RELATIONSHIP BETWEEN INK MILEAGE AND INK TRANSFER

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Abstract: Several inks were printed on a Prufbau and an IGT Model A2-3 Printability Tester under various conditions of printing speed and printing force. Models reported in the literature were used to fit the experimental data, from which parameters characterizing ink transfer and ink mileage curves were evaluated. It was found that the Calabro-Savagnone equation was the best model for ink mileage curves and the modified Walker-Fetsko equation for ink transfer curves.

The experimental results show that printing force and printing speed have minimal influence on the characteristics of ink mileage behavior, while their effect on ink transfer characteristics is significant. A logical conclusion would be that the optical density of a printed image is primarily determined by thickness of the ink film on the substrate rather than by how the ink is placed there. However, any change in the printing conditions will in fact alter the optical density of printed images because the amount of ink being transferred to the substrate will change. This indicates that when the printing conditions are known to have changed while printing, the ink input should be regulated accordingly in order to maintain a consistent optical density of the image. Implications of these relationships on wet trapping in process color printing are discussed. Also recommendations for more accurate setting ink thickness in the tack measurement are presented.

INTRODUCTION

An ink mileage curve is a plot of the printed optical density of an ink on a given substrate as a function of the ink film thickness. The curve makes it possible to predict

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how much ink is needed to produce a desired optical density. An ink transfer curve is a plot of the amount of ink transferred to a substrate as a function of the amount of ink on the last printing roller. It allows prediction of how much ink should be input to the printing plate to transfer a desired amount of ink to the substrate. These two curves are the result largely of ink/paper interactions and are therefore perceived very important to print quality.

Printers are generally most interested in the mileage characteristics of inks. Good mileage inks will produce a job with reduced amounts of ink. Ink makers are more willing to produce good mileage inks for improved value of the product. Paper makers are probably more concerned about ink transfer factors influencing the printability of papers. Press manufacturers are interested in both ink mileage and ink transfer. They need to know how to control ink flow through the inking train to the substrate to achieve the desired optical density.

In addition to the economic reasons for good mileage inks, several printed quality advantages accrue from printing with good mileage inks. The thinner ink films reduce dot gain, increase print contrast, and reduce print through. It is probably also easier to maintain ink-water balance with a thinner ink film on the plate. Thinner ink films also set and dry faster and hence set-off is less severe.

Ink mileage generally increases with increase in tinting strength. Specifics of the relationship could not be located by the authors and shall be investigated in the future. Increase in tinting strength can be accomplished by increasing the concentration of pigment or by improving the degree of pigment dispersion, or both. However, there are some limitations to either approach for increasing tinting strength of inks. The cost of making highly pigmented inks or ultra dispersed pigments is higher. Viscosities of such inks may become too high to handle. Too thin an ink film may result in incomplete coverage of solid, especially on rough substrate such as newsprint. Picking and linting of weak paper are additional problems since tack of an ink increases rapidly with decreasing thickness of ink film in the printing roller nip. So, there exists an optimum range of ink film thicknesses within which high quality prints can be produced practically.

Ink mileage and ink transfer properties are closely related because ink transfer determines the amount of ink transferred to the substrate which in turn determines the optical density of printed image. They are, however, generally discussed in the literature as separate issues. This paper investigates their relationship.

EXPERIMENTAL

Materials

A house-made, Goss experimental black newsink and a set of four process color newsinks received from a foreign supplier were used in this study. These inks were formulated to run on keyless lithographic presses.

The substrate was a standard 30-lb newsprint. Test strips were cut along the web direction to proper dimensions for the printability tester. They were marked on the same side to ensure that the same side of each strip was printed.

Experimental Procedures

Two instruments were used in this study. One was an IGT A2-3 Printability Tester with a rubber-coated printing disc. The paper strip was mounted directly on a steel impression sector. This system simulates a sheetfed offset press. The printing force was adjusted to 121 N/cm. The impression sector was steadily turned by hand at an average speed of about 0.4 m/s. Slippage occurred between printing disc and paper when the thickness of ink on the disc was greater than about 7 g/m^2, because the printing disc was frictionally driven by the impression sector.

The other instrument was a Prufbau Printability Tester with a blanket-covered printing disc. The paper strip was mounted on a blanket-covered carrier. This system simulates a perfecting offset press. The printing force was varied from 126 to 252 N/cm. The printing speed was precisely varied from 0.5 to 6 m/s (9 to 110 feet/minute). No slippage was observed with this system because both printing disc and test strip are running at the same surface speed.

With each instrument, a known volume of ink was distributed on its inking unit. The amount of ink on roller could be obtained from the weight difference of the printing disc before and after inking. The inked printing disc was then placed on the shaft of printability tester for printing. The quantity of transferred ink and hence the amount of ink on paper was determined by the weight difference of the printing disc before and after printing. So, ink film thickness is generally reported in units of g/m^2 since the surface area of printing roller and the printed area can be measured.

