Measuring CMYK Halftones:
The Case for Spot Color Tone Value Formula

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Abstract

The adoption of Spot Color Tone Value (SCTV) in ISO 20654:2017 represents a clear improvement over the density-based Murray-Davies TVI model for the characterization of spot color halftone gain, providing a closer correspondence with dot area and visual impression. However, CMYK halftone gain is still commonly characterized by the TVI method, and the continuation of this practice presents several challenges to practical process control of print jobs containing both CMYK and spot colors. The adoption of Colorimetric Tone Value as the default model for characterizing halftone gain of both spot colors and CMYK is proposed. Advantages include reduction of ambiguities in software and instrument displays and usability with a wider variety of CMY colorants. Disadvantages to be overcome include user unfamiliarity with the newer methods and metrics and certain incompatibilities with existing colorimetric target aims. Practical recommendations are made for providing backward compatibility of CTV with legacy print specifications by means of simple compensation curves.

Background of the Problem

Process control in commercial printing has a long association with CMYK density. Relatively simple colorimeters, using red, green, and blue filters aligned to the peak spectral reflection of typical press inks, deliver logarithmic density readings that are workable proxies for ink film thickness and align reasonably well with visual impression of color strength. Halftones can correspondingly be measured densitometrically and converted to approximate coverage values using the Murray-Davies formula (newer and original forms, respectively):

$$TV = \frac{100\,(R_{\mathrm{pap}} - R_{\mathrm{halftone}})}{R_{\mathrm{pap}} - R_{\mathrm{s}}}$$

where R is the X, Y or Z reflectance, or

$$TV = \frac{1 - 10^{-\mathrm{Dt}}}{1 - 10^{-\mathrm{Ds}}}$$

and where D_t and D_s are paper-relative status density values of the halftone and solid tone respectively.

Tonal Value Increase (TVI) is simply

$$\mathrm{TVI} = \mathrm{TV}_{measured} - \mathrm{TV}_{nominal.}$$

As uncontrolled dot gain is a chief cause of color variance in halftone printing, the Murray-Davies TVI formula is a widely used process control tool, allowing easy calculation of adjustment of dot size on the printing plate by means of analogue or digital controls. However, the usefulness of this system depends on and is circumscribed by the use of both standard CMYK press inks and corresponding RGB filter sets used in Status densitometry, whether these are physical filters or virtual ones modeled mathematically from multiband spectral measurements.

The limitations of this system for characterizing halftones of non-CMY colors can be seen Figure 1. In this example, the closest available filter for measuring the strength of reflex is the red status density filter, absorbing in the range of approximately 560 to 670 nm, corresponding to the highest absorption by process cyan ink. The overlapping of the lower lines, representing densities of 70% to 90% tints, might suggest an extremely steep tone gradient and thus very high gain. However, this ink's peak absorption begins around 520 nm, where one can see well-differentiated tint values suggesting much more moderate gain. The standard TVI measurement of this blue as "cyan" obviously misrepresents the halftone gain of this color.

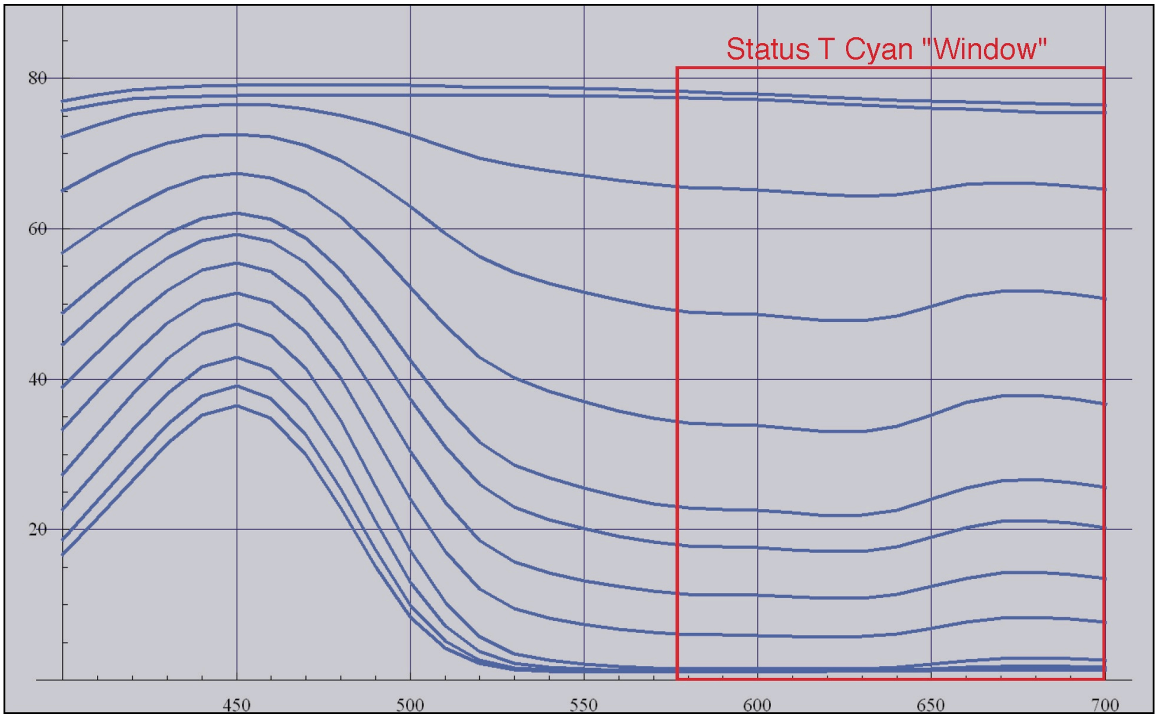

Figure.1. Spectra of tone curves of reflex blue showing inaccurate Status T definition as process cyan (Courtesy John Seymour)

This complicates an already difficult problem for practical process control of spot colors, which may also have widely varying inherent tonal gain. (This latter problem is not under study in this article.) The aggregate effect can be seen in Figure 2. Although all colors were printed identically, conventional density measurement and TVI calculation yield wildly different halftone values. These curves provide no reliable basis for norming gain to visually consistent aims, for example, by use of plate correction curves.

