Technical Summary of Research into Unit Power Density & Unit Uplight Density

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Unit Power Density (UPD)

Unit Power Density (UPD) is the ratio of the connected power for a roadway lighting system to the corresponding area of the roadway. UPD directly describes the amount of connected electrical power required by the lighting system, but it also provides information on proportional changes throughout that lighting system. A 10% increase in UPD between systems using the same wattage lamps corresponds to 10% more of most everything except the wiring in the ground (because the project is still as long as it is): lamps, installed lumens, ignitors, ballasts, photocells, luminaires, poles, arms, brackets, foundations, electrical controls, energy use and cost, maintenance requirements and labor, as well as pollutions associated with equipment production, delivery, and installation and of course energy generation and transmission. The proportion may apply even to installation costs and labor, light pollution and mercury from spent lamps going into landfills. Comparisons between systems with different wattage lamps are less directly proportional, because the number of poles and luminaires may be significantly different (because of the significant difference in "coverage" for each pole). Even so such comparisons across wattages can be informative.

UPD is calculated for one "typical" luminaire cycle [1] as:

Eq. 1: UPD = (# of luminaires) * (watts / luminaire) *1.15 / (area of roadway)

The number of luminaires per luminaire cycle is two for staggered (used throughout this work) and opposite patterns and one for single-sided patterns. Watts are the total input watts for each luminaire (shown in Table 2). The factor of 1.15 is included to account for the anticipated spacing reductions in some areas, compared to the "typical" spacing calculated according to [2]. The area of the roadway is the extent of the traveled way, equal to the length of the luminaire cycle times the number of lanes times the width of each lane. Shoulders are not included in the area of the roadway.

Unit Uplight Density (UUD)

Unit Uplight Density (UPD) is the ratio of the upward flux produced by a roadway lighting system to the corresponding area of the roadway. The model assumes that the reflectance of the roadway and surroundings are perfectly diffuse, and treats the uplight from the luminaires in the same manner. The model assumes that the roadway is a repeating cycle, so any flux from one cycle that goes beyond either end of that cycle is exactly matched by flux from the adjacent cycles.

The UUD calculation sums direct uplight and reflected downlight and divides by the roadway area, using values corresponding to the "average LLF" [6]. The downward lumens "LumsDn" and the upward lumens "LumsUp" are calculated from the photometric file and adjusted for any difference between the rated lumens of the photometry and the lamp lumens in the roadway calculation, then multiplied by the average Light Loss Factor (LLFavg). The average LLF is taken as the average of the maintained LLF (LLFmaint) and 1.0, and applied to the upward and downward lumens and also to adjust the illuminance onto the roadway (Eavg) from the maintained value to the average value. The reflected light was calculated as the sum of the roadway reflected light and the off-roadway reflected light. The roadway reflected light was calculated as the roadway reflectance times the roadway lumens, which was calculated as the average illuminance value times the roadway area. The off-roadway reflected light was calculated as the off-roadway reflectance times the off-roadway lumens, equal to the total downlight lumens minus the roadway lumens. The total downlight lumens were calculated as the number of luminaires per cycle times the downlight lumens per luminaire. The resulting value, when lengths are measured in meters, has units of lumens per square meter of roadway.

Eq. 2: UUD = [(#Lum * LumsUp * LLFavg) + (rhoRoad * Eavg * (LLFavg/LLFmaint) * Area) + (rhoOffRoad * {#Lum * LumsDn * LLFavg - Eavg * (LLFavg/LLFmaint) * Area})] / [Area]

Roadway reflectance (rhoRoad) was set at 0.07, the default Q0 value for R3 pavement [2], which is the roadway surface used throughout these calculations. Off-roadway reflectance (rhoOffRoad) was set to 0.18, the "Kodak average reflectance value". Area is the overall roadway width (the number of lanes times the width of each lane) times the LumCycle distance for the staggered layout. All the roadways have staggered layouts, so two luminaires are used when calculating lumens within each luminaire cycle.

The maintained LLF values used in the optimization calculations are shown in Table 2. For MHP, the maintained LLF is 0.50, so the average LLF (LLFavg) is 0.75 for all MHP systems. For HPS, the maintained LLF is 0.70, so the average LLF (LLFavg) is 0.85 for all HPS systems. The UUD values are all calculated using the average LLF, because typical roadway conditions - over both space and time - are midway between initial and maintained, so uplight calculations should be made at that level of maintenance.

The number of luminaires per luminaire cycle is two for staggered (used throughout this work) and opposite patterns and one for single-sided patterns. The area of the roadway is the extent of the traveled way, equal to the length of the luminaire cycle times the number of lanes times the width of each lane. Shoulders are not included in the area of the roadway.

UUD describes the amount of light that the system sends into the space immediately surrounding it. Of course the radiative transfer characteristics of that space significantly effect the amount, direction and even spectral profile of the radiation that reaches the atmosphere and potentially becomes redirected and appears as skyglow. The number of assumptions necessary to make such a model useful is very high, and most of the assumptions would need to vary depending on locality and even the specific project. For UUD, the significant variables can be reliably predicted by lighting designers.

Research Scope

The research discussed here has three steps: preliminary, intermediate and advanced. These three steps correspond roughly to [3], [4] and [5]. Each step includes evaluations of luminaire photometric data across a series of appropriate standardized roadways. The calculation procedure optimizes the roadway lighting design for each combination of photometric file and roadway, by determining the system geometry with the maximum distance between luminaires which still meets all the criteria. The optimum system's UPD and UUD values are calculated and evaluated by comparisons between source types, roadways, cutoff classifications, design criteria, rated lumens and Light Loss Factor. In addition, some design constraints - such as "no overhang allowed" - were investigated.

Calculation Procedure: Overview

The procedure discussed here has two steps: One and Two. These labels refer to the number of variables over which each optimization is made. The optimization routines adjust the system geometry of luminaire cycle distance, mounting height and possibly overhang/setback, to find the design with the greatest distance between luminaires which still meets the design criteria.

For procedure One, the luminaire is assumed to be located over the edge of the traveled way. Only the mounting height is varied to find the maximum luminaire cycle distance for luminaires located on the edge of the traveled way.

For procedure Two, the overhang/setback of the luminaire is varied as well as the mounting height, to find the maximum luminaire cycle distance.

Both procedures are optimizing a single combination of luminaire and roadway. This means that the photometric distribution, rated lumens, light loss factor and luminaire orientation are constant during the optimization procedure. The roadway characteristics of the number of lanes, width of each lane and the surface classification are kept constant through the optimization. Finally, the design criteria which correspond to the roadway classification are constant during the optimization.

Both procedures use a software routine which calculates the performance of a roadway lighting design according to [1] and compares the results to the relevant criteria from [1] to determine if the design meets the requirements. This single-calculation-and-comparison routine is called reiteratively by a routine which compares the results of the most recent single-calculation-and-comparison to earlier results and then either branches the program flow or makes changes to the system geometry in preset steps and proceeds with the next iteration.

Calculation Procedure: One

For procedure One, the reiteration starts with a low value (specified by the input file) for the mounting height and it calculates a corresponding short distance for the luminaire cycle distance. The single-calculation-and-comparison routine is called and the design calculations performed and returned. If this initial design does not meet the criteria, either the mounting height or luminaire cycle distance is increased and the procedure continues. Otherwise the process repeats with increasing luminaire cycle distance values, until the maximum-for-that-mounting-height is determined. This occurs when the results for the design with the next longer luminaire cycle distance do not meet the design criteria. The luminaire cycle distance that is the last-that-meets-the-criteria is also the maximum-for-that-mounting-height.

The mounting height is increased by one step and the process is repeated to determine the corresponding maximum-for-that-mounting-height. The two maximums are compared, and if the maximum-for-the-higher-height is equal to or greater than the maximum-for-the-lower-height, the routine continues with the next higher mounting height. Otherwise, the maximum-for-the-lower-height is the maximum for the combination of roadway and luminaire, so the routine records the design details in a file as the optimum.