After printing the strips were allowed to set for at least 24 hours before optical density measurements were made with a X-Rite 428 densitometer to assure absence of dry-back effect. The optical densities reported here are densitometer readings from which the optical density of paper is subtracted. At least twenty prints were made in each experiment to construct an ink mileage and an ink transfer curves.

INK MILEAGE

Background

Ink mileage is generally defined as the area which may be printed with one gram of the ink yielding a solid print with the target optical density (Kornerup et al., 1969). Figure 1 shows typical examples of ink mileage curves. These inks differ significantly in their ink mileage behavior. The ink film thickness needed to achieve the desired optical density can readily be found from the curve and its reciprocal is the mileage.

The mileage curves in Figure 1 show that the optical density initially increases rapidly with ink film thickness and eventually levels off. It is therefore also referred to by the industry as the saturation curve. The maximum optical density achievable by an ink is called the saturation density.

These curves provide only qualitative information about the ink mileage characteristics of inks. In Figure 1, for instance, the optical density of black ink is the highest of the four at any ink film thickness and that of yellow ink is the lowest. The cyan ink has higher optical densities at low ink film thicknesses than the magenta ink does, but its saturation density is lower. Comparisons among various inks have to be made case by case and are very impractical.

It is essential to describe quantitatively ink mileage characteristics using a mathematical equation. The regression coefficients derived from fitting an equation to the

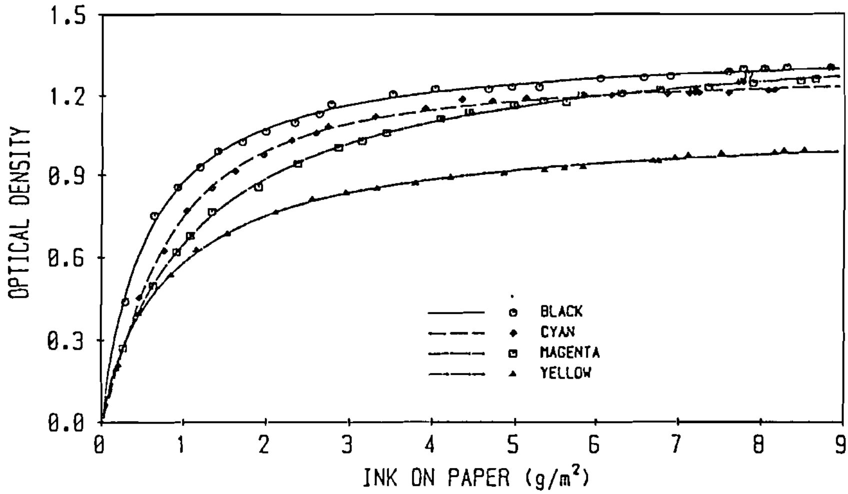


Figure 1. Ink mileage curves of the process colors obtained with the Prufbau Printability Tester. The printing force was 252 N/cm and the printing speed was 3 m/s.

experimental data are very useful for comparing different inks. The coefficients can also be related to some basic properties of ink and paper and/or to the printing conditions. The following models have been reported to fit ink mileage data reasonably well.

Tollenaar-Ernst equation (Tollenaar and Ernst, 1962)

$$D = D_s(1 - e^{-mw}) \qquad (1)$$

Oittinen equation (Oittinen, 1972)

$$D = D_s(1 - e^{-mw^n}) \qquad (2)$$

Calabro-Mercatucci equation (Calabro and Mercatucci, 1974)

$$\frac{1}{D} = \frac{1}{D_s} + \frac{m}{w} \qquad (3)$$

Calabro-Savagnone equation (Calabro and Savagnone, 1983)

$$\frac{1}{D} = \frac{1}{D_s} + \left(\frac{m}{w}\right)^n \quad (4)$$

Blom equation (Blom and Conner, 1990)

$$\frac{R}{R_p} = \frac{R_s}{R_p} + \frac{m}{w} \quad (5)$$

Kornerup-Fink-Jensen-Rosted equation (Kornerup et al., 1969)

$$\frac{R_p - R_s}{R - R_s} = 1 + (mw)^n \quad (6)$$

where w is the thickness of ink film on the substrate. D_s, m and n are regression coefficients which are similar in all of these equations because their physical meanings are similar. The terms D and R stand respectively for the optical density and reflectance of a print measured with a densitometer or spectrophotometer. The subscripts p and s represent paper and saturation. For example, D_s is the saturation density and R_p is the reflectance of unprinted paper. Optical density is related to reflectance by

$$D = -\log(R) \quad (7)$$

Five of these equations were recently reviewed and compared by Blom and Conner (1990). The empirical expressions of Eqs. 1 and 3 result from the shape of ink mileage curves, while Eqs. 2 and 4 are their modifications by introducing a power index to the ink film thickness. Eq. 6 originates from Bouguer's law with some assumptions and mathematical simplification (Kornerup et al., 1969). Eq. 5 has a slightly different format from the original one (Blom and Conner, 1990) which is a simplified version of Eq. 6.

As the ink film thickness approaches zero, the calculated optical density should become zero. This is the case for all the equations except Eq. 5, which mathematically results in negative optical densities at very low ink film thicknesses. Consequently, Eq. 5 is not suitable for that ink film thickness range.