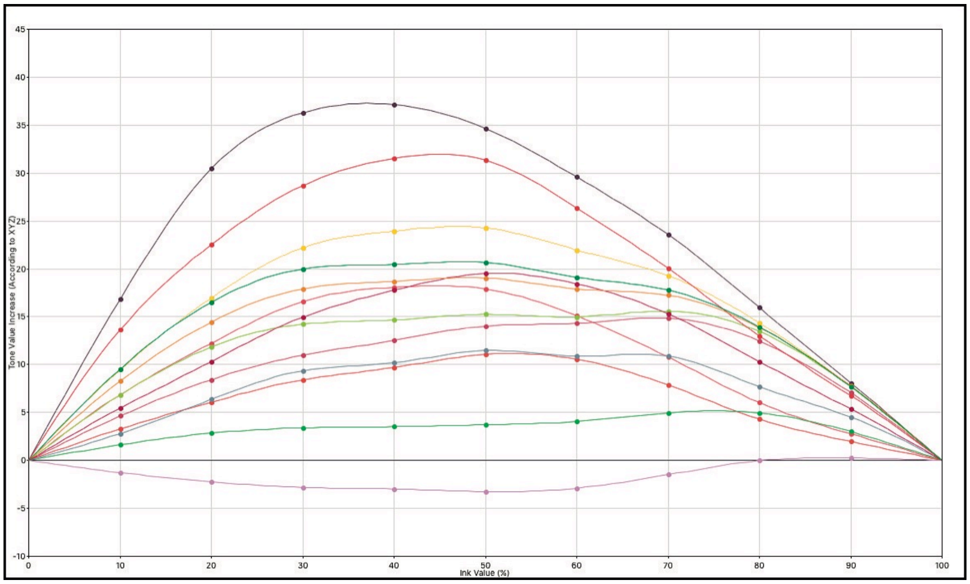

Figure 2. TVI of 13 spot colors

These obvious shortcomings of TVI for measurement of non-CMY halftones gave rise to attempts to improve the characterization using colorimetry made possible by the availability of affordable spectrophotometers. One of the more elegant formulae, Colorimetric Tone Value, was proposed by William Birkett and Charles Spontelli in 2005 and adopted as Spot Color Tone Value in ISO 20654 in 2017. CTV replaces the Murray-Davies's colorant-specific R, G, and B filters with a hue-agnostic Euclidean vector in XYZ color space. A simplified version is derived using CIELab measurements:

This neatly circumvents the "wrong filter" problem by considering only total color gain and light absorption. It also avoids certain defects of Lab-based formulae like dE-Paper, which can be distort the effect of hue shifts on the perception of tonal change. Zero gain in CTV therefore describes a gradient that is visually quite linear and incidentally similar to the 15-18% CMY TVI characteristic of offset printing with AM screening on coated stock. This makes possible a simpler, more intuitive way to display halftone gain, wherein a flat, horizontal line may describe the normal condition of visual linearity (Figure 3).

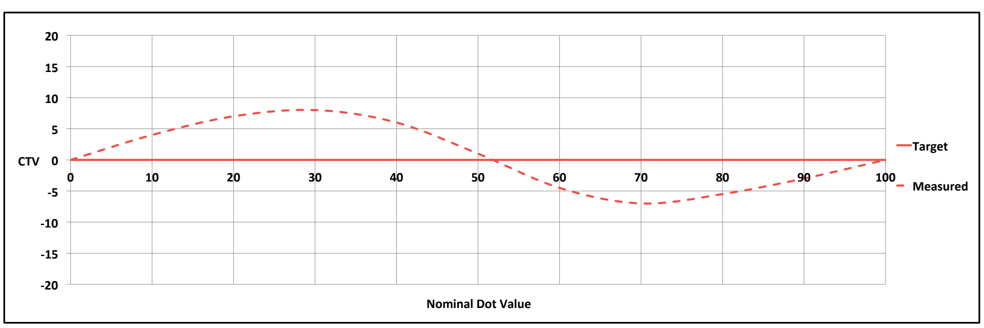

Figure 3. Newer style graph showing horizontal line as CTVI target

A comparison of results of TVI- and CTV-based calibrations may be seen in Figure 4. Stepped ramps of two colors, reflex blue and rhodamine red, were printed and measured, and adjustment curves applied as follows: The upper two ramps were aligned to 17% TVI (at 50%), while the lower two were aligned to 0% CTV. As can be seen, the rhodamine red ramp has higher visual gain than the reflex blue, with some compression between 60% and the solid tone. In the CTV-corrected ramps, tonal progression is more uniform and consistent between the two colors. (Note: Illustrations within this article, for obvious practical reasons, are reproduced without the benefit of spot inks; images have been modified in an attempt to preserve the visual effects described herein.)

