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Measurement of colour coordinates of LEDs used in the automotive exterior lighting

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ABSTRACT

Article deals with dichromatic white light-emitting diode (LED's) color coordinates used in automotive exterior lighting. This article also describes basic white automotive LED functionality and basic physical processes that create white light of these LEDs. It focuses on measuring color coordinates of white automotive LEDs with different temperature of LED and how the LED's color depends on LED's temperature. The article is comparing very important datasheet information of LED producers and values measured in the laboratory at university. The article contains statistical results of measurements and graphical representation of measured values and declared color bins which are very important for producers of headlamps for automotive companies.

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1. INTRODUCTION

Color coordinates of LED are important when adjusting color temperature of various light sources in car head or rear lamps. New trends in automotive lighting combine various light sources as halogen bulbs, high-intensity discharge (HID, also known as xenon lights), and LEDs. Each of these sources has different color and each customer has different requirements on color matching of headlamp functions. Usually, color of the white light is expressed as color temperature. The temperature of an ideal black body radiator that radiates light is meant by the color temperature of a light source. For illustration, the color temperature of halogen bulbs is appx. 3500 K, the color temperature of HID is usually 4500 K and the color temperature of LED is changing from 3000 K to 6000 K, depending on producers and a LED type. Generally, bluish LEDs (from 4500 K to 6000 K) are usually chosen for car white lighting functions [1]. When more types of light sources are used in the car's headlamp, e.g. halogen bulb for high beam, HID for low beam and LED for position and day time running lights (DRL) functions, the color of light sources is becoming a very important design feature. It is also possible to measure the dominant wavelength, peak wavelength, correlated color temperature (CTT) or the color rendering index (CRI) [2, 3], as well as spectral characteristics of the LED sources which were measured with the help of semi-empirical model based on the solid-state theory depending on the temperature. In this article, the composite author also dealt with an idea of temperature influences on colorimetric changes (chromaticity) [4]. Generally, the white LEDs for indoor illumination and similar applications are described by the parameters CCT or CRI [2]. White LEDs are usually described by chromaticity coordinates [5] which is only the way how to characterize different white light sources. Measuring and unification of white light emitted by the source is not only the task for the automotive industry. In general, it is also the task for illumination applications [6]. In the past, the temperature efficiency practical examination of the white LED Luxeon REBEL under different temperature conditions were carried out. In the past, the temperature efficiency practical examination of the white LED Luxeon REBEL under different temperature conditions were carried out [7]. Measuring LEDs characteristics using the integration sphere has been carried out by many researchers, which is one of the most reliable ways how to measure LEDs [1, 8, 9]. Various researches about measuring LED junction temperature were also made. One of the ways how to control LED temperature is by measuring the forward voltage of LED which was in the oil bath of specific temperature [8]. It has been proved that output luminous flux substantially changes with the temperature by implementation of the LED into the integration sphere and brings in fatal errors in determining the LED properties [10]. Measuring the temperature of the LED transition with the help of various experiments was reached by contact and contactless measurement [11]. Measurement of optical and electrical properties and calculation of the transition temperature was attained in the publication [12]. Another approach is mathematical-LED junction temperature can be calculated from its forward voltage [9]. This solution is very accurate, but it is limited by accuracy of measurement equipment. Modelling of temperature changes of LED diodes by computational fluid dynamics (CFD) analysis was also discussed in the article [13–15]. The Fan *et. al.* focused on degradation of LED aging and changes in spectral power distribution and efficiency. The LED chip parameters and its aging over time, as well as temperature, phosphorus and polymer used for the LED were measured. The process of the shift of LED elements, which is not linear, was monitored, and non-linear state-space model was developed. It predicts the time of color shift failure (CSF) [16]. The physical properties of the LEDs in time were also tested. It was monitored how their parameters would change, e. g. illumination, current through the LED on operation time, and efficiency coefficient on operation time [17]. A team of authors Qu focused on the LED temperature measurement and aging of installations while using pulse width modulation (PWM) for the red, green, blue (RGB) LED. It has been found out that the PWM modulation technique can effectively control color/luminosity without the necessity of feedback [18]. Similar results were achieved by another team of Umar and others [19] who designed a DC-DC converter with PWM lighting control or Dyble [20] and Gu [21]. Other way how to measure LED temperature is by using a sensor which contacts with printed circuit boards (PCB) near LED solder point [22, 23].

The measurements in this article aimed to find a process of measuring the color coordinates of white LEDs in the real applications in the company Varroc lighting system without using any special laboratory equipment. This process should be very simple easy enough for repeating even by a person that has only basic optical and electrical knowledge. For this reason, measuring of the color coordinate by integrating sphere and spectrometer and measuring the temperature of LED by the thermal camera was chosen and recommended to the company Varroc lighting systems. In the Table 1 we can see list of measured LEDs. Based on the measured data, conclusions and recommendations on how to work with different types of LED batches from different suppliers are made to minimize changes in the light emitted and negative impact on production.

