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**Study, Design and
Optimization of a Light Guide
on the Door Panel for Interior
Lighting of a Car**

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*Alla mia famiglia, per avermi permesso
di raggiungere questo traguardo, sostenendomi
nei momenti peggiori, vi voglio bene.*

*A Nicole, per essere stata sempre
al mio fianco, spingendomi a lottare e non mollare
mai per inseguire i miei sogni.*

*Ai miei amici, per aver reso
questo percorso più piacevole.*

Grazie a tutti.

Abstract

The thesis work was supervised and carried out with TECNOCAD, an expert company in the automotive sector that designed the Nucleus Icona.

Ambient light is constantly developing, and this favored the increasing of a new generation of safety and signaling lights, indicator lights, LEDs and soft lights in the interior of a car. Although in the 90s and 2000s the focus was on essentiality, with very basic cars, where mechanics clearly prevailed over electronics, nowadays, thanks to the great technological development, the situation has reversed. The interiors of a car look more and more like real rooms where the goal is also to make the driver feel as comfortable as possible.

The purpose of this thesis is to design a light guide for the door of the Icona Nucleus, a self-driving car prototype. The project starts from a study of photometry and optics that underlie the functioning of these lighting components, validated by some mathematical tests and with the help of TracePro, an optics simulation software. The results obtained will be the starting point for the development of the light guide. After having designed it with the CAD and after the first simulations on TracePro, the luminous performance has been optimized by observing the results and moving the position of the LEDs or adding new ones to obtain lighting uniformity.

This thesis keeps track of all the operational steps for the realization of a light guide. The results obtained, besides demonstrating the validity of the procedure, can be a starting point for future developments of this project or similar applications.

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1. Introduction

Nowadays, technology is constantly evolving, and this has inevitably changed every aspect of our life. Like everything else, cars have also suffered the consequences of this process, which has made them more and more comfortable, fast and safe. For all this, technology has been fundamental, by now there is no longer a purely mechanical automotive component, but the combination with electronics is an increasingly consolidated reality.

This has incredibly favored the progress of ambient light, which is now one of the strong points in the automotive field. In fact, if twenty years ago, internal LED lights were used exclusively in luxury cars, or in any case more expensive than normal, nowadays they are present in practically all cars, from the most equipped to the cheapest ones. Just think of how many LEDs, warning lights, light strips are present in the passenger compartment, from purely aesthetic ones to those for safety or reporting malfunctions and open doors.

By now all car manufacturers are focusing on interior lighting, not only for functional purposes, but also to improve style and comfort. Some of them, including Audi, Toyota and BMW, already in the first decade of the 2000s invested heavily in ambient lighting research to determine optimal colors and brightness levels in order to improve the transmission of safety information [1].

All purely aesthetic LEDs can be easily controlled in intensity and color according to the needs of travelers. Obviously, it's not just about style and aesthetics, but also about functionality and comfort. The possibility of dimming or increasing the interior lights becomes an important feature: the brightness should in fact be reduced for night driving and increased during the day; but this also depends on the task to be performed, such as reading the map or searching for some object, which may require more brightness [1].

Even the choice of color is not random, in fact each color has its own meaning. Red and orange are the colors associated with danger or attention, blue is ideal for safety related functions, green has been considered the color of relaxation and calm while warm white LEDs are used for soft lighting [1].

Car manufacturers have also specialized in providing a series of important notifications and information to drivers without distracting them. Illumination of displays and dashboards is a key factor in presenting data in an effective and timely manner. The overall effect should also be considered, such as glare and the reflection of colored lights on internal surfaces, especially when driving at night.

It cannot be denied, however, that ambient and mood lighting also means making cars more appealing to buyers, beautifying them and providing a sense of comfort and well-being [1].

The goal of my work is precisely to design a light guide for the door panel of the Icona Nucleus, a prototype of self-driving hybrid car. The light guide will have to meet various requirements, first of all a uniform luminance value of about 100 cd / m^2 , but at the same time not dazzle the passengers but create a pleasant atmosphere inside the passenger compartment. The project starts from a study of photometry and optics that underlie the functioning of these lighting components, validated by some mathematical tests and with the help of TracePro, an optics simulation software. Subsequently, the results obtained will be the starting point for the design of our tubular, which will then be modified to meet the requirements.



Figure 1 Icona Nucleus

2. Reference of optics and photometry

2.1 Reflection and refraction

Light is an electromagnetic wave that propagates in a vacuum; the human eye can perceive the rays included in the frequency range between $4 \cdot 10^{14}$ Hz and $8 \cdot 10^{14}$ Hz [2]. The set of colors that form visible light is called the spectrum and the range of frequencies visible field. Light propagates linearly, which is why we speak of light rays [2].

When a ray hits the separation surface between two different materials (for example air-water, or air-glass), a reflected ray is generated, which is rejected, and a refracted ray which propagates in the second medium [3]. All types of waves, not just electromagnetic ones, exhibit the same type of behavior.

2.2 Properties of reflection and refraction

The incident ray, the reflected one, the refracted one and the normal (perpendicular) to the separation surface between the two media belong to the same plane [3].

Furthermore, the angles with respect to the normal to the surface of the incident ray, reflected and refracted rays are linked together.

The angle of reflection is equal to the incidence ($i = r$).

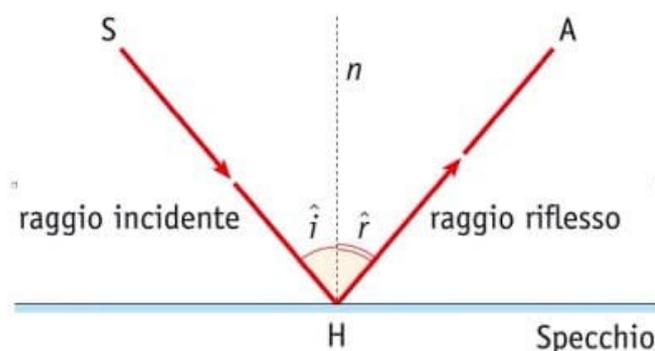


Figure 2 Reflection properties

The relationship between the angle of refraction and that of incidence is based on the so-called Snell's law:

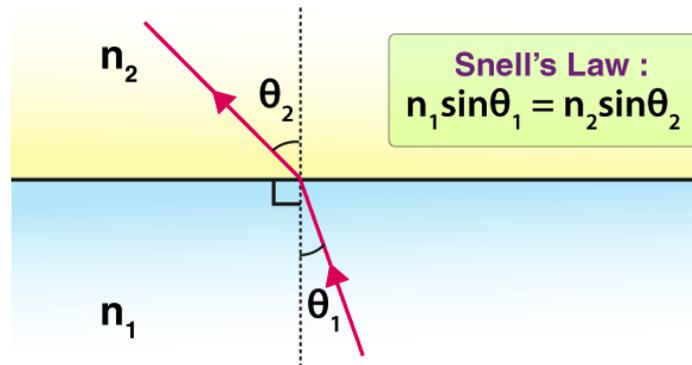


Figure 3 Snell's law

- n_1, n_2 are the refractive indices of the two materials involved
- $\sin(\theta_1)$ is the sine of the incident angle.
- $\sin(\theta_2)$ is the sine of the refracted angle.

2.3 Total internal reflection and limit angle

If the refractive index of the first material is less than the index of the second, the refracted ray will approach the perpendicular and consequently there will always be a reflected and a refracted ray.

Otherwise, the refracted ray moves away from the perpendicular. As the angle of incidence increases, the angle of refraction increases, until for a given value of the angle of incidence, the refracted angle is equal to 90° , and so the refracted ray does not penetrate the second medium at all [3]. This phenomenon is called total reflection and the angle for which it occurs is the limit angle, the value of which depends on the two materials taken into consideration [3].

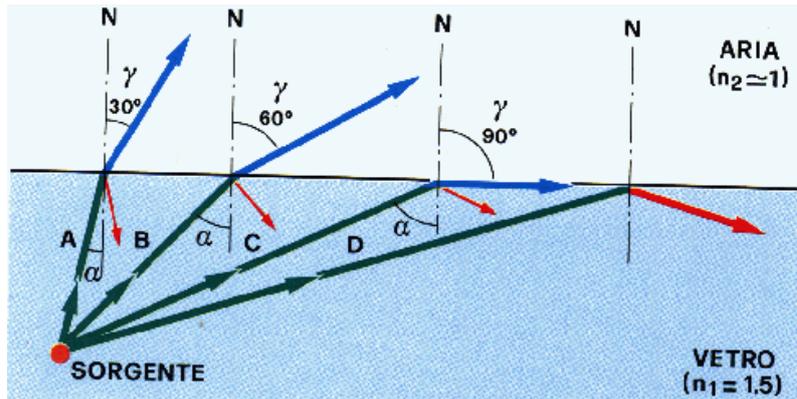


Figure 4 Example of total reflection

2.4 Photometry

“Photometric quantities are physical quantities that quantify the light emission in terms of the response of the human visual system, which has non-uniform sensitivity at different wavelengths” [4].

“The photometric quantities are as follows:

- **Light energy:** it is the photometric quantity that corresponds to the radiant energy carried by a field of electromagnetic radiation with frequencies belonging to visible light.
 - is indicated with Q_v .
 - the unit of measurement is the lumen per second ($\text{lm} \cdot \text{s}$).

- **Luminous flux:** it is the light energy emitted by a given source in the unit of time: Q_v / s .
 - is indicated with the Greek letter Φ (phi).
 - the SI unit of measurement is the lumen (lm); 1 watt = 683 lumens for a light radiation with a wavelength of 555 nm (maximum visibility).

- **Luminous emittance:** it indicates the ratio between the luminous flux and the emitting surface.
 - is indicated with E_v .
 - the SI unit of measurement is lux (lx), or (lm / m^2).

- **Illuminance:** ratio between the luminous flux received by a surface and the surface area itself.
 - is indicated with E_v .

- the SI unit of measurement is lux (lx), i.e. lumen per square meter (lm / m²).
- **Luminous intensity:** Luminous flux emitted within the unit solid angle (steradian) in a given direction.
 - is indicated with I_v and is a vector quantity.
 - the SI unit of measurement is the candle (cd).
- **Luminance:** ratio between the light intensity emitted by a surface in a given direction and the apparent surface area.
 - is referred to as L_v .
 - the SI unit of measurement is the candle per square meter (cd / m²).” [4]

3. Software for optical simulation and potentiality

Today engineers must deliver extreme innovation quickly, trying to moderate expenses and maintaining a high production. In the automotive, aerospace, and general lighting segments fields, the time and the budget to use for physical testing and prototypes are limited [5]. Therefore, lighting design and verification must take place thanks to software in a virtual manner, so there are no surprises when designs became a real element.

Many software could be used for optical design, 3 of the most important are:



Figure 5 Ansys Speos



Figure 6 LucidShape



Figure 7 TracePro

3.1 Ansys Speos

Ansys SPEOS helps optical engineers to study critical factors such as visibility, reflection, and propagation, also for identifying problems such as glare and hot spots. By designing, engineering and testing their lighting systems in a risk-free virtual space, optical engineers can work faster and so, minimize the costs [5]. From the CAD model to the real product, via SPEOS simulation we can work on LEDs, increasing the levels of optical energy efficiency, better lighting appearance and illumination [5]. This useful software can be applied in a wide range of lighting applications, from smart phones to computer screens and retail stores. Engineers can determine how displays and screens will appear in real conditions, and under every light condition thanks to the function called 'SPEOS Live Preview' that depicts the proposed lighting design under real-world conditions [5]. SPEOS can test different geometries, surface finishes and materials tanks to the library to ensure the right performance and aesthetic characteristics for their finished designs [5].

3.2 LucidShape

LucidShape is a 3D software for the design of lighting elements in automotive field and various optical products. It can be used in many applications, from the headlamps, lighting to the lightguides. This powerful program implements many features:

- "LucidStudio, an interactive development environment to design, display and analyze geometry and results of simulations.
- LucidShapeFunGeo, a library of algorithms to design functional geometry such as light guide and lenses.
- LucidShell, it permits thanks to a C-like language to modify and create your own applications.
- LucidObject, a useful toolbox of pre-defined lighting components ready to use in complex simulations.
- VisualizeModule, for high-speed photorealistic renderings." [6]

With its powerful tools for simulating light sources, surfaces, materials and sensors, LucidShape can be used to design a wide range of applications.

A CAD file could be used to import the geometry, or the model can be designed in LucidStudio. The features can be used together, for example by defining complex geometry in Lucid Studio and more easily designing the components surrounding the luminaire in a CAD system and later importing them into LucidShape.[6]

3.3 TracePro

TracePro is a commercial optical simulation software that was developed by Lambda Research Corporation of Littleton, Massachusetts, USA, and has been in continuous development since 1994 [7]. The program is a 3D CAD for the design and analysis of optical and lighting systems that through a virtual environment can perform various type of simulations to verify their functionality before any prototyping. It was immediately used by NASA for its studies. TracePro is widely used in the aerospace, defense, lighting, automotive and biomedical fields and for the design and analysis of all types of optical / lighting systems, from the transmission of diffused light in telescopes and cameras, to biomedical applications and modeling of LEDs, light guides [7].

4. The TracePro approach

User can work on TracePro using software's native CAD interface or by importing models that he has previously designed in other CAD software that exports IGES or STEP models [7]. TracePro also has Ray Viz an add-on to interface it directly with Solidworks, allowing users to apply and save optical properties, trace rays to visualize light propagation, and perform various types of analysis directly in the Solidworks file [7]. Using the software without RayViz, rays are plotted through bodies to find energy distributions on any surface or to plot volume flow through any space [7]. Users can also test the lighting of different systems and create renders to check for uniformity, hazy glow, glare and distortion issues. It is also possible to simulate thermal effects. Finally, there are optimization and programming features for more professional users.

All these features make the program suitable for our needs and ideal for studying the lighting performance by varying the shape, size, section and position of the lightguide. In fact, observing the characteristics of the 3 programs, LUCIDSHAPE is a very advanced software that, once you have given it photometric and spatial constraints to be respected, immediately creates the light guide. Although it is very valid, it could be useful for the design of the structure, but it isn't suitable for the study of the parameters under consideration. ANSYS SPEOS, also very valid, is used in many applications, which would make it suitable for a more superficial and not in-depth analysis as requested by us.

4.1 Functionality

The operation of TracePro is very simple and intuitive. The first thing is to create or import the geometry, the program immediately recognizes the various bodies previously defined in the CAD file. The pop-up menus at the top of the screen also

follow the sequence of operations that should be performed for each simulation in order from left to right (Figure 8). From the opening of the file up to the analysis of the results passing through the geometry and the raytrace.



Figure 8 TracePro interface

The next step is to assign the properties present in the preset libraries to the bodies and surfaces so that the various components of the work are recognized as real units and no longer just as empty containers having only a certain shape. If the properties to assign are not present in the database, they can also be imported.