Calculation Procedure: Two

The extension to procedure Two uses all of procedure One inside a reiterative routine which adjusts the overhang/setback and compares the maximum luminaire cycle distance found for each overhang/setback to the others to direct the calculations. The overhang/setback is the value corresponding to the horizontal distance perpendicular to the direction of travel between the edge of the traveled way and the luminaire position. Overhang/setback is positive when the luminaire is located over the traveled way and negative when the luminaire is located away from the traveled way.

Initial, Incremental and Final Values for Optimization Procedure

The initial mounting height is set in the optimization input file. For 150W or 175W luminaires, the initial mounting heights were set to 5 meters. For 250W and for 400W luminaires, the initial mounting heights were 6 meters. The increment for the mounting height is 0.5 meters throughout. The final mounting heights were 15 or 18 meters.

The initial luminaire cycle distance is calculated after each mounting height is set, as the distance equal to or less than two mounting heights and equal to an integer multiple of the step specified for the luminaire cycle distance. The increment for the luminaire cycle distance is 2 meters for the staggered layouts used throughout this research. The final luminaire cycle distance was recorded as the optimum for that combination of luminaire and roadway.

Design Criteria

The design criteria to be met are from [1] and shown in Table 1. The calculations use both the illuminance and the luminance criteria for the "base case" of these calculations, and each set of criteria separately for the "illuminance" case or the "luminance" case, as discussed below.

Table 1: Criteria from ANSI/IESNA RP-8-00

Classifications		Eavg			Eavg /	Lavg	Lavg /	Lmax /	Lveil/
Roadway	Area	R1	R2 & R3	R4	Emin		Lmin	Lmin	Lavg
Major	High	12.0	17.0	15.0	3.0	1.2	3.0	5.0	0.3
Major	Med	9.0	13.0	11.0	3.0	0.9	3.0	5.0	0.3
Collector	Med	6.0	9.0	8.0	4.0	0.6	3.5	6.0	0.4
Local	Med	5.0	7.0	6.0	6.0	0.5	6.0	10.0	0.4

Notes: - The units of Eavg are lux, the units of Lavg are cd/m2.
- For the Illuminance method, the Eavg value (appropriate to the roadway surface), the Eavg/Emin ratio and the Lveil/Lavg ratio, comprise the set of criteria.
- For the Luminance method, the Lavg value, the Lavg/Lmin ratio, the Lmax/Lmin ratio and the Lveil/Lavg ratio, comprise the set of criteria.

As discussed in the notes to Table 1, the criteria for each method must be met as a set - all the relevant criteria must be met for the design to meet the criteria. Therefore these are average magnitude, uniformity and veiling luminance requirements for every system considered in this work.

Luminaire and Lamp Data

Two different sources each have three different wattages included in this work. The sources are High Pressure Sodium (HPS) and Metal Halide Pulse-start (MHP). The three wattages correspond to small, medium and large: 150W for HPS and 175W for MHP; 250W; 400W.

The photometric distributions were all applied using standard values for the rated lamp lumens [7,8] and the Light Loss Factor (LLFmaint). In addition, the UPD values were calculated using standardized wattage values. Table 2 shows the values used throughout these calculations.

Table 2: Luminaire and Lamp Data

Source	Wattage	Rated Lumens	Luminaire Input Watts	LLFmaint	LLFavg
HPS	150	16,000	166	0.70	0.85
	250	27,500	295	0.70	0.85
	400	50,000	460	0.70	0.85
MHP	175	17,500	210	0.50	0.75
	250	21,500	295	0.50	0.75
	400	44,000	455	0.50	0.75

Photometric Files

The photometric files used in this research are a (still-growing) collection of files provided by many sources. Each file is made anonymous, analyzed and classified according to the IESNA distribution and cutoff definitions for roadway luminaires [1]. The set of files used for the preliminary phase of the research was increased for the intermediate and advanced phases, and a few files were dropped when they did not work properly with the optimization procedures (typically these files represented "poor performers" in the situations where they did work properly.) Some near-duplication exists, because files with and without house side shields may be effectively the same on the roadway side, but must both be included in the set of files because only such testing can confirm that they are effectively the same.

The photometric files were grouped by lamp wattage. A standard value was used for the "rated lumens" of each file (along with scaling automatically applied as necessary in the calculations) as discussed above and shown in Table 2.

The files were also grouped by IESNA cutoff classification [1], which includes full cutoff (FC), cutoff (CO), semi-cutoff (SC) and non-cutoff (NC).

For the preliminary phase, 73 photometric files were included, all HPS, in three different wattages and three different cutoff classifications. Because there were no non-cutoff files for some wattages, all non-cutoff files were excluded for this phase. The distribution of the files is shown in Table 3.

Table 3: Photometric Files, Preliminary

Lamp Wattage	Total	FC	CO	SC
150	18	2	7	9
250	17	5	6	6
400	38	8	16	14

For the intermediate and advanced phases, a total of 387 photometric files were included, 153 MH and 234 HPS, in three different wattages and including all four different cutoff classifications. The distribution of the files is shown in Table 4.

Table 4: Photometric Files, Intermediate and Advanced

Lamp	Wattage	Total	FC	CO	SC	NC
HPS	150	67	17	20	14	16
	250	70	30	19	14	7
	400	97	28	36	21	12
MH	175	59	25	6	13	15
	250	47	27	4	9	7
	400	47	20	16	4	7

The photometric files were also evaluated for completeness, because some files did not have complete intensity data for the upper hemisphere. These files had to be excluded from uplight calculations. The reduced set of files used for the uplight calculations is shown in Table 5.

Table 5: Photometric Files for Uplight Calculations, Intermediate and Advanced

Lamp	Wattage	Total	FC	CO	SC	NC
HPS	150	45	17	11	7	10
	250	44	30	8	6	0
	400	55	28	20	7	0
MH	175	50	25	6	10	9
	250	30	27	2	1	0
	400	33	20	7	4	2

In the advanced phase, the MH files were used with rated lumens for pulse start lamps, as described above, but no other changes were made.

Roadway and Area Classifications, Roadway Widths and Surface

The photometric files were applied to standard roadways which represent most of the full range of roadway criteria [1]. For the typical roadways investigated in this work, the roadway classification varies from local to collector to major, while the area classification is typically "medium", except for a few runs made with the "major high" combination to investigate the relative change in UPD values [5]. Theses combinations are discussed in detail below.

The photometric files were applied to standard roadways of varying widths, associated with the classifications and representing a full range of sizes. Each roadway width consists of the traveled way and does not include shoulders.

The roadway widths used in this work relate to the number of lanes, with between 3.5 and 4 meters as the width of each lane, depending on how it comes out to make an even total width for the roadway. For a given roadway, every lane is the same width, so the four lanes in a 13 m wide roadway are each 3.75 m wide. The summary of roadway width and number of lanes is shown in the first two columns of Table 6 below.

The combinations of roadway classification and width were combined again with the lamp wattages as shown in Table 6 below. The lower wattage lamps were used for local and collector roadways up to two or three lanes wide, while the higher wattage lamps were used for the collector and major roadway for all widths up to six lanes. The 250W lamps were used with all combinations.

Some combinations shown in Table 6 were not included in the preliminary phase and were added for the intermediate and advanced phases, and these combinations are shown in italics in Table 5.

Table 6: Roadway and Lamp Wattage Matrix

Roadway Class		Local	Collector	Major
Widths (m)	Lanes			
4	1	150/175 & 250	*150/175, 250 & 400*	*250 & 400*
7	2	150/175 & 250	150/175, 250 *& 400*	*250 & 400*
10	3		150/175, 250 *& 400*	250 & 400
13	4			250 & 400
17	5			250 & 400
20	6			250 & 400

The roadways considered in this work all have R3 surfaces as defined in [1]. The Q0 is left at the default of 0.07 throughout.

