LUX PACIFICA 2002

Title: **A Design Metric to Evaluate Sky Glow**

Authors: Swapna Sundaram, Yukio Akashi, Michele McColgan
Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY

ABSTRACT:

The purpose of this paper is to propose a method to evaluate the amount of sky glow resulting from a given exterior lighting scenario, by comparing the performance of various types of cutoff luminaires in an open parking lot application. This includes measurements of illuminance in the field as well as calculations using commonly used computer programs. Specifically, the study will evaluate whether there is actually a difference in the amount of light projected upwards for different cutoff types.

This study has attempted to find a valid calculation metric (for designers) to evaluate sky glow. This metric uses the summation of illuminance values on virtual calculation planes - one pointing downwards and located above pole mounting height, and four vertical planes, one located on each side of the parking lot - as an index of relative contribution of luminaires to sky glow. To verify the validity of the metric, illuminance in the parking lot was measured. Then, a computer software program which most closely simulated the site conditions was chosen to compare the relative contribution to sky glow from a wide range of commonly-used cutoff luminaires (full cutoff, cutoff, and semicutoff).

The findings may minimize the restrictions designers face in choosing site/roadway luminaires, and help in creating acceptable design layouts which conform to local and State guidelines.

Keywords:

Sky glow, parking lot, computer simulations, design metric, cutoff classifications, calculation planes, total lumens, light pollution index, lighting designers, design layouts, luminaire characteristics, illuminance uniformity

1. INTRODUCTION:

The Commission Internationale de l'Ėclairage (CIE) established guidelines for the effective minimization of "man-made" sky glow in 1997[1]. The intent of the guidelines was to minimize light emitted upward - either directly or as a result of reflection from horizontal or vertical surfaces - which can contribute to the already existing natural sky glow. In the United States, many communities have adopted lighting ordinances that are meant to reduce "man-made" sky glow. In this paper, the authors deal with "man-made" sky glow and refer to it simply as sky glow.

These guidelines and codes use simplified criteria to help designers choose proper luminaires to minimize sky glow; the CIE guidelines use $ULOR_{inst}$[a], and many state and local codes in the US restrict the luminaire cutoff classification[b]. However, it is still questionable if these criteria can precisely reflect the contribution of luminaires to sky glow. The $ULOR_{inst}$ ignores the reflective properties of the surfaces on which the light falls. It also ignores the

[a] $ULOR_{inst}$: Upward Light Output Ratio – Installed, defined as the amount of light (flux) emitted above the horizontal when the luminaire is mounted in its installed position; CIE Technical Report "*Guidelines for Minimizing Sky Glow*".

[b] The different cutoff classifications, as per the IESNA RP-33-99, are full cutoff, cutoff, semicutoff, and non cutoff[5]. These are differentiated according to the number (or percentage) of candela per 1000 lamp lumens that occurs at or above a vertical angle of 90° above nadir, as well as at or above a vertical angle of 80° above nadir. In the case of full cutoff, zero candela intensity occurs at or above 90° above nadir. For more information, refer to IESNA RP-33-99.

characteristics of the luminaire, while considering only the relative upward flux per luminaire. In terms of the cutoff classifications, how well these characterize the contribution of luminaires to sky glow has not been analyzed. Most governing bodies recommend the use of only full cutoff luminaires in order to reduce sky glow. However, in a recent study, Keith calculated Unit Uplight Density (UUD) for different luminaire cutoff classifications[2]. His results suggest that full cutoff distributions may not always provide the least amount of sky glow. Therefore, it is important to confirm whether the above described criteria can reflect the contribution of luminaires to sky glow and to establish a design metric that can appropriately evaluate the effects of luminaires on sky glow.

Most traditional methods of evaluating or calculating sky glow (star surveys, Walker's Law[3], Garstang's models) are mainly used by astronomers or scientists, and not by lighting designers. These prescriptive methods are of very large scale, and not easy to apply to localized applications like a street or parking lot. In addition, these methods do not take luminaire or ground surface characteristics into account, and do not consider IESNA illuminance uniformity recommendations. The above-mentioned UUD, proposed by J.F. Laporte in 1998[2], may be one of the most useful methods to quantify the effects of luminaires on sky glow. However, UUD deals with only the total amount of light emitted upward by a lighting installation, without considering the direction. Obviously, a candela distribution of the "site" in question would provide the most information. However, the study presented here is simplified to vertical and horizontal planes.