When a light hits the surface of a print, a fraction of the incident light is reflected from the air-ink interface, that is the first-surface reflection. The rest is transmitted to the ink layer and travels to the ink-paper interface, where it is partly transmitted to the paper and partly reflected. The reflected light travels through the ink film back to the air-ink interface, where it is partly transmitted to the air and partly reflected. The light therefore bounces back and forth in the ink film. This phenomenon is called the multiple internal reflection. As the light travels through the ink film, its intensity decreases because a portion of the light is transmitted to the paper or to the air at the ink-paper or ink-air interface and another portion is absorbed by the ink and scattered by pigment particles.

The light that is transmitted back from the ink film and reflected from the ink surface is, for simplicity, called the reflected light. The ratio of reflected to incident light is the reflectance. Due to the scattering and absorption by the ink, light that is transmitted back decreases with increasing ink film thickness and eventually vanishes. Further increase of ink film thickness can not cause further reduction in the reflectance. This minimum reflectance concept gives rise to the so-called saturation density. The saturation density thus results from the combining effects of the first-surface reflection and of the light scattered by pigment particles which is subsequently transmitted back to the air.

The smoothness of a surface affects the pattern of light reflection and hence the measured optical density. Surface roughness of an ink film is related to the ink's leveling property which is in turn determined by its rheological properties (Chou et al., 1990). The absorption and the scattering of light are determined by the ingredients of the ink and the size distribution of pigment particles. Surface roughness of the paper may also affect the pattern of light reflection at the ink-paper interface and the measured optical density. However, its contribution to the saturation density is much less than the ink. The saturation density is therefore expected to be determined primarily by the ink and to a lesser extent by the paper.

The parameter m determines how fast the ink mileage curve approaches the saturation density and is related to the rate of light diminution caused by the increase in ink film thickness. It has been reported that m correlates with the degree of contact between the ink film and the paper and is referred to as "density smoothness" (Tollenaar and Ernst, 1962; Calabro and Mercatucci, 1974). Kornerup et al. (1969) observed that m was related to ink's absorptance of light and its value decreased with decreasing pigment concentration. They called this parameter the "specific color strength coefficient". These previous results indicate that m is determined primarily by the paper characteristics and the pigment concentration.

Applying an exponent to the independent variable of an equation to improve its fit to the experimental data is a general practice in curve fitting. In most cases this exponent can be correlated with some property of the system. The ink film thickness exponent n in Eqs. 2 and 4 originates from this concept. It also characterizes the steepness of the ink mileage curve. Calabro and Savagnone (1983) observed that n was affected by ink formula variation. Kornerup et al. (1969) found that n was independent of pigment concentration but dependent on the spectral properties of the pigment.

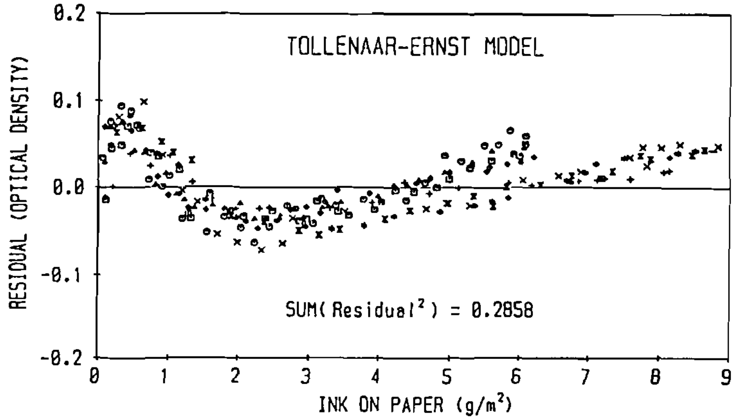
Comparison of Models

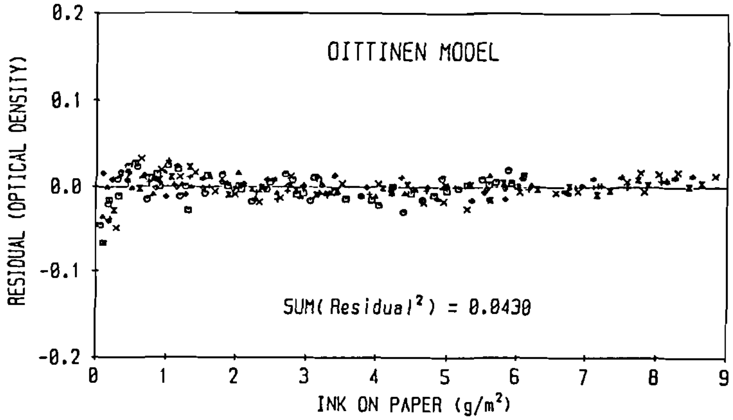
It has been reported that the selection of a best model to express an ink mileage curve is dependent on the substrate (Calabro and Mercatucci, 1974; Calabro and Savagnone, 1983; Blom and Conner, 1990). It is therefore appropriate to determine which equation best fits the experimental data reported here.