Calculations: Different Phases

Calculations were made for every photometric file in every appropriate roadway configuration and design criteria for each phase. In the preliminary phase, the calculations were only for the "base case" of meeting both the illuminance and luminance criteria together. This "base case" for design criteria is used throughout the research, with most comparisons being made relative to that case. As shown in the results, this "base case" does represent a more stringent set of design criteria than either illuminance or luminance alone. In the intermediate phase, al the appropriate combinations of the expanded photometric set and roadway & wattage matrix were all calculated for the "base case"

For the preliminary phase, 6,887 calculations were recorded, for each step from the initial "assumed" system to the final possibility at the limit for the mounting height (and with the luminaire located at the edge of the roadway, as discussed above.) This allowed for inspection of the optimization routine as the calculation proceeded along the path to optimization for mounting height. The results were evaluated and used for the further development of the optimization routine, as discussed above. The conclusion from this portion of the research [3] was that the optimization routine did work properly for the illuminance and luminance criteria (but not for the Small Target Visibility (STV) [1] criteria.)

For the intermediate and advanced phases, only the optimized systems were recorded. Over these phases, the combinations of design criteria and constraints were applied to some subsets of the photometric files and roadway configurations. These additional constraints are discussed in detail below.

The numbers of files, groups and runs calculated for the UPD calculations in the combined intermediate and advanced phases are shown in Table 7. The reduced number used for the UUD calculations are shown in Table 8. In those tables "#G" shows the number of groups - such as "C10s150H" - for that combination of lamp, wattage, criteria and constraints. For most groups, all appropriate photometric files were calculated, but in some only a subset were included (and the details are discussed below.) For these situations in Tables 7 and 8, after the number of groups there are numbers in parentheses, showing the number of photometric files in the subset that was calculated for each group in that combination. The standard (MH) and pulse start (MHP) calculations are shown separately, although as discussed above they differ only by the rated lumens values used and so could be considered one more variation.

As shown in Tables 7 and 8, the overall range of this research is wide and a number of individual situations were investigated. When comparisons are made, typically the "Base Case" is used and so that condition has the most complete set of calculations, including all of the roadway and wattage combinations shown in Table 6. For other situations - discussed in detail below - fewer combinations are included because completing the set of possible calculations is unnecessary, since the trends are evident within the reduced range, or the constraints are impractical. The "HPS LLF" calculations only included roadways with an odd number of lanes for Major, Collector and Local classifications. The calculations with the "Overhang" constraint only include roadway up to four lanes wide. The calculations using illuminance criteria were only made for 250W sources. Details about which combinations of roadways and sources were included in the calculations for which set of criteria and/or constraints can be found in Tables 10 and 11 below.

Table 7: Counts of Luminaires, Groups and Runs for Unit Power Density (UPD) Calculations

			Base Case		Luminance		OverHang		HPS LLF		Illuminance		Totals	
	W	#Lm	#G	Runs	#G	Runs	#G	Runs	#G	Runs	#G	Runs	#G	Runs
MHP	175	59	5	295	5	295	5	295					15	885
	250	47	16	750	11	517	9	423					36	1690
	400	47	14	655	9	423	7	329					30	1407
MH	175	59	4	236									4	236
	250	47	9	423	9(28)	252					9(28)	252	27	927
	400	47	7	329									7	329
	All	306	55	2688	34	1487	21	1047	0	0	9	252	119	5474
HPS	150	67	5	335	5	335	5	335	3	201			18	1206
	250	70	16	1120	11	770	9	630	6	420	9(33)	297	51	3237
	400	97	14	1358	9	873	7	679	5	485			35	3395
	All	234	35	2813	25	1978	21	1644	14	1106	9	297	104	7838
All		540	90	5501	59	3465	42	2691	14	1106	18	549	223	13312

Table 8: Counts of Luminaires, Groups and Runs for Unit Uplight Density (UUD) Calculations

			Base Case		Luminance		OverHang		HPS LLF		Illuminance		Totals	
	W	#Lm	#G	Runs	#G	Runs	#G	Runs	#G	Runs	#G	Runs	#G	Runs
MHP	175	50	5	250	5	250	5	250					15	750
	250	30	16	478	11	330	9	270					36	1078
	400	33	14	459	9	297	7	231					30	987
MH	175	50	4	200										200
	250	30	9	270	9(12)	108					9(12)	108	27	486
	400	33	7	231										231
	All	226	55	1888	34	985	21	751	0	0	9	108	119	3732
HPS	150	45	5	225	5	225	5	225	3	135			18	810
	250	44	16	704	11	484	9	396	6	264	9(16)	144	51	1992
	400	55	14	770	9	498	7	391	5	277			35	1936
	All	144	35	1699	25	1207	21	1012	14	676	9	144	104	4738
All		370	90	3587	59	2192	42	1763	14	676	18	252	223	8470

Calculations: Luminance and Illuminance

The calculations for luminance and illuminance differ from the "base case" by requiring that only one design method's criteria from RP-8-00 be met. For Illuminance, the criteria are average, uniformity ratio of average-to-minimum and veiling luminance. For Luminance, the criteria are average, uniformity as maximum-to-minimum and average-to-minimum and veiling luminance. Therefore every calculation meets criteria for the quantity of illumination, the uniformity of illumination and the allowable glare. The intent is to evaluate which design method allows for better system performance. This is part of the intermediate phase that was extended further during the advanced phase.

Calculations: Zero Overhang

The calculations for "zero overhang" were made with the system constrained to keep the luminaire at or set back from the edge of the roadway. This was achieved by resetting the range of overhang values in the parameters file for the optimization calculations for the group. The intent is to see if requiring that the luminaires have zero overhang makes a significant difference in the system performance, and in which photometric distributions perform best. This is part of the advanced phase.

Calculations: HPS LLF

The LLF for the HPS systems in this set of runs was changed from 0.70 to 0.50, a decrease of around 28% for the overall system. The change is described as a 40% increase [5] to allow for comparison with the changes made by the increase in rated lamp lumens for the MH systems using MHP lamps. The calculations for the adjusted Light Loss Factors with HPS systems were made for all the photometric files but only for roadway configurations with an odd number of lanes - one lane Local, one and three lane Collector, one, three and five lane Major. These calculation investigate two related aspects of the overall research. First is the change in overall performance compared to the scaled increase in "available lumens" and second is the confirmation that this LLF change works "equivalently" the change in lamp lumens works for the MH and MHP systems. This is not to say that the relative change is the same because the sizes of the changes are different - the rated lumens for the MHP are increases of 5% to 30%. What is of interest is confirmation that the size of the change in system performance is relative to the size of the change in the "available lumens" - regardless of whether that change is for MH or HPS, and whether it is applied through the LLF or lamp lumens. This is part of the advanced phase.

Calculations: Major High

The calculations for the Major High roadways were made with all the 250 and 400 Watt MHP and HPS photometry, for roadways from two to six lanes wide and meeting the "base case" design criteria. This changes only the average illuminance and luminance criteria, while the uniformity and veiling luminance criteria remain the same. The intent is to evaluate the increase in UPD (and installed lumens) as the illumination increases. This is part of the advanced phase.

Calculations: UPD and UUD

For each optimized system the corresponding UPD was calculated as described above. For each optimized system using luminaires with complete photometry, the corresponding UUD was calculated as described above.

Calculations: Groups, "Top 5" and "Top 10"

The specific combinations of roadway class, width, design method, design criteria, lamp type, and lamp wattage, along with specific restrictions or changes, were identified as a group.

Groups were identified by composite names, starting with the roadway class (M, C or L) followed by the total width (e.g. 07 for two lanes) followed by the criteria identifier followed by a tag for wattage (e.g. 40 for 400) and finished by a letter for the lamp type (H for HPS, M for MH and P for MH pulse start). A typical string - shown "mostly" in Table 9's header - is "C07s150H" for a collector roadway of 7 m width, meeting the standard (base case) criteria set for such a roadway using 150 lamps of HPS. The header in Table 9 has no "H" because this data is from the preliminary phase and only HPS lamps were used.

Each group was sorted by UPD, and the value associated with the fifth lowest UPD for the group was established as the criterion for that group's "Top 5". This procedure was repeated including only those photometric files with full cutoff distributions, to establish a group's "Top 5" UPD criterion for "full-cutoff only". All appropriate files in each group with UPD less than or equal to the "Top 5" criterion were averaged to produce the "averaged over the Top 5" UPD value for the group, separately for "any distribution allowed" and for "full cutoff only" (e.g. in Tables 10 and 11). Since different photometric files may produce optimized systems with the same UPD value, any group's "Top 5" may include more than five files. This procedure insures that at least five different photometric files are included in the group's "averaged over the Top 5" UPD value. Because of the possibility that systems have the same UPD value, there may be more than five systems that meet the "Top 5" criterion for a group.

