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Optical design of light guide prisms with surface roughness for automotive tail lights

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Abstract

This study presents the optical design of light guide prisms for automotive tail light applications to obtain the optimum luminous intensity and the illuminance uniformity. The design was achieved using optical design software, SPEOS. By considering the axial luminous intensity and legal requirements, the optimum prism angles of light guides were determined by simulations. After determining the prism angles, the effect of different surface roughness on the luminous intensity and the illuminance uniformity was investigated. The light guides designed by considering data from the simulation were manufactured as prototypes and their photometrical measurements were made. These measurements were compared to the simulation results. It was observed that simulation and prototype results are well in agreement with each other. Furthermore, it was found that as the surface roughness increases both the luminous intensity decreases and the illumination becomes more uniform.

Keywords

Light guides, optical design, luminous intensity, illuminance uniformity, surface roughness

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Introduction

According to a research performed in 2014, the accident rate occurring at night was reported to be about 30%, occurring due to insufficient lighting.[1] Therefore, the automotive lighting systems are vital to safe and comfortable driving. In addition to safety equipment, with a rapid progress in automotive technology, automotive lighting systems combined with high-efficiency light sources have become a very important part of vehicles, such as the styling element, the brand identity and the feature level of a car.[2] In the future, if vehicles with sensors and computer drivers recognizing conditions and surroundings replace vehicles with human drivers, the role of the automotive lighting systems will be much more important for the environmental traffic rules, and such vehicles will also need additional lighting systems.[3] According to the regulations set by Europe, the United States and other countries worldwide, currently manufactured lighting devices should not only use high-luminous light sources but also comply with the light shape provisions.

Today, there is a trend towards using light-emitting diodes (LEDs) rather than the conventional light sources. LEDs play an important role in both interior and exterior automotive lighting, due to their advantages such as styling opportunities, energy saving, lifetime, fast response and compact design ability.[4–6] The developments in the LED technology and demands for stylistic appearance induce the necessity of new optical systems. One of these systems is the light guide technology, which enables the design of contours and the illuminated signatures that are easily detectable and gives brand recognition immediately. The light guides have a wide range of applications such as automotive rear lamps (tail light, direction indicator) and headlamps (position, daytime running lamp (DRL), direction indicator), since they can be easily adapted to the desired place. Furthermore, these guides can fulfil legal requirements by less LEDs and provide more uniform illuminance.[7–9]

Aside from the stylistic appearance, the light guide technology needs to be expended more effort for

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simulation tools during the design process because it must fulfil the legal requirements of the lighting function and the illuminance uniformity. By the reason of geometric difference, the optical design parameters of the light guides vary from one situation to another. For the optical design of a long light guide with circular cross section, the most important parameters that affect the luminous intensity and the illuminance uniformity are length, diameter, possible bending, the prism geometry and the distribution characteristics of the light source.[7–15]

To our knowledge, although the light guide technology is widely used in exterior and interior automotive lighting systems, there is no report on the optical design of the light guides with the surface roughness. This study addresses the optical design of light guide prisms with the surface roughness for automotive tail light applications. Also, it considers the effect of different surface roughness on the luminous intensity and the illuminance uniformity.

Optical principle

It is well known that prisms play many different and important roles in the automotive lighting systems. These prisms serve as the dispersive and reflecting prisms. Typically, a ray entering a dispersing prism will deflect from its original direction by an angle known as the angular deviation. This deviation angle changes as a function of both the incidence angle of the ray and the prism angle. In reflecting prisms, the dispersion is not desirable and the ray beam is introduced in such a way that at least one internal reflection takes place, for the specific purpose of either changing the propagation direction or the image orientation or both. It is actually possible to get such an internal reflection without any dispersion.

In the light guide technology, the design and distribution of prisms have a key role in the design of light bar. In general, the prisms in the light guide bars are designed in the V-cut and cylindrical groove, which are served as an optical structure to divert light out of the desired surface of the light guide bar.[7,8] In this work, the V-cut prisms have been preferred and the structure of such a light guide is given in Figure 1. The system is a simple optical system for a headlamp consisting of a light source and a light guide. In the figure, α and β are the angles of prismatic surfaces, and V and w are the prism depth and width, respectively. The light from a light source (LED) propagates in the light guide and after reflecting on the prismatic surfaces leaves the light guide. The angles of prismatic surfaces (α and β) can be arranged to divert the light rays from the source towards the desired direction. Therefore, such prismatic surfaces allow to be controlled by the light distribution and the luminous intensity.[8,9]