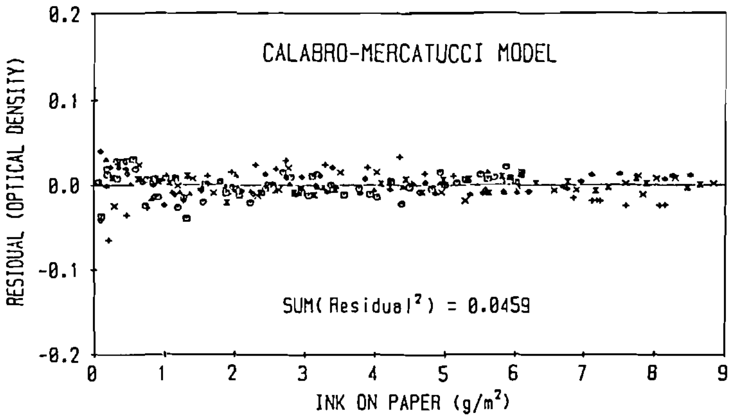
The degree of fit of an equation to the experimental data can be determined by the sum of the square of residuals and the distribution of residuals around the zero point. Figure 2 shows respectively the residuals of Eqs. 1 to 6 for eight ink mileage curves of the four process colors obtained with IGT and Prufbau Printability Testers. The results indicate that three-parameter equations fit, as expected, the experimental data much better than their two-parameter correspondents. Eqs. 4 and 6 both fit the data equally well, as evidenced by their minimal sum of square of residuals and their even distribution of residual errors around the zero point. Because it is easier to manipulate Eq. 4 in the curve fitting process, Eq. 4 is used exclusively in this study.

Effect of the Side of Paper

Figure 3 shows the mileage curves of Goss experimental black obtained on either side of the newsprint with the IGT


TOLLENAAR-ERNST MODEL
SUM(Residual²) = 0.2858
RESIDUAL (OPTICAL DENSITY)
INK ON PAPER (g/m²)
0.2
0.1
0.0
-0.1
-0.2
0
1
2
3
4
5
6
7
8
9


OITTINEN MODEL
SUM(Residual²) = 0.0430
RESIDUAL (OPTICAL DENSITY)
INK ON PAPER (g/m²)
0.2
0.1
0.0
-0.1
-0.2
0
1
2
3
4
5
6
7
8
9


CALABRO-MERCATUCCI MODEL
SUM(Residual²) = 0.0459
RESIDUAL (OPTICAL DENSITY)
INK ON PAPER (g/m²)
0.2
0.1
0.0
-0.1
-0.2
0
1
2
3
4
5
6
7
8
9

