Automatic luminance control summarized

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Abstract — Automotive automatic luminance control concepts are summarized for displays where the ambient illumination is measured and the display luminance is modified to maintain legibility. The most important aspects are reviewed to provide a high-level overview and insight.

Keywords *— logarithmic, light, ambient, sensor, automotive.*

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1 Introduction

Automatic luminance control methods are becoming important in the automotive industry because of the following reasons:

1. Luminance values for the display and ambient lighting have an impact on "legibility" of the display and printed icons, in addition to icon/text size and saliency.
2. Display luminances are exceeding 1000 cd/m^2 for visibility reasons in automotive applications, and it is becoming more important to manage the consequential thermal aspects.
3. Operating an exceeding bright display under all daylight conditions may be annoying or can actually lead to a hazard condition by causing a light adaptation response time problem under dawn or dusk conditions.
4. Display luminance degradation especially for OLED displays can be minimized by using automatic luminance control techniques.[1]

A summary of the key technologies is valuable to understand the "big picture" and properly implement an automotive automatic luminance control system that works properly. The most important elements are the following:

- *Silverstein luminance power function* that relates the required display luminance as a function of the reflected background luminance of the display because of ambient illuminance.
- *Angular reflectance measurements* of the target display to understand the relationship between illuminance and the reflected background luminance seen by the user.
- *Forward looking light sensor* in addition to ambient light sensors to solve the problem of eye adaptation mismatch when the user is observing a bright seen.
- *Logarithmic light sensors* to handle the required dynamic range and provide mathematical simplicity for the system implementation.
- *Luminance ratio tables* that allow the user preference offset control and which in conjunction with logarithmic light sensors provides the Silverstein luminance power function.
- *Inverse software filter* techniques provide a peak detector function and eliminates display luminance variations due to periodic sunlight shadowing conditions such as from trees and buildings.

To gain further insight, each of these major elements are discussed to provide a top level overview.

2 Silverstein luminance power function

The correct function to adjust the display luminance as a function of the reflected background luminance was researched by Dr. Silverstein *et al.*[2] This function forms the basis for automatic luminance control because it establishes how much display luminance is required as a function of the reflected background luminance that is proportional to the illumination level measured by the ambient light sensors located at the front of the display. As discussed by Silverstein *et al.*,[2] the relationship between observer-selected emitted symbol luminance and reflected background luminance from the display is given by Equation 2.0-1. The log–log nature of the Silverstein straight line transfer function in Fig. 1 is a mathematical fractional power function per Equation 2.0-1.

$$ESL = B_O(DBL)^C \qquad (2.0\text{-}1)$$

- ESL = Emitted symbol luminance in cd/m^2
- B_O = Luminance offset constant
- DBL = Display background luminance in cd/m^2
- c = Power constant (This is the slope of the luminance power function in logarithmic coordinates.)

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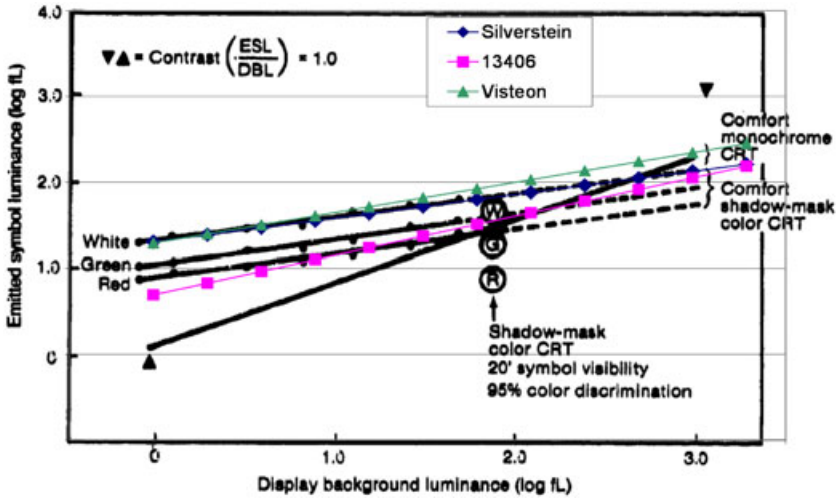


FIGURE 1 — Comparison of various Equation 2.0-1 Constants [2, adapted]. Note: ISO/DIS 13406 has been withdrawn for ISO 9241.

Dr. Silverstein was not the only researcher to understand the required relationship between the reflected background luminance from the display surface and the required display luminance for visibility. Historical work done in this arena started with varying projection spots on a wall with varying background luminances such as detailed by Blackwell.[3,4] A view of the observer's station for the Blackwell study[3] is shown in Fig. 2.

The studies progressed to translucent projection screens by Blackwell[5] and finally culminated with monochrome cathode ray tubes (CRTs) by Knowles and Wulfeck[6] per Fig. 3 and color CRTs by Silverstein *et al.*[2] Silverstein *et al.* (pp. 271–272)[2] provide a great synopsis of the various pioneering work by other pioneers including Chapanis,[7] Carel,[8] Burnette,[9] Gould,[10] Howell and Kraft,[11] Semple *et al.*,[12] and Shurtleff.[13] Cumulatively, these works show that in daylight-type conditions, the fundamental relationship between the emitted symbol luminance and the background luminance is a straight line on a log–log plot as shown in Fig. 1.

As an example, Fig. 4 shows the same straight line relationships on a log–log plot. Figure 4 also shows that the offset B_O for the comfort level is significantly higher than the minimum threshold. Finally, Fig. 4 shows consistency between the Burnette[9] comfort levels and the Silverstein, ISO 13406,[14] and Visteon measured levels.



FIGURE 2 — Blackwell observation station.[3]

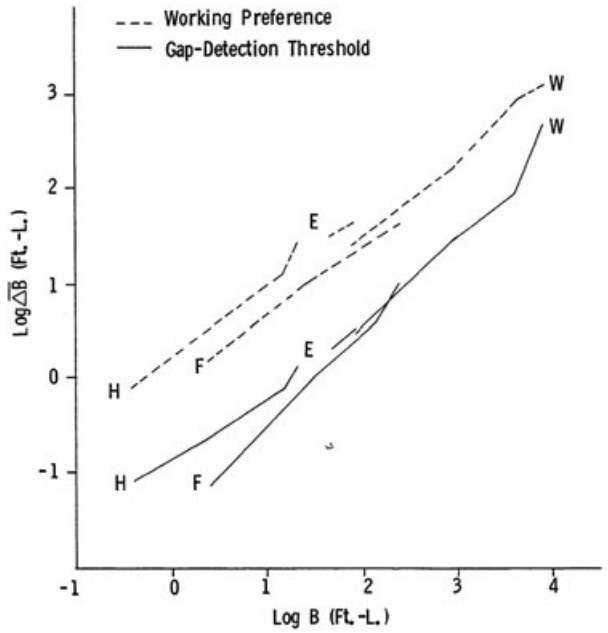


FIGURE 3 — Working preference and threshold.[6]

Interestingly, ISO13406[14] has been withdrawn and has been supplanted by ISO9241.[15] The big difference between the ISO documents is described in ISO 9241[15] and is related to the minimum contrast ratio (CR) for perception/legibility where ISO 9241[15] has a CR_{min} tending to 2.2 for large ambient illumination, whereas ISO 13406[14] has a CR_{min} tending towards unity. Per ISO9241,[15] the equation that relates the required CR to the background luminance is per Equation 2.0-2, which can be manipulated to yield Equation 2.0-3.

$$CR_{\min} = 2.2\times\left(1 + 2.2\times L_L^{-0.65}\right) \qquad ((2.0\text{-}2)[15, \text{EqD.8}])$$

$$ESL = 1.2DBL + 4.84DBL^{(1-0.65)} \qquad (2.0\text{-}3)$$

Plotting Equation 2.0-3 along with the other plots results in Fig. 5.

