# Tailoring free-form glass reflectors towards a homogeneous luminance distribution in roadway applications

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## ABSTRACT

Free-form reflectors are encountered in numerous illumination systems, especially in highly sophisticated applications. The construction of these kind of optics however remains a challenging task where only a few methods are available to derive the free-form shape. One such method is the multi-ellipse approach where a superposition of conic sections is utilized to create the desired illuminance or luminous intensity distribution. While it is useful in many areas one is not always interested in an illuminance or intensity distribution. Especially street lighting reflectors are often tailored towards a homogeneous luminance, taking into account the road's reflective properties, luminaire arrangement etc. While we used our implementation of the multi-ellipse method to design street lighting reflectors with a uniform illuminance before, we now extended this method to support the calculation of a roadway reflector with a homogeneous luminance. For a given roadway scenario we can quickly get an optimized reflector with a good performance compliant to roadway standards such as EN-13201 or IESNA-RP-8-00. Furthermore the optic can be quickly adapted to changing requirements.

**Keywords:** Free-form optics, illumination, glass, luminance, streetlight, extended sources, near-field, far-field, conics, ellipses, NURBS

## 1. INTRODUCTION

In non-imaging optics free-form surfaces are widely used nowadays to efficiently create optical components with very specific properties. Several methods for creating these surfaces have been developed in recent times such as tailoring,[1] simultaneous multiple surfaces (SMS)[2] and a design method based on multiple conic sections.[3,4] The fundamental principle behind these methods is quite different: tailoring solves the partial differential equations of the reflector problem directly, SMS iteratively constructs the surface by following edge-rays and the conic sections methods merges a manifold of conic sections into a singular, closed surface. However, the design target for all these methods is always an illuminance or luminous intensity distribution (or the radiometric equivalents). There are several applications which require different figures of merit that cannot be easily met with the existing methods. Especially in street lighting it is required to achieve a homogeneous luminance in some scenarios to ensure an observer moving along the road perceives it as homogeneously illuminated. The necessary luminous intensity distribution to achieve this not only depends on the geometry of the problem but also on the road surface's reflective properties.

In this paper we present our extension to the multiple conic sections approach to derive a reflector with a homogeneous luminance distribution for a particular setup. Details about our implementation of the multi-ellipse algorithm was presented in a previous paper.[5] The next chapter details the luminance calculation for a street light which is followed by the reflector design method we implemented. In the end we show an example where this method was used and finish with our conclusions.

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## 2. STREET LIGHTING

Street lighting is naturally a heavily regulated field as it has a high impact on the safety of traffic participants. However, those regulations mainly focus on the classification of different street lighting scenarios (i.e. major traffic ways, rural roads, participant composition etc.) and the photometric specifications that should be met in each situation. The actual geometrical setup of light fixtures can vary widely. Nevertheless the reflectors can be reused in different situations to some extent if the mounting height and pole spacing are scaled according to the road widths.

The optical performance for the different classes is always defined by an average value and minimum homogeneity for a photometric quantity such as the illuminance for smaller roads and luminance for major traffic ways. While the former is purely a property of the luminaire itself the latter additionally depends on the road surface's reflective properties and the observer location and thus makes it more difficult to calculate. In this paper we focus on a ME1 class road as defined by the European standard EN 13201, which has the most stringent requirements towards homogeneity (and glare).

The performance of such a luminaire is mainly gauged by three parameters: average luminance level, $L_{avg}$, overall homogeneity, $U_0$, and longitudinal homogeneity, $U_L$. Other photometric quantities such as glare and SR ratio shall be neglected in the following discussion. Luminance values are to be evaluated on a regular grid that depends on the road width and luminaire pole spacing. This leads to a rectangular grid of $M \times N$ points in-between two luminaires. The luminance values have to be evaluated on a per-lane basis, i.e. the average luminance is defined as the arithmetic mean of all values on a single lane. Consequently, the homogeneity measure, $U_0$, is the ratio $L_{min}/L_{max}$ for each lane whereas $U_L$ is defined as the ratio $L_{min}/L_{max}$ of all values along the center of each lane. This scheme is depicted in Fig. 1.