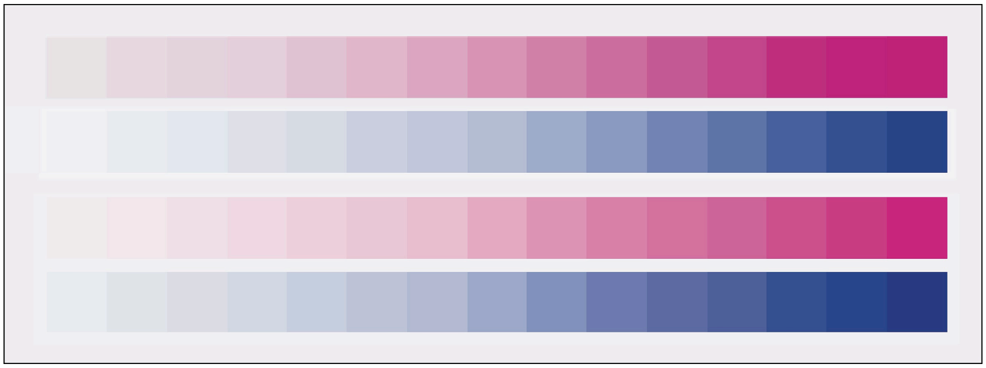

Figure 4. Tint ramps of two spot colors aligned by TVI (top) and CTVI (bottom)

CTV's effectiveness at modeling visual linearity also makes it a useful tool for assessing smoothness and consistency in printed gradients. Figure 5 shows the same sampling of spot color ramps as in Figure 2, calculated as CTV increase (hereafter referred to as CTVI).

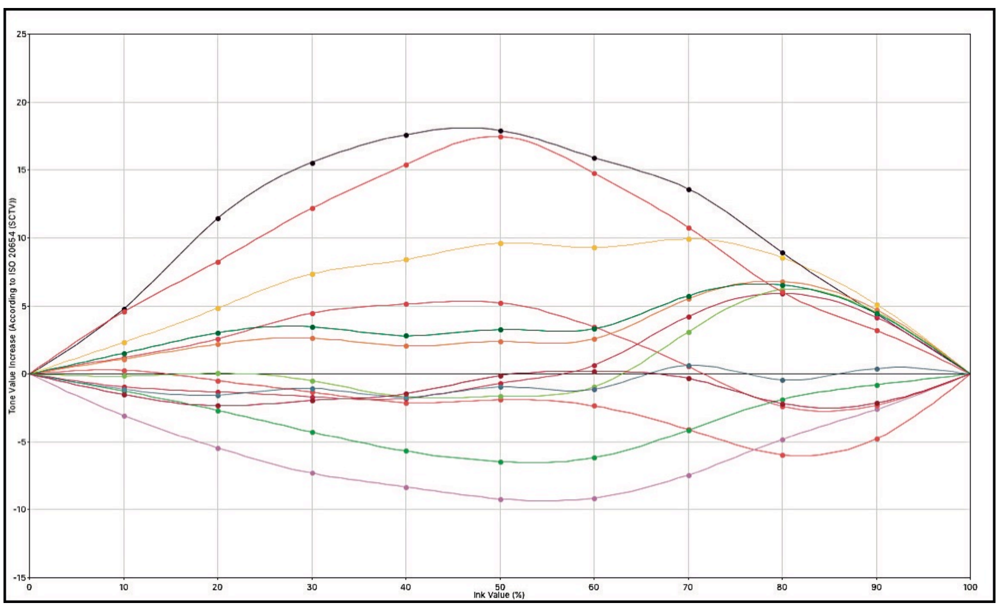

Figure 5. Colorimetric tone value increase (CTVI) of 13 spot color tone ramps

Figure 6 shows the result of norming TVI in all samples to ISO Curve B. The result plotted in CTVI is smoother but scarcely more linear.

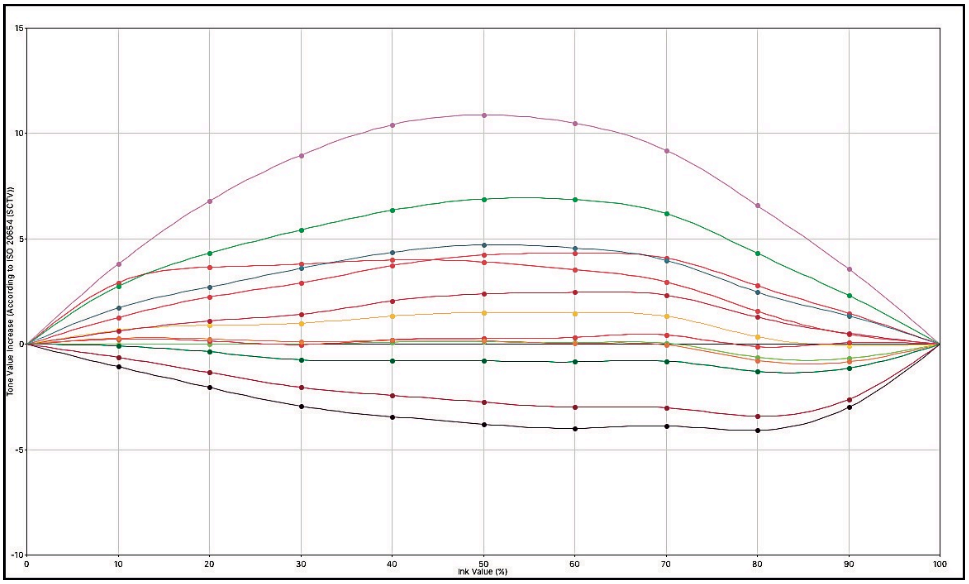

Figure 6. CTVI curves of 13 spot colors normed to ISO Curve A

Application of CTV to CMYK Halftones

The adoption of Spot Color Tone Value as ISO 20654 and its inclusion in process-control software nonetheless immediately introduced a new problem: Operators were suddenly confronted with two very different-looking displays of halftone gain, often simultaneously: CMYK in Murray-Davies-based TVI, and spot colors in CTVI (Figure 7).

