject for further investigation to establish the visual comfort indicators for the population of the region.

Evaluation in a rural town

This section includes the analysis of the existing public lighting system in the rural village named “El Puestito” (26º25’55” S, 64º45’6” W), located 75 km away to the Northeast from the city of San Miguel de Tucumán. It is a rural population of approximately 3500 inhabitants living in 500 houses, distributed in a surface of approximately 500 km^2. There is a nucleus of 100 houses and 500 inhabitants, around the official dependencies such as the Administration of the Commune, the Center of Primary Attention of Health, the Police Station, the Buses Terminal and stores. An important area of the commune is placed in the Yungas region, subtropical moist forest which encompass a narrow belt N–S on the West slope of the mountains from the Northwest Argentina to Venezuela. El Puestito is placed at the low Yungas (500 – 1200 m osl).

Public Lighting

The Public Lighting system at this village consists of two types of luminaries, fixtures of symmetrical luminous distribution around the vertical axis provided with a glass cover similar to already analyzed in the residential area (type Nº1) and globes, both equipped with 250W HPMV tungsten-ballasted lamps (see figures of *Table 4*). The luminaries type Nº1 are mounted in wood posts, 5 m high, with a arm of 0.50 m, an approximated amount of 60 dispersed units are installed in the zone. The globes, 23 units, are concentrated along an avenue, with a spacing of 20 m between posts 5 m high.

Table 4. Main characteristics of the analyzed luminaries in a rural town

Nº	Luminarie	closing	lamp	Efficiency [%]			Glare control
				Inf. emission (0-90º)	*Sup. emission (90-180º)*	*Total*	
3		Opaline polycarbonate	HPMW 250W	35%	40%	75%	Non-cutoff
4		Opaline polycarbonate	HPMV 250W	45%	31%	76%	Non-cutoff

Classification of the zone according to CIE 126

In the area there are two zones with different levels of environmental luminosity, morphology and habitat characteristics. The urban center or populated zone (E3) and the fields with dispersed houses (E2). According to CIE in both zones the maximal upward emission of luminous flow should be 15% for the E3 zone and 5% for the E2 zone. *Table 4* shows the photometric characteristics of emission of luminous flux of both types of luminaries. None of the luminaries fulfills the maximum limits of emission of upward luminous flux, being highly polluting from the point of view of the CIE recommendation. Particularly, the luminaries type globe, emits upwards 40% of the available luminous flux and 35% downwards. Besides, if we consider that the zone of interest to illuminate is within the area limited by the angles of emission of 60º with respect to the vertical axis, we conclude that it is an extremely inefficient luminarie to solve the lighting demand.

Influence of the artificial light source in the quantity of insects observed in the proximities of a luminarie.

The trajectory of the moon from its appearance in the horizon to the sunrise, is used by most of the species of insects as direction and point of reference for the fulfillment of certain vital cycles, whereas during the periods of dark moon, the activities of the insects are modified to fulfill other different vital cycles (larval state, feeding, growth and reproduction). Some species of insects complete all their vital cycle during only a complete lunar cycle of 28 days, being the presence and/or absence of lunar light the indicators of beginning and/or end of each vital cycle[11]. This means that in absence of moonlight, a greater amount of insects "is disoriented" in their cycles by the presence of an artificial light source, being attracted by this one until its death in most of the cases, thus interrupting some of its vital cycles and being in danger therefore the continuity of the species[11].

We are carrying out an experiment with light-traps in order to determinate the amount of insects by order trapped by light sources of different color temperature[14]. Preliminary results are showed in *Table 5* where are summarized the amount of insects trapped according to the color temperature of the luminous source.

Table 5. Amount of insects by order

Tc[K] Source*	Coleoptera	Diptera	Hemiptera	Homoptera	Hymenoptera	Lepidoptera	Neuroptera	Total
Tc < 2800K	60	182	68	129	91	27	7	564
Tc > 4000K	117	316	99	106	224	194	4	1060

- Tc < 2800K: corresponds to CF warm white and HPS lamps
- Tc> 4000K includes CF cool white, HPM and MH lamps

The orders of insects verified in the traps were *Coleoptera* (beetles), *Diptera* (flies, mosquitoes, black flies), *Hemiptera* (bugs), *Homoptera* (leafhoppers, cicadas), *Hymenoptera* (ants, bees, wasps), *Lepidoptera* (butterflies, moths), *Neuroptera* (libelullas or dragon fly).

We can observe that the luminous sources whose Tc > 4000K, attracts until 50% more of insects in each order, except in the orders Homoptera and Neuroptera, where the attraction is similar.

In the zone object of this evaluation, the presence of 23 globes with 250W HPMV tungsten-ballasted lamps directed in all directions is sufficient to attract a great amount of insects during the phase of dark moon, with the consequent ecological damage to all the biological chain of the affected zone.

The solution to this problem is the replacement of luminaries type globe by others with screening systems to direct the light towards the zones where it is really needed, that is, towards horizontal surfaces like roads and footpaths. Replacement of light source is other subject not less important, because a more adequate light source should be whose characteristic wavelength

and color temperature differs substantially from the full moonlight, for instance HPS lamps, temperature color around 2000K with lower effects in the attraction of insects.