This paper presents a simplified design method to evaluate the effect of luminaires and lighting installations on sky glow. This method quantifies the contribution of luminaires with various cutoff distributions in a specific lighting application, for the benefit of lighting designers. This method can also roughly estimate the amount of light going in each direction.

2. OBJECTIVES

The objectives of the study are:

- To find a valid calculation metric (for lighting designers) to evaluate the effect of luminaires on sky glow, in terms of a suitable transfer and simulation mechanism from the field (site measurements) to the computer (calculation software);
- To study the effects of different types of cutoff luminaires on sky glow, for a specific application (parking lot in isolation);
- To study the effects of different types of cutoff luminaires on sky glow for different design layouts, depending on whether the average illuminance values for each layout are similar, or whether the minimum illuminance and max/min ratio for each layout are similar and meet IESNA recommendations.

2.1 Proposed Design Metric

The concept of the proposed design metric is to calculate the amount of light going upwards and sideward from a parking lot. This metric uses virtual interior elements to cover a parking lot, i.e., simulating a ceiling and four walls around the parking lot. Then, the metric calculates illuminance values on each of the five virtual planes, pointing downwards as well as pointing sideways. These illuminance values are converted into luminous flux values (lumens). These lumens are considered as indicators of light pollution, i.e. the light that is either not directly falling on the parking lot surface or the light that is reflected off the lot surface. This method can also roughly estimate the amount of light going to each direction, i.e., upward or sideward.

3. METHOD AND RESULTS:

This proposed method uses one of the most commonly used computer programs[c] for the lighting calculations. A preliminary study determined that this software most met the

[c] AGI-32, property of and copyright by Lighting Analysts Inc.

requirements of the proposed metric. To confirm the accuracy of the software, the following measurements were conducted.

An open parking lot in Rensselaer Technology Park, North Greenbush, New York, with seven full cutoff pole-mounted 400W Type-III luminaires using high pressure sodium (HPS) lamps, was chosen for the measurements. Figure-1 shows the daytime and nighttime views of the parking lot. The lot surface is composed of black asphalt, with an average reflectance (as measured on site) of 0.07. The dimensions of the parking lot are approximately 40.54m (135') x 54.05m (180') (area = 11,363.81sq.m). A lift truck and an illuminance meter were used to measure "sky illuminances" (with the sensor pointing down) at various points above the ground.

Parking Lot – Daytime View

Parking Lot – Nighttime View

Figure-1. Parking Lot

The lighting in the parking lot was then simulated with the software program. Comparing the measured illuminance data with the results of the computer simulation suggested that this software could have approximately 11% error on average due to the limitations of the software. Next, using this design metric, actual luminaires with different cutoff types were evaluated within the parking lot context.

3.1 Method of Luminaire Evaluations

The evaluations used the same parking lot (in isolation, surrounded by a grass edge extending 60m (200') from the edges in all 4 directions) for the actual simulations. A total of 18 pole-mounted luminaires, from different manufacturers and of different cutoff distributions, were chosen. Table-1 summarizes the characteristics of the luminaires. There are four full cutoff luminaires, seven cutoff luminaires, and seven semicutoff luminaires in total.

Table-1. Luminaire Characteristics

Luminaire and Cutoff Type	Efficiency (%)	Candela per 1000 lamp lumens at 90° vertical angle above nadir (%)	Candela per 1000 lamp lumens at 80° vertical angle above nadir (%)
Manufacturer-A:			
Cutoff1	82.20%	1.10%	5.40%
Cutoff2	82.20%	1.10%	5.40%
Semicutoff1	68.60%	0.58%	14.33%
Semicutoff2	71.90%	1.47%	19.18%
Manufacturer-B:			
Full Cutoff1	76.30%	0.00%	2.00%
Full Cutoff2	71.00%	0.00%	4.50%
Cutoff1	82.20%	0.20%	5.80%
Cutoff2	58.70%	0.30%	6.16%
Semicutoff1	73.40%	3.32%	19.91%
Semicutoff2	71.70%	1.20%	15.60%
Manufacturer-C:			
Cutoff1	75.50%	1.43%	7.42%
Cutoff2	76.10%	0.24%	1.45%
Semicutoff1	62.30%	4.67%	8.92%
Semicutoff2	56.40%	3.14%	19.80%
Manufacturer-D:			
Full Cutoff1	71.90%	0.00%	2.95%
Full Cutoff2	73.90%	0.00%	1.67%
Cutoff	74.10%	0.09%	3.73%
Semicutoff	70.50%	0.02%	14.16%

Two sets of analyses were conducted as part of the evaluations. The height (9m), wattage (250W), and throw (Type-III distribution) of each luminaire was kept constant.

