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Design of Multi-module LED Headlamp of Vehicle Under Federal Motor Vehicle Safety Standard

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A light-emitting diode (LED) low-beam headlamp system was designed following the automotive headlamp regulations in Federal Motor Vehicle Safety Standard 108 (FMVSS 108). To design the system, we used the optical simulation software Light Tools. Using the focusing properties of an ellipsoidal reflector and an asymmetric light source floorboard, we enabled the light projected through the lens to form the cutoff lines that are required in regulations. The newly designed LED low-beam headlamp system can replace the shade component in conventional projector-type headlamp systems, reducing energy loss and effectively increasing light utilization efficiency. Using the concept of light pattern superposition, we superposed the light patterns of multiple modules to reduce the number of LED lights used and achieve satisfactory utilization efficiency. We used the simultaneous multiple-surface (SMS) design method to construct a high-focusing multiple-surface reflector and incorporated it into the system. By superposing the light patterns, the designed system satisfied illuminance regulations. Compared with conventional 55 W halogen low-beam headlamps, the LED low-beam headlamp systems in this study used 70% less energy.

1. Introduction

Light-emitting diodes (LEDs) are semiconductor components that emit light and are composite light sources consisting of trivalent and pentavalent elements. In recent years, they have been widely applied in various products such as automotive lighting, household appliances, and backlit displays. Regarding automotive lighting, researchers designed optical lenses with a total internal reflection freeform surface to improve the optical performance of LED front fog lamps.[1] By optimizing cylindrical lens arrays, the projecting light patterns enhance the linearity of the cutoff line. This optimized method suppresses the illumination in the dark zone

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and effectively increases the contrast across the cutoff lines.(2) Wu *et al*. proposed a modular LED headlamp system based on freeform reflectors while taking glare suppression and optical design into account.(3) Tsai designed an automotive headlamp system consisting of a freeform reflector and an LED light source.(4) Seo and Lee investigated the illuminance efficiency resulting from ferrofluid cooling systems for high-power LEDs with different input voltages, magnetic fields, and cooling fluids and analyzed their heat transfer characteristics.(5) Ma *et al*. proposed an achromatic LED headlamp system to compensate for the color dispersion of light patterns at the cutoff line.(6)

The main function of automotive headlamp reflectors is to gather or disperse light to achieve regulated patterns and positions. Reflectors may have ellipsoidal surfaces, parabolic surfaces, or quadric surfaces. Ellipsoidal reflectors have better reflective and focusing efficiency than others. Rausch and Herkommer used a freeform lens to correct the uniformity of irradiance at the secondary focus.(7) Shih and Cheng developed a multi-signal biological light-collecting sensor structure that used multiple ellipsoidal reflectors to combine the light source with a photodiode. This all-in-one design method was adopted to reduce positioning errors.(8) Chang *et al*. proposed a light detection and ranging (LiDAR)-embedded laser headlight module for autonomous vehicles. (9) Their experiment results revealed that the high-beam patterns of the module satisfied ECE R112 B regulation by United Nations Economic Commission for Europe (UNECE).

The simultaneous multiple-surface (SMS) design method is used to design lenses based on non-imaging optics. The method uses the different angles of reflected light and focus generated by an incident light reflected off an irregular surface or at refraction angles with different curvatures or slopes. The reflection of light and its control over the curvatures of different surfaces allow a uniform light focus with multiple reflective and curved surfaces. SMS provides a starting point for imaging quality optimization.(10) Hu *et al*. employed the edge-ray principle to design an ultracompact rotational symmetric lens with double freeform surfaces that redistribute the light from a Lambertian LED and increase illumination uniformity in the target area.(11) A genetic algorithm was used to optimize the design for optical compactness under structural constraints and illumination requirements. Xue *et al*. utilized the edge-ray principle in non-imaging optics to design a freeform lens with an extended light source.(12) Compared with conventional grid optimization methods, the SMS method saves time on optimization and increases design efficiency. The freeform surface lens is appropriate for high-power LED spotlights, LED flashlights, and security monitoring systems requiring uniform lighting at long distances. Han *et al*. presented a freeform lens for beam pattern transmission using flux partition to transmit arbitrary beam patterns.(13) Intensity distributions required for a Lambertian light source were calculated in their design, such as isotropic and exponential distributions.

With advances in technology, high-power LEDs are widely applied in the high-end automotive industry. At present, most mid- and low-end vehicles still use halogen lamps or high-intensity discharge lamps, whereas high-end vehicles use LED headlamps. However, partial blocking of the light from a light source using shades causes light energy loss and reduces light utilization efficiency although it has the standard light pattern. Therefore, we designed an asymmetric reflective floorboard based on the standard light pattern to replace the shade component in conventional projector-type headlamps to increase the light utilization efficiency and overall light intensity by recycling part of the lost light energy. Then, we developed a low-beam LED headlamp system with the designed asymmetric reflective floorboard to meet the requirements of the automotive lighting regulations in Federal Motor Vehicle Safety Standard 108 (FMVSS 108).(14) We used the freeform surface's automated design method to validate the proposed design. Conventional light sources with LED lights as automotive headlamps can be replaced with a low-beam LED headlamp system. In the overall design, we employed the advantages and disadvantages of headlamp products and a consistent optical design system for US standard low-beam headlamp modules and the US standard headlamp system with LED lights.

