

As with all design software, most designs in *LightTools* will eventually be manufactured. Optical designers pour vast amounts of time and energy into making designs that meet their specifications, and they trust their design software to produce simulated results that will match manufactured results. Depending on the experience of the designer, the amount of trust in the software that this process requires can be quite high.

LightTools has the ability to accurately model both an ideal design and the “as manufactured” system. With a high level of correlation between simulated performance and measured data, users can design with complete confidence; if the simulation meets the specification, so will the part.

This paper showcases three illumination designs in which good correlation was found between *LightTools* simulated results and measured data from physical hardware. While any discrepancies are small, the possible sources of error in the model will be discussed for each case.

Case 1: H7 Halogen Bulb

The source model is arguably the most important component of an illumination design simulation. If an inaccurate source model is used, the validity of the entire design comes into question. *LightTools* provides many tools to accurately represent filament sources, as well as other types of sources.

The H7 halogen lamp is primarily used in automotive headlamps for the low, or driving, beam. As with all automotive bulbs, its design and manufacture are highly regulated by the governments that allow its use.

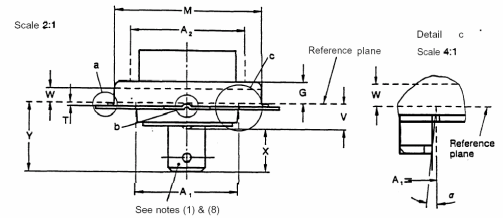
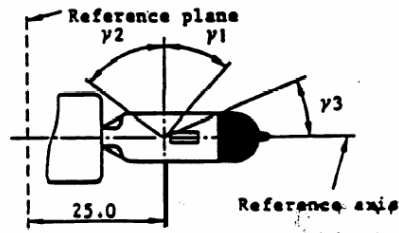


Figure 1: Sample DOT/NHTSA Drawings

Consequently, detailed drawings are available from sources such as the Economic Commission for Europe (ECE, www.unece.org) and the U.S. Department of Transportation (USDOT, www.dot.gov). These drawings, as shown in Figure 1, provide nominal and toleranced dimensions to which each individual bulb must adhere to be legal; however, many of the intricacies of the bulb, such as filament design, are left to the manufacturer. A good source model will be manufacturer specific, and will meet the tolerances for that manufacturer.

Building the Solid Model

In *LightTools*, the H7 model begins with the bulb envelope, which is the quartz globe that surrounds the filament and contains the halogen gas. Boolean operations, such as union, subtraction, intersection, and trim, are performed on simple geometric primitives to create the complex solid. There are also JumpStart functions available to create smoothly filleted geometry via a Microsoft® Visual Basic® macro.

The filament supports and other mechanical features on the bulb are important for creating the shadowed regions in the intensity distribution. These solids are created in the same manner as the envelope. Models of the H7 envelope, base, and filament supports are shown in Figure 2.

Defining the Optical Properties

An interface can reflect, transmit, or everything in between. *LightTools* can be used to model nearly all conceivable light interactions that take place in an optical system. Specular reflections and refractions can be defined to include Fresnel losses. Gaussian, Lambertian, or Cos^{nth} scatter can be added to surfaces to model surface roughness, as well as more complete scatter models. Volume absorption and scatter can be defined for a custom material or a material can be used from the glass catalog. For the most accurate representation of a surface, the optical

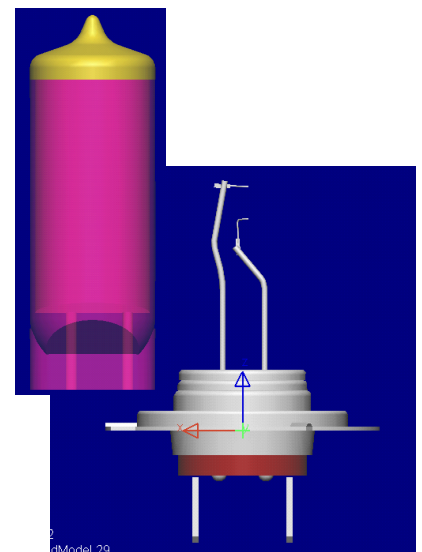


Figure 2: H7 Envelope, Base, and Filament Supports

properties can be defined based on percentages of reflection and transmission, each broken into their specular, diffuse, and near-specular components as a function of wavelength and angle of incidence.

