White Paper

Forward Looking Light Sensor Utilization for Automatic Luminance Control

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Forward Looking Light Sensor Utilization for Automatic Luminance Control

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Abstract

A mathematical framework is proposed for an automotive automatic luminance control system that adjusts the display luminance as a function of incident ambient light and forward field of view intensities from logarithmic light sensors.

Author Keywords

display; HUD; automatic; luminance; light; sensor; logarithmic

1. Introduction

As displays are utilized more often in automotive applications, the importance of being able to see the display presentation under various lighting conditions becomes important. As the automotive display luminance requirements are increasing beyond 1000 cd/m^2, the need to automatically adjust the display luminance to the value necessary for visibility is becoming important in order to minimize display temperatures. With the advent of automotive organic light emitting diode (OLED) displays, there is also a need to reduce the average luminance to minimize burned-in image artifacts. Currently, automotive automatic luminance control systems, with ambient light sensors near the display surface, do not properly address the problem of light adaptation when the driver is looking out of the windshield at a bright scene and then looks at a center information display whose luminance is determined via ambient light sensor(s) that may be shadowed as depicted in Figure 1-1. The use of a remote forward looking light sensor, that measures the luminance that the driver is seeing, may be utilized in conjunction with ambient light sensor(s) near the display to maintain display visibility under all lighting condition while minimizing average operational display luminance values.

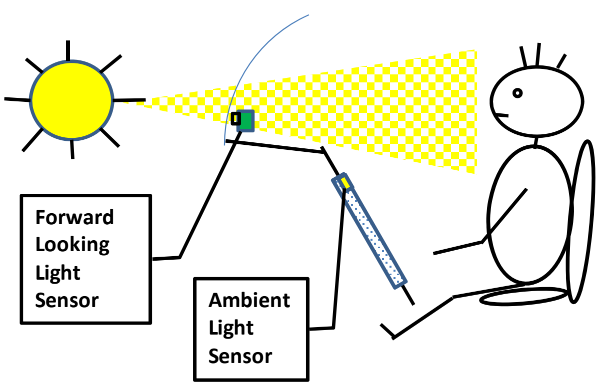


Figure 1-1. Forward Looking Light Sensor

2. Background/Objective

Many pioneers have studied and performed numerous human factor studies to understand what display luminance the human visual system requires for display visibility. Most notably, Dr. Silverstein published his work [1] which outlines an automatic luminance control system per Figure 2-1. In addition to increasing the display luminance as a function of the reflected display background luminance measured by the "Internal light sensor" (ambient light sensor) as shown in Figure 2-1, display visibility performance may be improved by the utilization of a forward looking "Remote light sensor" as shown in Figure 2-1 to compensate "for conditions of transient adaptation or eye adaptation mismatch" [1].

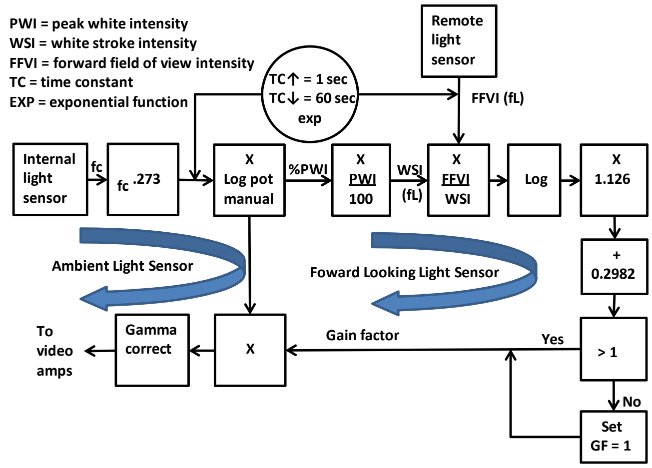


Figure 2-1. Silverstein Automatic Display Luminance System [1, pg. 304 redrawn for clarity & adapted with loop arrows]

The gain factor (GF) required for this forward looking eye adaptation mismatch compensation is described further by Dr. Silverstein per Figure 2-2.