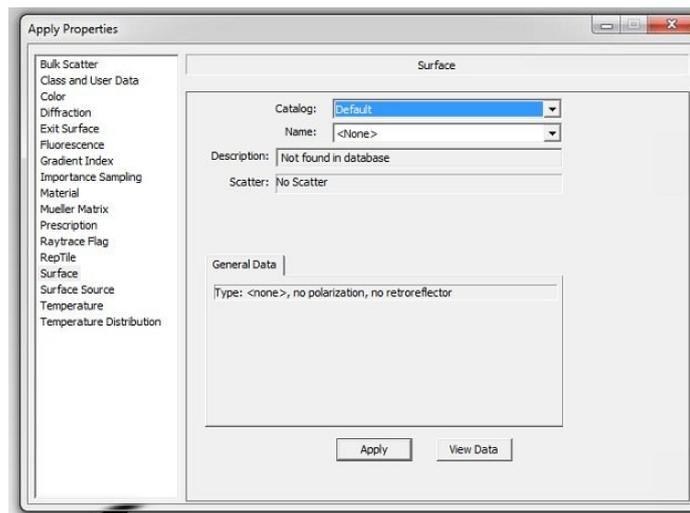


Figure 9 TracePro properties

Among the most assigned properties there are certainly the various material and surface properties.

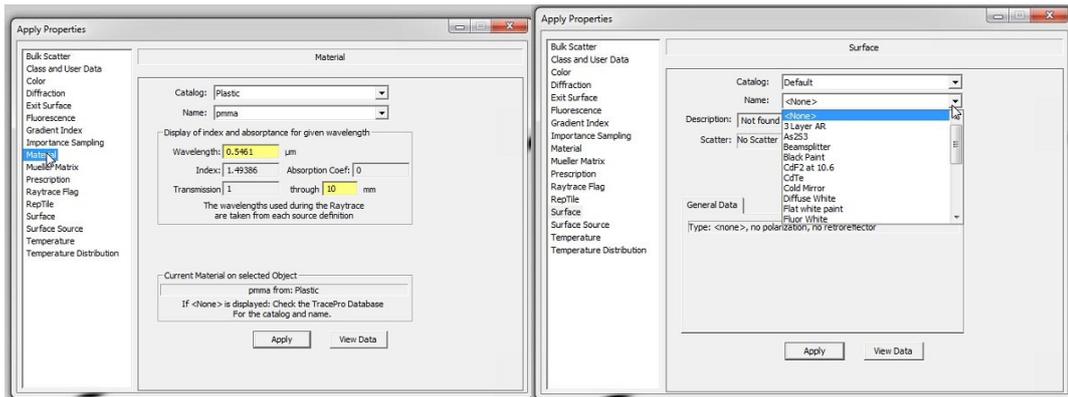


Figure 10 Material and surface properties

But to our bodies we can also define transparency color texture etc...

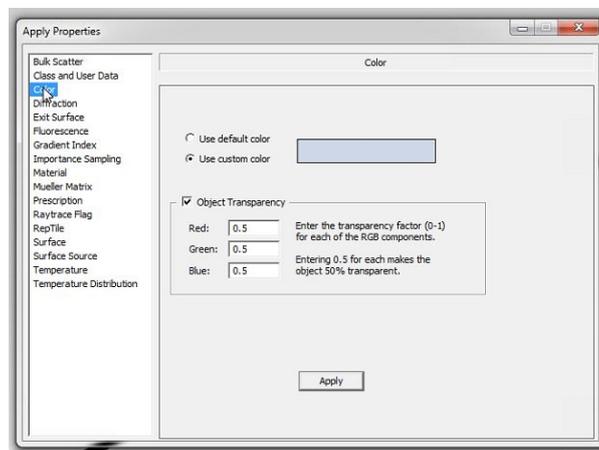


Figure 11 TracePro properties

Finally, the surface to be defined as a surface source is chosen, assigning to the latter properties of LED sources or lamps already present in the database. Assigning this properties, we must also set the wavelengths (in general we stay between value of 0.5 and 0.7, the visible light) and the number of rays to trace. Also in this case, if we want to import a particular LED of which we have a datasheet, it can be done.

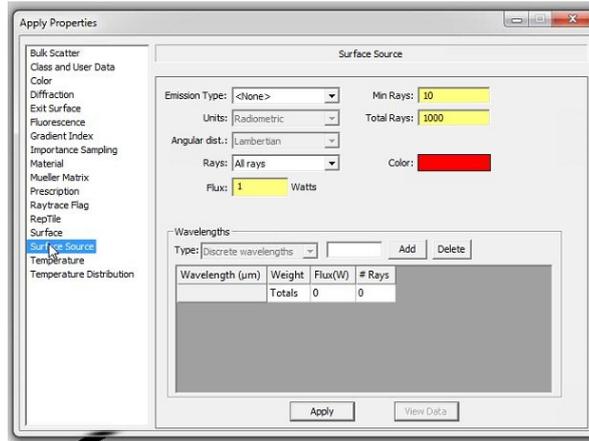


Figure 12 Assigning the LED properties

Once these preliminary phases have been completed, the raytrace can be performed. The length of this operation depends on the complexity of the optical system and surfaces, on the weight of the file and on the number of rays to trace previously set; naturally, the greater the quantity of rays, the greater the time taken by the software to provide the result.

Once the raytrace is finished, we move on to the analysis of the results. The program provides us with various tools depending on the quantity we want to analyze: illuminance maps, 3D illuminance, luminance/radiance maps, candela traces and much more.

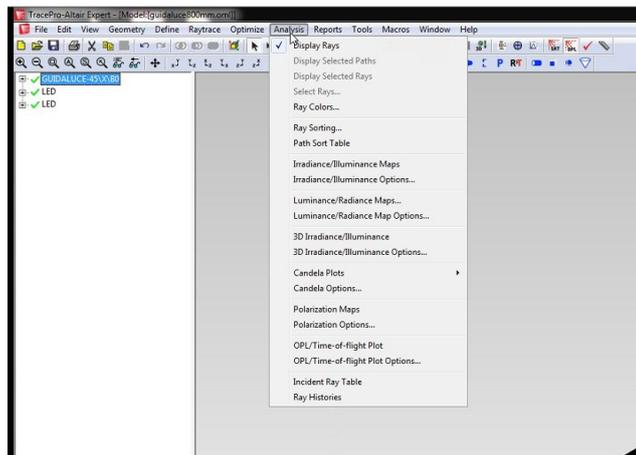


Figure 13 TracePro analysis tools

If the results are not those expected, or are below the requirements of a hypothetical customer, geometry or properties can be modified and the procedure repeated.

Finally, there is also the possibility of creating renders, to admire how our work would really be once finished. To do this, you must first set the quality, the number of photons to track, and different brightness levels:

- Anything
- Outdoor brightness
- Office brightness

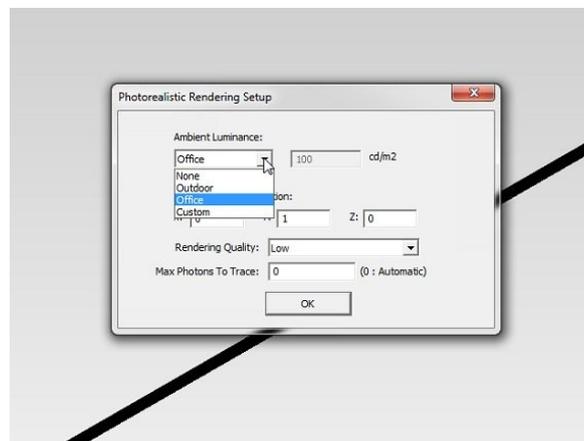


Figure 14 TracePro render options

Obviously, based on the settings provided, there will be a different length of time for creating the render, which can range from a few minutes to several days. It is better to start with low quality and moderate number of photons and if necessary, raise the parameters.

5. Lightguide principles

5.1 What Is a Light Guide?

A light guide is a device created to transport light from a source to a point at a certain distance with minimal light leakage by means of total internal reflection, or as we will see later spread it along its path [8]. Light guides are generally made of materials that meet certain optical properties such as acrylic and epoxy resin, polycarbonate and glass [8]. The uses of these components are endless; from beaming light from an LED to a front panel for use as a status indication, to gathering and directing light to backlight an LCD display.

5.2 Basic Principles

“Snell’s Law: When light rays are incident to a boundary between two mediums, for example glass and air, the light rays are deflected when they cross the 2 materials as illustrated in Figure 1. The angle at which the light rays are incident to the boundary is called the *angle of incidence*, ϕ_i , and the angle at which the light rays leave the boundary is called the *angle of refraction*” [8].

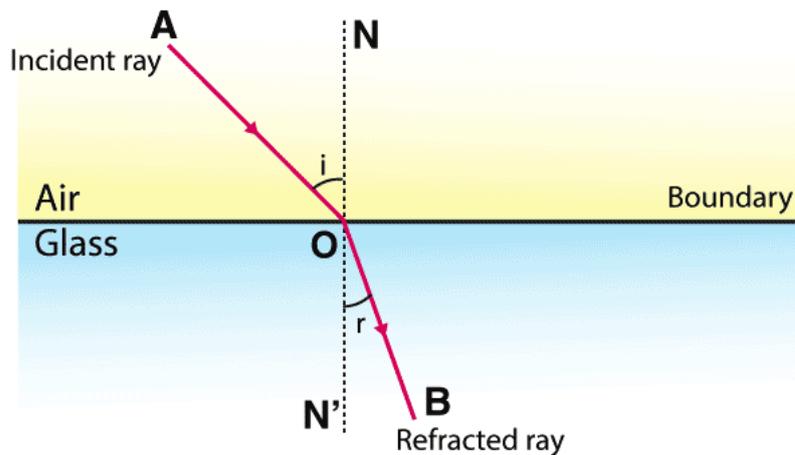


Figure 15 Refraction

Snell's Law =

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Where n_1 is the refraction index of the first material and n_2 the refraction index of the second material.

“Fresnel Loss: When light rays pass from one material to another, there is a loss due to reflection at the boundary [8]. This is called Fresnel loss and is calculated with the following expression”:

$$\text{Fresnel Loss} = 100 \cdot \left[\frac{n_i - n_f}{n_i + n_f} \right]^2$$

Figure 16 Fresnel loss expression

For plastic to air and glass to air interface boundaries, the Fresnel loss is about 4%.

In propagating inside a light guide, light rays follow the Snell law. In very elongated components it is important to remember the phenomenon of total reflection, according to which if the angle of incidence is greater than a certain angle, depending on the two materials taken into consideration, the refraction does not take place and we only have reflection. Considering air and glass-plastic materials, the limit angle for which this phenomenon occurs is 42° [8]. Having the critical

angle slightly less than 45° for most materials used in lightguide construction is very convenient because it allows the use of 45° inclined prismatic reflective surfaces when studying the design [8].

Ray Tracing: Ray tracing is a technique used to predict the path of light rays, in through and out of the light guide [8].

The three main design problems for this type of component are:

- 1) transmit the light rays from our source to the light guide entrance, limiting losses.
- 2) to transmit light internally without excessively dispersing it.
- 3) let the light escape through the exit surface

As regards point number 1, that is the most critical, the primary objective is to allow the capture of light with minimal loss. When the LED is external to the surface of the light guide, the transmission of light rays takes place ineffectively [8]. Efficiency can be improved only if the angle of the LED radiation pattern coincides with the angle of the light guide acceptance pattern [8]. This type of configuration is very difficult to implement and only less than 10% of the available stream is typically captured [8].

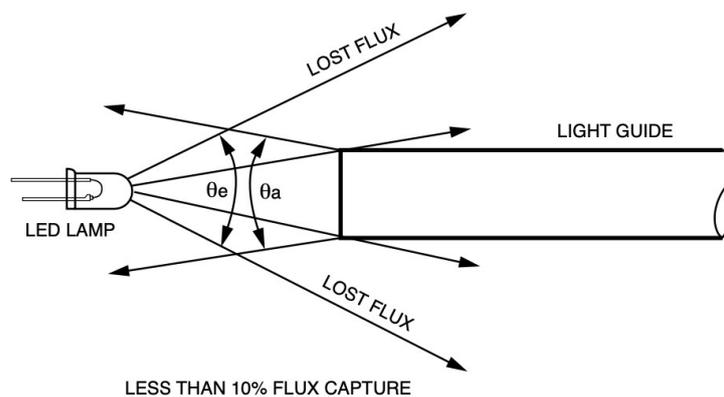


Figure 17 LED lamp external to light guide

A further solution may be the use of a lens to converge the flow towards the entrance, as shown in Figure 18. The light capture can be up to 80%, but the distance at which to arrange the components must be adapted to the focal length of the lens [8].

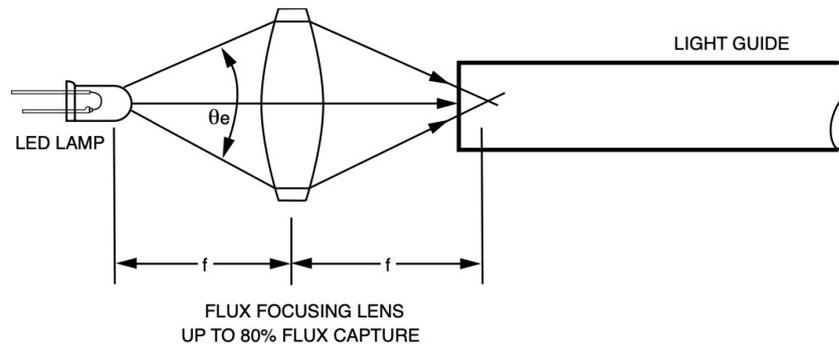


Figure 18 Lens technique for light guide

The best design to have an almost perfect absorption is to have the LED located within the envelope of the light guide surface at the air boundary [8]. This concept is illustrated in Figure 20a. In this configuration, all light rays emanating from the LED are captured. The effectiveness is 92%, considering the Fresnel losses across the air gap [8].

When the LED housing is bonded to the light guide with an optical grade epoxy resin, as shown in Figure 20b, the Fresnel losses are practically negligible, and the efficiency reaches values very close to 100% [8]. However, this technique is rarely used, and a small air gap is always left between the LED and the optical body.

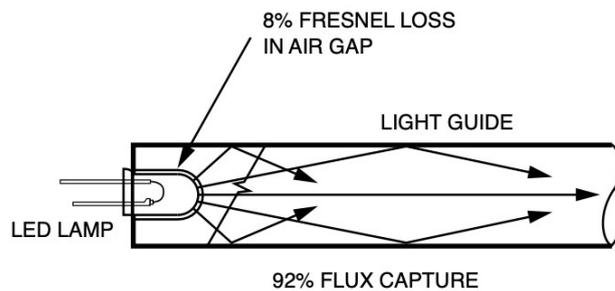


Figure 19 Led located within the envelop of the guide

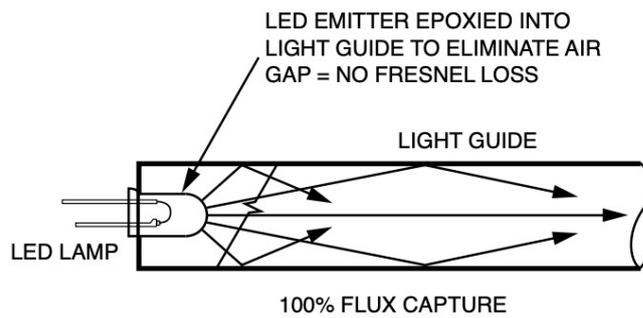


Figure 20 Led epoxied into the guide

For point 2 and 3 the only things to consider is to maintain the surface parallel to direction of light smooth and outer surface diffused in order to contain losses.