The IESNA RP-20-98[5] recommends that the minimum illuminance level should not be lower than 2 lux, and max/min ratio should not exceed 1:20, for a parking lot. However, there are no requirements for the average illuminance value on the lot surface.

The first analysis attempted to keep the average illuminance constant for the different cutoff types. One layout was designed using each luminaire type, i.e. 18 layouts in total. Accordingly, luminaires in each layout were added or subtracted, and their locations shifted, until the desired average value was achieved (in an acceptable range of 25 lux; refer Table-2). In all cases, the minimum value and the maximum to minimum (max/min) value met IESNA requirements as mentioned above.

Table-2. "Average Similar" Sets of Calculations for each Luminaire Type

Cutoff Type	No. of Luminaires	Minimum Illuminance (lx) on asphalt	Max/Min Ratio on asphalt	Average (lx) on asphalt
Manufacturer-A:				
Cutoff1	7	6.4	10.36	**24.8**
Cutoff2	7	6.3	10.75	**24.7**
Semicutoff1	8	9.1	5.62	**21.3**
Semicutoff2	8	9.8	4.20	**22.5**
Manufacturer-B:				
Full Cutoff1	7	6.4	7.38	**25.4**
Full Cutoff2	8	7.3	6.01	**25.3**
Cutoff1	8	7.7	7.57	**27.4**
Cutoff2	8	5.7	8.54	**22.8**
Semicutoff1	7	7.7	7.21	**23.5**
Semicutoff2	8	9.1	6.23	**23.3**
Manufacturer-C:				
Cutoff1	8	11.5	3.13	**23.8**
Cutoff2	7	9.0	6.06	**23.3**
Semicutoff1	10	12.8	2.84	**23.4**
Semicutoff2	11	11.2	2.80	**22.0**
Manufacturer-D:				
Full Cutoff1	7	8.0	6.63	**23.7**
Full Cutoff2	7	6.5	7.97	**24.7**
Cutoff	8	6.0	7.88	**24.8**
Semicutoff	8	6.9	8.64	**24.5**

The aim of the second analysis was to adhere to IESNA guidelines in terms of illuminance uniformity. Again 18 layouts in total were designed, and the minimum illuminance and the max/min ratio on the lot surface were always kept within an acceptable range. Accordingly, luminaires in each layout were added or subtracted, and their locations shifted, until the desired illuminance uniformity values were achieved (refer Table-3).

Table-3. "IES Recommendations Similar" Sets of Calculations for each Luminaire Type

Cutoff Type	**No. of Luminaires**	**Minimum Illuminance (lx) on asphalt**	**Max/Min Ratio on asphalt**	**Average (lx) on asphalt**
Manufacturer-A:				
Cutoff1	7	**7.9**	**8.70**	27.2
Cutoff2	7	**7.4**	**9.43**	27.5
Semicutoff1	6	**7.9**	**7.35**	14.3
Semicutoff2	7	**7.3**	**5.38**	19.6
Manufacturer-B:				
Full Cutoff1	7	**6.4**	**7.38**	25.4
Full Cutoff2	8	**6.5**	**6.91**	25.1
Cutoff1	8	**8.0**	**7.23**	27.9
Cutoff2	8	**5.7**	**8.54**	22.8
Semicutoff1	7	**7.7**	**7.21**	23.5
Semicutoff2	7	**8.2**	**6.21**	19.7
Manufacturer-C:				
Cutoff1	7	**6.5**	**6.78**	21.0
Cutoff2	6	**6.3**	**8.76**	21.4
Semicutoff1	9	**7.7**	**6.53**	22.3
Semicutoff2	9	**6.5**	**5.75**	19.2
Manufacturer-D:				
Full Cutoff1	6	**6.8**	**7.32**	19.4
Full Cutoff2	7	**6.5**	**7.97**	24.7
Cutoff	6	**6.4**	**6.69**	19.5
Semicutoff	8	**7.9**	**7.39**	22.6

In both the analyses, five virtual planes were created—one horizontal ceiling plane pointing downwards and located 10.50m (35') above the ground (1.50m above the 9m high luminaires); one 10.50m tall vertical wall plane (with seven rows of calculation points at a spacing of about 1.50m on center) on each side of the lot, each located about 60m (200') away from the edge of the lot (refer Figure-2).

