CASE 4

Evaluation of Photographic Systems Using a Dynamic Operating Window

Abstract: The function of photographic image formation is represented by the characteristic curves of photosensitive materials. In color photography, variation in the characteristic curves of three colors [blue, green, and red (BGR)] affects color change. The purpose of this study was to use the chemical reaction function and compare it with the results from a traditional approach.

1. Evaluation of Color Negative Film by a Conventional Characteristic Curve

A characteristic curve as a total system of color film and its coating structure are shown in Figures 1 and 2, respectively.

Each photosensitive layer (BGR) has multiple layers, each of which consists of a mixture of several types of silver halide emulsion (subsystems). Figure 3 illustrates characteristic curves of three types of silver halide emulsion forming a green-sensitive layer. Then we need to adjust a total system to a linear gradation with ample latitude by combining these emulsions. Therefore, even if we set up an input/output relationship that regards a characteristic curve of commercial photosensitive material as ideal, we cannot evaluate an essential photographic function but assess only its objective function. This technical issue is a major motivation for introducing quality engineering to the photographic field.

As a typical example, an image transfer method used for a color photocopy machine is well known. In this case, the idea occurs when the density of the original image is proportional to that of the photocopied image with a slope equal to 1. For a photographic system, if we consider the function to be to transfer the subject's image into a photographic density, we can conduct a similar analysis.

Setting the permeability to T and the amount of light to E we consider the input/output relationship expressed by

$$1/T = \beta E \tag{1}$$

$$\text{Log}(1/T) = \log E + \log \beta \tag{2}$$

Logarithmizing both sides of the equation, similar to the case of a photocopy machine, we obtain the following relationship between exposure (log E) and photographic density (more specifically, an omega-transformed value of permeability) with a slope of 1, as shown in Figure 4:

In a photographic system, there is no ideal relationship in this input/output system because the degree of slope (called *gradation* in photography) is an objective function determined by designers and is not appropriate in evaluating a generic function because photography density as an output depends on an amount of silver (or pigment) coming out in a development process.

If we regard a function of photography as forming the reaction of a latent image, a photographic system can also be considered as a system of converting light energy to latent image. Using a well-known theory of photosensitivity, we can derive the input/output relationship:

$$\log \frac{p}{1-p} = 2 \log E + A \tag{3}$$

where p, E, and A are the reaction rate (a ratio of the amount of silver developed to the total amount), the quantity of light, and a constant respectively.

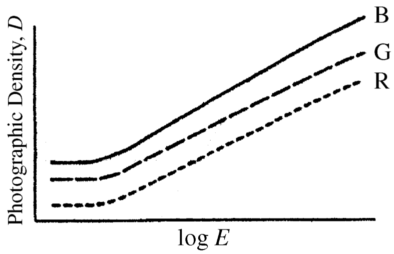

Figure 1
Characteristic curve of color negative film

In addition, considering that the photographic function is a developing reaction, we can regard the system as a system of amplifying a latent image in a development process. Since the ability to amplify the difference in the magnitude of the latent image is considered ideal, the following linear equation represents an input/output relationship (B is a constant):

$$\log \frac{p}{1-p} = \beta \log E + B \qquad (4)$$

In actuality, after analyzing the data using the foregoing two methods, we arrived at the same conclusion. This is because the slope cannot exceed 2, as shown in the latent-image-forming reaction.

Since these methods are tantamount to dealing with a photographic characteristic curve (log E and density), there is an advantage in expressing the variability in the characteristic curve. However, there are two problems in such an evaluation. The first problem is a considerable increase in the experimental effort. Figure 5 shows a characteristic curve for each development time in a subsystem using gradual exposure. The greater the quantity of light, the higher the corresponding photographic density. However, if the development time is lengthened, an unexposed area (i.e., a fogged area) develops.

Figure 6 illustrates the relationship of the SN ratio calculated using the aforementioned two methods for each development time with external disturbance given by the subsystem in Figure 5. This indicates a fluctuation in SN ratio in accordance with development time. Since each type of silver halide emulsion has a different development time when a peak emerges, we need a vast amount of experimental time simply to calculate this peak.