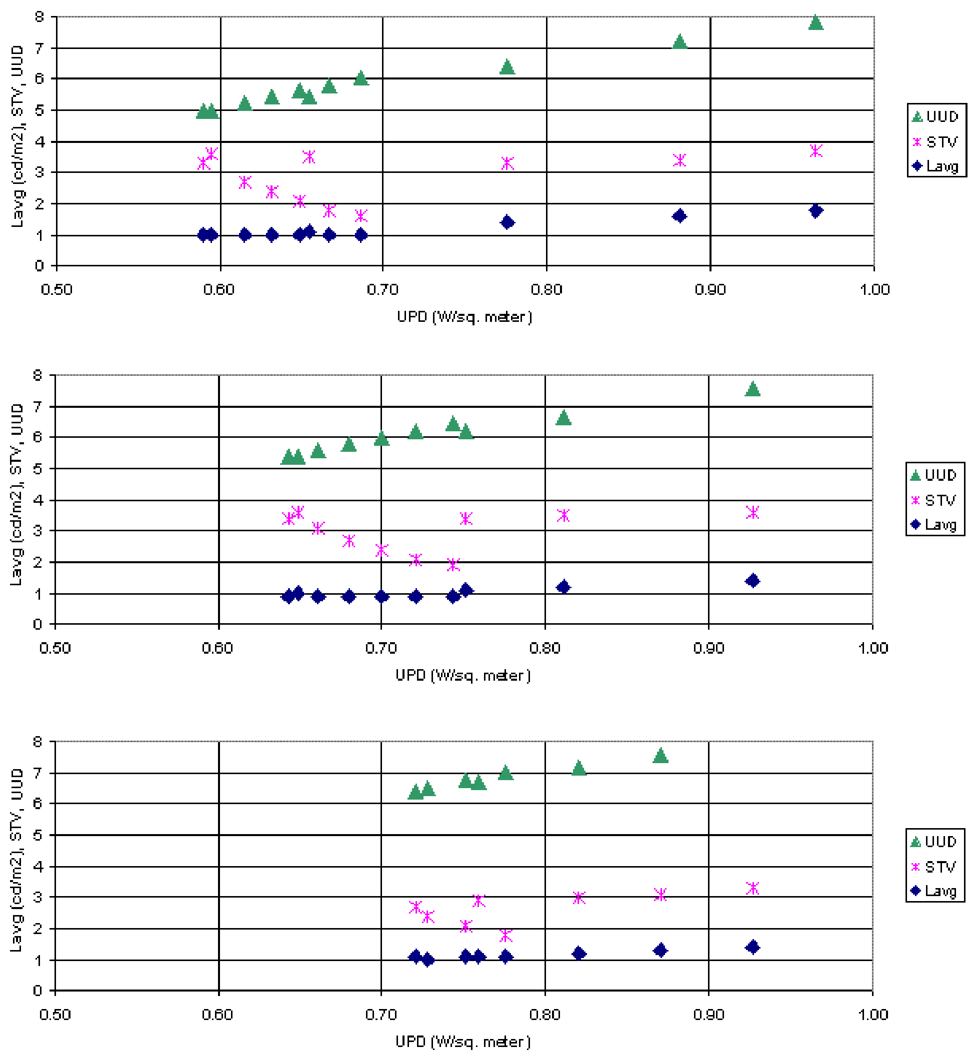
"Top 10" values were also established for every group, using the tenth lowest UPD value in the entire group. Because of the possibility that systems have the same UPD value, there may be more than ten systems that meet the "Top 10" criterion for a group.

This approach is introduced in the intermediate phase and applied throughout the advanced phase.

Results: Optimization, UPD and UUD

Results from the preliminary phase [3] demonstrate that the optimization routine identifies the system with the greatest spacing and therefore the lowest UPD for that configuration of lighting system and combination of roadway, photometric file and design criteria. Figure 1 shows the results for three different 250W HPS photometric files during optimization for a three lane major (medium) roadway.

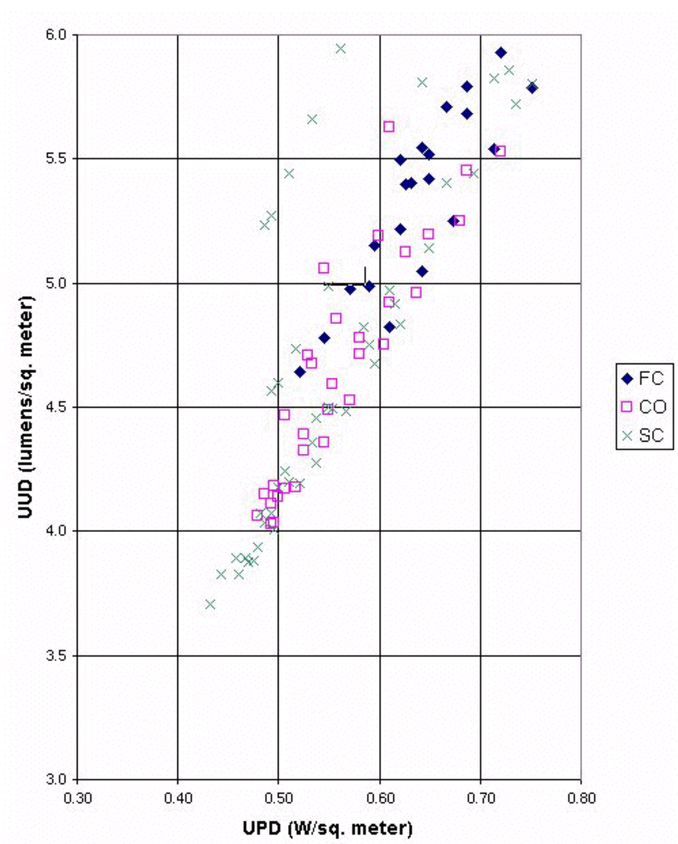
Figure 1: Lavg, STV and UUD values by UPD values for Different Photometric Files



The set of values for the first photometric file is on the top, and the second is in the middle, the third on the bottom. Each photometric file produces the best performance - defined as maximum spacing - among systems using that IESNA cutoff classification for that combination of wattage and roadway. Looking at the first one on top, there are three different metrics shown over the horizontal axis which is measured in UPD (Watts per square meter of roadway). The three values scaled together on the vertical axis are - from the bottom up - Lavg (average luminance in cd/m2), STV and UUD (in uplight lumens per square meter of roadway). The values of these three metrics are independent of each other, but each is related to UPD and - as shown - varies as the optimization procedure progresses.

The series of values shown are typical over the progress of the optimization routine. The optimization starts with low mounting heights, which correspond to high average luminance and short spacing - equal to high UPD values. So for each photometric files, the results from the start of the optimization are on the far right (or even off right hand side of the figure) and proceed to the left with each increase in mounting height - for a while. When the mounting height is relatively low, the limiting criterion will almost always be the uniformity, keeping the spacing from increasing any further for that mounting height, even though the average is more than its own criterion. As the mounting height increases, a particular combination of mounting height and spacing will appear that just meets the criterion for the average as it also just meets the criterion for uniformity. This is typically the system with the lowest UPD, shown in each of the three parts of Figure 1. As the mounting height increases further, the spacing becomes constrained by the average criterion instead of the uniformity criterion, shown by the succession of Lavg values of 1.0 in Figure 1. Clearly for each photometric distribution, the optimization routine can identify the system with the minimum UPD - the one with the maximum spacing.

Figure 2: Preliminary Phase UUD and UPD values for Collector 3 lane road with 250W HPS



The results also show that for a specific photometric file, lower UPD values correspond to lower UUD values. The relationship is direct for each of the three files.