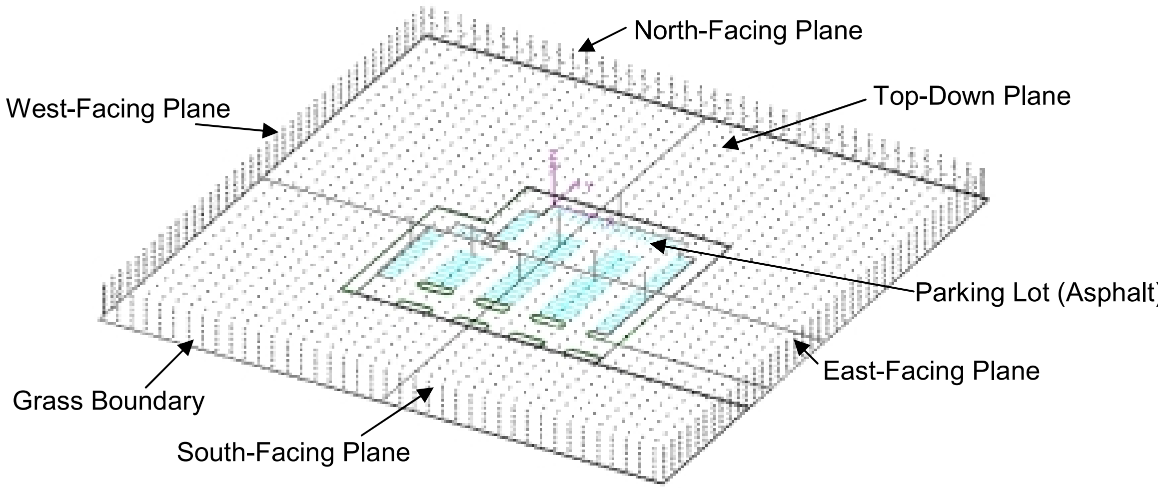
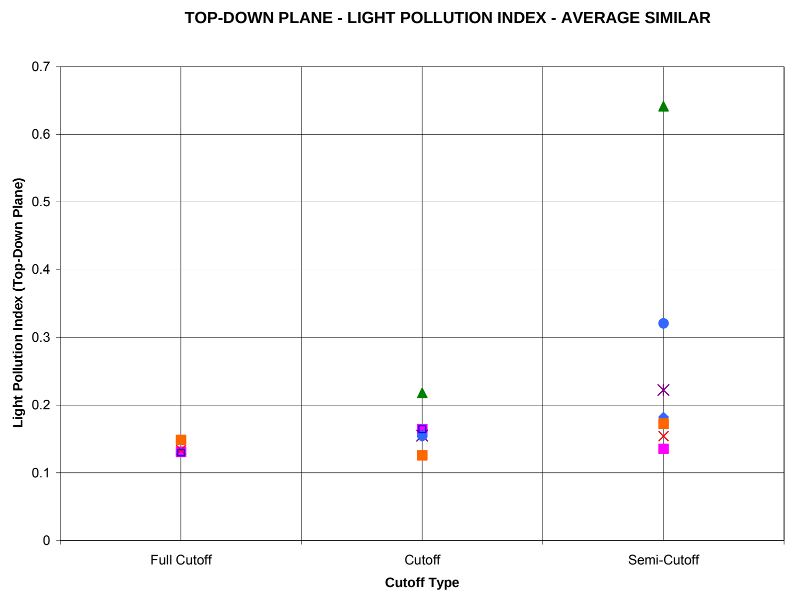


Figure-2. Computer Simulation of Parking Lot, Luminaires, and Virtual Calculation Planes