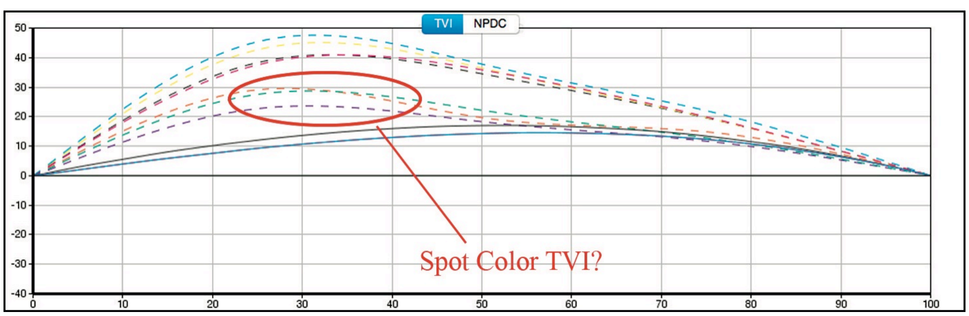

Figure 7: Process control display with mixed TVI and CTVI curves (courtesy Bodoni Systems)

This is not merely poor mathematical "housekeeping"; it is a potentially serious ambiguity. A worker accustomed to conventional TVI displays might instinctively interpret the spot color gain (lower curves) as too low, whereas in fact it is much too high. It is optimistic to assume that the error will be discovered before being acted upon, with serious consequences. Worse, perhaps, is that such a display demands that halftone growth on the same press be understood by two different and largely incompatible models. It should be noted that the software developer is not to be faulted: The display is consistent with current ISO specifications.

Given the evident superiority of CTV for the measurement of spot color halftone gain, it might be fair at this point to question its restriction to spot colors. In other words, can a good case be made for colorimetric tone value as the preferred method for characterizing all halftone gain, even for CMYK? Certain interrelated developments in the printing industry may strengthen the case for CTV:

1. The widesread use of device-independent, colorimetric aims for process and spot color inks

2. The increasing use of high-chroma CMYKN inks in sectors such as digital inkjet and electrographic printing

3. The recent inclusion of SCTV curve calculation in process control and data editing applications

In this light, the persistent use of TVI aims for CMYK haftone gain would seem to stand out as an almost unique anachronism in process control regimes, giving consistent results only where inks and print conditions are similar. Moreover, ISO 12647-2:2004 specifies no less than six normative TVI curves for various output conditions within offset lithography, each displaying different tonality in its primary ramps (Figure 8).

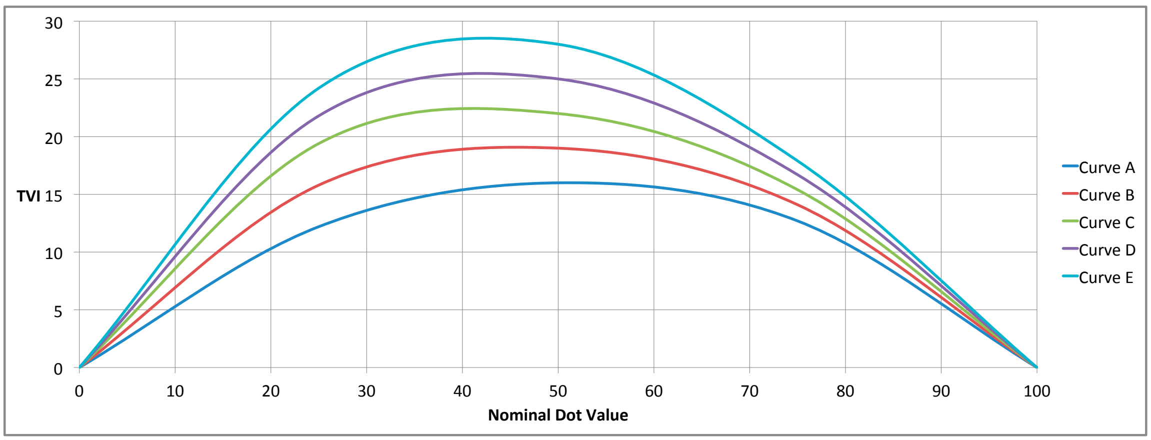

Figure 8: The five normative TVI curves of ISO 12647-2 (2013)

To be fair, these curves do provide a reasonable description of halftone gain of many printing processes and substrates using “linear,” uncorrected printing plates. Nonetheless it may be argued that colorimetric tone linearization has the important advantage of universality and simplicity as a visual norm against which deviations in output may be more easily assessed in any print process.

Figure 9 shows the magenta CTVI of five different digital and analog CMYK systems printing on coated stock.