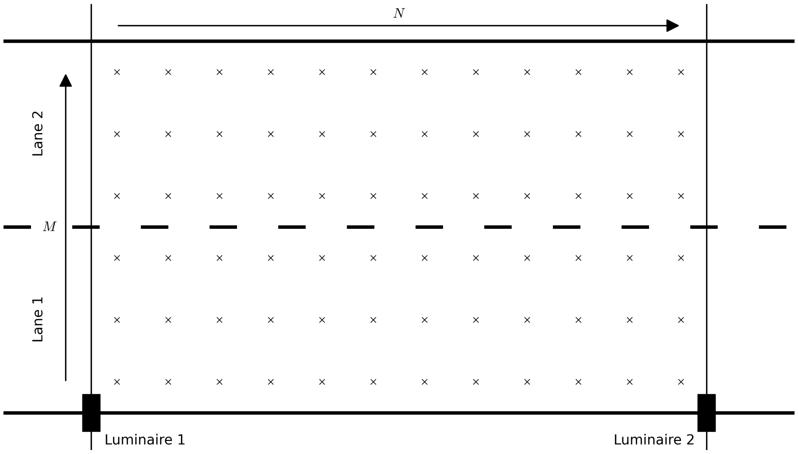


Figure 1. Luminance evaluation grid between two light points for a road with two lanes.

The EN specification further defines a standard observer at a height of 1.5 m looking downward at an angle of about 1.5° which corresponds to a viewing distance of 60 m to the evaluation point. The light that hits this particular point mainly originates in the two light fixtures in front of the observer on his side of the road. While the EN specification dictates more light fixtures to be taken into account this proved to be unnecessary in our calculations. On an actual road many factors influence the reflective properties of its surface (dirt, foliage, water, etc.), these factors can of course not be accounted for. Nevertheless a set of standard surfaces exists which is used by all software packages designed to analyze street lighting optics. They are distributed in form of lookup tables (R-table) that yield a reduced luminance coefficient depending on the observer and light point orientation towards each other (refer to Fig. 2). With this table the luminance at each point of the surface can be calculated by:

$$L = \frac{I(\chi, \gamma) \cdot R(\epsilon, \beta) \cdot 10^{-4}}{H^2} \tag{1}$$

where $I(\chi,\gamma)$ is the luminous intensity into the direction of the evaluation point (azimuth angle $\chi$ and vertical angle $\gamma$), $R(\epsilon,\beta)$ the reduced luminance coefficient obtained from the R-table and $H$ the mounting height of the light fixture. The constant factor is required due to the scaling present within the standard R-tables. Note that the observer's viewing angle is not stated explicitly and cannot be varied with the existing lookup tables.

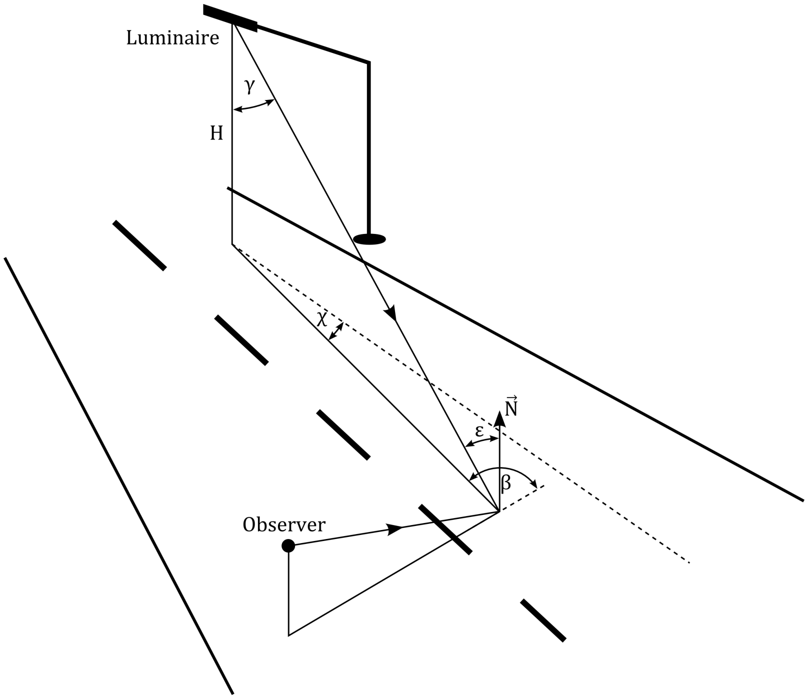


Figure 2. Angles between light point and observer required for the luminance calculation.