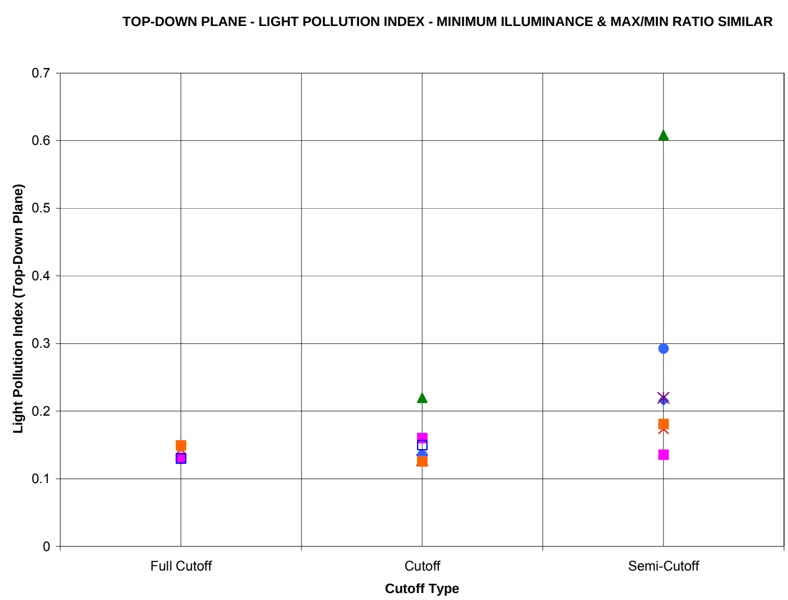
For each layout, once the desired illuminance level on the lot surface was achieved, the total luminous flux (in lumens) on the virtual top-down plane and on each of the four vertical planes was calculated. The lumens falling on the top-down plane and on the top four rows of the four vertical planes were considered as pollutant lumens contributing to sky glow because this is the light which, either directly or through reflection, reaches the sky. The lumen value on each virtual plane was divided by the lumens falling on the parking lot surface (useful lumens). This ratio, called the "**light pollution index**" or **LPI,** was then used as an indicator of sky glow, against which all results were analyzed.

3.2 Results of Luminaire Evaluations

In all the following graphs, the horizontal axis shows the cutoff classifications, and all luminaires in one cutoff classification are graphed on the same vertical axis (LPI). For the analyses of the top-down plane and all 5 planes, the LPI for the full cutoffs range from 0.13 to 0.15 for the four types of full cutoff luminaires used in this study. The LPI for the semicutoff luminaires range from 0.13 to 0.69 for the 7 semicutoff luminaires studied.



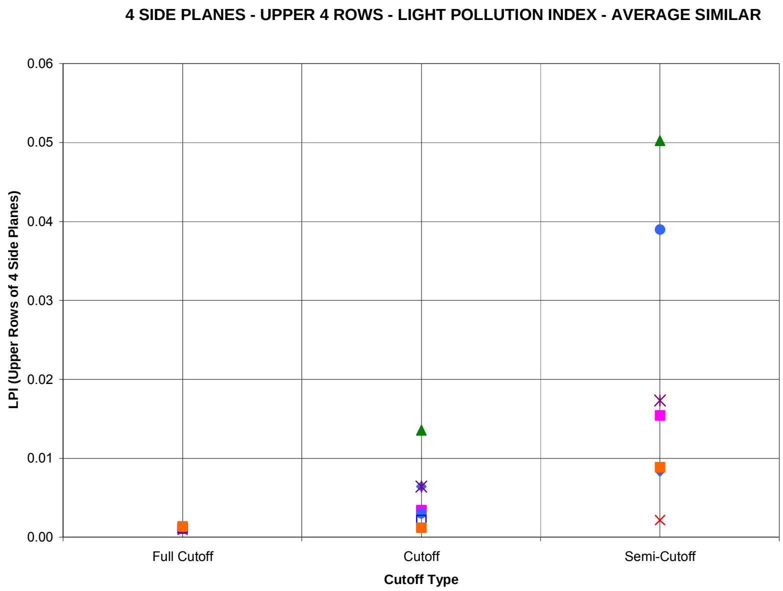
(a) Average Similar



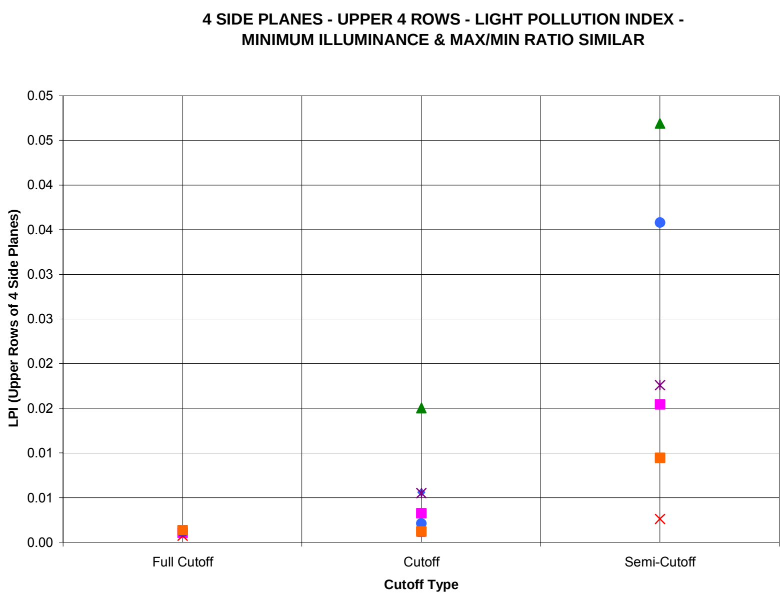
(b) Minimum Illuminance and Max/Min Ratio Similar

