



Advances in automotive interior lighting concerning new LED approach and optical performance

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Abstract

Automotive interior lighting has to follow general trends in lighting and will therefore evolve toward hundreds and even thousands of RGB LEDs per car. Creating mood at day and night, pixelated sign-like information, and theater-like effects like welcome and goodbye messages are examples for outstanding user experience. Furthermore, safety features such as warnings and driving state are a must for autonomous cars. It requires new concepts for the whole interior lighting system to reach premium quality such as data rate (beyond today's bus standard for lighting), support for safety rules, compensation of temperature effects, daylight performance (including huge dimming range for night drive), uniformity in terms of luminance and color along the light guide, and mixing of red, green, and blue (RGB) with white. We report a new automotive RGB light-emitting diode (LED) system that fulfills the above requirements and saves effort as well as cost by calibration before integration. Extensive studies were performed for daylight threshold evaluation with subjects and methods for judging on uniformity for direct-lit RGB light guides based on the contrast sensitivity function and Gaussian fit of the LED luminance profile.

KEYWORDS

automotive, binning, contrast sensitivity function, daylight perception, human centric lighting, LED, light guide, lighting, uniformity

1 | INTRODUCTION

Lighting has evolved over 100 years from (white) illumination of streets and in rooms toward smart dynamic colored animations.¹ Examples are architectural lighting, “pixelated” roofs in cruise ships and aircrafts, and finally, yet importantly, red, green, and blue (RGB) lighting systems at homes, which can be also voice controlled. It is

obvious that these trends have a huge impact on todays and future car interiors.

Nowadays, the usage of ambient lighting increases comfort and orientation inside the vehicle during night drive, which can be almost seen as standard for premium cars. The upcoming next big trend in automotive interior lighting are 1,000 of RGB light-emitting diodes (LEDs)² providing orchestrated effects and living room feeling for

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autonomous and robot cars including daylight performance. That is an enormous step from only a few white LEDs and some RGB LEDs of today's cars. Figure 1 shows examples of high-end interior lighting. The raising number of LEDs enables the improvement of safety like "attention flashes" or visualization of status for manual or semiautomated driving. Therefore, new concepts in terms of electronics and quality of light are required. An example is the display-like characteristic of contour lights (direct-lit light guides) in terms of luminance, uniformity, color, and bright ambient light performance.

Large area "pixelated" lighting with daylight performance requires an optimized combination of optic technologies as well as dedicated electronics, hardware and software:

- High power RGB LEDs (daylight readable)
- Light guides for direct-lit backlight
- Efficient current drivers with high speed digital interfaces (in the range of Mbit/s)
- Dedicated control units capable of addressing hundreds of RGB LEDs in real time with high frame rates (>400 Hz)
- Software for designers to create efficiently the content to be displayed

As the awareness and "image" quality of pixelated lighting is rising, outstanding animations will be shown on

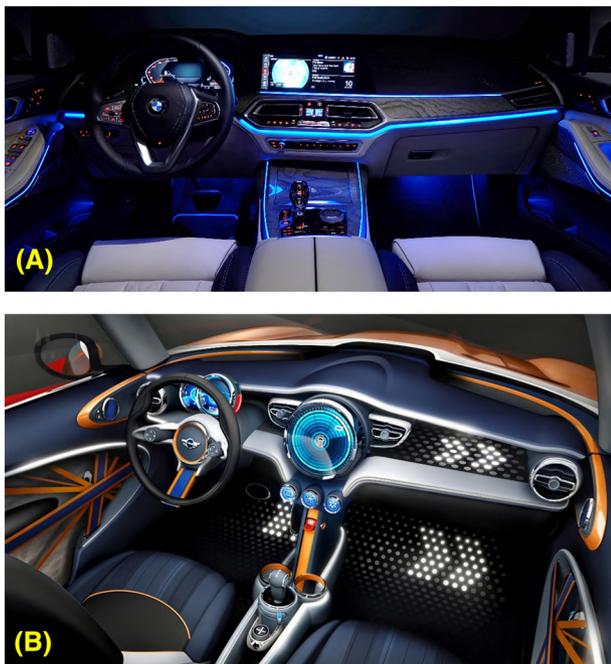


FIGURE 1 Top A: Today's high-end interior lighting with contour light (edge-lit light guide). Bottom B: Vision of interior lighting with direct-lit light guides and "pixel light" with daylight visibility (Sources: BMW Group, MINI)

display-like installations with a pixel pitch in the range of centimeters. An example for high optical requirements is the uniformity of both intensity and color, which have to be defined, fulfilled, and measured for series production. If those advanced lighting features should be implemented in cars, additional challenges arise like

- Temperature dependency of both intensity and color of RGB LEDs
- Long lifetime under harsh environmental conditions as replacement is costly
- Slim integration including direct-view (backlight) light guides
- Safety requirements like dimming at night and supervision of light output for the visualization of the autonomous mode status

Therefore, advanced interior lighting in cars has to be treated and optimized as a whole system. This paper focuses on challenges and solutions of several essential topics:

- Validation and performance of a new automotive RGB LED system with integrated driver, temperature compensation, calibration, and data connectivity in a single tiny package (housing)
- Perception of a RGB LED backlight structured surface under different illuminance conditions toward luminance levels evaluated by subjects for, for example, visualization of the autonomous mode below the windshield
- Adaptation of display uniformity contrast sensitivity function (CSF) to backlight pixelated light guides toward efficient measurement algorithms for end-of-line inspection
- Human centric lighting (HCL) by red, green, blue, and white (RGBW) LEDs for optimized control of color temperature from cool to warm white

2 | ADVANCED AUTOMOTIVE INTERIOR LIGHTING CONCEPT "ISELED"

Interior lighting today consists of light guides with a single edge-lit RGB LED as shown in Figure 2A. These systems are mostly controlled via the local interconnect network (LIN) bus, which is limited to a data rate of 20 kbit/s and 16 bus slaves.³ It is obvious that this data rate is too slow for addressing direct-lit systems (Figure 2B) with a large number of RGB LEDs to perform dynamic animations with large gray level resolution.