It should be noted that ISO9241[15] references a mathematical evaluation carried out by Kokoschka and attempts to modify the ISO13406[14] to make sure the CR is never lower than 2.2. However, actual test data by Silverstein and others clearly show that the ISO9241[15] recommendation is not consistent with other test results and is not acceptable for the lower background luminances. It should be noted that ISO13406[14] and ISO9241[15] were developed for "office ergonomics," and very low ambient (dark) and very high ambient (sunlight) conditions are extensions of the normal office ambient illumination range. ISO15008[16] was developed specifically for road vehicles and is titled *Road vehicles – Ergonomic aspects of transport information and control systems – Specification and compliance procedures for in-vehicle visual*

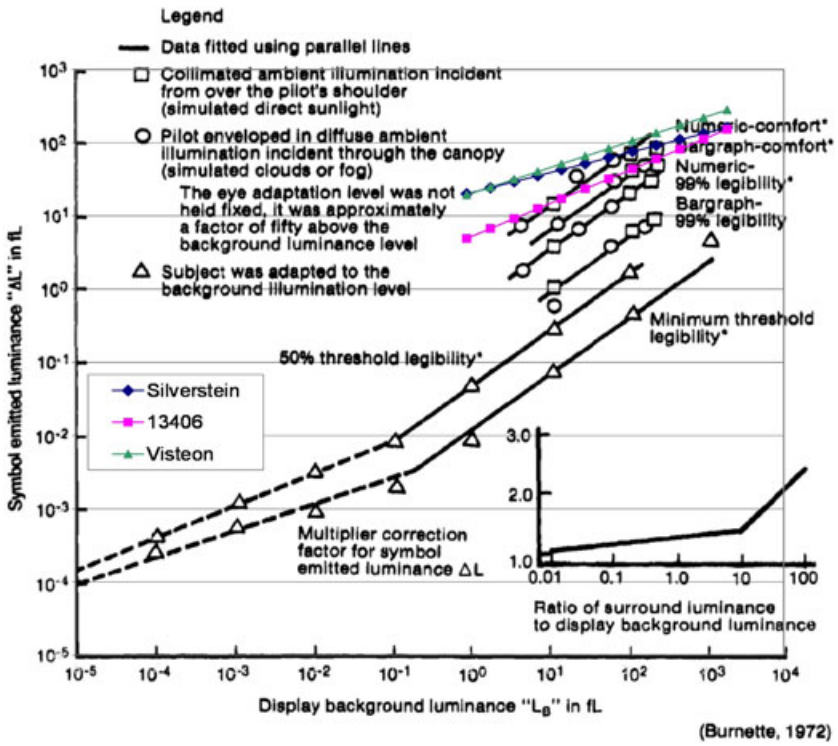


FIGURE 4 — Overlaid plots on Burnette adapted.[9]

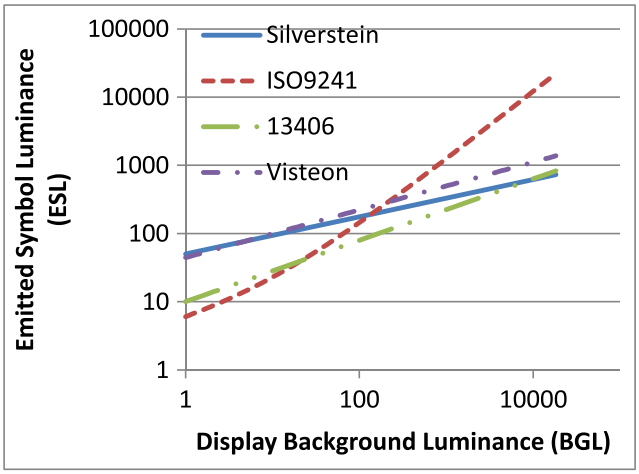


FIGURE 5 — Emitted symbol luminance versus BGL recommendations.

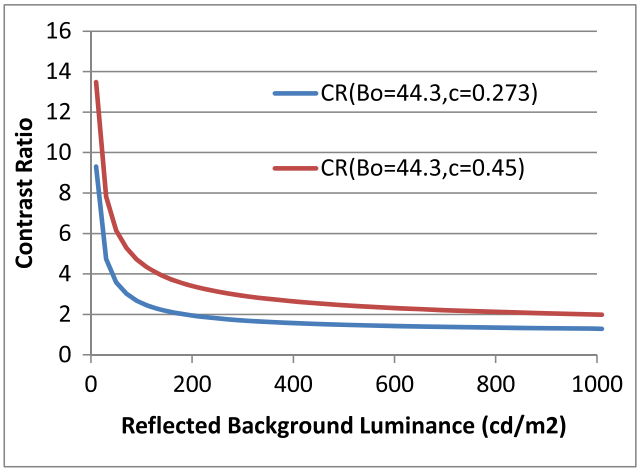


FIGURE 7 — Contrast ratio (CR) versus reflected background luminance using Equation 2.0-1.

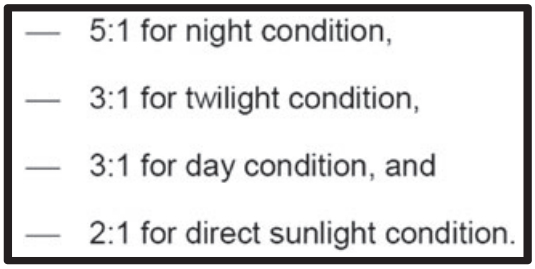


FIGURE 6 — ISO 15008[16] contrast ratio recommendation.

presentation.[16] ISO15008[16] has a non-mathematical recommendation per Fig. 6.

Furthermore, Dr. Silverstein comments on the nonsense of using constant CR methodologies. "These early 'constant-contrast' mechanizations did not prove popular or effective for several reasons. Display contrast requirements are not constant over the range of cockpit ambient illumination. An observer's contrast sensitivity increases as ambient illumination increases. Relatively high contrast is required at low ambient levels, while relatively low contrast is required at high cockpit illumination levels."[17] The Silverstein Equation 2.0-1, when plotted per Fig. 7, shows that less CR is required as the background luminance increases. When compared with Fig. 6, Fig. 7 further confirms the Silverstein mathematical luminance fractional power function relationship between emitted symbol luminance and display background luminance. One of the benefits of using the luminance power function is that the offset (B_O) and fractional power (c) may be adjusted to the desired legibility index as shown in Fig. 4.

SAE J1757-1[18] is a companion metrology specification on how to measure and determine the amount of reflected background luminance from the display under different recommended illuminance conditions. Additional insight on in-vehicle display legibility may be found in the Society of Automotive Engineers (SAE) paper "Legibility back to basics."[19] Therefore, in conclusion, the human factors work shows that the proper mathematical relationship for display luminance as function of the reflected background luminance is described per Equation 2.0-1 with the constants selected for the desired level of comfortable viewing.

3 Angular reflectance measurements

One of the more important aspects to implement a successful automatic luminance control system is to determine how much light is reflected back to the user. The amount of total reflected light is the display background luminance that the user sees and is a superposition of three major reflection components:

1. Lambertian diffuse – Important for general cockpit hemispherical diffuse illumination
2. Specular – Important for sources like white shirts, seats, and other mirror-type specular reflections
3. Haze diffuse – Important for direct sunlight illumination of the display

Although J1757-1[18] deals with measuring the diffuse and specular reflection components, the haze component from direct sunlight illumination is more difficult to assess. A measurement method based on Information Display Measurements Standard (IDMS) small–source reflection (page 212 of Information display measurements standard, version 1.03)[20] with a collimated light source may be utilized.

An overview picture of a small source measurement apparatus[21] is shown in Fig. 8. The system employs a geared potentiometer for angular measurements allowing different photometer scales to be combined into a single data set.

