

Street Lighting Design in LightTools

Type I, Medium and Type IV, Medium LED Street Light Designs

May 2012

Author Introduction

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Over the last few years, LED street lamps have turned into real products that one can see on the road. They make sense for many reasons, such as their compact size, high efficacy (lumens per watt), longevity, and robustness. LED sources also allow for interesting new design forms, often with slimmer profiles than traditional metal halide arc lamps. The LightTools Street Lighting Utility (SLU) is a new tool developed to aid optical designers working in street lighting. In this paper, we briefly discuss some street lighting basics and then use LightTools and SLU to design and optimize two types of street lamps, including optimization of their placement on a roadway.

Street Lighting Metrics

CIE140-2000 is the main standard used in Europe for street lighting specifications. In the United States, there is the *IESNA Lighting Handbook* chapter on street lighting, as well as the IESNA RP800 guideline. The LightTools SLU is based primarily on the CIE140 specification, but there is a lot of overlap with the RP800 guideline and other specifications. SLU also incorporates IES street lamp types (e.g., Type I, Type II, etc.), as well as longitudinal classifications (short, medium, long, etc.).

For the CIE140 specification, a roadway has to meet a surround ratio (SR) specification, which quantifies the illuminance spilling over the sides of the roadway relative to that on the roadway. Additionally, for each lane there are three luminance metrics (average luminance, L_{ave} , overall uniformity of luminance, U0, and longitudinal uniformity of luminance, UI), as well as a threshold increment (TI) specification, the latter being a measure of the glare the driver sees from the lamps. In addition to calculating these required metrics, SLU also provides average illuminance, minimum illuminance, and uniformity of horizontal illuminance (minimum illuminance divided by the average); all in a convenient merit function ready for use in optimization. For this work, we use the specifications for a ME4a classification roadway. This means we have the following requirements for our design:

RTable:	C2 (more on this below)
SR:	0.5 or higher
L_{ave} :	0.75 cd or higher
U0:	0.4 or higher
UI:	0.6 or higher
TI:	15 or lower

Figure 1: Design Requirements

How Street Lighting Calculations Are Performed

SLU assumes that street lamps are far away from the surface that they illuminate, so their intensity distributions, positions, and orientations are the only required data to calculate the test metrics (in addition to the RTable). Once the intensity distribution is known, it can be used to calculate the summed illuminance at any point on the roadway for all pertinent lamps, as well as the summed luminance at any point on the roadway. The luminance calculations are performed knowing the angle of light coming from the lamp and striking the roadway as well as the angle of the standard observer. Then, a table of reflectances for those angular coordinates, called the RTable, is interpolated to find the correct reflectance of the roadway and the luminance observed. The RTable is a specialized BRDF. The methods for these calculations are provided in great detail in the CIE140 specification, for instance.

LED Source and Model

SLU uses intensity data from a luminaire as described above. This intensity data for SLU can come from either standard IES files (Type C) — typically created from goniometric measurements — or it can come from a LightTools far field receiver. In this case, we want to design the lamp geometry in addition to the placement of the lamps, so we will use the latter option.

Before we can design the lamp geometry, we need to define a source model. There are many suitable, high-brightness LEDs on the market, some of which are specifically sold for street lighting applications. Here we choose the Philips Lumileds Luxeon ES LED, using the cool white color spectrum option (part number LXML-PWC2, with a 5650K color temperature). The specifications sheet shows that it provides 130 to 310 lumens of optical flux when driven at a current of 350 mA to 1 A, with an ambient (25° C) thermal pad temperature.

In addition to the specifications sheet, the manufacturer provides a CAD model of the LED exterior, as well as ray files, the intensity distribution, and other pertinent information. An LED model was constructed in LightTools using the CAD model and assuming a silicone dome material with index 1.5. A chip was immersed in the silicone, and its size and spatial apodization adjusted to match the intensity distribution, which is nearly Lambertian. Figure 2a shows an image of the LED and its intensity distribution from the specifications sheet, Figure 2b shows the corresponding LightTools model and intensity distribution, and Figure 2c shows the spatial luminance seen when looking backward at the lit LED model in LightTools at normal incidence and 48°. The distortion seen in the chip image is caused by refraction of the LED dome.