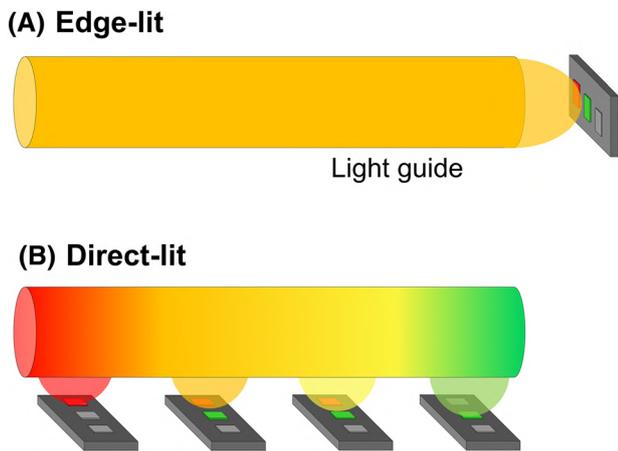


FIGURE 2 Top A: Static edge-lit system. Bottom B: Dynamic direct-lit system (comparable with direct LCD backlight)

Additional challenges of these “pixelated” (direct-lit) light guides are both luminance and color uniformity over the automotive temperature range (see below).

The ISELED concept⁴ provides an elegant solution for those problems. It is based on a controller chip developed by Inova Semiconductors, which is integrated together with RGB LEDs to a system in package (SIP), see Figure 3. These packages can easily be connected to a long daisy chain (two wire link), which is controlled via the customized and proprietary ISELED protocol. The RGB gray level data and the control data protocol run at a data rate of 2 Mbit/s. It can control up to 4,079 LEDs in one daisy chain and enables also safety functions such as readout of LED forward voltages for the status visualization of autonomous driving. The achievable repetition (frame) rate depends on the number of LEDs to be updated as every single LED can be individually addressed. About 200 ISELEDs can be serialized with a frame rate over 80 Hz when all RGB gray level data are updated every frame for dynamic animations.

FIGURE 3 ISELED RGB LED system block diagram capable of serializing up to 4,079 LEDs including calibration and temperature compensation

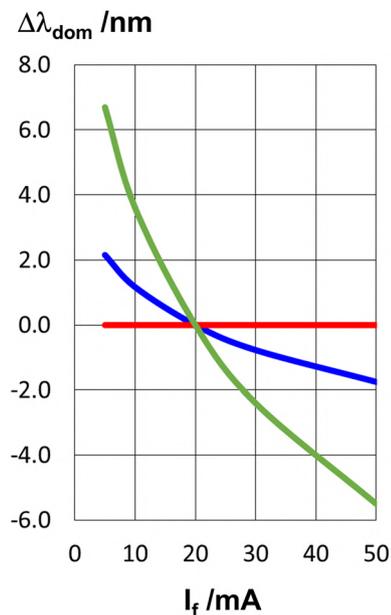
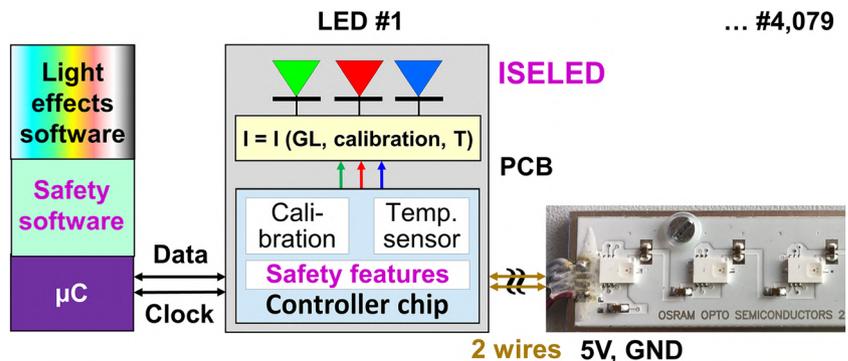


FIGURE 4 Typical RGB dominant wavelength shift versus LED forward current⁵; ± 2 nm is noticeable

In addition, the chip enables a high-precision calibration of RGB LEDs, which is performed by the LED manufacturer directly after package assembly. The calibration data are stored in an on-chip nonvolatile memory. The calibration process consists of two steps: dominant wavelength adjustment by individual LED currents (§ 2.1) and RGB intensity calibration for D65 white point (§ 2.2).

2.1 | Calibration of dominant wavelength

It is typical for monochrome color LEDs except for red that the dominant wavelength λ_{dom} is dependent on the forward current. This is particularly noticeable for green

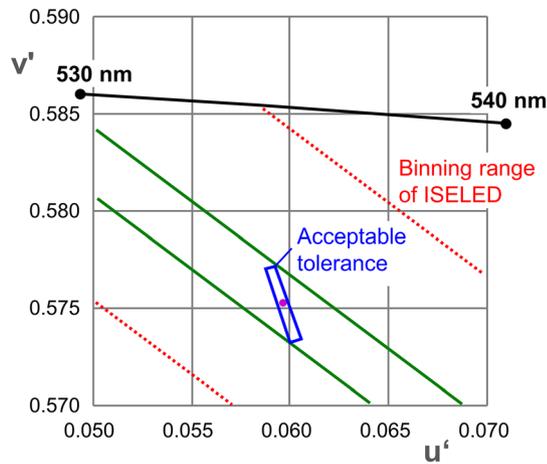


FIGURE 5 CIE 1976 UCS chart (excerpt) with typical binning range for green (dotted red line), ISELED calibration range (green line) and acceptable area (blue square)

LEDs. Their emitted peak and dominant wavelength can be shifted in the range from 5 to 50 mA up to 10 nm and up to 4 nm for blue, see Figure 4. This effect can be used for applying individual dominant wavelength variations $\Delta\lambda_{\text{dom}}$ of the blue and green LED to reduce binning effort. Red LEDs consist of a different material composition so that their dominant wavelength shows no dependency of the LED forward current.⁵ Therefore, there is no need for the controller chip for current trimming of the red channel.

The result of this first calibration step is shown in Figure 5 as an excerpt of the CIE 1976 UCS color space for green. The blue square visualizes the acceptable tolerance for green; the scaling of the scaling of both axes are chosen in a way that this area is clearly visible. This results in a center dominant wavelength of 528 nm with ± 3 nm tolerance (green line). Consequently, the maximum allowed green LED binning range for ISELED spans from 520 to 536 nm as ± 5 nm can be compensated for green (red dotted line); 520 to 536 nm is the typical wavelength range for standard automotive green LEDs. The practical wavelength tolerance is about half of these values as the intensity output of 5 mA is too low.