Table 1. List of measured LEDs

LED type	Bin	Nominal current [mA]	Light temperature
Seoul SZW05A0A Z5	U2C3H	350	Cool
Seoul SZW05A0A Z5	U2E7I	350	Neutral
Seoul SZW05A0A Z5	U3C8I	350	Cool
Seoul SZW05A0A Z5	U1D5H	350	Neutral
Seoul SPW08F0D P8	-	350	Cool
Osram OSTAR LE UW D1W4 01	JM	700	Cool
Luxeon Rebel LXML PWN1 0100	NTPD	350	Neutral

2. AUTOMOTIVE WHITE LED

In the automotive industry, is usually used only one type of white LED-blue LED with luminophore that is converting blue light into white. In that case a luminophore, yttrium-aluminum garnet activated by cerium is usually used. This material is activated by blue light of the InGaN diode. In automotive industry, usually only one type of white LED is used-blue LED with luminophore. The luminophore is yttrium-aluminium garnet (YAG) doped by cerium in most cases. The YAG is activated by blue light from InGaN diode and it converts a part of blue light in yellow light. This yellow light is mixed together with the rest of blue light.

Correct proportions of lights (blue and yellow) create white light. LED producers divide each type of LED into various groups according to the color coordinates in CIE *x, y* chromaticity diagram. These groups are called color bins. Differences in LED color and dividing LED into various bins is caused by technology of LED production. For LED production, a simple substrate is used. On the surface of the substrate thin crystalloid layer is grown. This process is called epitaxy. As a result, semiconductor forming die of blue LED is created. This semiconductor is cut to small pieces afterwards. The electrical connections are inserted and layer or suspension of luminophore is added into its surrounding. This setup is encapsulated and creates a white LED. The luminophore layer is thin in order 10^{-2} mm, epitaxy processes create natural differences in LED properties [8]. Even the manufacturers are trying to minimize these differences; it is not possible to create highly consistent and strictly controlled LED production with the same characteristics. For this reason, LEDs are divided into groups with similar characteristics. These groups are called “bins” and they can be organized into three main groups: by luminous flux, color coordinates and voltage.

2.1. Sorting automotive LEDs according to colour coordinates

Manufacturers sort LEDs to color bins according to their *x* and *y* coordinates in chromaticity diagram defined in CIE 1931. These bins are defined usually by 4 points that create convex rectangle in chromaticity diagram. Pentagons or hexagons defining color bin are not unusual, too. Size of the bins depends on manufacturing quality-generally, the more accurate production, the smaller color bins can be produced.

3. EXPERIMENT REQUIREMENTS AND DESCRIPTION

The task of the measurement was to measure color coordinates of white automotive LEDs in the range of different temperature of LED and to evaluate the difference between color coordinates of LEDs in different temperatures. All measurements were aimed at automotive industry needs, so measuring of color coordinates was chosen for this purpose. A dark room was used to prevent direct light to affect the results of experiments. Measurements were made in a special dark room situated in VSB-Technical University of Ostrava. Sizes of the dark room were $2.6 \times 3 \times 2.5$ m. Amount of photons in this room was only 7 photons per second (Declared dark counts of photodetector 1 cps). Setup scheme consists of LED, Peltier cooler, CPU cooler and fan as it is shown in Figure 1.

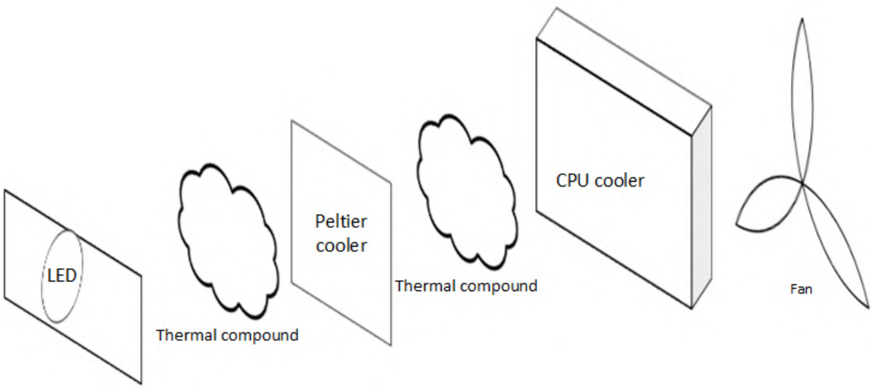

Figure 1. LED thermal regulation system assembly

The real final setup can be seen in Figure 2. All main components are described in the paragraph above. All experimental measurements were made $30\times$ for each LED and each temperature. The types of LEDs used for measurements can be found in Table 2. All LEDs are certified for using in the automotive industry and are proven as light sources for the automotive industry. Seoul LEDs are a simple and cheap example of automotive LED; they are widely used owing to their low price and a good luminous flux. Luxeon Rebel LEDs are known because of their great thermal management and thermal stability. Osram OSTAR LED used in this experiment is powerful 4-chip LED with a very high luminous output. Aim of the measurement was to verify the hypothesis that the colour coordinates change with the growing temperature of LED. As the P-N junction is situated inside of the LED structure, temperature of the LED's surface T_s was measured.

