

Research Article

Comprehensive Evaluation System for LED Driver Concerned of Visual Comfort

Jieqiong Song, Liqing Tong, Minhua Qian, Yaojie Sun and Yandan Li

Institute for Electric Light Sources, Engineering Research Center of Advanced Lighting Technology of Ministry of Education, Fudan University, Shanghai 200433, China

Abstract: Special features and varied applications make complex claims for LED driver selection. The aim of study is to establish a comprehensive evaluation system for LED driver for selection under varied applications. This study first analyzes the importance of key elements for driver evaluation concerned of visual comfort. Besides, research shows that the change of driver current, driver mode and dimming procedure will have impact on the LED SPD (Spectrum Power Distribution), color and visual comfort. Thus, visual comfort index including dimming Linearity, dimming stability and strobe is added to the evaluation system besides the traditional evaluation index of circuits. As the complex evaluation factors can not be described using one equation, we structure a comprehensive evaluation system containing these three factors system performance, driver performance and visual performance based on the Analytic Hierarchy Process (AHP) method. Finally, an application case is implemented and applied to clarify the proposed method.

Keywords: Analytic hierarchy process (AHP), LED driver, flicker, visual performance

INTRODUCTION

With the improvement of whole social living standard and process of semiconductor technology, people are demanding more for the lamp of energy saving (Rubinstein, 2007; Aldrich *et al.*, 2010), personalized illumination (Muthu *et al.*, 2002) concerned about psychological mood regulation (Figueiro, 2010) and circadian rhythm, rather than just as extension of natural light. Some parameters for traditional circuit evaluation such as cost, power factor and harmonic content can be applied in the construction of evaluation system for LED driver. However, considering the special current-luminous flux characteristic of LED and complex visual applications, we should pay more attention for other influencing factor. For instance, the life difference between the driver and LED lamp will reduce the application value of LED as long life light source 5, thus it is necessary to take the life and stability of driver into account to build an evaluation system. The impact on the visual comfort caused by driver is another problem that is easily overlooked.

Visual channel, as the main method for human to get information, has already been adapt to the sun's rays and developed a special spectrum sensitive characteristics called $V(\lambda)$ after long evolutionary in nature, as Fig. 1 showed below.

People's visual perception is decided by the spectrum of light source, which is affected by the power

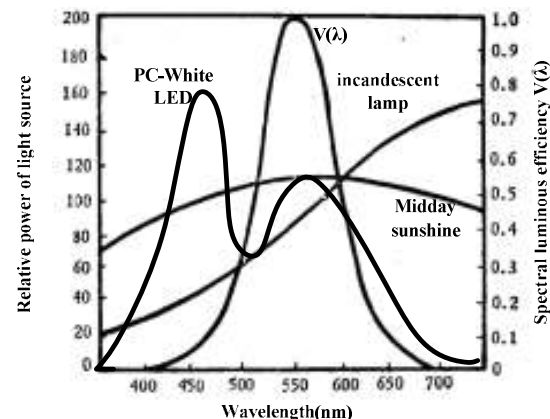


Fig. 1: Relative spectrum power distribution (SPD) of light source & $V(\lambda)$

of drive current. Therefore, the thesis will focused on the study of relation between LED driver and visual comfort and breaking the professional barriers between circuit and visual, then use it as the basis for building-up LED driver evaluation system, As Fig. 2 showed. As a complicated system evaluative process, the evaluation of LED driver involve many factors, which are difficult to be expressed by unified equation. Thus, Analytic Hierarchy Process is chosen to help establish evaluating model as objective guidance for different drive application choice. As the complex evaluation factors can not be described using one equation, we structure a

Corresponding Author: Jieqiong Song, Institute for Electric Light Sources, Engineering Research Center of Advanced Lighting Technology of Ministry of Education, Fudan University, Shanghai 200433, China