5.3 Physical attributes of a lightguide

The outer surfaces are important to ensure proper function, as shown in Figure 21. The sides parallel to the direction of propagation of light rays should be smooth like a mirror, to ensure near-perfect internal reflection [8]. Furthermore, to reflect even the diagonal rays that strike with angles smaller than the critical angle with the risk of escaping, the exterior can be painted with a white paint [8].

The entry surface should be smooth and contoured [8].

The exit end should instead be diffused because having transverse random critical angles there is a high probability that the light rays will escape in a dispersed manner producing a large radiation pattern [8].

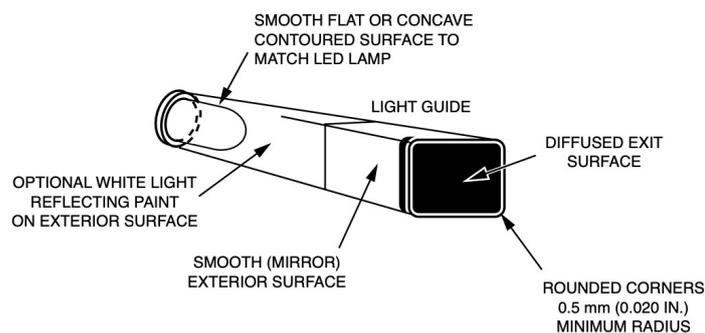


Figure 21 Physical attribute of a light guide

The light conductors can be made in any desired shape, cylindrical (oval)rectangular (square), conical (increasing in size from the input end to the output end) or any special shape (arrow, star-shaped, quarter of the moon, etc.)

[8]. For rectangular and special shapes, the corners must have a radius greater than 0.5 mm, not excessively acute, to guarantee illumination [8]. The shape of the light conductor can vary gradually along its length.

For devices with LEDs that have a light emitting area that is a flat surface, the input end of the light guide must also be a flat, smooth surface.

5.4 Light guide around corners

The light guides can be bent to go around corners. The bend radius should be at least equal to or greater than twice the diameter of the light conductor, to minimize losses [8]. The reflected light rays follow the shape of the lossless beam curve, as shown in Figure 22.

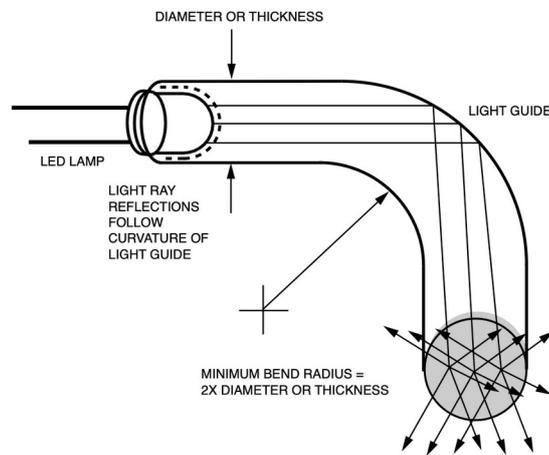


Figure 22 Bent light guide around corners

It is also possible to achieve abrupt changes in direction at right angles by using a reflective prism positioned at the 90° curve, as shown in Figure 16 [8].

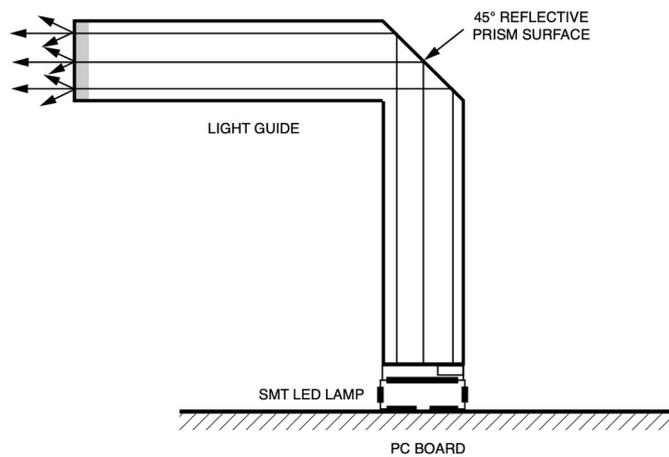


Figure 23 Reflective surface for corner

5.5 Types of light guide

As we have seen, in some cases the objective is to transport light from one end of the guide to the other, in others it is instead to extract the light along the entire length of the guide and to direct it specifically [9]. This type of extraction causes the lightguide to appear bright along its entire length and is achieved by adding certain components to the fixture such as dots of paint or textures (small bumps or holes) that affect how light is reflected, disrupting the TIR and making go out the light gradually [9].

In the first case, our guide will have a very simple shape, generally cylindrical with smooth and homogeneous surfaces (a kind of optical fiber).

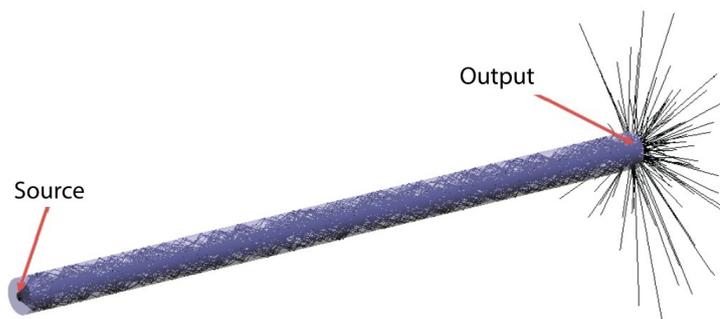


Figure 24 Cylindrical light guide

On the contrary, if we want to extract the light along the guide, as previously mentioned, we must insert elements that interrupt the TIR. These can take many forms, but some of the most common are dots of paint and small prismatic structures carved into the guide, often referred to as textures, shown in the figure below [9]. The latter change the direction of the light hitting the element,

extracting it from the guide. By varying the density and size of the extraction features, it is possible to obtain a uniform light emission, and with some textures it is even possible to control the direction of the outgoing light [9].

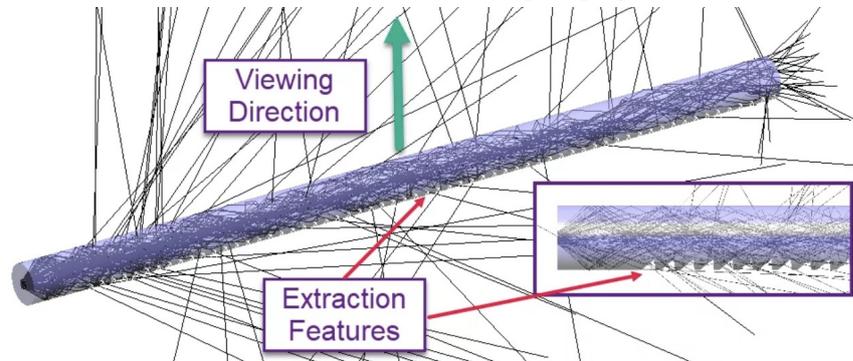


Figure 25 Light guide with textures

6. Validations

To validate these theoretical texts is first carried out a more mathematical study on the inclination of the angles, and subsequently some simulations with Tracepro.

6.1 Study inclination angles

One of the first steps of the project was a study of the angular variation to obtain an outgoing light beam at 90° , perpendicular to the horizontal direction of the light guide, hypothesized of PMMA.

Considering that the limit angle of PMMA is 42° , a ray that strikes a PMMA surface will be refracted in the air only if the angle of incidence is less than 42° . Otherwise, it will be reflected internally in the light guide.

Although, as previously seen, the light extraction direction is in correspondence with the smooth part of the tube, opposite the teeth, but in this experiment pretending not to know how light guides work, the study will be carried out on both sides.

6.2 Study on the toothed part

Thus, by 'shooting' 3 beams at 3 different distances from the LED (50,100,150 mm), the goal of the first part of the experience is to calculate the angles of inclination of the refractive surface (y and z angles in the figure below), so that the beam is first refracted and then reflected to come out of the light guide at 90° and illuminate the outside as homogeneously as possible.

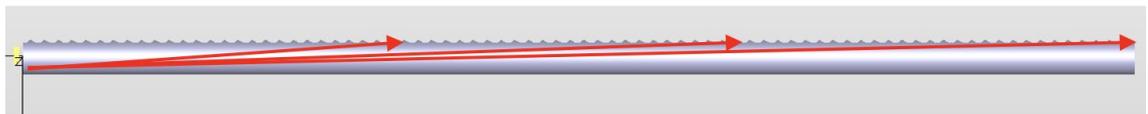


Figure 26 Light guide and 3 rays

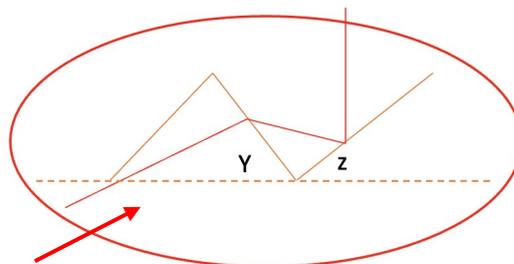


Figure 27 Goal of the experience

To find the solution, first of all the angle of inclination of the refracted beam is calculated, with respect to the horizontal section of the light guide.

Assuming the source of the rays positioned 2 mm below the horizontal surface where the teeth are and knowing the distance at which the beam hits the tooth, we obtain this angle by doing:

$$X^\circ = \arctg(2\text{mm}/d)$$

Varying the d distance, we obtain:

$$1) X^\circ(d=50\text{mm})=2.3^\circ$$

$$2) X^\circ(d=100\text{mm})=1.15^\circ$$

$$3) X^\circ(d=150\text{mm})=0.76^\circ$$

Subsequently a geometric construction is carried out to clarify the procedure.

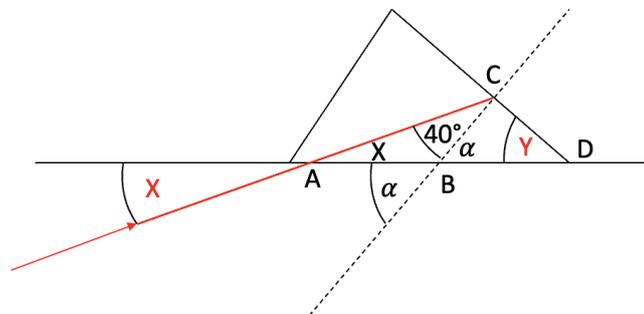


Figure 28 Rays that hit the tooth

We impose the incident angle of 40° , in order to have refraction. Then, the following steps are done:

- 1) Considering the triangle ABC, knowing the angle x and the angle in C, assumed to be 40° to have refraction, the angle in B is obtained.
- 2) Knowing the angle at B, its supplementary alpha can be obtained.

- 3) Considering the triangle BCD, knowing alpha and the right angle in C we can find the amplitude of our first unknown angle Y.

So, by exploiting the properties of internal angles of a triangle, the properties of supplementary angles, and finally with a little mathematical simplification, we arrive at the formula:

$$Y^{\circ} = 50^{\circ} - X^{\circ}$$

The next step is to obtain the value of the refracted angle. Recalling Snell's law:

$$\frac{\sin i}{\sin r} = n$$

Figure 29 Snell's law

And knowing that the refractive index for a ray passing from PMMA to air is 0.67, it is possible to calculate the exit direction of the light ray with respect to the normal.

$$R^{\circ} = \sin^{-1}(\sin i^{\circ} / 0.67)$$

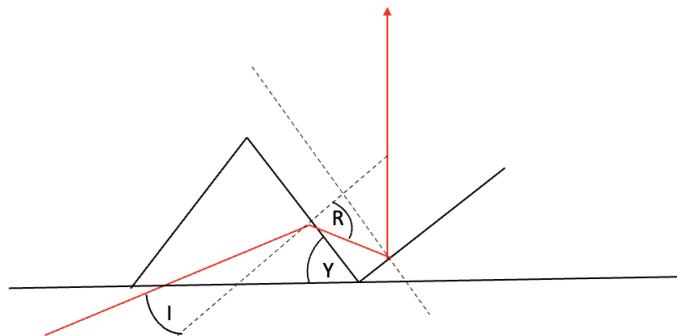


Figure 30 Refracted and reflected rays

We will therefore have the refracted ray exiting at an angle $R^{\circ} = 73.6^{\circ}$ with respect to the normal.

Finally, exploiting the properties of reflection, with a further geometric construction we obtain with the following the steps above the z angle:

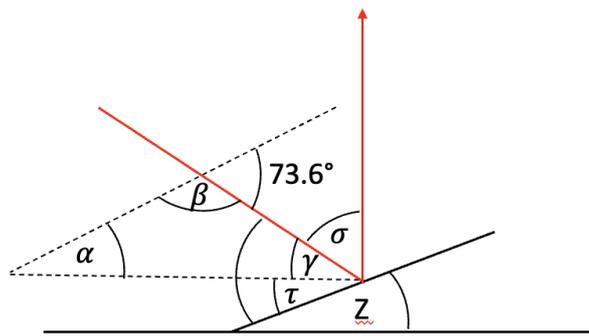


Figure 31 Reflection on the second tooth

$$1) \beta = 180 - 73,6$$

2) Knowing α , γ is obtained.

$$3) \sigma = 90 - \gamma$$

$$4) \gamma + \tau = (180 - \sigma) / 2$$

$$5) \tau = \gamma + \tau - \gamma$$

Finally, we can see that $\tau = Z$.

With some mathematical simplifications, we obtain that:

$$Z^\circ = 65^\circ - (R^\circ / 2) + (X / 2)$$

By putting the previously obtained formulas into practice, it is possible to obtain the angles of inclination of the teeth in these 3 ideal cases.

$$1. Y^\circ(d=50\text{mm}) = 47,7^\circ$$

$$2. Y^\circ(d=100\text{mm}) = 48,85^\circ$$

$$3. Y^\circ(d=150\text{mm}) = 49,24^\circ$$

$$1. Z^\circ(d=50\text{mm})=29,35^\circ$$

$$2. Z^\circ(d=100\text{mm})=27,42^\circ$$

$$3. Z^\circ(d=150\text{mm})=27,8^\circ$$

6.3 Study on the smooth side

In the second part only the phenomenon of reflection is taken into consideration and the inclination of the single tooth y is evaluated to let a light beam exit at 90 degrees from the smooth part of the tubular, opposite to where the teeth are present (real functioning of lightguide).

