White Paper

Automotive OLED Luminance Consumption Control Methods

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Abstract

Automatic luminance control and consumption rate limit methods are proposed to minimize the luminance consumption and associated image burn-in artifacts of OLED displays used in automotive applications.

Author Keywords

display; automotive; OLED; life

1. Introduction

As active matrix OLEDs are being considered for automotive applications, methods to minimize the amount of luminance degradation and associated "burned-in image" require careful consideration. With the desire to drive OLEDs above 600 cd/m^2 to maintain display visibility, the amount of permanent luminance consumption (amount that the luminance decreases) increases dramatically with rising OLED operating temperatures. The amount of compensation that may be applied at the pixel level to minimize burned-in image effects is limited which necessitates the use other methods to minimize the OLED consumption rate under infrequent adverse conditions. Such methods are:

- Automatic luminance control
- OLED display luminance consumption rate limit
- Minimize OLED display operating ratio (OPR) to reduce both time and temperature burn in rate
- Gaussian spatial distribution of symbology over time
- Improved thermal design to minimize OLED temperature

Automatic luminance control methods drive the display luminance to the level required for display visibility. By utilizing advanced automatic luminance control methods, the average temperature and luminance of the OLED are reduced thereby reducing overall luminance consumption. To properly implement automatic luminance control and mitigate light adaptation effects, a forward looking light sensor is required in addition to ambient light sensors on the display unit [1]. Beyond the use of advanced automatic luminance control methods, a luminance consumption rate limiting method is proposed to effectively limit the amount of luminance degradation under infrequent scenarios of high luminance and high temperature operation usually associated with hot starts when the vehicle has been roasting in the sun. A luminance consumption rate limit method is different than a thermal derating method which limits the display temperature below critical component temperatures (e.g. polarizer, plastics, etc). A consumption rate limiting method takes into account both the variables of luminance and temperature to limit the luminance consumption rate of the OLED display.

2. Background/Objective

This paper primarily discusses the use of automatic luminance control and consumption rate limit control methods to minimize driving the OLED at a constant high luminance level which would result in unacceptable burned-in image performance over the life of the vehicle. The objective of this paper is to demonstrate how intelligent OLED driving methods may be used to successfully implement an automotive OLED display.

2.1. Automatic Luminance Control

An automatic luminance control system as discussed in reference [1] may be utilized to properly control the display luminance. To properly control the display luminance, both the observer forward looking luminance and the ambient illumination on the display are required. The forward looking light sensor is necessary to adjust the display luminance to avoid a light adaptation mismatch condition when the driver is experiencing a bright forward looking scene and the ambient light on the display is shadowed as shown in Figure 2.1-1. By adjusting the display luminance to the level required for display visibility, the average temperature of the OLED is reduced, thus minimizing image burn-in. In addition, the automatic luminance control works in conjunction with the rate limit control by minimizing hot start image burn-in.

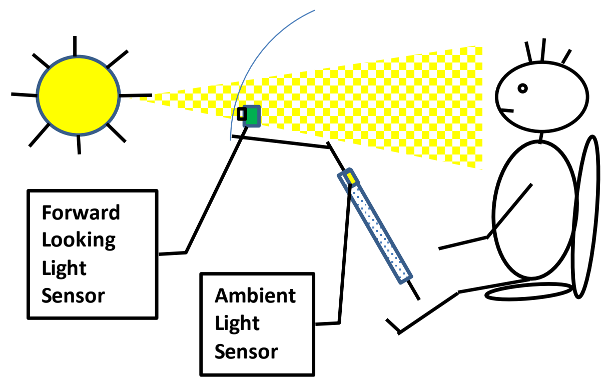

Figure 2.1-1. Automatic Luminance Control [1]

In order to assess the benefits of an automatic luminance control system, a consumption rate formula must be developed such as is discussed in references [2], [3], and [4]. Generally these consumption rate formulas are based on actual life testing of the OLED device under consideration. As an example, a heuristic consumption rate formula was developed in reference [4] as a result of 10,000 hours of device testing per Equation 2.1-1 as plotted per Figure 2.1-2.