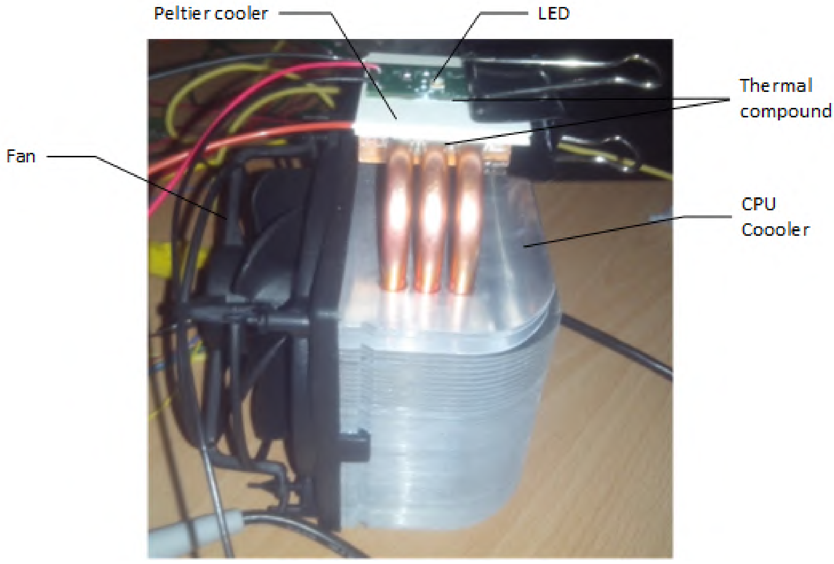

Figure 2. Thermal control system for measurements

Table 2. Results of SSC Z5 U2C3H

Surface temperature	**$T_s = 25\,^{\circ}C$**		**$T_s = 100\,^{\circ}C$**		**Difference**	
Coordinates	x	y	x	y	x	y
Mean	0.3643	0.3755	0.3659	0.3827	0.0016	0.0072
Median	0.364	0.375	0.366	0.383	0.002	0.007
Modus	0.364	0.375	0.366	0.383	0.002	0.007
75% quartile	0.365	0.376	0.36675	0.383	0.002	0.008
25% quartile	0.364	0.375	0.365	0.382	0.001	0.00625
Minimum	0.364	0.375	0.363	0.381	−0.002	0.005
Maximum	0.365	0.377	0.368	0.386	0.004	0.011
Variance	0.0004661	0.0005724	0.001094	0.0013429	0.0012484	0.0016692

4. MEASUREMENT RESULTS

LEDs were measured for various temperatures of surface and the nominal current of LEDs was kept. Color coordinates were measured by the procedure:

- Assembly of the thermal control system see in Figures 1 and 2.
- Connecting electronic components (Peltier cooler, fan, LED) to power supplies.
- Setting the nominal current of LED according to producers datasheet.
- Turning on power supplies for Peltier cooler and fan.
- Monitoring LED's surface using thermocamera, regulation of temperature using Peltier cooler and LED's forward current until the temperature on LED's surface and forward current reach the values defined in vendor's datasheet.
- Measuring color coordinates using Avantes spectrometer and integration sphere.
- Changing LED's surface temperature by adjusting Peltier cooler current.
- Adjusting LED's forward current to nominal.

All results were placed into the graph with proper bin definitions and bin's tolerances. Osram OSTAR LE UW D1W4 01 nominal temperature was not measured according to the datasheet, because the vendor provides information about color shift according to temperature changes and the LED was already assembled on its cooler. This does not allow fitting it on the cooling system described in Figure 2. Results for each LED were compared for nominal temperature and heated LED. All results were evaluated using exploratory statistic methods of data analysis and the statistical data were calculated: Mean (μ), Median ($\widetilde{x}$), Mode ($\widehat{x}$), 75%

quartile, 25% quartile ($Q_{0.75}$ $Q_{0.25}$), Minimum, maximum and Variance (σ_2). All measured values of color coordinates were tested for mean equation based on the test of the significance difference of the two sample averages (t-test). Hypotheses were tested for 95 % confidence interval separately for *x* and *y* coordinates. The following chapters gradually describe the results of experimental measurements and then the processing by means of the Statgraphics Centurion XV. The different types of LED boards with LEDs were always labelled according to the bin to which the LED type fell. As can be seen in Figure 2, a zero series resistor was used for all the LED samples, and therefore, it was not necessary to perform exhaustive calculations to determine the electric current flowing through the tested LEDs.

4.1. Seoul semiconductors Z5

First of the tested LED was Seoul semiconductors (SSC) Z5 LED shown in Figure 3. In Figure 4 shows distribution of heat on PCB and areas on PCB used for the thermal management measurements by thermocamera for 25 °C, or for 93.9 °C on the LED sample SSC Z5 LED. The thermocamera was aimed at the LED. As can be seen on the left part of the picture, these areas have higher temperature as they are leading a heat away. On the right part of the picture there is the cooler that can not handle all the heat.