Creating the Filament

LightTools provides many useful mechanisms for creating filament sources. Filaments can be round or square, straight or curved, or consist of a coiled coil. As with the solid model, simple source primitives are combined to form the complex coil shown in Figure 3.

The surfaces of a filament coil are reflective to its own light. As such, optical properties need to be assigned to simulate this self-obscuring functionality.

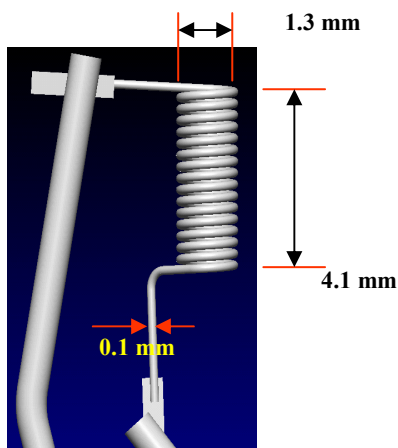


Figure 3: H7 Filament Model with Associated Dimensions

The photon emission of the filament can be controlled in a number of ways. Angular, spatial, or volume apodizations can be applied to control the luminance of the filament from any perspective. This ability facilitates the accurate modeling of the cold ends and hot centers of the filament.

The final component of the filament that can be modeled in *LightTools* is the spectral power distribution (SPD). In many systems, tracing light of only one wavelength is not sufficient. Through built-in utilities, an SPD can be applied to a source that models a blackbody or tungsten of a particular color temperature. The SPD's for a