An example of the small source reflectance data of a display is shown in Fig. 9 where the red lines show the

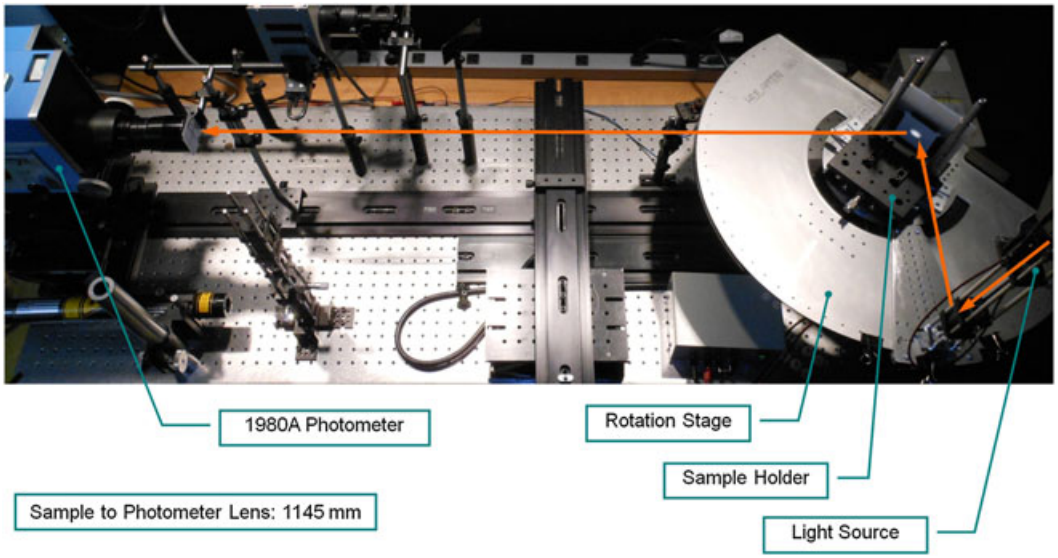


FIGURE 8 — Reflection measurement system.[21]

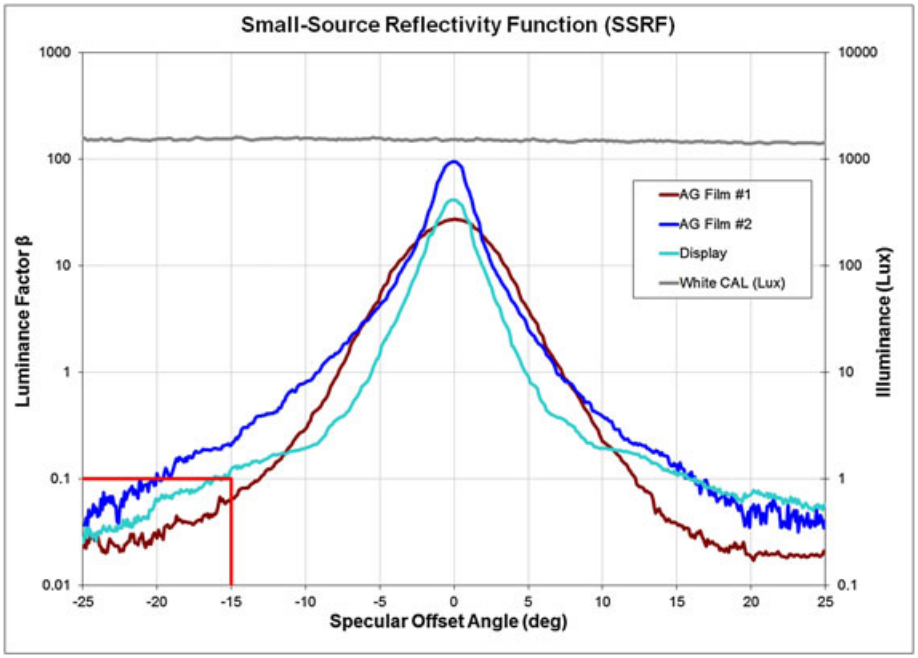


FIGURE 9 — Small source reflection measurement example[21] showing how different antiglare (AG) films over a display affect the reflectance performance compared with the display itself.

reflectance of $\beta = 0.1$ at a deviation angle of $-15°$ from the specular angle. This means that the user is offset by 15° from the sunlight specular (mirror) angle. Using the reflectance of $\beta = 0.1$ and assuming a 60 K lux sun source (100 K lux modified by the side window transmission of about 60% at 45°), the reflected background luminance, L, is calculated per Equation 3.0-1.

$$L = \frac{\beta \times E}{\pi} = \frac{0.1 \times 60K \times \cos 45°}{\pi} = 1351 \text{ cd/m}^2 \qquad (3.0\text{-}1)$$

Having the measurement equipment to properly measure the reflectance based on vehicle geometry is important in

order to determine the amount of display luminance per the Equation 2.0-1.

4 Forward looking light sensor

As shown in Fig. 10, as introduced in the study of Weindorf,[22] a successful automatic luminance control system not only will have ambient light sensors on the display surface to determine the amount of reflected light from the display surface but also will incorporate the use of a forward looking light sensor to compensate "for conditions of transient adaptation or eye adaptation mismatch."[2]

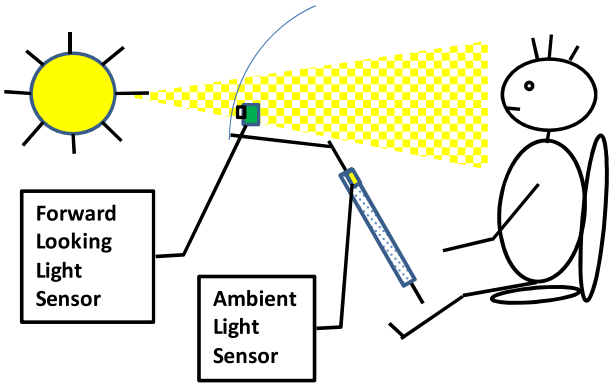


FIGURE 10 — Automatic luminance control.[22]

Many pioneers have studied and performed numerous human factor studies to understand what display luminance the human visual system requires for display visibility. Dr. Silverstein published his work[2] that outlines an automatic luminance control system per Fig. 11 that includes a forward looking light sensor in addition to the normal ambient light sensor on the front of the display. 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 Fig. 11, display visibility performance due to luminance may be improved by the utilization of a forward looking "remote light sensor" as shown in Fig. 11 to compensate "for conditions of transient adaptation or eye adaptation mismatch."[2]

If a logarithmic forward looking light sensor is utilized, the implementation is simplified because the mathematics becomes addition and subtraction to determine the gain factor (GF) instead of determining the logarithm of a ratio with subsequent multiplication complexity per the Silverstein method as shown in Fig. 11. If a logarithmic forward sensor is used, Fig. 12 shows that the GF may be determined with simple addition and subtraction in block 7. Figure 12 also shows that if a luminance ratio table per block 4 is utilized, the GF multiplication is easily accomplished by using a GF look up table and moving up or down ΔN steps from the ambient light sensor determined luminance step. The use of a logarithmic forward looking light sensor also solves the problem of limited dynamic range as explained by the OSRAM SFH 5711 application note.[23]

