Automotive OLED Life Prediction Method

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Abstract

Currently there is a lot of industry buzz surrounding the use of OLED displays and their purported benefits. In contrast to light valve technologies that do not suffer significantly from aging, emissive technologies must be carefully analyzed to ensure that lifetime expectations are met. A prediction method has been developed to determine the amount of luminance degradation under automotive usage profiles.

Keywords/Acronyms

OLED – Organic Light Emitting Diode

LCOS – Liquid Crystal on Silicon

CRT – Cathode Ray Tube

VF – Vacuum Fluorescent

FED – Field Emission Display

EL – Electroluminescent

1. Introduction

In general light valve technologies such as liquid crystal, interferometric modulator, LCOS, micro-mirror, and electrophoretic displays depend on a general light source that decays over time. Light valve displays do not suffer appreciably from aging whereby portions or color of the display used more frequently emit or reflect a lower luminance than portions or colors used less frequently. On the other hand, emissive technologies such as CRT, VF, FED, Plasma, EL and OLED displays all suffer from the aging phenomena thus requiring screen saver functions if the same data is displayed for long periods of time. Although OLEDs have many benefits, their Achilles heel is aging which is accelerated substantially at elevated temperatures commonly associated with automotive environments. By developing an analysis method to predict and understand the amount of aging under automotive usage profiles, it can be determined whether an OLED display can be successfully utilized in the application.

2. OLED Life Prediction Model

The goal is to develop a mathematical model whereby the amount of OLED aging can be determined under dynamic temperature conditions found in automotive environments.

2.1 Life versus Temperature Formula

The first step towards developing a luminance degradation model is to obtain OLED life data at 3 different temperatures of interest such as 25°C, 60°C and 85°C, the goal being to develop a mathematical relationship that gives luminance degradation as a function of temperature. Example data from an OLED vendor is shown in Figure 2.1-1.

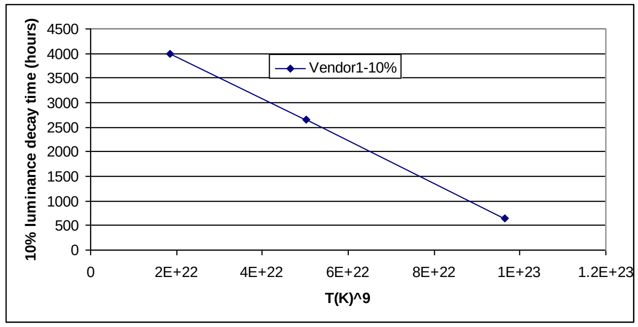

Figure 2.1-1, OLED Vendor Life Data

The next step is to develop the best heuristic curve fitting function described by a linear equation. As an example, the function versus $(1/T)^9$, as shown in Figure 2.1-1, shows that the function can be described per Equation 2.1-1. Note that the data for this vendor is plotted for a 10% reduction in luminance.

$$H_{-10\%} = -4.29 \times 10^{-20}\left[T(K)^9\right] + 4793.65 \quad \text{(Eq 2.1-1)}$$

where H is in hours for the luminance to degrade by 10%. Note that other linear formula types may be used depending on the shape of the curve. Using this formula, the consumption rate (CR) formula can be determined per Equation 2.1-2.

$$CR = \frac{120 \times 0.1}{-4.29 \times 10^{-20}\left[T(K)^9\right] + 4793.65}\frac{Nits}{Hour} \quad \text{(Eq 2.1-2)}$$

where CR is the luminance consumption rate. Note that 120 is the starting luminance for the OLED tested and 0.1 represents a 10% luminance reduction.