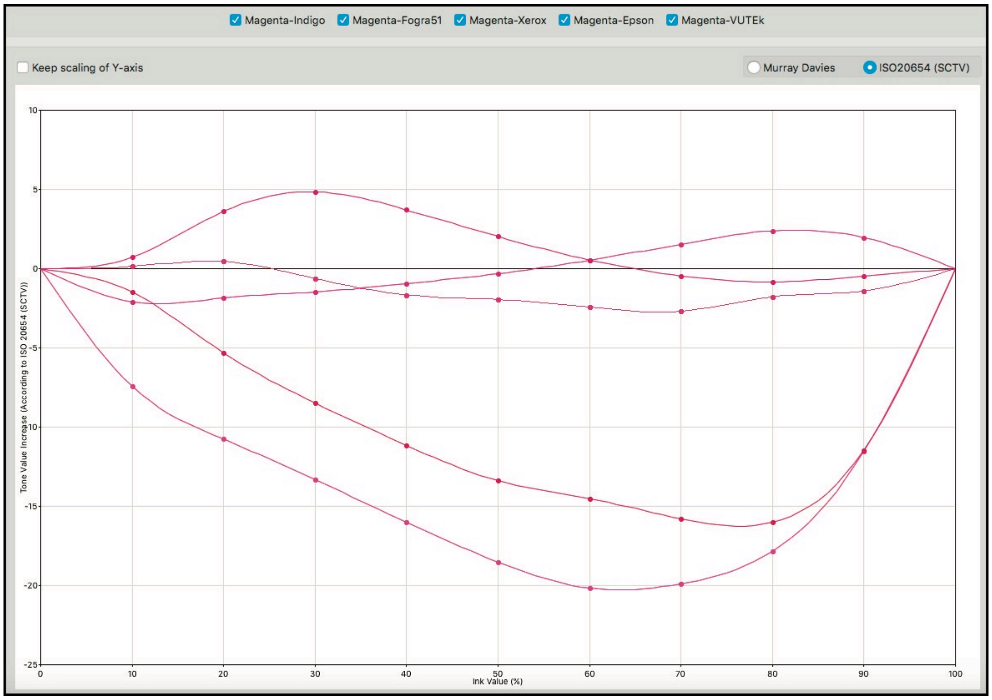

Figure 9. CTVI curves of 5 printing systems

It is important to note that these systems were carefully linearized according to their manufacturer's specifications. However, system design objectives within this industry sector are often motivated by factors that militate against standardization, including especially the need for high-chroma CMY inks as well as special gamut-expanding colors such as orange and violet—important for competing in markets such as photographic, display, and label printing, for which such systems are well suited. Color matching is handled primarily through ICC or other color management, and therefore little importance is placed on aligning "raw" device output to any industry standard. In any event, this is not necessarily easy, as smooth tonal curves and colorimetric aims such as gray balance and overprint Lab values may prove to be mutually conflicting objectives with inks that display significant hue shifts throughout their tonal scale. G7 curves, for example, must create a smooth, neutral CMY gray ramp, requiring much more complex calculations (Figure 10).

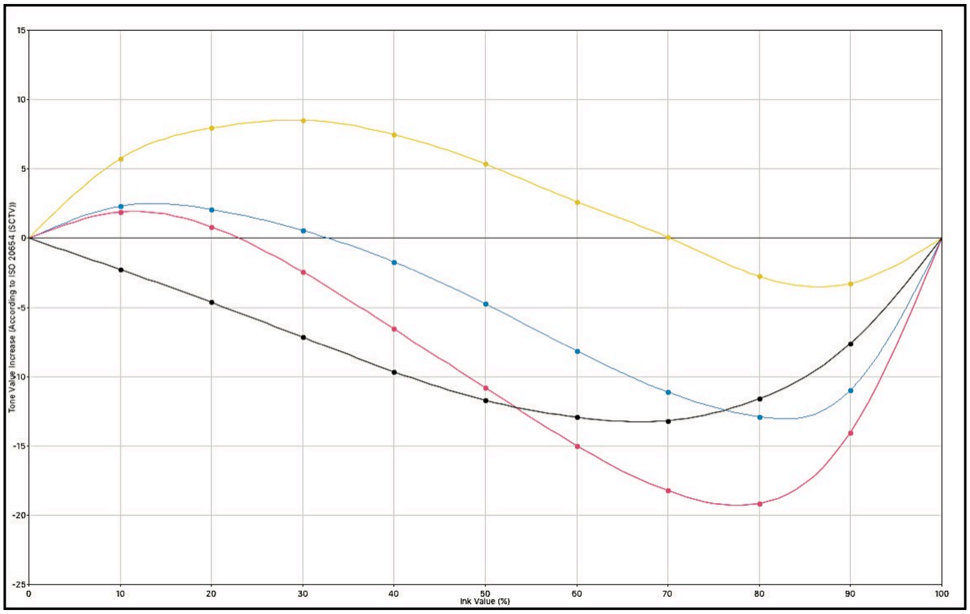

Figure 10. CTVI curves after G7 gray balance correction: inkjet printer

CTV-based calibration, less affected by such hue shifts and unburdened with CMY gray-balance considerations, more easily produces smoother single-color curves with improved visual consistency over a broad range of ink, screening, and substrate. Figure 11 shows magenta tone ramps linearized in CTV, TVI Curve A, and G7 (extracted from the full CMYK data set) printed on coated stock by 5 different systems (top to bottom): aqueous inkjet, web gravure, digital toner, sheetfed offset (Fogra51), and UV inkjet. The G7 linearization is the least smooth and the tone scales least well matched, while the TVI and CTV linearizations show better matching of tones, with CTV providing the smoothest ramp.