The light rays coming from a source are kept in the transparent light guide by total internal reflection (TIR), which is defined as 100% reflection of the rays at a surface between an optical medium with high and low index of refraction. The refractive index of the surrounding material, which is air for the automotive applications, must be lower than the refractive index of the light guide material (n). TIR occurs if the incident angle is bigger than the critical angle γ_c, which is given as $\gamma_c = \arcsin(n)$ according to Snell law. However, for the prismatic structures used to decouple the light rays from the light guide, the TIR rule is not valid.[10] The direction of the decoupled rays and the efficiency of the reflection on each prism are given by the α angle [rad] between the input surface of the prism and the wall of the light guide. From Figure 1(b), the α angle can be founded using the relation given in equation (1)

$$\alpha = \frac{\frac{\pi}{2} - \mathrm{arctg}\left[\frac{\frac{h}{2} - V}{d}\right]}{2} \tag{1}$$

where h is the prism height (the diameter of the light guide) and d is the distance from the entrance surface of the light guide to the prism.[10] Equation (1) provides good results for direct light from a light source especially at the beginning of the light guide, but in the centre of the light guide, it is more beneficial to use equation (2), which considers one reflection on the sidewall of the light guide[10]

$$\alpha = \frac{\frac{\pi}{2} - \mathrm{arctg}\left[\frac{\frac{h}{2} - V + h}{d}\right]}{2} \tag{2}$$

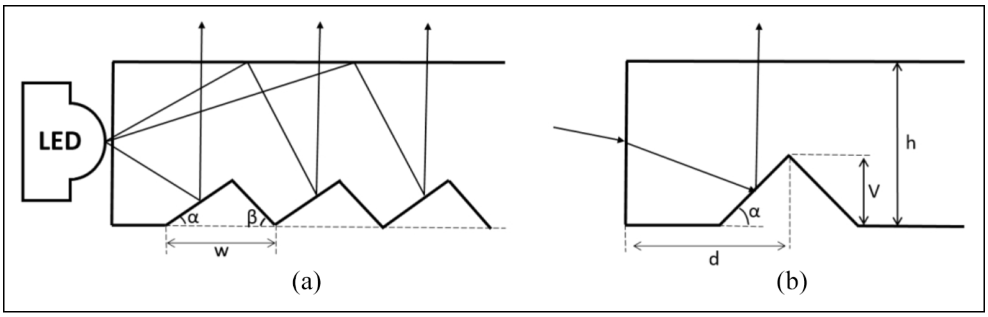

Figure 1. (a) Typical light guide with prismatic structures and (b) the shape of prismatic structure.
LED: light-emitting diode.

After determining the α angle, the β angle can be obtained from the prism geometry, depending on the prism parameters.

It is possible to find the optimum values for the light distribution and the luminous intensity by adjusting the parameters (α, β, V, w and h) of a light guide. The size of the V-cut prisms will affect the local reflecting and refracting illuminance of the light bar. A larger V-cut will result in a higher local illuminance. The illuminance uniformity along the light guide bar can be manipulated by adjusting the size distribution of V-cut prisms.[7,8]

Optical design of light guide prisms

In the design process, many parameters implemented in simulation software, including materials, must be well known because they affect brightness, colour and appearance of light guide systems. The main goal of the light guide design is to bring all material parameters affecting optical system and to find simulation results being very close to the real values and giving reliability to the development of new products. So, the light guides must have the right angular, spatial and colour distribution and also meet the traffic regulations set by the countries such as European Union (EU) and the United States.

In this study, an optical design of the light guides used in automotive lighting systems was made using the design software SPEOS. The light guides with two different geometrical structures have been designed for upper and bottom tail lights as shown in Figure 2. Upper part is a cylindrical bar with one bending, the bottom one is the curved cylindrical bar with a curvature radius of 5 cm (see Figure 3 for their technical properties). Each light guide is lit by one red LED. There is an opaque black cover above the LEDs to prevent light leakage and hide LED geometries in cold appearance. The coupled light from the source is diverted by the prismatic structures through the front lighting surface. The luminous intensity distribution and the illuminance uniformity of the light guides are determined and controlled by changing the parameters of prismatic structures.