Figure 3. LED seoul semiconductors Z5 assembled

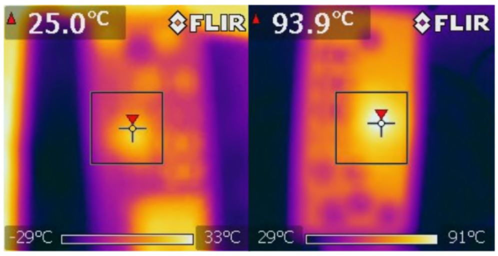

Figure 4. Heat distribution on PCB assembled with SSC Z5 LED

4.1.1. U2C3H

Statistical results for LED SSC Z5 binned as U2C3H are shown in Table 2. After, we found the basic statistical functions and outputs it was proceeded to more thorough analysis based on hypotheses through t-test.

Hypothesis test for x-coordinates:

$$\begin{aligned} H_0 &: \mu(x)_{T_s=25} = \mu(x)_{T_s=100}, \\ H_A &: \mu(x)_{T_s=25} \neq \mu(x)_{T_s=100}, \end{aligned} \tag{1}$$

Hypothesis test shows that temperature change has influenced color coordinates *x* and *y* for LED SSC Z5 U2C3H. Comparison of measured results for T_s with data declared by the vendor is shown in Figure 5.

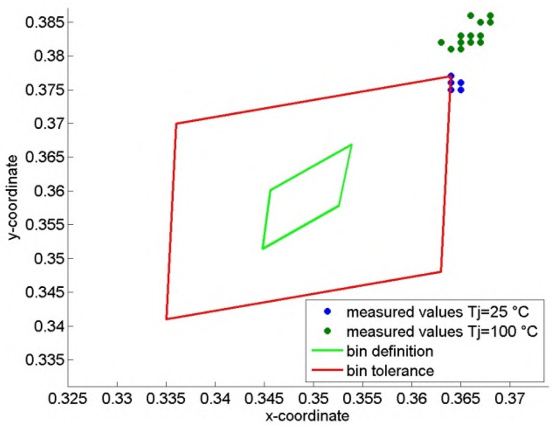

Figure 5. Comparison of measured values to company's information for SSC Z5 LED binned as U2C3H

4.1.2. U2E7I

Statistical results for LED SSC Z5 binned as U2E7I are in Table 3, where we can observe that the changes range at very low levels.

Hypothesis test for x-coordinates:

$$\begin{aligned} H_0 &: \mu(x)_{T_s=25} = \mu(x)_{T_s=100}, \\ H_A &: \mu(x)_{T_s=25} \neq \mu(x)_{T_s=100}, \end{aligned} \tag{2}$$

$P - Value = 0 \ll 0.05 \longrightarrow$ rejecting H_0 on confidence interval 95%.

Hypothesis test for y–coordinates:

$$\begin{aligned} H_0 &: \mu(y)_{T_s=25} = \mu(y)_{T_s=100}, \\ H_A &: \mu(y)_{T_s=25} \neq \mu(y)_{T_s=100}, \end{aligned} \tag{3}$$

$P - Value = 0 \ll 0.05 \longrightarrow$ rejecting H_0 on confidence interval 95%. Hypothesis test shows that temperature change has influenced color coordinates x and y for LED SSC Z5 U2E7I. Comparison of measured results of T_s with data declared by vendor is shown in the Figure 6.

Table 3. Results of SSC Z5 U2E7I

Surface temperature	$\mathbf{T_s = 25\ ^\circ C}$		$\mathbf{T_s = 100\ ^\circ C}$		**Difference**	
Coordinates	x	y	x	y	x	y
Mean	0.3915	0.3689	0.4052	0.389	0.0137	0.0192
Median	0.391	0.37	0.405	0.389	0.014	0.019
Modus	0.391	0.37	0.406	0.389	0.014	0.018
75% quartile	0.392	0.37075	0.406	0.39	0.014	0.02075
25% quartile	0.391	0.369	0.40425	0.38725	0.013	0.018
Minimum	0.388	0.368	0.402	0.385	0.009	0.015
Maximum	0.393	0.371	0.408	0.392	0.017	0.024
Variance	0.0010417	0.0009248	0.0012847	0.0018473	0.0016174	0.0021669

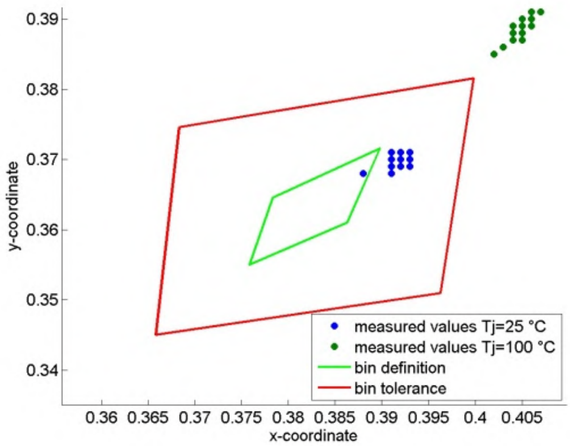

Figure 6. Comparison of measured values to company's information for SSC Z5 LED binned as U2E7I

4.1.3. U3C8I

The basic statistical analyses were again used according to the exploratory analysis through the Statgraphics Centurion XV software environment for the LED SSC Z5 binned as U3C8I. Statistical results for LED are shown in Table 4. Afterwards, the analysis through the t-test based on the hypotheses was proceeded to find out whether the mean values differ at a significant level.