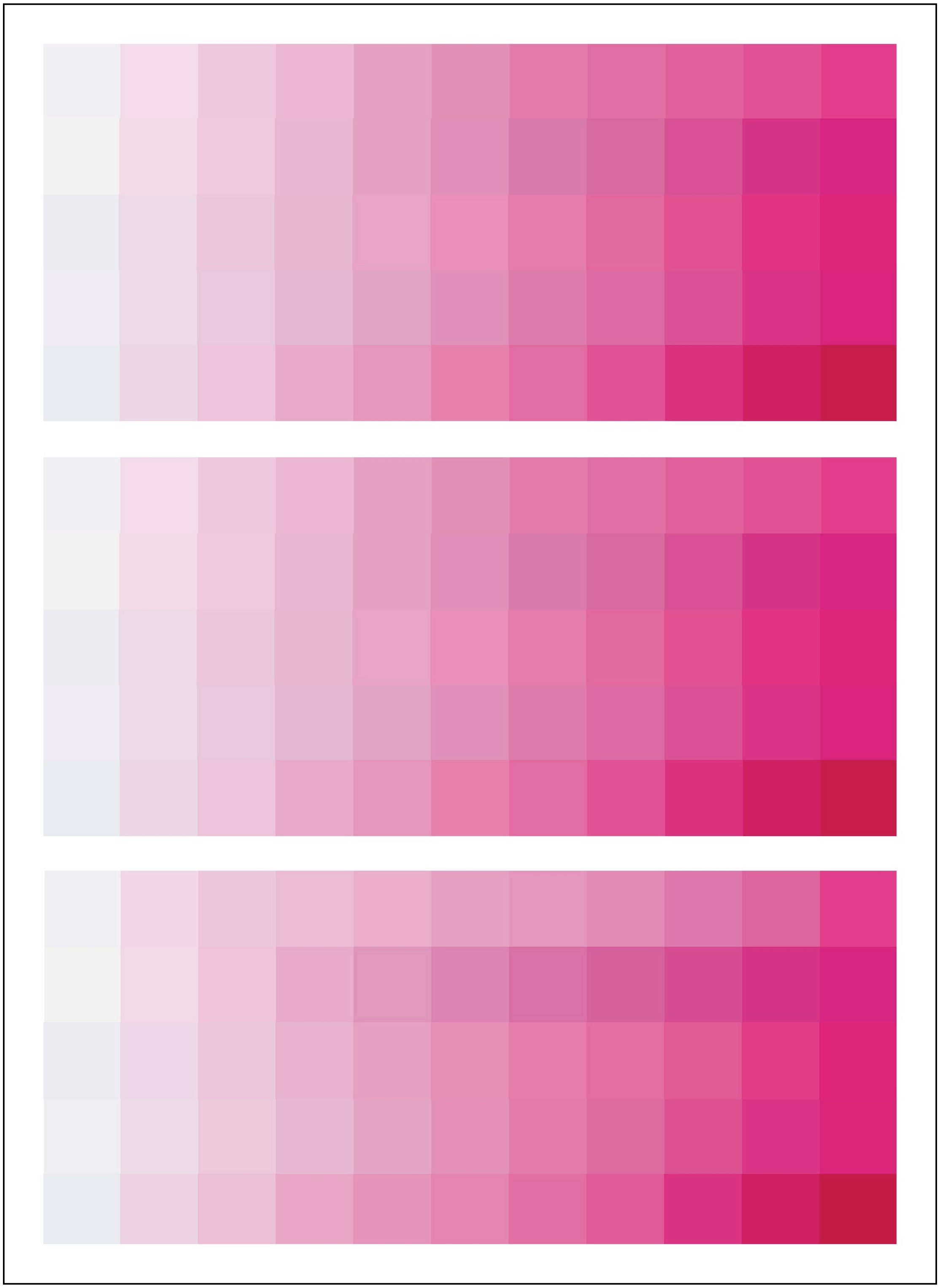

Figure 11: Magenta tone ramps of 5 different systems linearized to CTVI (top), ISO Curve A (middle), and G7 CMY neutral tone curve (bottom).

However, before we hoist the CTV banner and proclaim victory, we might wish to consider some complications attendant to CTV's practical implementation, and thereby anticipate likely objections. The most serious of these is the fact that improvements in tonal linearity nonetheless bring visible changes printed results. This is particularly of concern in conventional printing sectors such as offset and flexography, where standardized output conditions and process control aims are well established. It is therefore critical that some simple means of translating existing aims to CTV be made available to ease its acceptance and aid in the eventual transition to revised reference print conditions.

An attempt was undertaken to provide forward-compatibility of existing CMYK target aims by recharacterizing their tonal gain in smooth CTV curves, anticipating the availability of software capable of setting non-zero CTV gain as a process control target.

The GRACoL2013 (coated) and Fogra52 (uncoated) characterization data sets were chosen as representative of typical print conditions in offset lithography. A CTV plot of CMYK tone ramps (Figure 12) suggests the modifications that will be required to achieve smooth CTV curves. It may be objected that this alteration will result in a different print condition and not merely a different way of expressing its tone curves. As will be seen, however, the necessary curve adjustments result in small deviations from the unaltered colorimetric aims that are of little significance in practical work.