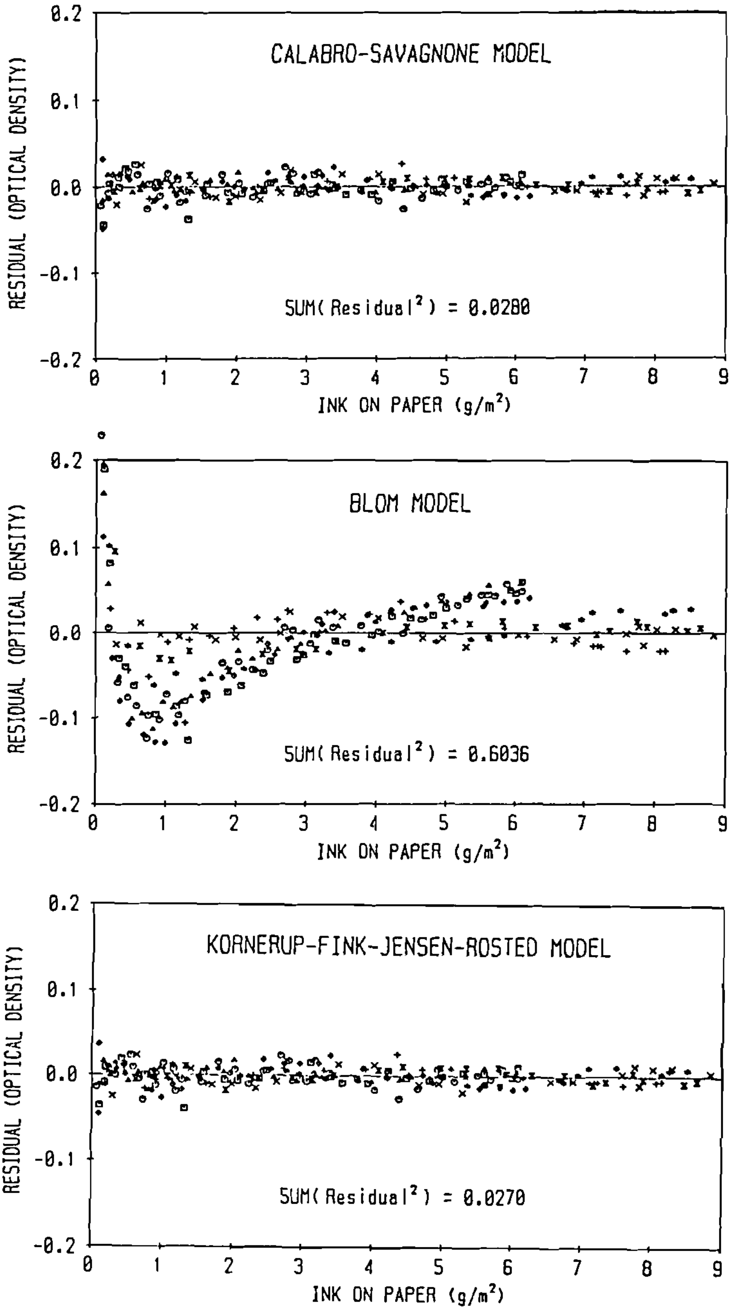


Figure 2. Sum of the square of residual errors and their distribution for various ink mileage models.

Printability Tester. The two curves essentially overlap each other, indicating the side of this newsprint had no perceptible effect on the ink mileage characteristics. Nevertheless, for consistency, the same side of paper was used in the remaining experiments.

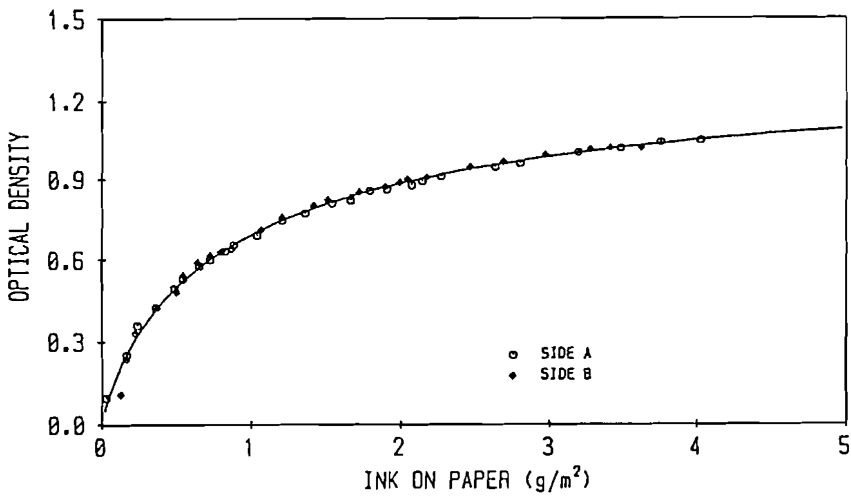


Figure 3. Ink mileage curves of Goss experimental black produced on either side of the newsprint.

Effect of Printing Conditions

The magenta ink was selected in this experiment for studying the effects of various printing conditions on ink mileage parameters. The Equation 4 regression coefficients of five mileage curves obtained at different printing speeds and forces are summarized in Table I. The saturation density varies from 1.28 to 1.48; m from 0.852 to 0.944; n from 0.943 to 1.346. These data indicate that printing conditions may influence ink mileage characteristics.

Figure 4 shows the corresponding ink mileage data. It was a surprise to note that a single, master curve could be produced by fitting Eq. 4 to these five sets of data, as shown by the solid curve in Figure 4. The parameters characterizing this master ink mileage curve are virtually identical to the averaged values of the individual curves (Table I). The standard error of estimate for this master curve is about twice as much as the averaged value, as shown by the Std

Table I. Ink mileage characteristics of the magenta ink as a function of printing conditions.

Speed	Force	D_s	m	n	Std
0.5	252	1.39	0.902	1.056	0.0085
3.0	252	1.48	0.852	0.943	0.0076
6.0	262	1.28	0.944	1.346	0.0098
0.5	126	1.47	0.907	0.964	0.0085
3.0	131	1.39	0.936	1.141	0.0093
Average		1.40	0.908	1.090	0.0087
Master Curve		1.39	0.914	1.095	0.0196

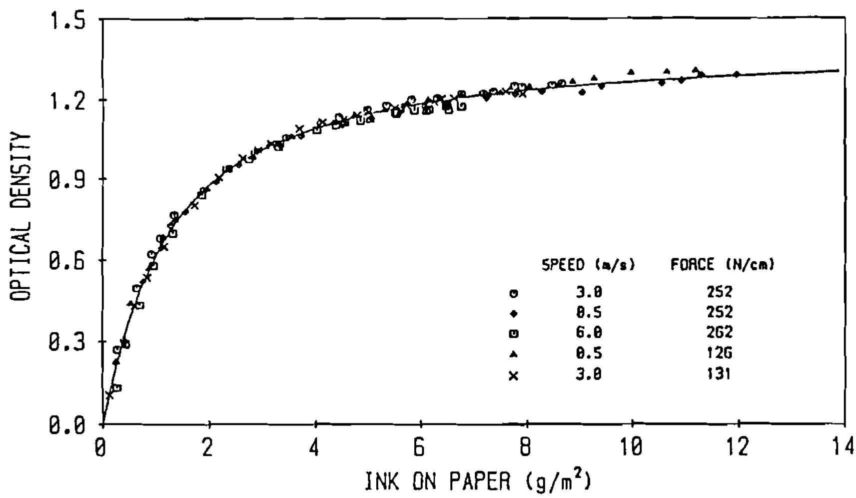


Figure 4. Effect of printing conditions on the ink mileage characteristics of the magenta ink.

column of Table I. A portion of the increased standard error of estimate can be attributed to the experimental error. In a separate study (Chou, 1991), an ink mileage experiment was repeated five times. It was observed that the standard error of estimate for the master curve was larger than the averaged value of its constituent curves. These results indicate that the effect of printing speed and force on the ink mileage characteristics may not be so significant as one would expect. Similar observations were also made by De Grace and Mangin (1984).