$$CR = \frac{L_{op}^2}{L_{\max}} \frac{0.1}{\left(6.42\times10^{10}\right)\times{}^\circ K^{-3} - 1075.5} \frac{nits}{hour} \tag{2.1-1}$$

L_{op}= Operating Luminance

L_{max}= Maximum Display Luminance for the device tested

°K = Temperature in Kelvin

For the device tested in reference [4], the initial consumption rate (CR) is a function of the square of operating luminance (L_{op}) and the cubed power of degrees Kelvin. Testing of other devices may yield different formulas. However in all OLED devices, the luminance consumption rate is a function of both the operating luminance and temperature of the OLED. Therefore by automatically controlling the OLED luminance to only the level required for visibility, the luminance consumption rate may be significantly decreased. A synergistic benefit is that as lower luminance levels are commanded by the automatic luminance control system, the average display temperature is reduced which leads to less luminance consumption.

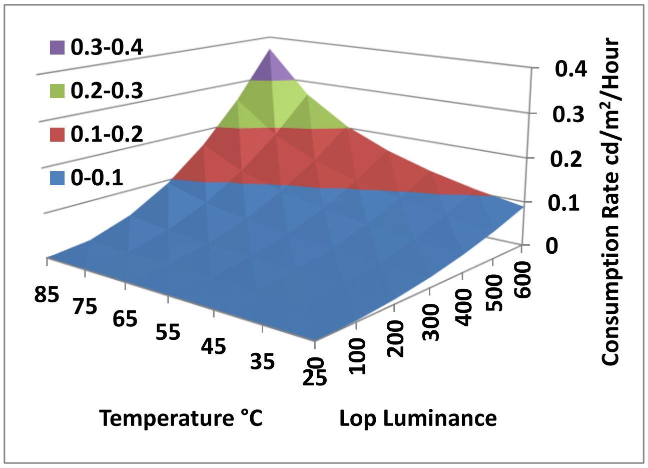

Figure 2.1-2. Luminance Consumption Rate as a Function of Temperature and Operational White Luminance

To gain a perspective on the magnitude of luminance consumption savings that an automatic luminance control system may afford, Equation 2.1-1 may be used to calculate the luminance consumption rates for two cases.

1. With no automatic luminance control, operate at a daytime level of 600 cd/m^2 at 45°C (318°K) per Equation 2.1-2.
2. With automatic luminance control operate at a non-peak level of 300 cd/m^2 at 35°C (308°K) per Equation 2.1-3. Note that the lower temperature is estimated due to the lower operating luminance compared to the 600 cd/m^2 Case 1.

$$CR_1 = \frac{600^2}{300}\frac{0.1}{\left(6.42\times 10^{10}\right)\times 318^{\circ -3} - 1075.5} \qquad (2.1\text{-}2)$$

$$CR_1 = 0.13\frac{nits}{hour}$$

$$CR_2 = \frac{300^2}{300}\frac{0.1}{\left(6.42\times 10^{10}\right)\times 308^{\circ -3} - 1075.5} \qquad (2.1\text{-}3)$$

$$CR_2 = 0.0267\frac{nits}{hour}$$

By operating at a lower automatic luminance controlled level for most of the operating hours when peak luminances are not required for display visibility, the luminance consumption rate is lowered by a factor of almost 5X!

2.2. Luminance Consumption Rate Limit Control

The luminance consumption rate (CR) limit method clamps the luminance consumption rate at some predetermined maximum level that may occur infrequently under hot start up scenarios. The method utilizes the consumption rate as the control variable instead of temperature for the feedback control system.

The consumption rate formula per Equation 2.1-1 may be utilized to understand how the system will operate when the consumption rate is limited to a maximum value. The controlling variable is the display operational luminance, L_{op}, and therefore Equation 2.1-1 may be solved for L_{op}, per Equation 2.2-1. The CR value is held at the desired constant value and the required L_{op} value to limit the OLED CR may be determined as a function of temperature.

$$L_{op} = \sqrt{\frac{CR\times L_{\max}\left(6.42\times 10^{10}\times {}^{\circ}K^{-3} - 1075.5\right)}{0.1}} \qquad (2.2\text{-}1)$$

Equation 2.2-1 is plotted in Figure 2.2-1 for difference consumption rate CR values.

