# Exposure-Speed Relations and Tone Reproduction

*Jack Holm*
*Imaging Consultant, Rush, New York*

## Introduction

One of the practical problems in photography, both electronic and conventional, is the determination of optimal exposure. Standards have been established for film[1-7], and are under development for electronic still picture cameras, but in evaluating and utilizing these standards it is helpful to understand their basis. In pictorial photography, a wide variety of scenes are typically captured. Due to this variety, deter-mination of the optimal exposure for every scene is some-what complicated. A significant amount must be known about the film, camera, and scene; yet film speeds provide only one data value for the film, and exposure meters are designed to produce one data value from the scene. Advanced photographers frequently take multiple readings, but current exposure determination systems are based on the correlation of only two data values. In view of the variety of films and scenes typically encountered, it is surprising that the current exposure determination systems are successful. They are successful because they take advantage of a number of valuable characteristics of silver halide materials, and make a number of assumptions in relation to scene statistics.

Exposure determination requirements for electronic photography, however, are fundamentally different than for silver halide systems. Electronic sensors possess repeatable characteristics and are typically a permanent part of the camera. In electronic photography, different output media requirements are met at the output stage, and different image quality requirements are achieved by either adjusting gain to control noise, or by using cameras with different resolution capabilities. In all cases, the response characteristics of the camera are known. Also, with electronic cameras it is possible to immediately access as much information about the scene as is required for optimal exposure determination. Finally, due to practical considerations, it is desirable with electronic cameras to precisely determine the exposure in relation to the camera response. 8-bit quantization does not allow for significant exposure latitude, and must be adaptive to different scene ranges. 16-bit quantization can be fixed, and allows for latitude comparable to that of film, but requires twice as much storage.

The differences between electronic and film cameras result in different methodologies for exposure determination being desirable. In fact, the opportunity afforded by solid state area detectors to obtain significant amounts of scene data has already resulted in some manufacturers producing "smart" film cameras that measure a number of areas of the scene to allow for more reliable exposure determination (although this information is used only to place the scene into general "categories" as none of the cameras are yet able to integrate scene and film characteristics). This additional data is not required for low-end film cameras, but will logically become the norm in electronic and possibly in high-end film cameras. With film cameras, the camera could read the DX code to identify the film being used and look up its characteristics in an on-board ROM chip. Electronic cameras would be provided with knowledge of their response to allow for optimal determination of exposure based on image quality requirements, and optimal gain and quantization based on the scene statistics. It is even reasonable that lower resolution sensors be used for exposure determination in both cases, allowing for similar systems to be employed by both film and electronic cameras (although film contrast is not as easily adjustable, precluding the use of identical systems).

With all the developments presented above, one may question the need for mononumeric speed values for electronic cameras. Indeed, these values should be only part of the complete exposure determination system, but they remain important because of their simplicity and familiarity. The complete exposure determination "picture" is too complex to be grasped in its entirety for every image capture situation. It is the computer's ability to deal with the available data that allows one to go beyond mononumeric exposure determination. Speed values allow the photographer to make quick estimates of the amount of illumination required for a particular camera. Also, photographers are used to the speed-noise tradeoff and are able to quickly compare speed values, even when applied to totally different systems.

In summary, the determination of a protocol for meaningful speed values is complex, and must take into consideration many factors. The determination of a reliable, general speed protocol for electronic cameras is particularly difficult in view of the limited dynamic range imposed by 8-bit quantization. Also, electronic cameras need not rely on speed values to the extent that most film cameras do, in that a great deal of scene information is readily accessible. Nevertheless, speed values which are correlatable with film speeds should serve an important function in electronic photography by allowing for comparison between systems and quick determination of required illumination levels. The following work is an attempt to present a unified set of assumptions and a framework for speed protocol determination. It is based on past research, current standards, and the logical reconciliation and extension of these resources.

## Assumptions

### Spectral Conditions

Most standardized photographic exposure determination schemes are based, at least loosely, on photometric quantities. For this reason it is commonly assumed that the image capture medium has a spectral response similar to that of human photopic vision. This assumption is almost always false, but schemes based on this assumption are used widely because the *limits* of the spectral response of the capture media *are* similar to those of the eye. Assumption number one is therefore as follows:

a. That the spectral response of the exposure meter or automatic exposure determination system and the image capture medium are similar to that of the human eye as described by the photopic vision response function $V(\lambda)$, or

b. That the spectral response limits of the exposure meter or automatic exposure determination system and the image capture medium are similar to that of the human eye as described by the photopic vision response function.

If only assumption 1b. holds, it becomes necessary to make other assumptions:

a. That the spectral response of the exposure meter or automatic exposure determination system and the image capture medium are similar, and

b. That the sensitometry used to determine the film characteristic curve or electronic camera opto-electronic transfer function is carried out using the same source as will be used in image capture.

and

c. That the speed values obtained are designated as applicable only for a specific source (*i.e.* 3200K tungsten or 5500K daylight).