2. Automotive Lighting Regulations in FMVSS 108

Low-beam headlamp regulations were added to FMVSS 108 in the US in 1997 so that the light patterns of US standard headlamps could conform to European regulations. We used the low-beam headlamp regulations in FMVSS 108 as the verification standards in this study. Figure 1 shows the test points stipulated for the measurement of low-beam headlamp luminous intensity in the regulations, and Table 1 presents the luminous intensity required for each test point. The stipulated distance between the headlamp and the photometer is 60 ft, which is equivalent to 18.3 m, and the test voltage is 12.8 V ± 20 mV. The headlamp regulations in FMVSS 108 require using low-beam headlamps to measure luminous intensity in lux with the optical simulation software Light Tools. The relationship between luminous intensity and illuminance is as follows.

$$Illuminance = luminous\ intensity\ /\ (measured\ distance)^2 \tag{1}$$

3. Materials and Methods

3.1 Methodology

The design of a low-beam LED headlamp system was carried out in two directions: (1) designing the system with cutoff lines following low-beam headlamp regulations in FMVSS 108

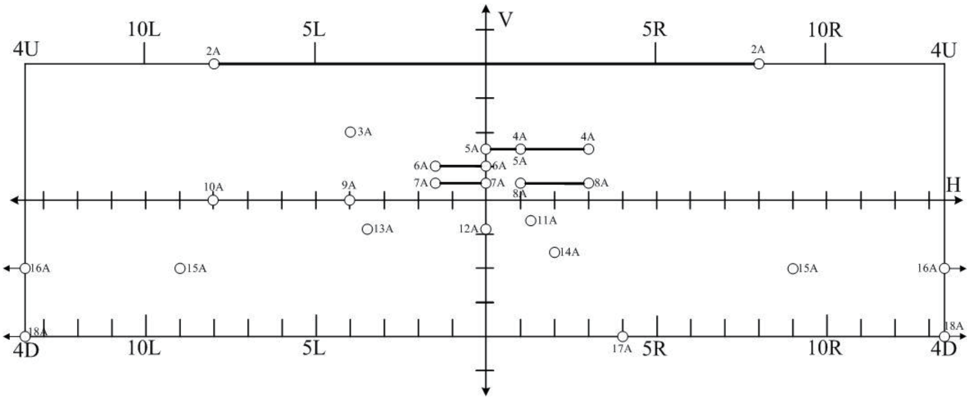


Fig. 1. Measurement test points in low-beam headlamp regulations.

Table 1
Measurement test points and luminous intensity regulations for low-beam headlamps.

Test point	Position	Luminous intensity (cd)	Illuminance (lux)
1	10U-90U	≤125	≤0.37
2	4U-8L and 8R	≥64	≥0.19
3	2U-4L	≥135	≥0.40
4	1.5U-1R to 3R	≥200	≥0.6
5	1.5U-1R to R	≤1400	≤4.18
6	1U-1.5L to L	≤700	≤2.09
7	0.5U-1.5L to L	≤1000	≤2.99
8	0.5U-1R to 3R	500–2700	1.49–8.06
9	H-4L	≥135	≥0.40
10	H-8L	≥64	≥0.19
11	0.6D-1.3R	≥10000	≥29.86
12	0.86D-V	≥4500	≥13.44
13	0.86D-3.5L	1800–12000	5.37–35.83
14	1.5D-2R	≥15000	≥44.79
15	2D-9L and 9R	≥1250	≥3.73
16	2D-15L and 15R	≥1000	≥2.99
17	4D-4R	≤12500	≤37.33
18	4D-20L and 20R	≥300	≥0.90

and (2) constructing and simulating headlamp components using optical simulation software. The design process is shown in Fig. 2. In designing the system, we used an asymmetric design for the floorboard of the LED to increase light utilization and achieve cutoff requirements by replacing the shade component in conventional projector-type headlamp systems. We added an ellipsoidal reflector, lenses, and a condenser to project the light efficiently into the target area. Once we completed a single module design (light source, floorboard, reflector, and lenses), we defined the configuration of the proposed system to satisfy the low-beam headlamp regulations. The final design of the LED automotive (low-beam) headlamp system was completed following the US regulations for automotive headlamps.

3.2 LED light source

We used Visera 6363 and Nichia-NVSW119A LEDs as the light sources of the headlamp. The rated output power, drive current, and a beam angle of the Visera 6363 LED were 5 W, 700 mA, and 130°, respectively. The measurement result of the integrating sphere and emitted light using a goniophotometer showed that the luminous flux of the rated output power was 340 lm and the beam angle was 135°. The rated output power, drive current, and a beam angle of the Nichia-NVSW119A LED were 3 W, 900 mA, and 115°, respectively. Its luminous flux of 3 W rated output power was 190 lm, and the beam angle was 115°. We used the two types of LED as the light sources of the LED low-beam headlamp system. The wide beam angle and high luminous flux of the Visera 6363 LED enable the projected light to brighten the area surrounding the test points, whereas the Nichia-NVSW119A LED enhances the illuminance in the central area. We input the luminous flux and light distribution data of the LEDs into Light Tools to simulate the light emitted from the LED light sources.