Human color perception depends on the actual color so that CIE 1976 UCS is chosen due to nearly constant relationship of coordinate differences and noticeable color differences compared with CIE 1931,⁶ which is mostly used in LED metrology. Figure 6 shows the gamut variations of typical RGB LEDs with three bins per green and blue color (white squares). By calibrating the dominant wavelength, these variations can be reduced to a minimum (see Figure 7) thus reducing

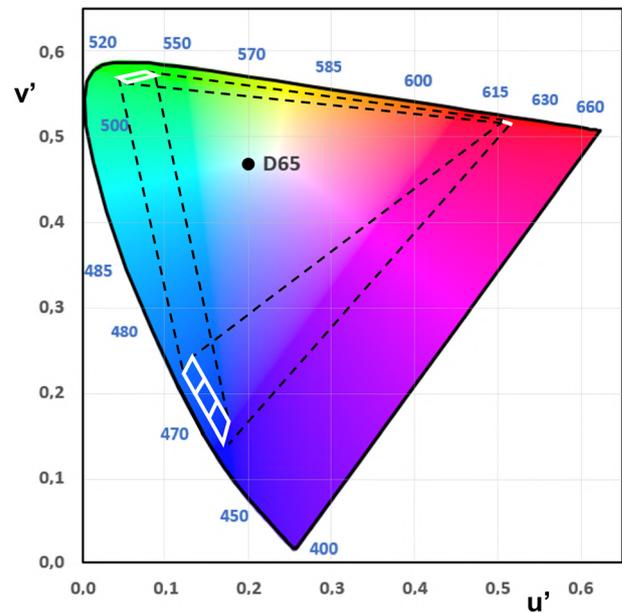


FIGURE 6 CIE 1976 UCS chart with typical RGB LED gamut variations by binnings of a RGB LED⁷

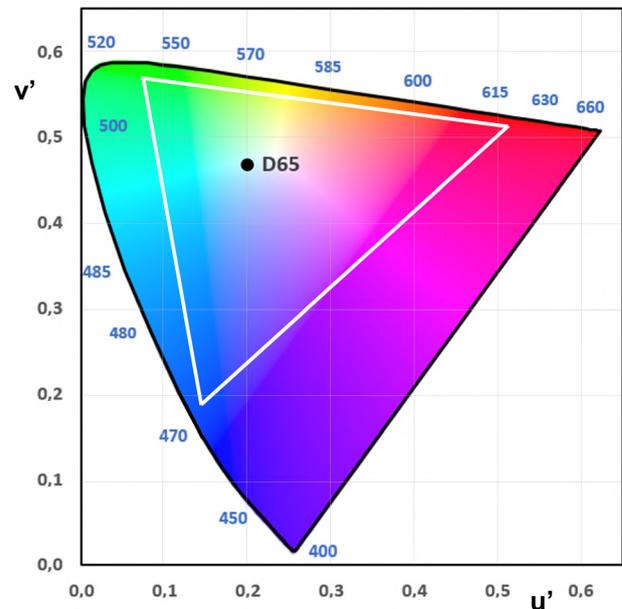


FIGURE 7 CIE 1976 UCS chart with calibrated ISELED gamut⁷ thus avoiding calibration at end-of-line inspection

software effort and memory for calibration data in the microcontroller.

2.2 | White point calibration and temperature compensation

In the second calibration step, the intensity (luminance) is adjusted via pulse width modulation (PWM) with a

12-bit resolution for R, G, and B individually. This enables a white point calibration (for instance, to D65) with an accuracy of one-step MacAdam ellipse. However, such a calibration would be only good for the temperature range during this calibration. Figure 8 shows the measured relative intensity of RGB LEDs versus the junction temperature T_j .⁸ In order to keep the calibrated white coordinate constant over the automotive temperature range of -40°C to 105°C , the intensity of mainly the red LED has to be compensated. On the one hand, red LEDs show significant changes in intensity, ranging from +40% to -60% relative to 25°C . Therefore, the controller chip has an integrated temperature sensor that measures continuously the temperature near the red LED and automatically adjusts its intensity. On the other hand,

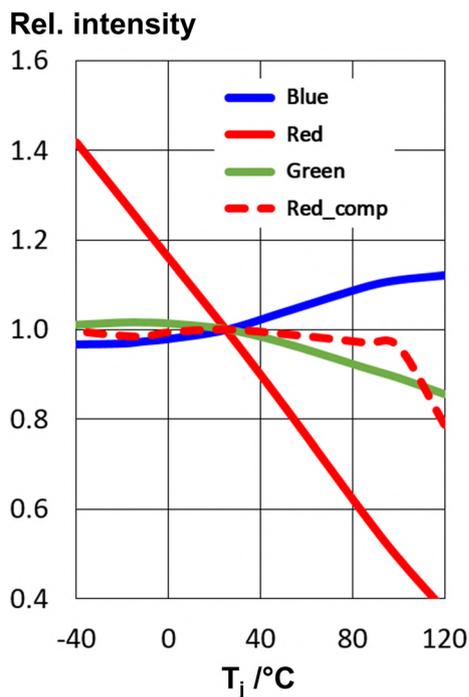


FIGURE 8 Typical RGB relative intensity versus junction temperature⁸; red is compensated for ISELED (dashed line)

green and blue LEDs only vary by about 10%. For this reason, the controller chip was developed without temperature compensation for green and blue for cost optimization. The shift of the white point at $+80^\circ\text{C}$ relative to 25°C due to opposite intensity behavior of green and blue results in $\Delta u' \approx -0.002$ and $\Delta v' \approx -0.009$. This equals about a one-step MacAdam ellipse (just notable difference [JND]) in u' -direction and four steps in v' and results in a nearly unnoticeable shift toward blue.

3 | PERCEPTION OF INTERIOR LIGHTING AT DAYLIGHT CONDITIONS

In case of visual communication using light, for example, in interior or exterior signage, the effectiveness of the signage requires optimal recognition. In cars, this must be ensured at different illuminance levels of the environment (night, dawn, cloudy sky, sunshine, etc.). The most essential and challenging topic is daylight and sunlight visibility. An example is pixelated warning indication as shown in Figure 9 left. Keeping the user-centered design process in mind,⁹ the optimal values for best recognition should not only be calculated but rather evaluated by a user study. The test setup (see Figure 9 right) was based on the different surface characteristics for interior and exterior signage. Here, we report as example on a structured surface with different reflection properties, which is backlit by ISELED LEDs.