The second problem is one for which we probably cannot obtain a universally applicable result. Figure 7 shows the curve of E versus $\log[p/(1-p)]$ for a subsystem combining a basic condition and two external disturbances. Operators A and B have different regions for which to calculate an SN ratio, and eventually each SN ratio computed by each operator differs. So we cannot expect good reproduc-

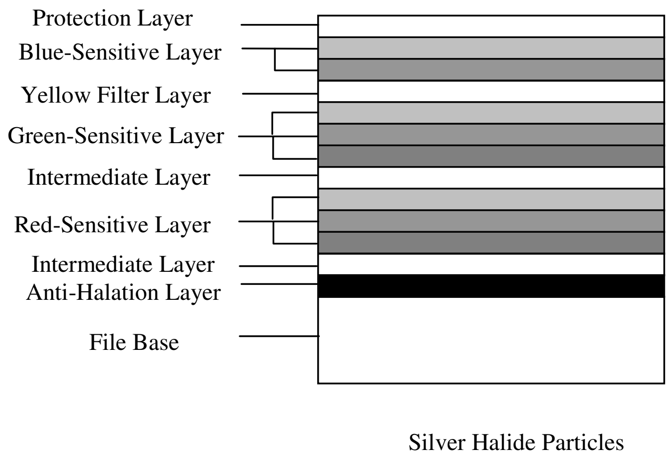

Figure 2
Structure of color negative film (cross section)

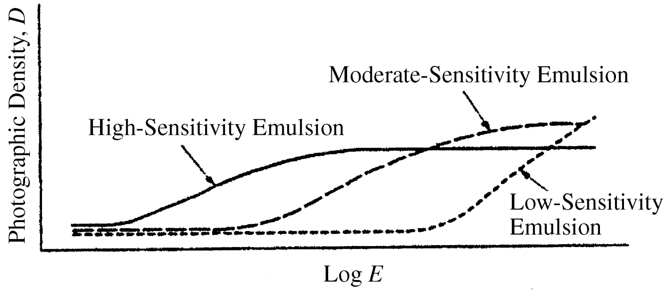

Figure 3
Characteristic curve of subsystem

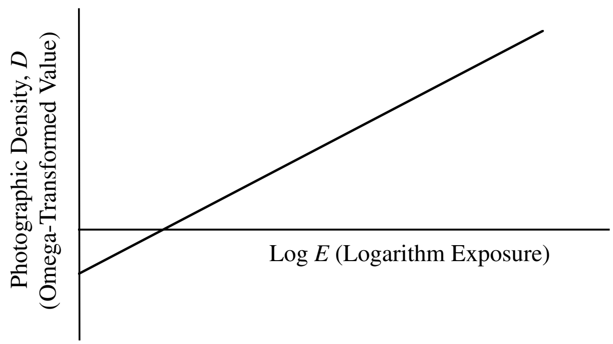

Figure 4
Input/output in the image transfer method

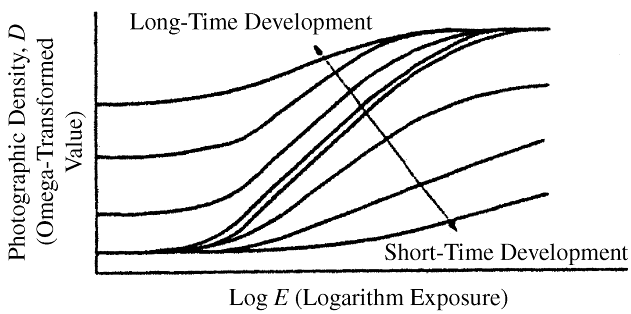

Figure 5
Fluctuation of characteristic curve for each development time

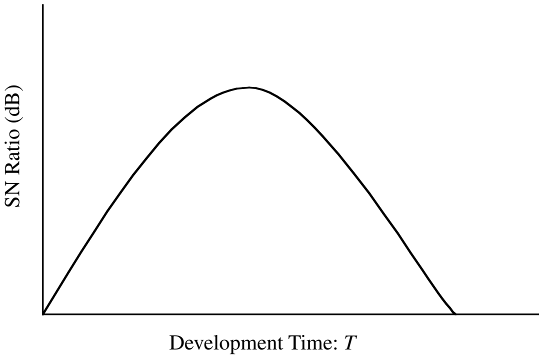

Figure 6
Development time and conventional SN ratio

ibility and generally practical results due to these differences.