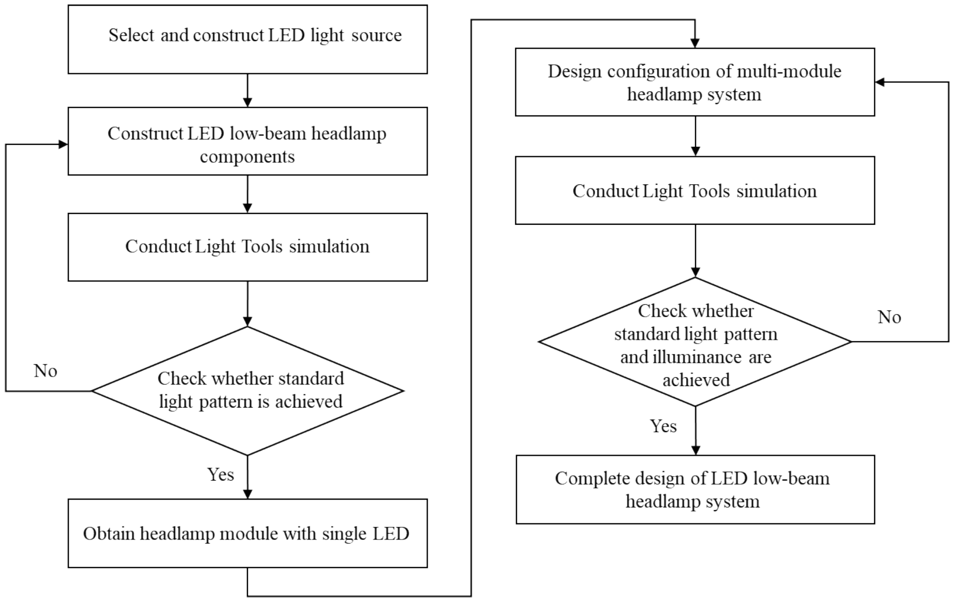


Fig. 2. Design process for LED low-beam headlamp system.

3.3 Asymmetric floorboard

Conventional projector-type low-beam headlamps use shades to shape the projected light to make regulated cutoff light patterns. This shade design blocks light that reaches the lens, thereby resulting in energy loss. We altered the shade design on the basis of the standard light pattern to reduce the energy consumption of the proposed system and increase the overall light intensity. In conventional projector-type headlamp systems, the light source is placed at the first focus of the ellipsoidal reflector so that the light reflected off the ellipsoidal reflector can converge at the second focus. The focuses of the shade and the aspheric lens are placed at the second focus of the reflector so that the light converged at the second focus forms the desired pattern by the shades and is then projected and dispersed by the lens.(15) This mechanism of using shades shapes the light pattern to block nearly half of the light, which causes energy loss.

To reduce headlamp energy loss, we replaced the shade design of conventional projector-type headlamps with an asymmetric floorboard design to meet cutoff requirements and increase light and energy utilization. To meet the regulations in FMVSS 108, the light pattern must have horizontal cutoff lines at varying heights on the left and right sources. The light from the source in the automotive headlamp system reflects off the reflector to the lens and then is focused on the target plane, so the projected light pattern is inverted. After removing the conventional shade component, we added a floorboard with left-right asymmetry as shown in Fig. 3.

The floorboard on the right of the LED light source was a non-angled horizontal floorboard for the cutoff line on the left target light pattern (0.4° below the H-H line). The floorboard on the left was placed in front of the light source and was tilted 4° downward according to the cutoff line on the right of the standard light pattern. Compared with using horizontal floorboards on both the left and right to create a height difference, floorboards with a tilted angle reflect the

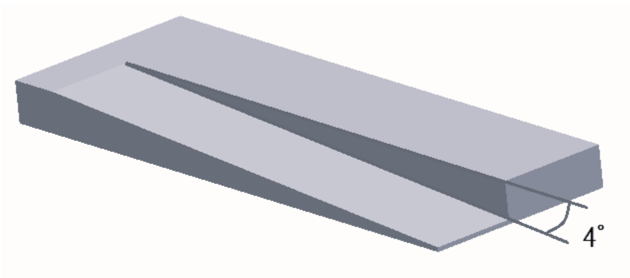


Fig. 3. Schematic diagram of asymmetric floorboard.

light forward more efficiently and produce cutoff lines at varying heights on the left and right sides of the lens, thereby meeting the requirements of the standard light pattern. With the luminous flux of the LED light sources at 340 lm, we used Light Tools to simulate and compare the result with those of previous studies. The resulting luminous fluxes of the shade and asymmetric floorboard were 228.9 and 334.6 lm, respectively. Thus, replacing the shade component with the asymmetric floorboard considerably reduced light energy loss.

3.4 Ellipsoidal reflector

We used Light Tools to design and simulate the ellipsoidal reflector in the proposed LED headlamp system. Ellipsoidal reflectors are commonly used in headlamp systems as they have satisfactory reflective and focusing efficiency. When a light source emits light onto the ellipsoidal reflector, the curved surface of the reflector allows a consistent focusing effect, making the light focus on the lens effectively. The LED light source at the first focus of the ellipsoidal reflector makes the light reflect off the reflector and converge at the second focus. We merged the boundaries of multiple ellipsoidal reflectors to form multiple ellipsoidal reflectors. When light is emitted from the light source, the distribution of the light pattern on the target plane is altered by controlling the parameters of the multiple ellipsoidal reflectors. The closer the LED light source is to the focus, the better is the reflection efficiency of the reflector. Thus, the light source of the proposed LED headlamp system was placed near the first focus so that the energy of the light source could be effectively reflected in the lens. The diameter of the ellipsoidal reflector and the radius of curvature in the system were 41 and 1.5 mm, respectively.