Effect of Printing Systems

Figure 5 shows that the Prufbau Printability Tester delivers better ink mileage values than the IGT does. Table II summarizes the parameters characterizing these mileage curves. Since the experimental printing conditions had minimal effect on the ink mileage characteristics, the differences in Figure 5 must represent differences in the printing systems. Both printing and impression surfaces of the Prufbau Printability Tester are deformable, while one is deformable and the other is rigid for the IGT unit. Both surfaces of the former instrument can easily conform to the rough surface of newsprint and hence the printing smoothness increases. The increased printing smoothness is consistent with the increased density smoothness which is evidenced by the results that the mileage curves obtained with the Prufbau Printability Tester have lower m values and higher n values than those obtained with the IGT Printability Tester.

Table II. Parameters characterizing mileage curves of the process colors obtained with Prufbau and IGT Printability Testers.

Ink	Tester	D_s	m	n
Black	IGT	1.42	0.575	0.885
	Prufbau	1.38	0.424	1.018
Cyan	IGT	1.35	0.711	0.961
	Prufbau	1.29	0.628	1.262
Magenta	IGT	1.37	0.957	0.956
	Prufbau	1.48	0.852	0.943
Yellow	IGT	1.04	0.820	0.910
	Prufbau	1.09	0.795	0.944

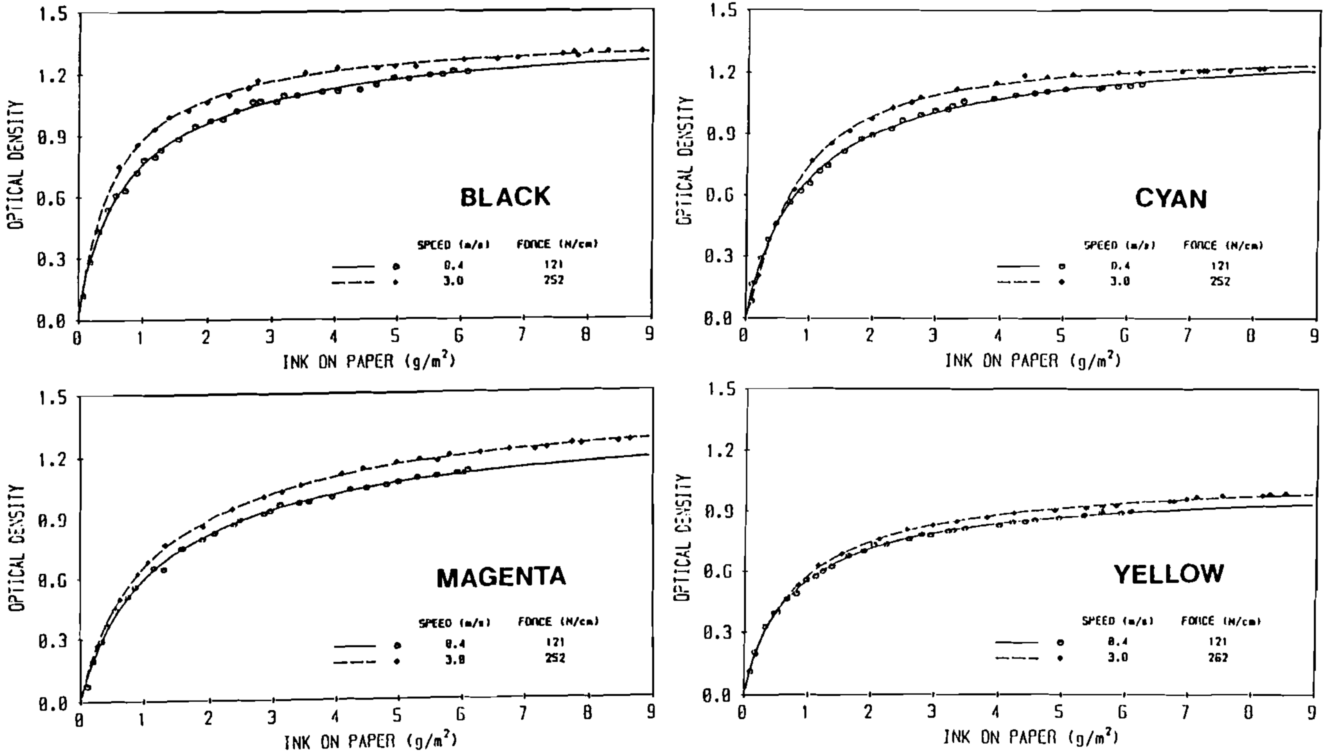


Figure 5. Differences in the ink mileage curves of the process colors produced with the Prufbau and IGT Printability Testers.

