LCD Reflection Model for Simulation of Automotive and Mobile **Displays under Daylight Condition**

Ramazan Ayasli¹, Julian Bürner¹, Maxim Schmidt¹, Sascha Xu²

Ramazan.Ayasli@Ime.uni-saarland.de ¹ Saarland University, Saarbrücken, Germany ² X-Motive GmbH. Saarbrücken. Germanv Keywords: LC Reflection, Readability, Sunlight Compensation, Daylight Compensation, tone-mapping.

ABSTRACT

The reflection on an LCD degrades the visual quality and particularly readability of a display. While the linear dependence of the reflection on the daylight intensity is it has been found out by extensive well-known. measurements that the reflection also depends on the gray-value of a pixel and thus image contents. The reflection model presented in this paper consists of two parts: one dependent on the transmission value of a pixel and one constant, respectively. It allows simulation of an image displayed considering the ambient light and development of proper daylight compensation. Also, examination of safety requirement and/or safety integrity may be enabled.

Introduction 1

Daylight, particularly strong sunlight, significantly deteriorates the image quality of a display. One method to mitigate this problem is to increase display brightness. Another way is to apply image processing method like tone-mapping [1]. For automotive applications the problem is severe since it is safety relevant [2]. Standard like ISO 15008 and 26262 must be met. A critical value is the threshold for local contrast which must be met or exceeded. The measurement of the local contrast particularly for HMI contents, which make use of the full gray-value range (not just black and white or 0/255), may be difficult and inaccurate. Beside of this issue, the color gamut may get significantly shrunk due to daylight and contrast the (HMI) color of image may aet reduced/distorted.

A reflection model might be helpful for the calculation of the local contrast for HMI design, development of daylight image enhancement for a display etc. It is apparent that the reflection is proportional to the intensity of the ambient light, like sunlight. Other dependencies like that of display pixel gray value have not been investigated yet. Thus, measurements of LCD's behavior under strong ambient light and varying pixel gray value have been conducted.

Measurement of LCD Reflection 2

The setup is shown in the photograph of Figure 1. A daylight lamp (ARRI Daylight Compact 2500) is placed in a dark room. The D65 illuminant has a maximum brightness of 62K LUX at a distance of 2 meters and 45°/45° angles to the test object, an automotive display (12.3", 1920RGB720). The display is measured by a

spectroradiometer (Photo Research SpectraScan PR-740) and/or a colorimeter (Eldim UMaster). Photographs captured by a consumer camera is used for various comparisons. The wall of the room is black, and the table is covered by black cloth for minimizing reflection of other objects.



Figure 1 Setup of an LCD under daylight

Various series of measurements of the electro-optical transfer function (EOTF) are conducted and analyzed. In the first series (Figure 2), the LCD is operated in the standard mode: the backlight unit (BLU) is turned on and red, green, blue and gray uniform images at varying gray values (gv) were measured in a dark ambient, as the daylight lamp is off. The measurements results exhibit a well-known Gamma-curvature (gamma=2.37)



Figure 2 EOTF characteristics of an LCD w/o daylight In a second series, the same images were displayed, while the LCD was in the standard operation condition and the daylight lamp is on (Figure 3). An offset value of ~20 nits for all four measurements is visible. It is assumed that the slight variation of these four curves at gv=0 is due to temperature variations during the measurements, while at a constant temperature the offset-value is constant, too. At full-scale gray-value (gv=255), the luminance increases for all four colors exceed the offset value for gv=0. The increase is due to the reflection, which is apparently dependent of the gray-value.



Figure 3 EOTF characteristics of an LCD with daylight

In a third series (Figure 4), the displayed images are unaltered, the daylight lamp remains on, while the BLU is turned off. Thus, the measurement is affected only by the reflected daylight.



Figure 4 EOTF characteristics of an LCD w/o backlight

The curves from Figure 2 and Figure 4 can be summed up yielding to the curves in Figure 3. This confirms the consistency of the measurements. Beside these quantitative measurements, the daylight reflection causes severe deterioration of the image quality, e.g. a drastically reduced contrast ratio. For the example of Figure 3, the static contrast ratio is just 7. Another unwished effect is the significantly reduced color gamut (Figure 5). The large triangle represents the native gamut of the LCD, if no reflected light exists (Figure 2). The inner triangle is extracted from the measurement of Figure 4. The triangle in between is the gamut for the case, when the daylight lamp is on, and the reflection is superposed (Figure 3). This case is accordant to a real operation under daylight condition. Beyond, the shrunk gamut, the color contrast particularly for lower and median gv is diminished.



Figure 5 Gamut from Figure 1, 2 and 3

3 LC Reflection Model

The measurements in the last section are performed on uniform images. No spatial resolution is required. A measurement of a real image with pixelwise individual gray value and luminance is much more difficult or technically hardly possible, as a matching between display pixels and camera pixels cannot be maintained. Thus, an LCD reflection model will help to allow a realistic simulation of an image under daylight and probe if specifications like ISO 15008 are fulfilled.