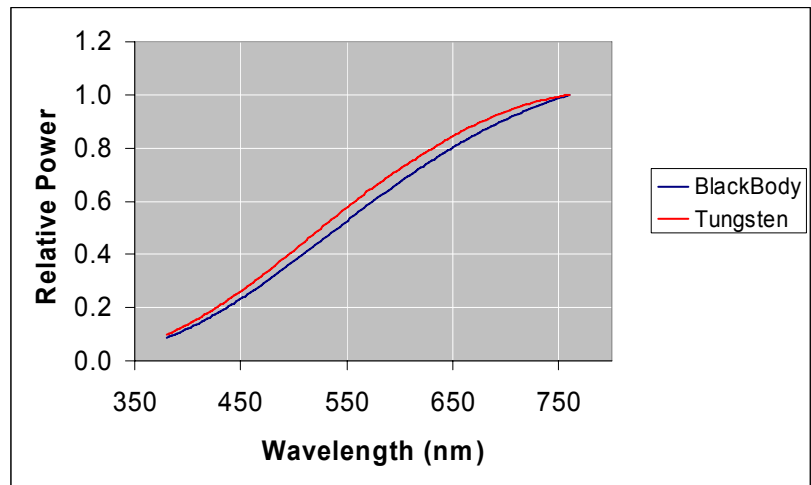


Figure 4: Blackbody and Tungsten SPD's for a Given Color Temperature

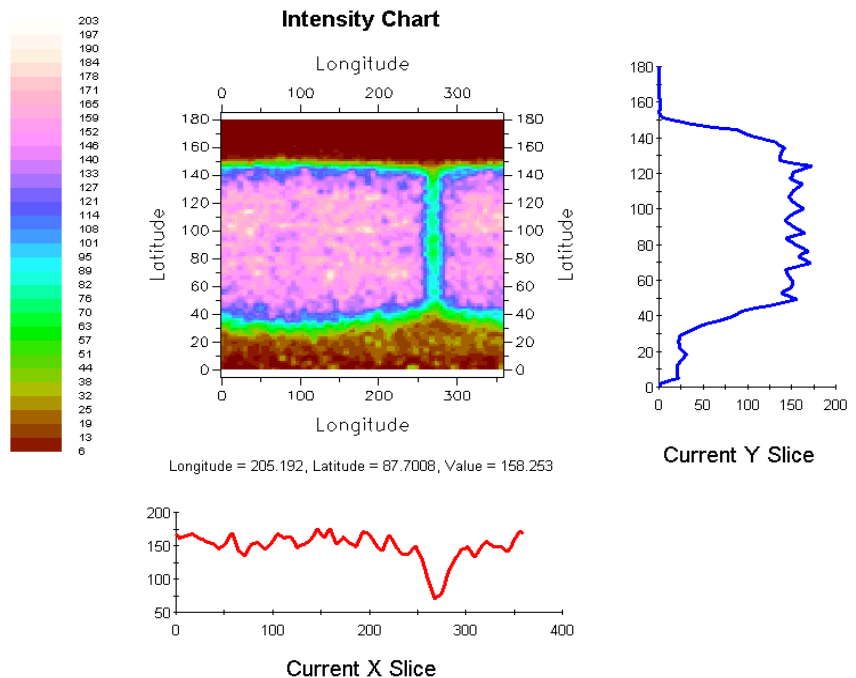


Figure 5: LightTools H7 Simulated Intensity Distribution

blackbody and tungsten are shown in Figure 4 for a particular color temperature.

Simulated Results

The angular intensity distribution was simulated on a far-field receiver. The results are shown in Figure 5. The shadow created by the filament support can be clearly seen, as well as the dark regions created by the opaque envelope cap and the metallic base structures.

Simulated vs. Actual Results

In Figure 6 and Figure 7, the simulated results are shown and compared to data received from Philips Corporation for slices in the distribution perpendicular to and coplanar with the bulb axis. Generally, the simulation is within 10% of the nominal. If a more accurate source model is needed, then changes can be made to correct for some of the more likely sources of error.

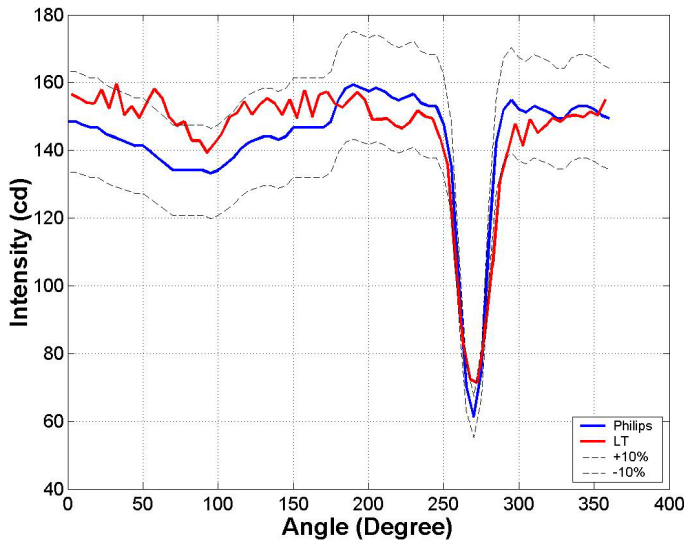


Figure 6: Simulated Performance vs. Measured Data for H7 Perpendicular to Bulb Axis

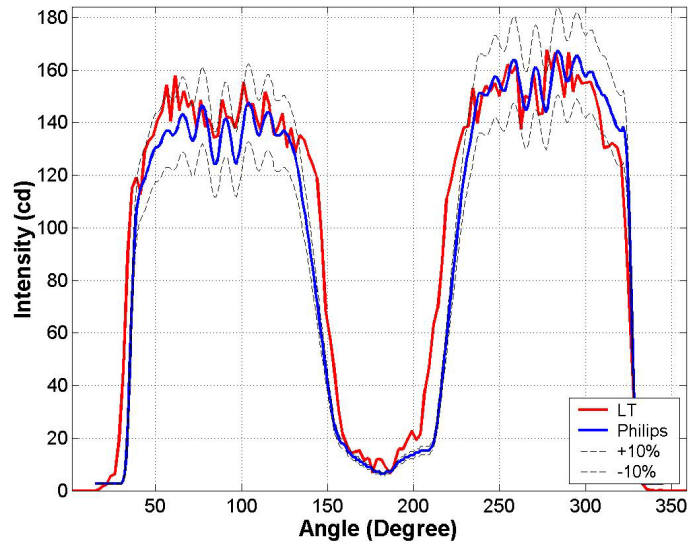


Figure 7: Simulated Performance vs. Measured Data for H7 Coplanar to the Bulb Axis

Potential Sources of Variation

As with any complex system, there are many potential sources of error in the simulation. The easiest to identify stem from errors associated with the Monte-Carlo simulation, in which accuracy is directly proportional to number of rays traced. For instance, in order to achieve a 5% error with a 2-degree resolution, approximately 8 million rays should be traced. Tracing fewer rays would introduce more errors. Other sources of error are associated with the model and its implementation with regards to geometry, optical properties, etc. Slight variations in these parameters can sometimes create large variations in the simulation.