INK TRANSFER

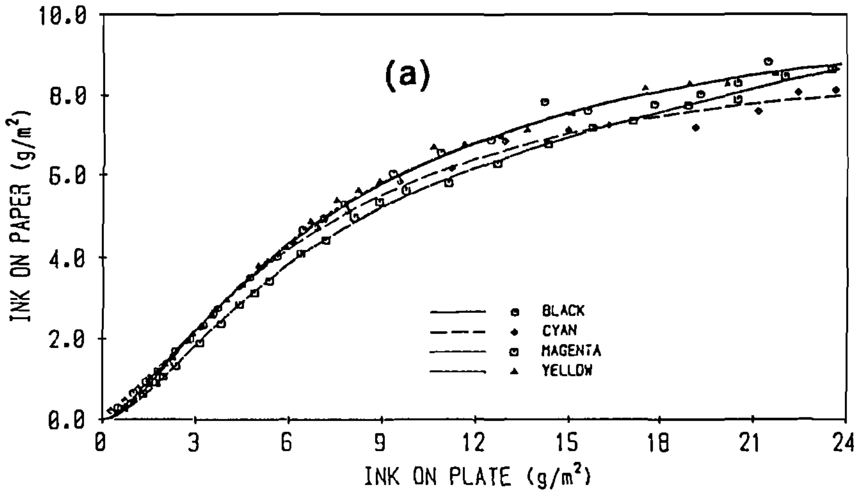
Background

As mentioned in the previous section, the thickness of an ink film needed to give a target optical density can readily be derived from the ink mileage curve. Ink transfer characteristics of a given ink-paper combination determine the amount of ink on the printing roller necessary to deliver a desired ink film to the paper. If the ink receptivity of the paper is low, a relatively heavy inking of the plate is needed. When printing tones, this will result in excess dot gain and poor print contrast because it is easier for a thicker ink film to spread laterally in the roller nip. Ink transfer character is therefore one of the most important factors influencing the optical density as well as the quality of printed images.

Figure 6 shows the ink transfer curves for the process colors obtained with the Prufbau Printability Tester at a printing speed of 3 m/s and a line pressure of 252 N/cm. Ink transfer is generally characterized by a S-shaped curve. It is very difficult to predict from the curves in Figure 6 if the ink transfer curve will asymptotically approach a straight line or if it will level off at high ink film thicknesses.

Figure 6 also shows the corresponding fractional ink transfer curves. A fractional transfer curve illustrates the percentage of an ink on the plate that is transferred to a substrate as a function of the amount of ink on the plate. As the ink film thickness on the plate increases, the percent transfer initially rises very rapidly, reaches a maximum, and then decreases. Similar to the ink transfer curves, it is not certain if the fractional ink transfer curve will decrease to zero or to an asymptote.

To quantitatively describe this ink transfer behavior and to relate it to properties of paper and ink and printing conditions, a mathematical equation is necessary. Walker and Fetsko (1955) proposed a model that fits very well these S-shaped ink transfer curves. According to their model, a fraction of the ink film in contact with the paper surface at the nip during impression is absorbed and immobilized by the paper. The remainder of any given ink film splits with a constant ratio between the paper and the printing disc when it exits the printing nip. The Walker-Fetsko equation is as follows,



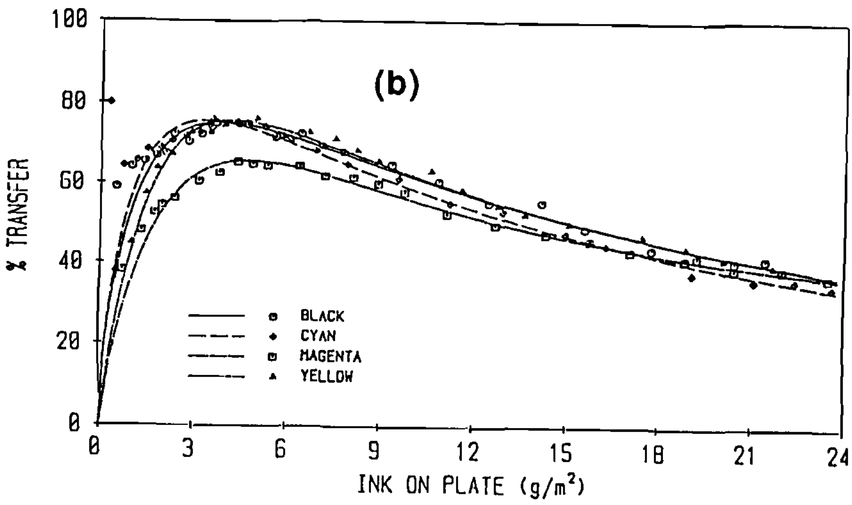


Figure 6. (a) Ink transfer and (b) fractional ink transfer curves of the process colors.