3.5 Aspheric lens

For the headlamp lens of the proposed system, we used aspheric lenses, as they are commonly contained in optical systems, and they focus better than general spherical lenses. The equation of the aspheric lens constructed in Light Tools is

$$z = \frac{C_v r^2}{1+\sqrt{1-kC_v^2 r^2}} + Br^4 + Cr^6 + Dr^8 + Er^{10}, \tag{2}$$

where C_v denotes the curvature at the center of the lens surface, and $r^2 = x^2 + y^2$, where r^2 is the conic constant. If $Br^4 + Cr^6 + Dr^8 + Er^{10} = 0$, then Eq. (2) is applied to a quadric conical surface. We chose transparent polymethyl methacrylate (PPMA) as the material of the aspheric lens. The transmittance of the lens (n = 1.49) was set at 90%, and the radii of curvature of the convex front surface and the concave back surface were 40 and 162 mm, respectively. The design diameter was 50 mm. To fully utilize the light and project it on the target, the diameter of the lens was determined to be greater than that of the reflector, which was 41 mm. Owing to the smaller curvature of the reflective surface of the reflector, the distance between the first and second focuses needed to be large, considering the overall size of the system. Thus, we placed it at the focus of the reflector so that the lens could focus and project the light on the target plane. In a focused state, the lens projected a light pattern with a sharper cutoff than in an unfocused state.

3.6 Cylindrical condenser

Figure 4(a) shows the simulated illuminance of a low-beam headlamp module with a single LED, reflector, lens, and asymmetric floorboard. Although the middle part had the required cutoff effects, excess light was scattered around the light pattern, which made the dark area above the cutoff line too bright. The luminous intensity at the test point above the cutoff line thus exceeded the stipulated 0.36 lux, and energy loss occurred due to the scattered light. This light scattering was caused by the distance between the focus of the headlamp lens and the reflector. When the light was reflected off the reflector onto the lens, the light on the outer edges scattered instead of being focused and projected to the target area. This gap between the reflector and the lens resulted in energy loss. To eliminate the scattered light, the easiest approach is to use a condenser to guide the light to the lens. As the reflector and the lens were round-shaped, a cylindrical condenser was used. The inner diameter of the cylinder was 50 mm, which was the same as that of the lens. As shown in Fig. 4(b), the scattered light issue above the cutoff line was resolved, and the illuminance at the test point was reduced from the original 2 lux to the

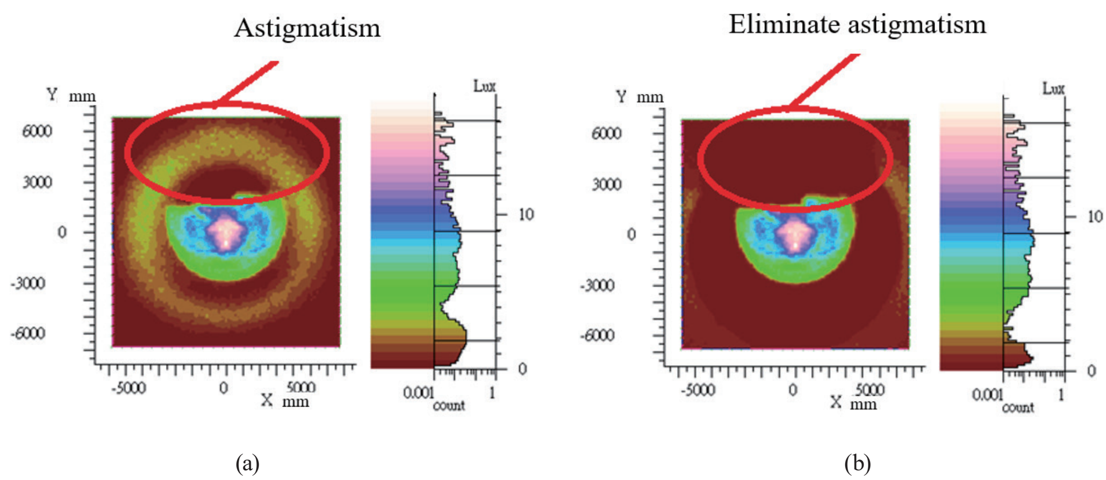


Fig. 4 (Color online) Simulated illuminance of headlamp with single module: (a) without condenser and (b) with condenser.

compliant 0 lux. With the illuminance of scattered light, drivers of approaching vehicles on the opposite lane do not suffer from any glare caused by scattered light from headlamps. In addition, less light energy loss was observed as the scattered light was effectively used. This increased the overall illuminance.

4. Results and Discussion

4.1 Headlamp module with asymmetric floorboard

The simulation with the developed headlamp module with an asymmetric floorboard and a single LED was performed using Light Tools. The distance between the headlamp and the target plane was set at 18.3 m according to the regulations in FMVSS 108. We placed the reception plane of 15 m × 15 m in size at 18.3 m from the front end of the headlamp module so that it could receive all of the light projected from the headlamp (Fig. 5). The vertical (V–V) baseline was aligned with the center of the headlamp, whereas the horizontal (H–H) baseline was 0.4° above the cutoff line. Trigonometric calculations revealed that the distance between the center and the baseline was 128 mm. Once the vertical and horizontal baselines were calibrated, we measured various test points' coordinates. Table 1 shows the luminous intensity value required for each test point.

After we set the parameters, simulations for the headlamp module were carried out. The results are shown in Fig. 6. The light pattern and cutoff line meet the requirements but the luminous intensity was inadequate. Table 2 shows that the illuminance does not meet the regulations at many test points, so we superposed more LEDs on the headlamp module to obtain the required luminous intensity.