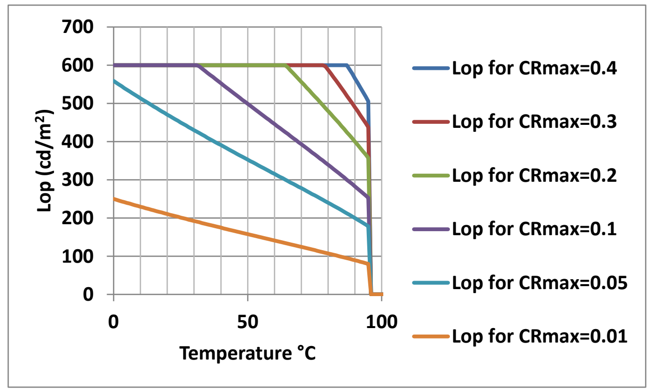

Figure 2.2-1. L_{op} versus Temperature for Different CRs

Figure 2.2-1 also shows the typical temperature derating function after the polarizer reaches 95°C to prevent polarizer damage. Figure 2.2-1 shows that for different selected consumption rate maximum limits, the 600 cd/m^2 would need to decrease as a function of operating temperatures so that the selected consumption rate maximum is not exceeded. An interesting perspective that Figure 2.2-1 provides is the reduction or savings in consumption rate at the intersects of vertical lines. As an example, at 80°C, the consumption rate is reduced from 0.2 cd/m^2/hour at L_{op}=480 cd/m^2 to 0.05 cd/m^2/hour if L_{op} is reduced to 245 cd/m^2. Therefore a reduction in luminance by half reduces the luminance consumption rate by a factor of 8.

In general for the example shown in Figure 2.2-1, a consumption rate limit of 0.15 cd/m^2/hour may be chosen because it provides the desired 600 cd/m^2 under normal automotive cabin temperatures while providing a reduction in luminance consumption rate of 2-4 times at higher temperatures that are experienced more infrequently such as during hot starts until the cabin temperature can be cooled by the air conditioning system.

There are many methods to implement the consumption rate limiting function. The most popular methods may include:

- Utilize a lookup table to determine the operating luminance as a function of measured OLED temperature
- Utilize a mathematical computation to calculate the operating luminance as a function measured OLED temperature
- Utilize a PID control loop to control the operating luminance as a function of the measured OLED temperature

All methods will employ the use of a temperature measuring device such as a thermistor which is thermally coupled to the OLED display whereby the display temperature is converted to a digital value via an A/D converter on a microprocessor. The A/D temperature value is then utilized to control the operating luminance to not allow the display luminance consumption rate to exceed a predetermined maximum limit value.

Assuming a hot start exponential temperature decrease from 85°C to 45°C, Figure 2.2-2 shows how the CR limit method works.

