

Automotive Interior Ambient Lighting Design and Optimization

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Abstract: Ambient lighting is a crucial component of automotive interiors, and its design significantly impacts both user convenience and perception. Optical simulation technology enables effective optimization of the optical pattern structures in interior ambient lighting, facilitating continuous improvement of design solutions. This paper analyzes the composition and working principles of automotive interior ambient lighting, outlines the design process and key considerations, and conducts simulation studies to enhance the design quality of interior ambient lighting, thereby improving user experience.

Keywords: automotive interior; ambient lighting; optical structure Product Design

1 Introduction

A survey on key design elements of automotive interiors based on consumer preferences reveals that ambient lighting is one of the aspects most closely watched by consumers, with many placing greater emphasis on its avant-garde and luxurious characteristics. For instance, incorporating a soft white dot-matrix ambient light along the ceiling or arranging a ring of blue ambient lighting around the top contour edge can significantly enhance consumer perception. In the design of automotive interior ambient lighting, optical structure optimization plays a crucial role, directly influencing the overall rationality of the design solution.

2 Composition and Working Principle of Automotive Interior Ambient Lighting

2.1 Composition of Automotive Interior Ambient Lighting

Interior ambient lighting in vehicles enhances interior illumination, meeting users' needs for nighttime driving and usage. Through thoughtful application of colors, brightness adjustment, and dynamic lighting patterns, it can also better support emotional relief and expression, highlight brand identity, and satisfy diverse consumer demands [1]. Typically installed along dashboard outlines, instrument panels, secondary dashboards, air vents, cup holders, and door trim panels, automotive interior ambient lighting systems mainly consist of LED light sources, lamp heads, light guides, connectors, and light strip brackets. Additionally, multi-color ambient lighting may require a corresponding controller.

2.2 Working Principle of Automotive Interior Ambient Lighting

Automotive interior ambient lighting primarily operates by connecting power through in-vehicle wiring harnesses to illuminate light sources, with light propagation achieved via light-guiding strips. Taking LED ambient lighting—a commonly used type—as an example, it employs solid-state semiconductor devices to directly convert electrical current into light. Between a p-type and an n-type semiconductor chip lies a transition layer; when activated, current flows from the anode to the cathode, generating light emission. The color of the emitted light is determined by its wavelength, which depends on the material of the PN junction, while the brightness is influenced by the intensity of the current. In designing automotive interior ambient lighting, the principle of the three primary colors—red, green, and blue—is applied to combine these hues and create various colors, thereby meeting diverse design requirements.

Additionally, depending on the desired decorative lighting effect, either rigid or flexible light strips are selected. Furthermore, the design must meet specific illumination width requirements for targeted areas and optimize the structure of the ambient lights according to their installation locations, ensuring both optimal performance and compliance with safety regulations [2].

3 Automotive Interior Ambient Lighting Design Process and Key Points

3.1 Design Process

To address common issues associated with automotive interior ambient lighting, optimization must begin at the design stage. By leveraging the principles of light propagation through media, it is essential to maximize light energy efficiency while ensuring desired illumination performance, thereby guaranteeing the rationality of the design. Typically, the design process consists of three fundamental steps. First, model construction and simulation: based on the functional requirements and design concepts of different lighting areas, appropriate software is used to create structural models of light-guiding components and conduct optical simulations. Second, optimization design: visual patterns are defined and brightness distribution is analyzed; if the analysis results fail to meet design specifications, parameter optimization is carried out by adjusting light ray tracing and optical pattern structures. Third, if the brightness pattern analysis meets testing and validation criteria, designers proceed to analyze customer requirements—should these be satisfied, the optimization process concludes directly; otherwise, step two is repeated until the final optimized design is achieved.