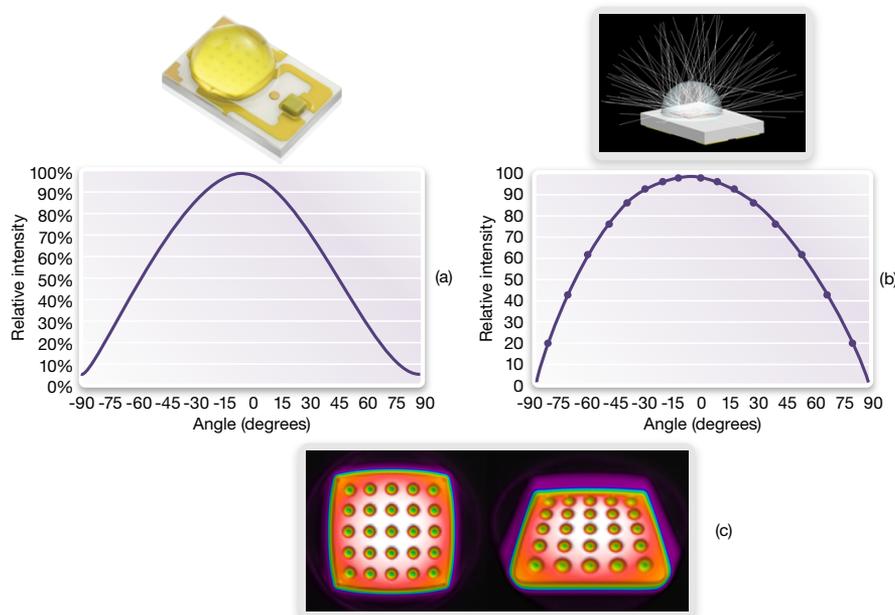


Figure 2: LED model. (a) LED image and intensity pattern from spec sheet, (b) LED model and intensity distribution in LightTools, (c) spatial luminance looking back at the LED model in LightTools at normal incidence and 48° incident angle

Type I, Medium Street Lamp Design

Armed with a model of the LED, we next move on to create a street light. The IESNA (Illumination Engineering Society of North America) lighting handbook provides classification definitions for different types of street lamps. While these designations do not characterize a full roadway layout, they are helpful for understanding the type of layout you might want to work with for a given lamp. For our first street lamp, we chose to make an IES classification Type I lamp with a Medium longitudinal classification. Medium refers to how many mounting heights away from the lamp the intersection of the maximum intensity point along the length of the roadway is. For a medium lamp, this intersection needs to be between 2.25 and 3.75 mounting heights away. Type I refers to the intersection points of the $\frac{1}{2}$ peak intensity directions with the roadway. For a Type I lamp, this locus of intersection points needs to fit within 1 mounting height in each direction towards the sides of the road. A Type I intensity distribution points directly along the roadway, rather than bending. Additionally, for this street lamp design, we will assume a two-lane roadway, with each lane being 3.5 meters in width.

Rotationally Symmetric, Low-Spread Optic

For a typical street lamp, you would like to have some light directly below the lamp, even if most of the light for the lamp type is exiting at higher angles. For our street lamp, we use two different types of optics. One optic spreads a small amount of light directly below the lamp and the other creates the high angle distribution needed for the Type I, Medium lamp. We choose to use TIR optics, since they offer high efficiency and more optical surfaces to control the light. Furthermore, we choose the material PolycarbonateLED2045 for all the optics. Figure 3a shows the optimized design created using the LightTools integrated optimizer for the low-spread optic. The TIR surface near the bulb was parameterized using a 2nd degree rational Bezier curve and the refractive surface is represented as an asphere with 4 free parameters. Figure 3b shows the rotationally-averaged target intensity distribution (red curve) for this optic. As can be seen, it was chosen to be uniform out to $\sim 40^\circ$, with a falloff after that. The optimized solution (blue curve) matched the target intensity distribution well.

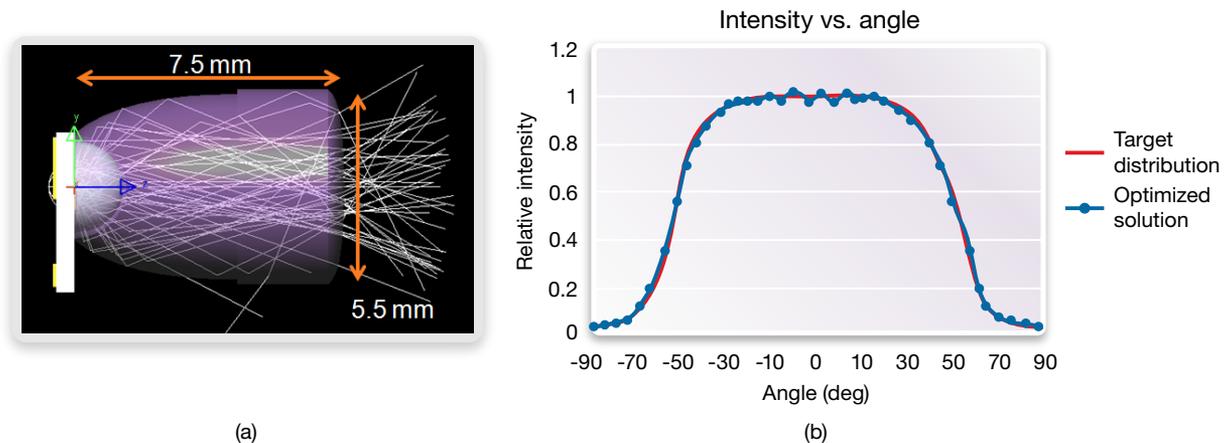


Figure 3: Rotationally-symmetric, low-spread optic and intensity. (a) LED with designed optic, (b) rotationally-symmetric target intensity distribution (red), and rotationally averaged intensity distribution of the optic with LED (blue) after optimization

Wide-Spread Optic

Next, we consider the wide-spread optic. We know that that we want to have the peak of the intensity distribution strike the road in the medium longitudinal zone as defined above. We can use the following simple equation to figure out the range for the location of the peak intensity:

$$\theta = \text{ArcTangent}(\text{Mounting Heights})$$

In this case, the desired range of 2.25 to 3.75 mounting heights gives us a range of angles for the peak intensity between 66° and 75° . (We can also use SLU's IES mounting height plot to check the IES classification for the lamp at any point in the design process.) Furthermore, we know that the distribution should be reasonably well collimated for the lobes that point in opposite directions creating the Type I distribution.