Case 2: Cadillac Escalade Taillamp

The taillamp of the Cadillac Escalade was designed in CAD software and evaluated in *LightTools*. The taillamp, shown in Figure 8, provides the stop lamp, tail lamp, turn signal, and backup lamp functionality; however, only the stop, turn, and tail lamp functionality are discussed here.

The design utilizes two stacked faceted reflectors behind a medium red acrylic (PMMA) lens. Each reflector, also known as a compartment, has 12 facets that are

convex perturbations of a base parabola. The curvatures of each facet are designed to create the required far-field intensity distribution. The reflectors are made by putting a metalized coating onto the plastic housing. The coating is likely to be either a vapor-deposited aluminum or chrome. The lens is made of a dye-impregnated acrylic plastic.

Model Summary

The reflectors were modeled with a completely specular reflectivity property zone. The reflectance value was based on measured data, and depending on the quality of the metalized coating, can be anywhere between 70-85%.

The absorption of the medium red acrylic lens was modeled on the input surface of the lens as a single

transmission loss based on measured data for this lens thickness and source. The second surface of the lens was set to 100% transmission without Fresnel losses.

Sources

Each compartment contains one 3157 dual-filament incandescent bulb. A model of the 3157 can be seen in Figure 9. The major filament nominally produces 32 mean spherical candela (MSCD) and the minor filament nominally produces 3 MSCD. MSCD is the ratio of the total power of the source, as measured in an integrating sphere, to 4π steradians. The color temperature of the source is $\sim 3500\text{K}$; however, as all of the filtration losses were figured into the lens transmission factor, the source spectrum can be ignored. As with the H7 bulb discussed in the previous



Figure 8: Cadillac Escalade Taillamp

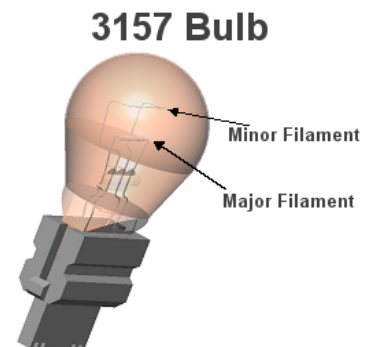


Figure 9: 3157 Bulb

section, this bulb model was made in *LightTools* and correlates well with the actual source.

Figure 10 shows how the various lighting functions are mapped into the available compartments; the tail function uses the minor filament of both bulbs, while the stop and turn signal use the major filaments of their respective compartments. A clear aperture is drawn into Figure 10 to show that not all of the available reflector area is usable due to obstructions.

Regulatory Compliance

In the United States, regulated exterior automotive lamps must conform to the Federal Motor Vehicle Safety Standards (FMVSS), which are written by the U.S. Department of Transportation’s National Highway Traffic Safety Administration (NHTSA, www.nhtsa.gov). Figures 1a-c of Section 108 of the FMVSS, which are summarized in the “Required” columns of Table 1, contain the test-point values for the required far-field intensity distribution based on SAE Type A photometry. Zonal requirements are the sum of the non-zonal point immediately above them.

Simulated and Measured Results

Simulations were made in *LightTools* with a far-field receiver oriented to mimic a Type A photometer. The simulated intensity distributions for each function are shown in Figure 11. The simulated and measured data for each test-point is summarized in Table 1 for the tail and turn signal. The measured data was acquired by measuring a physical lamp on a calibrated goniophotometer.

Potential Sources of Variation

All of the simulated test point values match the measured data to within ±30%, with most falling within ±10%. There are many areas in which the model can be made more realistic, and potentially decrease the variance between simulated and measured results.