Furthermore the results show that full-cutoff distributions did not provide the lowest UPD or UUD values among those evaluated. In Figure 1, the photometric distribution on the bottom is the best of the full cutoff (FC) for that roadway, and its best UPD value is 0.72 W/m2. The best cutoff (CO) distribution - shown in the middle - has a best UPD of 0.65 W/m2, while the best semi-cutoff (SC) distribution's value is 0.59 W/m2 - over 20% less than the best FC. The same trend appears across the UUD values as well. Figure 2 shows the results for the preliminary phase [3] for 250W HPS luminaires on three lane collector roadways.

It is obvious from this figure that among the best systems and for every specific system, increases in UPD always correspond to increases in UUD, but that two systems can have equal UPD while one has significantly higher UUD than the other. In general the lowest UPD and UUD values are for semi-cutoff (SC) distributions, while the best UPD values for systems with cutoff (CO) distributions are lower than the best UPD values for systems using full-cutoff (FC) distributions.

In the intermediate phase [4], each group was evaluated using presentations like Figures 3 and 4, showing a scatter plot of the average roadway luminance and UPD data pairs for each system in the group. In Figure 3, the group is C07s250H - collector two lane roadway meeting the base case using 250W HPS lamps - and in Figure 4 the group is C07s250M - the same but with metal halide lamps.

Each system has been identified by cutoff classification and is shown on these charts by the corresponding symbol. The distribution of the symbols shows the criterion for the average luminance at 0.6 cd/m2, and that some systems provide higher luminance than the criterion, and some of them do so with lower UPD values, providing more illumination at lower "cost" in terms of UPD.

Inspection of the these figures shows supports the discussions in this document about cutoff classifications, and comparison between the figures supports the discussion about the differences between sources.

Figure 3: UPD and Average Luminance for Collector Two Lane with 250 HPS (C07s250H)

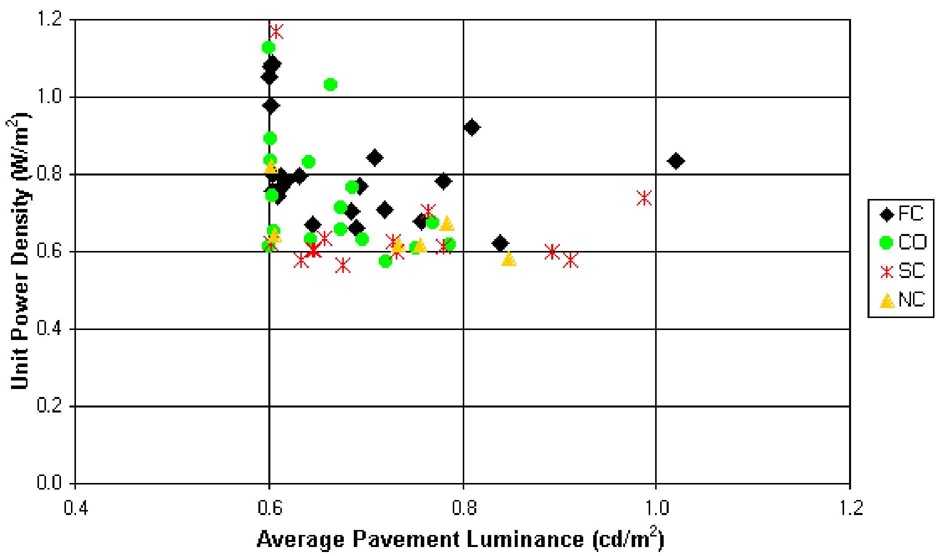
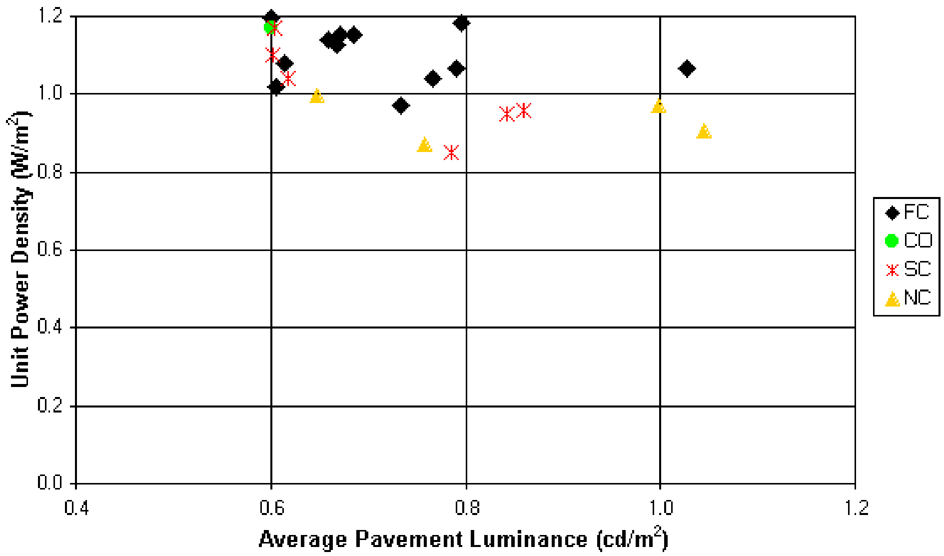


Figure 4: UPD and Average Luminance for Collector Two Lane with 250 MH (C07s250M)



Results: Design Criteria

The preliminary phase included limited calculations done with the same software as the optimization program, but "by hand" (to check the optimization routine and) to investigate the differences that design criteria made to the UPD and UUD results. Following the "base case" runs, the systems with the lowest UPD were identified for each photometric classification of full cutoff (FC), cutoff (CO) and semi-cutoff (SC). Runs were made with those photometric files meeting just the luminance criteria and meeting the Small Target Visibility (STV) criteria. The results of the preliminary phase [3] show that significant reductions in UPD - up to 33% - may be achieved by using these design methods compared to the "base case" of meeting both the illuminance and luminance criteria. The preliminary results also show that full cutoff (FC) distributions do not necessarily provide the lowest UPD or UUD values. For the photometry considered, the full cutoff (FC) distributions consistently use more energy and produce more uplight than the semi-cutoff distribution (SC) (and the cutoff (CO) also outperformed the full cutoff (FC) in most cases.) Some of the results are shown below in Table 9.

Table 9 includes the values for FluxRoad, Flux Off and Flux Up, which are the lumens for each path to uplight in one spacing of that particular system. Therefore the total of all three Flux numbers is equal to the lumens out of the luminaire, and each lumen follows one of three paths. Flux Up is lumens leaving the luminaire above horizontal which contribute directly to uplight. FluxRoad is lumens onto the roadway surface, which are multiplied by the roadway reflectance (7%). Flux Off is lumens off of the roadway surface (equal to downward lumens less lumens onto the roadway), which are multiplied by the off-roadway reflectance (18%) to establish the amount of uplight due to that path. These three values are summed to make the total uplight, which is divided by the area (spacing times the roadway width of 7 meters in Table 9). The relationship between Flux Up and total uplight is clearly not direct - the lowest UUD does not correspond to the lowest Flux Up, as seen for the full cutoff distributions .

This relationship between the three different contributions to uplight was investigated further, with example calculations and intermediate values shown. That investigation is reported in the "white paper" at "http://www.resodance.com/mdi/UUDCalc.html" and the photometry used for those calculations is also available through that website.