With some exposure determination systems, only assumptions 1b., 2b., and 2c. will hold. In those cases the exposure determined may be incorrect for non-neutral scenes. Fortunately, on the average, scenes are neutral with respect to the source. The errors in exposure resulting from exposure determination of non-neutral scenes using systems for which assumption 2a. does not hold are therefore considered generally acceptable or correctable in practical applications. The framework outlined below does not take such spectral corrections into account. They are generally accounted for at the time the scene is photographed. In summary, the exposure-speed relations outlined in this framework assume that, at a minimum, assumptions 1b., 2b., and 2c. hold, and that if assumption 2a. does not hold that the exposing radiation is neutral with respect to the source.

### Geometric Conditions

Another assumption deals with the geometric conditions of exposure determination:

That the angular acceptance of the exposure meter or automatic exposure determination system is appropriate for exposure determination with the camera system used.

This assumption is generally true, although the circumstances under which it holds fall into four general categories:

a. Where the angular coverage of the exposure determination system is the same as the field of view of the camera; commonly referred to as "averaging" metering.

b. Where the angular coverage of the exposure determination system is somewhat less than the field of view of the camera, or more weight is attached to the central area; commonly referred to as "center weighted" metering.

c. Where the angular coverage of the exposure determination system is a great deal less than the field of view of the camera, but the area measured for exposure determination is chosen to represent a particular tone in the scene, and the exposure reading obtained is then adjusted using knowledge of tone reproduction principles to provide the correct exposure; commonly referred to as spot metering.

d. Where the exposure determination system is configured to measure the illumination falling on the scene and calculates the correct exposure settings based on an assumed mean scene reflectance; commonly referred to as incident metering.

All of the above metering modes are useful, and geometric conditions are not a major source of exposure determination errors for experienced photographers. Modes a. and b. are typically used by inexperienced photographers but still provide adequate results for the vast majority of scenes, as inexperienced photographers are not sensitive to minor exposure errors.

### Scene Statistics

Two significant assumptions which are often neglected in exposure determination concern the scene range and mean reflectance. They are as follows:

That the luminance range of a statistically average scene is 160:1 (log range 2.2), and the resulting exposure range on the image capture medium is 80:1 (log range 1.9), corresponding to a camera flare factor of 2.

That the mean log luminance of a statistically average scene is approximately 0.95 log units below the highlight log luminance (edge of detail in white) and 1.25 log units above the shadow log luminance (edge of detail in black), and that this mean luminance is assumed to be the luminance metered, directly or indirectly, for exposure determination. These values result in the mean luminance correlating with a Lambertian scene reflectance of 12% for 100% highlight reflectance or 14% for 128% highlight reflectance. Values ranging from 10 to 18% have resulted from various experimental determinations. The 14% value is used throughout this discussion as it is assumed that the highlight reflectance in a statistically average scene will contain some specular elements. Flare results in the mean log exposure being halfway between the highlight and shadow log exposures.

Clearly all scenes are not statistically average, and these assumptions do not always hold. However it has proven sufficient in the past that they are approximately correct for a significant number of images captured. Studies[8] have shown that the log luminance ranges of pictorial scenes are approximately normally distributed with a mean of 2.20 and a standard deviation of 0.38. This distribution results in the probability of error resulting from an unusual scene range decreasing rapidly as the magnitude of the potential error increases. The flare factor also tends to increase as the scene log luminance range increases, decreasing the variability in the log exposure ranges produced and in the difference between the shadow and mean log exposure values. This results in the shadow exposure based film speeds provided for wide exposure latitude negative films correlating well with metered mean exposure values for a wide range of scene contrasts. Reversal and direct positive films typically have insufficient latitude to completely capture extremely wide range scenes, so judgment must be exercised by the photographer in these situations. Bracketing is also commonly employed. Some exposure determination systems such as the Zone System and Meter Index System allow for more precise exposure determination with unusual scene ranges and/ or mean luminances, but assumptions 4 and 5 have proven adequate for most situations.

## Tone Reproduction

The final assumption which must be made with regard to exposure determination concerns tone reproduction. Different viewing conditions result in different preferred densities for reproduction of the same scene tone. In general, higher illumination levels result in darker preferred scene tones with all images, and larger amounts of ambient light result in lighter preferred scene tones with transparencies. The shape of the preferred tone reproduction curve stays approximately the same, however, regardless of the viewing conditions. It is therefore possible to specify the curve to some extent by specifying the density at which detail is just perceivable in the black. This density, which typically must be less than or equal to 90% of the maximum density of the print or transparency material, is called the shadow density, Zone 1 density, or edge of black density (although the term shadow density is sometimes also used for other densities). Table 1 lists Zone 1 density values for a variety of viewing conditions:

**Table 1. Zone 1 Densities for a Variety of Viewing Conditions.**

| Viewing Condition | Zone 1 Density |
|---|---|
| Overhead transparencies projected in a lighted room | 1.2 |
| Reflection prints in a dim room (museum preservation lighting) | 1.4 |
| Reflection prints in a normally illuminated room | 1.9 |
| Transparencies viewed on a light table | 2.2 |
| Reflection prints in direct sunlight | 2.4 |
| Transparencies projected in a darkened room | 2.7 |

The above table illustrates another factor in the determination of preferred tone reproduction—the maximum density capability of the material. Photographic prints are rarely viewed in direct sunlight not only because extended exposure to sunlight can damage the print, but also because the maximum density capabilities of most print materials are insufficient to allow for preferred tone reproduction. For reflection hardcopy, the minimum reflectance or maximum density obtainable with the medium limits the Zone 1 density to a value which is sufficiently low that preferred tone reproduction is relatively constant for moderate viewing illumination levels. With transparencies, however, the preferred tone reproduction depends on the viewing conditions.