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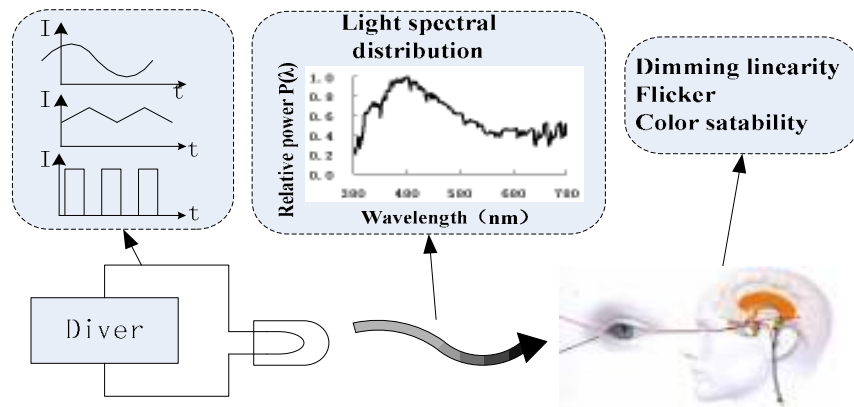


Fig. 2: Relation between driver and visual comfort

comprehensive evaluation system containing these three factors system performance, driver performance and visual performance based on the Analytic Hierarchy Process (AHP) method.

THE EFFECT OF DRIVER CIRCUIT ON THE VISUAL PERCEPTION

The role of lamp is to convert the electrical energy to the light energy, thus the change of light energy form is closely related to the input power. Considering the difference between LED and rational light source, this study will discuss the relation between drive and visual comfort from the following points:

- **The effect of light spectrum on the visual:** Due to the differences between the artificial light spectrum and the daylight spectrum, human vision will be some inadequacies, such as information misreading and visual discomfort. To take the color rendering as example, which is fully decided by the spectrum power distribution of light, the lamp with continuous spectrum have better color rendering. The change of light spectrum will make an impact on the visual perception.

The study shows, the dominant wavelength will shift toward short wavelength with the increase current, due to band filling and QCSE dominated effects (Gu *et al.*, 2006). At the same time, it takes very little shift in wavelength, in the range of 1 to 6 nm, before the color shift crosses the 3-step MacAdam ellipse boundary, as Fig. 3 showed.

LED has fast response times within nanosecond and is a kind of current driven device. With current control, the LED brightness L (cd/m^2) will be roughly linearly proportional to current I :

$$L = KI_F \quad (1)$$

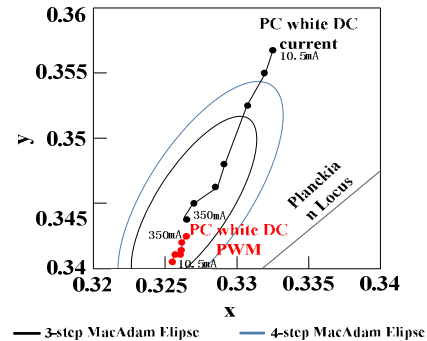


Fig. 3: Color change in CIE1931(x, y) coordinate system of PC white and mixed-color LED system under continuous current and PWM dimming mode

Therefore, the subtle change of the drive current will cause the LED brightness change. In order to realize perfect luminous effect, it is necessary to control current within ideal range and set a evaluation indicator for the effect of driver current on stability of light wavelength at the same time.

- **The effect of dimming process on vision:** The LED is commonly used in different dimming occasions for its feature such as fast response and changing color, providing variety combinations of brightness and color.

As the nerve structure accepted stimulation is divided into individual units according function, eyes are very sensitive to subtle changes of light under low brightness, while difficult to detect greater change under lighter condition due to the saturation of the human visual system. It means that people are aware of stimulate when incremental amount is large enough to excited an additional neural quantum unit. So we can see that visual psychological feeling and the actual

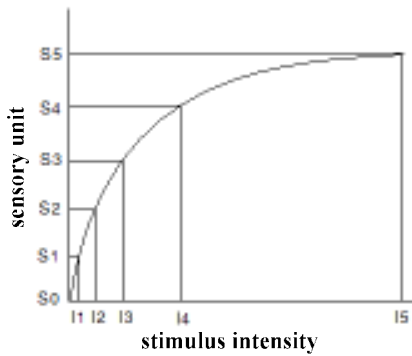
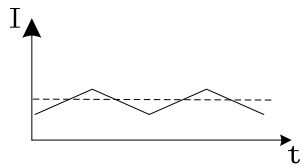
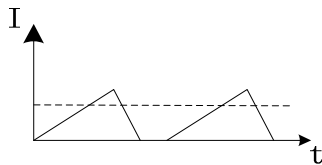