Design of prismatic structures for optimum luminous intensity

The material characteristics and the light source affect significantly the appearance of the light guides. These effects arise from the spectra of the light sources and the wavelength-dependent absorption coefficient of the used material.[9] Therefore, the design of prismatic structures requires the right choice. In our designs, the used material for light guides is transparent polymethyl methacrylate (PMMA), which has 92% light transmittance at 3 mm (Altuglass, V825T). The geometrical properties of the light guides designed for this work is given in Figure 3. As seen from the figure, upper and

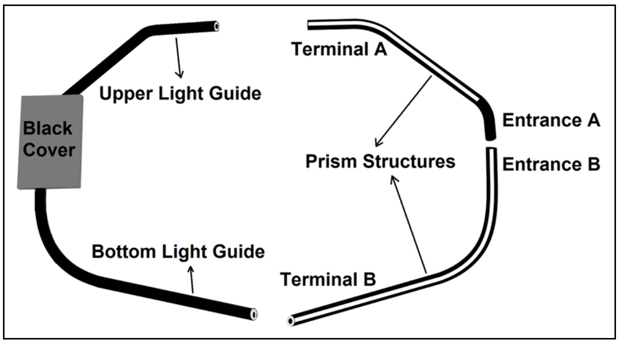

Figure 2. Upper and bottom light guide geometries: front surface view (left) and back surface view (right).

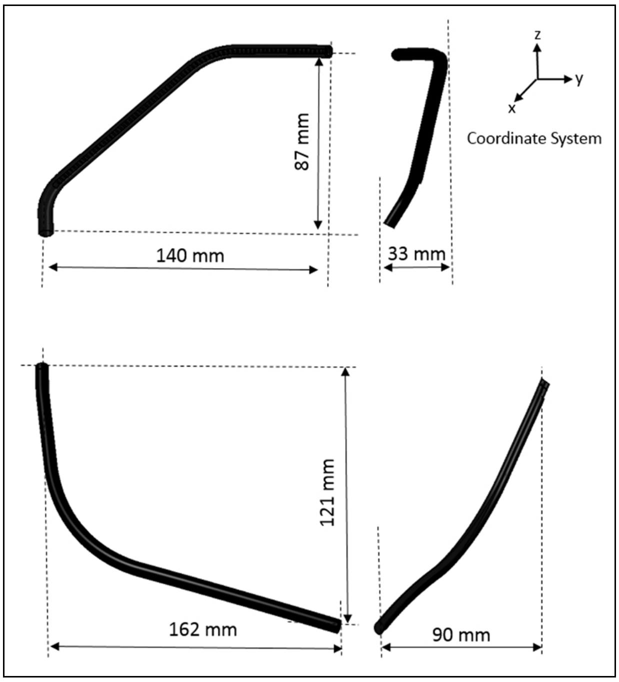

Figure 3. Upper and bottom light guide geometry dimensions in X, Y, Z coordinates.

bottom light guide geometries have different base curves. Upper curve has 33 mm depth (X-direction), 140 mm width (Y-direction), 87 mm height (Z-direction) and the total length is 172.5 mm. Bottom curve has 90 mm depth (X-direction), 162 mm width (Y-direction), 121 mm height (Z-direction) and the total length is 232.8 mm. As seen in Figure 4, LEDs are placed at the centre of the light guide entrance surface with 0.3 mm space and both light guides have circular cross section with 6 mm diameter. The width for all used prisms is 2 mm, and there is no gap between prisms.

The simulated LEDs are Osram red Power Side LED (LA B6SP-DBEB-24-1) with a viewing angle of 120° and the minimum luminous intensity is 17.5 lm for an LED current of 140 mA and 13 lm for 110 mA.[16] After a continuous operation for 30 min at room temperature according to the related regulation for LED lamp measurement requirements,[17] the thermal

Table 1. Simulation and prototype luminous intensity values and the required minimum values according to the ECE R7 and SAE J585 regulations.

Regulation points	Minimum luminous intensity of ECE R7 (cd)	Minimum luminous intensity of SAE J585 (cd)	Simulated luminous intensity (cd)	Prototype measured luminous intensity (average ± error) (cd)
1. 10U-5L	0.8	1.0	5.43	3.76 ± 0.26
2. 10U-5R	0.8	1.0	5.68	5.17 ± 0.18
3. 5U-20L	0.4	0.7	1.86	1.48 ± 0.14
4. 5U-10L	0.8	2.0	5.05	3.25 ± 0.21
5. 5U-V	2.8	4.5	7.26	4.77 ± 0.18
6. 5U-10R	0.8	2.0	5.18	4.18 ± 0.23
7. 5U-20R	0.4	0.7	1.95	3.11 ± 0.13
8. H-10L	1.4	2.0	4.82	4.09 ± 0.11
9. H-5L	3.6	5.0	7.06	5.52 ± 0.33
10. H-V	4.0	5.0	7.47	5.37 ± 0.28
11. H-5R	3.6	5.0	6.56	5.47 ± 0.24
12. H-10R	1.4	2.0	5.05	5.20 ± 0.12
13. 5D-20L	0.4	0.7	1.14	2.15 ± 0.20
14. 5D-10L	0.8	2.0	4.84	4.36 ± 0.19
15. 5D-V	2.8	4.5	5.87	5.09 ± 0.19
16. 5D-10R	0.8	2.0	4.73	4.53 ± 0.26
17. 5D-20R	0.4	0.7	2.04	4.15 ± 0.14
18. 10D-5L	0.8	1.0	5.41	5.20 ± 0.20
19. 10D-5R	0.8	1.0	4.89	4.87 ± 0.22