## 3. REFLECTOR DESIGN METHOD

The reflector design method was presented in an earlier paper[5] so here only a brief outline of the method is given. It uses multiple ellipsoids to approximate the reflector surface that produces a desired illuminance distribution on a target surface. Every conic's first focal point is placed on the light source whereas the second focal points are distributed over the target surface in a regular pattern. Both focal points define the orientation of the ellipsoid while its size remains a free parameter. The relative size with regard to its direct neighbors dictates the amount of light this particular conic receives and directs towards the second focal point on the target surface. An iterative algorithm modifies all size parameters until the desired illuminance distribution is achieved. With a sufficiently large number of ellipsoids a good approximation to the final surface is obtained. Fitting a NURBS surface to this gives a smooth reflector shape. Almost arbitrary illuminance distributions can be realized with this method.

The luminous intensity distribution, which will result in a homogeneous luminance distribution on the road is a priori unknown for a new street lighting reflector. As stated previously, the perceived brightness on the street is mainly determined by the two luminaires in front of the observer. With the additional condition that both of them illuminate the full space up to the next pole (refer to Fig. 3), the proper illuminance distribution required for a homogeneous luminance can be easily derived.

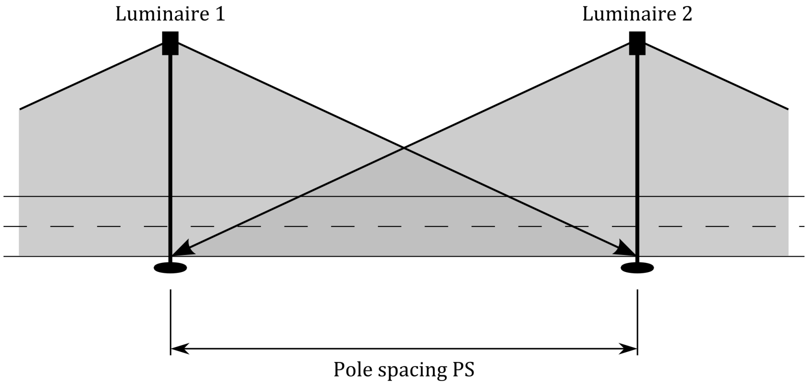


Figure 3. Luminaire geometry and light field extent.

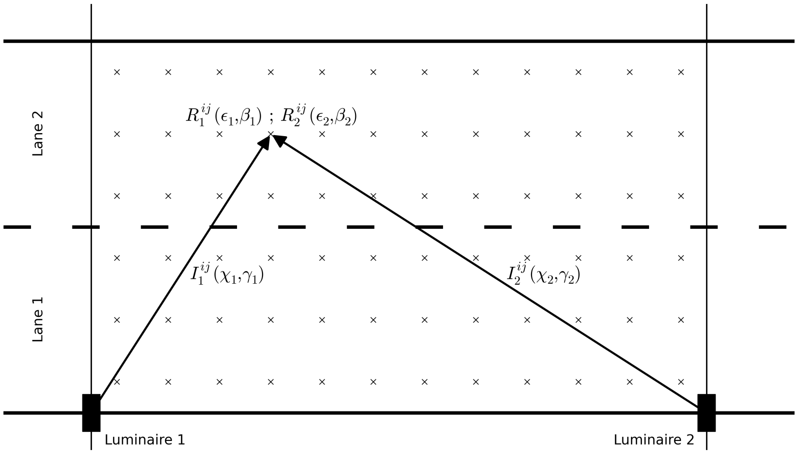


Figure 4. Luminance calculation for a single point on the road.

In Figure 4 the scheme is presented. A single point at $(ij)$ receives light with different intensities $I_1^{ij}, I_2^{ij}$ from two luminaires. Both parts are scattered by different amounts $R_1^{ij}, R_2^{ij}$ towards the observer. The sum of both is the perceived luminance at this point:

$$L^{ij} = L_1^{ij} + L_2^{ij} \qquad i \in [1, M], \quad j \in [1, N] \tag{2}$$

$$= \frac{10^4}{H^2} \cdot \Big[ I_1^{ij}(\chi_1, \gamma_1) \cdot R_1^{ij}(\epsilon_1, \beta_1) + I_2^{ij}(\chi_2, \gamma_2) \cdot R_2^{ij}(\epsilon_2, \beta_2) \Big] \tag{3}$$