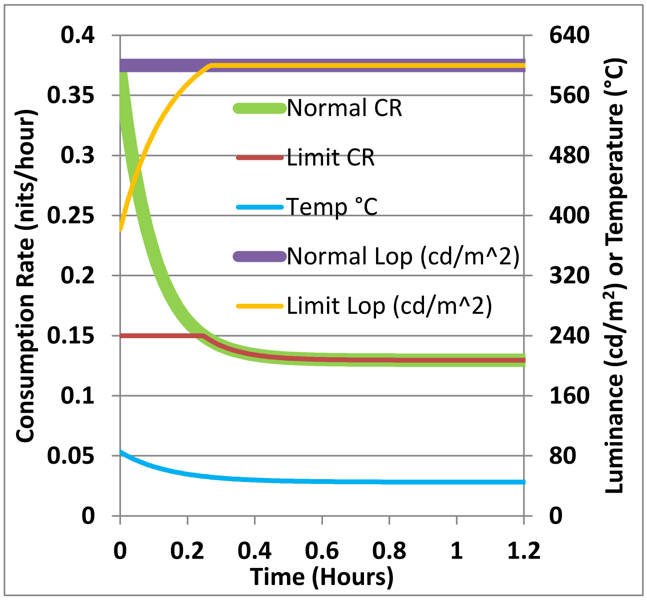

Figure 2.2-2. Hot Start Example

In order to limit the consumption rate to 0.15 nits/hour, the display luminance "Limit Lop" is initially lowered to around 400 cd/m^2 and then as the temperature decreases, the luminance is allowed to increase to the desired 600 cd/m^2. The area between the "Normal CR" and "Limit CR" lines is the amount of luminance that is saved for each hot start by utilizing the consumption rate limit control method. As described in reference [4], the consumption rate formula per Equation 2.2-1 with an exponential temperature decay from +85°C to 45°C with a time constant of 0.25 hours may be dramatically simplified via curve fitting methods to yield Equation 2.2-2.

$$CR = \frac{L_{op}^2}{L_{\max}}\left[1.08\times10^{-4} + 2.01\times10^{-4}\times e^{-t/0.1}\right]\frac{nits}{hour} \tag{2.2-2}$$

Equation 2.2-2 is shown by the "Normal CR" plot in Figure 2.2-2. To calculate the amount of luminance degradation (LD), Equation 2.2-2 may be integrated to yield Equation 2.2-3.

$$LD = \int_0^t CRdt$$

$$LD = \frac{L_{op}^2}{L_{\max}}\left[1.08E^{-4}t + 2.01E^{-5}\left(1 - e^{-t/0.1}\right)\right]nits \tag{2.2-3}$$

Equation 2.2-3 can be used to determine the luminance decrease (area under the curve) as a function of time for the "Normal CR" curve in Figure 2.2-2. The first term ($1.08E^{-4}t$) describes the steady state luminance consumption at 45°C while the second term calculates the additional initial start-up luminance consumption when the temperature is changing from +85°C to the steady state level of 45°C. Therefore the additional delta luminance consumption due to the hot start from 85°C at 600 cd/m^2 may be determined per Equation 2.2-4.

$$\Delta LD = \frac{L_{op}^2}{L_{\max}}\left[2.01E^{-5}\left(1 - e^{-\infty/0.1}\right)\right]$$

$$\Delta LD = \frac{600^2}{300}2.01E^{-5} = 0.02412\frac{nits}{start} \tag{2.2-4}$$

Similar integration methods may be utilized to determine the delta luminance consumption for the "Limit CR" curve per Equation 2.2-5 where the luminance consumption rate is limited. Note that the intersection time between the "Normal CR" curve and the "Limit CR" curve is calculated to be at t=0.247 hours.

$$\Delta LD = (0.15 - 0.1296)0.247 + 0.02412e^{-0.247/0.1}$$

$$\Delta LD = 0.00704\frac{nits}{start} \tag{2.2-5}$$

The difference between Equations 2.2-4 and 2.2-5 of 0.01708 nits/start shows the benefit gained by the luminance consumption rate limit control method.

3. Modeling Example

A modeling example shows the benefit that may be obtained over the life a vehicle by using automatic luminance control in conjunction with luminance consumption rate limit control for the hot starts. The methods as described in reference [4] are utilized. The automotive life example assumes:

- 10 years at 15K mi/year for a total of 150K miles. At an average speed of 30 miles/hour, the total number of operational hours is 5000 hours.
- 3,650 hot summer starts (2 hot +85°C starts/summer day X 182.4 days/year X 10 years). Note that 182.4 days assumes 6 months of hot days per year such as in Phoenix Arizona.
- The morning and afternoon peak 600 cd/m^2 automatic luminance conditions are assumed to occur in a 20° sun angle aperture and only in 2 directions resulting in a 12% occurrence percentage.
- An automatic luminance level of 300 cd/m^2 is assumed for most of the 2200 daytime hours and 600 cd/m^2 is used for the peak luminance occurrences of 300 hours (12% of the time).
- A consumption rate limit of 0.15 nits/hours is used for the "Auto" hot start at 600cd/m^2 scenario.