In the above paragraph, the reproduction of only one tone, Zone 1, was discussed. However the reproduction of all tones is important. To facilitate this discussion it is helpful to define other tonal values of importance. One can start this process by considering the perception of different Lambertian reflectances or densities. The Munsell System first defined equal perceptual differences in tone, with a value of 1 defined to be black and a value of 10 white[9]. The L values in the CIELab System are based on Munsell values multiplied by a factor of ten. One can therefore establish a relation between perceived lightness and density based on the densities of Munsell values. Table 2 lists Munsell values and corresponding densities. Figure 1 is a plot of these values, and of the equation:

$$D = 2.0248 - 0.06878\ V_m - 0.59\ \ln[V_m] \qquad (1)$$

where D is the density and $V_m$ is the Munsell value. This equation was fit to the data points using a least-squares regression.

**Table 2. Munsell Values and Corresponding Densities.**

| Munsell Value | Density | Munsell Value | Density |
|---|---|---|---|
| 1 | 1.93 | 6 | 0.53 |
| 2 | 1.52 | 7 | 0.38 |
| 3 | 1.19 | 8 | 0.24 |
| 4 | 0.93 | 9 | 0.12 |
| 5 | 0.72 | 10 | 0.00 |

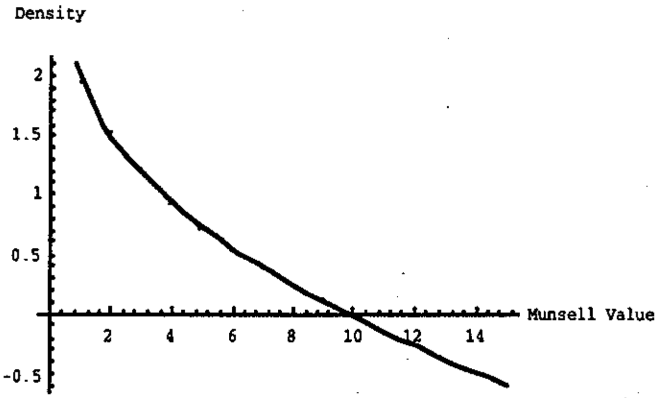

*Figure 1. Density - Munsell Value Curvefit.*

Equal perceptual differences do not equate precisely with important tonal levels, however, because the eye is more sensitive to changes in light tones than in dark tones. For the purposes of defining tone reproduction, the zones as defined by the Zone System[10] provide for slightly better spacing of important tonal levels. Also, as scene ranges change the Munsell values and corresponding densities, reflectances and log luminances associated with each zone change (with the actual log luminance being affected by the overall scene illumination). However the eye adapts when viewing a scene so that most scenes possess most zones. Unless a scene is unusual in content, one will see a range of tones from black to white regardless of the scene range. Consequently, preferred tone reproduction generally requires that the imaging system reproduce the scene in a range of tones from black to white; and with all scenes, the zones of the scene should map to the same zones in the image. Table 3 lists the eleven zones, along with the corresponding Munsell value, density, reflectance, log luminance, and a brief description. These values are typical for a normal scene range of 160:1, and must be scaled for other scene ranges.

The numerical values associated with the different zones in a scene may change, but due to the fixed output range required for the optimal viewing of a specific image, the numerical values associated with the zones in an image are constant. It is therefore possible to assign values to the zones of an image for particular viewing conditions. These values are provided for three different viewing conditions in Table 4. Figure 2 is a plot of these densities vs. the scene log luminances for a typical scene as presented in Table 3.

**Table 3. The Zones of the Zone System. (Munsell value, density, reflectance, log luminance, and log exposure values are for a typical 160:1 scene and a scene illumination level of 128 lux.)**

| Zone | Munsell Value | Density | Reflectance | Log Luminance | Description |
|---|---|---|---|---|---|
| 0 | | 2.70 | 0.002 | -0.60 | Absolute black - Dmax |
| 1 | 0.8 | 2.10 | 0.008 | 0.00 | Edge of detail in black |
| 2 | 1.8 | 1.55 | 0.028 | 0.55 | Texture in black |
| 3 | 2.8 | 1.22 | 0.060 | 0.88 | Average dark objects |
| 4 | 3.9 | 0.95 | 0.111 | 1.15 | Dark midtones |
| 4.5 | 4.4 | 0.85 | 0.142 | 1.25 | Average scene reflectance |
| 5 | 5 | 0.73 | 0.186 | 1.37 | Midtone - 18% reflectance |
| 6 | 6.2 | 0.52 | 0.301 | 1.58 | Light midtones |
| 7 | 7.6 | 0.31 | 0.495 | 1.79 | Average light objects |
| 8 | 9 | 0.11 | 0.777 | 1.99 | Texture in white |
| 9 | 10.6 | -0.10 | 1.251 | 2.20 | Edge of detail in white |
| 10 | | -0.40 | 2.501 | 2.50 | Absolute white - Base + Fog |