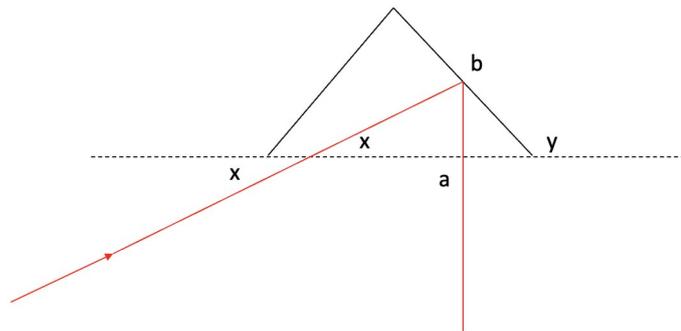


Figure 32 Goal of the experience

As in the previous case, knowing the angle x , and considering the abx triangle, the b angle can be calculated.

By exploiting the property of reflection for which the angle between the incident ray and the surface is equal to the angle between the refracted ray and the same surface, the angle at b , of the triangle aby is easily calculated.

Finally, considering the same triangle, we easily arrive at the angle in y .
With some mathematical manipulation the final formula is obtained:

$$Y=45-X/2$$

By substituting the same angles x , previously calculated, the angles of inclination y are obtained also for this second case:

1. $Y^\circ(d=50mm)=43,75^\circ$

2. $Y^\circ(d=100mm)=44,43^\circ$

3. $Y^\circ(d=150mm)=44,62^\circ$

In conclusion, it can be immediately observed that this experiment is an ideal case, which except for the teeth immediately near the LED will never come true. In fact, for such small radially and very long components, a light beam will never directly strike the inclined surface of the tooth but will certainly first be reflected internally several times. Despite this, knowing the direction of the incident beam before the teeth it is possible to calculate the direction of the exit beam. Although it is an ideal case, the results are very satisfactory because they reflect observable characteristics in all real components.

The angles are in fact around 45° , and the inclination increases as the distance from the LED increases.

6.4 TracePro simulations

In support of what was stated in the previous paragraphs, various simulations are carried out by varying the section, length and tooth inclination of a 150 mm straight light guide.

For these test simulations, they are simply entered into the software:

- A parallelepiped, whose surface, the one facing the light guide, is defined as the surface source. A white LED is chosen from the catalogue, imported into the program libraries.
- The 150 mm light guide, setting pmma in the material properties, and transparency in surface property.

In the first simulation a light guide with a simple circular section (like an optical fiber) is placed. Running the ray trace on TracePro we see what we expected: the rays are continuously reflected inside the light guide, and only come out from the opposite end (Figure 33). This are in fact the type of light guide used for transportation of light without diffusing it.

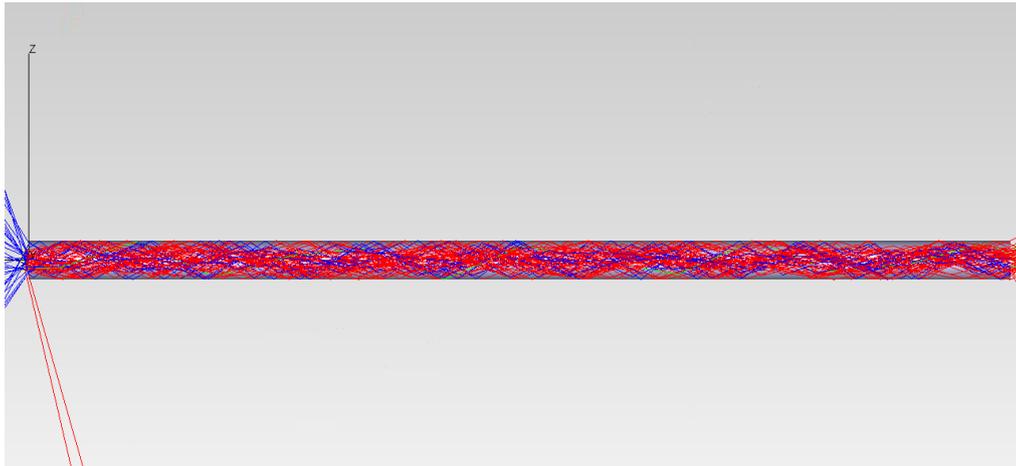


Figure 33 Cylindrical light guide

In the subsequent simulations, the behavior of a light guide with trapezoidal texture is evaluated, making the shape and angle of the teeth vary.

As expected, in this case, the textures are responsible of interrupting the total internal reflection and so for the exit of the light rays refracted by the light guide, that in this way can illuminate the outside. In the image before, the plotted rays are filtered, only the 20% of the total are shown in order to have a clearer result.

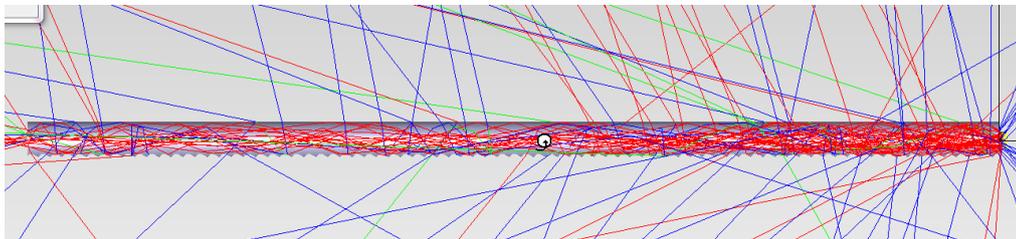


Figure 34 Light guide with texture

By comparing the 3D illuminance map along the length of the light guide for the 3 tooth inclinations chosen (Figure 35), no marked differences are noticed, this is probably because the pieces in question are only 15 cm long. The only things we can note is that for bigger angles the illuminance map seems better, because in this way we increase the refraction and so more rays can escape throughout the length of the guide.

N.B. the scale of values has been deliberately increased for these first simulations in order to better highlight the differences between the various cases.

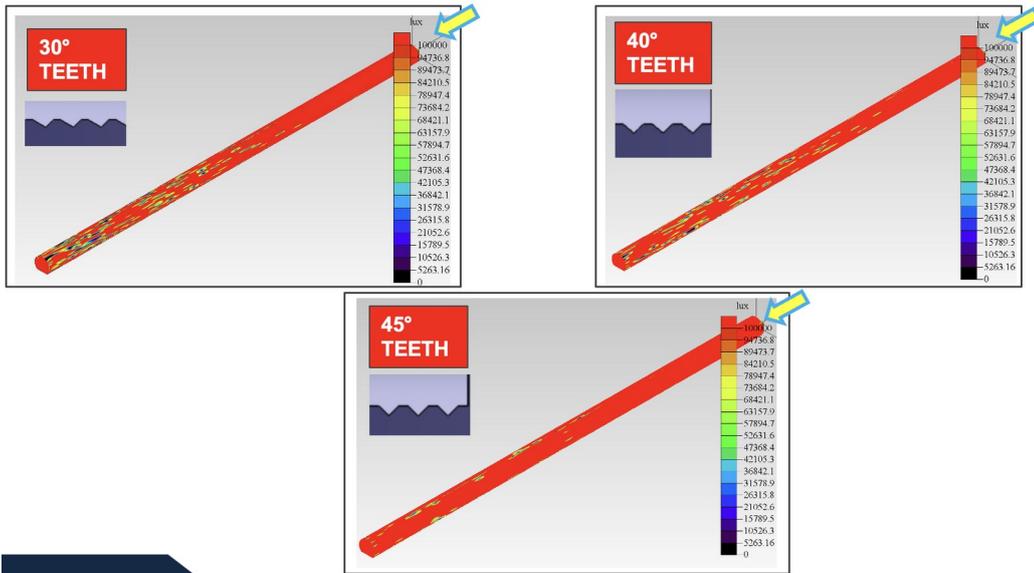


Figure 35 3D illuminance map in 3 different cases

So, to have a more specific analysis that emphasizes on the differences, another type of experiment is carried out. In fact, a plane defined as an absorbent surface is placed, first 4 mm below and then above the center of the section.

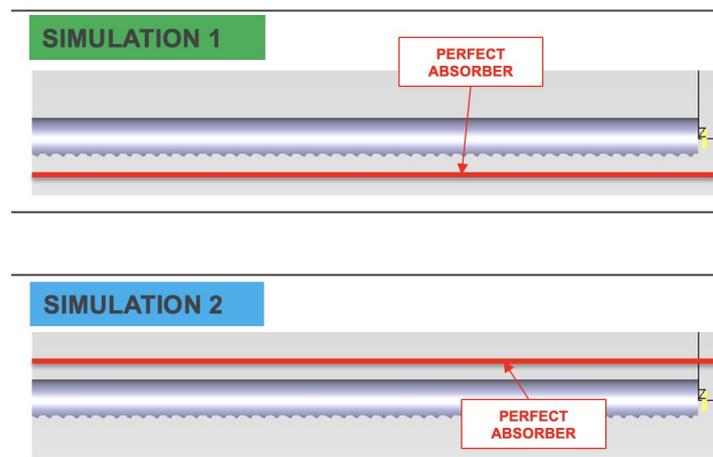


Figure 36 Disposition of surface

By performing ray tracing and always subsequently analyzing the illuminance map on this plane, it is possible to have a clearer idea of how angles affect the transmission of light rays.

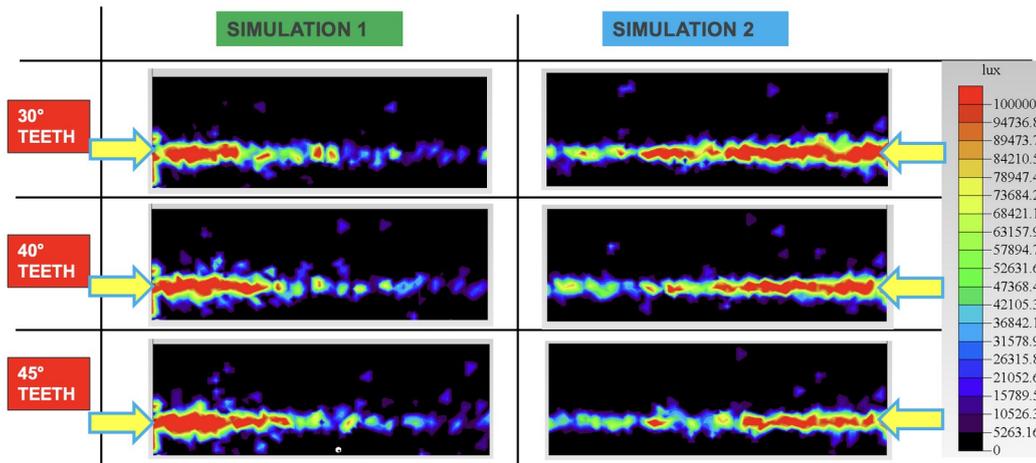


Figure 37 Illuminance map on the plane

Also in this case the results are those expected. Analyzing the images above, the piece with the 45° angles favors the phenomenon of refraction right from the start, favoring the escape of the rays. In fact, we see that the illuminance is very marked at the beginning and fades almost immediately. On the contrary, by decreasing the angle of the weaves, the phenomenon of reflection tends to be favored, even if slightly, by 'keeping trapped' more light rays inside the light guide which will subsequently come out only after being reflected several times. In fact, the map appears more uniformly illuminated.

This quick and simple experiment demonstrates some features that can be found to improve light transmission:

- the angles in fact increase as you move away from the LED, in order to extract more light rays as you move away from the source.
- with these small angle variations of the teeth, it is possible to control how much light we want to extract and the direction of extraction.

The next step was to analyze the length that a single LED can illuminate. To do this, the results of two experiments carried out on an 800 mm light guide are evaluated:

- Illuminance along the guide.

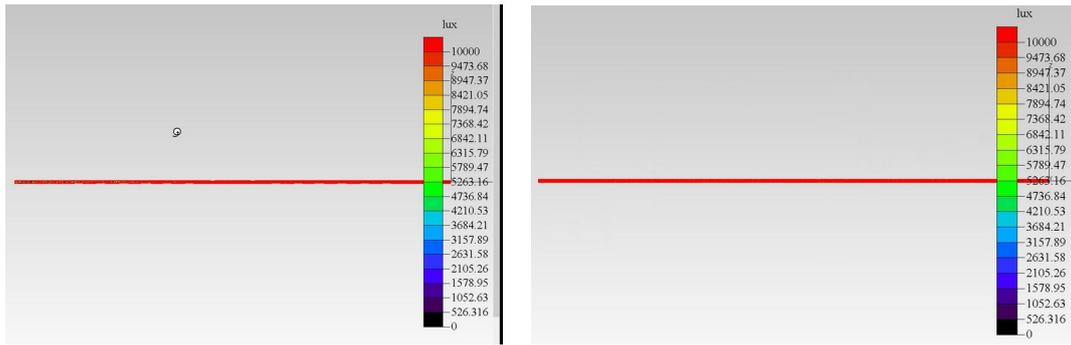


Figure 38 Illuminance maps for 1 and 2 LEDs

- Illuminance on absorbing surface positioned 4mm below and above the center of the section.

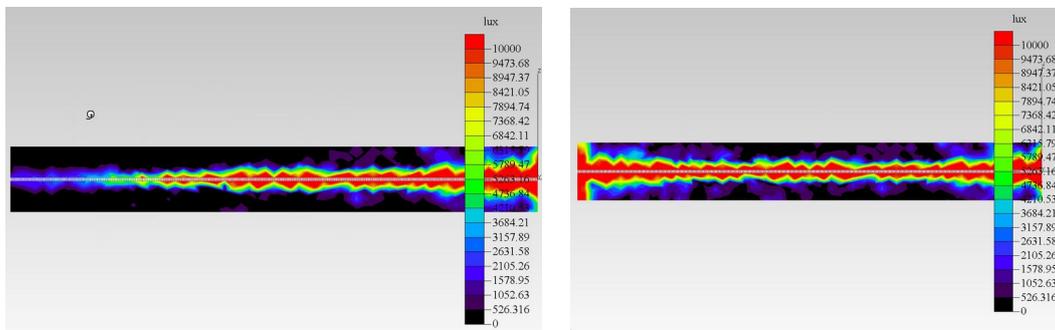


Figure 39 Illuminance on a plane with 1 and 2 LEDs

Analyzing the results, it's evident that a single LED is not sufficient for a uniform illumination of 800 mm, at least 2 are needed. In fact, if in the first case the guide would seem well lit, with only small points of darkness, the second experiment that better reflects what is the aim of the thesis project, demonstrates the opposites. All these results will be our starting point for the design of our circular section light guide.

7. Nucleus lightguide

The goal of my thesis is to exploit the results obtained up to now through simulations and theoretical studies on optics and photometry to develop a light guide.

Consider all the various requirements that we must respect, the main one is undoubtedly the homogeneity of lighting, as far as possible, taking into consideration the large dimensions of the area in question. It will also be necessary to ensure that the light guide does not dazzle the passengers with a too strong light but creates a pleasant atmosphere inside the passenger compartment.