Table 9: Preliminary Phase Results Summary for Systems with Lowest UPD Values

	Method	UPD W/m2	Lavg cd/m2	STV	Spacing m	FluxRoad lms/spcg	Flux Off lms/spcg	Flux Up lms/spcg	UUD lms/m2	%UPD	%UUD	%Lavg
C07S150												
Semi-cutoff	I & L	0.51	0.8	4.2	126	8203	15919	12	3.9	100%	100%	100%
Samp0053	L	0.39	0.6	4.5	163	7417	16706	12	3.1	77%	79%	75%
	STV	0.34	0.5	4.5	189	7012	17110	12	2.7	67%	69%	63%
Cutoff	I & L	0.54	0.7	4.3	119	7664	17670	760	5.4	100%	100%	100%
Samp0052	L	0.45	0.6	4.6	142	7057	18277	760	4.6	84%	85%	86%
	STV	0.40	0.5	4.5	160	6496	18838	760	4.1	74%	77%	71%
Full Cutoff	I & L	0.60	0.7	3.1	107	6741	16633	0	4.6	100%	100%	100%
Samp0048	L	0.48	0.6	3.5	133	6052	17323	0	3.8	80%	81%	86%
	STV	0.42	0.5	3.6	153	5676	17698	0	3.3	70%	72%	71%
C07S250												
Semi-cutoff	I & L	0.57	0.7	5.0	180	10710	32038	50	5.2	100%	100%	100%
Samp0021	L	0.49	0.6	4.4	206	9229	33519	50	4.7	87%	90%	86%
	STV	0.44	0.5	4.3	232	8282	34466	50	4.2	78%	81%	71%
Cutoff	I & L	0.67	0.8	4.3	151	9936	31398	110	6.1	100%	100%	100%
Samp0069	L	0.53	0.6	4.9	192	9274	32060	110	4.9	79%	80%	75%
	STV	0.48	0.5	4.6	214	8389	32945	110	4.4	71%	72%	63%
Full Cutoff	I & L	0.65	0.8	4.2	157	9671	33407	0	6.1	100%	100%	100%
Samp0064	L	0.54	0.6	3.9	190	8246	34832	0	5.1	83%	85%	75%
	STV	0.49	0.5	3.7	209	7461	35617	0	4.7	75%	78%	63%

Results: Illuminance and Luminance

Results from the intermediate phase [4] clearly show that under the "base case" (Both) the optimization is almost always limited by the illuminance criteria, and an example of this - for Collector roadway of two lanes with 250W MH - is shown in Figure 5. The letters (F, C, S, or N) at the bottom of the figure corresponds to the cutoff classification of the luminaire used in that system.

When the illumination requirements increase and the roadway is particularly wide, for example Major roads with four or more lanes, the luminance criteria may be limiting the optimization. An example with Major roadway with 6 lanes using 250W MH is shown in Figure 6.

This shift generally improves the performance of more stringent cutoff classification distributions more compared to other distributions. Comparison of Figures 5 and 6 show this to some extent, as the distributions with the most improvement (i.e. reduction in UPD) using the illuminance method are consistently full cutoff (F in these figures). This is quite evident in Figure 6 where - counting from the left end - the fourth and fifth and the ninth, tenth and eleventh are all type F and have significant improvement for the illuminance method alone compared to the base case (Both). Otherwise almost all the improvements from the base case are for luminance method and tend to correspond to less stringent cutoff classifications, such as non-cutoff (N) and semi-cutoff (S). Throughout this research, this is the dominant trend in the results [3,4,5]. Systems using the luminance method consistently have lower UPD values than those using the illuminance method, except for situations with wider roadways and distributions with more stringent cutoff.

Figure 5: Intermediate Phase Results for Both, Illuminance & Luminance, Coll. 2 lanes 250W MH

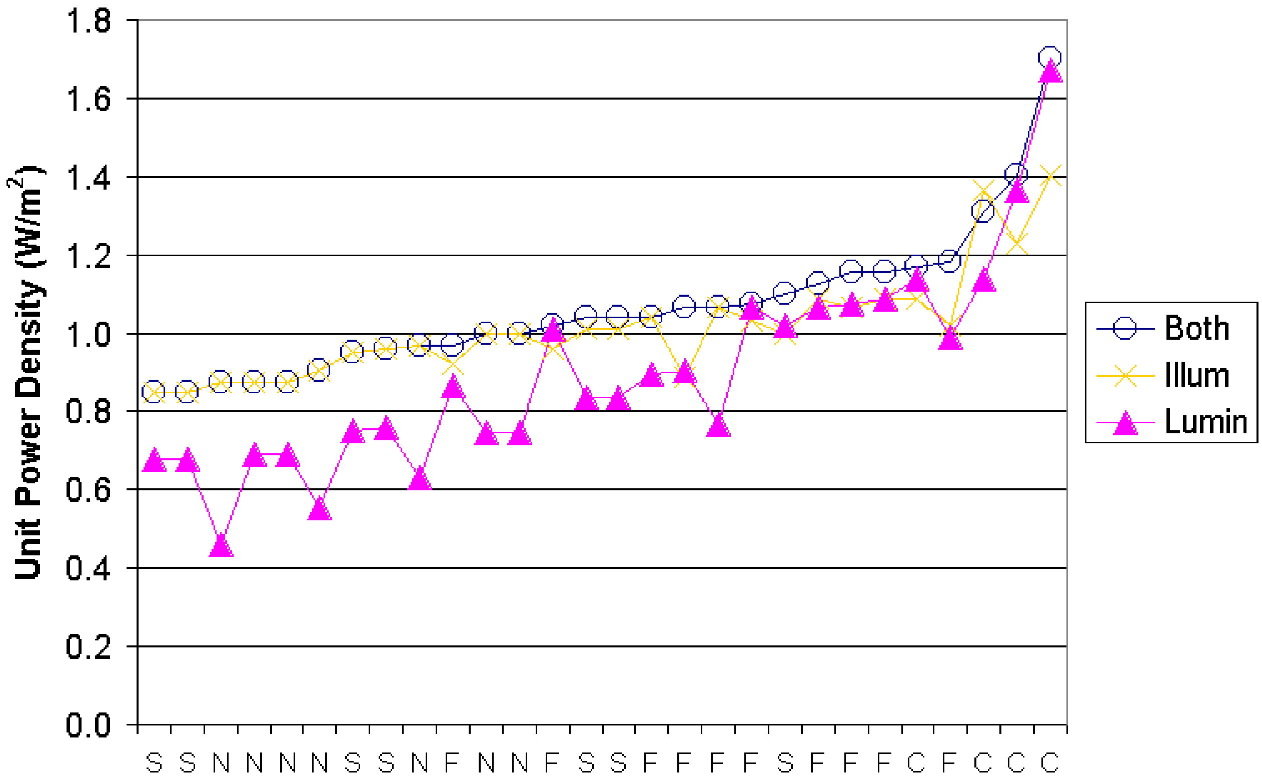
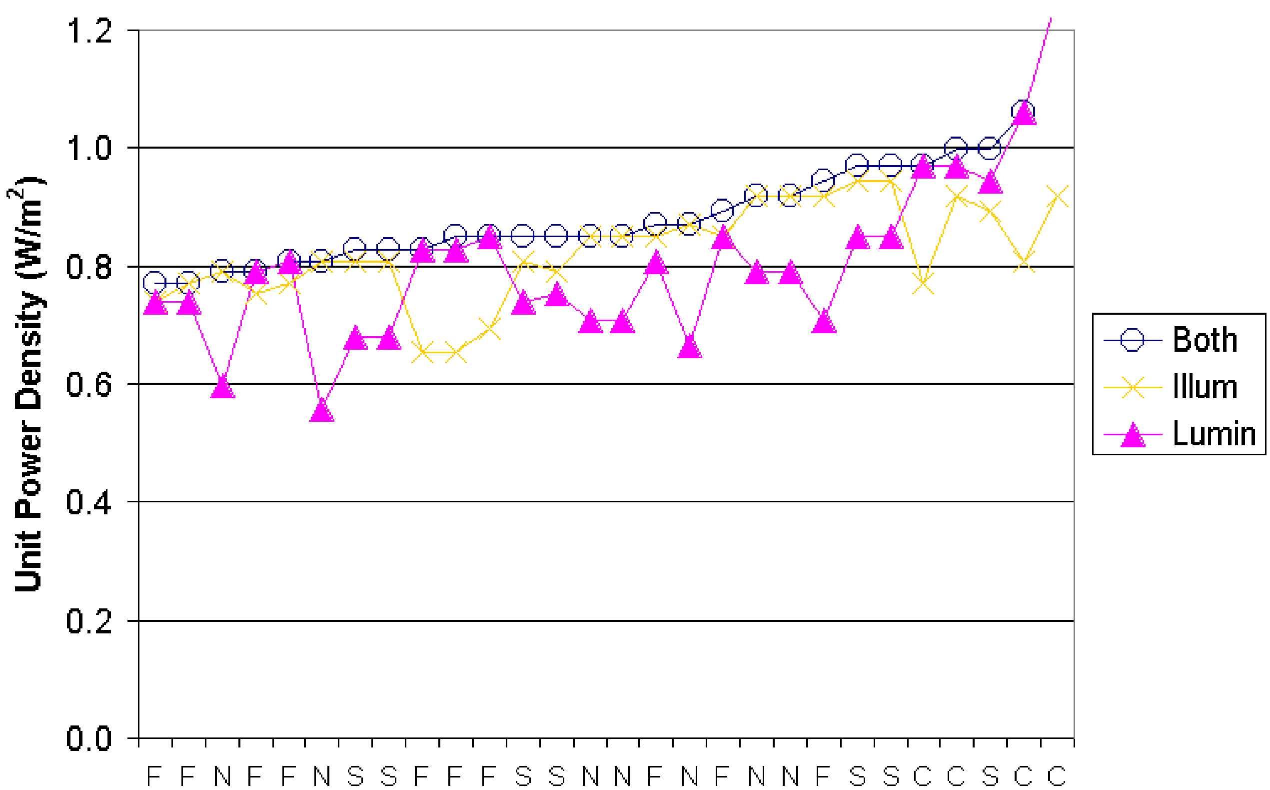