Figure 10 provides an overview of the test setup in terms of optics: An adjustable large area light source was set to three different illuminance levels (1,000, 2,700, and 6,000 lx), which represent typical values in a vehicle (with roof) and hit the structured surface at an angle of 60° . An illuminance of, for example, 50,000 lx would require cooling of the participants due to radiation heating and a LED video wall as monitor with $\sim 5,000$ cd/m. This might be part of a future study. The measured luminance values

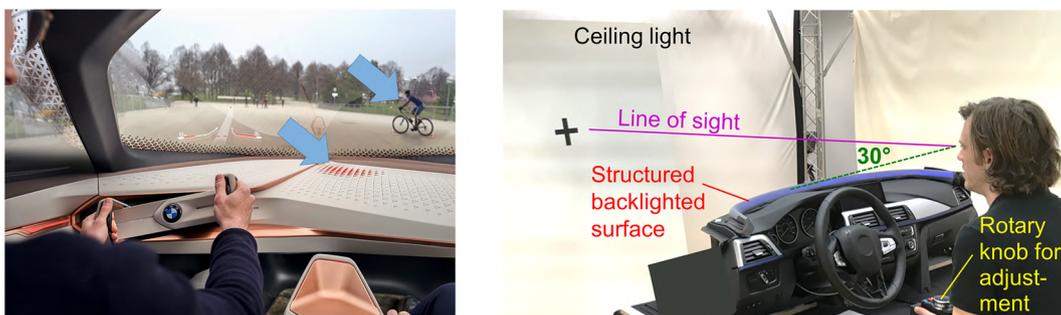


FIGURE 9 Left: Design vision of dashboard red warning light (blue arrow, source: BMW Group). Right: Test setup including the examined surface (illuminated here in blue) and a rotary knob in the hand of the participant for adjusting the luminance of the LED backlight

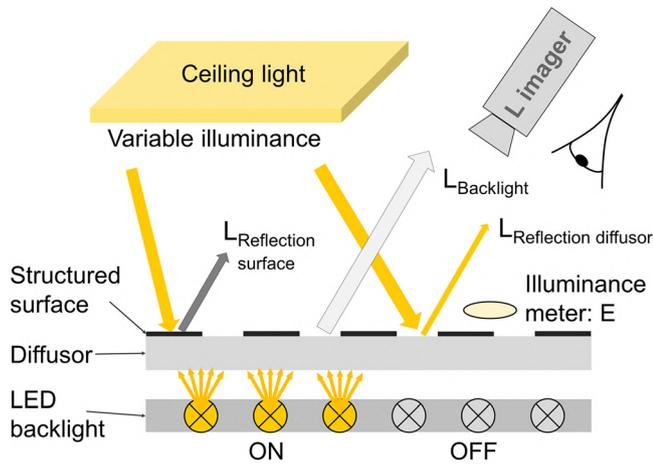


FIGURE 10 Test setup of structured surface with both variable LED backlight luminance (adjustable by subjects) and illuminance E by the ceiling light source (1,000, 2,700, and 6,000 lx used)

(acquired by a luminance imager) of the structured surface (front material and diffuser) with backlight OFF from a driver's perspective were 20 cd/m^2 for 1,000 lx (illuminance E) and 120 cd/m^2 at 6,000 lx, respectively. The structured surface has mostly diffuse characteristics so that the diffuse reflection coefficient r can be calculated from these measurements via $L_{\text{diffuse}} = r E / \pi$. This results in $r = 0.063$, which corresponds to the visual impression in Figure 9 with backlight (here, blue) switched off.

The user focused horizontally on a wall with a large display (at the place of the cross in Figure 9) to look at. The surface under evaluation was 30° below the gaze to the display in a distance of 70–80 cm. The perceived luminance was the sum of the illuminance (measured as luminance, see above) reflected from the structured surface and diffuser plus the luminance emitted by the backlight (direct-lit):

$$L = L_{\text{Reflection surface}} + L_{\text{Reflection diffuser}} + L_{\text{Backlight}} \quad (1)$$

It is obvious, that, for example, the threshold luminance for the perception of the LED backlight must be larger than the total reflected luminance from the surface. To determine this threshold by subjects was one of the goals of our evaluation.

The user study focused mainly evaluating the value for a “pleasant” luminance (B) as a function of different illuminance levels. However, two more parameters were added to validate the data: the luminance perception threshold (A) and the luminance that was labeled as “annoying” (C, too bright). In summary, the aim of the study is to obtain a user-based luminance range in relation to the illuminance level. Thirty-seven people participated in the study, more than 85% of them were older than 40 years, all with normal or normalized vision and without color blindness. Each participant adjusted

individually the backlight luminance by a rotary knob. Therefore, we were able to gather the important “self-reported data” without any bias of the test supervisor.¹⁰ The order of the setting was always the same (A → C → B: threshold → annoying → pleasant), while the order of illuminance by the ceiling varied for the subjects. They adjusted the luminance of the LED backlight in levels from 0 to 255 by a control dial with no end stops.

At the start of the data analysis, the data sets had to be verified for integrity. The recorded values of the individual LED backlight intensity settings are supposed to fulfill three conditions to be taken into account for final data analysis:

- 1 $A < B < C$ for each illuminance level: The values of each participant need to increase from A to C for each of the three illuminance levels. The initial perception threshold cannot be higher than the value for pleasant, while the level of annoying cannot be lower than the value for pleasant, since it is assumed, that the disturbance increases with the level of luminance.
- 2 $A (E = 1,000 \text{ lx}) < A (2,700 \text{ lx}) < A (6,000 \text{ lx})$: The recorded perception threshold values of a single participant must be higher at brighter illuminance E .
- 3 Preferred $L_{A,B,C} (E) > L_{\text{Reflection surface} + \text{diffuser}} (E)$: The preferred luminance values for the different categories need to be brighter than the reflected luminance of the structured surface including diffuser depending on the different illuminance levels.

Values mismatching those requirements were removed: Seven single data set values mismatched the first two conditions, and no data set showed a mismatch for the third condition.

The average luminance for the LED backlight results based on the users' preferences are summarized in Figure 11. The values are normalized to the smallest value, the perception threshold at 1,000 lx. At this threshold, the backlight luminance is about 50% higher as the reflected luminance. For the pleasant and the annoying

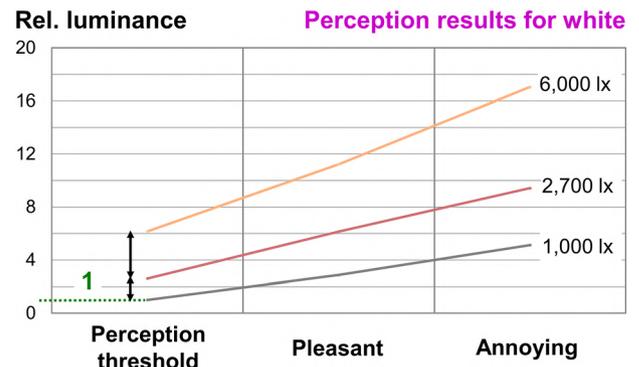


FIGURE 11 Average results of the user study in dependence of the different illuminance conditions