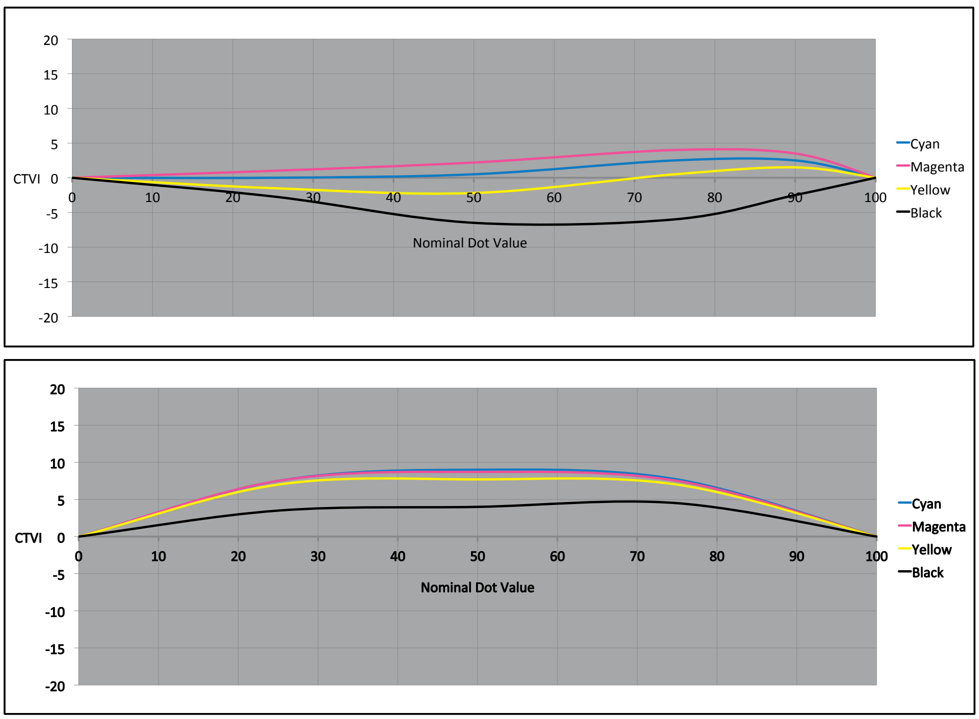

Figure 12. CTVI curves of GRACoL2013 CRPC6 (top) and Fogra 52 (bottom)

A lack of software that directly modifies CTVI curves necessitated a workaround. ColorAnt editing software (ColorLogic GMBH) was used to convert the data to the zero-gain CTV condition as an important preliminary step in conditioning the curves. The black curve, showing the steepest slope, was edited by simple 3-point adjustment; the magenta and yellow curves were then adjusted to match the TVI of cyan, which is closest to visual linearity. The resulting CTVI was checked and further corrections were made. A few iterations sufficed to produce smooth CVTI curves. A similar operation was performed on the Fogra 52 characterization data set. These curves were further simplified as shown in Figure 13.

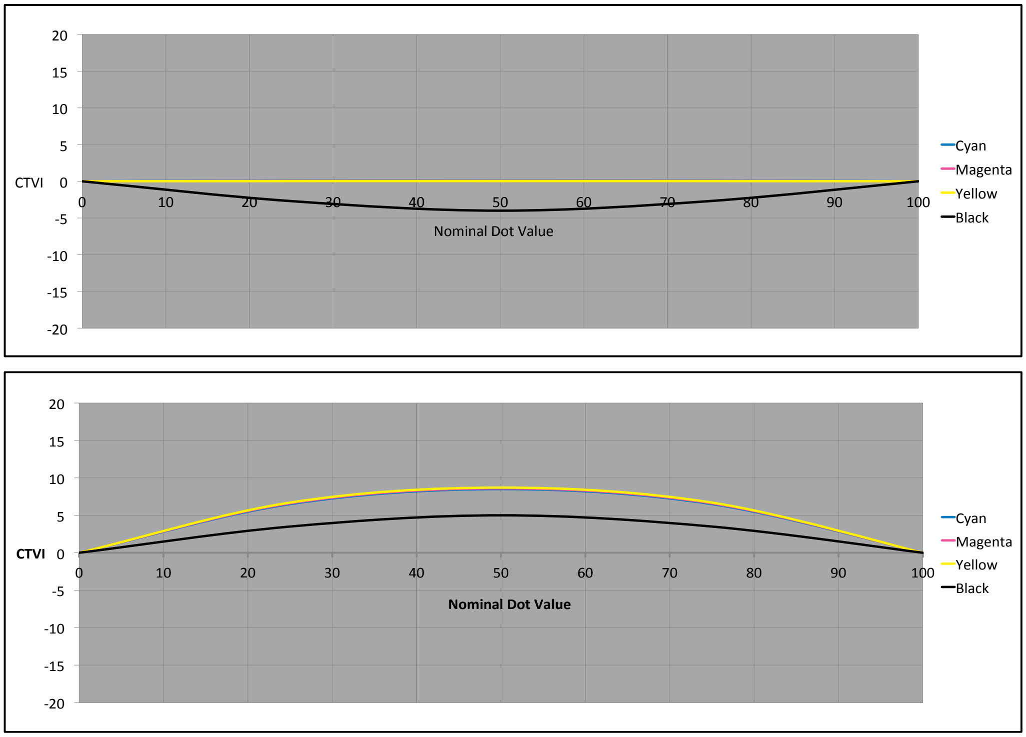

Figure 13. Simplified CTVI curves of GRACoL2013 CRPC6 (top) and Fogra52 (bottom)

SpotOn Verify software was used to quantify the impact of the adjusted curves on overall color match as well as CMY gray balance and tonality (NPDC). The reported deviations from the original data sets are of little importance for any practical purposes (Figure 14). (It should be noted GRACoL2013 and other nominally G7-compliant data sets, show small deviations from G7 specification, as their primary tone ramps reflect a preference for smooth process control curves. The CTV target curves generated here represent a similar compromise.) Further refinements might be applied for an even better balance between curve smoothness and fidelity to the original target print condition.

