Optical Design Considerations for Automotive Lighting with LEDs

Strategies In Light Workshop
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Main Considerations

- Flux Requirements
- Intensity Requirements
- Real Estate, Style and Orientation Constraints
- Source Characteristics
- Thermal Constraints
- Optical Approaches
Minimum Flux Requirements Assuming a Perfect Optical System - Lumens

<table>
<thead>
<tr>
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<th>Color</th>
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<th>ECE</th>
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<tr>
<td>Fog lamp</td>
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Typical Parameters Affecting Flux Requirement

- Guard band – for example, GM has 35% added for many lamp types
- Transmission and absorption losses of outer cover lens/es – 10% red or clear lens and 20% for amber
- Realistic best optical efficiency – 70%
- Realistic adjustment factor – red $1.35 \times 1.11 \times 1.43 = 2.14$; amber $1.35 \times 1.25 \times 1.43 = 2.41$; white $1.11 \times 1.43 = 1.59$ (no guard band on some forward lighting)
- Not including thermal de-rating – amber LEDs can be as low as 50%
Realistic Minimum Flux Requirements for Some Automotive Lights - Lumens

<table>
<thead>
<tr>
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<td>Fog lamp</td>
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</table>

* No guard band
Real-World Requirements of Flux

- Values in previous table need to be increased for aesthetic and other reasons.
- For example to achieve a “good” beam pattern for a US low beam there are 350 lumens in the “on-the-road” beam pattern.
- Using the adjustment constant derived earlier (1.59), we get a minimum flux requirement for a US low beam of 557 lumens.
Minimum “Peak” Intensity Requirements – Cd

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<td>938</td>
<td>938</td>
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</tbody>
</table>

*grouped 3 lighted sections  ** non-sealed beam  ***Category 1 - not less than 40 mm from headlamp

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Real World “Minimum” Peak Intensity Requirements

- The typical values are considerably higher than those given in the previous table.
- A realistic requirement for LED headlamps would be 25,000 cd for a low beam and 45,000 cd for a high beam. This would increase the flux requirements from the values stated earlier. For fog lamps a typical value for intensity is 5000 cd with 280 lm on the road.
Real Estate, Style and Orientation Constraints

- Aperture size and shape have a big effect on the maximum intensity and beam divergence that is possible.
- Compact and/or high efficiency optics (in depth) may necessitate tighter tolerances for the manufacture of optical components and placement and positioning of LEDs.
- The number of stand-alone optic/LED units with respect to the aperture size has a big effect on the max intensity and beam collimation that is achievable.
- Off-axis requirements (style) for a design may require the use of unusual optical approaches to achieve compact high efficiency optics.
Example – The Effect of Size of Optic on Peak Intensity and Beam Divergence

- Max. Intensity < Luminance (source) * Aperture Area
- The larger the ratio of the area of the aperture of the optic to the area of the source is, the smaller the beam divergence angle that is achievable without any loss of efficiency.
- For a 1 mm flat Lambertian 30 lumen disk source, encapsulated in a dome with an index of refraction of 1.53, the luminance is approximately 4.08 cd/mm²
- To achieve a peak intensity of 45,000 cd we need a minimum of 11029 mm²
- A more realistic figure is 11029 * 1.43 * 1.1 = 17,348 mm² -- 3 to 5 times the size of existing lamps!
Example of The Effect of the Ratio of the Source Size to Optic Size and Beam Divergence

- The minimum angle of collimation for an LED source of dimensions DxDx L where D = 2mm and L = 0.18mm with a circular optic with a radius, R, of 24.5 mm. The source is encapsulated within a spherical dome with index of refraction n = 1.53.

- The phase space, or etendue (3D), (E), of this source is 34.71mm²-str.