Fig. 4: Relation between psychological feeling and physical stimulation



(a) Continuous conduction mode



(b) Discontinuous conduction mode

Fig. 5: Driving waveform of switching-mode power supply under different mode

Table 1: LED driving waveform and topology

Driving waveform	Topology
Constant current	Voltage stabilizer
Triangular wave	Buck, Boost, Fly back
PWM	555 circuit, constant current + PWM
Others	chopper, Microcontroller timer AC driver, thyristor control

amount of physical stimulation and is not linear corresponding amount, as Fig. 4 and formula 2 showed.

$$B \propto L^{0.5} \tag{2}$$

Control parameters of light source and practical brightness have the following relationship:

$$L = f(\theta) \tag{3}$$

When feeling evenly brightness changes from B_1 to B_2 , actual brightness changes from L_1 to target brightness L_2 according to the formula 2. Thus we get the following result:

$$\theta = f^{-1}(L) = f^{-1}\left(\frac{L_2}{L_1} \cdot t^2\right) \tag{4}$$

In the process of light dimming, the drive control should meet the request of formula 4 in order to realize the light smooth transition.

Professor Jinno Ya.'s study turns out that when imposed 5% duty cycle, the cycle frequency of about 60Hz high-speed pulse voltage on LED, the experience brightness of human eye is about 2 times compared with DC voltage condition¹¹. This illustrates further that LED driven by the same way will have different performance while dimming.

- **The effect of driver waveforms on visual perception:** With special current-voltage driving characteristics, LED driver need proper design and topology selection to maximum the advantage of LED. According to the final output drive current forms, different driving scheme is shown as Table 1.

Due to different driving waveform, LED takes different time to keep lighten each cycle and produces different heat to change junction temperature, which cause changes caused band widen, wavelength shifted then color changed. According to the study of Marc Dyble, the chromaticity shifts of LED system with the PWM performing are slightly better than the continuous current dimming scheme⁹. The driving waveform is concerned of driving topology; however the change of control information will have an impact on the driving waveform in the same topology, as Fig. 5 showed.

To sum up, the capture of human eye for visual information is closely related with light source spectral distribution. Driving current, driving topology and dimming process will all change the spectral distribution and color of LED, even because the visual discomfort. These various connections between driving waveform and the visual comfort should be taken into account of LED driver evaluation system. Specific index will be given in the next chapter.

Establish evaluation index about the driver's effect on visual perception: Set up the index as follows according to the discussion above:

linear correlation of dimming current: The change light output will lag behind the control parameter and increase the instability of dimming system, when the linear relation is poor. So the index is definite as followed:

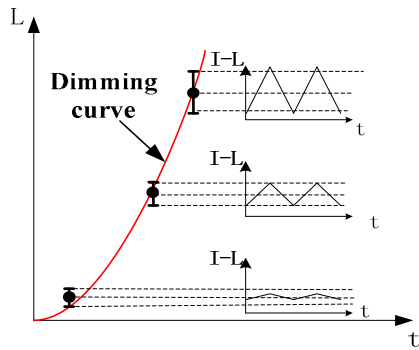


Fig. 6: Dimming stability under different diving and dimming mode

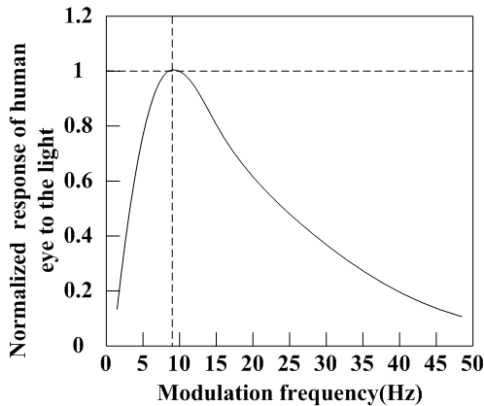


Fig. 7: Frequency response of lamp

$$r = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2} \sqrt{\sum (y - \bar{y})^2}} \quad (5)$$

X represents the control signal of dimming system; Y represents the average output in one cycle. The linear correlation is bigger when |r| is bigger. |r| = 1 means completely linear correlation.