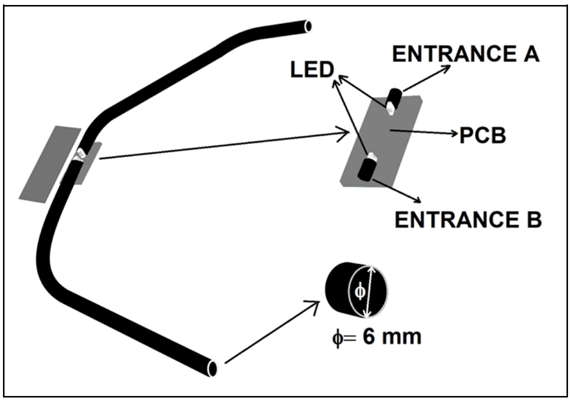

Figure 4. LEDs positions on PCB and cross section view of light guides.
LED: light-emitting diode; PCB: printed circuit board.

degradation was calculated by considering printed circuit board (PCB) area and an LED current of 110 mA and found to be a decrease of 30%. So, after the degradation, the total hot flux becomes about 9 lm per each LED.

Commercial SPEOS optical simulation software was used to simulate the intensity values and the illuminance properties of the light guides. A luminous intensity sensor was placed at the geometric centre of the light guides and an illuminance sensor was placed at a distance of 3000 mm from the geometric centre of the light guides. Both sensors have a resolution of 10 nm in visible wavelength spectrum. PMMA material file was retrieved from material database of OPTIS/SPEOS. There is a light guide carrier under the light guides to collect the light going out from the guides and an average reflectivity of 75% for the carrier are assumed.

As known, the international regulations define minimum and maximum luminous intensity values at different angular positions for each lighting function. These regulations are United Nations Economic Commission for Europe (UNECE) and American Federal Motor Vehicle Safety Standard 108 (FMVSS 108) standards. ECE R7 and SAE J585 are related to the specifications belonging to the tail lamps of passenger cars for European and American market, respectively. The legal values regarding to these specifications are given in Table 1. The optical design process of the light guide prisms was carried out by considering these regulations. The luminous intensity was studied depending on α and β angles of the prismatic structures. In order to find the optimum α and β values, first the α angle was fixed at 5° and the β angle was changed from 5° to 90° by a step of 5°. For upper light guide, β angles that provide the maximum intensity were determined to be 40° and 50°. Figure 5 shows the luminous intensity distributions for α = 5°, β = 40° and β = 50°. As seen from the figure, for β = 40°, the maximum intensity shows a deviation of 20° from the axial direction (0° position), while for β = 50°, there is no deviation and the intensity is lower compared to that at β = 40°.

For the bottom light guide, the best β value giving the maximum intensity was determined to be 30°. For α = 5° and β = 30°, the luminous intensity distribution is shown in Figure 6. As seen in the figure, there is no deviation from the axial direction.

By considering data obtained from the upper and bottom light guides when the α angle is 5°, the optimum β angles were selected between 40° and 50° for the upper light guide and 30° for the bottom light guide.

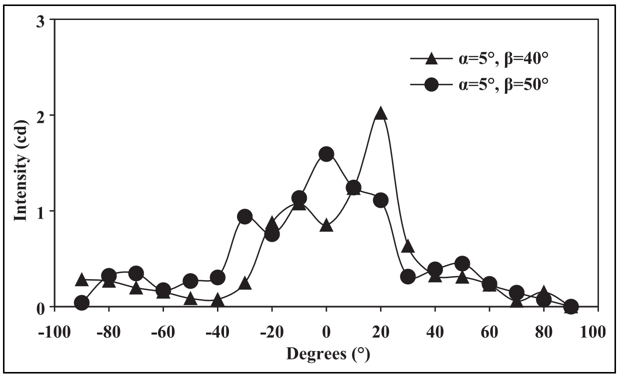

Figure 5. Luminous intensity distribution curves of the upper light guide for α = 5°, β = 40° and α = 5°, β = 50°.