- For a circular symmetric optic the theoretical minimum beam divergence half-angle is θ, where

\[ \theta = \sin^{-1} \sqrt{\frac{(E)}{(\pi^2R^2)}} \]

- Using the above values in this equation we find the minimum half-angle divergence is 4.39 degrees.
Conclusion: Beam Divergence is Defined by the Distance of the Source from the Active Surface/s of the Optic

- This principle is embodied in designs which are required to achieve high collimation and/or sharp cut-offs or gradients – especially low beams and fog lamps.
- Other Corollary Principles:
  - The larger the distance from the source to a redirecting element of the optic the smaller it looks from that element.
  - Off-normal views of a thin flat source yield a smaller solid angle of the source at the optic.
General Tolerance Considerations

- The more compact and efficient the optics, the more accurately the parts have to be manufactured and the more accurately the position and orientation of the LEDs need to be maintained.
- For example, a very compact TIR lens with a tight collimation requirement may need to have the source located within 0.05 mm of the nominal design position.
Special Tolerance Considerations for Forward Lighting—The Gradient

- Tolerance requirements for headlamps and fog lamps are particularly problematic because of the high “gradient” (see for definition US FMVSS 108) requirements (0.13 or better) associated with these lamps.

- These problems are further exacerbated by the variability of the today’s LED sources with regard to:
  - the total flux output,
  - the positional accuracy in the overall package of the die,
  - the variability of the die shape on its boundaries,
  - and the variability of the surface luminance of the LED die.
Example of Variability of Luminance Distribution of a White “Luxeon” LED

- Considerable variation of luminance across the face of the die
- Note that the “boundary” of the 85% luminance area is not linear
The Effect on Performance of the Number of Sources and The Number of Optical Elements

- Typically, the larger the number of sources and the larger the number of individual optics for each source, the more difficult it is to tightly collimate the beam.
- However, there are optimum solutions as to the number of sources and the number of optics, for a given optical prescription when the cost per piece and performance of the LEDs is well defined.
Beam Divergence Angle as a Function of the Number and Size of Sources and Optics

Smaller number/size of sources with larger and fewer optics – the smaller the divergence angle without any lose of efficiency
"Compact” Off-Axis Optics

- Most automobile designs require that the optics follow the contours of the car. If these optics are thin then the optical designer is faced with the problem of redirecting light off-axis.

- High efficiency solutions incorporating off-axis in “one direction” have been explored for both symmetric and asymmetric beam profiles. For example, LPI recently designed a compact optic for a 40 degree off-axis DRL.

- 2-way curvature constraints are particularly difficult for compact optical solutions but can be worked out. For example, there are LED taillights using a multiplicity of freeform reflectors that have been recently introduced (see the latest ideas from BMW and Audi) which handle the rear lighting problem reasonably well. The approaches used in these designs employ a large number of small reflectors each with its own LED.
Some Recent LED Based Designs – LA Auto Show January 2003
Controlling the “junction temperature” of the LED so that it is below a manufacturer’s max limits (typically 120 °C) is possibly the biggest problem facing LED headlamp designers. For example the environment around the engine can be over 60 °C and visible heat sinking features (to the outside air) can be in aesthetic conflict with traditional design approaches.

Some optical solutions lend themselves to improved thermal management:

- High efficiency approaches employing large apertures can minimize heat buildup.
- A variety of LED configurations have merit including those using distributed and centralized architectures.
Optical Approaches – Example of the Variety of LED CHMSL Solutions

- The variety of optical solutions that are possible with LEDs is extensive!
- For example, for LED CHMSLs there have been a number of “looks” already being produced, that are about to be released or that could be produced:
  - Pixellated look – very common (typically seen on air spoilers)
  - The uniform look with jewel-like or sparkly highlights (see new Chevy SSR – a highly compact TIR lens)
  - Neon look - side injected LEDs (seen in some cars for ornamental purposes)

Above: TIR lens used in SSR truck
Below: Lit appearance of SSR CHMSL
Chevy SSR CHMSL – TIR Optic (4 mm thick) with pillow lens-19 LEDS at 1 lm each – achieves 100 cd peak intensity

The lit SSR CHMSL is noticeably more “conspicuous” to the viewer than larger aperture CHMSLs, which use more lower brightness LEDs to achieve the same peak intensity as the SSR CHMSL. This is one of the advantages of using a smaller aperture optic in combination with high luminance LEDs.