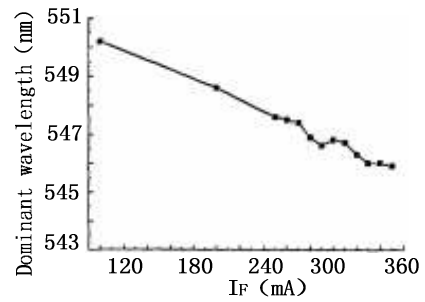


Fig. 8: Dominant wavelength vs forward current (IF)

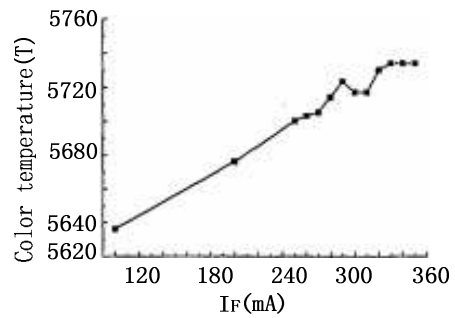


Fig. 9: Color temperature vs forward current (IF)

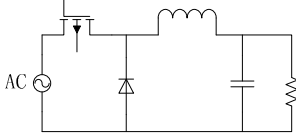
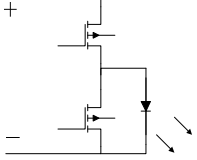
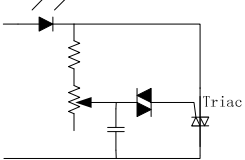
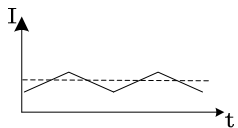
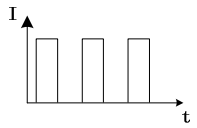
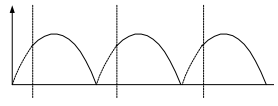
Dimming stability: Although LED has the advantages of quick response, it also becomes a disadvantage for causing fluctuation when brightness changes' fast, as Fig. 6 showed.

There is a kind of psychophysics of vision that the intermittent light stimulus appears to be completely steady to the observer, as long as modulation frequency is above the flicker fusion threshold (or flicker fusion rate), besides the perceived intensity can be changed by changing the relative periods of light and darkness. However, the light above the flicker fusion threshold can also cause visual fatigue, headache and other symptoms. It depends on the fluctuant depth and frequency. As Daniele Gallo's study shows, the perception of light varies with the frequency and presents maximum spectral response between (Fig. 7).

Fluctuation depth is used as an index to represent the depth of light disturbance. As formula 6 shows, E_{max} , E_{min} , E_{av} express the maximum, minimum and average change values in one dimming cycle. The proportion of the light output can be equal with the proportion of the current for LED brightness is proportional to the current:

$$\delta = \frac{E_{max} - E_{min}}{E_{av}} = \frac{I_{max} - I_{min}}{I_{av}} \quad (6)$$

Table 2: Compare of different topology by evaluation index

Topology	Buck	Half-bridge	SCR controller
Circuits			
Output waveform			
Waveform characteristics	Fluctuations as triangle wave	Keep still during lighting on	Chopped wave
Relation between output and control signal	$V_O = D \times V_{IN}$, $I_{avr} = I_s e^{\frac{qV_O}{kT}}$	$I_{avr} = D \times I_{max}$	$\bar{I} = \frac{1}{\pi - \theta} \int_{\alpha}^{\pi} I_s e^{\frac{qV_m \sin \theta}{kT}} d\theta$
Linear correlation	Middle	Good	Bad
Fluctuation depth	$\frac{\Delta i}{I}$	$\frac{1}{D}$	$\frac{I_{max}}{\bar{I}}$
Color stability (absolute light output changes)	Middle	Good	Bad

Color stability: Luminous characters and even the color of LED will change with the current fluctuation for band filling effect. The PWM dimming schemes performs slightly better than the continuous current dimming scheme, as the output of light keeps still when lighting on under PWM schemes. Besides, Fig. 8 and 9 shows that dominate wavelength will decrease, related color temperature increase linearly with the current increase. Therefore, the absolute value of the current changes during conduction is used to measure the color stability of driver.