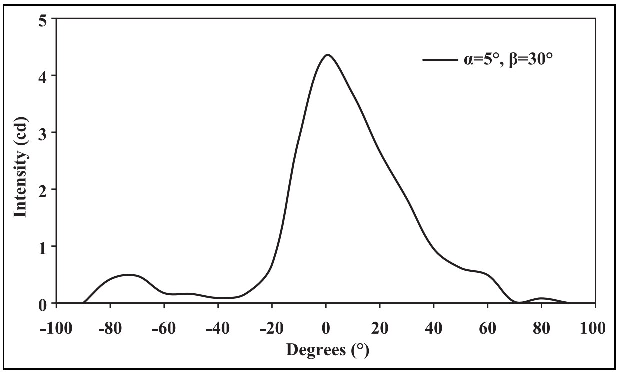

Figure 6. Luminous intensity distribution curve of the bottom light guide for α = 5° and β = 30°.

In order to study the dependence of the intensity distribution on the α angle, it was changed from 5° to 90° by a step of 5°. For the upper light guide, the β angle was arranged to be 40° at the beginning (Entrance A) and 50° at the end (Terminal A) of the light guide prisms. For the bottom light guide, the β angle was fixed at 30° along the whole light guide. Figure 7 shows the variation of the intensity with the α angle for upper and bottom light guides. As seen in the figure, since the maximum intensity occurs at 20° for both light guides, the α angle was adjusted to 20°. The upper light guide has two bendings (as seen from Figure 3), which causes an efficiency lower than that of the bottom, because the rays go out of the light guide at these bendings. As a result of this, the luminous intensity decreases with increasing α angle due to the fact that TIR is invalid for the prism surfaces having larger angles. The optimum α and β angles are different from the results reported in references,[7,8] probably due to the selected geometrical structure.

After determining α and β values, the intensity simulation was carried out by considering upper and bottom light guides, the light guide carrier and the black LED cover. As a conclusion of the simulation, an intensity distribution map was obtained as in Figure 8. As seen

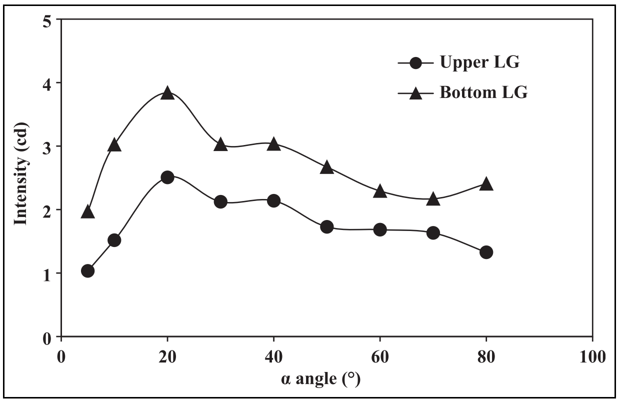

Figure 7. Variation of luminous intensity with α angle for upper and bottom LGs.
LG: light guide.

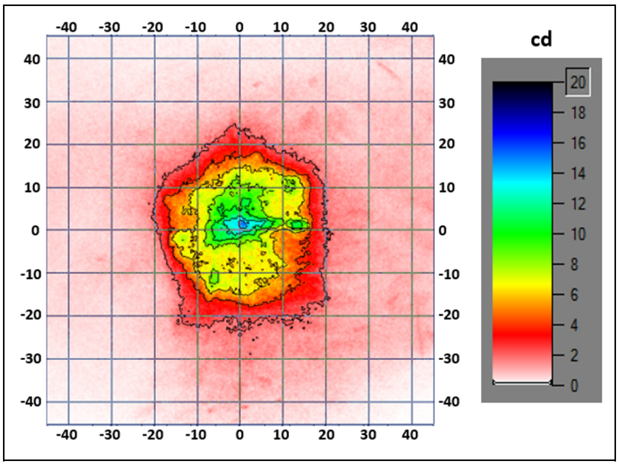

Figure 8. Luminous intensity distribution map for the combined geometry of upper and bottom light guides.

from the map in the figure, the maximum light is located on horizontal 0.6° and vertical 1.1°. This combined geometry of upper and bottom light guide fulfils the legal requirements of ECE R7 and SAE J585. Similar intensity distribution, located at the horizontal–vertical intersection, was reported by Yu et al.[8]