Hypothesis test for x–coordinates:

$$\begin{aligned} H_0 &: \mu(x)_{T_s=25} = \mu(x)_{T_s=100}, \\ H_A &: \mu(x)_{T_s=25} \neq \mu(x)_{T_s=100}, \end{aligned} \tag{4}$$

$P - Value = 5.03093 \cdot 10^{-9} \ll 0.05 \longrightarrow$ rejecting H_0 on confidence interval 95%.

Table 4. Results of SSC Z5 U3C8I

Surface temperature	$\mathbf{T_s = 25\ °C}$		$\mathbf{T_s = 100\ °C}$		**Difference**	
Coordinates	x	y	x	y	x	y
Mea	0.3517	0.376	0.355	0.3839	0.0033	0.0079
e Median	0.352	0.376	0.354	0.385	0.003	0.009
Modus	0.352	0.376	0.354	0.385	0.002	0.009
75% quartile	0.352	0.376	0.357	0.385	0.005	0.009
25% quartile	0.351	0.375	0.353	0.384	0.00125	0.008
Minimum	0.35	0.373	0.352	0.358	−0.002	−0.018
Maximum	0.355	0.379	0.36	0.388	0.009	0.012
Variance	0.0011492	0.0013391	0.0023413	0.005047	0.0028032	0.0050265

Hypothesis test for y–coordinates:

$$H_0 : \mu(y)_{T_s=25} = \mu(y)_{T_s=100},$$
$$H_A : \mu(y)_{T_s=25} \neq \mu(y)_{T_s=100}, \quad (5)$$

$P - Value = 2.02931 \cdot 10^{-11} \ll 0.05 \longrightarrow$ rejecting H_0 on confidence interval 95%

Hypothesis test shows that the temperature change has influenced color coordinates *x* and *y* for LED SSC Z5 U3C8I. Comparison of measured results of T_s with data declared by vendor is shown in the Figure 7.

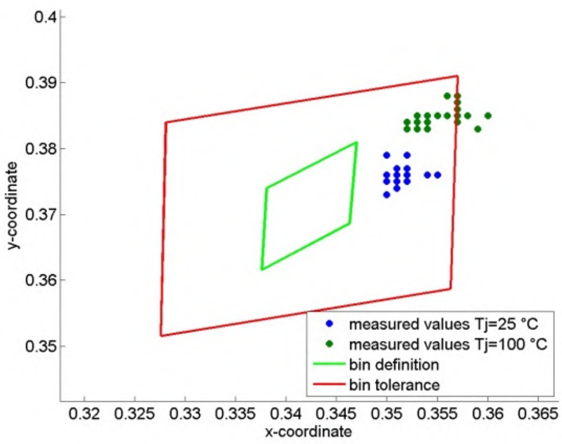

Figure 7. Comparison of measured values to company's information for SSC Z5 LED binned as U3C8I

4.1.4. U1D5H

Statistical results for LED SSC Z5 binned as U1D5H are shown in Table 5.

Table 5. Results of SSC Z5 U1D5H

Surface temperature	$\mathbf{T_s = 25\ °C}$		$\mathbf{T_s = 100\ °C}$		**Difference**	
Coordinates	x	y	x	y	x	y
Mean	0.3754	0.3671	0.3837	0,375	0.0083	0.0079
Median	0.375	0.367	0.385	0,376	0.0095	0.009
Modus	0.375	0.368	0.385	0,376	0.01	0.009
75 % quartile	0.376	0.368	0.385	0,377	0.01	0.01
25 % quartile	0.375	0.366	0.384	0,375	0.009	0.008
Minimum	0.375	0.366	0.355	0,36	−0.02	−0.006
Maximum	0.376	0.368	0.386	0,378	0.011	0.012
Variance	0.0005040	0.0008996	0.0055207	0,0041021	0.0054719	0.0040406

Hypothesis test for x–coordinates:

$$H_0 : \mu(x)_{T_s=25} = \mu(x)_{T_s=100},$$
$$H_A : \mu(x)_{T_s=25} \neq \mu(x)_{T_s=100}, \quad (6)$$

$P - Value = 2.82712 \cdot 10^{-11} \ll 0.05 \longrightarrow$ rejecting H_0 on confidence interval 95%.