4.2 Headlamp module with horizontal floorboard

Figure 7 shows the distributions of test points where the illumination did not meet the regulations. These test points were located in three areas: the center concentration area, the area

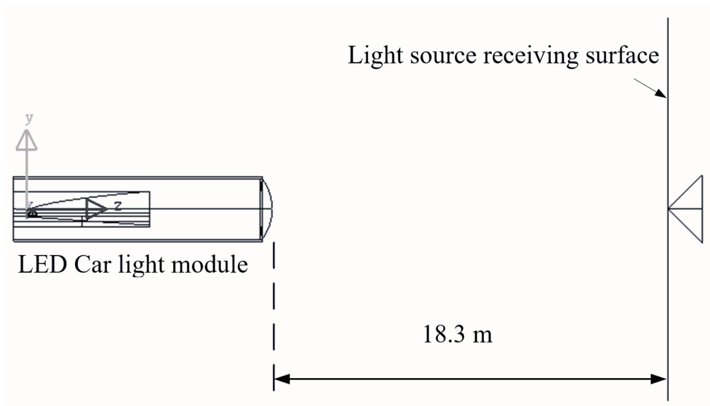


Fig. 5. Distance in simulations of headlamp module with single LED.

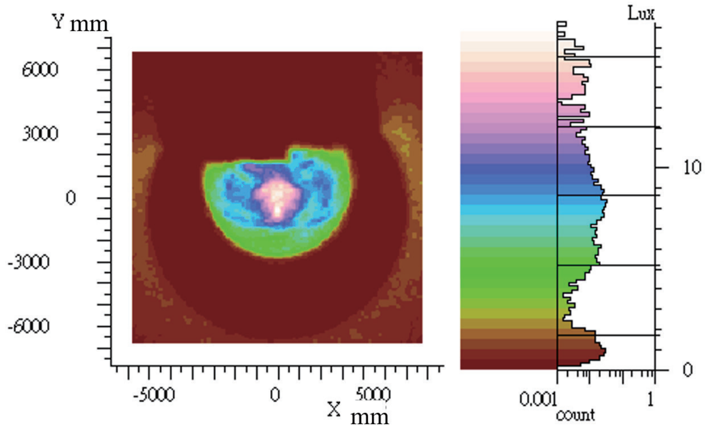


Fig. 6. (Color online) Simulated illuminance in headlamp module with asymmetric floor board and single LED.

Table 2
Comparison of illuminance at test points.

Test point	Position	Regular illuminance (lux)	Simulated illuminance (lux)
1	10U-90U	≤0.37	0
2	4U-8L and 8R	≥0.19	0
3	2U-4L	≥0.40	0
4	1.5U-1R to 3R	≥0.6	0.60–8.070
5	1.5U-1R to R	≤4.18	0.60
6	1U-1.5L to L	≤2.09	0.11–0.65
7	0.5U-1.5L to L	≤2.99	1.74–2.66
8	0.5U-1R to 3R	1.49–8.06	2.86–7.98
9	H-4L	≥0.40	6.62
10	H-8L	≥0.19	2.07
11	0.6D-1.3R	≥29.86	8.44
12	0.86D-V	≥13.44	9.86
13	0.86D-3.5L	5.37–35.83	11.21
14	1.5D-2R	≥44.79	9.54
15	2D-9L and 9R	≥3.73	5.35–5.62
16	2D-15L and 15R	≥2.99	0
17	4D-4R	≤37.33	9.27
18	4D-20L and 20R	≥0.9	1.56–1.65

above the H–H line, and the outer regions to the left and right. At the maximum illuminance of 44.79 lux in the center concentration area at test points 11, 12, and 14, the headlamp module only had 9.54 lux. With the light pattern superposition, we needed at least 5 LEDs in the headlamp module to meet regulations. However, the LEDs caused excessive illuminance at test points 7 and 8. We altered the light pattern superposition by replacing the asymmetric floorboard with cutoff lines at varying heights on the left and right sides of a non-angled horizontal floorboard. In addition, we used a Nichia light source to increase the overall luminous intensity to prevent excessive illuminance at test points 7 and 8 and to produce a higher maximum illuminance than the headlamp module with an asymmetric floorboard. Figure 8 shows a diagram of the light pattern superposition.

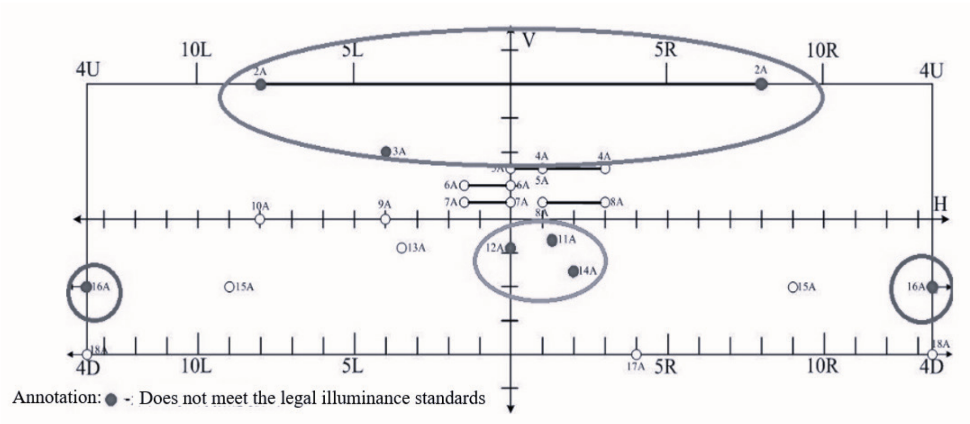


Fig. 7. Distribution of test points does not meet illuminance standards.