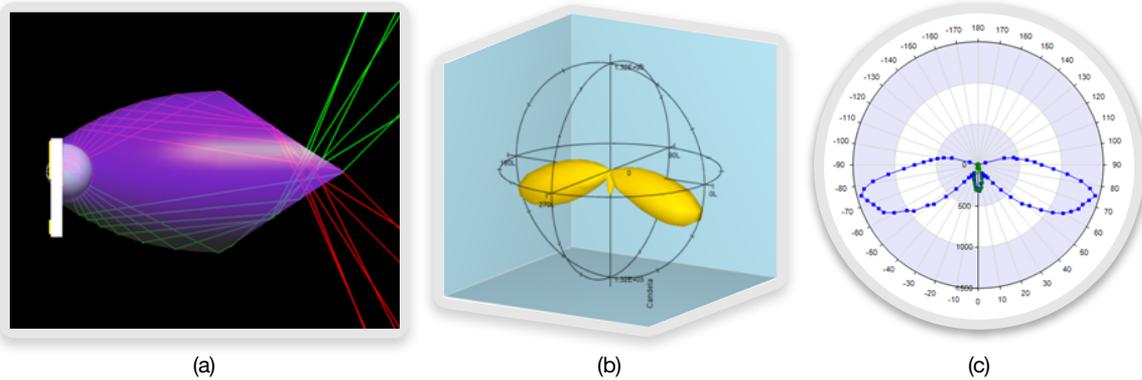


Figure 4: Wide-spread optic and intensity. (a) optimized optic, (b) intensity distribution surface, (c) orthogonal slices through the intensity surface

The approach that worked best for the design of this optic after some trial and error was to start by optimizing a TIR optic to collimate the LED light to a half cone of 25° . Next, an extruded object made with two equal-but-opposite Bezier curves was intersected with a cylinder equal to the output radius of the collimating portion of the optic and everything was booleanned together. The resulting geometry is shown in Figure 4a. You can see that rays collimated from one side of the LED are then folded by TIR reflecting off of the same side of the output surface and then refracted out the opposite side. The output surfaces have a slight concave curvature made with the extruded Bezier curve, and the angle of the cut is roughly 33° neglecting the curvature. The length of the collimating section is 7 mm and the length of the folding portion is 5.7 mm, while the largest diameter is 7.3 mm. Figure 4b shows a 3D intensity surface for this optic with LED. One can clearly see the two intensity lobes that it forms in opposite directions. Additionally, in Figure 4c, slices through the intensity surface in orthogonal directions are shown. The blue slice shows that the peak of the intensity distribution is close to 75° , which means we are at the upper end of the Medium longitudinal classification. Another important thing to notice in Figure 4c is that there is light up to and even above 90° at this point. Since we want to reduce glare and pass our threshold intensity requirement, we will also design the luminaire to reduce light past 80° .

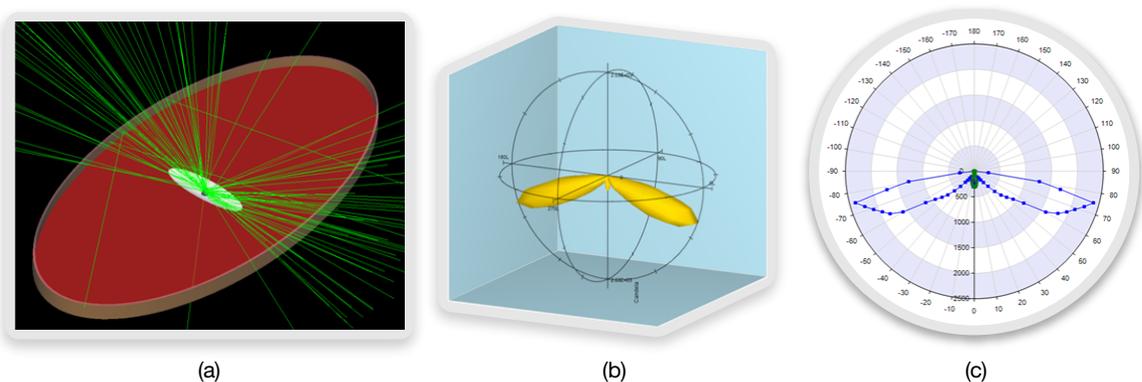


Figure 5: Wide-spread optic with recessed metal reflector. (a) metal plate with recessed reflector and wide-spread optic, (b) resulting intensity distribution surface, (c) orthogonal slices through the intensity distribution