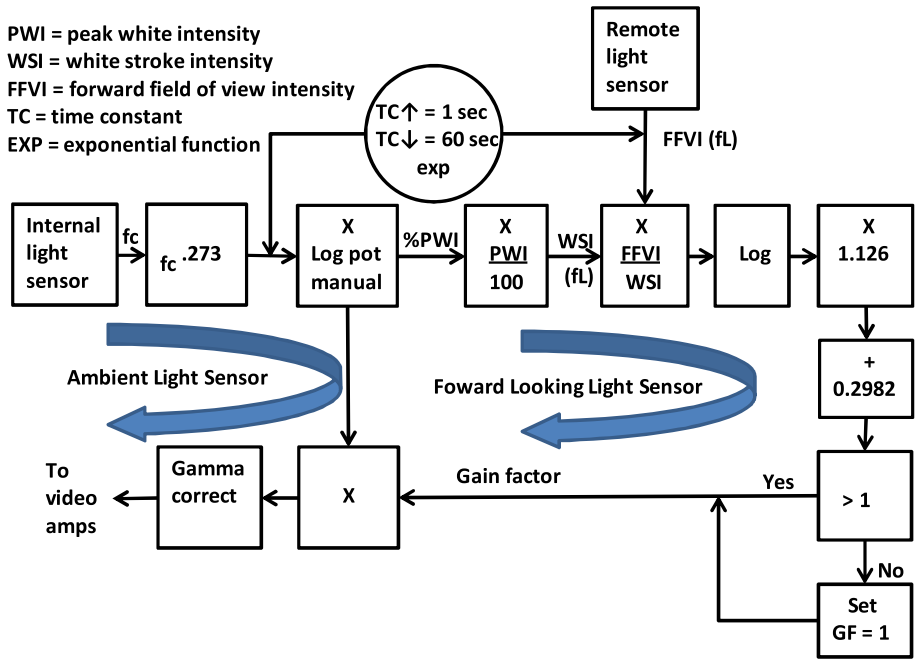


FIGURE 11 — Silverstein automatic display luminance system [redrawn for clarity and adapted with loop arrows; p. 304].[2]

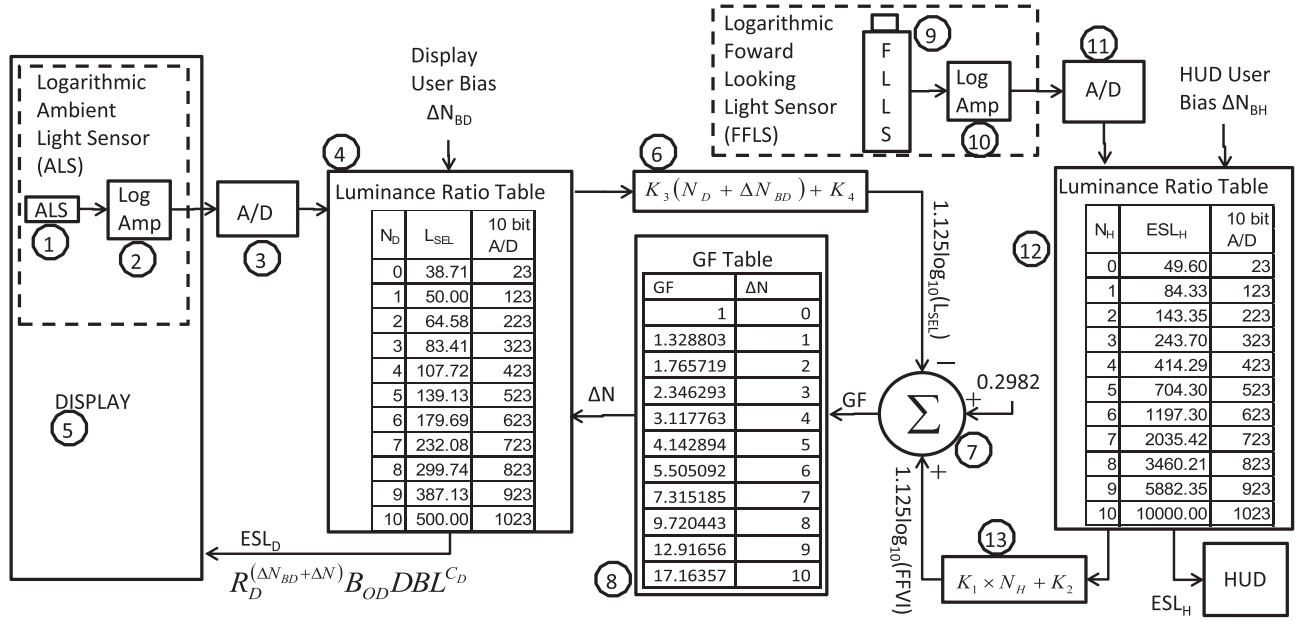


FIGURE 12 — Automotive automatic luminance control system simplified example.[22]

5 Logarithmic light sensors

The selection of the light sensors used for automatic luminance control must consider many attributes to ensure that the final system will work properly:

- Logarithmic response
- Single power supply operation
- Rail to rail operation
- Photopic spectral response
- Accuracy
- Dynamic range
- Gain control
- Reference current control
- Dark current
- Temperature dependence
- Directional sensing characteristic
- Outline characteristics
- Automotive qualified
- Cost

In order to properly measure the amount of ambient and forward looking light levels for automatic luminance control in automotive applications, the best way is to utilize a light sensor with a logarithmic response. Because of the non-availability of either logarithmic light sensors or suitable automotive qualified logarithmic amplifiers in the past, discrete logarithmic light sensor designs have been successfully utilized in production applications. The use of a discrete logarithmic amplifier and sensor designs allows more design flexibility at the expense of complexity. Figure 13 shows a discrete logarithmic light sensor design.

The transfer function for the discrete logarithmic sensor is given per Equation 5.0-1.

$$V_O = A_V V_T \ln\left(\frac{i_p}{I_2}\right) + V_{Th} \tag{5.0-1}$$

A_V = logarithmic amplifier gain (note that the gain is temperature compensated such that $A_V V_T$ remains constant over temperature)

$V_T = KT/q$ = thermal voltage

i_p = photodiode current

I_2 = reference current

V_{Th} = thevenin offset voltage

Logarithmic amplifiers that operate off a single low-voltage supply such as the MAX4206 as shown in Fig. 14 are not currently automotive qualified, but this may change in the future.

As a cost-competitive solution, the OSRAM SFH 5711[23,24] integrated logarithmic light sensor affords most of the desired features and is automotive qualified in a field with a very few alternatives. In addition, because of the current source output topology, the SFH 5711 sensor is extremely versatile and easy to use. The OSRAM SFH 5711 light sensor, as shown in Fig. 15, warrants careful consideration because it has many of the desirable attributes and is special in a field of many sensor options because it is an "Opto hybrid with logarithmic current output."[24]

As shown in Fig. 16, the gain of the SFH 5711 logarithmic amplifier can be adjusted via the external load resistor because the output is a current source defined by Equation 5.0-2 where E_V is the ambient light illuminance in lux.

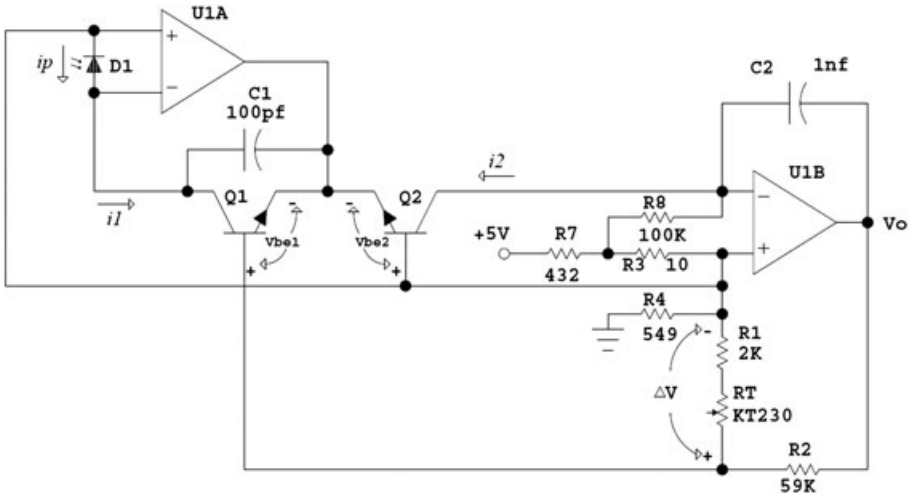


FIGURE 13 — Logarithmic light sensor legacy circuit.[31]