First modeling step is to correlate the reflection characteristics with physical structure and mechanism. As gained from the last section, the reflection depends on the gray value. The dependence is a non-linear function. At gv = 0, there is an offset luminance measured. At lower and median gray values, the reflection hardly or just slightly increases. At higher gray values, the reflection substantially increases for each RGB-channel.

These phenomena may be assigned to the physical structure of an LCD. In Figure 6 a cross-section of an LC pixel is shown.





The surface area is coved by a glass, diverse films, polarization filters, RGB color filters with underlying optically active LC-cells as well as optically passive structures like ITO, metal or TFTs. These passive structures may have own transmission and reflection. The daylight is reflected by these structures independent of the gray value of a pixel, but just proportional to the intensity of the incoming light.

The daylight will also pass the color filters and enter the open area (aperture) of a pixel with polarization filters and LC-cell. In case of gv = 0, the transmission of a (sub)pixel is negligible. The light is absorbed. In the opposite case (gv=255), the transmission rate is maximum, the daylight may go through the LC-cell up to the BLU plate. The plate has usually a reflective surface for higher out-coupling of the LED light. Thus, the light will take the adverse direction and go back to the front of the display as the direction of the backlight. This results a further reflection in addition to the constant reflection generated by passive structures. Therefore, the following equation may be established for the luminance of the reflection light

$$Y_{REFL} = f_{CON} \cdot L_{AMB} + f_R(gv_R) \cdot L_{AMB} + f_G(gv_G) \cdot L_{AMB} + f_B(gv_B) \cdot L_{AMB}$$
(1)

The first term of RHS describes the constant reflection. The proportionality to the ambient light L_{AMB} is noted as f_{CON} . The 2nd, 3rd and 4th term of RHS describe the gray value dependent reflection of the RGB-subpixels, respectively. Assumed that the 2nd, 3rd and 4th terms are zero/negligible, if the gray-values and thus the corresponding transmission values are zero or negligible, the curves measured in Figure 2, Figure 3 and Figure 4 in the low gray-value region can be mapped by this model. Physically it may be interpreted that the incoming light from the front to the LC cells are not reflected but absorbed.

If the gray value of a pixel is higher, the LC pixel may get transparent. Thus ambient light will go through the LC pixel and beam the BLU. The light having passed the LCpixel will be partially reflected and takes the way back towards the front and the viewer of the display. This means, that the transmissive LC-cell is passed twice. Thus, equation (1) may be detailed to.

$f_R(gv_R) \sim t_R^2 = f_R \cdot gv_R^{2\cdot\gamma}$	(2)
$f_G(gv_G) \sim t_G^2 = f_G \cdot gv_G^{2 \cdot \gamma}$	(3)
$f_B(gv_B) \sim t_B^2 = f_B \cdot gv_B^{2\cdot\gamma}$	(4)

 t_R , t_G and t_B are the normalized transmission values of R, G and B subpixels, respectively. The square function stands for the two paths through the LC-cell of the ambient light, from the display front to BLU plate and from BLU plate to the display front. The normalized transmission values may be described by the gamma function.

In Figure 7, a good agreement between the measurement (crosses) and the model function (lines) is shown. The model parameters are listed in Table 1. The model function is however steeper than the measurement. One reason may be the reflection of the active LC-cell

surface, which may vary with the polarization of the cell (gray value/transmission). This reflection is not a square function of the transmission or has no power of $2 \cdot \gamma$ for the gray value. Compared to the reflection from the BLU plate, is relatively low. The square function in equation 2, 3 and 4 might be too strong, i.e., the power shall be slightly below two. This is however just a matter of curve-fitting.



Figure 7 Comparison between reflection model and measurement for Figure 4

For the model development the daylight lamp (D65) with a constant color temperature/index is used. For future research, the varying chromaticity of daylight may be considered. It includes measurements with various light sources having different color temperatures. The reflection model may be amended to a three-dimensional output (XYZ) with a three-dimensional input (XYZ) stating the incoming daylight.

Notation	Value
f _{con}	$2.805 \cdot 10^{-4}$
f_R	$1.535 \cdot 10^{-11}$
f_G	$5.223 \cdot 10^{-11}$
f_B	$0.869 \cdot 10^{-11}$

Table 1 Parameters for the reflection model

4 Simulation and Validation

The LC reflection model may allow a simulation of an image produced by an LCD under daylight. Since the reflection model is physically based, a reasonable method for summing up the light generated by LCD and the reflection light is the XYZ model. While the reflection light may be assumed as spatially invariant, the LCD emits a pixelwise individual tristimulus value. The XYZ value for each pixel is:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{LCD} = Y_{BL} \cdot \begin{pmatrix} R_X & G_X & B_X \\ R_Y & G_Y & B_Y \\ R_Z & G_Z & B_Z \end{pmatrix} \cdot \begin{pmatrix} t_R \\ t_G \\ t_B \end{pmatrix}$$
(5)