2.2 Exponential Temperature Decay

Equation 2.1-2 only describes the consumption rate at any one temperature (Kelvin). Next, an exponential decay temperature function can be substituted for the temperature variable to describe how the ambient temperature in the vehicle decreases from an 85ºC hot start and a 20 minute time constant down to 25ºC yielding Equation 2.2-1. This situation may describe a hot start for a display under a solar load situation in a location like Phoenix, Arizona. The 20 minutes (0.15 hours time constant) may describe how long it takes for the air conditioning system to reduce the internal temperatures to a normal ambient.

$$CR = \frac{12}{-4.29 \times 10^{-20}\left[298 + 60e^{-t/0.15}\right]^9 + 4793.65}\frac{Nits}{Hour} \quad \text{(Eq 2.2-1)}$$

2.3 Curve Fitting Simplification

The next step in the process is to determine a good exponential function curve fit to the above equation in order to simplify the integration mathematics and to give a resultant formula which has separate steady state and hot start components as is shown in

Figure 2.2. The reasonable curve fit exponential formula is as shown in Equation 2.3-1 and as shown in Figure 2.2.

$$CR = 0.003 + 0.0154 e^{-t/0.035} \frac{Nits}{Hour} \qquad \text{(Eq 2.3-1)}$$

Integrating the consumption rate (CR) formula (Eq 2.3-1) yields the Luminance Degradation (LD) formula per Equation 2.3-2.

$$LD = \int_0^t 0.003 + 0.0154 e^{-t/0.035} dt = 0.003t + 0.000539\left[1 - e^{-t/0.035}\right]$$

(Eq.2.3-2)

The first term is the steady state luminance consumption at 25ºC and the second term shows that 0.000539 Nits is consumed for each +85ºC start. By knowing how many hot starts/day can be expected, one can simply calculate how much luminance is used up by adding the number of hot starts and adding this result to the steady state consumption.

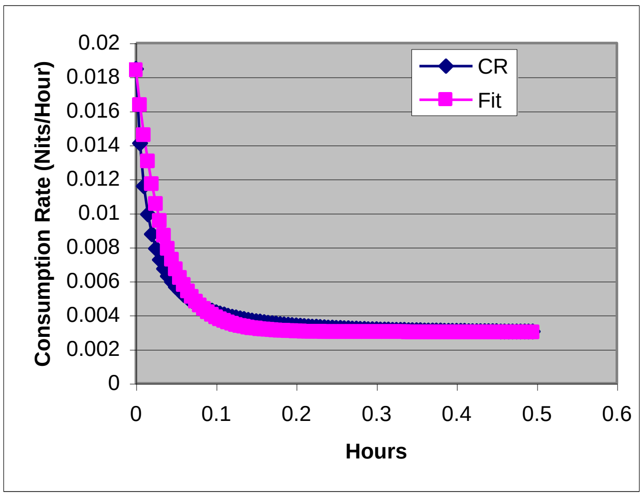

Figure 2.2 Luminance Degradation Function Curve Fit

2.4 Luminance Component

To account for various OLED luminance levels, the lifetime of OLED devices is generally inversely proportional to the luminance level under test. For instance if a display has a half-life of 10,000 hours for a luminance of 100 cd/m^2, then it is expected to have a half-life of 1,000 hours if tested under 1,000 cd/m^2 conditions. Furthermore this relationship generally is correct under different temperature conditions. To add this drive relationship to the equation developed so far, the consumption rate formulas are simply modified by multiplying the equation by the factor L_{OP}/L_N where L_{OP} is the operating luminance and L_N is the normal operating luminance under which the device was tested. Since the integral of a constant times a function is the constant times the integral, the luminance decrease formula (Eq 2.3-2) can be multiplied by the L_{OP}/L_N ratio to yield Equation 2.4-1.

$$LD = \frac{L_{OP}}{L_N}\left\{0.003t + 0.000539\left[1 - e^{-t/0.035}\right]\right\} \qquad \text{(Eq. 2.4-1)}$$

3. Automotive Life Example

Assuming 10 years at 15Kmi/year (150Kmi total) and an average speed of 30mi/hr, the total number of operational hours is 5000 hours with an estimated 3650 hot summer starts (2 hot start/summer day). The luminance degradation over the life of the vehicle may be estimated as shown in Table 3-1.

Condition	Luminance Decrease	Notes
3650 +85ºC Hot Starts	1.97 Nits	1.97=3650x0.000539
2500 hours @ 120 Nits Day Time Operation	7.5 Nits	2500x0.003
2500 hours @ 40 Nits Night Time Operation	2.5 Nits	2500x0.003x40/120
Total Luminance Decrease @ End of Life	12 Nits	10% decrease from initial 120 Nits.