Surface roughness influence on luminous intensity and illuminance uniformity

The illuminance uniformity is one of the most important parameters for automotive tail light applications. One of the techniques employed to get better illuminance uniformity from the light guides is the surface roughness application. In order to examine the effect of the surface roughness on the light intensity and the illuminance uniformity, the roughness on the prismatic structure surfaces was formed by simulation. The surface roughness in the light guide is schematically showed in Figure 9. Seven different surface roughness processes were applied on the light guides using OPTIS

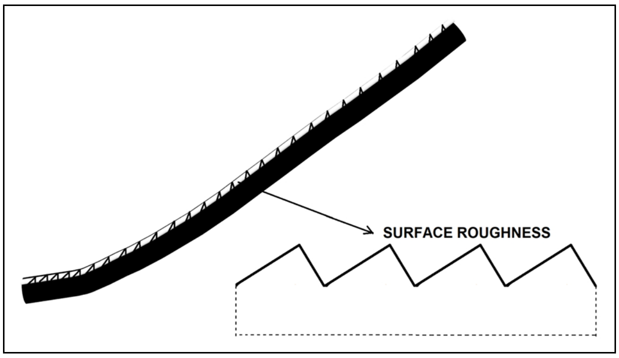

Figure 9. Prismatic surfaces with surface roughness.

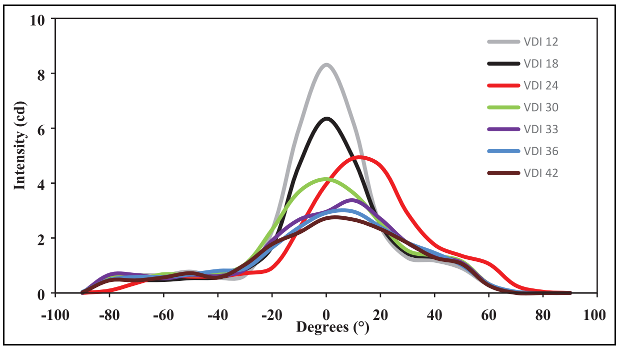

Figure 10. Intensity distribution curves depending on surface roughness.

scattering files including German VDI 3400 standard with VDI 12, VDI 18, VDI 24, VDI 30, VDI 33, VDI 36 and VDI 42.[18,19]

The intensity distribution was obtained depending on the applied surface roughness. Figure 10 shows the variation of the intensity distributions with the axial direction for different surface roughness. Since the increase of the surface roughness leads to more scattering, resulting in losing TIR of the prism surfaces, the intensity decreases. The other observed effect of the increase in the surface roughness is that the light distribution at full width at half maximum (FWHM) propagates to larger angles from the axial direction (0° position). As seen from the figure, the smallest surface roughness (VDI 12) corresponds to a narrower distribution and higher peak intensity compared to the other surface roughnesses. As the surface roughness increases, the intensity distribution gets wider and wider, and its maximum value decreases.

According to the simulation results in Figure 10, it is clearly seen that the maximum intensity is achieved by VDI 12. Therefore, for VDI 12, the illuminance uniformity of the light guides was studied. Figure 11 shows the illuminance uniformity maps of the finalized light guides without (Figure 11(a)) and with (Figure 11(b)) surface roughness. As seen from the figure, the light guide having the surface roughness on prismatic surfaces has better illuminance uniformity than that of without the surface roughness. Especially, at the beginning of the upper light guide without the surface roughness (Entrance A), the light intensity is too much (dark blue), but it does not continue uniformly by the end of the light guide (Terminal A). On the contrary, as seen from the figure (Figure 11(b)), the surface roughness provides the uniform light transition from the beginning (Entrance A*) to the end (Terminal A*).

Furthermore, for upper and bottom light guides with and without surface roughness, the variation of the illuminance uniformity with length is numerically analysed in Figure 12, which corresponds to the illuminance uniformity maps of the upper and bottom light guides shown in the Figure 11. As seen from the Figure 12, the light guides without surface roughness have fluctuations in illuminance from the beginning to the end, while for the light guides with surface roughness the illuminance is more uniform.