2.2
2.10 - -.1 = 2.2

90%
.05

In Table 4, the reflection hardcopy material is assumed to be capable of producing a maximum density of 2.1. This is the preferred value for moderate illumination levels, although some materials have a lower maximum density capability. The approximate preferred densities for these materials can be obtained by multiplying the densities listed by the quotient of the maximum density of the material and 2.1. Also, the information provided here is for average scene ranges. For high and low contrast scenes, the shape of the tone reproduction curve and the aim densities stay the same, but are respectively more or less separated on the log luminance axis. Relative scene log luminance values for different contrast scenes can be calculated for Zones 1 through 9 by multiplying the above values by the quotient of the actual scene log luminance range and 2.2. Since the Zone 0 and 10 log luminances are outside the endpoints of scene range measurements, they are not as easily determined, but they are generally not of importance for exposure determination. Note also that different scenes may have different reflectances, and in particular that depending on the distribution of light and dark tones in a scene, the mean log luminance may not correspond to a Zone 4.5. Variations in the difference in log luminance, and therefore log exposure, between the mean and speed point log exposures affect exposure determination with most systems.

**Table 4. Preferred Reproduction Densities (above base + fog) for Different Zones. (approximate values; scene luminance range 160:1, scene illumination level 128 lux, flare factor 2)**

| Zone | Scene Tone | Log Luminance | Log Exposure | Preferred Reproduction Density | | |
|---|---|---|---|---|---|---|
| | | | | A | B* | C |
| 0 | Absolute black - Dmax | -0.60 | -0.20 | 2.1 | 2.4 | 3.0 |
| 1 | Edge of detail in black | 0.00 | 0.00 | 1.9 | 2.2 | 2.7 |
| 2 | Texture in black | 0.55 | 0.36 | 1.6 | 1.88 | 2.3 |
| 3 | Average dark objects | 0.88 | 0.63 | 1.32 | 1.56 | 1.89 |
| 4 | Dark midtones | 1.15 | 0.88 | 1.0 | 1.18 | 1.42 |
| 4.5 | Average scene reflectance | 1.25 | 0.98 | 0.85 | 1.02 | 1.21 |
| 5 | Midtone - 18% reflectance | 1.37 | 1.09 | 0.7 | 0.85 | 1.0 |
| 6 | Light midtones | 1.58 | 1.29 | 0.47 | 0.6 | 0.7 |
| 7 | Average light objects | 1.79 | 1.50 | 0.27 | 0.37 | 0.45 |
| 8 | Texture in white | 1.99 | 1.69 | 0.12 | 0.2 | 0.25 |
| 9 | Edge of detail in white | 2.20 | 1.90 | 0.04 | 0.08 | 0.1 |
| 10 | Absolute white - Base + fog | 2.50 | 2.20 | 0.0 | 0.0 | 0.0 |
| Preferred midtone gamma | | | | 1.15 | 1.27 | 1.62 |
| Preferred average gradient | | | | 0.98 | 1.12 | 1.37 |

A: Print (reflection hardcopy).
B: Transparency (for viewing on a light table).
C: Transparency (for projection viewing in a darkened room).
*Note that a mismatch exists between typical reversal film gammas of approximately 1.6 and the preferred value for transparencies to be viewed on a light table. This mismatch occurs because transparency films are designed for projection in a darkened room. A common consequence of this mismatch is the intentional use of scene ranges of less than 160:1 for transparencies intended for light

table viewing or magazine reproduction. A scene range of approximately 32:1 will produce an appropriate density range for light table viewing, and a scene range of approximately 16:1 will produce an appropriate density range for reflection hardcopy. These lower scene ranges require somewhat more exposure in order to keep the highlights at the preferred density levels.

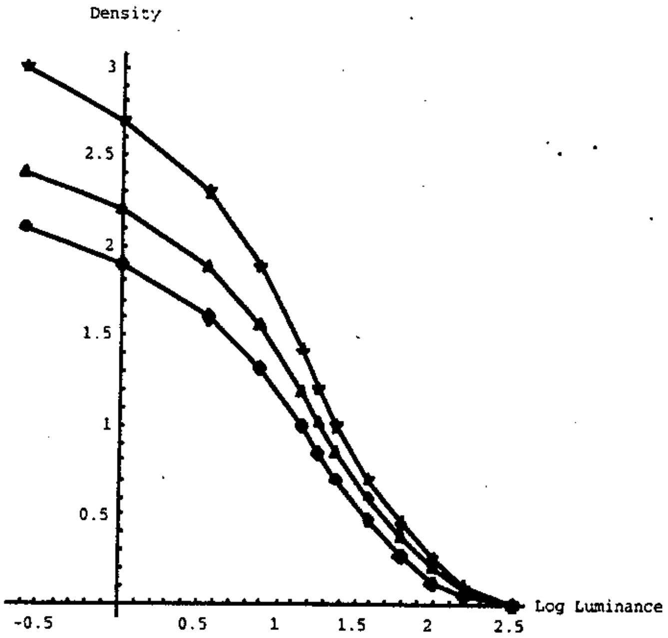

*Figure 2. Preferred Tone Reproduction Curves.* From top to bottom: transparency (projection), transparency (light table), print.