Table 3.1 OLED Automotive Life Example

Although a 12 Nit 10% reduction from the original 120 Nit starting point can be detected by the eye (a "5% change in white luminance is hard to see[1]"), this amount of degradation is probably acceptable and would be less than this if the pixel is not always lit compared to a background that is never lit.

It is interesting to note that for this OLED material, instead of the hot starts, the major contributor is steady state operation. This is due to the fact that the +60ºC curve of Figure 2.1-1 for the OLED life data is very close to the +25ºC curve and since the exponential temperature decrease from 85ºC to 60ºC occurs very quickly, the amount of luminance degradation for the high temperature hot starts has been greatly reduced with this particular OLED vendor. However this result may be different for different OLED vendors. This luminance degradation estimation method can be used to evaluate OLED suppliers under a variety of automotive environmental profiles and can effectively be used to determine the amount of luminance reduction based on limited OLED life data from OLED vendors.

4. OLED Comparison Summary

A summary of different OLED vendor display data was analyzed for comparison purposes. Two steady state temperatures conditions consisting of 25°C and 45°C were analyzed with the results as shown in Figure 4.1.

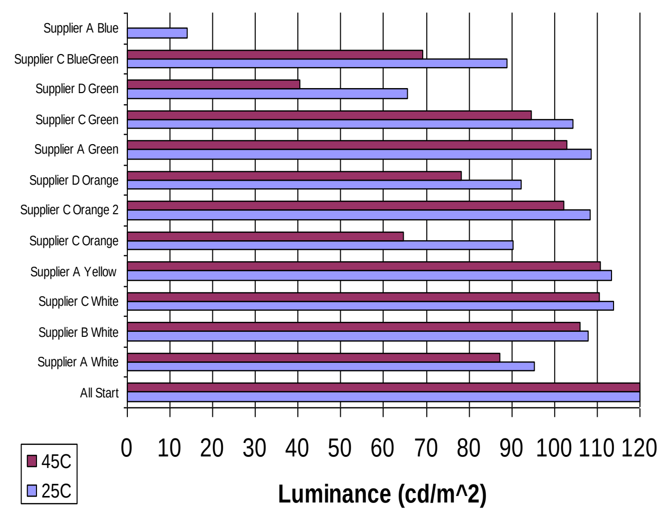

Figure 4.1, OLED Automotive Life Comparison

5. Vacuum Fluorescent Display Life

Since dot matrix Vacuum Fluorescent (VF) Displays have been accepted in automotive platforms, a useful analysis is to compare the lifetime performance of Vacuum Fluorescent Displays to OLEDs. As an example, the lifetime measurements for a 64x128 dot matrix display with a typical luminance of 1800 cd/m^2 is shown in Figure 5.1. Luminance degradation for VF displays is primarily a function of:

- Filament wear out (majority of the wear out)
- Out-gassing contamination
- Barium deposition on the phosphor that is lit

The "On Dot" data in Figure 5.1 has all three components, whereas the "Off Dot" data has the 1st two components. The more important component is the barium deposition on the lit phosphors since it will contribute to image burn-in; whereas the filament wear out and out-gassing generally affect the overall luminance of the display. Therefore plotting the difference between the "On Dot" and "Off Dot" (Figure 5.2) shows the luminance decrease that would contribute to image burn-in.

Using these approximately linear curves, the life analysis can be performed in a similar fashion to the OLED analysis by determining the transfer function of "90% Luminance Degradation" as a function of "Temperature" as shown in Figure 5.3. The curve fit function depicted in Figure 5.3 is per Equation 5-1.

$$H_{-10\%} = 36015 - 87.3T_K \qquad \text{(Eq 5-1)}$$

Using Equation 5-1 that describes how many hours it takes to get to 90% of initial luminance as a function of temperature, the Consumption Rate (CR) formula can be developed per Equation 5-2.