2. Generic Function

In evaluating a photographic system using a dynamic operating window, we regard the photographic function to be the relationship between developing reaction speed with light. Development is a chemical reaction in which a microcrystal of silver halide is reduced to original metallic silver using a reducer, the developing chemical. Even unexposed photosensitive material will be developed sooner or later if the developing time is extended long enough. On the other hand, a microcrystal of silver halide used as the photosensitive material in a photograph forms a latent image in which several atoms of silver metal gather on a crystal of silver halide through a reaction activated by exposure. The latent image acts as a catalyst for the chemical reaction of development. In short, the existence of the latent image accelerates the developing reaction. Since the magnitude or number of latent images amplifies this action, exposure causes the developing speed to increase continuously. In a photographic system, by halting a developing reaction halfway and taking advantage of a difference between unexposed and exposed areas or of exposure in both areas as a difference in reaction speed, we form an image as a different amount of reaction.

As a matter of fact, as the total reaction speed increases, the reaction speed in an exposed area increases. However, an unexposed area's reaction speed also increases. Therefore, the function of a photographic system is to increase the developing speed in an exposed area without raising the speed (and without lowering the speed in an unexposed area). This is none other than the dynamic operating window in a chemical reaction.

A general calculation process based on a dynamic operating window in a photographic system is shown below. Using the characteristic curve of a sample for each development time in Figure 6, we converted image density into a reacted fraction of development, *p*. Since this system is a closed reaction system with a constant material used in chemical reactions, an ideal relationship between developing time and reacted fraction is identical to

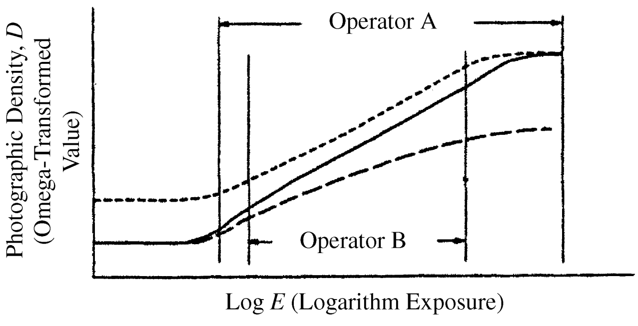

Figure 7
Signal range for calculating conventional SN ratios

the equation of the speed in a first-order reaction in the theory of reaction speed:

$$p(T) = 1 - e^{-\beta T} \tag{5}$$

where β is a constant of a developing reaction speed. Setting $y = \ln[1/(1 - p)]$, we can obtain a zero-point proportional equation (Figure 8):

$$y = \beta T \tag{6}$$

Defining exposures M_1, M_2, and M_3 and developing times T_1, T_2, ... , T_6 as signals, we calculated an SN ratio from Table 1.

Variation of differences between proportional terms due to exposure M:

$$S_{M\beta} = \frac{L_1^2 + L_2^2 + L_3^2)}{r - S_\beta} \tag{7}$$

Variation of proportional term due to exposure (fog) M_1:

$$S_{\beta M_1} = \frac{L_1^2}{r} \tag{8}$$

SN ratio:

$$\eta = 10 \log \frac{S_{M\beta} - 2V_e}{3r(V_e + S_{(M1)})} \tag{9}$$

Sensitivity:

$$S = 10 \log \frac{S_{M\beta} - 2V_e}{3r} \tag{10}$$

A key point in this calculation is that we handle a reaction at exposure M_1 [i.e., a reaction with no exposure (fog)] as a noise and include it in the noise part of the SN ratio. This is because we expect that if light hits a film, the reaction will be faster; and if it does not, the reaction will be slower.