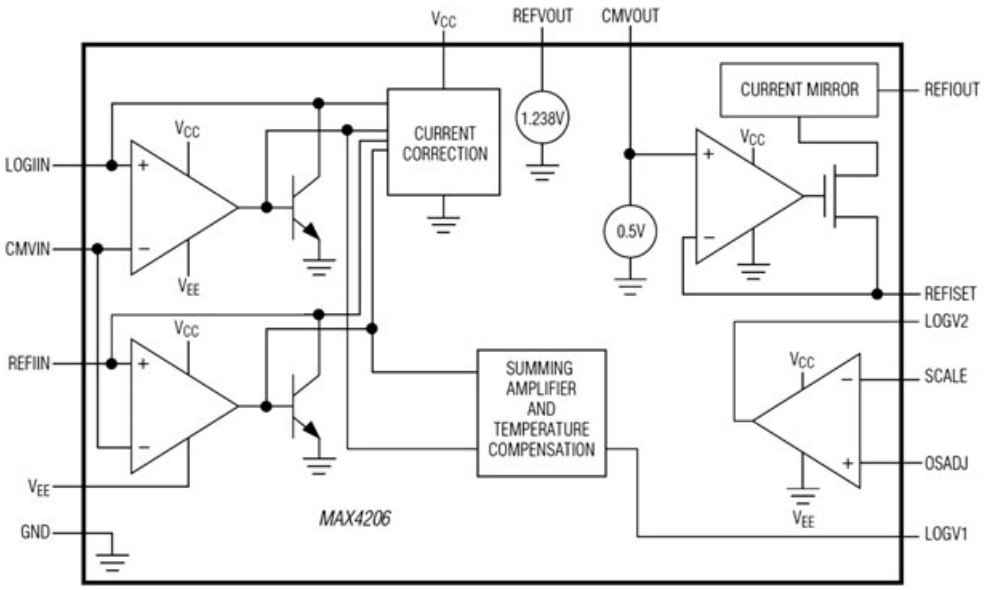


FIGURE 14 — MAX4206 precision transimpedance logarithmic amplifier with over five decades of dynamic range.[32]

$$I_{\text{out}} = S{*}\log(E_v/E_o) \qquad (5.0\text{-}2)$$

[23]with $E_o = 1\,lx$, sensitivity $S = 10\,\mu\text{A/dec}$.

With a dynamic range of five decades of illuminance performance, the OSRAM 5711 is expected to be the workhorse for most future automatic luminance control systems.

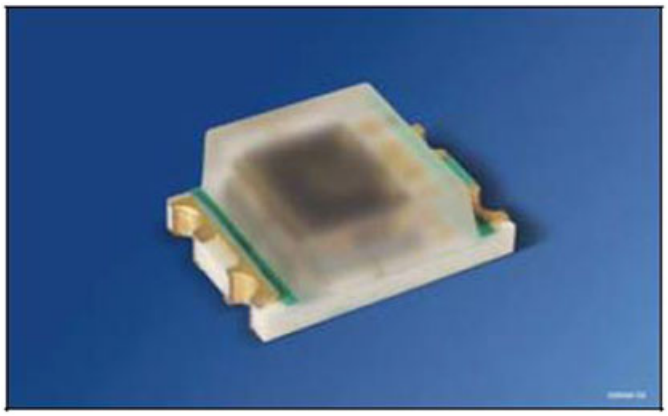


FIGURE 15 — OSRAM SFH 5711 logarithmic light sensor.[23]

6 Luminance ratio tables

As shown in block 4 of Fig. 17, the use of luminance ratio tables facilitates

- the user offset or preference function, and

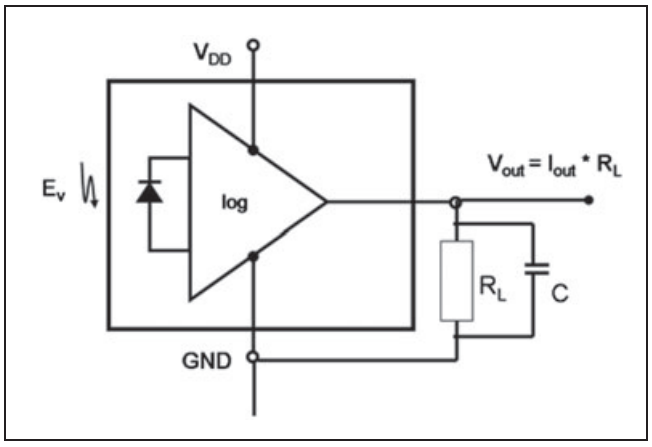


FIGURE 16 — Operating circuit for SFH 5711.[23]

- the mathematics to execute the Silverstein luminance power function when used in conjunction with logarithmic ambient light sensors.

The entire system architecture starts with a constant luminance ratio table as shown in block 4 of Fig. 17 where the ratio between successive luminance values is a constant. A constant ratio luminance table is also required because the user must be able to adjust the display to satisfy his or her luminance preference. As recognized by some OEMs, the perception of the human eye is to interpret luminance ratio steps as equal brightness changes. As an example, the eye perceives a luminance change from 1 to 1.2 cd/m^2 (ratio = 1.2) as equal to a luminance change from 100 to 120 cd/m^2. This nonlinear logarithmic response of the eye is what allows the visual system to work over many orders of magnitude.

To understand that the eye works on luminance ratios, IDMS (page 482)[20] states:

> The human visual system is highly nonlinear, and this nonlinearity involves spatio-temporal properties of the light stimulus as well as adaptation levels of the eye and chromatic dependencies. However, standards bodies and display technologies adopt the following rule of thumb: "Roughly speaking, perceived lightness is the cube root of luminance". (C. A. Poynton, SMPTE Journal, December 1993, p. 1101). This law appears in the uniform color spaces such as CIELUV and CIELAB (see § B1). The cube-root law is the result of experiments such as the following: An observer is given a black and a white chip and asked to select a gray chip that is halfway between the two in lightness (on a particular background, and under a given illuminant). Then, the observer is asked to halve the black-gray and gray-white intervals by the same procedure. Continuing this process yields a series of chips that are subjectively equally spaced, and are assigned numerically equal increments of lightness. The measured luminances of these chips complete the lightness-luminance relationship, which has the appearance of a power function, most characteristically the cube-root function. What this means is that if the luminance L1 of one object appears to the eye to be half the luminance of another object L2, then their luminance ratio is approximately 8:1; $\sqrt[3]{L_2/L_1} = 2$, so then L2/L1 = 8. Thus, if we have a computer display that has a luminance of 100 cd/m2 and want a new display to appear twice as bright, then we would need the new display to have a luminance of 800 cd/m2.