3.2 Design Considerations

In the design of automotive interior ambient lighting, it is essential to clearly define four fundamental constraints: styling, engineering structure, optical principles, and optical simulation validation. Based on validation results, optimization can be achieved through simulation-based corrections to address optical non-uniformity and prevent issues such as chromatic deviation [3]. Meanwhile, simulation analysis significantly improves design efficiency and reduces the cost associated with iterative validation cycles. Additionally, five key aspects require enhanced attention during the design process. First, proper arrangement of the light source layout in the ambient light module should ensure a gap of at least 1 mm between the light head and door trim panel, while increasing the hardness of the light head area to effectively prevent vibration from negatively affecting lighting performance. Second, the main optical axis direction of the ambient light should be reasonably arranged, precisely determining the emission direction so that it remains perpendicular to the light-emitting surface whenever possible, thereby minimizing light loss [4]. Furthermore, selecting appropriate translucent structural components for the light-emitting positions enhances overall visual continuity. Third, the assembly method between the ambient lighting module and the door trim panel must be carefully designed. A two-step approach—first using hot riveting welding to attach the ambient light to the door trim strip, followed by final assembly—ensures high positional accuracy and secure fixation. Fourth, the optical design of the light guide component should be optimized to achieve superior optical performance and enhance the overall functionality of the ambient lighting system. Fifth, anti-leakage design at non-emission areas must be properly implemented to avoid light leakage and confusion, which could otherwise compromise the overall visual effect.

4 Automotive Interior Ambient Lighting Design Simulation and Modeling

4.1 Simulation and Modeling Conditions Setup

Taking a specific vehicle model as an example, when designing its ambient lighting, optical simulation should be employed to analyze the brightness uniformity and color consistency achievable with the design. At the same time, a simulated brightness range should be established to predict the simulation results, setting the interior ambient light emission color to white with a brightness value of at least 20 cd/m².

4.2 Selection of Component Materials

After determining the simulation conditions, it is necessary to reasonably select materials for each component and establish optical material models based on their optical properties. First, priority should be given to selecting materials for light-guiding components, ensuring that their physical properties meet certain requirements, with a light transmittance of at least 92%. Additionally, diffusing agents within the translucent components must be properly selected to achieve isotropic light diffusion, thereby minimizing discontinuous, uneven, or glaring[5] light effects while maintaining sufficient brightness. In this design, the actual transmittance of the translucent parts reaches 96%, meeting the overall design requirements. Prior to simulation, individual components such as the lamp housing, light-transmitting film, base, light guide bar, LED module, top cover, bottom cover, LEDs, and PCB must be defined, with appropriate transmittance, reflectance, and refractive index values assigned to analyze potential shortcomings in the design through simulation.

4.3 LED Light Source Selection

When selecting an LED light source, it is essential to pay close attention to its brightness requirements. For example, for a brightness level of 10–100 cd/m², the rated current of the selected LED should be 20–70 mA [6].

4.4 Simulation Data Definition

The simulation data should be defined according to the actual human eye observation direction, and by combining the determined simulation orientation, the overall brightness value of the ambient lighting is obtained after simulation.

4.5 Optical Pattern Structure Improvement

If the optical pattern structure has issues, it may result in a deviation between the ambient lighting effect and the intended design, failing to meet product requirements. To address this, improvements can be made in three aspects.

First, the dark areas at the front and overly bright regions at the rear of automotive interior ambient lighting are mostly caused by the smooth design near the front section, which fails to generate effective optical reflection. As a result, light passes directly through the light-guiding medium, creating dark spots in those areas. Meanwhile, the end face at the rear becomes the direct light-emitting surface, resulting in relatively high brightness and causing excessive brightness at the rear. To address this issue, designers can incorporate optical pattern structures into the front safety area, replacing the original smooth design to enhance reflection and effectively improve brightness while preventing dark zones. Additionally, applying black material to the rear end face can effectively prevent light leakage and avoid over-brightness at the rear.

Second, the noticeable brightening along the upper edge of the ambient lighting is primarily caused by excessively high light guide pattern teeth, resulting in an overly large reflective surface. Additionally, the designed tooth spacing is too narrow, leading to a dense concentration of reflective areas. Under conditions where light energy is highly concentrated, this inevitably causes excessive brightness at the upper edge. To address this issue, designers should adjust the parameters for light guide pattern tooth height and gradient coefficient within the simulation software's built-in data tables during the design process. This helps reduce the number and density of reflective surfaces, effectively preventing over-brightness in areas such as the upper edge.