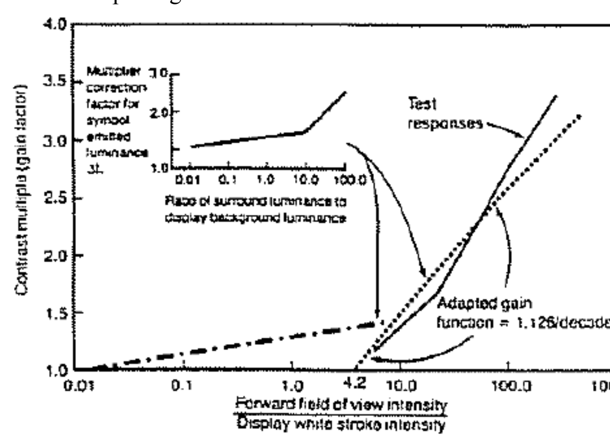


Figure 2-2. Silverstein Adaptation Function [1, pg. 303]

As can be deduced from Figures 2-1 and 2-2, the forward looking adaptation gain factor (GF) function proposed by Dr. Silverstein is described by Equation 2-1.

$$GF = 1.125 \log\left(\frac{FFVI}{WSI}\right) + 0.2982 \qquad (2\text{-}1)$$

- GF = Gain Factor
- FFVI = Forward Field of View Intensity
- WSI = Display White Stroke Intensity

Figure 2-3 shows the importance of using a forward looking light sensor to adjust the display for the eye adaptation compensation.

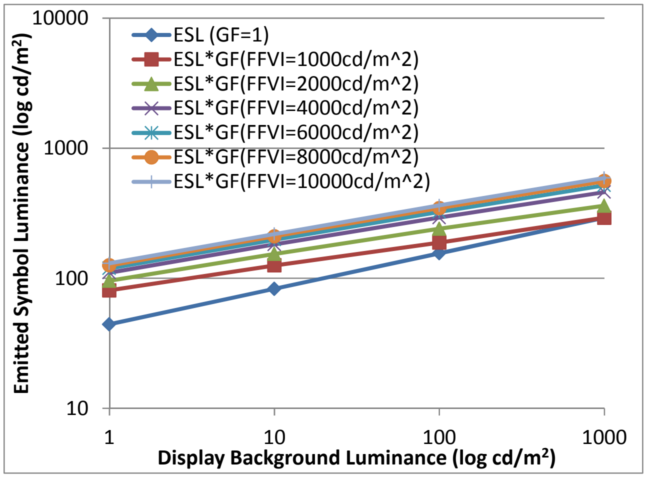


Figure 2-3. Light Adaptation Mismatch Compensation

The bottom line in Figure 2-3 represents ambient light sensor controlled automatic luminance control (GF=1), while the other lines show what is needed when the forward looking light adaptation gain factors are applied for varying forward field of view intensities (FFVI).

The actual implementation of the automatic luminance control algorithm as proposed by Dr. Silverstein may encounter the following problems:

1. The use of linear light sensors in conjunction with A/D converter resolutions do not have the sufficient dynamic range of 6-8 decades required for automotive applications.
2. The processor throughput required to compute the automatic luminance control mathematical functions needs to be minimized for processors used in automotive applications which are used to process a variety of vehicle functions.

As described in reference [2], these problems may be solved for the ambient light sensor control loop (Figure 2-1) by:

1. Using logarithmic light sensor(s) instead of linear light sensor(s).
2. Using luminance ratio look up table structures

The objective of this paper is to propose a simple extension of the methods described previously [2] and determine the forward looking light adaptation gain factor (GF) that may be used to increase the display luminance when required by the FFVI to WSI ratio operational conditions. The proposed mathematical construct adds a forward looking view intensity compensation per the Silverstein relationship using a logarithmic forward light sensor instead of a dynamic range limited linear light sensor. The logarithmic forward looking sensor may also be utilized to automatically adjust the heads up display (HUD) luminance level.