By starting with a constant display luminance ratio table, the user can modify the ambient light sensor (ALS) determined luminance by constant ratios for his or her preference as specified by some OEMs. Combining the user adjustable

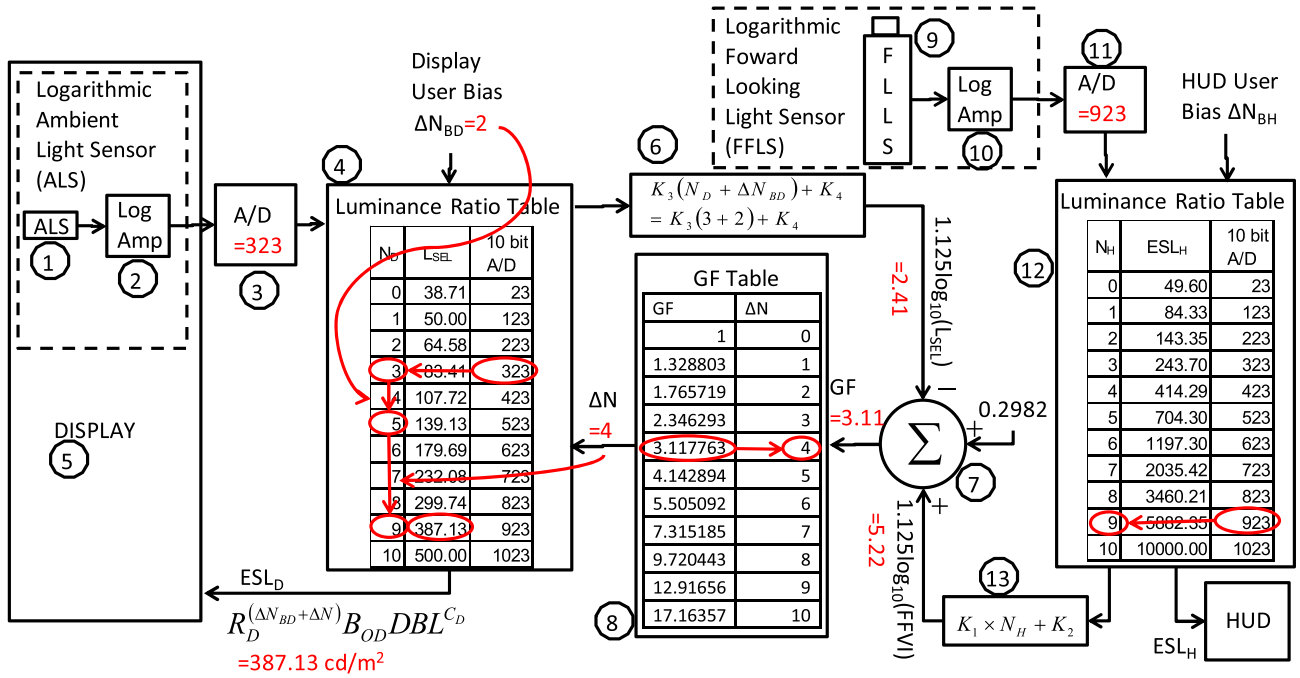


FIGURE 17 — Automatic luminance control example.

feature with the requirement that the display luminance must be a luminance power function of the display illuminance is accomplished simply by increasing or decreasing the ALS resultant brightness step number by the number of user selected steps. An understanding of the crucial elements to implement the system is required to understand the concepts behind constructing luminance control tables.

Crucial elements:

1. Luminance power function based on display background luminance
2. Equations governing constant ratio steps
3. The use of a logarithmic light sensor

By using a luminance ratio table in conjunction with equal logarithmic light sensor A/D counts between luminance ratio steps, the Silverstein luminance power function per Equation 2.0-1 is realized. The important relationship that relates all of the important parameters is governed by Equation 6.0-1 if a 5 V A/D is utilized and the logarithmic light sensor per Fig. 13 is utilized. It is important to note that Equation 6.0-1 is based equal A/D count deltas assigned to each luminance ratio step as shown in block 4 of Fig. 17. Equal A/D steps is a mathematical outcome of the system design and ensures that resolution is not lost over the entire dynamic range.

$$\Delta ADC = \frac{(A_V)(V_T)\left(2^{N_{A/D}} - 1\right)(\ln(R))}{5V \times c} \qquad (6.0\text{-}1)$$

- A_V = gain of the logarithmic amplifier
- V_T = KT/q term for the diode of Q1
- R = brightness ratio between brightness steps
- c = power of the Silverstein $B = Bo \times (\mathrm{BGL})^C$ equation for the eye preferred function of brightness *versus* reflected ambient
- $N_{A/D}$ = number of ADC bits
- $5V$ = input dynamic range of the ADC

In order to cement the concepts, Fig. 17 is shown where actual example values are shown. In this example, the inputs to the system are as follows:

1. Ambient light sensor A/D = 323 counts
2. Forward looking light sensor = 923 counts
3. User bias $\Delta N_{BD} = 2$ steps

For a logarithmic ambient light sensor count of 323, the nominal display luminance would be set at 83.41 cd/m^2 per block 4 of Fig. 17. However, because the user bias of $\Delta N_{BD} = 2$ was selected, the N_D step number is increase by 2 resulting in a display luminance of 139.13 cd/m^2. So without the forward looking light sensor, the display luminance would be set to 139.13 cd/m^2. It is perhaps interesting to notice that the ambient light sensor algorithm can work on its own, and the forward looking light sensor can be added as a feature enhancement to the system. Because the logarithmic forward looking light sensor is looking into a relatively bright scene with a count = 923 for this example, the corresponding N_H step number of 9. This step number could also be used to command a head up display (HUD) luminance of 5882.35 cd/m^2. Or if the HUD had a light sensor, it may be utilized to build the table shown in block 12 and could be used to enhance the center stack or instrument cluster display performance assuming the displays utilized an automatic luminance control system. Returning to the example, a N_H step would result in a 1.125log(FFVI) = 5.22 out of block 13. The 5.22 value would have the 1.125log(139.13) = 2.41 subtracted from it and an offset value of 0.2982 is added as shown in block 7, resulting in a final GF value of 3.11. This means that the 139.13 cd/m^2 value should be multiplied by 3.11 to obtain the final desired display luminance value. This may be accomplished with a lookup table as shown in block 8. The 3.11 GF corresponds to a ΔN value of 4 per the GF table in block 8. Therefore, a count of 4 is added to the original count of 5 in block 4 to result in a final value of 9 corresponding to a final display luminance value of 387.13 cd/m^2. Note that because the luminance ratio structure of the table in block 4, it would not matter where you started from. An increase in four steps would always result in a GF increase of 3.11.

The block diagram as shown in Fig. 17 does not show the filter functions that are necessary to prevent display luminance variations due to periodic sunlight shadowing conditions such as from trees and buildings.

7 Inverse software filter

The goal of automatic luminance control is to determine the daytime display luminance level based on the ambient lighting conditions as measured by the ambient light sensor(s). Because it is undesirable to have the display luminance fluttering with rapid changes in ambient luminance, a filter is incorporated. Many types of filtering methods may be utilized, but one method that has historically worked very well is counter intuitive to normal filtering methods. The basic operation of the filter is to determine how many steps away the desired luminance is from the current display luminance. This number of steps is multiplied by a time constant to determine how long to wait before stepping up or down by one step towards the desired step. By using this algorithm,[25] the software waits a longer time before changing the commanded display luminance should the ambient level change by large amounts. Large changes in ambient illuminance is usually indicative of abnormal shadowing events (hands, trees, buildings, etc.), and therefore, the algorithm filters these abnormal conditions out. By using this algorithm, annoying display luminance variation effects are avoided. However, if the ambient change is small, the delta number is small, and therefore, the change to the desired display luminance occurs more quickly. Small changes in ambient luminance are indicative of more permanent "true" changes in ambient brightness and correspondingly the algorithm is to more quickly respond to the

change. In addition to the filtering, it is generally desirable to allow the user to set a preference luminance level.

To illustrate the operational principle of the inverse filtering technique, Fig. 18 shows a simulation case under the following conditions:

- 40 step table
- Step 1 luminance = 79.43 cd/m^2
- Step 40 luminance = 430.36 cd/m^2
- Tcup time constant = 0.01 s

The luminance scale is logarithmic to better indicate what brightness the eye perceives. Because the input ambient light sensor indication has a sudden unnatural change from step 1 to step 40, the inverse filter waits 39 × 0.01 s before changing from step 1 to step 2. Then because the situation persists, the next change from step 2 to step 3 occurs 38 × 0.01 s later. The sequence continues until step 40 is attained.