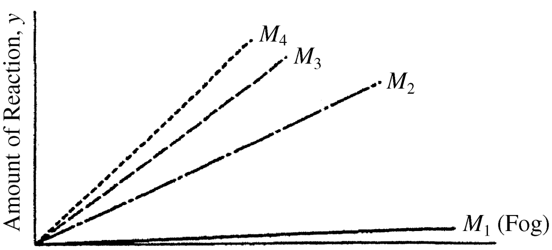

Figure 8
Input/output relationship for a dynamic operating window

3. Analysis Example

As an example of further simplifying the dynamic operating window method for photography, we selected two levels for exposure, M (no exposure: $M_1 = 0$, maximum exposure: M_2). It is considered easy to alter the developing time in a photographic system. A photographic emulsion is made primarily through a two-stage process. The first stage is a process in which the crystal of silver halide is grown, and the second, one in which the sensitivity of the silver halide is chemically enhanced (or color-sensitized such that it can carry a preferred spectral sensitivity distribution). Then, taking up control factors from the silver halide development process, which determine the majority of fundamental characteristics of a photographic emulsion, we designed an experiment based on an L_{18} orthogonal array. Table 2 shows the control factors and levels. For the amount of exposure, we selected two levels, no exposure M_1 and maximum exposure, M_2. Ten levels were chosen for developing time T:

Level:	1	2	3	4	5	6	7	8	9	10
Time:	24	41	69	118	195	340	578	983	1670	2839

Figure 9 shows an example of raw data obtained via the above described above. This reveals that we could estimate a slope of β even if we had not picked up as many as 10 points. The following calculation is based on two points for a developing time, 69 and 195 seconds.

Linear equations:

$$L_1 = 69y_{11} + 195y_{12}$$

$$L_2 = 69y_{21} + 195y_{22} \tag{11}$$

Effective divider:

$$r = 69^2 + 195^2 = 42{,}786 \tag{12}$$

Table 1
Data for dynamic operating window

Exposure	Developing Time						
	T_1	T_2	T_3	T_4	T_5	T_6	Linear Equation
M_1 (= 0: fog)	y_{11}	y_{12}	y_{13}	y_{14}	y_{15}	y_{16}	L_1
M_2	y_{21}	y_{22}	y_{23}	y_{24}	y_{25}	y_{26}	L_2
M_3	y_{31}	y_{32}	y_{33}	y_{34}	y_{35}	y_{36}	L_3

Total variation:

$$S_T = y_{11}^2 + y_{12}^2 + y_{21}^2 + y_{22}^2 \qquad (f = 4) \qquad (13)$$

Variation of proportional term:

$$S_\beta = \frac{L_1 + L_2^2}{2}(42{,}786) \qquad (f = 1) \qquad (14)$$

Variation of differences between proportional terms due to exposure M:

$$S_{M\beta} = \frac{L_1^2 + L_2^2}{42{,}786} - S_\beta \qquad (f = 1) \qquad (15)$$

Variation of proportional terms due to exposure (fog) M_1:

$$S_{\beta M_1} = \frac{L_1^2}{42{,}786} \qquad (f = 1) \qquad (16)$$

Error variation:

$$S_e = S_T = (S_\beta + S_{M\beta}) \qquad (f = 2) \qquad (17)$$

Error variance:

$$V_e = \frac{S_e}{2} \qquad (18)$$

Total error variance:

$$V_N = V_e + S_{\beta M_1} \qquad (19)$$

Table 2
Control factors and levels

Control Factor	Level		
	1	2	3
A: density of ammonia	0	1.2	
B: pH	3	6	9
C: temperature (°C)	75	65	55
D: particle diameter of silver halide (μm)	0.55	0.65	0.75
E: silver ion index (p_{Ag})	6.5	8.1	9.1
F: constitution of iodine (mol %)	0	3	6
G: amount of additive agent A	10	5	0
H: surface treatment of silver halide	Oxidation	None	Reduction

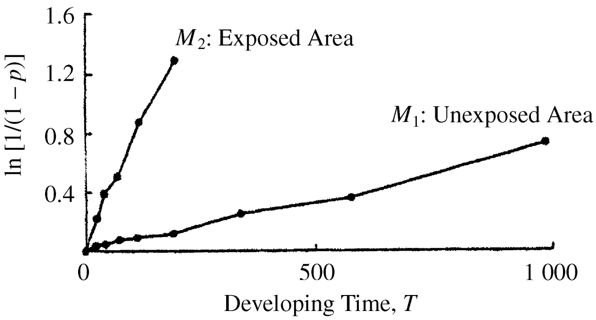

Figure 9
Actual plot for color negative film (dynamic operating window)