Test Point	Tail				Turn			
	Required Minimum (cd)	Simulated (cd)	Measured (cd)	% Difference	Required Minimum (cd)	Simulated (cd)	Measured (cd)	% Difference
10U – 5L	0.7	13.6	10.2	25	16	90.7	101.8	-12
5U – 20L	0.525	14.3	12.7	11	10	31.4	27.5	12
5D – 20L	0.525	13.9	11.9	14	10	32.6	31	5
10D – 5L	0.7	9.8	9.7	1	16	48.9	54.6	-12
Zone 1	2.45	51.7	44.5	14	52	203.7	214.9	-5
5U – 10L	1.4	15.5	14.3	8	30	101.9	106.1	-4
H – 10L	1.4	16.6	16.8	-1	40	99.6	104.2	-5
5D – 10L	1.4	13.1	13.2	-1	30	103.4	98.5	5
Zone 2	4.2	45.3	44.3	2	100	304.9	308.8	-1
5U – V	3.15	15.5	16	-3	70	121.3	127.7	-5
H – 5L	3.5	16.9	17.3	-2	80	129.4	112.5	13
H – V	3.5	16.4	18.3	-12	80	150	144.3	4
H – 5R	3.5	17.1	18.4	-8	80	131.8	140.1	-6
5D – V	3.15	12	14.1	-18	70	154.6	140.5	9
Zone 3	16.8	77.9	84.1	-8	380	687.1	665.1	3
5U – 10R	1.4	15.8	15.5	2	30	107.5	131.2	-22
H – 10R	1.4	17.3	18.8	-9	40	119	135.1	-14
5D – 10R	1.4	14.2	15.4	-8	30	120.7	131.4	-9
Zone 4	4.2	47.4	49.7	-5	100	347.2	397.7	-15
10U – 5R	0.7	13.1	12	8	16	77.5	100.9	-30
5U – 20R	0.525	16.8	15.5	8	10	54.9	67.5	-23
5D – 20R	0.525	15.9	15.4	3	10	61	73.6	-21
10D – 5R	0.7	13.1	9.9	24	16	77.5	66.2	15
Zone 5	2.45	58.8	52.8	10	52	270.9	308.2	-14

Table 1: FMVSS Taillamp Requirements with Simulated and Measured Results

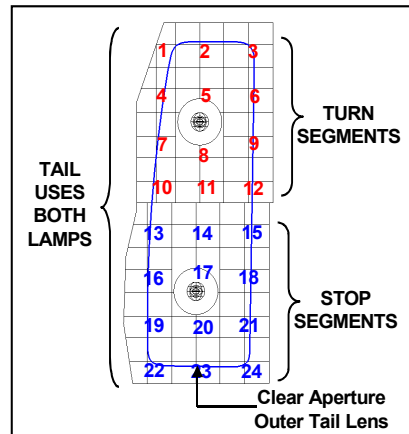


Figure 10: Layout of Taillamp Functions

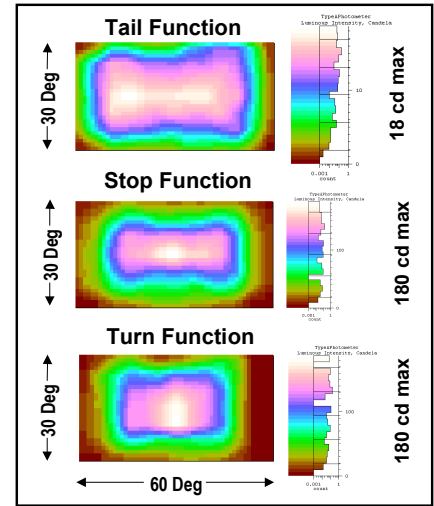


Figure 11: Escalade Taillamp Simulated Intensity Distributions

The easiest to pinpoint is the non-realistic model of the source coupled with the medium red acrylic lens. The actual loss mechanism in the lens is spectral volume absorption, which implies that those rays that have a shorter path through the material will retain a higher percentage of their initial power than those rays whose path length in the material is longer. Once the spectral response of the material is taken into account, the spectral response of the source must be as well. As discussed in the previous case, the spectral response of

tungsten is not exactly that of a blackbody, so the best model would be that of tungsten with the correct color temperature.

Another probable source of variation is in the reflector coating. In practice, a completely specular reflection will not take place on this type of metalized coating. Some percentage of the light will be scattered. Measurements of the coating must be taken to determine what type of scatter model best fits the real coating.