Figure 19 shows a simulation case under the following conditions:

- 40 step table
- Step 40 luminance = 430.36 cd/m^2
- Step 1 luminance = 79.43 cd/m^2
- Tc(down) time constant = 0.1 s

The luminance scale is logarithmic to better indicate what brightness the eye perceives. Because the input ambient light sensor indication has a sudden unnatural change from step 40 to step 1, the inverse filter waits 39 × 0.1 s before changing from step 40 to step 39. Then because the situation persists, the next change from step 39 to step 38 occurs 38 × 0.01 s later. The sequence continues until step 1 is attained.

Figure 20 shows a simulation case for alternating high and low illuminance conditions that can occur due to periodic shading by objects such as trees or buildings under the following conditions:

- 40 step table
- Step #1 luminance = 79.43 cd/m^2
- Step #40 luminance = 430.36 cd/m^2
- Tc(up) time constant = 0.01 s
- Tc(down) time constant = 0.1 s

The luminance scale is logarithmic to better indicate what brightness the eye perceives. Because the step up time constant (0.01 s) is smaller than the step down time constant (0.1 s), the system works like a peak detector and eventually remains at the highest indicated luminance which in Fig. 20 is step 40. Although it appears as if the time constants in the examples are rather long, these levels of response time have been successfully implemented in several production programs with no complaints primarily because the system works like a peak detector for the worst case luminance condition over a long period of time. The long time constants also minimize irritating changes in display luminance that would be seen with shorter time constants.

The same software filtering techniques may be used for both the ambient and forward looking light sensors.

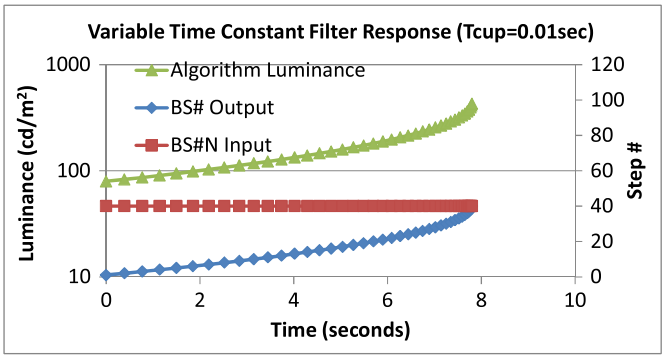


FIGURE 18 — Input steps 1 → 40 change.

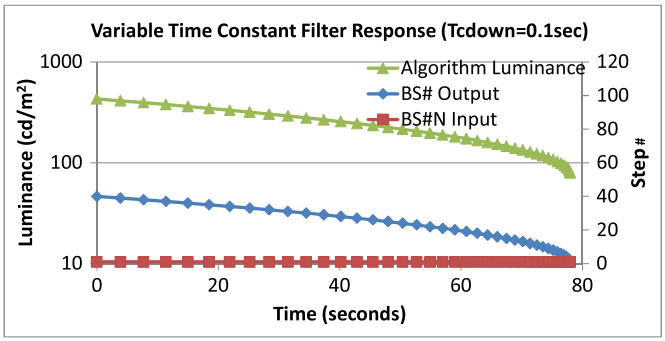


FIGURE 19 — Input step 40 → 1 change.

8 Biometric light sensor

The biometric light sensor may prove to be the ultimate light sensor for future automatic luminance control systems. The basic operating principle of biometric light sensor is to use the driver's eye pupil diameter and eye gaze direction to determine the luminance that the driver is observing as shown in Fig. 21.

The pupil diameter is measured using eye gaze cameras that are being utilized more often in automotive applications. The biometric light sensor method has the potential to replace not only the forward looking light sensor,[26] but also the light sensors associated with all the in-vehicle displays such as the center information display(s) and the instrument cluster. In addition, the biometric light sensor has the potential of detecting the veiling glare that is "scattered in the lens and the vitreous body of the human eye."[27] In order to use the observer's pupil diameter to determine the observed luminance, one model is the unified formula per Equation 8-1[28] as plotted in Fig. 22.

$$D_U = D_{SD} + (y - y_0)[0.02132 - 0.009562D_{SD}] \qquad (8\text{-}1)$$

- y_0 = 28.58 years
- y = age in years
- D_{SD} = Stanley Davies function per Equation 8-2

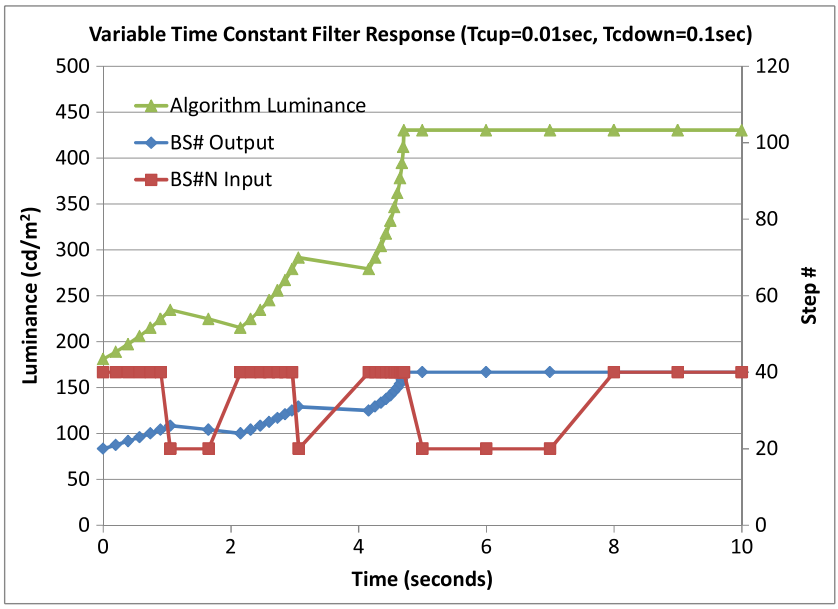


FIGURE 20 — Peak detector simulation for alternating high and low illuminance condition.

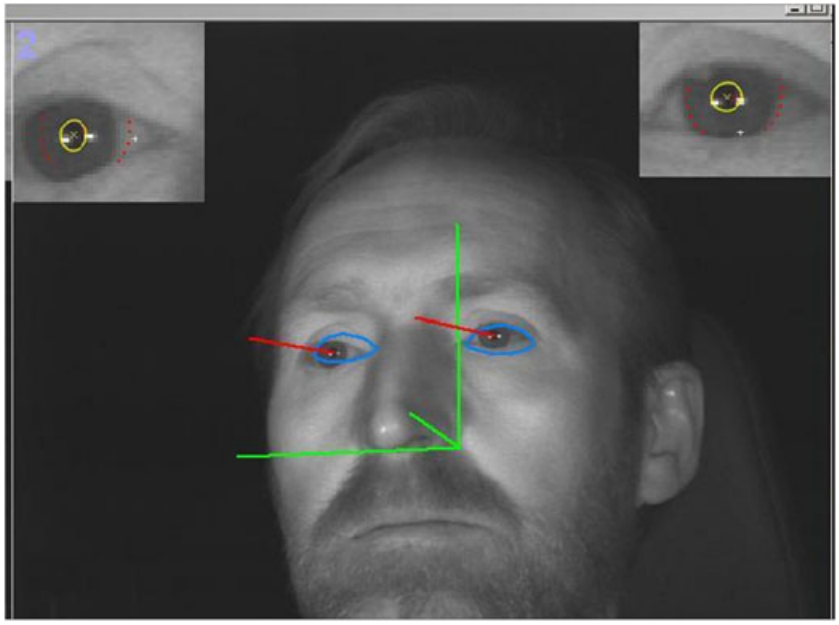


FIGURE 21 — Eye tracking camera images.[26,29]

$$D_{SD}\left((L,a) = 7.75 - 5.75\left[\frac{(La/846)^{0.41}}{(La/846)^{0.41}+2}\right]\right. \qquad (8\text{-}2)$$