3. Description

A review of the concepts as previously described [2] for the ambient light sensor control loop, as highlighted in Table 3-1, forms the basis for adding the light adaptation function. The A/D output from the logarithmic ambient light sensor (column 4, Table 3-1) is used to look up the required display luminance drive value (column 2, Table 3-1). Column 2 of Table 3-1 shows the display luminance ratio structure where the display luminance ratio between steps is a constant.

Step # N_D	Display cd/m^2 L_N	Display Background Luminance cd/m^2 DBL_N	Log 10bit A/D	Linear 10bit A/D
0	38.71	0.68	23	0.68
1	50.00	1.41	123	1.42
2	64.58	2.94	223	2.95
3	83.41	6.10	323	6.13
4	107.72	12.66	423	12.74
5	139.13	26.30	523	26.46
6	179.69	54.64	623	54.96
7	232.08	113.49	723	114.15
8	299.74	235.73	823	237.11
9	387.13	489.63	923	492.51
10	500.00	1017.03	1023	1023.00

Table 3-1. Ambient Light Sensor Luminance Ratio Table

The last column shows that the linear light sensor resolution is insufficient whereas the logarithmic A/D value (column 4, Table 3-1) is a constant incremental delta between steps with ample A/D resolution. As can be deduced from Table 3-1 [2], the display luminance ratio construct with equal logarithmic light sensor A/D increments between steps yields the desired power function as shown in Equation 3-1 and as shown by Dr. Silverstein in Figure 2-1 (i.e. $fc^{.273}$) [1].

$$ESL = B_O\left(DBL\right)^C \qquad (3\text{-}1)$$

- ESL = Emitted Symbol Luminance in cd/m^2
- B_O = Luminance Offset Constant
- DBL = Display Background Luminance in cd/m^2 proportional to the display ambient light sensor value
- c = Power Constant (This is the slope of the power function in logarithmic coordinates)

A graphical plot of the power function as described by Dr. Silverstein is shown in Figure 3-1. The power function shows the relationship between the display background luminance measured by the ambient light sensor and the associated required display emitted symbol luminance on a log-log plot. By utilizing the luminance ratio construct with a logarithmic light sensor (e.g. Table 3-1), the slope of the lines in Figure 3-1 are determined by the power "c" value in Equation 3-1 and is adjusted/controlled by:

1. The number of A/D counts between successive luminance ratio steps and the resolution of the A/D converter (ref. Table 3-1)
2. The display luminance ratio between successive steps
3. Gain of the logarithmic light sensor

The luminance offset constant "B_O" is controlled by the relative position of the A/D count to the display luminance levels (ref. Table 3-1).

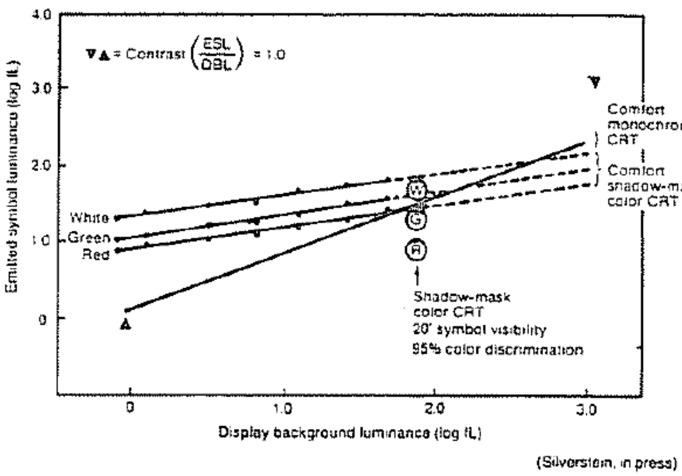


Figure 3-1. Display Emitted Symbol Luminance as a function of Display Background Luminance [1, pg. 274]