Hypothesis test for y-coordinates:

$$H_0 : \mu(y)_{T_s=25} = \mu(y)_{T_s=100},$$
$$H_A : \mu(y)_{T_s=25} \neq \mu(y)_{T_s=100}, \quad (7)$$

$P - Value = 0 \ll 0.05 \longrightarrow$ rejecting H_0 on confidence interval 95%. Hypothesis test shows that temperature change has influenced color coordinates x and y for LED SSC Z5 U1D5H. Comparison of measured results of T_s with data declared by vendor is shown in the Figure 8.

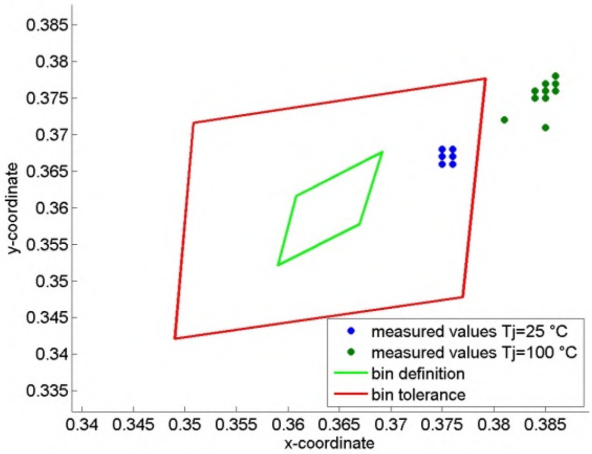

Figure 8. Comparison of measured values to company's information for SSC Z5 LED binned as U1D5H

4.2. Seoul semiconductors P8

For SSC P8 LED measurement, the same procedure was used as for SSC Z5. As this LED was only for demonstrational purposes, it was not binned in any color bin. Nominal current for this LED is 350 mA, lower temperature limit 25 °C, the highest measured temperature was 100 °C. Photo of SSC P8 can be seen in Figure 9, heat distribution on PCB is shown in Figure 10.

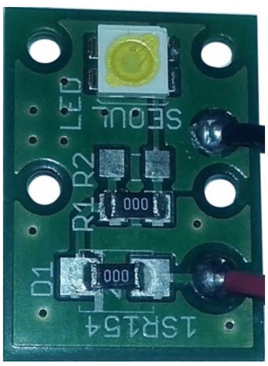

Figure 9. LED seoul semiconductors P8 assembled on PCB

PCB for this LED has little bit worse ability for heat leading. This is the reason why the holes for heat leading not clearly visible on thermocamera pictures. Statistical results for LED SSC P8 are shown in Table 6.

Hypothesis test for x-coordinates:

$$H_0 : \mu(x)_{T_s=25} = \mu(x)_{T_s=100},$$
$$H_A : \mu(x)_{T_s=25} \neq \mu(x)_{T_s=100}, \quad (8)$$

$P - Value = 0 \ll 0.05 \longrightarrow$ rejecting H_0 on confidence interval 95%.
Hypothesis test for y-coordinates:

$$H_0 : \mu(y)_{T_s=25} = \mu(y)_{T_s=100}, \\ H_A : \mu(y)_{T_s=25} \neq \mu(y)_{T_s=100}, \quad (9)$$

$P - Value = 0 \ll 0.05 \longrightarrow$ rejecting H_0 on confidence interval 95%. Hypothesis test shows that temperature change has influenced color coordinates *x* and *y* for LED SSC P8. Comparison of measured results of different T_s is shown in the Figure 11.

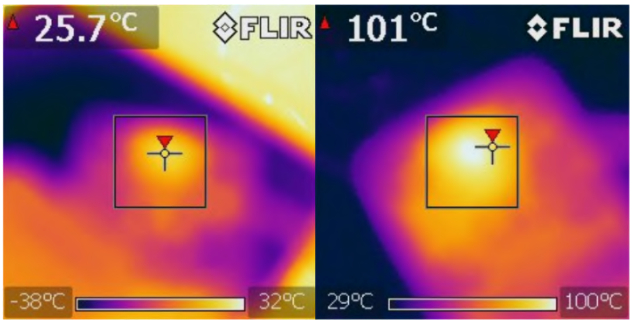

Figure 10. Heat distribution on PCB assembled with SSC P8 LED

Table 6. Results for LED SSC P8

Surface temperature	$T_s = 25$ °C		$T_s = 100$ °C		Difference	
Coordinates	x	y	x	y	x	y
Mean	0.3381	0.3537	0.3445	0.3606	0.0064	0.0069
Median	0.338	0.354	0.345	0.361	0.006	0.007
Modus	0.338	0.354	0.345	0.361	0.006	0.007
75% quartile	0.339	0.354	0.345	0.361	0.007	0.008
25% quartile	0.338	0.353	0.344	0.36	0.006	0.00625
Minimum	0.337	0.352	0.343	0.358	0.005	0.003
Maximum	0.339	0.357	0.346	0.362	0.008	0.01
Variance	0.0006815	0.0012848	0.0006789	0.0008137	0.0009714	0.0015698