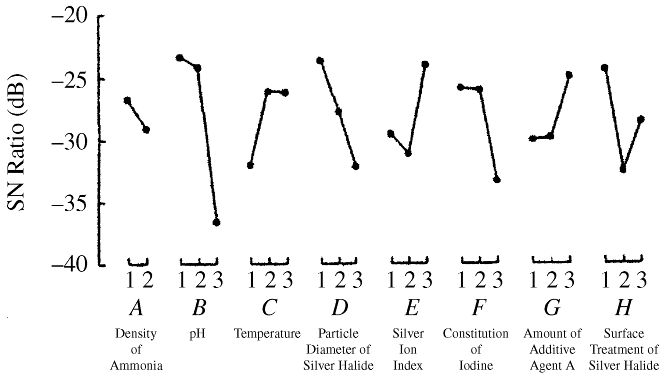

Figure 10
Response graphs of SN ratio by dynamic operating window

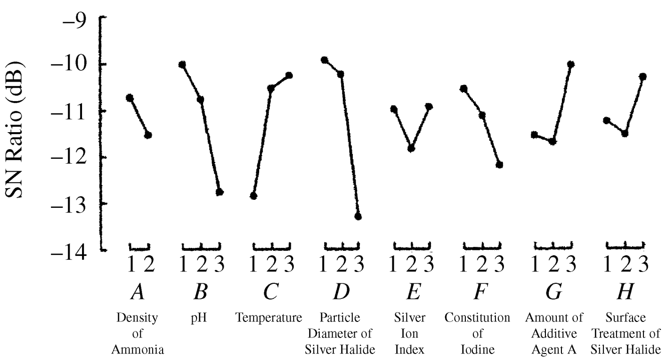

Figure 11
Response graphs of SN ratio by conventional procedure

SN ratio:

$$\eta = 10 \log \frac{[1/(2)(42{,}786)](S_{M\beta} - V_e)}{V_N} \qquad (20)$$

On the other hand, using the same L_{18} experimental configurations, we attempted to compute an SN ratio by the conventional method grounded on a characteristic curve as an input/output relationship. For the purpose of evaluating stability, in addition to the linearity of a characteristic curve, we allocated a compounded noise factor, including storage or development conditions, to the outer array and select exposure expressed by log E as a signal factor and the omega-transformed value of a reacted fraction as an output for an analysis using the zero-point proportional equation. Figures 10 and 11 show the response graphs of the SN ratio obtained from characteristic curves based on both the dynamic operating window and conventional (i.e., input/output of characteristic curve) procedures. Comparing the response graphs obtained by both a dynamic operating window and a conventional SN ratio, we can see that almost all of the plots are consistent. The SN ratio in the conventional procedure assesses the change of slope of gradation due to external disturbance ($S_{N\beta}$), magnitude of variability (S_N), and nonlinear portion (S_e) as noises. Since we tried to avoid such problems, as the difference in developing conditions between experiments or the difference in signal factor ranges, quality features consistent with the magnitude of variability of the characteristic curve were evaluated. They can thus be considered to represent the stability of a photographic emulsion in this experiment.

In contrast, although the result derived from use of a dynamic operating Window never evaluates variations in quality features, such as the shape of a characteristic curve or external noise, it shows almost the same variation as that of the SN ratio of a characteristic curve. This implies that improvement in a photographic function based on developing speed eventually leads to stability of a characteristic curve, the objective quality characteristic.

Reference

Shoji Matsuzaka, Keisuke Tobita, Tomoyuki Nakayama, Nobuo Kubo, and Hideaki Haraga, 1998. Functional evaluation of photographic systems by dynamic operating window. *Quality Engineering*, Vol. 7, No. 5, pp. 31–40.

This case study is contributed by Shoji Matsuzaka.