Without further information or assumptions we get one equation with two unknowns (the intensities) at each point. However, the problem exhibits a left-right-symmetry: there is a point on the right side with identical intensities but different scattering coefficients. This leads to two equations for two unknown intensities and can be solved by standard linear equation solving techniques such as LU-decomposition.

$$I_1^{ij} \equiv I_2^{i(N-j)} \tag{4}$$

$$L^{ij} = C_1 \cdot I^{ij} + C_2 \cdot I^{i(N-j)} \tag{5}$$

$$L^{i(N-j)} = C_3 \cdot I^{i(N-j)} + C_4 \cdot I^{ij} \tag{6}$$

The reflection coefficients and other factors are composed into the constant values $C_k$. After solving the linear equation systems for either the left or right half of the grid all intensities are known.

$$\begin{pmatrix} C_1 & C_2 \\ C_4 & C_3 \end{pmatrix} \cdot \begin{pmatrix} I^{ij} \\ I^{i(N-j)} \end{pmatrix} = \begin{pmatrix} L^{ij} \\ L^{i(N-j)} \end{pmatrix} \qquad i \in [1, M], \quad j \in [1, N/2] \tag{7}$$

These intensities can be easily transformed into illuminances and used as the optimization target for the multi-ellipse method.

## 4. EXAMPLES

The method is demonstrated on a reflector that one of our customers requested. It should fulfill the photometric specifications for a ME1-class road according to EN 13201. Table 1 lists the basic setup.

Table 1. Description of the street lighting setup.

| Property | Value |
|---|---|
| Mounting height [m] | 10 |
| Pole spacing [m] | 35 |
| Street width [m] | 12 |
| Lanes | 3 |
| Road surface | R3 |
| Light source | HID 210 W |

The evaluation grid is defined in the EN 13201 specification and although we could choose a finer grid for the reflector we settled with the exact same grid. This allows us to compare our calculations to those in commercial software packages. With the geometry defined in Table 1 the grid should be composed of $9 \times 12$ points. The reduced luminance coefficient for this particular setup is shown in Figure 5. On each of them the illuminance was calculated by the method presented above and a multi-ellipsoid reflector was optimized to achieve this distribution (refer to Fig. 6(a)). Although the actual source has a size of several millimeters the spot-like images on the road can still be clearly distinguished. Fitting a NURBS surface to the 108 ellipsoids yields a smooth surface with a smooth luminance distribution. The resulting surface is shown in Figure 6(b).

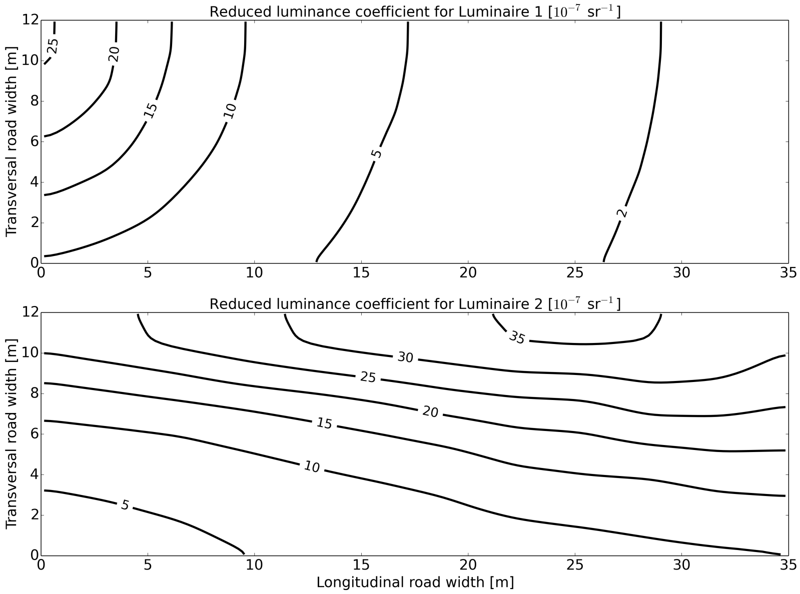
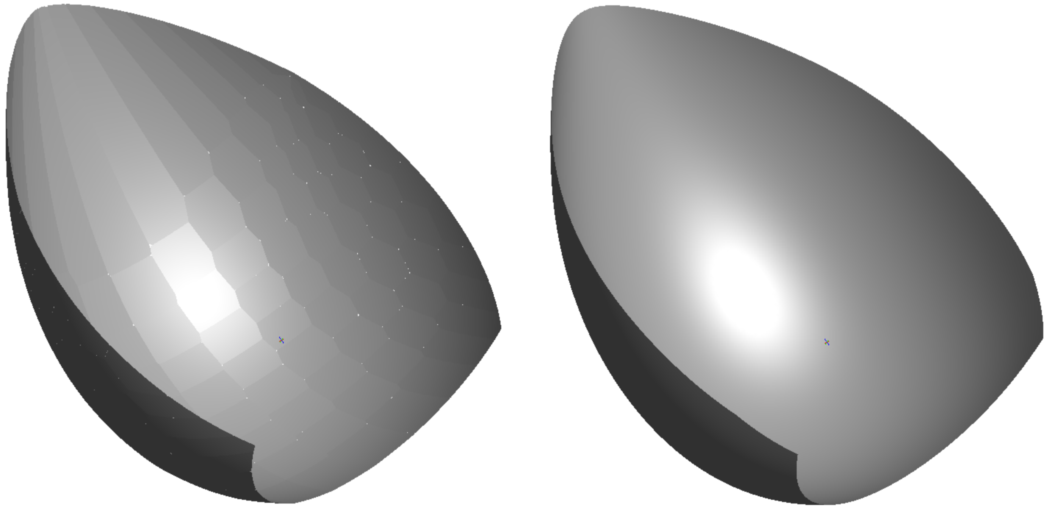