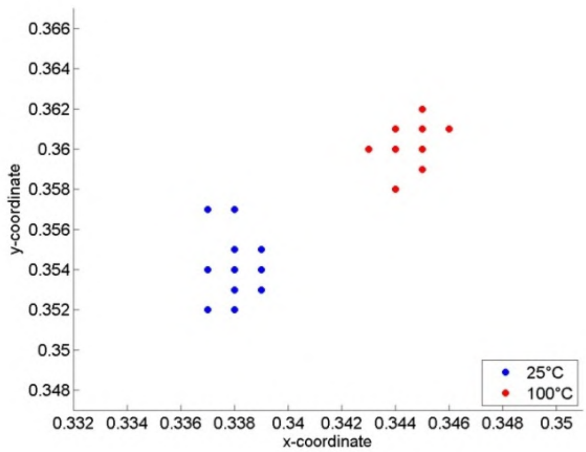

Figure 11. Comparison of colour coordinates between different temperatures of LED SSC P8

4.3. Philips Luxeon Rebel PWN1 0100 NTPD

Vendor Philips has other criteria for color coordinates measuring temperature. They recommend measuring the temperature of the LED using pad situated on the PCB near LED solder point known as T_{pad}. For this measurement, the same technology of measuring LED temperature is used for all other LEDs. Generally, the equation $T_{pad} = T_s - 17.64$ can be used for conversion between T_{pad} and T_s. Vendor determines inaccuracy in bin definitions 0.005 for both coordinates. PCB has a system of holes used for great thermal management, as can be seen in the Figure 12. As can be seen in Figure 13, has much better thermal management than previous LEDs. Heat is distributed evenly all over PCB. Statistical results for LED Luxeon Rebel NTPD are shown in Table 7.

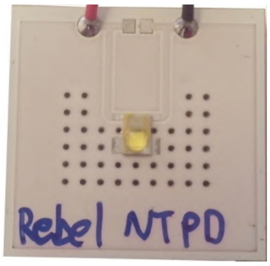

Figure 12. LED luxeon Rebel assembled on PCB

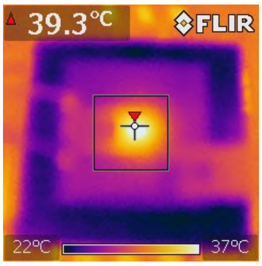

Figure 13. Heat distribution on PCB assembled with Luxeon Rebel LED

Table 7. Results of Philips Luxeon Rebel NTPD LED

Surface temperature	$\mathbf{T_s = 25\ ^\circ C}$		$\mathbf{T_s = 100\ ^\circ C}$		**Difference**	
Coordinates	x	y	x	y	x	y
Mean	0.3767	0.3697	0.3822	0.3814	0.0055	0.0117
Median	0.376	0.3695	0.382	0.382	0.0055	0.0125
Modus	0.376	0.369	0.382	0.382	0.005	0.013
75% quartile	0.377	0.37	0.383	0.383	0.006	0.013
25% quartile	0.376	0.369	0.382	0.38125	0.005	0.011
Minimum	0.376	0.369	0.379	0.363	0.003	−0.007
Maximum	0.379	0.372	0.387	0.387	0.009	0.017
Variance	0.0009154	0.0008684	0.0012972	0.003748	0.0013582	0.0039034

Hypothesis test for x–coordinates:

$$\begin{aligned} H_0 &: \mu(x)_{T_s=25} = \mu(x)_{T_s=100}, \\ H_A &: \mu(x)_{T_s=25} \neq \mu(x)_{T_s=100}, \end{aligned} \tag{10}$$

$P - Value = 0 \ll 0.05 \longrightarrow$ rejecting H_0 on confidence interval 95%.
Hypothesis test for y-coordinates:

$$\begin{aligned} H_0 &: \mu(y)_{T_s=25} = \mu(y)_{T_s=100}, \\ H_A &: \mu(y)_{T_s=25} \neq \mu(y)_{T_s=100}, \end{aligned} \tag{11}$$

$P - Value = 0 \ll 0.05 \longrightarrow$ rejecting H_0 on confidence interval 95%. Hypothesis test shows that temperature change has influenced color coordinates *x* and *y* for LED Luxeon Rebel NTPD. Comparison of measured results of T_s with data declared by vendor is shown in the Figure 14.

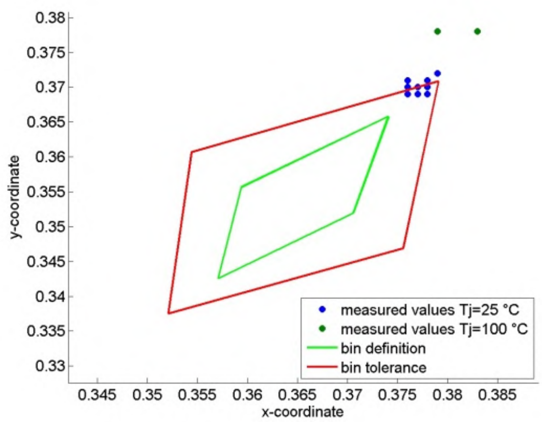

Figure 14. Comparison of measured values to company's information for LED Philips Luxeon Rebel binned as NTPD

4.4. OSRAM LE UW D1W4 01 JM

This LED is built from 4 dies assembled on one chip. This solution offers high luminous flux (630 lm in this case) and wide area of application thanks to its small dimensions. Nominal voltage of this LED is 14.1 V, the nominal current 700 mA. PCB with LED was mounted on aluminum cooler see in Figure 15 that provides its cooling as this LED produces a lot of heat.