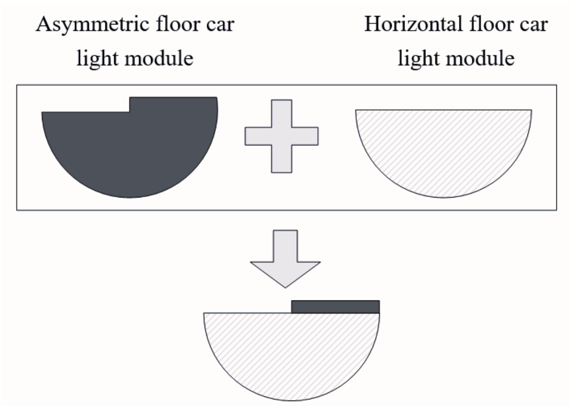


Fig. 8. Diagram of light pattern superposition.

The simulated light pattern of the headlamp module with a horizontal floorboard showed the maximum illuminance occurring on the V–V line, whereas the test point with maximum illuminance in the regulations was at (1.5D, 2R). Thus, we adjusted the angle of the horizontal headlamp module so that the light projected from the headlamp module could fall on the right location. Figure 9 shows the angle adjustment of the horizontal headlamp module. As the test point was located 2° (2R) to the right of the V–V line, the headlamp module was also moved 2° so that the maximum illuminance fell on the target location. We did not use parallel displacement to focus the headlamp module because, at the testing distance of 18.3 m, a trigonometric calculation showed that at coordinates of 2R (2° to the right), a displacement of 640 mm was needed to shift the center of maximum illuminance. Thus, we rotated the horizontal headlamp module 2° clockwise for superposition as shown in Table 3.

The adjustment of the test points in the center area allowed the illuminance to meet the regulations as shown in Fig. 10. The test points above the H–H line and in the outer regions also needed to move to the left and right to increase the illuminance at test points 2 and 3 above the H–H line, which was positioned in the dark area above the cutoff line. The required illuminance

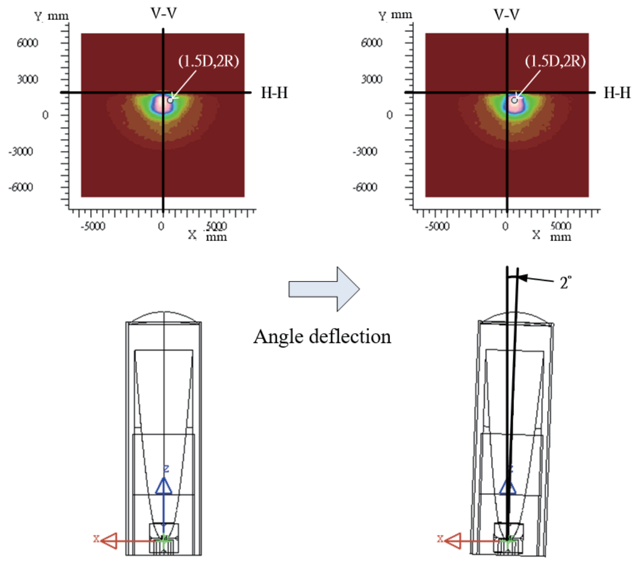


Fig. 9. (Color online) Angle adjustment of horizontal headlamp module.

Table 3
Comparison of illuminance resulting from superposed horizontal headlamp module.

No.	Position	Regular illuminance (lux)	Number of lights superimposed	
			1 set	2 sets
			Simulated illuminance (lux)	
11	0.6D-1.3R	≥29.86	18.34	31.75
12	0.86D-V	≥13.44	15.04	26.15
14	1.5D-2R	≥44.79	25.43	46.01

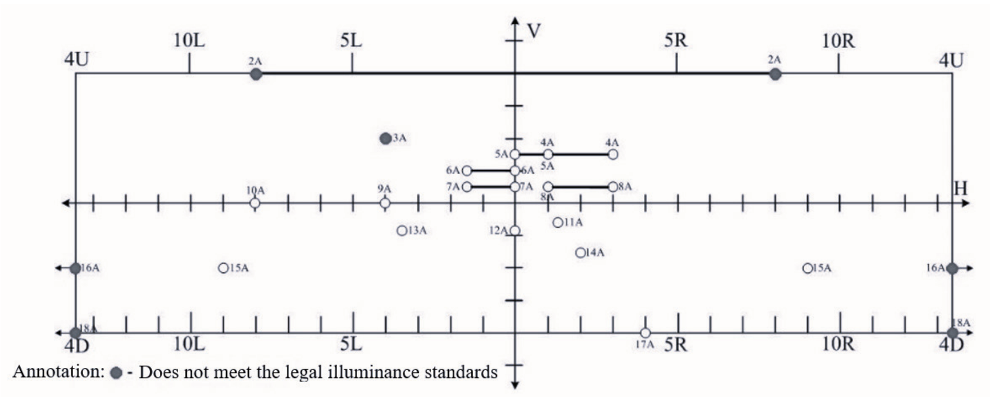


Fig. 10. Distribution of test points that do not meet illuminance standards.

was 0.19 lux or higher. Less light was required to meet regulations in the dark area. Thus, we superposed a third headlamp module with a horizontal floorboard. We used Visera 6363 as the LED light source with the same headlamp module with an asymmetric floorboard for Nichia-NVSW119A. Owing to the wide beam angle and high luminous flux, Visera 6363 creates a wider overall light pattern. We also reduced the curvature of the lens to produce a wider light pattern and distribution. The headlamp module with a horizontal floorboard was used to alter the light pattern and distribution so that scattered light made up for the required illuminance above the cutoff line. The configuration and simulation results from the superposition of the headlamp module are shown in Fig. 11.