Taking buck, half-bridge and SCR controller topology as example, compare of different topology by evaluation index is shown as Table 2.

ESTABLISHMENT OF EVALUATION MODEL AND CASE ANALYSIS

Establishment of comprehensive evaluation system and relative weight: The objective of the synthetic assessment system is to assess the best LED drivers for specific occasions. This study builds an evaluation system which is based on the match degree between driver and lamp, performance of the driver and visual comfort. Determination matrix can be generated based on the evaluation model using 1-9 scale method and finally get the weight of each level for the overall target LEDs can be used in many occasions and each factor has different significance in different occasion to be allocated different weight. In this study, the example is

about traditional lighting system of a studio replaced by LED lighting system. The flicker of the lighting sources used in videos will cause pictures fuzzy. The tint of the lighting sources should be as steady as possible. So, lighting sources used in videos has high requirements in visual comfort. Fig. 10 is the evaluation model and the weight of different factors.

Example introduction: Two dimming methods were used in this study. In method A, LM3445 was used which is compatible with traditional SCR dimming system to drive the LEDs. The driver turns TRIAC signal into PWM control signal whose duty cycle matches the conduction angle of SCR. The PWM control signal was then used to control the BUCK circuit in order to generate specific current. So, finally the relationship between the output voltage of the driver and the conduction angle is linear. And the value of the conduction angle is controlled by the RC circuit. The SCR turns on, only when the voltage of the capacitor reaches a fixed value. As we can see, the relationship between specific conduction time and adjustable resistor is linear. That means the output voltage is linear to the adjustable resistor. Light intensity of the LEDs is in proportion to the drive current, but the relationship between drive current and voltage is nonlinear. So, the linear correlation of the driver is unacceptable. The rated current of the designed driver is 400 mA and the fluctuation is usually 15%~30% of the rated current.