 Y_{BL} is the brightness of the BLU. The 3X3 matrix represents the display property. t_R , t_G and t_B are the normalized transmission values and are controlled by the subpixel gray values. Now, the light received from a pixel is superposed by the reflection light.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{TOTAL} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{LCD} + \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{REFL}$$
(6)

The luminance of the reflection light is as modelled in equation (1). It is assumed, that the chromaticity (x, y) is unaltered, as the chromaticity is fixed at D65. X and Z values of the reflected light can subsequently be determined. The resulting total tristimulus values (XYZ)_{TOTAL} can be used to construct an image under daylight. Equation (5) may be inverted.

$$\begin{pmatrix} t'_{R} \\ t'_{G} \\ t'_{B} \end{pmatrix} = \frac{1}{Y_{BL}} \cdot \begin{pmatrix} R_{X} & G_{X} & B_{X} \\ R_{Y} & G_{Y} & B_{Y} \\ R_{Z} & G_{Z} & B_{Z} \end{pmatrix}^{-1} \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{TOTAL}$$
(7)

An inverse gamma function may be applied to the transmission values t'_R , t'_G and t'_B for construction of the image under daylight perceived. Figure 8 shows two photographs of an automotive HMI displayed on an LCD. The upper image was captured under the condition, that the original image is displayed, while the daylight lamp is on. Unwanted structures like fingerprint or dust particles are visible due to the lamp and the different reflection characteristics. The lower photograph captures the image displayed, which is constructed according to equation 7, while the daylight lamp is off. Both photographs were taken by same exposure conditions on one and the same display.



Figure 8 Image displayed under daylight

The perceptions are similar. This means that the simulation may deliver a dependable result about an image displayed under daylight. This may make a pixelwise luminance measurement, which is difficult and not dependable, in many cases obsolete.

5 Applications

Daylight deteriorates the image quality. Diverse methods have been introduced to mitigate the problem. One is physical like increasing the display luminance and/or reduction of the reflection of a display surface. Another one is based on image processing like tone-mapping, gradient enhancement, compensation of color distortion etc. [2].

The effectiveness of these methods needs to be evaluated. The reflection model and the corresponding

simulation presented in this paper may provide an efficient tool for validation and evaluation. Relevant applications are automotive and mobile displays.

One is the assessment of image quality. Methods like SSIM may be applied by comparing the original image with a simulated image under daylight.

Since automotive displays are safety relevant, further evaluation may get necessary. One is the exam if standard like ISO15008 and/or ISO26262 is fulfilled. Also, specific algorithms may be used like ASIL protected video to calculate the distance between the original image and the image perceived[4]. Since the most automotive images are artificial HMIs, the outputs may be also feedbacks to HMI designers who can consider in addition to functional and esthetic aspects also the influence of daylights and make the HMI's more robust.

6 Conclusion

This reflection model is according to the best knowledge of the authors novel. The model for reflected light comprises of reflection of passive (invariant) structure and reflection of active LC-cells. The reflection of active LC-cells depends on the pixel gray value and may be modelled as a square function of its transmission value. This way, the light reflected is pixelwise individual. The model allows simulation of an image displayed under daylight. The quality of the image altered by daylight may be predicted. It also allows an examination if ISO standards like ISO15008 is fulfilled or ASIL classification. Difficult pixelwise measurement of an image displayed may be obsolete in many cases. It also provides a tool to evaluate image processing algorithm particularly for compensation of daylight influence and thus to ensure enhancement of the image guality. Design of HMIs which shall be readable under daylight may get much simpler and straightforward.

7 References

- [1] Blankenbach K, Sycev A, Kurbatfinski S, Zobl M. Optimization and evaluation of automotive displays under bright ambient light using novel image enhancement algorithms. J Soc Inf Display. 2014; 22(5): 267–279.
- [2] Paul Weindorf, Elijah Auger, Bian Hayden, "Automotive Image Enhancement", Vehicle Displays & Interface Symposium, proceeding, pp. 25-31, 2022
- [3] H. Su, C. Jung, S. Wang and Y. Du, "Readability Enhancement of Displayed Images Under Ambient Light," in IEEE Transactions on Circuits and Systems for Video Technology, vol. 28, no. 7, pp. 1481-1496, July 2018, doi: 10.1109/TCSVT.2017.2676881.
- [4] Xu, S., Bauer, J., Axmann, B., Maass, W. (2020). CD2: Combined Distances of Contrast Distributions for Image Quality Analysis. In:, et al. Advances in Visual Computing. ISVC 2020. Lecture Notes in Computer Science, vol 12510. Springer, Cham. https://doi.org/10.1007/978-3-030-64559-5_35