To reduce the glare and further shape the light distribution, we make use of a specularly reflective metal plate that has a recessed reflector in it with a hole in the center, through which the spreading optic is extended. Anticipating that several LEDs will be necessary to have enough light to make meet specifications, we choose

an ellipse with full widths of 500 mm x 1 meter to form the metal plate. The oval plate with the recessed reflector is shown in Figure 5a (and also in Figure 6a). The reflecting section is a lofted set of elliptical cross sections whose half widths are controlled using Bezier curve parameterizations along the length. The larger edge of the reflector is 30 mm x 100 mm full width, and the smaller edge is an 8.6 mm diameter circle — large enough for the optic to push through with some clearance. The thickness of the reflective section is 5.7 mm. The shape and size of the reflector was optimized to produce a good cutoff without changing the direction of the beam lobes too much. Additionally, a lip of 13 mm length with a Lambertian-scattering white paint was added around the outside elliptical aperture of the lamp to further reduce glare — the lip is also shown in Figure 5a. Figure 5b shows the resulting intensity distribution surface and Figure 5c the orthogonal slices. Figure 5c shows that the light above 80° has been dramatically reduced.

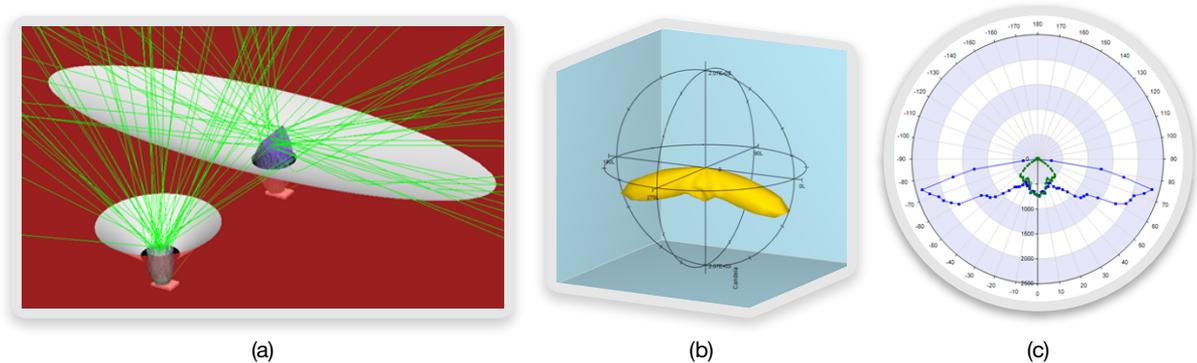


Figure 6: Optimized wide and narrow spread optics. (a) geometry for both recessed reflectors and optics, (b) combined intensity surface, (c) intensity slices for the combined optics.

Now that we have reasonable wide-spread and low-spread solutions, we put them together to form the total luminaire distribution. Both LEDs were placed on the same circuit board plane height, and next a second recessed reflector was added for the low spread optic to catch any light that comes out at high angles and allow the optic to penetrate the metal plate. With both optics designed, the next step is to optimize the total flux for all low and high spread optics combined in conjunction with the roadway parameters to meet our design specifications in Figure 1. Since we are on the high side of a Medium longitudinal classification for the luminaire, we expect to achieve a luminaire separation of at least three mounting heights. A luminaire spacing of 32 meters was chosen for the roadway layout. Then, using SLU to optimize the mounting height as well as the powers of the two source components, a 7.5 meter mounting height was achieved for the chosen roadway length. In other words, the optimized luminaire arrangement had spacing equal to 4.3 mounting heights. This was achieved using 2000 lumens for the wide-spread optic's total power and 1500 lumens for the small spread optic's total power.

Figure 7a shows the results of the optimization. The merit function items, based on the specifications from Figure 1, are all passing. Also in Figure 7a, top right, is the summed illuminance distribution for the lamp configuration shown in false color. The plot directly below it is the luminance as seen by an observer positioned in the center of the lower lane at $y = 1.5$ meters and $x = -60$ m down road from the test area starting at $x = 0$. Figure 7b shows the IES mounting height plot. The red '+' indicates where the peak intensity direction intersects the roadway, expressed in mounting heights. As expected from our earlier calculation, this is near the upper end of the medium longitudinal classification. The black curve represents the locus of $\frac{1}{2}$ intensity directions intersecting the roadway, also expressed in mounting heights. Since all points on the black curve are contained within ± 1 mounting height in the vertical direction, this is a Type I IES classification lamp.