Figure 6: Intermediate Phase Results for Both, Illuminance & Luminance, Major 2 lanes 250W MH



Results: Cutoff Classifications

Results from all three phases [3,4,5] indicate that - comparing the best from each classification - the more restrictive cutoff classifications correspond to higher UPD values than the less stringent classifications. Figure 1 shows the performance of the systems with the lowest UPD values in that classification, for the full cutoff (bottom), cutoff (middle) and semi-cutoff (top) distributions in the preliminary phase. This trend is also shown in Figures 2 through 6, which show results for a variety of roadways and include some results from the intermediate phase. Part of the investigation in the advanced phase [5] was to look closely at the difference in system performance when full cutoff lighting is required (as is the case now due to legislation or ordinance) compared to when any distribution is allowed. This is not exactly the same as comparing the performance of systems with full cutoff distribution to systems with any other distribution, although in response to a discussion at the 2002 IESNA conference, such data was developed. Instead the comparison between "full cutoff only" and "any distribution allowed" provides clear information on the cost of requiring full cutoff distributions, as is now mandated in some legislation and ordinances.

UPD values for systems with "any distribution allowed" are shown in tabulated form in Table 10 below, and values for systems using "full cutoff only" are shown in Table 11. A graphical presentation of the percentage differences between these two sets of data is shown in Figure 7.

Figure 7: % Differences in “Top 5” UPD from "Any Distribution Allowed" to "Full Cutoff Only"

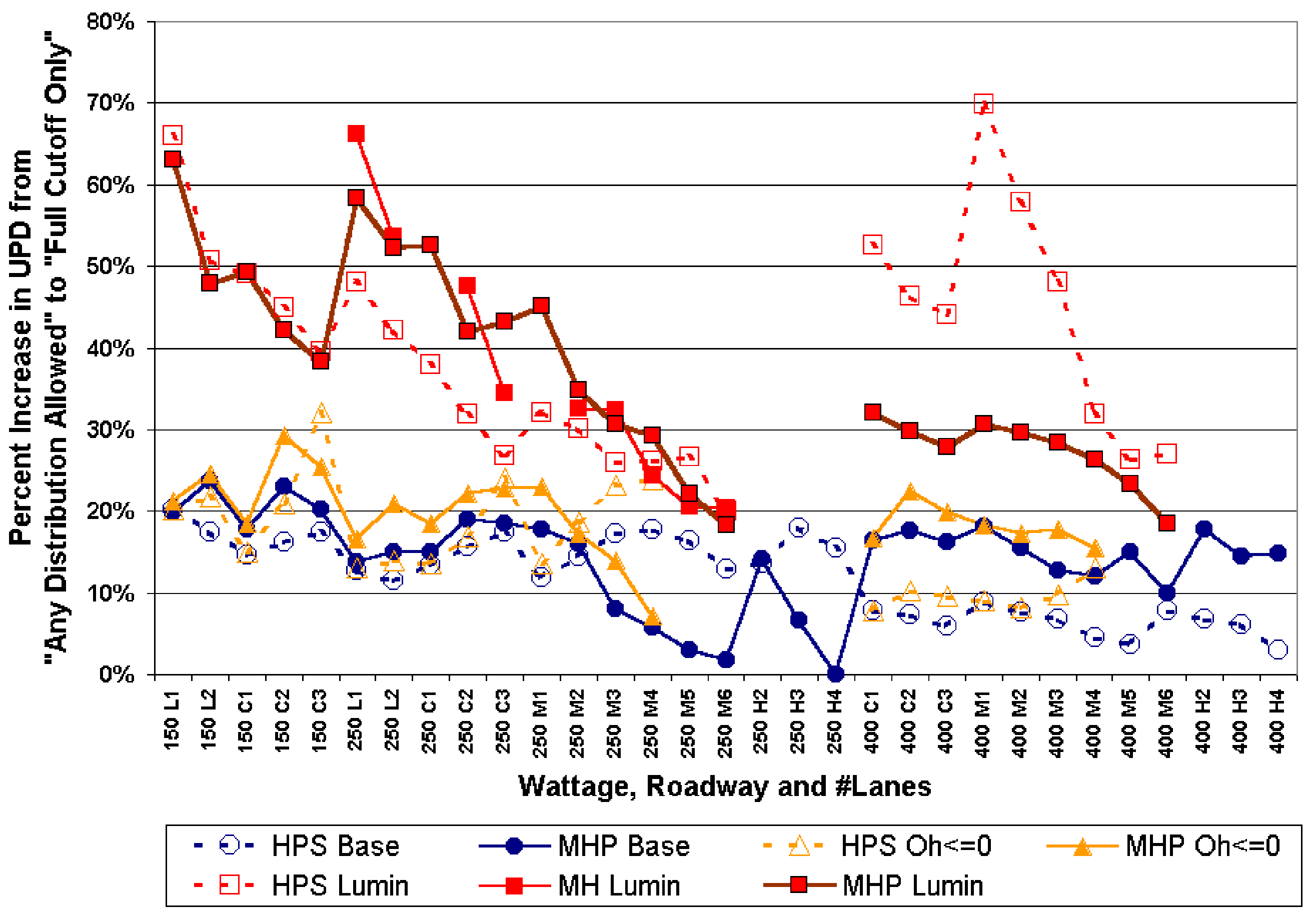


Table 10: Averaged "Top 5" UPD Values For "Any Distribution Allowed"

			Base Case			*Luminance Method*			*Ohang <= 0*		*LLF*
Watts	Road	#L	HPS	MH	MHP	HPS	MH	MHP	HPS	MHP	HPS
150 or 175W	Local	1	0.59	1.07	0.94	0.37		0.64	0.59	0.94	0.70
		2	0.35	0.66	0.56	0.25		0.44	0.35	0.56	
	Coll.	1	0.73		1.12	0.50		0.83	0.73	1.12	0.87
		2	0.44	0.79	0.68	0.32		0.56	0.45	0.68	
		3	0.34	0.67	0.54	0.25		0.46	0.35	0.59	0.42
250W	Local	1	0.82	1.20	1.17	0.54	0.68	0.70	0.82	1.17	0.98
		2	0.48	0.71	0.69	0.34	0.46	0.46	0.48	0.70	
	Coll.	1	0.98		1.41	0.70		0.89	0.98	1.41	1.17
		2	0.58	0.86	0.84	0.44	0.60	0.60	0.58	0.86	
		3	0.42	0.68	0.65	0.34	0.51	0.47	0.43	0.70	0.52
	Major	1	1.26		1.79	0.97		1.23	1.26	1.80	1.50
		2	0.74	1.16	1.13	0.58	0.88	0.84	0.74	1.19	
		3	0.57	0.95	0.95	0.46	0.73	0.72	0.58	1.03	0.69
		4	0.46	0.88	0.84	0.40	0.69	0.66	0.51	0.95	
		5	0.41	0.82	0.80	0.36	0.65	0.62			0.56
		6	0.41	0.79	0.75	0.36	0.64	0.61			
	High	2	0.86		1.36						
		3	0.66		1.18						
		4	0.57		1.10						
		5	0.53		1.00						
		6	0.51		1.00						
400W	Coll.	1	1.17		1.53	0.71		1.14	1.17	1.53	1.39
		2	0.68	1.01	0.90	0.43		0.69	0.68	0.90	
		3	0.50	0.75	0.66	0.32		0.53	0.50	0.67	0.59
	Major	1	1.47		1.93	0.80		1.46	1.47	1.93	1.75
		2	0.87	1.30	1.16	0.50		0.91	0.87	1.17	
		3	0.63	0.99	0.88	0.40		0.70	0.64	0.92	0.78
		4	0.52	0.84	0.73	0.37		0.61	0.55	0.82	
		5	0.45	0.77	0.66	0.33		0.57			0.57
		6	0.41	0.76	0.63	0.32		0.55			
	High	2	1.00		1.36						
		3	0.74		1.03						
		4	0.62		0.89						
		5	0.54		0.84						
		6	0.53		0.80						