An extension of the luminance ratio table construct to implement the forward looking light sensor light adaptation function is shown in Figure 3-2. The ambient light sensor control loop is formed in Figure 3-2 by elements 1, 2, 3, 4, and 5 with GF=1 (ΔN=0) in block 8. The underlying idea towards simplification of the gain factor (GF) mathematics is to again utilize constant luminance ratio concepts as shown in block 12 in Figure 3-2 together with a logarithmic forward looking light sensor. Therefore in addition to simplifying the power function mathematics to determine the display luminance (L_{SEL}) [2], the same luminance ratio concepts can simplify the gain factor calculation. To simplify the determination of the light adaptation gain factor GF, Equation 2-1 may be rewritten as the summation of three terms as shown in Equation 3-2 and as shown in Figure 3-2, block 7.

$$GF = 1.125\log(FFVI) - 1.125\log(WSI) + 0.2982 \tag{3-2}$$

The second term of Equation 3-2 may be easily determined if a constant display luminance ratio construct is utilized [2] as shown in Figure 3-2 block 4. Equation 3-3 may be formulated to describe the display luminance L_{SEL} as a function of the ambient light sensor determined step number N_D and the user bias ΔN_{BD}.

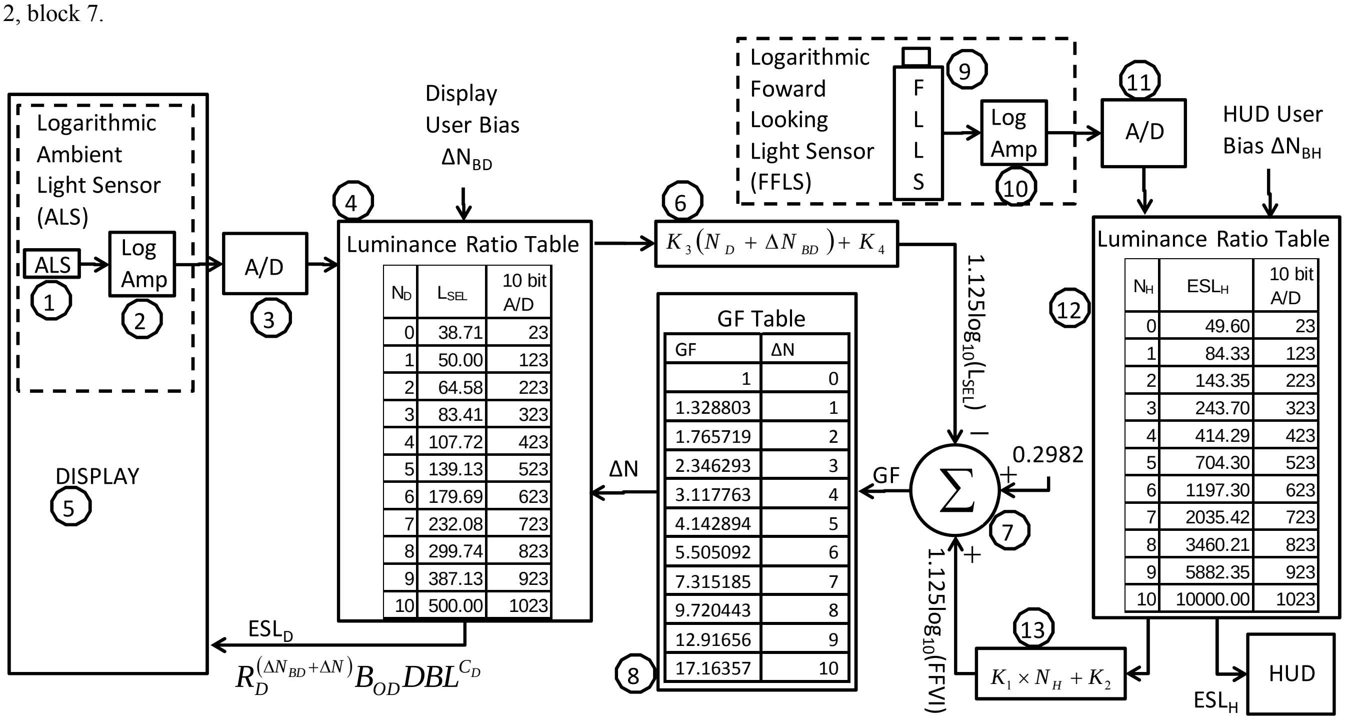
$$L_{SEL} = \frac{L_{Max}}{R_D^{T_D}} R^{(N_D+\Delta N_{BD})} \tag{3-3}$$