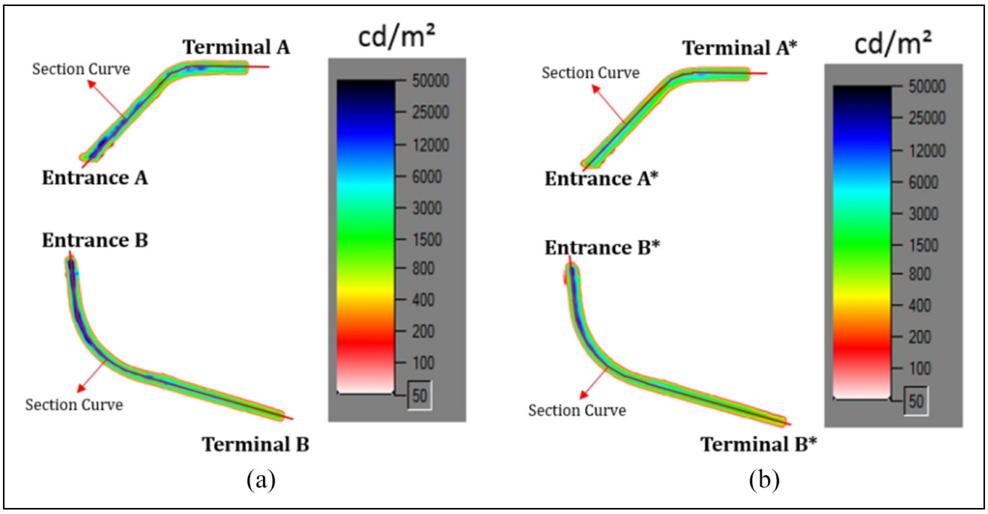

Figure 11. Illuminance uniformity maps of light guides (a) without surface roughness and (b) with surface roughness.

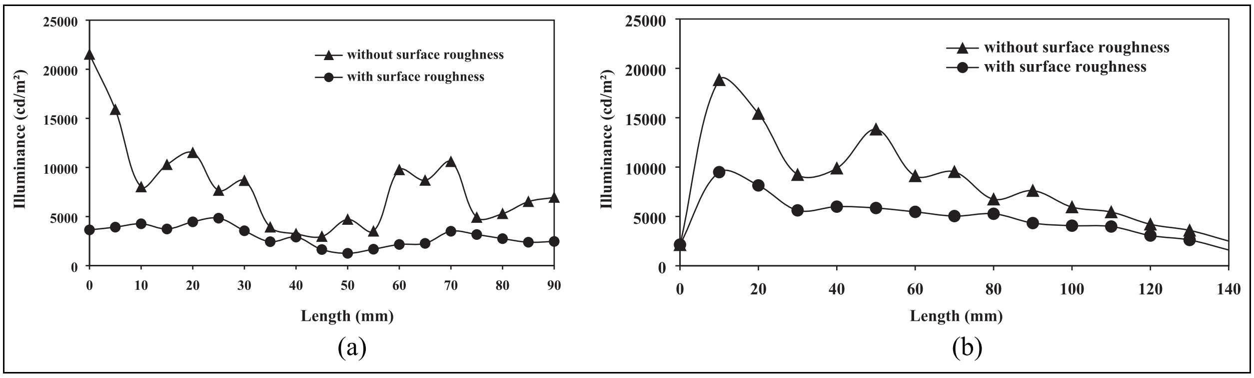

Figure 12. Illuminance uniformity variations of (a) upper light guides and (b) bottom light guides without and with surface roughness.

Comparison of simulation and prototype results

By using the optimum values of α and β that affect the luminous intensity (section 'Design of prismatic structures for optimum luminous intensity') and the results of the surface roughness that influence the illuminance uniformity (section 'Surface roughness influence on luminous intensity and illuminance uniformity'), light guide prototypes were milled from bulk PMMA material. The milling radius of the prismatic surface edges is 0.1 mm. All surfaces of the light guides were polished with diamond paste by hand, except for prismatic surfaces, which are too small to be polished. Osram red Power Side LEDs (LA B6SP-DBEB-24-1) were used to illuminate upper and bottom light guide prototypes, one LED for both upper and bottom, with an operating current of 110 mA as in the simulations.

At the stage of the prototype design, the intensity values were checked by considering the legal requirements such as ECE R7 and SAE J585. The measurement points of ECE R7 and SAE J585 regulations (10U-5L to 10D-5R) were labelled by the numbers from 1 to 19, respectively (see Table 1). For these regulation points, the prototype measurements were made four times by LMT GO-H 1660 Gonio photometer with an error of ~5% and their average values were taken. Furthermore, the statistical errors for each measurement points were determined. The simulated and the average intensity values of the prototype are listed in Table 1, as well as minimum intensity values required according to the measurement points of ECE R7 and SAE J585 regulations. As seen from the Table 1, both simulation and prototype luminous intensity values are in agreement with each other for many measurement points and are over the minimum values of the legal requirements.