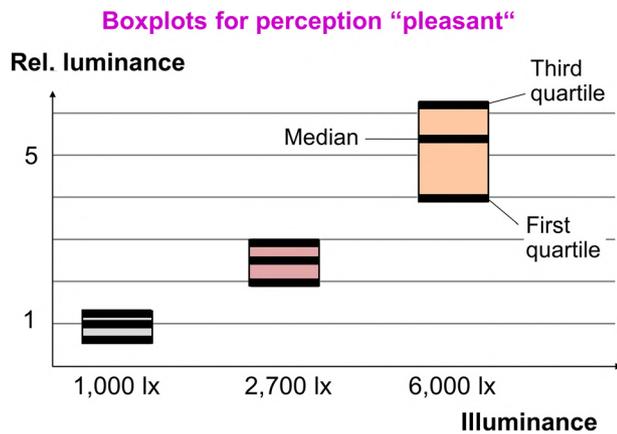


FIGURE 12 Boxplots for perception level "pleasant," presenting ratio of median, first and third quartile: The variance is rising with the illuminance level

perception for the backlight luminance, this ratio is larger. The luminance differences for the backlight between 1,000 and 2,700 lx is smaller than between 2,700 and 6,000 lx, which is visualized by two black arrows. It is noticeable, that this relation is more pronounced for the small illuminance than for the greatest illuminance condition that was examined (6,000 lx). Since the collected values are based on subjective user preferences, variance in the data is common. However, examining the variance could provide further insights.

Figure 12 presents boxplots for the pleasant value in dependence of the three levels of illuminance under test: The variance is growing for greater illuminance, and there are clear outliers upward. That means, the brighter the environment, the more the customer preferences spread. In consequence, the backlight luminance for "pleasant" should be adjustable by the user of a car.

4 | UNIFORMITY CHALLENGES AND EVALUATION METHOD OF LIGHT GUIDES

An essential topic in premium interior lighting is the perception of a uniform light output. Especially during night

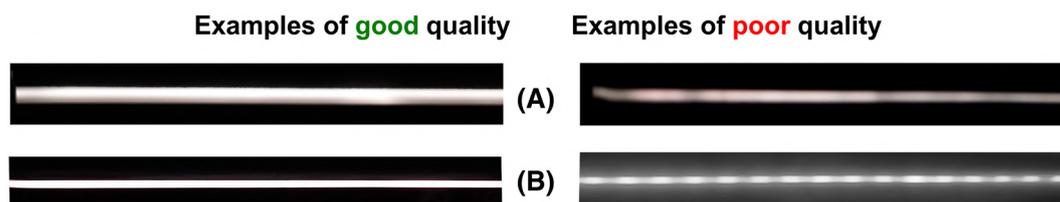


FIGURE 13 Examples of light guides with good (left) and poor (right) uniformity: (A) edge-lit, (B) direct-lit (definition, see Figure 2). The degradations of the uniformities on the right are clearly noticeable for even untrained subjects

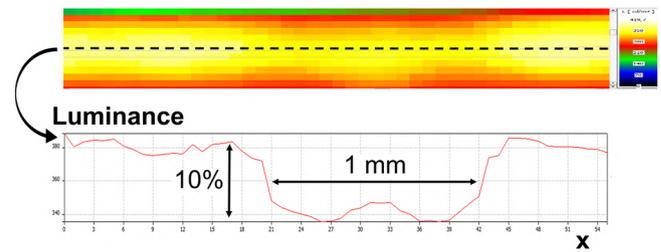


FIGURE 14 Detail of luminance acquisition by imager: Luminance as false color (top) and line profile measured in the vertical center (bottom). Such nonuniformity is typical for light guides but hardly visible. These effects "confuse" uniformity algorithms

drive, the eye is very sensitive to luminance (intensity) and color variations along a light guide or pixelated signs. Examples of good and poor quality are visualized in Figure 13; the criteria for evaluations is that potential nonuniformity cannot be noticed by observers: The picture "A" shows camera images of edge-lit light guides, "B" of the direct-light type (definitions, see Figure 2). The "good" examples show a highly constant intensity along the light guide, even for direct-lit with 10 LEDs (none of them is noticeable by a potential horizontal modulation of the intensity). Opposite to that, the "poor" examples show intensity inhomogeneity: A strong drop can be observed on the left side for the edge-lit light guide (picture "A"), and the intensity varies horizontally. Every single LED of the direct-lit light guide is noticeable in image "B." Inexperienced subjects easily identified the shown nonuniformities for edge-lit and direct-lit light guides. Finding appropriate methods, which can be used in both evaluation phase and end-of-line test for series production, to measure and judge on uniformity (also called MURA¹¹) is challenging and the focus of this section.

Figure 14 shows an excerpt of a light guide luminance measurement: The reduction in luminance is about 10% for 1 mm with relative steep edges. Today's premium quality requirements limit the luminance deviation to $\pm 5\%$ (10%) because of those measurement difficulties. Other issues for algorithms are caused by dark dots, which are not noticeable. From the viewpoint of Weber's law (threshold $\Delta L/L = 1\%$) and display uniformity

methods (see e.g., SID International Committee for Display Metrology¹²) such a degradation should be clearly noticeable. Opposite to that, these effects are visually judged as “not or hardly noticeable” during evaluation or final visual inspection of light guides in series production. Our work aims to find optimized methods and algorithms that are robust to “invisible” inhomogeneity of light guide and reflect vision thresholds.

4.1 | Contrast Sensitivity Function (CSF)

Today's measurement judgements base on Weber's law with some experimental tolerances. This is in total not effective in terms of “acceptance” at end-of-line test of poor quality and vice versa. The reason is that Weber's law refers to neighboring boxes (step-like luminance variation). Opposite to that, the CSF (e.g., Campbell & Robson and Watson & Ahumada^{13,14}) that bases on smooth sine wave variations is better suitable for light guides; CSF is also evaluated for black/white squares. CSF was therefore used here as basis for further calculations, simulations, and validation toward an improved test method.