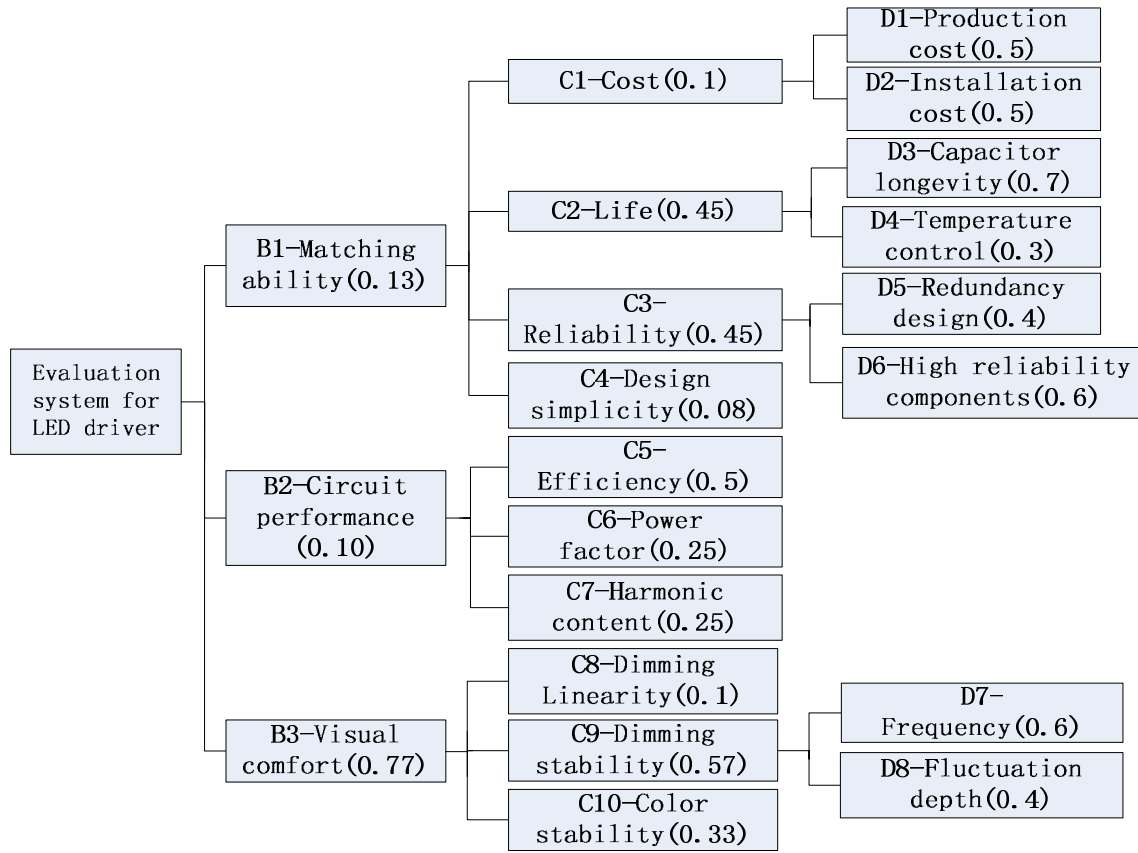


Fig. 10: Comprehensive evaluation system and relative weight for LED driver

Table 3: Comparison of performance between two kinds of driver

	LM3445	UCC25710
Installation cost	Existing system	Rebuilding
Efficiency	85%	92%
PFC	PPFC	APFC
LLC resonant circuit	No	Yes
Temperature control	No	Yes
Linearity	Unlinear	Linear
Dimming stability		
$\delta = \frac{E_{max} - E_{mix}}{E_{av}}$	$\frac{\Delta I}{I} = 30\%$	$\frac{1}{D} \geq \delta_{LM3445}$
Color stability	Bad	Good

The frequency of the fluctuation is 250 kHz. So, the maximum value of the fluctuation is $400 \times 30\% = 120$ mA. This fluctuation will cause the color to be unstable. The driver used in method B is designed based on a half-bridge resonant converter. So, the output luminous flux is totally linear to the duty cycle of the control signal. The current is constant when the LED is on, so the color is stable.

Comparison of different driving modes: The parameter of two kinds of driver is listed in Table 3 as follows:

Due to the different properties and dimension, quantitative index and qualitative indexes is hard to express in unified digital quantity. This evaluation system brings in the Fuzzy theory to dismiss the effect of different index on the judging result. The judging indexes are divided in five levels to get fuzzy score. According to the above model, the indicators set is $V = \{1, 3, 5, 7 \text{ and } 9\}$, while comments set is $V = \{\text{Extremely Low, Low, Medium, High, Extremely High}\}$.

Evaluation score of each index is listed Table 4. The calculating of fuzzy comprehensive evaluation is shown below:

$$A = S * W = \begin{bmatrix} 6.0101 \\ 6.2001 \end{bmatrix} \quad (7)$$

By the biggest membership principle, PWM dimming method is proper for the studio lighting considering driver, system performance and visual comfort, although LM3445 has the advantage of cost and the PWM dimming is too complex to design.

Table 4: The evaluation scores of each index

Evaluation index	D1	D2	D3	D4	D5	D6	C4	C5	C6	C7	C8	D9	D10	C10
Compaible of Scr														
dimming	6	4	5	1	3	7	8	6	7	7	9	8	9	3
PWM dimming	8	9	5	5	3	7	4	9	9	9	9	8	1	8
Weight	0.0065	0.0065	0.041	0.0176	0.0234	0.035	0.0104	0.05	0.025	0.025	0.025	0.2633	0.1756	0.2541

CONCLUSION

Based on the former previous studies, the study sets up an evaluation system combining the driver and visual sensory together appropriate in different situations. This system concludes several indexes such as driver performance, system performance and visual comfort. The method designed by the analytic hierarchy process can balance effectively the subjective and objective aspects, theory and practice. It's a new concept for driver assessment, while the selection of indicators and the determination of the weight should be further refined in practice.

ACKNOWLEDGMENT

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