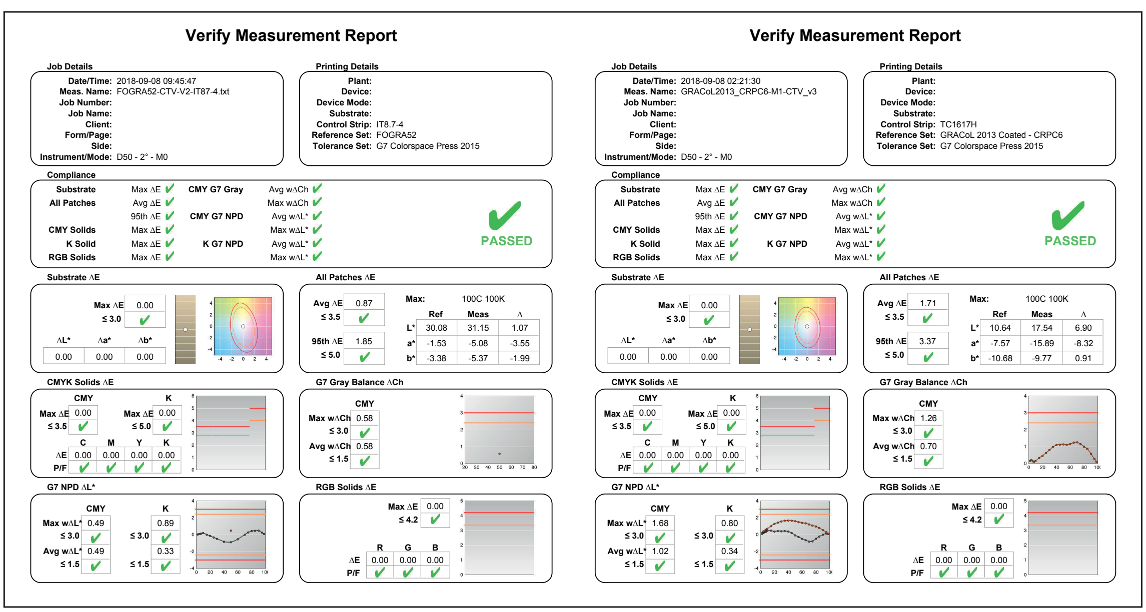

Figure 14. Measurement reports showing minimal impact of sight realignment of data with smooth CTVI curves

Final observations and conclusions

As of the time of this writing, ISO has endorsed, in 12647-6, Annex B, a limited use of Colorimetric Tone Value Formula for setting target tone curves for process control in Flexography, in cases where use of standard characterization data sets and/or color-managed workflows is impractical. Implicit in the recommendation is the assumption that visually linear print condition approximated by zero gain in CTV will be used normatively for aligning disparate printing systems. As suggested earlier, the same case is equally strong for other sectors of the print industry where a lack of standardized colorants, substrates, and screening methods can benefit from a common calibration method. It is, in fact, in printing systems where color management is routinely used that native color output typically exhibits both the greatest visual nonlinearity and the least uniformity of linearization and methods among manufacturers of printers and associated control software. This increases the burden on developers as well as users, who must learn a variety of routines each specific to a particular RIP or other control software. In addition, changes in tonal gain are much harder to detect in visually nonlinear ramps without resort to measurement and calculation. Finally, the absence of standard colorimetric or TVI aims actually eases forward-compatibility of print conditions with linear CTV, as there are few "broken plates" to be concerned with.

In traditional areas of print such as offset lithography and flexography, the picture is more complicated. Printed output based on visually linear tone curves may appear noticeably lighter or darker than in corresponding ISO 12647 reference print conditions, depending primarily on the density, or "dynamic range" of the system. Moreover, visually linear CMY tone curves may fail to produce consistent gray balance at standard control points commonly used in color bars and wedges, and thus altered gray-balance patches for different print conditions may be needed, a situation not likely to generate much enthusiasm. However, even within offset printing, improvements such as stochastic screening and high-chroma inks normally trigger the need for color management to match reference overprint and tint values. The fact is that the proportion of all printing today that does not rely on some form of color management is increasingly small, and consequently device calibration might sensibly be trimmed of those functions better served by device link profiles. Seen in this light, the visually-based Colorimetric Tone Value formula merits serious consideration as a versatile, simplified calibration model for nearly any printing system.

Appendix

Colorimetric Tone Value Formula

This more complete version of the formula published in ISO 20654 is required for measurements using illuminants other than D50:

$$SCTV = 100\sqrt{\frac{(V_{x,\mathrm{t}}-V_{x,\mathrm{p}})^2+(V_{y,\mathrm{t}}-V_{y,\mathrm{p}})^2+(V_{z,\mathrm{t}}-V_{z,\mathrm{p}})^2}{(V_{x,\mathrm{s}}-V_{x,\mathrm{p}})^2+(V_{y,\mathrm{s}}-V_{y,\mathrm{p}})^2+(V_{z,\mathrm{s}}-V_{z,\mathrm{p}})^2}}$$

where $V_{x,\mathrm{s}}, V_{y,\mathrm{s}}, V_{z,\mathrm{s}}$ are the V_x, V_y, V_z values calculated for the solid ink, $V_{x,\mathrm{p}}, V_{y,\mathrm{p}}, V_{z,\mathrm{p}}$ are the V_x, V_y, V_z values calculated for the substrate, and $V_{x,\mathrm{t}}, V_{y,\mathrm{t}}, V_{z,\mathrm{t}}$ are the V_x, V_y, V_z values calculated for the halftone.

$$V_x = f(u_1)\,116 - 16,$$
$$V_y = f(u_2)\,116 - 16,$$
$$V_z = f(u_3)\,116 - 16,$$

where $u_1 = X/X_\mathrm{n}$, $u_2 = Y/Y_\mathrm{n}$, $u_3 = Z/Z_\mathrm{n}$ and X, Y, Z are tristimulus values calculated as specified in ISO 13655, and $X_\mathrm{n}, Y_\mathrm{n}, Z_\mathrm{n}$ are tristimulus values of the selected illuminant and observer. The functions f of $u_i, i = 1, 2, 3$ are defined by

$$f(u_i) = (u_i)^{\frac{1}{3}}$$

if $u_i > (6/29)^3$ and

$$f(u_i) = \frac{841}{108}u_i + \frac{4}{29}$$

if $u_i \leq (6/29)^3$.

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