**Table 5. Zone 1-9 Log Luminances and Preferred Reproduction Densities for a 500:1 Scene Printed on a Material with a Maximum Density of 1.6.**

| Zone | Relative Log Luminance | Preferred Reproduction Density |
|---|---|---|
| 1 | 0.00 | 1.45 |
| 2 | 0.67 | 1.22 |
| 3 | 1.08 | 1.01 |
| 4 | 1.41 | 0.76 |
| 5 | 1.68 | 0.53 |
| 6 | 1.94 | 0.36 |
| 7 | 2.20 | 0.21 |
| 8 | 2.44 | 0.09 |
| 9 | 2.70 | 0.03 |

## Goals

The ultimate goal of any exposure determination scheme is the optimization of image quality. However the independent variable in exposure determination is exposure, so this optimization must be accomplished as related to exposure. Techniques such as noise removal, sharpening, and color calibration all affect image quality, but are not of interest in this discussion to the extent that they are not related to exposure.

Film system exposure determination standards are based on the correlation of two experimental values, the film speed and the average scene luminance. These standards describe a speed point exposure which is deemed to produce a density or densities of significance for a particular film type. The optimal ratio between this exposure and the typical mean scene exposure is then determined and used in the calculation of a constant for the speed equation. Film speeds are obtained for specific films by determining the speed point exposure and plugging the value into the speed equation to get the film speed. Since this film speed was determined assuming a particular speed-point-exposure/mean-exposure ratio, if this ratio is approximately correct, setting the film speed value on an exposure meter and reading the scene should indicate the correct exposure. The trick is to select a speed point which allows for the maximum variation in the actual speed-point-exposure/mean-exposure ratio with the minimum variation in image quality.

In the standard under development for electronic cameras, it is specified that speed be determined based on the image data output by the camera. Also, two exposure values are determined for each camera, one based on signal-to-noise and the other on highlights. The speed values obtained from these exposure values should place the exposure values so that the corresponding tones of the scene are optimally reproduced. It is assumed that camera manufacturers will adjust camera responses to allow for preferred tone reproduction using these two, and possibly other speeds.

It is important to note, however, that mononumeric speed values provide information about the predicted output at only one point on the characteristic (or other) curve. If a speed value is based on a shadow density, it will predict only the exposure required to produce that density, and similarly for highlight, signal to noise, and other speed point exposure criteria. Also, typical light meters can only read one luminance value for a scene and thereby predict only one film plane exposure. The actual tone reproduction is therefore dependent on: the speed point exposure, the desired reproduction of the speed point exposure, the metered exposure, the desired reproduction of the metered exposure, and the difference between the speed point and metered exposures. The following discussion outlines the mathematical framework on which exposure and speed determination protocols are based.

## Nomenclature

A number of quantities will be considered and interrelated below. The symbols used and their definitions are as follows:

$A$ = lens f-number
$A_{max}$ = the maximum aperture of a camera lens, or smallest f-number
$C$ = exposure meter equation constant (illuminance or incident metering)
$E$ = Scene illuminance (lux)
$EI$ = exposure meter exposure index
$F$ = lens focal length (meters)
$H$ = film plane exposure (general, lux-seconds)
$H_f$ = film plane flare exposure (lux-seconds)
$H_s$ = film plane shadow exposure (including flare, lux-seconds)
$H_m$ = film plane speed point exposure (lux-seconds)
$H_g$ = film plane mean exposure (scene specific, lux-seconds)
$\langle H_g \rangle$ = statistically average film plane mean exposure (lux-seconds)
$H_{18\%}$ = film plane midtone exposure (lux-seconds)
$H_h$ = film plane highlight exposure (lux-seconds)

$i$ = image distance (meters)
$k$ = film speed equation constant (for specific film type)
$K$ = exposure meter equation constant (luminance or reflected metering)
$L$ = scene luminance (general, candelas per square meter)
$L_s$ = scene shadow luminance (candelas per square meter)
$L_g$ = scene mean luminance (scene specific, candelas per square meter)
$<L_g>$ = statistically average scene mean luminance (candelas per square meter)
$L_{18\%}$ = scene midtone luminance (candelas per square meter)
$L_h$ = scene highlight luminance (candelas per square meter)
MI = exposure meter index
$q = (\pi/4)\, T\, v\, [\mathrm{Cos}^4(\theta)]$ = exposure - luminance equation constant
$r$ = Lambertian (perfectly diffusing) surface reflectance
$S$ = film speed
$T$ = transmission factor of the lens
$t$ = exposure time (seconds)
$v$ = vignetting factor
$X$ = general EI - mean exposure equation constant
$\theta$ = angle of image point off axis
$\Delta H = H_m/<H_g>$ = speed point exposure and average mean exposure ratio