4.3 Configuration of multi-module LED low-beam headlamp system

With the adjustments mentioned in the previous section, the illuminance of test points 16 and 18 in the outer regions still did not meet the regulations as shown in Fig. 12. Therefore, we rotated the headlamp module with an asymmetric floorboard and the superposed third headlamp module symmetrically around the centerline so that the resulting light increased the luminous intensity. Rotating the module by ±5° allowed enough light with higher illuminance at the test points to meet the regulations. Although the rotation of the module reduced the illuminance, the illuminance of the test points in the center area still satisfied the requirement of 44.79 lux. Thus, all test points met the requirements of the regulations (Table 4).

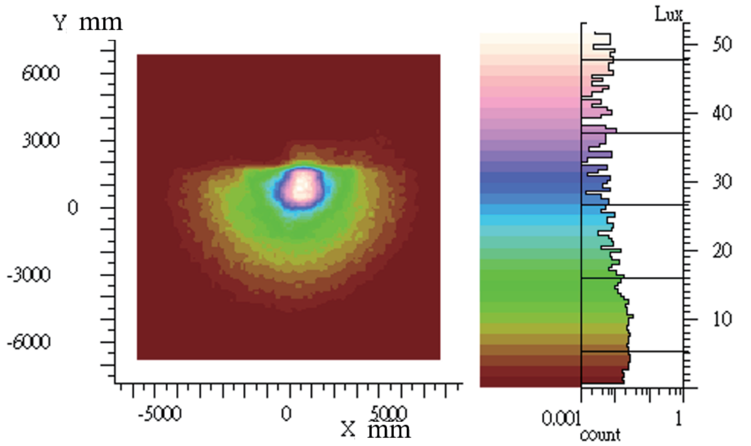


Fig. 11. (Color online) Configuration and simulation results resulting from superposition of third headlamp module.

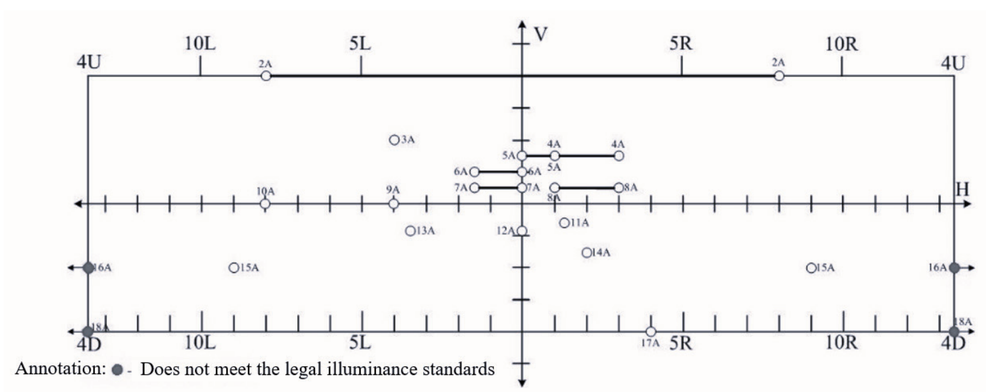


Fig. 12. Test points that do not meet illuminance standards.

Table 4
Comparison of illuminance in simulation and regulations.

Test point	Position	Illuminance (lux)	Rotated angle (°)			
			±2	±3	±4	±5
			Simulated illuminance (lux)			
1	10U-90U	≤0.37	0	0	0	0
2	4U-8L and 8R	≥0.19	0.53	0.40	0.24	0.33
3	2U-4L	≥0.40	0.96	0.70	1.13	0.88
4	1.5U-1R to 3R	≥0.6	1.58	0.76	0.79	0.77
5	1.5U-1R to R	≤4.18	1.09	1.32	1.03	1.22
6	1U-1.5L to L	≤2.09	2.08	1.44	1.76	1.48
7	0.5U-1.5L to L	≤2.99	2.88	2.36	2.77	2.21
8	0.5U-1R to 3R	1.49–8.06	9.86	9.59	7.71	6.92
9	H-4L	≥0.40	5.87	5.91	5.35	5.32
10	H-8L	≥0.19	3.16	3.15	3.54	3.92
11	0.6D-1.3R	≥29.86	35.39	34.22	32.97	31.99
12	0.86D-V	≥13.44	30.02	29.10	29.07	29.85
13	0.86D-3.5L	5.37–35.83	15.21	14.61	14.66	13.14
14	1.5D-2R	≥44.79	48.79	48.37	46.80	46.08
15	2D-9L and 9R	≥3.73	6.29	7.26	9.03	8.04
16	2D-15L and 15R	≥2.99	1.84	1.68	2.94	3.32
17	4D-4R	≤37.33	37.43	35.95	37.28	36.44
18	4D-20L and 20R	≥0.90	0.45	0.78	1.09	1.15

The LED low-beam headlamp system comprised one headlamp module with an asymmetric floorboard and three headlamp modules with a horizontal floorboard. The total wattage of the system was 16 W. The simulated illuminance and the configuration of the LED headlamp system are shown in Fig. 13. The two modules on top were rotated ±5°, and the two modules below were rotated 2°, enabling each set of light rays to reach the target points. The two horizontal headlamp modules below lighted the intense light area in the center. The headlamp module with an asymmetric floorboard at the top right showed the primary light pattern, whereas the headlamp module at the top left increased the luminous intensity at the outer edges of the standard light pattern. Defocusing and altering the curvature of the lens expanded the range of the light pattern. The overall dimension of the headlamp was 200 × 113 × 106 mm ($w \times h \times l$). The projected light pattern had cutoff lines at varying heights on the left and right, and the illuminance at the various test points met the requirements of FMVSS 108 for low-beam headlamps.