Third, significant color differences may occur in the design scheme, negatively affecting users' perception. To address this, light-guiding components that meet relevant standards should be selected to prevent color variation. Additionally, the chromaticity coordinates of ambient lighting should be adjusted to fall within the standard range.

After completing the above optimizations, simulation and modeling must continue to ensure the design meets the required target values, thereby laying a solid foundation for subsequent optical performance testing and validation.

4.6 Optical Performance Test Verification

In the optical performance testing and verification, the designed ambient light was turned on for 0.5 hours, with brightness verified using a luminance meter and colorimetric tests conducted using a spectrometer. The verification results showed that all parameters met the target requirements.

5 Trends in Automotive Interior Ambient Lighting Design

5.1 Design Based on Light-Emitting Forms

As automotive interior design increasingly influences user perception and consumers pay greater attention to ambient lighting, different trends in interior ambient lighting design have emerged based on varying illumination methods. Therefore, in practical design, it is essential to optimize the ambient lighting scheme according to overall vehicle design requirements to achieve superior design outcomes and enhance the lighting experience. Currently, there are five main types of automotive interior ambient lighting.

One type is the direct-emission ambient light, which consists of a light-distributing faceplate, LED circuit board, housing, and other components. It is commonly used in areas such as front and rear footwells and door handles [7]. This design is relatively simple and enables direct illumination upon activation, effectively lighting up the surrounding environment with high brightness. However, its lighting effect is generally modest, meeting only basic user requirements.

The second type is the point-source strip-reflection ambient lighting, typically composed of a light-emitting module, light guide, and mounting bracket. It is primarily used in areas such as main and auxiliary instrument panels, door trim panels, and sunroofs. When activated, the LED light source within the module emits light that travels through the light guide and evenly illuminates the receiving surface, creating a reflective light band effect. This design offers advantages such as uniform illumination and simple installation; however, it generally provides mediocre lighting performance with relatively low brightness. Moreover, significant changes in the angle of the receiving surface or noticeable color deviations can negatively affect the visual lighting experience.

The third type is the point-source strip direct-emission ambient light, whose structure is similar to that of the point-source strip reflective ambient light, and it is applied in largely the same areas. This solution requires high uniformity of the light-emitting surface, offers higher brightness and better lighting effects, effectively addressing the issue of poor illumination performance, and is widely used in most vehicle models.

The fourth type is the point-source surface-emitting ambient light, which features a relatively complex structure consisting mainly of a luminous face cover, surface light guide, LED circuit board, and housing. It delivers excellent application results in areas such as instrument panels and door trim panels. This type of ambient lighting enhances illumination effects and offers superior visual appeal. However, it requires high precision in engraving techniques during design, demands substantial installation space, and has relatively higher costs, making it primarily used in premium vehicle models.

5.2 Design Based on Material Optimization

As automotive market competition intensifies, consumers' perception and demand for interior ambient lighting continue to rise. By adopting new fiber-optic lighting materials, it becomes possible to optimize the color of emitted light, allowing users to select variable colors according to personal preferences while effectively reducing light source power consumption and achieving superior energy[8] efficiency. In practical design, common materials include end-emitting polymer optical fibers, side-emitting polymer optical fibers, and side-emitting glass optical fibers. Each material has its own advantages and disadvantages, so selecting the appropriate type based on specific design requirements is essential to achieve optimal results [9]. Additionally, in certain designs, adding an appropriate proportion of color masterbatch to the cover material can reduce material transparency, improve scattering performance, and effectively address issues such as bright spots and sawtooth shadows.

6 Conclusion

As consumer interest in automotive interior ambient lighting continues to grow, designers must place greater emphasis on the design of such lighting systems. Starting from overall design objectives, appropriate design methods

should be selected to accurately analyze optical structures and identify issues within the overall design. By employing structural optimization, material optimization, and light source brightness adjustment, design improvements can be made to ensure excellent visual effects. This approach lays a solid foundation for enhancing driving safety and user convenience, effectively improving vehicle quality and market competitiveness, and promoting the sustainable development of China's automotive industry.

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