Recommendations about luminaries

Considering the light distributions of the studied luminaries and the way that the outdoor space is used by inhabitants and visitors as well as energy efficiency and minimal upwards light emission, it is recommended to install luminaries like the types shown in *Table 6*.

The luminarie type Nº5 is adequate for lighting systems of parks and gardens equipped with 150W clear HPS lamp, with a ring of metallic louvers to avoid glare; being this luminaries the better to replace the 23 globes of the access avenue. The luminaries type Nº6 is the same that the luminaries (type Nº1) in the rest of the commune, but equipped with 150W HPS lamp and with metallic screen (similar to type Nº 2). Both luminaries substantially diminish the environmental impact reducing the luminance contamination. Both luminaries fulfill the requirements of the recommendation [1] for zones E2 and E3.

Table 6. Main characteristics of the proposals luminaries

Nº	**Luminarie**	**closing**	**lamp**	**Efficiency [%]**			**Glare control**
				Inf. emission 0-90º)	*Sup. emission (90-180º)*	*Total*	
5		Clear polycarbonate	HPS 150W	41%	15%	56%	Semi-cutoff
6		Clear polycarbonate	HPS 150W	73%	5%	78%	Cutoff

Evaluation of intrusive light at a astronomical observatory

The influence of the dispersed light in the atmosphere around an astronomical observatory was carried out in a area of the Calchaquies Valleys, an semiarid Andean canyon land placed along 156 km at the West of the Tucuman City. The observatory is on a hill of a place called Ampimpa, 2600 m osl. The economic activities of this region are based on goat cattle breeding, agriculture of subsistence, small wine yards, paprika farming and mills, elaboration of crafts and tourism.

The main sources of dispersed light are the public lighting systems of two nearby towns: Amaicha del Valle (2000m osl, 5000 inhabitants, 360 sunny days per year) 8 km away from the observatory and Santa Maria (1800 m osl, 25000 inhabitants), 30 km away on the southwest direction of the valley.

The public lighting of the towns and roads around the observatory are composed mainly by luminaries type Nº 1 with clear HPS 150W or 250W HPMV tungsten ballasted lamps and shielded fixtures (type Nº 2) with incandescent 75–150W lamps. The urban design of the towns follows a "chess board" distribution of streets organized around a main square. The glaring effects of a small amount of luminaries on the road near the observatory are reported by the telescope operators. *Figure 5* shows a nocturnal view of the distribution of luminous points around the observatory, specially the lights from Santa Maria City, with an amount of 1500 HPS lamps.

Measurements of vertical (Ev) and semi cylindrical (Esc) illuminances were performed on the dome of the observatory's telescope, aiming the detectors towards the two towns. The average results are recorded in *Table 7*.

Table 7. Vertical an Semi cylindrical illuminances on observatory's telescope window

Measurement target from Observatory dome (26º36 S , 65º 53 W)	E_v [lux]	E_{Sc} [lux]
Amaicha (26º 36 S, 65º 55 W)	0.01	0.30
Santa María (26º 40´S, 66º 3´ W)	0.02	0.32

The analysis of these results suggests that the semi cylindrical illuminance Esc could be a most significant photometric magnitude of the dispersed light reaching 180º around the detector.

Conclusions

The three cases described are different in urban environmental and inhabitants characteristics as well as by geographic and climatic aspects, but have a common link, the use of a similar inadequate technology for public lighting. The experience carried out at the urban residential area of San Miguel de Tucumán city shows that introducing simple and low cost modifications is possible to control lighting pollution and intrusive light as

Figure 5. Nocturnal view from the observatory. To the left, far lights of Santa María city, to the right, near lights of Amaicha del Valle town.

well as to increase energy efficiency. Another important objective was to enhance footpaths lighting in zones with dense and medium heights vegetation.

Although the magnitude of the pollution in the rural areas has still not been estimated in our studies, is possible to emphasize the multiplying effect of this study on the rural towns of Argentina and the region where the technological standards and design criteria are similar to the analyzed ones in this work. The economical impact of the reduction of the public lighting electrical energy consumption in towns of the studied scale is large. By example, in the smallest settlement studied, El Puestito, the monthly cost of electrical energy destined to public lighting represents currently around 60% of the total electric bill of the commune[10]. As the research work progress, more valuable data will be available to contribute on these very important questions related with the environment, the comfort and security of the inhabitants and the economy of rural towns.

Figure 6. Astronomical observatory used for pedagogic and divulgations proposals in Ampimpa (hill in a semiarid Andean canyon land placed along 156km at the West of the Tucuman City -26º36 S , 65º 53 W. The main sources of dispersed light are the public lighting systems of two nearby towns: Amaicha del Valle (2000m osl, 5000 inhabitants) 8 km away from the observatory and Santa Maria (1800 m osl, 25000 inhabitants), 30 km away on the southwest direction of the valley.

Figure 7. type reflector, diameter 28 cm, luminosity f8, eyeglass interchangeable

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