Our component must have a length of about 2.280 meters surrounding a trapezoidal-like area of about 800*600*300*300 mm.

The component will be positioned on the door panel and will surround the central medallion (red zone in the figure below).

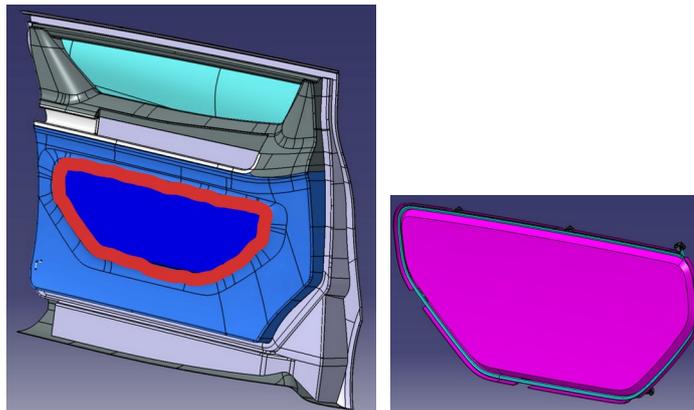


Figure 40 Light guide and location

7.1 Concept study

Referring to various light guides already in production, it was decided to apply the following shape to the tubular:



Figure 41 Section of the light guide

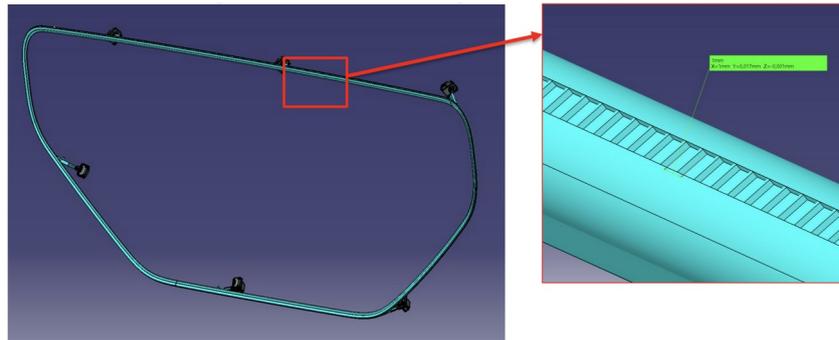


Figure 42 Light guide and textures

The tubular is a single whole and as we can see in the section above, it has a circular upper part with a diameter of about 6 mm where triangular textures with inclination angles at 45° are inserted at 1 mm from each other, in the external arc of circumference. This is the most functional part of the tubular, responsible for breaking the total internal reflection and transmitting and diffusing the light rays. In the internal arc of circumference opposite to the textures, the tubular part is instead inserted to direct the light which, breaking against the medallion, will illuminate its external contour.

In fact, what the passenger will see will not be the actual light guide, which is hidden by the door panel, but the light reflected on the medallion.

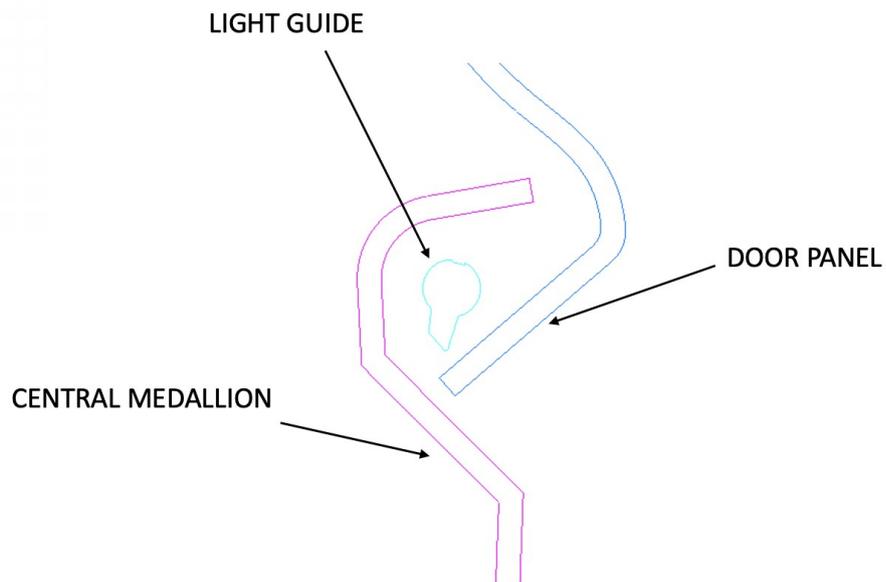


Figure 43 Section of the car door

The first step was to choose the type and quantity of LEDs to use. From previous tests it was concluded that a LED can uniformly illuminate approximately 400 mm. So, our medallion being about 2.3 meters long, we used 6 LEDs for our first simulation. The LEDs used are single color white LEDs, grafted into the tubular as follows.

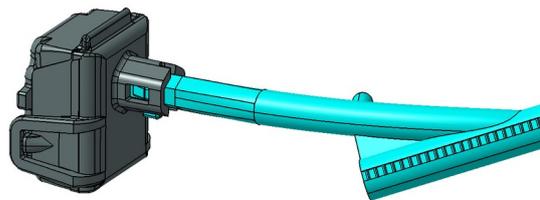


Figure 44 LED plugs

Each LED (the yellow component in the figure below), has its own PCB (in green), the black LED housing to contain all these components and avoid light leaks and the electronic components necessary for operation; the latter not described because they are not the subject of our study.

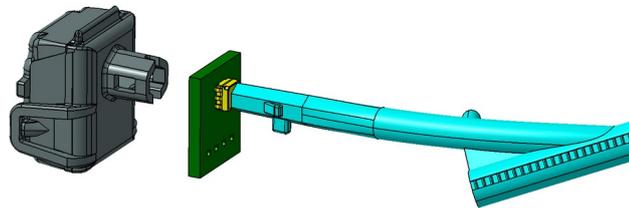


Figure 45 LED housing and component inside

7.2 Preliminary simulation

With these elements, an initial simulation is carried out to start seeing the response of the program, and to understand if the way forward is the right one. In TracePro the following properties are assigned to bodies:

BODY	MATERIAL	SURFACE
LED HOUSING	POLYCARBONATE	PAINT
PCB	GLASS FIBER	PAINT
LED	/	SOURCE PROPERTY
LIGHTGUIDE	PMMA	TRANSPARENCY
CENTRAL MEDALLION	ACRYLIC	PAINT
DASHBOARD	POLYCARBONATE	PAINT

Table Components and properties

After performing the ray trace, we proceed to the analysis of the results, in particular a fast render is shown below, and the main problems highlighted.

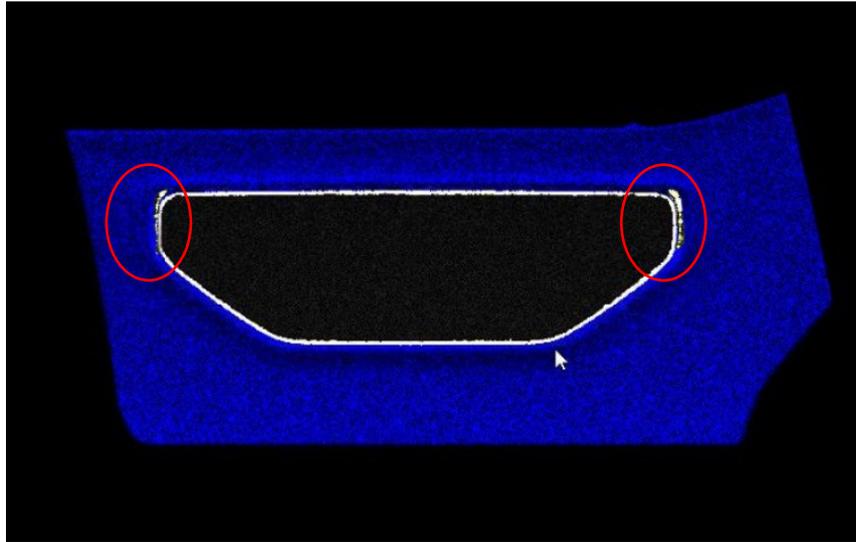


Figure 46 First render

The render demonstrates the validity of our procedure, however there are non-negligible criticalities, such as the reflections present in the lateral curved sections. These, because in curves the phenomenon of refraction is very accentuated, being the angle of refraction very small. As a result, the light comes out of the tube with greater intensity. Two ways will be followed to solve this problem. In the first, the LEDs are moved to a new position, with the hope that the light rays arriving with less intensity, do not create annoying reflections. The second solution, on the other hand, provides for a reduction in the density of the texture in the area of interest. The goal is to favor the phenomenon of reflection inside the tubular instead of refraction, in order to extract fewer light rays.

Moreover, in some areas there are lack of brightness, or in any case they are less illuminated.

7.3 Component division study

Before trying to solve the problem of reflections along the curves, a more functional division of the light guide into segments is studied. In fact, the light guide, given its large size, cannot be made in a single molding, both for reasons related to the feasibility of the operation and for the costs of making such a large component. It will therefore be divided into several segments which will be brought into contact later.

Thus, even before thinking about how to decompose the light guide in a functional way, we evaluated the angle of the cut to divide it and the behavior of the light rays in the joints.

The first test carried out was to take an 800 mm tubular, divide it with a 45° cut into two 400 mm segments and, by placing a source at the end of one of them, the behavior of the light rays in the junction was evaluated.

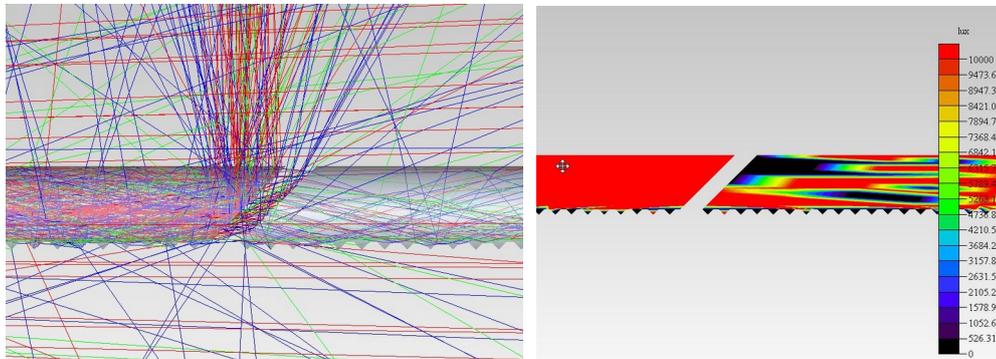


Figure 47 45° cut division ray trace and illuminance map

As can be seen from the previous figures, cutting the light guide with oblique sections isn't an optimal solution; the inclined surface in fact acts as a mirror, reflecting the rays out of the tube, and only a few are transmitted in the second guide segment.

Making cuts with vertical surfaces is the most suitable solution for our requests. After understanding how to cut the various light guide segments, we move on to studying the distance to leave between one segment and another due to molding tolerances and assembly requirements.

So, we take the first version of the lightguide, and a further simulation is thus carried out by varying the gaps between one segment and another, from 0.2 to 1.5 mm. The most significant cases are shown in the figures below (different color are to differentiate the different part in which we decompose the structure).

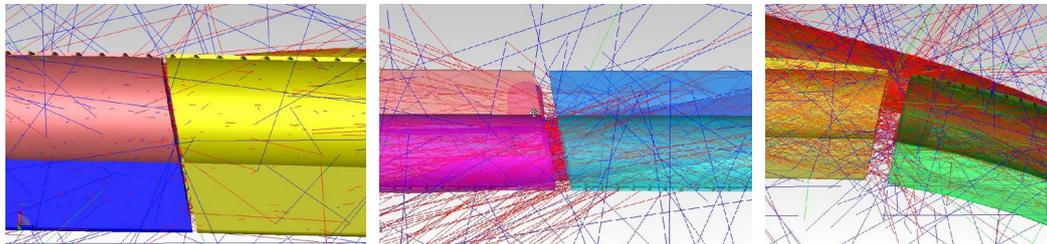


Figure 48 0.2 mm, 1 mm and 1.5 mm gap

Up to 1 mm of distance between the various segments there seem to be no marked differences with respect to the united light guide, very few rays escape. As

the gap starts to approach 1.5mm things change, more light rays escape the lightguide.

In support of what has been stated, the 3D illuminance maps are compared for the distances between segments of 1.2 and 1.5 mm.

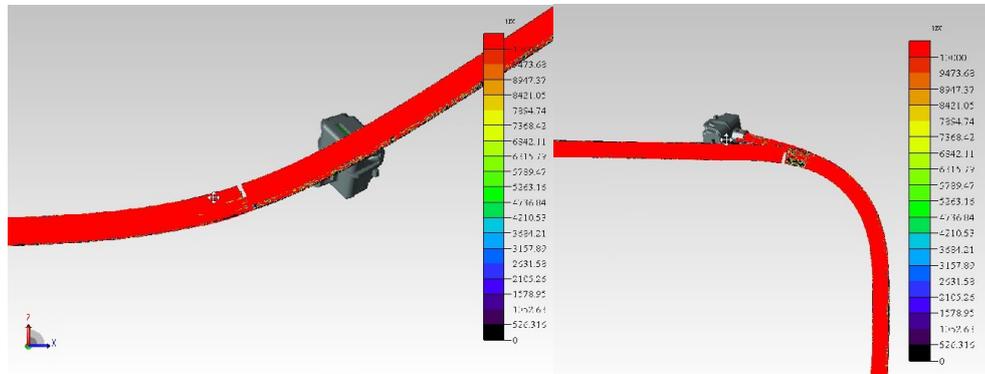


Figure 49 3D illuminance map in 1.2 mm and 1.5 mm gap junction

It can be clearly seen that if for distances of 1.2 mm the simulation still gives good results, the 1.5 mm gap instead creates a considerable lack of illumination when the next segment is inserted. In order not to risk falling in this case, the distances chosen between our segments will always be 1 mm.

In support of our results, we evaluate the effect of the gap, on the surfaces of the medallion and the dashboard of the door, to verify if what is observed in the ray trace is also reflected in the renderings. Let us consider the two gap limit distances:

- 0.2mm gap.
- 1.5mm gap.

This is the portion of car door under study. (The different colors of the guide are only to differentiate the different segments of the component, but the program 'sees' them of the same color).