The typical observer distance for automotive interior lighting range from 50 to 150 cm, which equals about 0.4 cycles per degree (cpd) as reasonable mean value. The CSF value does not strongly vary for luminance values from night (3 cd/m²) to daylight (1,500 cd/m²). This results in a CSF threshold of about 40 for 500 cd/m² and sine wave conditions,¹³ which equals a luminance variation of $\pm 5\%$. It is essential that such thresholds are only noticed under ideal conditions, the motivation for us to evaluate “acceptable” thresholds. Figure 15 shows the results of applying CSF (blue line) to automotive interior lighting conditions. The relative peak-to-peak luminance difference (amplitude) of the sine waves is plotted as red

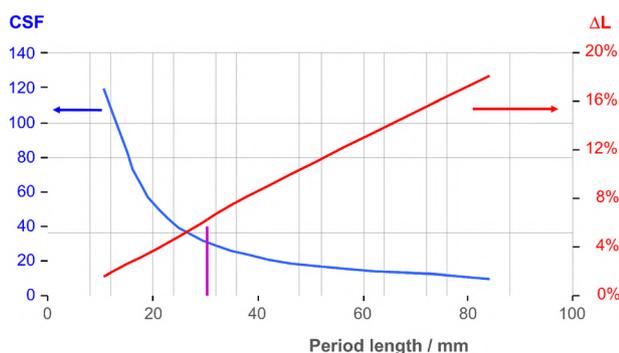


FIGURE 15 Contrast sensitivity function (CSF, blue line) and relative luminance difference (red line) depend on the period length; this corresponds here mostly to the distance between neighboring LEDs (example: 30 mm, magenta line)

line. The luminance difference is more practical in terms of measurement results (distance between LEDs is fixed, here, 30 mm; see following figures).

4.2 | Uniformity measurements versus CSF

We performed many measurements and evaluations to judge on modulations of the luminance and the corresponding perceived uniformity or nonuniformity. Light guides (see Figure 2B) with 16 calibrated ISELED LEDs were used and addressed by a microcontroller using software programmed in C. The luminance profiles were measured by a TechnoTeam LMK 5¹⁵ luminance and color imager. All measurement results shown here are an extraction of a subset of LEDs (mostly five) as the uniformity of the LEDs, and the quality of the light guide was so high that there is no significant influence on the results compared with 16 LEDs. Figure 16 shows two examples of fundamental measurements and settings: All LEDs have the same RGB gray level (white, RGB > 0) for the blue line while every second LED is switched off (RGB = 0) for the green line. The peak luminance was about 70 cd/m², and the peak-to-peak luminance difference (magenta, blue line) of 5 cd/m² was hardly noticeable (see Figure 15).

Several relevant effects are easy to identify from Figure 16:

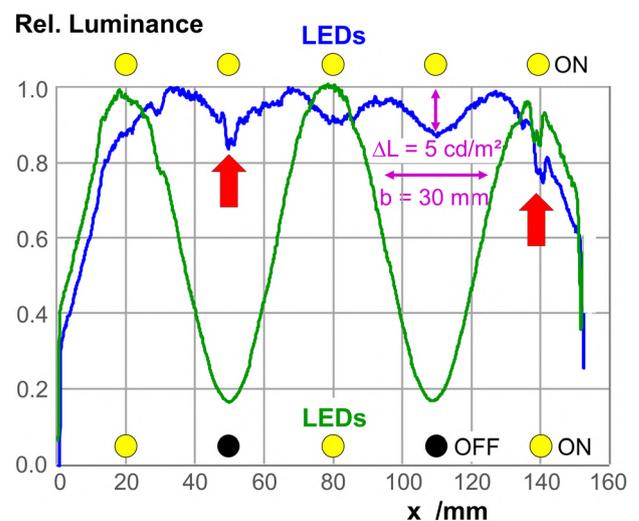


FIGURE 16 Measurement examples of five LEDs (distance 30 mm each): All ON (blue line) and ON/OFF (green line). The acquired waveforms are noisy, and the red arrows indicate luminance drops, which are hardly noticeable (see Figure 14). Both effects limit significantly the application of simple algorithms for uniformity

- The luminance profiles are somewhat “noisy” with luminance drops (read arrows, see also Figure 14). These effects are very difficult to suppress in algorithms for CSF judgments. If the false alarm rate should be not too high, noticeable nonuniformity is likely to pass the test.
- The luminance drops at the edge of the light guide (blue curve on the left side for 0 to 20 mm with all LEDs ON) are noticeably and can be partially compensated at the edges by increasing the relative luminance of LEDs or by a smaller LED pitch (distance).
- It appears at first look for the blue line that only four LEDs are on (same gray level) due to the “edge drop” effect. Alternating LEDs by “ON” and “OFF” (green line) demonstrates clearly that there are five LEDs.
- The luminance of every LED spread to its neighbors (green line) at a percentage of about 8%. This depends strongly on the diffuse characteristics of the light guide and the angular emission characteristics of the LEDs.
- Furthermore, the luminance curve of a single LED has a Gaussian shape (e.g., LED at 80 mm). This is used for fitting Gaussian functions by the parameters maximum intensity and full width at half maximum (FWHM). Using this, we are able to judge on uniformity by fits (see below) without influence of “noise” and drops in luminance (see Figure 16). For light guides with only small variations of the diffuse properties, all FWHM values are very similar, so only FWHM has to be fitted for the luminance profile of a single LED. Therefore, just the maximum has to be extracted from the luminance profile for every LED.

In order to verify CSF thresholds by subjects, we forced “nonuniformity” by different monochrome gray levels of neighboring LEDs like shown in Figure 17 for relative high luminance differences of the LED located at 110 mm. These differences were clearly noticeable

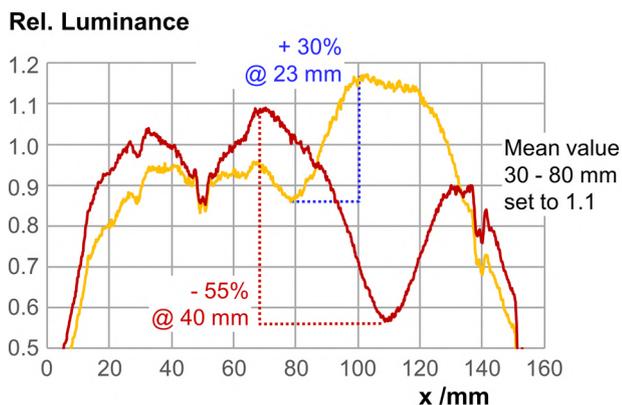


FIGURE 17 Large luminance differences set by different gray levels for the LEDs. This is used for evaluation of CSF