The "Normal" columns describe what would happen when automatic luminance and CR rate limit control is not used resulting in an unacceptable 68.9% decrease in luminance over the life of the vehicle. In contrast, the "Auto" columns show the improvements secured with the use of automatic luminance control and CR limit control with a lifetime decrease of 19.55% which may allow the OLED pixel compensation method to minimize the burned in image.

Table 3-1. OLED Automotive Life Example

Condition	Normal cd/m²	Normal OLED Temp °C	Normal Decrease cd/m²	Normal Consumption Rate (nits/hr)	Auto cd/m²	Auto OLED Temp °C	Auto Decrease cd/m²	Auto Consumption Rate (nits/hr)
3168 Day +85C Hot Starts @ Auto=300 nits	600	45	76.41	0.02412 nits/start (Eq. 2.2-4)	300	45	19.10	0.00603 nits/start
432 Day +85C Hot Starts @ Auto=600 nits	600	45	10.41	0.02412 nits/start (Eq. 2.2-4)	600	45	3.04	0.00704 nits/start (Eq. 2.2-5)
2200 Hours Daytime Nominal Luminance	600	45	286.66	0.130303336 (Eq. 2.1-2)	300	35	58.83	0.026743516 (Eq. 2.1-3)
300 Hours Daytime Auto Peak Luminance	600	45	39.09	0.130303336 (Eq. 2.1-2)	600	40	35.35	0.117861979 (Eq. 2.1-3)
2500 Hours Night Time Operation	40	25	0.98	0.000394923	40	25	0.98	0.000394923
Total Luminance Decrease End of Life (cd/m²)			413.58				117.33	
% Decrease			68.93%				19.55%	

4. Demonstrator

An OLED prototype was fabricated to demonstrate and dynamically observe the automatic luminance control and consumption rate limit functions per Figure 4-1. The demonstrator has both forward looking and ambient logarithmic light sensors and the automatic luminance control system as described in reference [1]

Figure 4-1. Dual OLED Demonstrator

Figure 4-2 shows the auto-luminance control screen to demonstrate both the automatic luminance control and the consumption rate limit function. One of the nice features of the test screen is the capability to artificially change the OLED screen temperature and observe the instantaneous consumption rate.

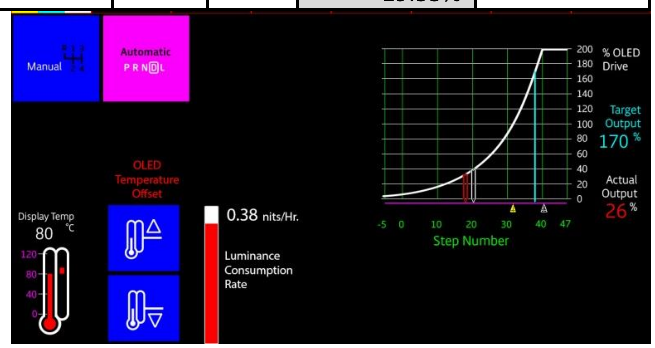

Figure 4-2. Auto-luminance Control

5. Conclusion

An automatic luminance control system in conjunction with a luminance consumption rate limiting method has been developed for OLED displays that may be utilized to minimize the amount of luminance degradation and associated image burn-in artifacts. This consumption rate limiting method is particularly applicable to automotive environments where high OLED luminances may be commanded under elevated temperature environments such as a hot start up condition.

6. References

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[2] P. Weindorf, “Automotive OLED Life Prediction Method, Detroit SID 2005 Proceedings

[3] Paulo Neilson Marques dos Anjos (2013), “Analysis of electroluminescence degradation for organic light-emitting diode using a rate equation of chemical kinetics”, Journal of Information Display, 14:4, 115-120, DOI: 10.1080/15980316.2013.851126.

[4] P. Weindorf, D. Andres, J. Hatfield, “Automotive OLED Life Test and Prediction”, Detroit SID 2013

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