Figure 13 shows a graphical comparison of simulation and prototype intensity values according to the regulation points. As seen from the figure, the simulation and prototype curves show a similar behaviour and are generally well in agreement; however, the simulation intensity values are larger than those of the prototype intensity at some points. This is probably due to few reasons such as the prototype quality, measurement conditions and especially the difference between calculated and real degradation. The thermal degradation calculated by simulation was 30% while the real thermal degradation for the prototype was measured to be approximately 20%. This difference arises from thermal degradation calculation method because the thermal degradation simulations are performed at steady-state condition, instead of time dependent solution (transient). So the degradation values predicted by simulation can be considered as the worst case, which leads to higher degradation values than that in the real state.

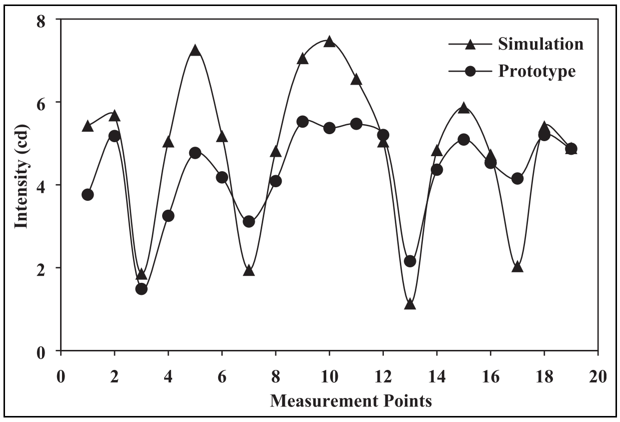

Figure 13. Variation of simulation and prototype luminous intensity values with measurement points.

Figure 14 shows the illuminance uniformity pictures for the light guide prototypes without (Figure 14(a)) and with (Figure 14(b)) surface roughness. As seen from the figure, the light guide prototype having surface roughness on prismatic surfaces has better illuminance uniformity than that of without surface roughness. This result confirms the simulation results given in Figures 11 and 12.

Conclusion

For automotive tail light applications, an optical design of light guide prisms providing optimum luminous

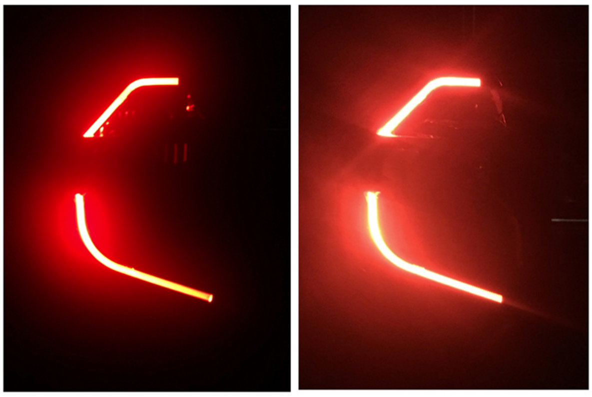

Figure 14. Illuminance uniformity pictures of light guide prototypes (a) without surface roughness and (b) with surface roughness.

intensity and illuminance uniformity was achieved. Prismatic surfaces on the guides were employed to divert light through the desired direction. The optimum values of the prism angles, α and β, were determined by considering the sufficient luminous intensity providing legal requirements. These are the following: the α angle for both (upper and bottom) light guides is 20°, while the β angles are between 40° and 50° for the upper light guide and 30° for the bottom light guide. Furthermore, using the optimum α and β values, different surface roughness was applied on the prismatic surfaces to examine its effect on luminous intensity and the illuminance uniformity. It was observed that an increment in the surface roughness causes more scattered light and the luminous intensity distribution at FWHM broads to larger angles from the axial direction. As a result, the intensity values decrease with increasing surface roughness. Also, the simulation intensity values are generally larger than those of the prototype. This difference was attributed to the prototype quality, measurement conditions and especially difference between calculated and real thermal degradation. On the contrary, better illuminance uniformity was gained by applying the surface roughness on prismatic surfaces. It was found that the illuminance uniformities of simulation and prototype are in agreement with each other for many measurement points and are over the minimum values of the legal requirements.

Declaration of conflicting interests

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Appendix 1

Notation

d	distance from the entrance surface of the light guide to the prism
h	prism height (diameter of light guide)
n	refractive index of the light guide material
V	depth of the prism
w	prism width
X, Y, Z	directions of coordinate system
α	start angle of prismatic surfaces
β	end angle of prismatic surfaces
ϕ	diameter of bar
γ_c	critical incidence angle