Figure-3. LPI Values for the Top-Down Plane

Figures 3 (a) and (b) show the LPIs on the top-down plane for the different cutoff distributions. Most of the cutoff luminaires, and even some of the semicutoffs, are in the same range as the full cutoff luminaires, i.e. contributing as much to sky glow directly above the installation. Although the full cutoffs do not emit any light directly above 90°, it can be inferred that their sharp cutoff angles, combined with the reflectivity of the ground surface, still contribute to this sky glow above.



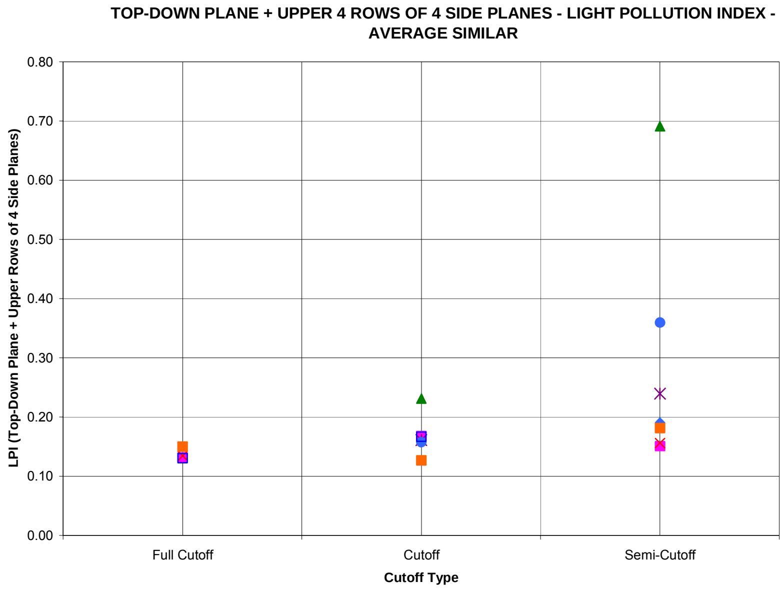
(a) Average Similar



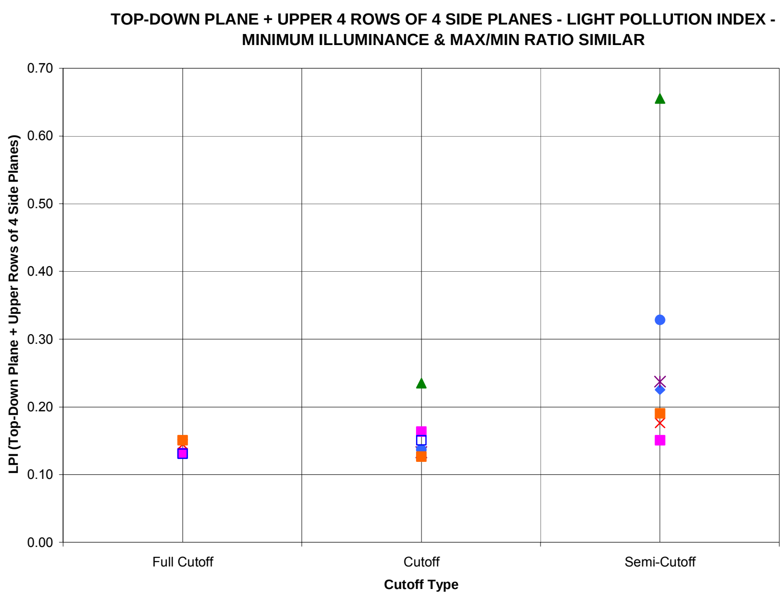
(b) Minimum Illuminance and Max/Min Ratio Similar

Figure-4. LPI Values for the Upper Part of the Four Vertical Planes

Figures 4 (a) and (b) show the LPIs on the upper rows of the four side-facing planes, i.e. the light falling either directly or through reflection, and thus contributing to sky glow to an observer looking above the site from a distance. Obviously, many of the semicutoff luminaires have a much higher LPI than the full cutoff and most of the cutoff luminaires. However, one of the semicutoff luminaires has a very low LPI.