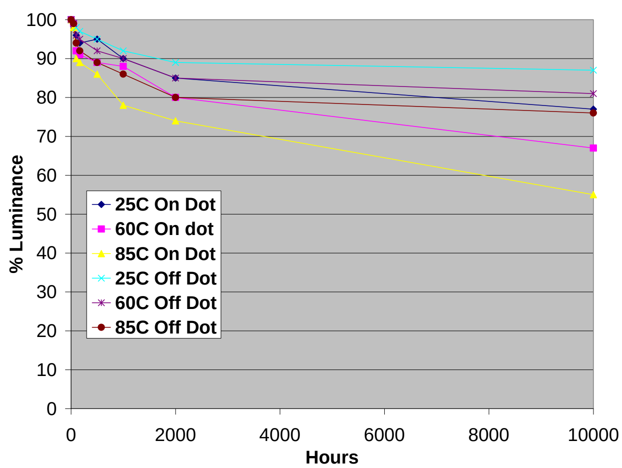

Figure 5.1, Vacuum Fluorescent Display Life

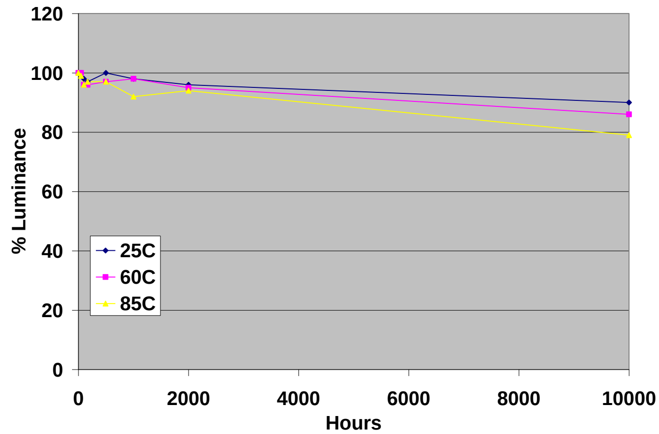

Figure 5.2, VF Linear Curve Approximation

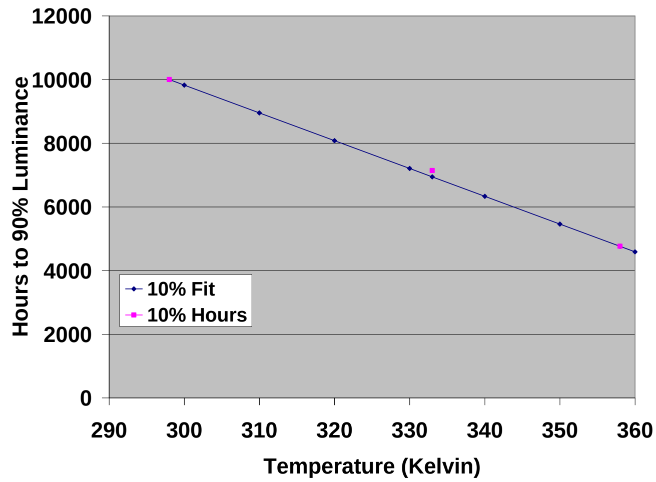

Figure 5.3, VF Temperature Function

$$CR = \frac{1800 \times 0.1 \times 0.067}{36015 - 87.3T_K} \qquad \text{(Eq 5-2)}$$

1800 = Initial Luminance in cd/m^2

0.1 = 10% Luminance Reduction

0.067 = VF Filter Transmission adjusted for 120 cd/m^2 to match the OLED initial luminance

T_K = Temperature in degrees Kelvin

Assuming that the stabilized operational temperature is 45°C, the temperature T_K from an 85°C hot start with a 10%-90% time constant of approximately 20 minutes can be described by Equation 5-3.

$$T_K = 318 + 40e^{-t/0.15} \qquad \text{(Eq 5-3)}$$

Substituting Equation 5-3 into Equation 5-2 yields the consumption rate formula per Equation 5-4 that describes a hot start from +85°C.

$$CR = \frac{1800 \times 0.1 \times 0.067}{36015 - 87.3\left(318 + 40e^{-t/0.15}\right)} \quad \text{(Eq 5-4)}$$

Since Equation 5-4 is difficult to deal with mathematically, Equation 5-5 can be used instead for simplification as shown in Figure 5.4.