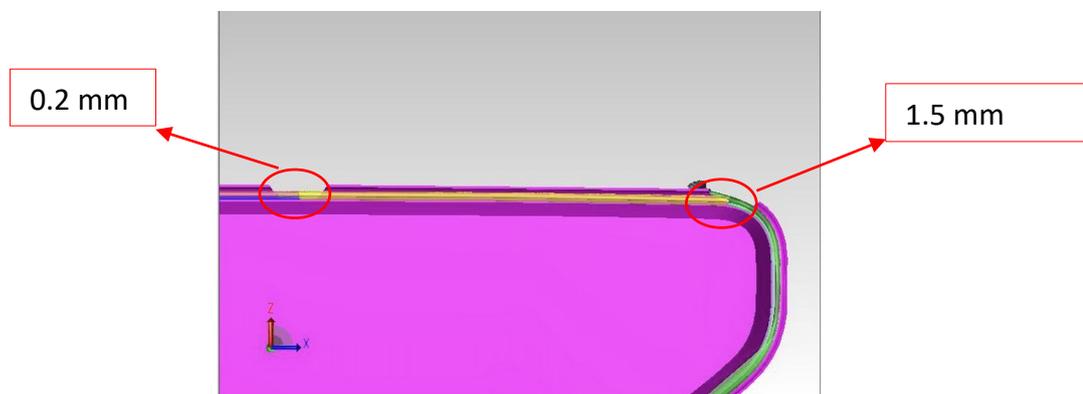


Figure 50 Portion under study, hiding the dashboards

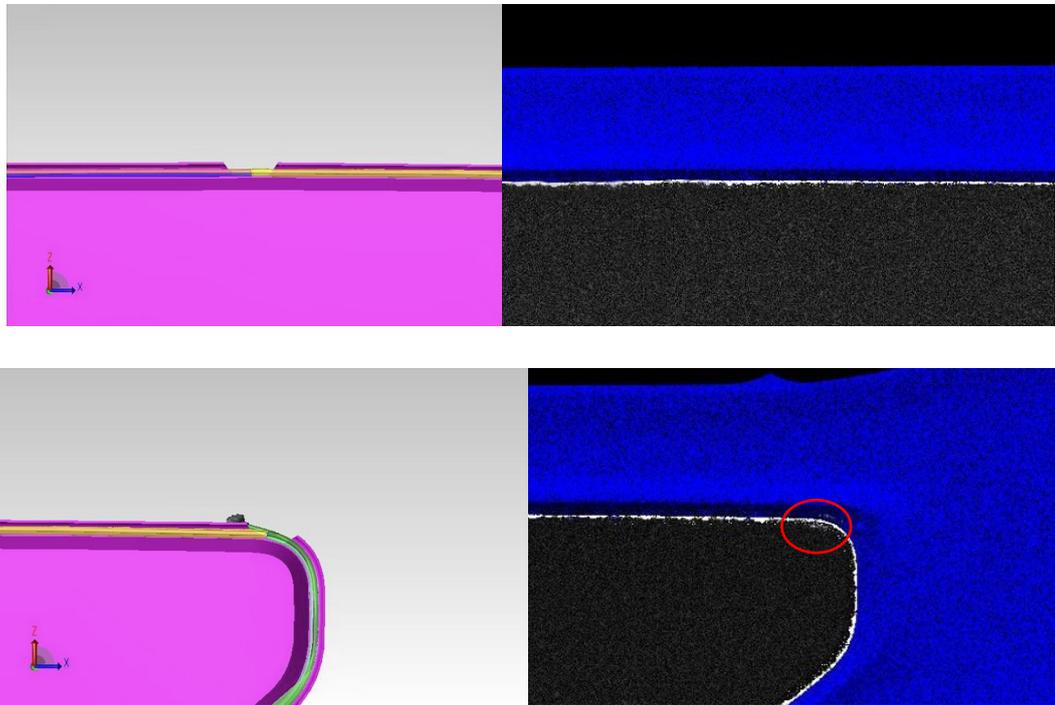


Figure 51 Render of dashboard and medallion

Observing the figures above, as expected, the minimum gap is not perceived and the result is the same of a light guide without gap, the maximum one instead creates light leaks, though minimal. In the upper right part, near the curve some rays escape and also if these losses are perceptible only after a careful evaluation, to avoid loss of intensity it is better to use smaller gaps between the various segments.

7.4 Second simulation

After having simulated and collected the first results, a more functional and cost-saving redesign is done. In fact, initially the light guide was broken down into 6 parts of 380 mm all different from each other, and with constant texture step 1 mm (Figure 52). Therefore, 6 different molds would have been needed for the production, leading to excessive cost and time to produce the component.

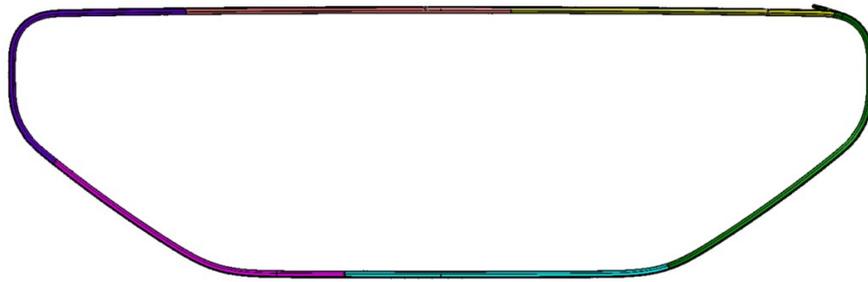


Figure 52 First design of the component

For the second simulation, for the reasons explained above, the component is redesigned as follows:

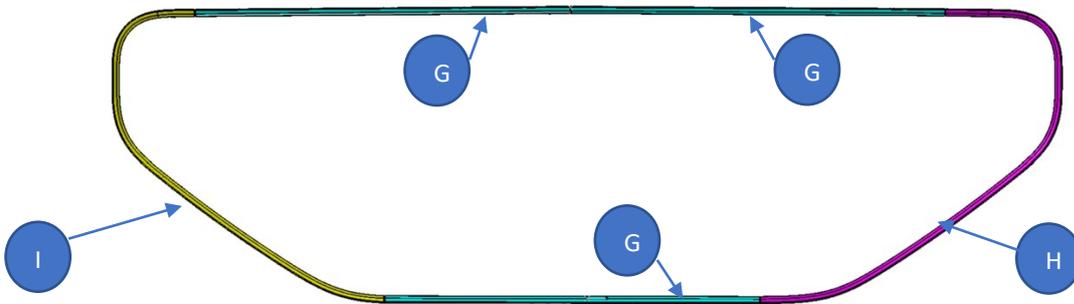


Figure 53 Final division of the component

- The straight horizontal segments decomposed to be obtained by replicating the same piece G, 3 times. In this way, with only one mold we can produce 3 different segments (about the 60% of the entire component).

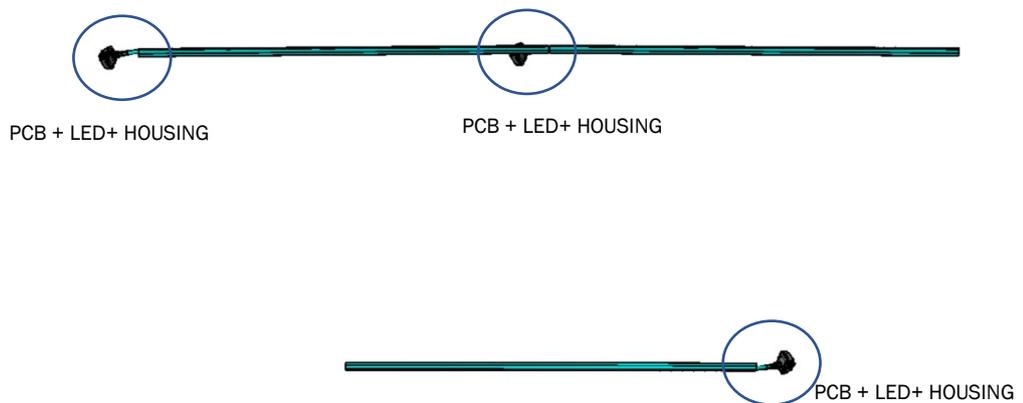


Figure 54 Straight segments decomposed in 3 parts

- The curved segments I and H to complete the structure, modeled based on subsequent simulations.

To eliminate reflections along the curved sections, 3 tests are carried out, first on the left curved segment I:

1. 1 single LED at one end of the segment, in the hope that being placed further away from the curve the intensity will be lower and reflections will be eliminated. Optics spaced 1 mm.



Figure 55 Segment I test 1

2. 1 LEDs positioned as in option 1. Optics spaced 2 mm in the vertical zone, where we have reflection, and 1 mm in the rest of the segment.

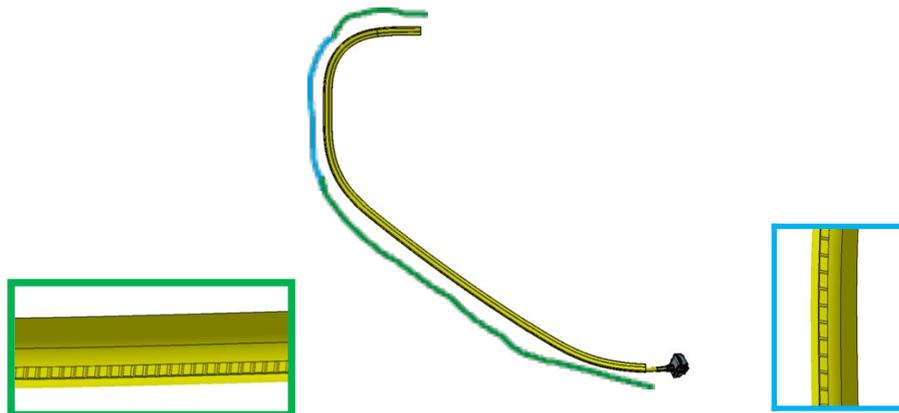


Figure 56 Segment I test 2

3. 2 LEDs, one in the same position of option 2, and the second just before the vertical segment. Optics spaced 2 mm in the section where the reflections were present, in order to extract fewer light rays, and 1 mm for the rest of the segment.

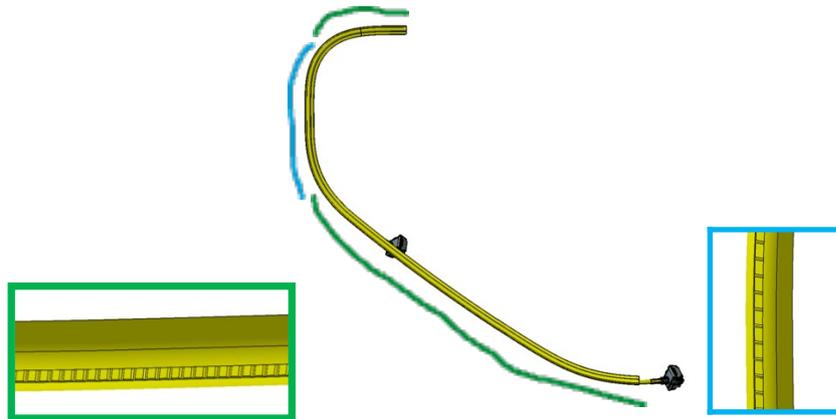


Figure 57 Segment I test 3

7.5 Results of these second simulations

Once the 3 structures have been modeled with the CAD, having the different left curved segment I, they are imported into TracePro. Simulations are carried out to verify which one best meets our requests and gives the best result. The material and surface properties are exactly the same as in the previous simulation for the various components.

N.B. For these simulations the right curved section H is not considered, the structure is only figurative. The section will in fact be modeled subsequently based on the results obtained on section I.

7.5.1 Option 1

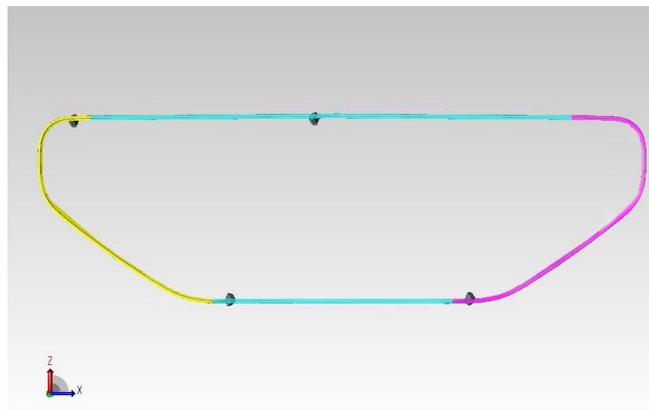


Figure 58 Structure option 1

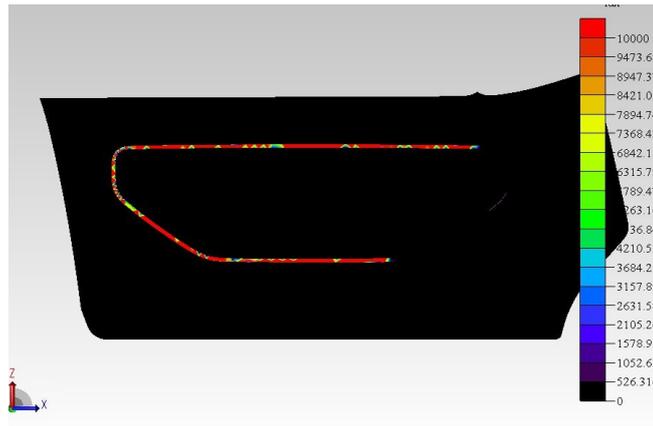


Figure 59 3D illuminance map test 1

The 3D illuminance map is very good. The whole area of interest is uniformly illuminated, with high illuminance values tending towards the maximum. Perfection will certainly never be achieved mainly due to the large dimensions of the light guide in question. In fact, there will always be areas with slightly lower values (in green and blue), but the difference will be imperceptible to the naked eye. It can be observed the most critical zone are those in correspondence of the curve, in accordance with the results of the previous simulation.

The next step was to make a render, to observe how our component would really appear.

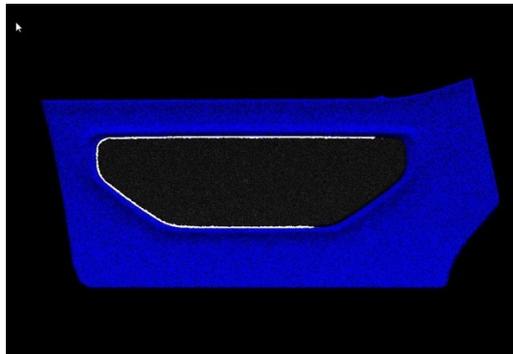


Figure 60 Option 1 render

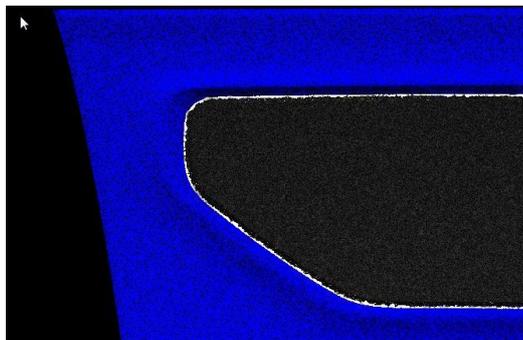


Figure 61 Render of the curved zone

The result is very satisfactory, the light rays reach the critical area with less intensity (since the LED is more distant) and reflections are thus eliminated. Figure 2 shows a more zoomed render of the curved segment, in order to observe if there are already some problems. As we can see this second figure is less defined because TracePro tends to bring out the defects in the renders, but no evident problems are observed.