(a) Average Similar



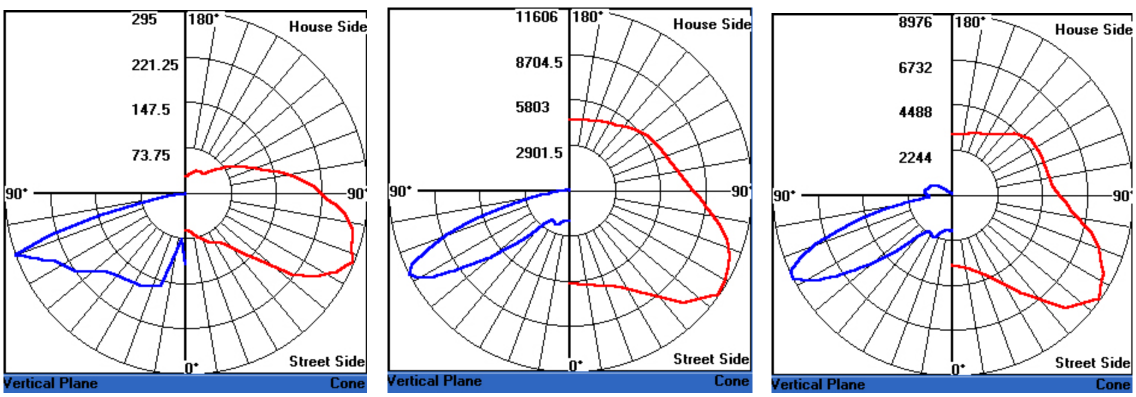
(b) Minimum Illuminance and Max/Min Ratio Similar

Figure-5. LPI Values for Top-Down Plane and Upper Part of the Four Vertical Planes

Figures 5 (a) and (b) show the combined effect of the lumens falling on the top-down plane as well as on the upper part of the side-facing planes, from all the three cutoff distributions. The data shows that the increase in cutoff distribution from full cutoff to cutoff to semicutoff in general increases sky glow lumens in all directions. However quite a few cutoff luminaires perform as well as full cutoff luminaires, and a few semi cutoffs perform almost as well.

4. DISCUSSION

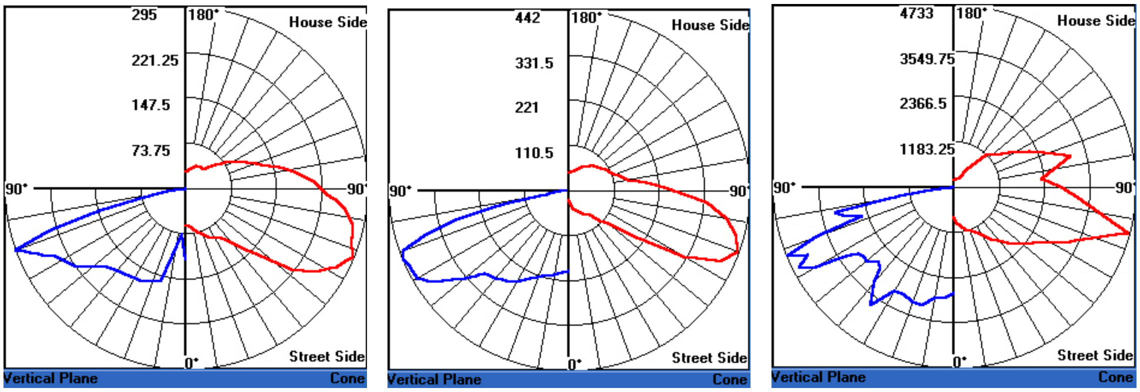
All of the previous charts and graphs indicate that full cutoff luminaires may not always contribute the least to sky glow in all directions. In the case of pollutant light going directly towards the sky, the reflectivity of the ground surface and the sharp cutoff angles of the full cutoffs could increase the amount of sky glow lumens due to reflected light. In the case of sky glow when looking in a sideways direction, the semicutoffs perform the worst in general, but some cutoffs and one semicutoff actually perform almost as well as full cutoffs. What this may mean is that in most cases the lighting designer can suggest a cutoff luminaire, or even a semicutoff, instead of a full cutoff luminaire, for a particular application in order to meet uniformity or average illuminance requirements, without increasing overall sky glow. This would depend on the distribution characteristics as well as the efficiency (%) of the cutoff or semicutoff luminaire under consideration, and how similar those are to the full cutoff luminaire. The following figures illustrate this point.