"The unified formula is adapted from the Stanley Davies (1995) formula … which uses the concept of corneal flux density. Note that field of view area 'a' … is in deg^2 and luminance, L, is in cd/m^2. Therefore the pupil diameter is not only a function of the luminance that the eye sees, but also responds to the viewing area 'a' of luminance."[29] Equation 8-1 may be manipulated to provide Equation 8-3 that can be used to determine the log(La) as a function of the measured pupil diameter.

$$\log(La) = \left(\frac{1}{0.41}\right)\log\left[\frac{\begin{bmatrix}7.75 - D\\ -0.05279(y - y_0)\end{bmatrix}2(846)^{0.41}}{D - 2 - 0.0022(y - y_0)}\right] \qquad (8\text{-}3)$$

A plot of Equation 8-3 for two difference observer ages in shown in Fig. 23. By knowing the age of the user, the

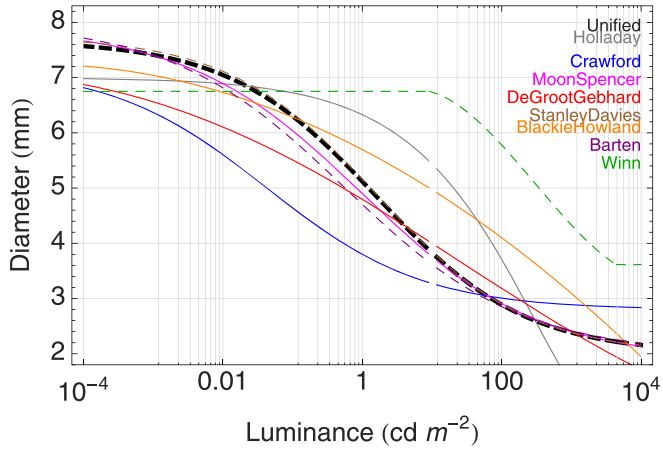


FIGURE 22 — Pupil diameter functions [fig. 16 of the work of Weindorf],[31] unified parameters are as follows: age = 30 years, binocular vision, and 60° field diameter.

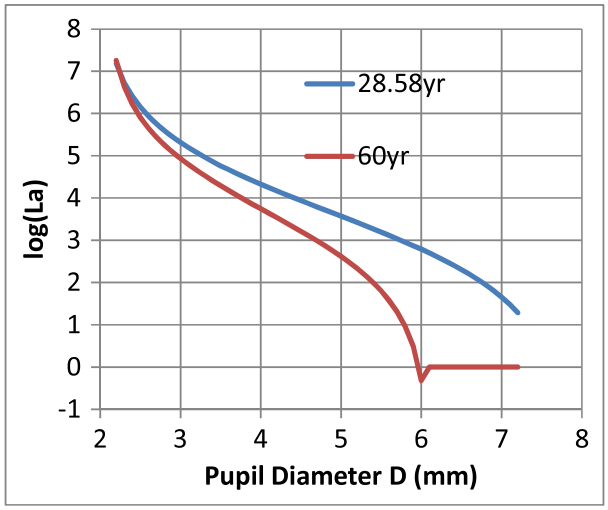


FIGURE 23 — Age factor example for pupil dilation.[29]

biometric light sensor method has the potential to compensate based on the age of the user. Per Fig. 23, it can be observed that the human eye pupil diameter responds approximately in a logarithmic fashion, and therefore, the automatic luminance control structure outlined in Fig. 12 may be easily adapted to the biometric sensor as shown in Fig. 24 where the pupil diameter lookup tables are employed.

One of the problems associated with an eye gaze camera approach is the dynamic response of the pupil diameter as the driver gazes towards the display. Because the pupil diameter is dynamically changing in an exponential manner towards the steady state condition as shown in Fig. 25, it is necessary to employ a steady-state predictive algorithm to determine the final amount of reflected light being seen by the user.

The predictive algorithm is based on the observation that the pupil diameter approximately responds in an exponential manner. One method to determine the final steady-state diameter is to use Equation 8-4 at any point along the dynamic response time.

$$D_F = D - \frac{S^2}{A} \tag{8-4}$$

[29]

- D = instantaneous diameter
- S = instantaneous slope
- A = instantaneous acceleration
- D_F = final predicted steady-state pupil diameter

By utilizing this method to determine the steady state pupil diameter in conjunction with inverse software filtering methods described previously, a suitable biometric automatic luminance control system may be developed.

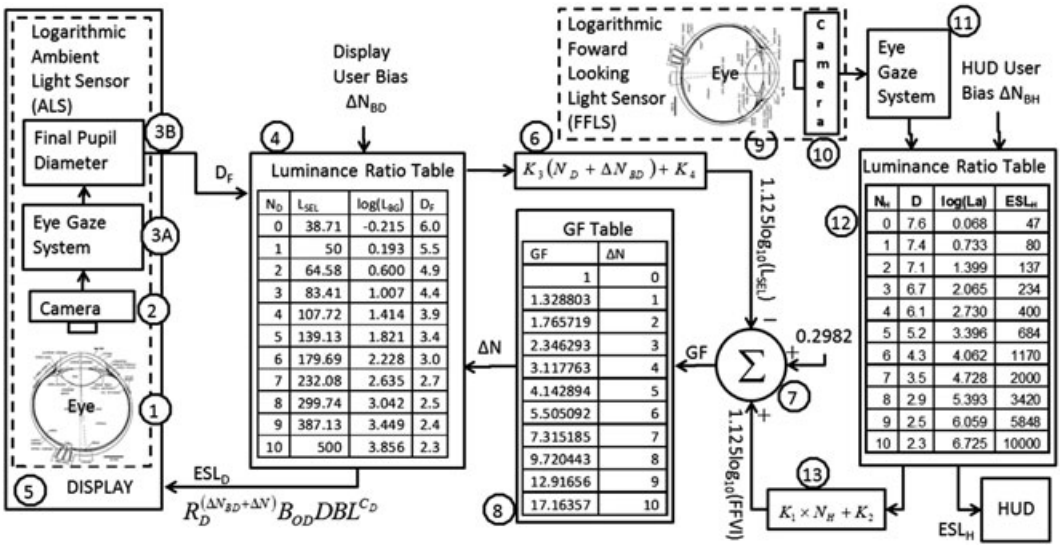


FIGURE 24 — Automotive biometric automatic luminance control system.[29]

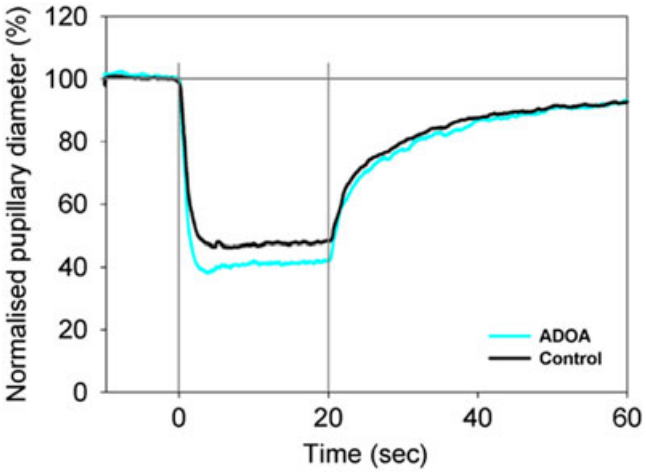


FIGURE 25 — Pupillary light reflex to a blue light stimulus.[33]

9 Conclusion

The automatic luminance control method developed by Visteon is a complete system that becomes a simple implementation based on a wealth of development activities. The Visteon automatic luminance control software has been developed to implement the filter function not only to eliminate display luminance variations caused by abnormal shadowing events but also acts as a peak detector to adjust the display luminance based on the highest illuminance levels. Eye gaze camera based systems hold the potential for improved automatic luminance control for the future. Further information may be found in the "Automotive Automatic Luminance Control Anthological Primer."[30]

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