$$CR_{FIT} = 0.001461 + 0.001072\, e^{-t/0.11} \quad \text{(Eq 5-5)}$$

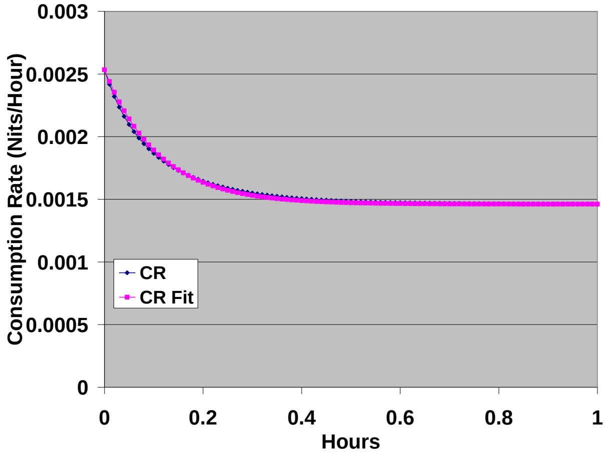

Figure 5.4, Consumption Rate Curve Fit

Equation 5-5 can be integrated to yield the Luminance Degradation (LD) formula, Equation 5-6, that describes how much luminance is lost during a hot start from +85°C.

$$LD = 0.001461t + 0.000118\left[1 - e^{-t/0.11}\right] \quad \text{(Eq 5-6)}$$

From Equation 5-6, each hot start consumes 0.000118 cd/m^2 of display luminance and the steady state loss at 45°C ambient is 0.00146 cd/m^2·hr. Table 5.1 shows a summary of the luminance degradation for 5000 hours of operation at a 45°C ambient with 3650 hot starts from +85°C. Note that as stated previously, this is the amount of image burn luminance difference and not the overall decrease in luminance.

Condition	**Luminance Decrease**	**Notes**
3650 +85ºC Hot Starts	0.43 Nits	1.97=3650x0.000118
2500 hours @ 120 Nits Day Time Operation	3.65 Nits	2500x0.001461
2500 hours @ 40 Nits Night Time Operation	1.21 Nits	2500x0.001461x40/120
Total Luminance Decrease @ End of Life	5.31 Nits	4.4% decrease from initial 120 Nits.

Table 5.1, VF Automotive Life Example

As shown in Figure 5.5, the calculated VF burn-in performance is slightly better than OLED performance. A similar analysis for total VF life (including filament wear out) estimates the total luminance decrease to 92 cd/m^2. This leads to the conclusion that when compared to VF displays, certain OLED colors/display may perform better from an overall luminance decrease, but will be slightly worse with respect to burned-in image performance under automotive life conditions. However other considerations such as storage stability must be considered.

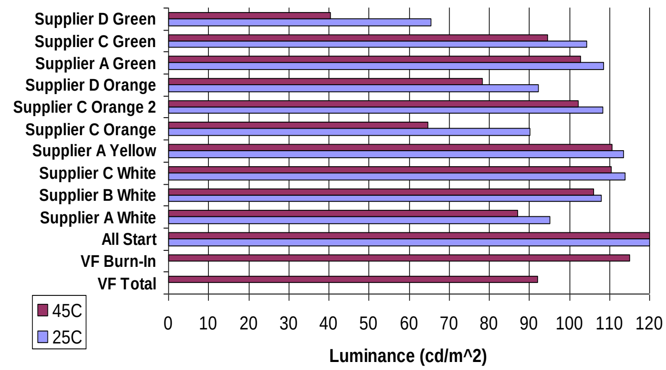

Figure 5.5, VF and OLED Life Comparison

6. Conclusion

A mathematical method has been developed to determine OLED luminance degradation as a function of the following variables:

- Steady state temperature
- Hot start temperature
- Hot start exponential cool down time constant
- Luminance

The mathematical model can be used to determine the expected amount of luminance decrease as a function of the operational profile over the life of the vehicle. This modeling method is also helpful to normalize and compare OLED data from different vendors and with other accepted automotive display technologies such as Vacuum Fluorescent (VF) Displays. When compared to VF displays, several OLED choices may be available that are close to VF operational lifetimes in the automotive environment.

6. References

1. VESA, *FLAT PANEL MEASUREMENTS STANDARD*, Version 1.0, May 15, 1998, p 88.