- R_D - is the display luminance ratio between steps
- L_{Max} – is the maximum display luminance
- T_D – is the total number of steps
- N_D – Step number determined by the ambient light sensor A/D value
- ΔN_{BD} – User offset preference added or subtracted from the N_D step number to provide a logarithmic potentiometer control (ref. "pot" Fig. 2-1).

Note that the display luminance L_{SEL} term is the same as the Silverstein WSI terminology.

Equation 3-3 may be reformulated to yield Equation 3-4

$$\log_{10}(L_{SEL}) = \frac{\log_R\left(\frac{L_{Max}}{R_D^{T_D}}\right) + (N_D + \Delta N_{BD})}{\log_R(10)} \tag{3-4}$$



$$R_D^{(\Delta N_{BD}+\Delta N)} B_{OD} DBL^{C_D}$$

N_D	L_{SEL}	10 bit A/D
0	38.71	23
1	50.00	123
2	64.58	223
3	83.41	323
4	107.72	423
5	139.13	523
6	179.69	623
7	232.08	723
8	299.74	823
9	387.13	923
10	500.00	1023

GF	ΔN
1	0
1.328803	1
1.765719	2
2.346293	3
3.117763	4
4.142894	5
5.505092	6
7.315185	7
9.720443	8
12.91656	9
17.16357	10

N_H	ESL_H	10 bit A/D
0	49.60	23
1	84.33	123
2	143.35	223
3	243.70	323
4	414.29	423
5	704.30	523
6	1197.30	623
7	2035.42	723
8	3460.21	823
9	5882.35	923
10	10000.00	1023

Figure 3-2. Automotive Automatic Luminance Control System

Therefore utilizing Equation 3-4, the $1.125\log_{10}(L_{SEL})$ term required for light adaptation gain factor GF calculation may be simplified from Equation 3-4 to a simple linear equation as shown in Figure 3-2 block 6 since all the terms except N_D and ΔN_{BD} are constants. For each step ($N_D+\Delta N_{BD}$), a $\log_{10}(L_{SEL})$ look up table may be compiled per Equation 3-4.

Next the forward looking light sensor 1st term in Equation 3-2 may be extracted from the analog to digital converter count value from the Forward Looking Light Sensor (FLLS) per Equation 3-5 where all the terms except N_H are constants associated with the logarithmic forward looking light sensor and the table structure shown in Figure 3-2 block 12.

$$1.125\log_{10}(FFVI) = \frac{1.125[N_H \Delta ADC_{FLLS} + ADC_{0FLLS}]V_{ADC}}{A_{FLLS}(2^{N_{A/D}}-1)\ln(10)} - \frac{1.125V_{ThFLLS}}{A_{FLLS}\ln(10)} + \frac{1.125\ln(K_{FLLS}I_{2FLLS})}{\ln(10)} \quad (3\text{-}5)$$

If all of the constant terms are coalesced, Equation 3-5 is simplified to Figure 3-2 block 13. Using Equation 3-5, a table may be constructed which relates $1.125\log_{10}(FFVI)$ to HUD step number N_H.