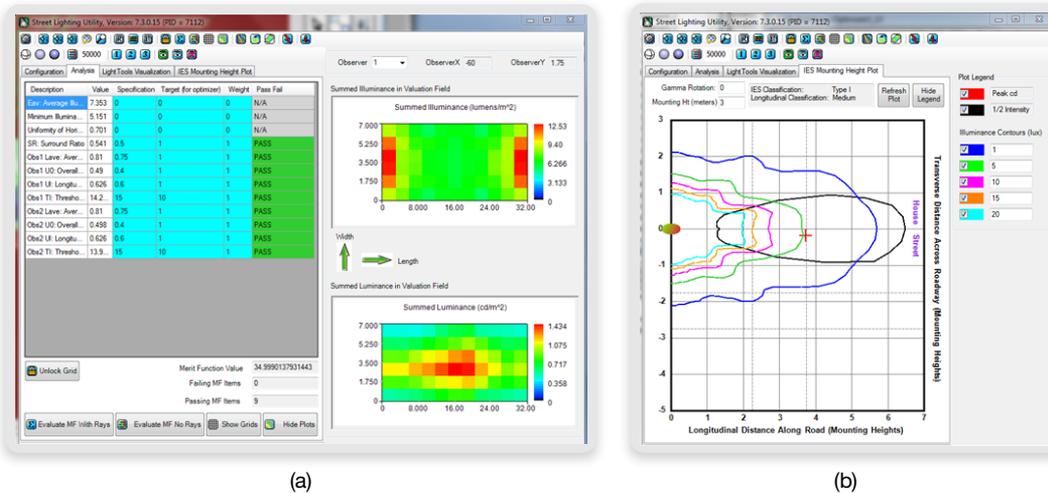


Figure 7: Passing system results after optimizing the mounting height and source component powers. (a) merit function items from specifications of Figure 1 are all passing, and summed illuminance as well as summed illuminance for the lower-lane observer are shown, (b) IES mounting height plot. Red '+' shows max intensity point – designates Medium longitudinal classification. Black curve shows 1/2 intensity – designates Type I IES classification

Figure 8 shows two images of the roadway layout for this optimized design. The top image is a bird's eye view of the test area (two lanes, 32 meters long, and 7 meters across). Wireframe representations of the intensity distribution surface are shown with the luminaire locations and a grayscale plot shows the summed illuminance on the roadway along with grid dividers and values for the illuminance at the test points. (Note the number of test points was determined based on the length and number of lanes as per the CIE140 specification here – the default option in SLU.) The lower image shows a false color view of the lit roadway with luminaires to help visualize the layout.

The final step for this luminaire design is to construct the full luminaire and re-verify that we are meeting specifications. For the full luminaire, we chose to drive the LEDs such that they each produce 150 lumens (lower side of the range specified for this particular LED). This means that we will use 10 low spread systems and 13 high spread systems, with a total lamp LED flux of 3,450 lumens. The full luminaire design is shown in Figure 9, along with a mounting height plot confirming the IES Type I classification and Medium longitudinal classification. Figure 10a shows that we are still passing our design specifications with the full lamp. Additionally, Figure 10b shows the intensity surface for the full luminaire and Figure 10c shows the slices through the intensity distribution.

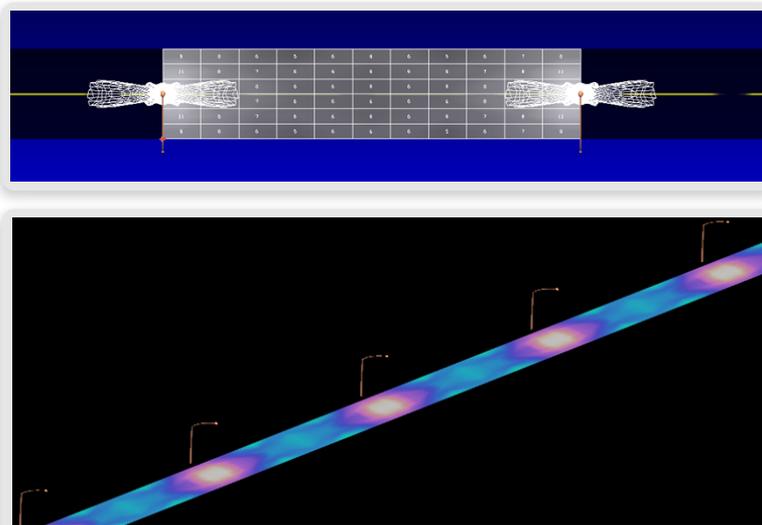


Figure 8: Roadway images with the design. (Top) bird's eye view of test area with summed illuminance and intensity wireframe meshes. (Bottom) false color plot of summed illuminance with lamp posts

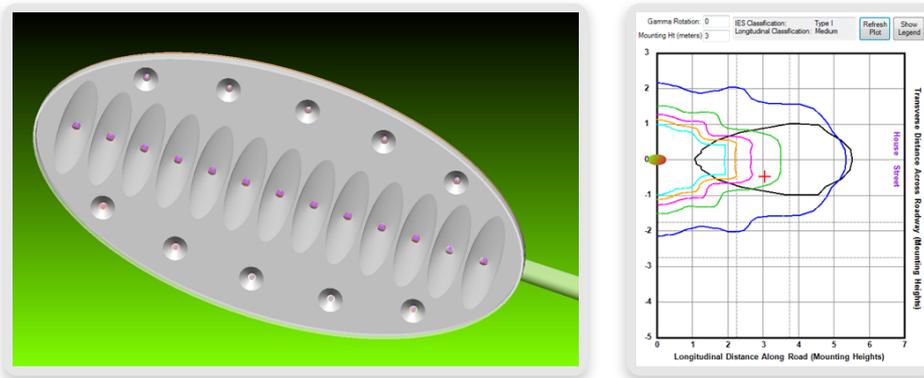


Figure 9: Full Type I, Medium luminaire. (left) image of the luminaire geometry, (right) mounting height plot for the full luminaire, verifying that it has a Type I, Medium distribution