Table 11: Averaged “Top 5” UPD Values For "Full Cutoff Only”

			Base Case			Luminance Method			Ohang <= 0		LLF
Watts	Road	#L	HPS	MH	MHP	HPS	MH	MHP	HPS	MHP	HPS
150 or 175W	Local	1	0.71	1.33	1.12	0.62		1.04	0.71	1.14	0.85
		2	0.41	0.82	0.69	0.38		0.66	0.43	0.70	
	Coll.	1	0.84		1.32	0.74		1.24	0.84	1.33	1.00
		2	0.52	0.98	0.84	0.46		0.79	0.54	0.88	
		3	0.39	0.79	0.65	0.35		0.63	0.46	0.74	0.50
250W	Local	1	0.92	1.37	1.33	0.80	1.13	1.10	0.92	1.36	1.10
		2	0.54	0.83	0.80	0.49	0.71	0.69	0.55	0.85	
	Coll.	1	1.11		1.62	0.97		1.37	1.12	1.67	1.33
		2	0.67	1.03	1.00	0.58	0.89	0.86	0.68	1.05	
		3	0.49	0.79	0.77	0.43	0.69	0.68	0.53	0.86	0.61
	Major	1	1.40		2.11	1.28		1.78	1.43	2.21	1.69
		2	0.85	1.35	1.31	0.75	1.16	1.13	0.88	1.40	
		3	0.67	1.08	1.03	0.58	0.97	0.94	0.71	1.17	0.79
		4	0.54	0.93	0.89	0.50	0.86	0.85	0.63	1.02	
		5	0.48	0.85	0.82	0.46	0.79	0.76			0.64
		6	0.46	0.79	0.76	0.43	0.77	0.72			
	High	2	0.98		1.55						
		3	0.77		1.25						
		4	0.66		1.12						
		5	0.61		1.00						
		6	0.57		0.99						
400W	Coll.	1	1.27		1.78	1.08		1.51	1.27	1.78	1.50
		2	0.73	1.20	1.06	0.63		0.90	0.75	1.10	
		3	0.53	0.87	0.77	0.46		0.67	0.55	0.80	0.64
	Major	1	1.60		2.28	1.36		1.91	1.60	2.29	1.91
		2	0.94	1.54	1.34	0.79		1.18	0.94	1.37	
		3	0.67	1.11	0.99	0.59		0.90	0.71	1.09	0.81
		4	0.54	0.95	0.82	0.48		0.77	0.62	0.95	
		5	0.46	0.86	0.75	0.41		0.71			0.61
		6	0.44	0.81	0.70	0.40		0.65			
	High	2	1.07		1.60						
		3	0.79		1.18						
		4	0.64		1.03						
		5	0.57		0.92						
		6	0.55		0.86						

Conclusions

The conclusions from this research are many and varied, addressing the procedure used and the details of comparisons of the results. However there is one primary conclusion from all the parts of this research: the performance of lighting systems must be evaluated as complete systems, and not by evaluating individual components or their characteristics.

From the preliminary phase [3], conclusions include that the optimization routine works properly for finding the lowest UPD value for a given combination of roadway and photometry, and that this system corresponds to the lowest UUD value for that combination. This procedure works for the illuminance and luminance methods, but does not work reliably for the STV method. The preliminary phase conclusions also indicate substantial potential for reductions in equipment, costs, energy use, and uplight, when luminance or STV methods alone are used instead the combination of illuminance and luminance methods used for all the other runs. Under the criteria in [1], the STV method appears to offer the lowest UPD, UUD and associated costs among the three methods.

The conclusions from the intermediate phase [4] further support this. UPD values for the Illuminance criteria are equal to or slightly better than those for Both criteria, while the UPD values for the Luminance criteria are consistently lower than for the other sets of criteria. This trend is less significant for full cutoff distributions, which frequently indicate lower UPD for the Illuminance criteria than for the Luminance criteria, particularly on wider roadways as shown in Figure 4.

Among the conclusions of the intermediate phase are that the best UPD values for MH are around 1.5 to 1.8 times the best for HPS, when comparing similar wattage and roadways. Lower wattage luminaires consistently have lower UPD values than higher wattage luminaires. The lowest UPD values in any group are typically systems with non-cutoff or semi-cutoff distributions, although this trend becomes less significant as wattage decreases or roadways become wider. This trend is less evident in MH than in HPS, since the differences in UPD values between systems using distributions with different cutoff classifications is less for MH than for HPS systems. The reductions in UPD values when using the luminance method are proportionally greater for MH systems than for HPS systems, and allow some exceptional MH systems to approach the UPD values for comparable HPS systems. The increase in UPD values when full cutoff distributions are required is evident and relatively consistent over the range of wattages and roadways, but diminishes as roadways get wider and wattage increases.

From the advanced phase of the research [5], the conclusions include further confirmation of all the earlier conclusions, and more. The restriction of "overhang less than or equal to zero" makes little if any change to UPD values. As the width of the roadway increases, the change in UPD increases. When comparing differences in rated lamp lumens or LLF, the percentage decrease in UPD is only one-half to three-quarters of the increase in the "available lumens", the product of these two factors. This is significantly different from the widely held assumption that increases in maintained lumens produce "inversely equivalent" decreases in UPD. For example, a 10% increase (11/10) in maintained lumens has been expected to produce a -9% (10/11) change in UPD. The data indicates that this is not the case for narrower roads and may be the case only for wider roads and lower wattages.

The comparison for the change from Major Medium to Major High criteria shows that the conclusions about the rated lumens and LLF comparisons apply for even more aspects of lighting systems. The change in criteria has typically been assumed to correspond to a change in UPD of equal percentage, but instead the change in UPD is only one-half to three-quarters of the change in the criterion of average illuminance.

Finally, the results indicate a substantial potential for reductions in equipment, costs, energy use and uplight which correspond to lower Unit Power Density values for roadway lighting systems.

References

1. IESNA. 2000. *American Standard Practice for Roadway Lighting*, ANSI/IESNA RP-8-2000. New York, NY: IESNA.

2. IESNA. 1987. *IES Guidelines for Unit Power Density (UPD) for New Roadway Lighting Installations*, IESNA LEM-6-1987. New York, NY: IESNA.

3. Keith, D. 2000. "Roadway Lighting Design for Optimization of UPD, STV and Uplight," *J of the IESNA*, Vol. 29 (No. 2) pp. 15-23

4. Keith, D. 2001. "Unit Power Density Evaluations of Roadway Lighting Systems," *J of the IESNA,* Vol. 31 (No. 2) pp. 66-77

5. Keith, D. 2002. "Evaluating Lighting System Components through Comparisons of Roadway UPD Values," *J of the IESNA,* Vol. 32 (No. 1) pp. 14-28

6. Keith, D. 2002. "Correlations of Roadway UUD Values to UPD, Uplight and Classifications," *J of the IESNA,* Vol. 32 (No. 1) pp. 29-40

7. California Energy Commission. 1993. *Advanced Lighting Guidelines*, CEC Publication 400-93-014. Sacramento, CA: CEC.

8. New Buildings Institute. 2001. *Advanced Lighting Guidelines: 2001 Edition*: NBI.