4.4 Measurement with multi-module LED low-beam headlamp system

On the basis of the design of the multi-module LED low-beam headlamp system, we created a prototype and measured the actual light pattern and illuminance. Then, we compared the result with the simulation results of Light Tools to verify the system efficiency in Table 5. The measurement was conducted at a distance shorter than 18.3 m using an illuminometer to measure the maximum illuminance at the center. We also shortened the distance between the reception plane and the headlamp in the Light Tools simulation to 4 m to compare the simulated illuminance with the measured value. The light pattern projected by the proposed system showed

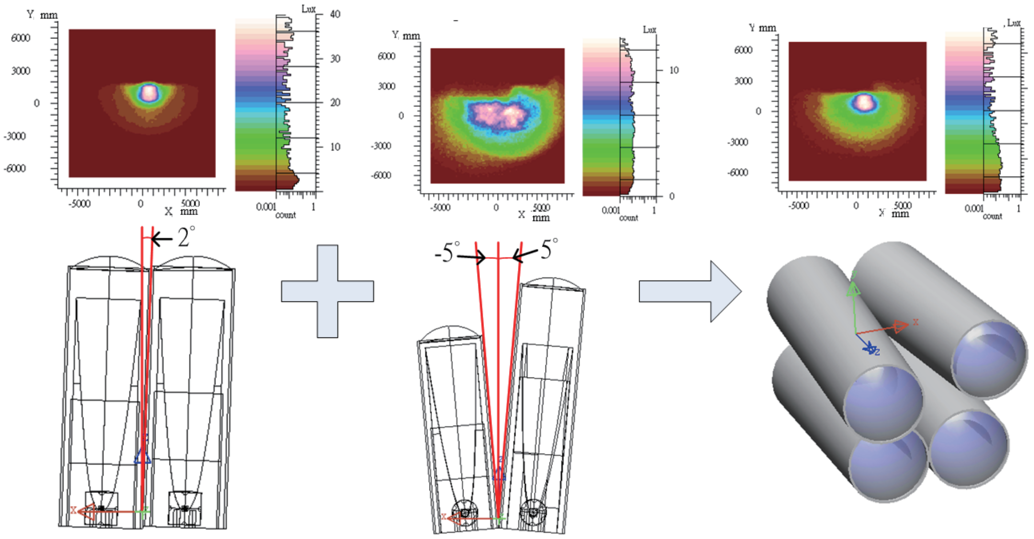
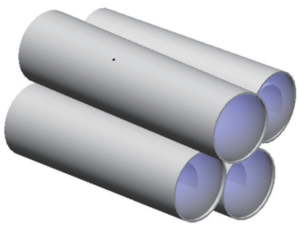
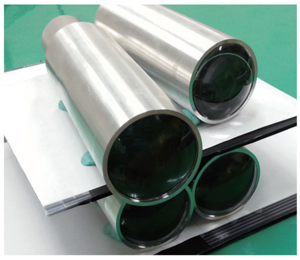
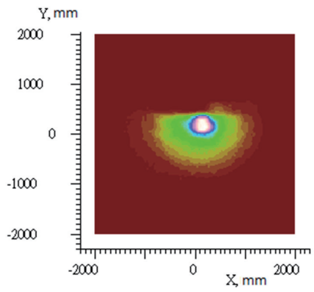


Fig. 13. (Color online) Configuration and simulated illuminance of LED low-beam headlamp system.

Table 5
(Color online) Comparison of actual and simulated values.

	Software simulation	Physical measurement
LED low-beam light system		
Spot pattern		
Measuring distance (m)	4	4
Maximum illumination (lux)	1071	700
Spot width (mm)	2600	2300

a mirror image of the simulated light pattern. The reception plane in the simulation faced the headlamp module so the projected light pattern was reversed from left to right compared with the actual light pattern. The light pattern projected by the system showed clear cutoff lines at varying heights on the left and right as required by the regulations, and the range of the light pattern also matched that of the simulated light pattern. The maximum illuminance measured from the system at 4 m was 700 lux, whereas that in the simulation was 1071 lux. The difference of 371 lux was caused by the following. First, during actual headlamp assembly processes, the assembly and rotation angle tolerances became extremely small. Thus, any offsets altered the light pattern or shifted the superposition, which resulted in energy loss. Headlamp components were made of polished aluminum materials that did not have a highly reflective electroplated surface, so the light reflection efficiency was lower than those with the electroplated surface.

5. Conclusions

We developed a multi-module LED low-beam headlamp system with improved energy efficiency and overall performance to replace the conventional light source of automotive headlamps. We constructed basic headlamp components and designed the developed system through simulation with Light Tools and various analyses and configurations. The developed system comprised one headlamp module with an asymmetric floorboard and three headlamp modules with a horizontal floorboard. To optimize the system performance, we superposed the light patterns of headlamp modules with an asymmetric floorboard and semicircle headlamp modules. We also rotated the modules to expand the range of the light pattern to improve the utilization efficiency of the system. Compared with conventional 55 W halogen low-beam headlamps, the multi-module LED low-beam headlamp system required only 16 W with 70% less energy, while still meeting the regulations in FMVSS 108. The shade component in conventional projector-type headlamp systems can be replaced with an asymmetric floorboard with ellipsoidal reflectors and aspheric lenses used in this study to achieve the left and right cutoffs of the standard light pattern. This design effectively reduced energy loss by 30%.

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