Figure 15. Heat distribution on PCB assembled with 4-chip LED Osram LE UW D1W4

However, the temperature on the surface of LED has reached 120 °C, as shown in Figure 16. Once the LED reaches this value, the temperature of LED is stabilized and no significant swings of temperature can be observed. As this LED was assembled on the heatsink, it was not possible to add the Peltier cooler. Vendor provides information about color coordinates shift in LED's datasheet. Value for color shift for 120 °C and nominal current 700 mA is 0.012 for x-coordinate and 0.014 for **y**-coordinate. Vendor guarantees tolerance of color coordinates binning equal to 0.005. For verifying LED's binning, color bin definitions were shifted according to information about color shifting in datasheet. Comparison of measured values and shifted vendor's definitions can be seen in Figure 17.

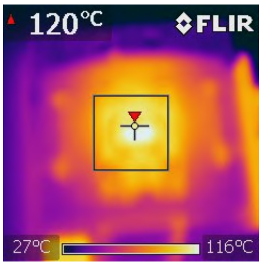

Figure 16. Thermal distribution of Osram LE UW D1W4

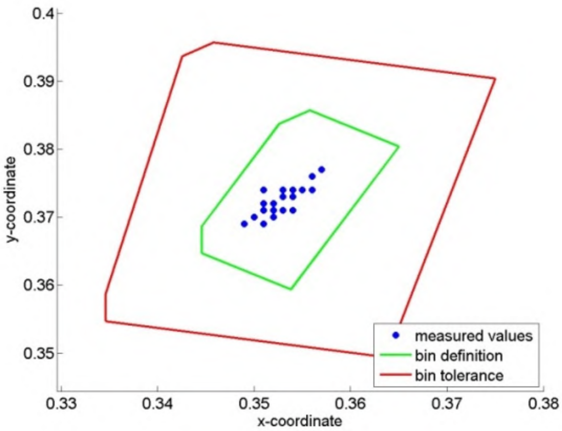

Figure 17. Comparison of measured colour coordinates and shifted bin definition for LED Osram LE UW D1W4 binned as 01JM

5. RESULTS OF EXPERIMENT AND DISCUSSION

All experimental measurements proved that color coordinates of LEDs are changing according to the LED temperature. Average shift in coordinates is 0.011 for *x*-coordinate and 0.018 for *y*-coordinate. In these numbers, results of measuring two prototype LEDs have been counted-unfortunately, concrete results of these two prototype LEDs cannot be published as they are still in process of development. According to the hypotheses test that rejects equality of means of measured color coordinates we can claim that there is a shift of color coordinates caused by the change of LED's temperature. This shift is caused by change of the intensity of LED die. As mentioned before, the spectrum of white LED used for automotive industry is created by blue part of LED die and yellow/orange luminophore layer providing color conversion. LED die's luminous output is getting lower with rising temperature, but luminophore layer's optical properties do not change dramatically with temperature change. This leads to a fact that less amount of blue light is converted by the same amount of luminophore layer. This means the color coordinates shift to the yellow part of chromaticity diagram. Results of this experiment can be used in automotive lighting industry for matching colors of various types of light sources as the temperature of LED changes during car operation time. Head lamps of any cars with LEDs will be very important in the future in case of security issues of vehicle to vehicle (V2V) communications via visible light communication (VLC) [24-26].

6. CONCLUSION

The measurements of different characteristics and their dependence on the temperature of the P-N transition for the most commonly used types of LED samples in the automotive industry, or more precisely for manufactures of lighting components, were made within the experimental measurements. The first hypothesis through the t-test was that the change of the temperature of the P-N transition had an effect on the shift of color coordinates. This hypothesis was confirmed after processing the measured data with statistical methods. At the same time, it has been proved that the manufacturer Seoul designates incorrectly the temperature, at which the color bins are defined, as the ambient temperature. It has been shown that the temperature control of the P-N transition is more important than the ambient temperature control in terms of achieving values given in the data sheet. The verification also determined the average value of the color coordinate shift at the temperature change of the P-N transition for the selected LED samples. The color coordinates of the specified LEDs correspond to the bin definitions given by the manufacturers and into which they were classified. In the future it will be necessary to make further measurements of other LED bathes, as the latest trends in the development and use of lighting or automotive components are driven by the demand for high-quality radiation sources that enable to reduce energy consumption and, therefore, to achieve greener operation combined with further possible use of these radiation sources, e.g. for communication via VLC.

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