Case 3: Fiberstars Dimpled Luminaire

The Fiberstars® luminaire was designed in *LightTools* to create a specific output illuminance distribution for a given input source distribution. The system, shown in Figure 12, is an acrylic rod which has been flattened. Along the length of the flat is a variable density dimpled texture.

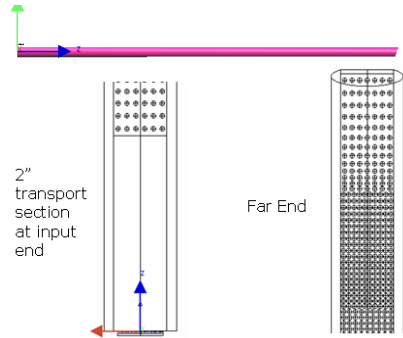


Figure 12: Diagram of the Rod and Both Ends of the Texture

Initial Simulation

As can be seen in Figure 13, the simulated relative illuminance along the length of the rod was nearly uniform, with the exception of the ends. A mockup was made with this design to determine how well it matched simulated performance.

Prototype and Matching Simulation

Once the prototype was made, it was determined that the depth of the textures was not that of the modeled system. In order to make an apples-to-apples comparison, the simulation was rerun with the as-built dimple depth. Figure 14 shows the relative illuminance along the rod length for the measured part as well as the matching simulation. The simulated data falls to within ±2% of the measured data. The entire measured and simulated distributions are shown

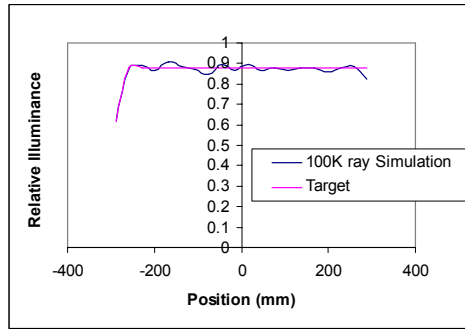


Figure 13: Initial Simulation Results Compared to Target

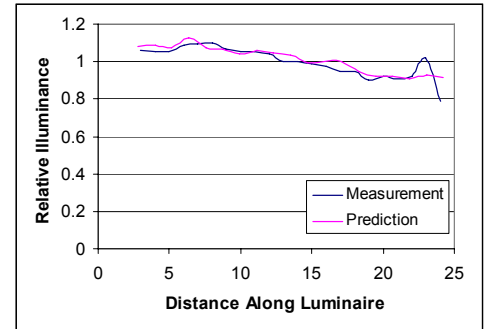


Figure 14: Measured Results Compared to Second Simulation

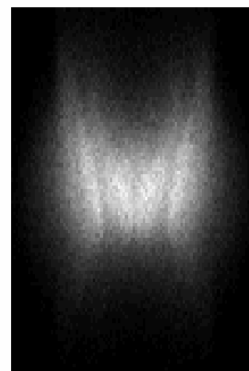
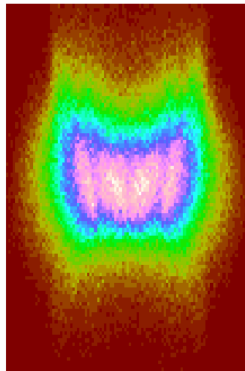


Figure 15: False-color Simulated Results, Grayscale Simulated Results, and Digital Photograph of Prototype Distribution (From Left to Right)

in Figure 15 as a photograph of the real system and as false-color and grayscale images of the simulation data. Even the striations in the quasi-near field illuminance distribution are plainly visible, constituting a good match.

Potential Sources of Variation

The light in this system spends a lot of time in the acrylic rod. As such, the volumetric scattering of the material plays a large role in the outcome. Good models of volumetric scattering are hard to make, and while this simulation uses a scatter model, the level of scatter may change along the length of the rod or a similar variation.

Conclusion

These three examples show that *LightTools* simulations can closely correlate to the measured results of the same system. In all of these systems, most of the variance can be described as manufacturing deviations from the intended design. In each case, the simulation model parameters can be modified to more accurately represent the manufactured system. *LightTools* offers many design and analysis features to enable the user to simulate as-built systems.

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