## Mathematical Framework

### Scene Luminance and Film Plane Exposure

The development of a mathematical framework requires that a relationship be established between the scene luminance and the resulting film plane exposure. This relation is expressed by the following equation:

$$H = \frac{\pi\, v\, T\, \mathrm{Cos}^4(\theta)\, L\, t\, F^2}{4\, A^2\, i^2} + H_f = \frac{q\, L\, t}{A^2}\left(\frac{F}{i}\right)^2 + H_f \qquad (2)$$

When the camera is focused on infinity, $H_f << H$, $T = 0.90$, $\theta = 10°$, $\mathrm{Cos}^4\theta = 0.94$, and $v = 0.98$, $q$ is equal to 0.65 and the formula reduces to:

$$H = \frac{0.65\, L\, t}{A^2} \qquad (3)$$

And since $<H_g>$, $H_{18\%}$, and $H_h$ are all $>> H_f$, one can determine the following relations:

$$<H_g> = \frac{0.65 <L_g> t}{A^2} \qquad (4)$$

$$H_{18\%} = \frac{0.65\, L_{18\%}\, t}{A^2} \qquad (5)$$

$$H_h = \frac{0.65\, L_h\, t}{A^2} \qquad (6)$$

Note that $H_s$ cannot be determined using the simplified equation 3 because $H_f$ is comparable in size to $H_s$. Likewise, $H_m$ and $H_g$ cannot be determined using equation 3 if $H_f$ is comparable in size, which may be the case under some conditions. However equation 2 holds under all conditions, and for standard scene ranges and flare conditions:

$$H_s = 2\, H_f \qquad (7)$$

So the equation:

$$H = \frac{0.65\,(L + L_s)\, t}{A^2} \qquad (8)$$

holds for $H_s$, $H_m$, and $H_g$ as long as $q = 0.65$ and the flare factor is 2. Equation 8 is the general equation relating film plane exposure to scene luminance for statistically average scenes. For other scenes, the actual amount of flare light must be determined and:

$$H = \frac{0.65\, L\, t}{A^2} + H_f \qquad (9)$$

### Exposure Index, Light Meter Calibration, and Mean Film Plane Exposure

For the purposes of this discussion, the exposure index (EI) will be the value input to the exposure meter (usually as a speed or ISO number) for the determination of camera settings which produce a specified mean film plane exposure. If the meter is used to determine some other film plane exposure, the value input to the meter will be designated the meter index (MI). Following this convention, exposure meters are calibrated according to the equations:

$$K = \frac{EI <L_g> t}{A^2} \qquad (10)$$

for reflected meters, and

$$C = \frac{EI\, E\, t}{A^2} \qquad (11)$$

for incident meters.

The constants K and C are allowed to vary over the following ranges to allow manufacturers to optimize their meters in anticipation of spectral or geometric errors:

$10.6 < K < 13.4$ $\qquad 240 < C < 400$

The nominal value for K which will be used throughout the rest of this discussion is the one obtained by Scudder, *et. al.*[11] of 12.4. The C values correspond to mean reflectances of 10 to 14%. Combining equations 4 and 10 results in the following general EI equation:

$$EI = \frac{K\, q}{<H_g>} = \frac{X}{<H_g>} \qquad (12)$$

where X is nominally equal to 8 for a K value of 12.4 and a q value of 0.65. Note that for statistically average scenes and reflected light meters *only*:

$$<H_g> = 0.8\, H_{18\%} \qquad (13)$$

so that:

$$MI_{18\%} = \frac{10}{H_{18\%}} \qquad (14)$$

However equation 14 should not be used for the calibration of exposure meters, as in practice meters are aimed at a scene to measure the average luminance, as opposed to being aimed at an artificial subject which is one-third stop lighter than the average. Reflected light meter calibration may be carried out using a uniform Lambertian target of *any* reflectance, using equation 10, as long as the luminance of the surface is known. This luminance may be conveniently calculated from the illuminance falling on the surface using the equation:

$$<L_g> = \frac{r\, E}{\pi} \qquad (15)$$

Incident light meter calibration is somewhat more straightforward, since only the illuminance falling on the meter must be known. EI's for incident metering can also be correlated with the lux values used for video camera sensitivity specification through the calibration equation (11). Using a C value of 240 in this equation (corresponding to a mean scene reflectance of 14%) gives the following relation:

$$EI = \frac{240\, A_{max}^{2}}{E\, t} \qquad (16)$$

where E is the lux rating of the camera. It is important to remember, however, that EI's specify a quantity of exposure at the film plane (the mean exposure), and are therefore not a measure of camera sensitivity. In equation 16 it would be more correct to use speed as opposed to EI on the left hand side, were it not for the fact that no formal relationship exists between video camera sensitivity and film speed. Informally, the equation interprets the minimum scene illumination provided by the camera manufacturer as a type of reversed light reading (obtained from the maximum aperture of the camera lens and the effective video exposure time).