Figure 5. Iso-contour plots of the reduced luminance coefficient for both luminaires.



(a) Multi-ellipsoid reflector (b) Fitted NURBS surface

Figure 6. Resulting reflector shapes that produce a homogeneous luminance distribution on the road.

Although the smooth surface already results in a homogeneous luminance distribution we added spherical facets to the final 3D model. This makes the reflector less prone to lamp misalignment and other deviations always present in a real world setup. Also the impact of manufacturing tolerances is reduced when facets are applied, making it a more robust design.

The performance of the final reflector model was tested in the DIALux software package.[6] Results are listed in Table 2. All luminance values are above the required limits. Additionally, the glare rating (threshold increment) is also below the specified maximum value.

Table 2. Photometric evaluation of the final reflector model in the DIALux software package.

| Property | Target value | Final reflector (lane 1 / 2 / 3) |
|---|---|---|
| Average luminance [cd/m$^2$] | 1.5 - 2.0 | 1.50 / 1.52 / 1.52 |
| Overall uniformity U$_0$ | $\geq 0.4$ | 0.55 / 0.58 / 0.61 |
| Longitudinal uniformity U$_L$ | $\geq 0.7$ | 0.72 / 0.80 / 0.87 |
| Threshold increment [%] | $< 10$ | 7 / 6 / 5 |

## 5. CONCLUSIONS

Common reflector design methods are based on describing a luminous intensity or illuminance distribution. In many cases this is the proper description for the problem, however, in street lighting applications a homogeneous luminance distribution is often required to ensure a driver moving along the road sees it as homogeneously lit. Consequently, the reflective properties of the street itself and the location of an observer with regard to the light sources has to be taken into account. None of the standard reflector design methods is prepared for such a problem since it's out of their scope. Therefore, we extended the multi-ellipse approach to free-form reflectors to ease the creation of street lighting reflectors. The lighting setup is used to derive the necessary illuminance distribution by solving a manifold of linear equation systems. The resulting reflectors perform very well and produce a very homogeneous luminance distribution on the street.

However, this method only works if the assumptions stated before hold true: each lighting fixture must illuminate the area up to the next pole and be left-right symmetric. In some setups with large pole spacings this can be a problem due to high glare if light is emitted under large vertical angles. We found that pole spacing to mounting height ratios up to 3.5 can be used with this method. Additionally, care has to be taken that the linear equation systems yield a strictly positive solution. While negative luminous intensity will solve the problem mathematically they have no physical meaning.

In principle this method is also applicable to transmissive optics, e.g. for LED-based luminaires. Cartesian ovals provide a similar function in refractive optics that ellipsoids do in the reflective case: they direct light from one focal point to another.[7] And even with some generic design method the derived illuminance distribution can serve as a merit function for an optimizer.

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