Also for options 2 and 3 the 3d illuminance map and the 2 renders are shown exactly as for the first option in order to understand which is the best solution

7.5.3 Option 2

This test was carried out to further reduce the extraction of light rays in the critical area, in case option 1 had given bad results.

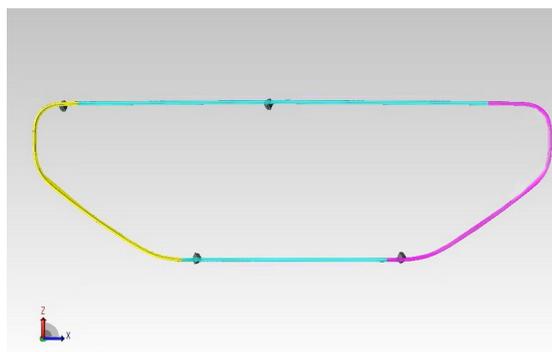


Figure 62 Structure option 2

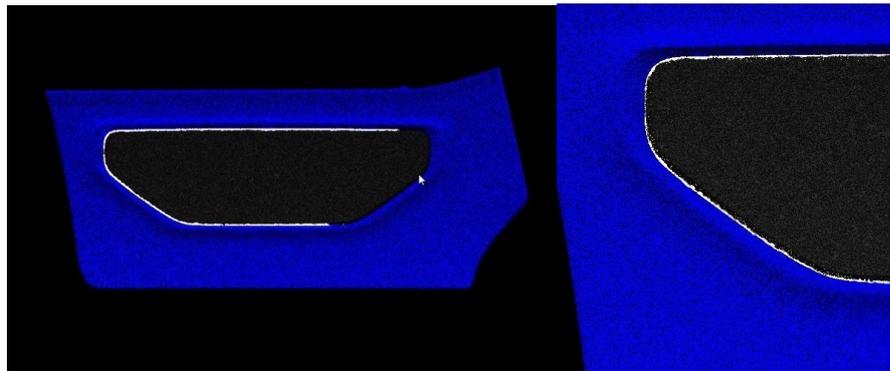
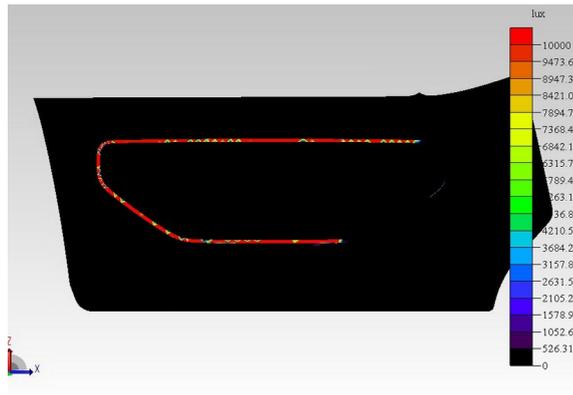


Figure 63 3D illuminance map and renders for option 2

7.5.2 Option 3

This last test is a good compromise between adding an additional LED and reducing the optics in the critical area.

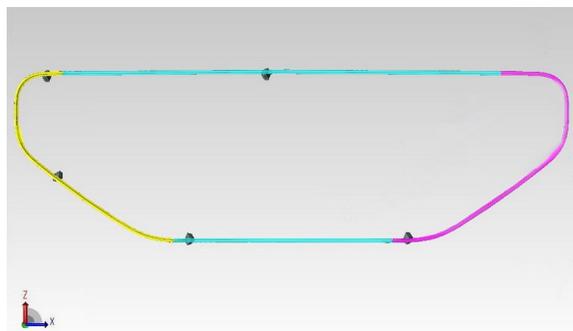


Figure 64 Structure option 3

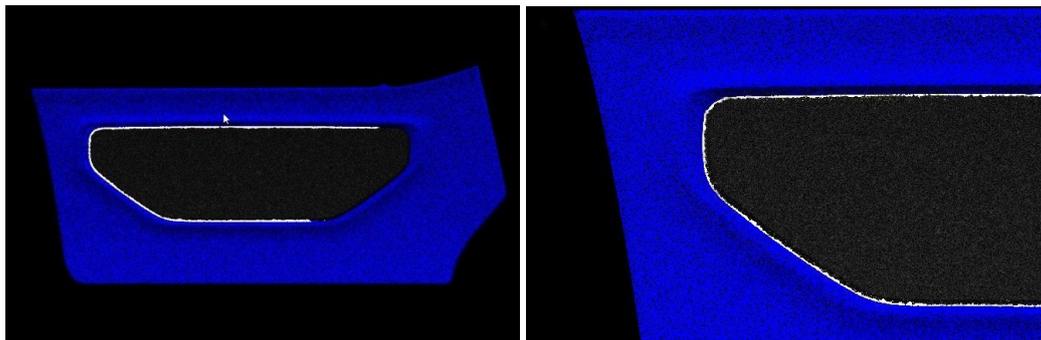
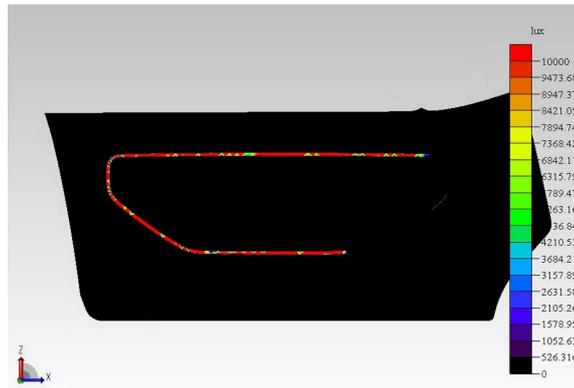


Figure 65 3D illuminance map and renders for option 3

7.5.4 Conclusions

Observing the results of the simulations relating to the 3 options and comparing them, it can be observed that:

- Option 2 is undoubtedly pejorative, in fact in correspondence of the curvature, where the density of the optics is lower, there is a loss of brightness, and the luminous band is visibly thinner.
- Options 1 and 3 give very similar results. Option 3 has a better illuminance map in correspondence with the curve (having an extra LED), but the resulting render is practically the same as that of option 1.

Consequently, option 2 is immediately discarded. Analyzing the simulations relating to the first and the third option, as the results are so similar and the benefit given

by the inclusion of an additional LED (option 3) so small, to avoid an unnecessary increase in costs and complexity of the circuit, it is decided to adopt option 1.

7.6 Segment H development

For the segment H an iterative process was followed. Based on the previously obtained results, the first version of H curved segment is modeled with a single LED and texture always with a 1 mm pitch. Then, after seeing the results the initial structure is changed and so on.

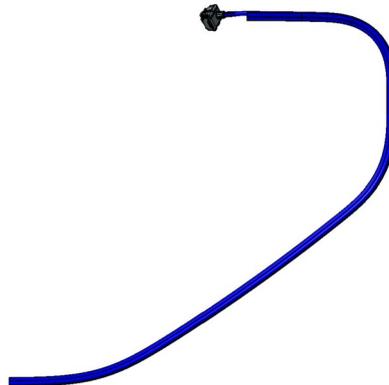


Figure 66 H segment first modeling

7.6.1 Simulations on TracePro

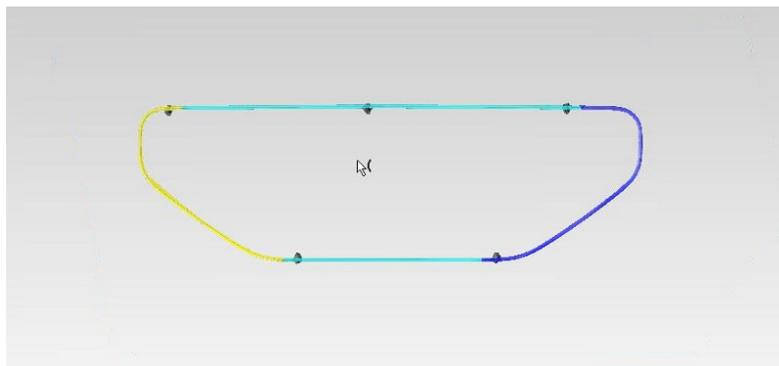


Figure 67 Simulated structure

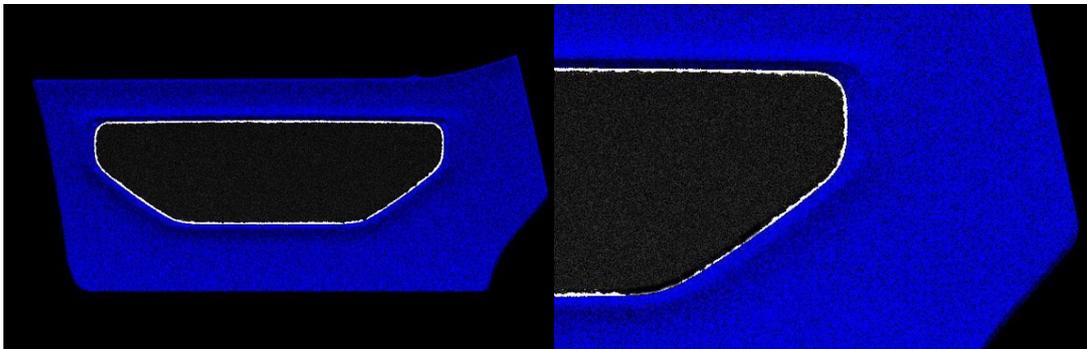
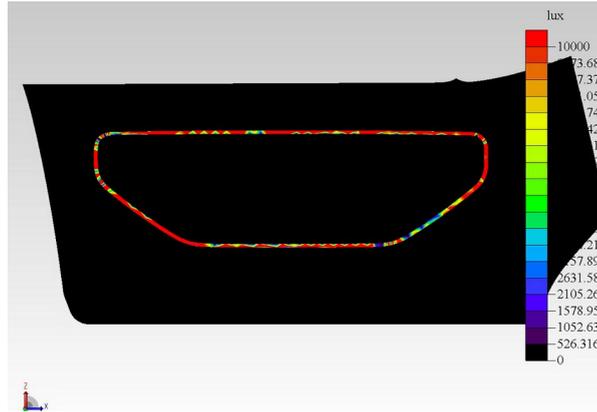


Figure 68 3D illuminance map and renders

In relation to the obtained results, it can be noted that at the end of the curved sections H (opposite side to the LED connection), there are parts that are not illuminated, or in any case less illuminated. This can be seen in the illuminance map where we have color that are near blue and green in the illuminance scale, but also in the second render, where we have important lack of illuminance and darker zone.

As a solution, the LED located at the top left is moved lower, about halfway along the vertical section, to illuminate the lower areas where there are deficiencies.

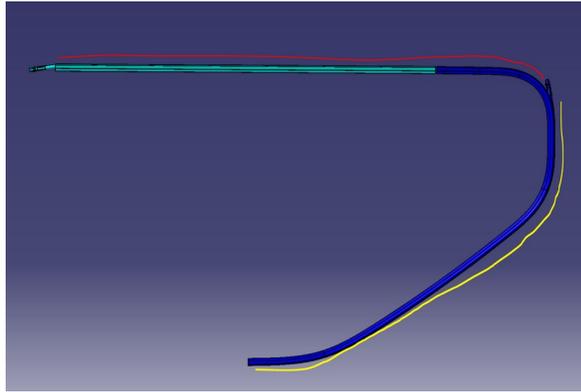


Figure 69 New version of the H segment

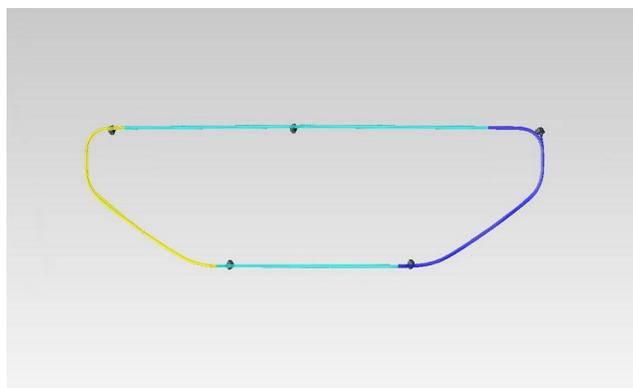
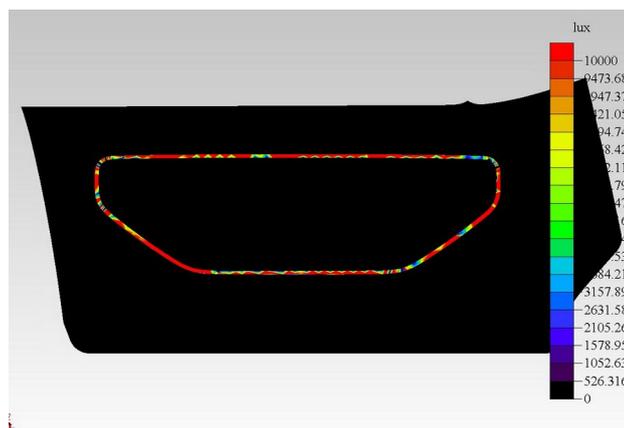


Figure 70 New structure of the light guide

Subsequently the same analyzes made previously are carried out with the hope of obtaining better results.



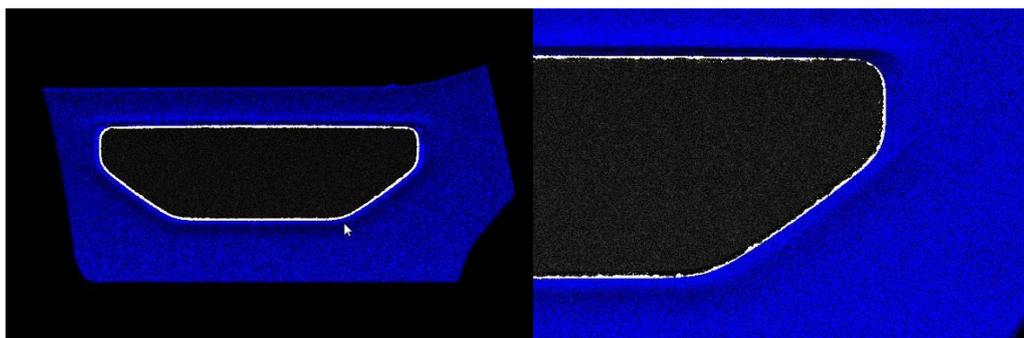


Figure 71 3D illuminance map and renders for this second trail

Analyzing the results, a better illuminance map is obtained but also if the general render seems good, in the upper left curve and towards the end of the oblique section there are parts that are not illuminated, or in any case less illuminated with illuminance values of about 2000, 3000 lux, far from the maximum. This is visible in the render of the H segment zone.

To solve this problem a LED is thus placed in the upper left, and an additional one is added just below the vertical stroke. The medallion later shaped accordingly.

The structure after this last modification of the H section and the results relating to the simulation are thus shown below.