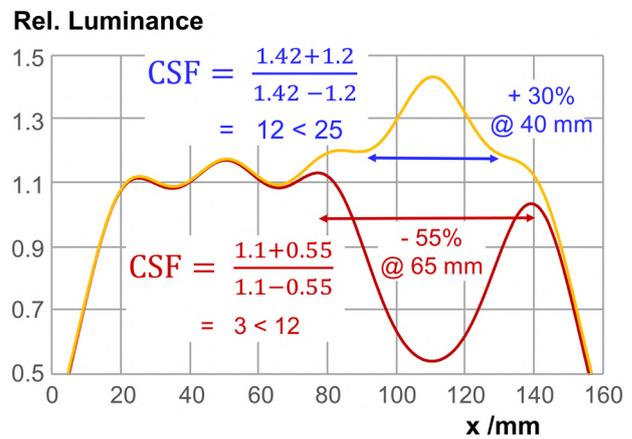


FIGURE 18 Simulations of the measurements shown in Figure 17 by Gaussian fits

however show as well that the period of the sine wave-like modulations is not constant, and therefore, the CSF threshold value is not constant (see Figure 15) for such profiles. Figure 18 shows the result of Gaussian fits of Figure 17. The relevant luminance modulations were close to the measurements. It is as well shown (see equations and values as insets) that the “overshoot” (yellow line) of one LED at 110 mm of about 30% results in a value for the corresponding CSF of 25, which is about twice the threshold. This variation was judged as less noticeable as the “breakdown” of 55% for the red line with a CSF value of about 25% of the threshold (here, 12). Many more measurements and evaluations were performed resulting in an acceptable threshold for CSF of about 10 instead of 30 (under ideal conditions) for 30-mm distance of the LEDs and 70-cm observer distance (see Figure 15).

4.3 | Uniformity evaluation approach

For developing advanced methods for uniformity validation, we used direct-lit light guides with 30-mm LED pitch (see Figure 2B), which is a reasonable compromise between spatial resolution and perceived value for dynamic color effects. We improved the uniformity tolerance values by a four-stage approach:

- 1 Visual simulations on monitors of PCs (see excerpts as insets in Figure 19) are easy to program and provide a more in-depth understanding of luminance (gray level) variations with the parameter distance (corresponds to cpd), absolute value, and slope (maximum–minimum luminance divided by their distance) rather than “fixed” light guides. The goal was to evaluate CSF thresholds more easily than setting individual RGB gray levels by a microcontroller.

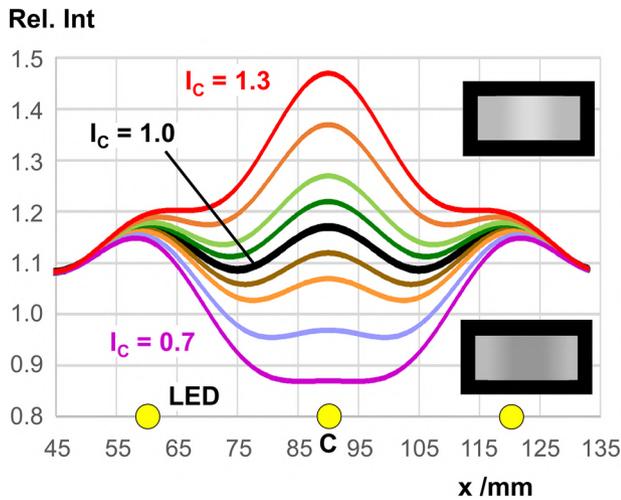


FIGURE 19 Superposition of Gaussian fit of single LED intensity for light guides with 30-mm LED pitch. The intensity levels of the center LED “C” (90 mm) were varied from 0.7 to 1.3. The intensity of the LEDs at 60 and 120 mm is set to 1.0. The visual insets show effects for 0.7 and 1.3

- 2 Measurements on light guides of luminance profile (and color, not described here) over distance with individual variations of gray levels of (neighboring) LEDs and visual judgment and rating by subjects on the basis of the monitor tests (see 1.).
- 3 Extracting and fitting of luminance profiles by Gaussian function (most suitable fit function, easy to parameterize by FWHM).
- 4 Prediction of noticeability and comparison with evaluations toward a specification for acceptable tolerances.

Figure 19 shows an example of simulations with Gaussian functions extracted from measurements. The LEDs are located at 60, 90, and 120 mm (yellow circles, excerpt of many neighboring LEDs). The intensity of the left and right LED was constant (relative value 1.0). The gray level and therefore the luminance (intensity) of the center LED “C” was varied from 70% to 130% (0.7, 0.8, 0.9, 0.95, 1.0, 1.05, 1.1, 1.2, and 1.3). It is clearly visible that neighboring LEDs influence “each other”: About 10% of the intensity at the center spread to the center of the neighboring LEDs (maximum of 1.17, black curve). This leads to a sine wave-like (basis of CSF) modulation of about $\pm 4\%$ (period 30 mm), which was not noticed by any subject and is slightly below the CSF threshold.

This “crosstalk” helps to reduce the effect of slightly different intensities of neighboring LEDs. A CSF of 20 ($\pm 10\%$ intensity variation) was the upper threshold for expert judgements. In terms of acceptable performance, a CSF of 10 is proposed as reasonable threshold

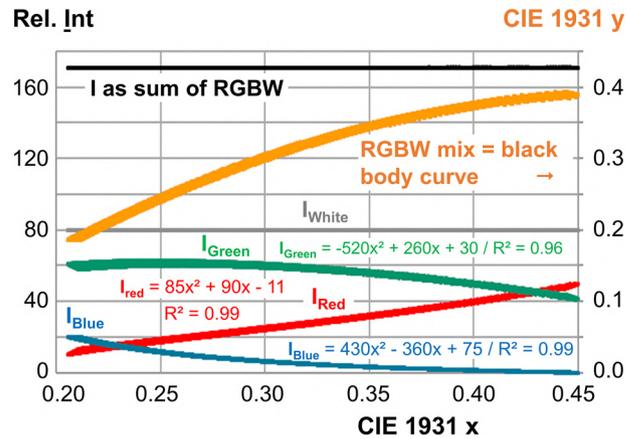


FIGURE 20 Enabling human centric lighting by RGBW LEDs at constant luminance level along the black body curve. The RGB dependency of the individual intensity from the x -coordinate can only be achieved by simulations. The implementation of the fit functions into software of a microcontroller is easy

allowing $\pm 20\%$ variations (modulations) for luminance profiles with smooth slope and 30-mm LED pitch for 70-cm observer distance. An example is “C 0.8” (light blue curve): A relative intensity difference of 0.2 (from 1.15 at 60 mm and 0.96 at 80 mm) spreads over 20 mm (half period length, instead of 15 mm), so CSF is smaller than for 15 mm. Our findings correspond to evaluations of mixing zone evaluations of edge LED backlights of LCDs by Hu et al.¹⁶ Vision is significantly less sensitive for color variations,¹⁷ which allows relying on white luminance values for final inspection of light guides equipped with precalibrated and compensated ISELED RGB LEDs.