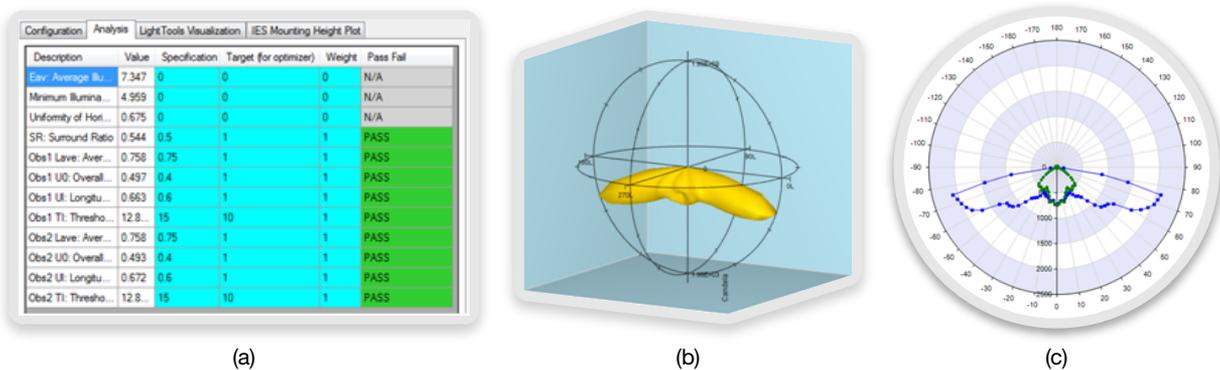


Figure 10: Performance of the full system and lamp intensity distribution. (a) results of merit function item specifications tests – all pass, (b) intensity surface for full luminaire (c) slices through the intensity distribution

Type IV, Medium Street Lamp Design

Now we move on to a different type of street lamp design. Here we would like to have a distribution that is asymmetric across the roadway, so that more light falls on one side of the lamp than the other. Often this type of distribution is convenient if you want to place the luminaires closer to one of the sides of a given roadway than the other. For this design, we will assume that luminaire separation will be 20 meters and that roadway will now have three lanes. To accommodate the third lane, we increase the roadway width from 7 meters to 10 meters, so that each lane is 3.3 meters in width.

We already have designed a low spread optic, so we can re-use that design for the Type IV lamp. However, since this design is not symmetric across the roadway, we cannot use the same spreading optic design. Rather, we use two separate collimator-plus-fold optics that are rotated 25° each away from a symmetric solution. Without being able to TIR and refract as in the spreading optic described above that is symmetric, it is very challenging to fold the distribution enough using only TIR. For this design, the ‘folding’ surface required a specular reflective coating to achieve the desired distribution without leaking too much light. Figure 11a shows the optimized geometry for this optic. The collimating portion of the optic is identical to the spreading optic described above. However, the turn mirror in this case has a 41° degree angle, and also a concave spherical curvature of 40 mm radius in the transverse direction. The total length of the optic is 17.3 mm and the maximum diameter is 7.3 mm. Figure 11b shows the intensity lobe created by the spreading optic.

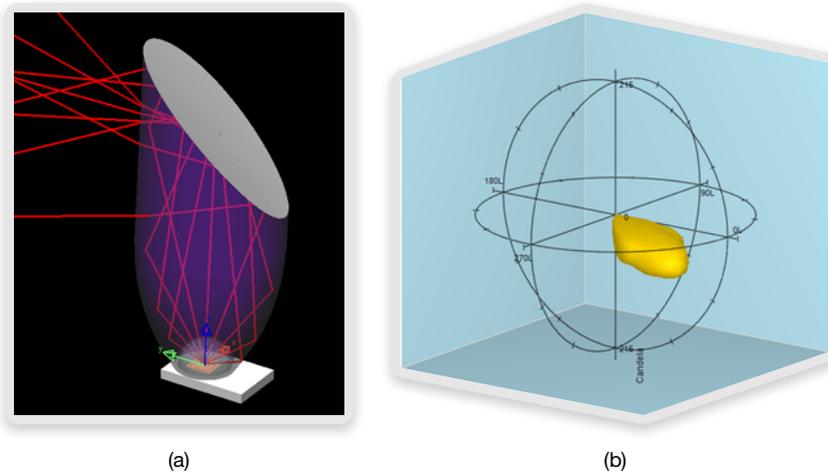


Figure 11: Large spread optic design for the Type IV system. (a) spreading optic geometry, (b) intensity distribution surface

Next, a recessed reflector similar to the previous design was designed and optimized. The new design has a different output aperture shape since the intensity distribution is one-sided in this case. The reflector helps redirect the light that is at angles higher than 80° similar to the Type I design. The optimized optic and reflector are shown in Figure 12a. The reflector is 88 mm by 18 mm at the widest point of the output aperture in orthogonal directions, with a 9.3 mm depth. Figure 12b shows the resulting intensity surface, and Figure 12c shows slices through the surface. The peak angle of the intensity slice is 67° and the light above 80° is minimal.