### Film Plane Exposure and Speed

Speed is a characteristic of a photographic material or electronic camera, as opposed to the EI, which is a value input to a metering system. Specific speed equations for different photographic materials are based on $H_m$, where:

$$H_m = \Delta H < H_g > \qquad (17)$$

and:

$$S = \frac{\Delta H\, X}{H_m} = \frac{k}{H_m} \qquad (18)$$

The values for $H_m$ and $\Delta H$ (and therefore k) are determined based on exposure(s) which are deemed of particular significance for the material, and on the anticipated ratio between $H_m$ and $<H_g>$. Exact speed determination is best accomplished using actual film plane exposure values, but if the lens of an electronic camera is not removable, equations 3 and 18 may be combined for midtone and highlight based speed determination as follows:

$$S = \frac{k}{0.65}\,\frac{A^2}{L\, t} \qquad (19)$$

where A, L, and t are the camera aperture, exposure time, and subject luminance necessary to produce the output corresponding to $H_m$. For shadow based speed determination, equations 8 (for a statistically average scene) or 9 (for any scene) and 18 may be combined similarly.

## Results

The preceding discussion of the assumptions, goals, and framework of exposure determination now allows for the placement of existing and future standards in context. Table 6 lists values from seven ISO standards. Surprisingly, this table indicates that ISO 2720 is in conflict with ISO 2721 and ISO 5763. This conflict is not immediately obvious because one lists values for K and the others list values for X, but the calculated value for K of 15.38 from ISO 2721 and ISO 5763 does not fall in the range of values for ISO 2720. It is possible to resolve this conflict, however, by determining X values from the film speed standards using tone reproduction considerations. These values are presented in Table 7.

**Table 6. Speed Point Constants and Densities from Various Standards. (All constants are for arithmetic speeds; standards are consistent between arithmetic and logarithmic notation. All density values are above base plus fog. Calculated values are in italics; other values are directly from the standards.)**

<table>
<tr><th>Std.</th><th>Application</th><th colspan="4">Constants, Reflectances, & Densities</th></tr>
<tr><td>ISO 2720</td><td>Exposure Meters</td><td>Min. Meter Eqn. K</td><td>Min. EI Eqn. X</td><td>Max. Meter Eqn. K</td><td>Max. EI Eqn. X</td></tr>
<tr><td></td><td>Reflected</td><td>10.6</td><td><i>6.89</i></td><td>13.4</td><td><i>8.71</i></td></tr>
<tr><td></td><td>Incident</td><td>Min. Meter C</td><td>Mean Refl.</td><td>Max. Meter C</td><td>Mean Refl.</td></tr>
<tr><td></td><td>(cosine receptor)</td><td>240</td><td><i>0.139</i></td><td>400</td><td><i>0.105</i></td></tr>
<tr><td>ISO 2721</td><td>Automatic Cameras</td><td colspan="2">Meter Eqn. Const. K</td><td colspan="2">EI Eqn. Const. X</td></tr>
<tr><td>ISO 5763</td><td>Automatic Flashes</td><td colspan="2"><i>15.38</i></td><td colspan="2">10</td></tr>
<tr><td>ISO</td><td>B&W Pict.</td><td colspan="2">Speed Point Den.</td><td colspan="2">Speed Eqn. Const. k</td></tr>
<tr><td>6</td><td>Neg.</td><td colspan="2">0.1</td><td colspan="2">0.8</td></tr>
<tr><td>ISO 2240</td><td>Color Reversal</td><td>Shadow Point Den.</td><td>Highlight Point Den.</td><td colspan="2">Speed Eqn. Const. k</td></tr>
<tr><td></td><td>(trans. den.)</td><td>2.0</td><td>0.2</td><td colspan="2">10</td></tr>
<tr><td></td><td colspan="5">(speed point logH is geometric average)</td></tr>
<tr><td>ISO 5800</td><td>Color Negative</td><td>Green Layer Den.</td><td>Slowest Layer Den.</td><td colspan="2">Speed Eqn. Const. k</td></tr>
<tr><td></td><td></td><td>0.15</td><td>0.15</td><td colspan="2">1.414</td></tr>
<tr><td></td><td colspan="5">(speed point logH is geometric average)</td></tr>
<tr><td>ISO 7187</td><td>Direct Pos. Color</td><td colspan="2">Speed Point Visual Den.</td><td colspan="2">Speed Eqn. Const. k</td></tr>
<tr><td></td><td>(refl. den.)</td><td colspan="2">0.5</td><td colspan="2">9</td></tr>
</table>

**Table 7. Film Speed Standard Formulas and Calculated EI Equation Constants. (Log[ΔH] values are for a scene range of 160:1 and a flare factor of 2, except † which is for a scene range of 32:1 and a flare factor of 1.5.)**

| Std. | Speed Point Den. | Den. on Positive | Speed Const. k | Log [ΔH] | Calculated X |
|---|---|---|---|---|---|
| ISO 6 | 0.1 | 1.9 (Dmax=2.1) | 0.8 | -0.98 | 7.6 |
| ISO 2240 | ~0.8 | 0.8 (Dmax=3.0) | 10 | 0.26 | 5.5 |
| ISO 2240† | ~0.8 | 0.8 (Dmax=2.4) | 10 | -0.18 | 15.1 |
| ISO 5800 | ~0.15 | 1.9 (Dmax=2.3) | 1.414 | -0.78 | 8.5 |
| ISO 7187 | 0.5 | 0.5 (Dmax=1.8) | 9 | 0.22 | 5.4 |

~approximate values are provided for materials which use the average of two measured exposures for the speed point log exposure; these values are typical for commercial materials.