Full Cutoff2 (Manufacturer-B) Cutoff1 (Manufacturer-C) Semicutoff1 (Manufacturer-C)

Figure-6. Luminous Intensity Distributions—the Worst Performing Cutoff and Semicutoff Luminaires Compared to a Full Cutoff Luminaire

Figure-6 shows the luminous intensity distributions of three of the luminaires used in the analysis. The two cutoff and semicutoff luminaires in Figure-6 direct most of their light to the sides (vertical plane), and very little light below the luminaire. In addition, it can be assumed that the combined effect of luminaire efficiencies and the candela values per 1000 lumens at 80° and 90° in each case (refer Table-1) have resulted in the above cutoff and semicutoff luminaires being the worst-performing in terms of sky glow. These have the highest LPI values in all directions in their category, as compared to the full cutoff. It is also interesting to note that the layout using the above semicutoff uses almost the highest number of luminaires to achieve ground illuminance requirements, as compared to the other luminaire types (refer Table-2 and Table-3).



Full Cutoff2 (Manufacturer-B) Cutoff2 (Manufacturer-A) Semicutoff1 (Manufacturer-B)

Figure-7. Luminous Intensity Distributions—the Best Performing Cutoff and Semicutoff Luminaires Compared to a Full Cutoff Luminaire

Figure-7 shows the luminous intensity distributions of the same full cutoff (as shown in Figure-6) and two other cutoff and semicutoff luminaires used in the analysis. The two cutoff and semicutoff luminaires direct more light below the luminaire, and less above and to the sides as compared to the ones in Figure-6. In addition, it can be assumed that the combined effect of luminaire efficiencies and the candela values per 1000 lumens at 80° and 90° in each case (refer Table-1) have resulted in the above cutoff and semicutoff luminaires being the best-performing in terms of sky glow in their category. These have much lower LPI values in all directions, similar to the full cutoff luminaire.

It is important to remember, however, that when the lighting designer recommends a particular type of cutoff luminaire for a specific application in order to reduce sky glow, other issues such as aesthetics, brightness perception, sense of safety, illuminance uniformity, glare from the luminaires, and light trespass must also be considered before making such recommendations for either a new or retrofit installation. In addition, in order to meet ground illuminance uniformity requirements, it may be necessary to increase the number of luminaires (refer Table-2 and Table-3), and this may increase energy consumption in terms of the lighting power density (watts/sq.ft).

5. REFERENCES:

1. CIE Technical Report: *Guidelines for Minimizing Sky Glow*, CIE 126-1997. Commission Internationale de l'Eclairage, ©1997.
2. KEITH, DM. Roadway Lighting Design for Optimization of UPD, STV and Uplight. *J. Illum. Eng. Soc*. Summer 2000, 15-23.
3. IDA Information Sheet 11, *Estimating the Level of Sky Glow due to Cities*, International Dark-Sky Association, 1996.
4. SAN MARTIN, R & GARCIA M. Light Pollution: Information and Energy Waste. *Right Light 5*, May 2002, Nice, France, 57-62.
5. IESNA RP-33-99 *Lighting for Exterior Environments,* Illuminating Engineering Society of North America, ©1999.
6. IESNA RP-20-98 *Lighting for Parking Facilities*, Illuminating Engineering Society of North America, ©1998.

6. AUTHORS

Swapna Sundaram, Yukio Akashi, Michele McColgan
Lighting Research Center
Rensselaer Polytechnic Institute
21 Union Street
Troy, NY 12180
Phone: 518.687.7100
Fax: 518.687.7120
Email: sundas3@rpi.edu; akashy@rpi.edu; mccolm@rpi.edu

7. ACKNOWLEDGEMENTS:

The authors wish to thank Dr. Peter Boyce, and Dr. John van Derlofske at the Lighting Research Center for their invaluable guidance and advice, and Michael Myer, Janani Ramanath, and Shyamal Somaroo for their help at different stages of the project.