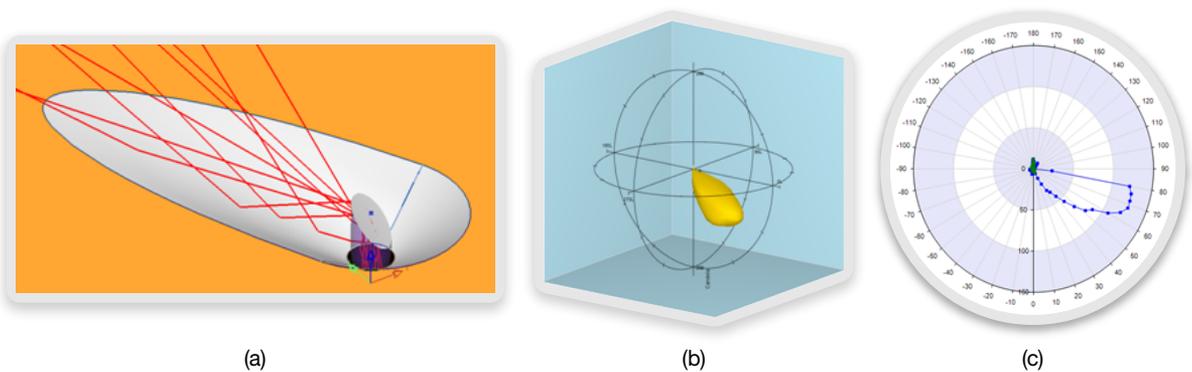


Figure 12: Recessed reflector design optimized for new large spread optic. (a) recessed reflector design and spreading optic, (b) new intensity surface, (c) slices through the intensity

The full luminaire construction is shown in Figure 13. The outer aperture of the luminaire is the same size and shape as the Type I luminaire design. For the large spread optics, 14 subsystems were used. For the small spread optics, 10 subsystems were used.

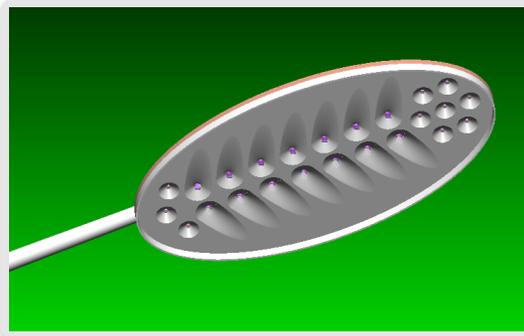


Figure 13: Full geometry for the Type IV, Medium luminaire

For this design, it was necessary to increase the power for the LEDs to meet the specification. All 24 LEDs used for this design were calibrated to 220 lumens, which is mid range of the output flux shown in the LED specifications. SLU was used to optimize the configuration of the lamps and a passing solution was found using a mounting height of 8.6 meters and an overhang of 2.7 meters from the edge of the roadway. Since the roadway is 20 meters long, the lamp spacing is 2.3 mounting heights, which is reasonable since the peak intensity intersects the roadway at about 2.7 mounting heights for this lamp. Figure 14a shows the passing specification items, and Figure 14b shows the mounting height plot, which indicates that the lamp is Type IV, Medium. Figure 14c shows the intensity distribution surface for the full luminaire.

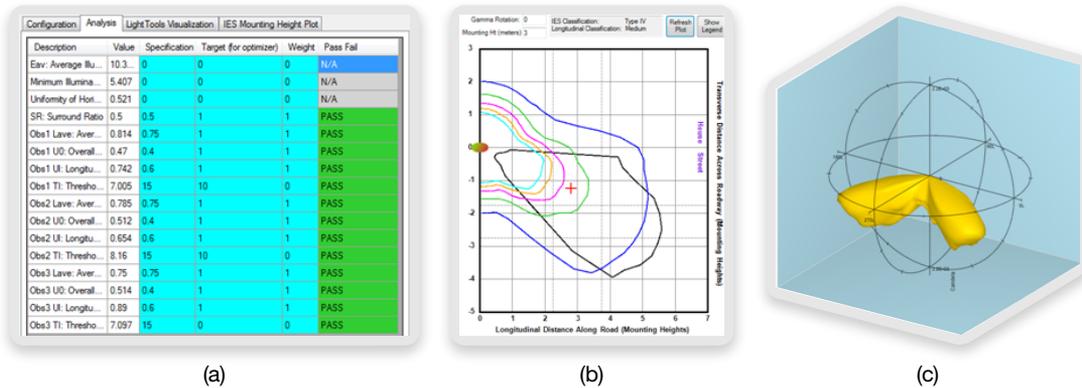


Figure 14: Results for Type IV, Medium luminaire design. (a) passing specifications tests, (b) IES mounting height plot, (c) intensity distribution

A bird's eye view of the optimized lamp configuration is shown in Figure 15. The luminaries are 2.7 meters from the top edge of the roadway and the intensity distributions are represented as wireframe meshes. The summed illuminance, false-color raster plot and data values are shown for the test zone of the three-lane roadway.