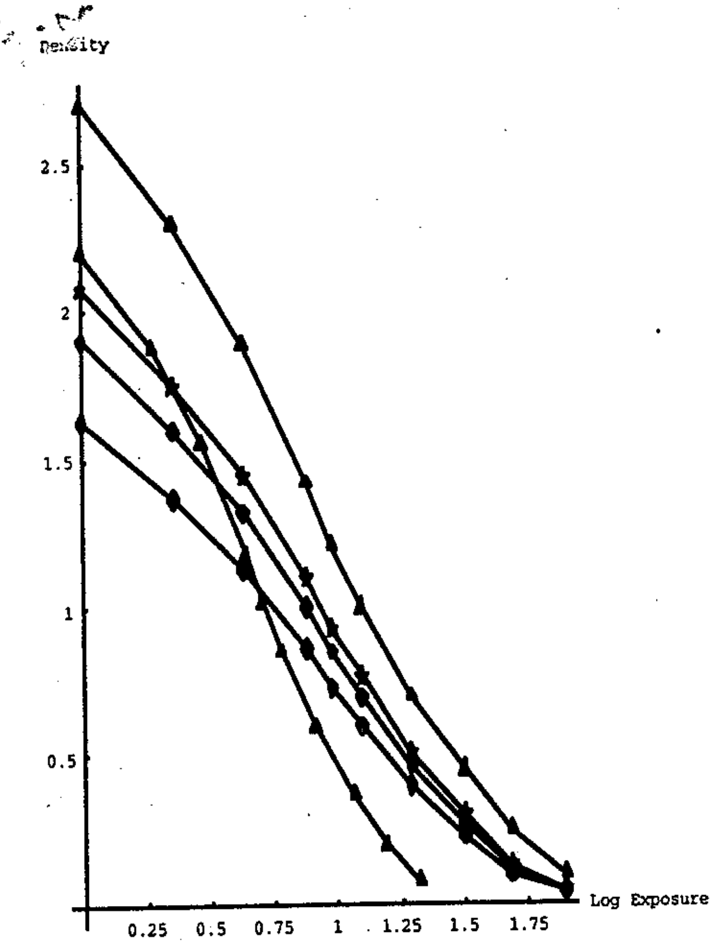

*Figure 3. Preferred Tone Reproduction Plots for Various Materials* From left side top to bottom: color transparencies for projection - normal scene range; color transparencies for light table viewing - low contrast scene; color prints from negatives; black and white prints from negatives; and direct positive (i.e. instant) prints.

The log[$\Delta$H] values in Table 7 were obtained from the preferred tone reproduction plots in Figure 3 by subtracting the mean exposure logH (log$\langle H_g \rangle$ or the Zone 4.5 logH) from the speed point logH (the logH which results in the speed point density being produced). The X values were then calculated by dividing the speed equation constant k by $\Delta$H. The average value for the standard (160:1) scenes is 7, which is in the range described in ISO 2720, but is significantly smaller than the value of 10 in ISO 2721 and ISO 5763. It is noteworthy, however, that the value of X increases dramatically for lower contrast scenes.

## Conclusions

The exposure-speed relation framework presented attempts to cover all aspects of pictorial exposure determination, and it is clear that the choice of speed point exposures and constants for speed determination with new systems must be based on tone reproduction considerations. The development of the framework also codified some terminology which has been used loosely in the past, such as the difference between speed and EI. Also, it was found that two ISO standards do not fit into this framework, namely ISO 2721 and 5763. They vary by one-third of a stop from the rest of the standards, but this variance is in relation to the exposure produced by metering the mean scene luminance. This mean value is variable from scene to scene, and a large statistical base of exposures would be required to detect such a small difference. The other five standards considered fit into the framework well.

## References

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4. ISO 2721 - 1982, *Photography - Cameras - Automatic controls of exposure.*
5. ISO 5763 - 1989, *Photography - Electronic flash equipment - Automatic control of exposure.*
6. ISO 5800 - 1987, *Photography - Colour negative films for still photography - Determination of ISO speed.*
7. ISO 7187 - 1983, *Photography - Direct positive colour print camera materials - Determination of ISO speed.*
8. Nelson, C.N., "Tone and Color Reproduction: I. Tone Reproduction," in *The Theory of the Photographic Process*, Fourth ed., ed. T.H. James, Eastman Kodak Co. (1977).
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