5 | HUMAN CENTRIC LIGHTING (HCL) BY ADJUSTING RGBW LEDs

Another thought after feature in interior lighting is HCL, for example, as reading or search light. Today’s approach for premium vehicles is mixing of cool and warm white LEDs. However, full color performance of such lights will provide additional benefits like flashing warnings in red. The first step toward a RGBW LED system is to proof the black body curve capability for HCL. This is basically possible but mathematical not solvable for RGBW gray level values.

Therefore, “brute force” simulations using LED data, tristimulus calculations¹⁸ and transformation to CIE 1931 (or other CIE spaces) were made. A typical result is plotted in Figure 20: The resulting intensity is here kept constant over the resulting black body curve (orange line, CIE 1931 y -axis). For easy implementation, the white

LED (gray line) is kept constant as well. The RGB intensity curves depend on the CIE 1931 x -coordinate (corresponds to color temperature on the black body curve) and can be fitted with lowest deviations (coefficient of determination: $R^2 = 0.99$ or 0.96) by a second order polynomial regression. This enables a simple microcontroller program to provide HCL using RGBW LEDs at constant intensity. The absolute intensity can be easily adjusted by PWM dimming.

6 | SUMMARY

We have successfully developed, integrated, and evaluated major topics for advanced automotive interior lighting with “pixelated” direct-lit light guides with daylight performance:

- ISELED system: This advanced approach with integrated “intelligence” was successfully evaluated for several key features: The temperature compensation for red intensity (significantly larger temperature dependency than for green and blue LEDs) works well including the temperature stability of the specified white point D65. The calibration of the dominant wavelength by LED-specific currents (height of PWM pulse and adjusted duty cycle for intensity) shows promising results thus reducing the effort (including cost) for binning.
- Direct-lit light guides with ISELEDs were optically and electrically evaluated for applications in automotive interior lighting with very promising results.
- The perception of daylight readable structured surfaces, which are backlit via a diffusor by LEDs on the top of the dashboard, is strongly influenced by the level of illuminance. We performed intensive tests with subjects for elaborating the most suitable luminance level for a “pleasant” perception for the three most relevant illuminance levels; “threshold” and “annoying” (dazzling) luminance values were as well recorded. The larger the illuminance, the larger the variation of the subjects for “pleasant” luminance. In consequence, the luminance level should be individually adjustable in series production cars by the user (besides the compulsory automatic dimming).
- “Pixelated” direct-lit light guides are more sensitive to luminance (LED intensity) variations than edge-lit ones. Enhanced uniformity requirements and evaluation methods for direct-lit light guides were successfully introduced and evaluated. The basis is the CSF, which was adapted from displays.
- HCL by adjusting RGBW LEDs for black body curve provides mobile living room feeling and enables, for

example, warnings as well. We engineered an easy-to-implement algorithm for the RGB LED intensity along the black body curve, as the coordinate of the white LED is constant (as selected).

Our findings help to implement advanced interior lighting into cars more efficiently in terms of effort (hardware, software, calibration, compensation, and integration) and cost.

GLOSSARY

ASIL	Automotive Safety Integrity Level, see e.g., ISO 26262
Bin, binning	Selection of LEDs with very narrow tolerances in, e.g., intensity at given current, color coordinate, and forward voltage. Binning has a similar meaning like bin but is used as well as verb.
CAN	Controller area network, the most widespread automotive data bus
CIE yyyy	Commission International de l'Eclairage (on illumination) publishes color space standards like CIE 1931; yyyy is the year of standardization. CIE 1976 UCS (uniform chromoaticity scale) is recommended for displays and lighting evaluations.
CSF	Contrast sensitivity function; most prominent example is from Campbell-Robson. ¹³
Daisy chain	Method for digital systems, which are connected in a serial manner.
Dominant wavelength	The dominant wavelength λ_{dom} of LEDs is defined as intersection with CIE horseshoe-like curves of the line through white point and color coordinate of the LED.
D65	Abbreviation for daylight white with 6,500 K correlated color temperature
FWHM	Full width at half maximum refers to the width of a (spectral) peak at half of its maximum.
ISELED	Abbreviation of “Intelligent Smart Embedded LED” for an advanced automotive interior lighting RGB LED system. The corresponding alliance has about 40 members (2020) (information, see http://iseled.com).
JND	Just notable difference: 1 JND is the minimum useful discrimination threshold. Further details see “MacAdam.”
Junction temperature	The junction temperature T_j is the temperature of the light-emitting

	semiconductor. Its value influences the optical properties. T_j is calculated via the solder point temperature and thermal resistance.
LED	Abbreviation for light-emitting diode
LIN	Local interconnect network, a serial bus (up to 20 kbit/s) with less performance than CAN (up to 1 Mbit/s, see "CAN").
MacAdam (ellipses)	Describe how color coordinate differences are noticeable by human vision. X steps refers to x just notable differences (JND).
MURA	A Japanese word for nonuniformity or nonhomogeneity, which mostly cannot be specified in a traditional way, e.g., by using mathematics.
PWM	Pulse width modulation; the usual driving scheme for LEDs with constant current. PWM consist of pulses of different length but identical repetition rate (duty cycle). The ON pulse length represents the set intensity.
RGB(W)	A red, green, and blue (white) LED, typically integrated in a single package.
T_j	See "junction temperature."
Tristimulus	Fundamental color coordinates which are usually transformed to CIE such as CIE 1976 UCS.
Weber's law	Similar to MacAdam and JNDs (see above). It defines a luminance threshold $\Delta L/L = 1\%$ for minimum discrimination.
λ_{dom}	See "dominant wavelength"

ACKNOWLEDGMENTS

The authors thank the interior lighting team from BMW, Inova Semiconductor (both Munich), and the ISELED Alliance (<http://iseled.com/>) for outstanding support of this work.

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Karlheinz Blankenbach graduated in physics at the University of Ulm, Germany, where he also received his PhD in 1988. Until 1995, he was with AEG-MIS, Germany, developing display electronics, LCDs, and software. A highlight was a 3D helmet mounted monitor for stereo endoscopy founded by

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How to cite this article: Blankenbach K, Hertlein F, Hoffmann S. Advances in automotive interior lighting concerning new LED approach and optical performance. *J Soc Inf Display*. 2020; 1–13. <https://doi.org/10.1002/jsid.887>