Figure 16 shows the luminance observed by the driver for each of the three lanes. As defined in the CIE140 specification, each observer is located in the center of the lane and 60 meters behind (to the left in figure 15) the target zone. All three of these patterns meet the specifications as shown in Figure 14a. Finally, in Figure 17, we show two photorealistic lit renderings created in LightTools that show several of the Type IV, Medium lamps placed along the roadway at night.

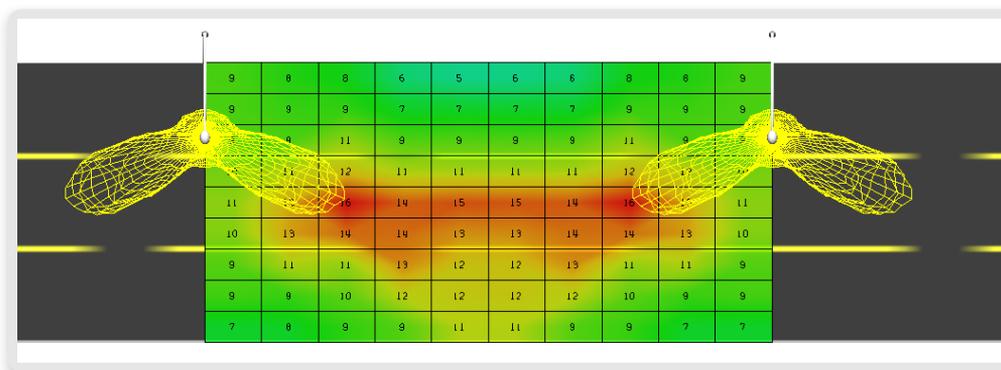


Figure 15: Bird's eye view of optimized lamp configuration for the Type IV, Medium luminaire

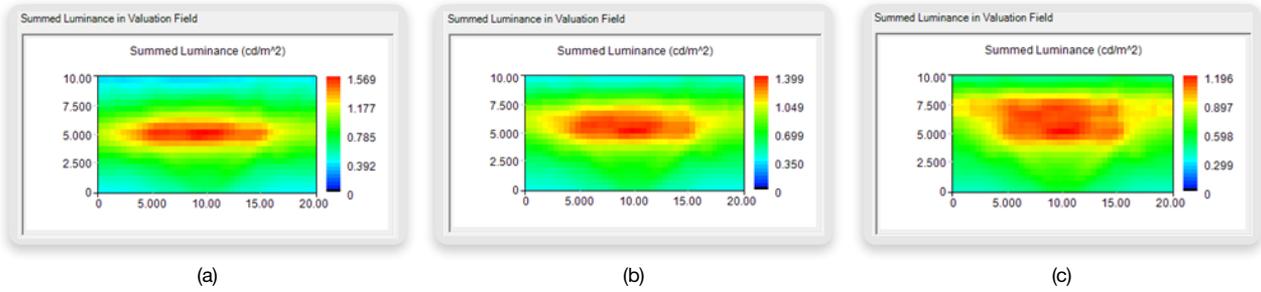


Figure 16: Luminance seen by the driver in each lane. (a) bottom lane (b) middle lane (c) top lane

Summary

In this paper, we used LightTools and the Street Lighting Utility (SLU) to design and optimize two types of solid state street lamps: Type I, Medium and Type IV, Medium. In addition to designing lamp geometry, we used SLU to optimize the lamp configuration and power for the lamp sub-systems in order to pass the specifications for a ME4a class roadway. LightTools quickly showed us the intensity surface distributions and slices as well as allowing flexible optical surface parameterizations. SLU also let us analyze the street configuration quickly and visualize the summed illuminance, luminance for each observer, and IES classification of the lamps.

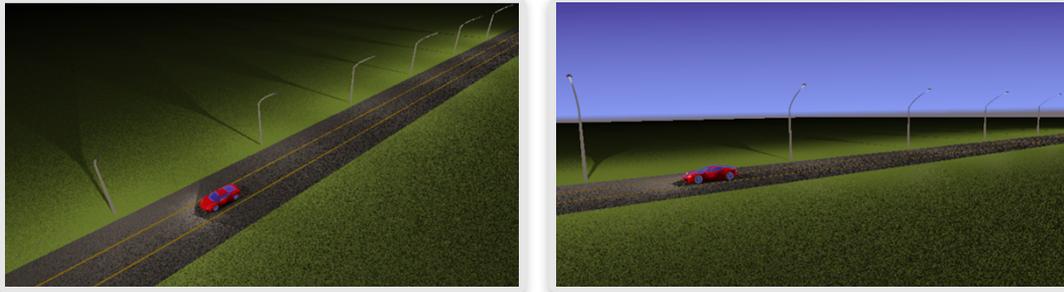


Figure 17: LightTools night-time photorealistic renderings of a scene with a roadway and several of the Type IV Medium lit lamps