If the gain factor determined by block 7 is greater than 1, then the display luminance L_{SEL} value determined by the ambient light sensor could be multiplied by the gain factor to ensure the proper display luminance for light adaptation as is outlined by Dr. Silverstein in Figure 2-1. The method to perform the gain factor (GF) multiplication may be done by a processor. However a less computationally intense method is to construct a look up table that may be determined by starting with Equation 3-6 based once again on luminance ratio steps.

$$L_{SEL} = \frac{L_{Max}}{\left[\frac{L_{Max}}{L_{Min}}\right]^{\left(\frac{T-N_S}{T-1}\right)}} \quad (3\text{-}6)$$

N_S is the ($N_D+\Delta N_{BD}$) value from the ambient light sensor calculation per block 4. Per Equation 3-7, the modified luminance L_{GF} as a result of multiplying by the gain factor GF is defined.

$$L_{GF} = GF \times L_{SEL} \quad (3\text{-}7)$$

Manipulation of Equations 3-6 and 3-7 result in Equation 3-8 where the ratio R_D between successive steps is defined by Equation 3-9.

$$(N_{GF} - N_S) = \Delta N = \frac{\ln(GF)}{\ln(R_D)} \quad (3\text{-}8)$$

$$R_D = \left[\frac{L_{Max}}{L_{Min}}\right]^{\left(\frac{1}{T-1}\right)} \quad (3\text{-}9)$$

Equation 3-8 shows that it does not matter what step level the ambient light sensor is indicating and that only the index difference $\Delta N=(N_{GF}-N_S)$ needs to be added to ($N_D+\Delta N_{BD}$) as shown in Figure 3-2. Figure 3-3 shows an example of the relationship between the gain factor and the resulting ΔN value assuming the following as an example:

- L_{Max} = 500 cd/m^2
- L_{Min} = 38.71 cd/m^2
- T = 10 (total number of steps)

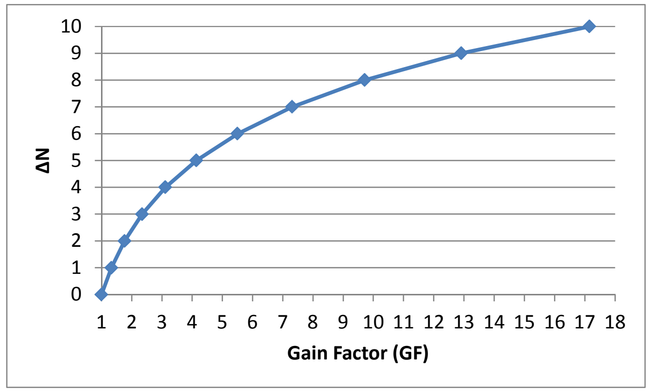


Figure 3-3. ΔN versus GF Relationship

The use of a GF index table greatly simplifies the mathematics and implementation.

As an example of the light adaptation gain factor concepts, if a scenario occurs where the ambient light sensors on an automotive center display are shadowed as the driver is driving into the sunset, the display luminance may be reduced to 50 cd/m^2 (N_D=1) per block 4 in Figure 3-2. However the driver is squinting due to looking at the sun and the forward looking light sensor is determining a high luminance level resulting in block 7 in Figure 3-1 indicating a GF=10. Accordingly per Figure 3-2, the required ΔN for GF=10 is 8 steps and the display luminance is therefore increased by 8 luminance ratio steps to 387.13 cd/m^2 (ratio step 9) and the user will then be able to see the information on the display.

4. Conclusion

A simple mathematical framework based on luminance ratio concepts has been developed that determines the required gain factor required to automatically compensate the display luminance for the driver light adaptation mismatch. By using the light adaptation factor in conjunction with the typical ambient light sensor approach, the display visibility will be improved under most driving conditions. Additionally the display luminance is only increased to the level required for visibility and not operated continually at the maximum level thereby minimizing display power and improving thermal performance.

5. References

[1] Silverstein, Louis D., Merrifield, Robin M., Hoerner, F. C., The Development and Evaluation of Color Systems for Airborne Applications – Fundamental Visual, Perceptual, and Display Systems Considerations, Reference No. 851774.

[2] Weindorf, P., Automotive Automatic Luminance Control, Society for Information Display 2014 Vehicle Displays and Interfaces Symposium Digest of Technical Papers.

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