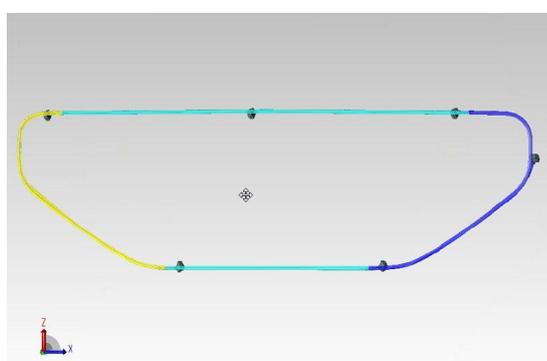


Figure 72 Third trail of the light guide

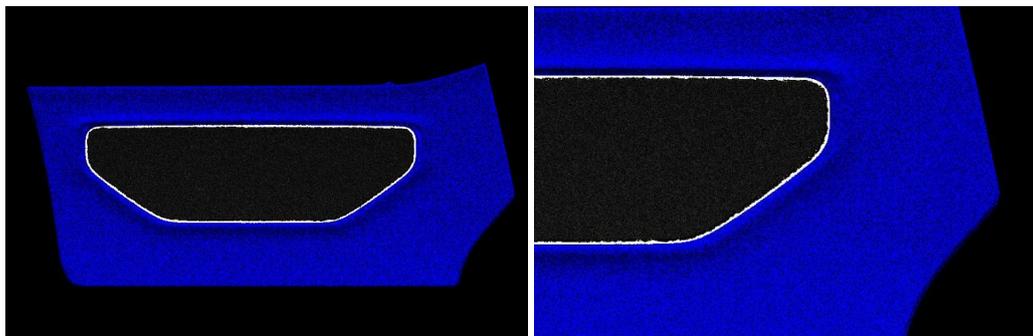
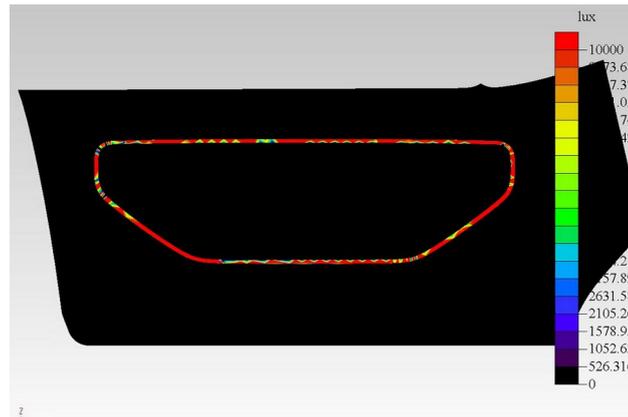


Figure 73 Results after the third simulation

The latter simulation gives the best results, so the use of 2 LEDs in section H (right curve) is necessary and not accessory as in the case of section I (left curve).

This is due to the fact that the light travels clockwise, and in the H section it first encounters the sharpest curvature, undergoing greater dispersion, and then the milder one, having lost much of its intensity. In section I the reverse phenomenon occurs, and the result is visibly better.

A final test is carried out by modeling the H section as the I section, to have the light travel counterclockwise in the H section (right-curved section). This is done to see if it's possible to save money and time to use only one mold for the 2 curved segments.

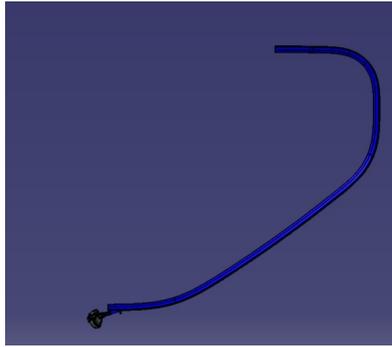


Figure 74 4th trail of the H segment

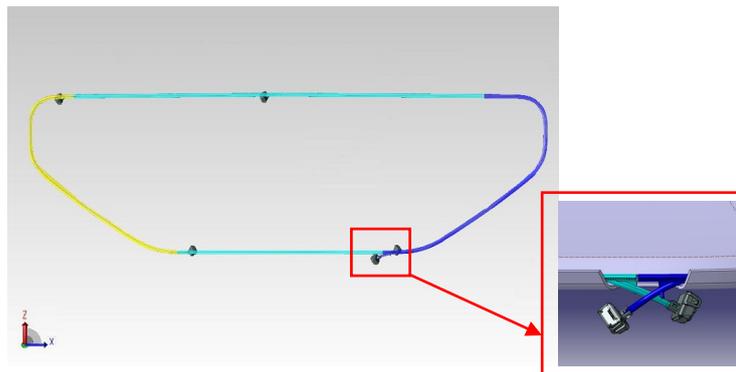


Figure 75 Structure with the 4th trail of the H segment

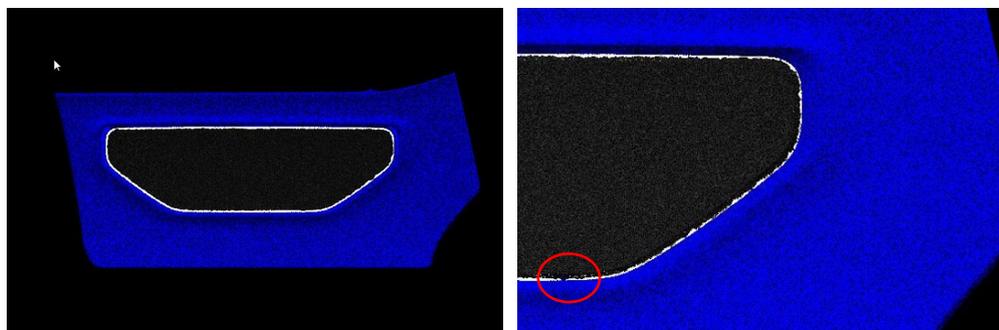
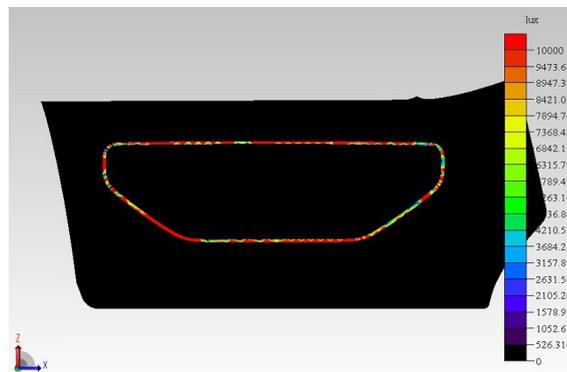


Figure 76 Results after fourth simulation

In the upper images, but in the 3D illuminance map and in the render on the right there are brightness lacks located in correspondence with the curve and in the area where the LEDs are inserted. So, this isn't an applicable solution that must be immediately discarded.

7.7 Support insertion

For the last simulation, the support for the solution that gives the best results is inserted (2 LEDs in the curved segment H on the right, and only one LED for the curved segment I on the left). The support is in PC, a material that guarantees hardness and impact resistance, and surround all the structure in the upper part where we have the optics. Also the color is not casual, this white-grey acts like a sort of mirror to reflect rays towards the area of interest.

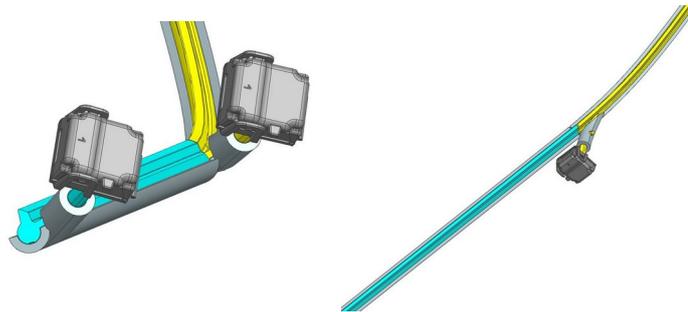


Figure 77 PC lightguide support

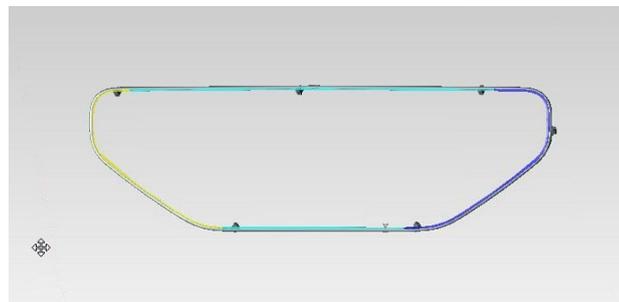


Figure 78 Definitive structure of the light guide with the support

The complete structure with support (in the figure), is inserted into TracePro and simulated. It can be observed how the insertion of the support improves the result previously obtained without it.

In fact, the support acts as a further protection which limits light losses even further and allows the light guide to reach higher illuminance values and uniformity of illumination.

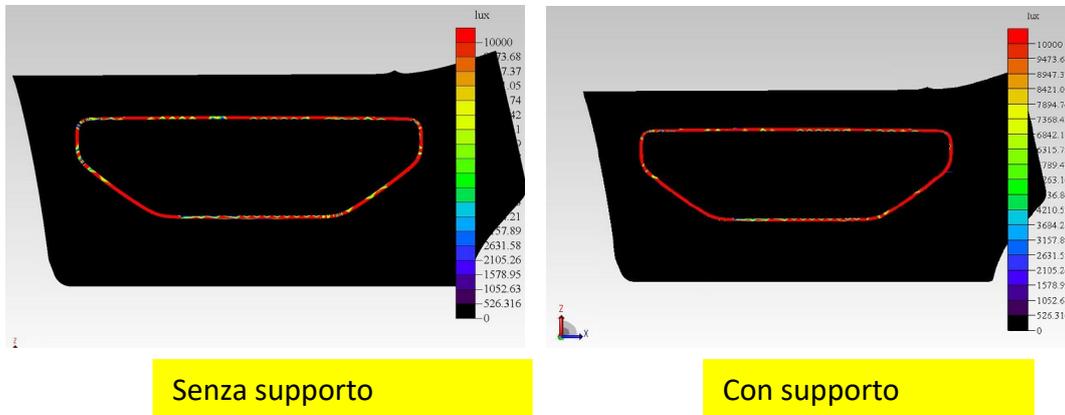


Figure 79 Comparison of 3D illuminance maps without and with support

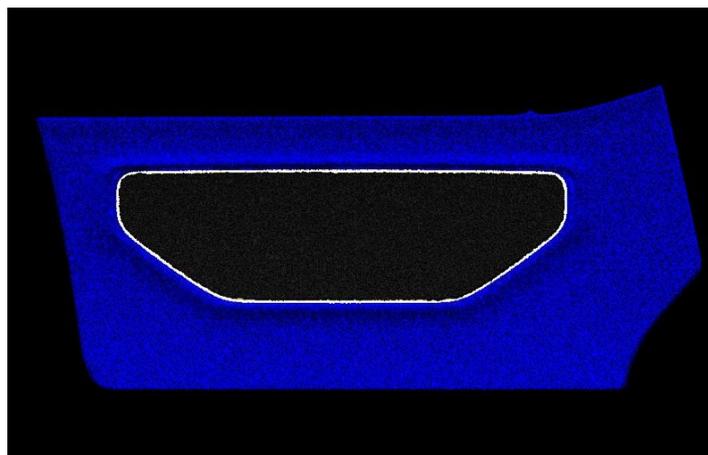


Figure 80 Final render

7.8 Luminance Evaluation

The last step of the project was to evaluate if the initial requirements were met. The renderings and illuminance map show that the illumination is uniform and with acceptable values. The requests were to obtain an average luminance of about 100 cd/m^2 . To verify this last photometric characteristic, TracePro allows once the render has been made, to see the luminance values by hovering over the various points of interest with the mouse. It should be remembered that illuminance is an indication of the energy that derives from the light source on a given surface while luminance is more linked to the vision we have of the surface itself. The quantities are related but they are not the same thing. The figure below shows the main points of luminance in the strip of interest around the medallion, for the definitive render of the structure with the support.

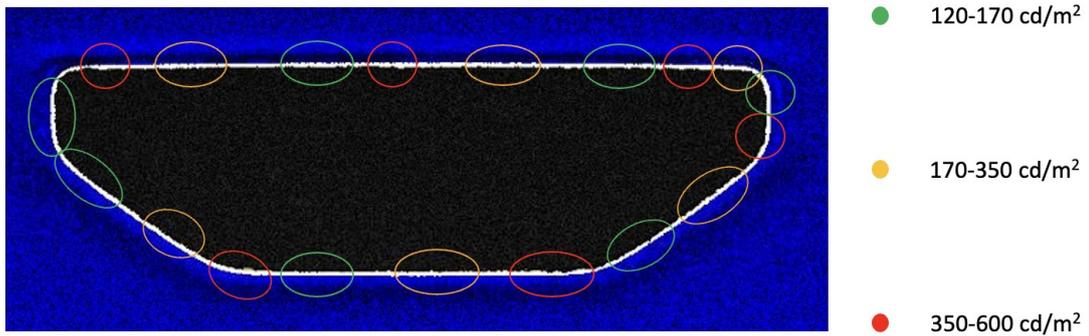


Figure 81 Luminance values

As we can see, the average luminance requirement is also met. The values vary from 120 to 600 cd/m², and as expected, the highest values are reached in correspondence with the LED joints and at the opposite end, on the contrary, we have the minimum values. In the length of the light guide the values decrease gradually, due to the losses and the extraction of the light rays, while in the curves for the same reasons the luminance is lower. These imperfections are entirely acceptable considering the large size of the component and having been found in other similar light guides already in production.

8. Conclusion

This project follows in detail all the phases of the development of an automotive light guide from the design to the various feasible solutions in terms of feasibility and optimization. The component was positioned on the door of the ICONA NUCLEUS hybrid car surrounding the central medallion. Initially the tubular had to satisfy some fundamental requirements such as the uniformity of illumination of the area concerned and the absence of reflections that could disturb the driver.

The results obtained in the simulations for the final version with the support are very satisfactory. The illuminance map is in fact very good with values close to the maximum, however there are areas with slightly less illuminated values but, as we can see from the render, the difference is imperceptible.

Also the final render is very good; however, by making closer renders of specific areas there are some differences in brightness, completely acceptable considering the very large dimensions of the structure. We have higher luminance values than the rest of the structure, especially in correspondence with the LED joints. However, these problems have also been found in the light guides of some vehicles already on the market.

In trying to achieve even brightness and eliminate visible reflections along the curves in our initial simulation, we moved the position LEDs to decrease the light intensity. The same result could have been achieved by changing the density, angle or size of the textures. However, as demonstrated by our second and third experiment on the curved left side, acting on the textures is very complicated, a small variation, create a large difference in brightness. For this reason, there are more specific software which, receiving a basic shape and the photometric characteristics to be respected as inputs, already output the design of the finished component.

Future developments for this project can be:

- A more accurate assessment of brightness.
- A more in-depth study of the surrounding circuit, analyzing cables and power supplies.
- CAE simulation of the system, in particular a fem analysis.
- Prototyping.

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