$$y = A\ [bB + f\,(x - bB)] \qquad \textbf{(8)}$$

in which

$$A = 1 - e^{-kx}, \quad B = 1 - e^{-x/b} \qquad \textbf{(9)}$$

where x = the ink film thickness on the plate before transfer.
y = the amount of ink transferred to the paper.
k = a constant related to the printing smoothness of the paper.
b = the immobilization capacity of the paper under a given set of printing conditions.
f = the splitting coefficient which is the fraction of the free ink transferred to the paper.
A = the contact factor which is the fraction of paper surface contacted by ink.
B = the immobilization factor which is the fraction of ink immobilized by the paper during impression.

Several modifications of the Walker-Fetsko equation have been proposed that basically use different expressions for the contact factor A.

Modified Walker-Fetsko equation (Mangin et al., 1982)

$$A = 1 - e^{-(kx)^n}, \quad B = 1 - e^{-x/b} \tag{10}$$

Laraignou equation (Mangin et al., 1982)

$$A = \frac{x^2}{x^2 + k^2}, \quad B = 1 \tag{11}$$

Modified Laraignou equation (Karttunen et al., 1973)

$$A = \frac{x^2}{x^2 + k^2}, \quad B = 1 - e^{-x/b} \tag{12}$$

Karttunen-Kautto-Oittinen equation (Karttunen et al., 1973)

$$y = Afx + (A - A_o)\,bB(1 - f) \tag{13}$$

in which

$$A = 1 - (1 - A_o)\,e^{-kx}, \quad B = 1 - e^{-x/b} \tag{14}$$

where the parameter n is a power index that improves the fit of Eq. 10 to experimental data. The term k in Eqs. 11 and 12, similar to the term k in Eq. 9, is a constant characterizing the printing smoothness of paper. A_o is the flattened fraction of the paper surface that is in forced contact with an ink film of any thickness in the printing nip.

Referring to Figure 6a, at low ink film thicknesses on the plate the slowly increasing ink transfer rate results from incomplete contact between ink and paper and is characterized by the contact factor A. Both contact and immobilization factors increase with increasing ink film thickness on the plate, so does the amount of ink immobilized by the paper. The fractional ink transfer will reach a peak when the immobilization factor is equal to one. With further increase in the ink film thickness on the plate, the amount of ink transferred to the paper still increases but the fractional ink transfer decreases. This is because the amount of ink transferred thereafter comes solely from the splitting of free ink film. According to these models, the fractional ink transfer curve should eventually level off at a value equal to f and the corresponding ink transfer curve should asymptotically approach a straight line with a slope of f.

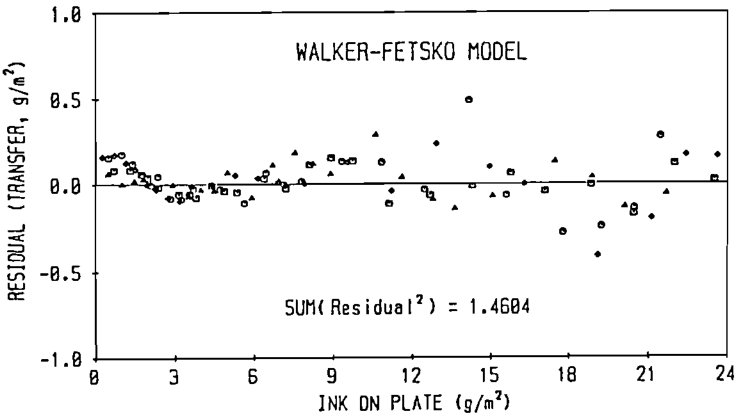
Hultgren (1973) proposed a model significantly different from the Walker-Fetsko model. The ink transfer curve levels off at high ink film thicknesses to a zero slope, instead of asymptotically approaching a straight line. The Hultgren equation is given by

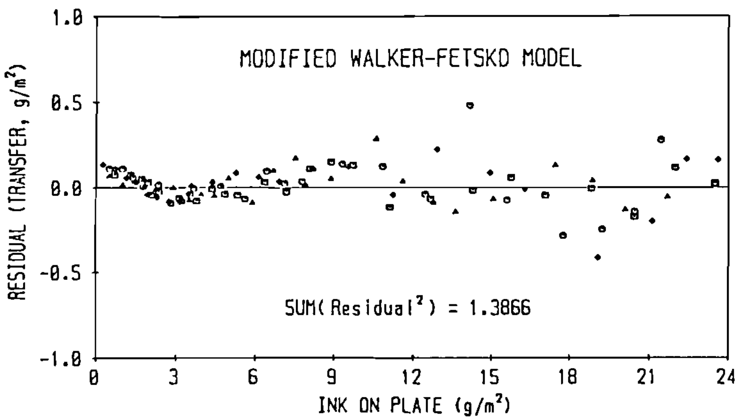
$$y = \frac{y_{max}}{1 + \frac{1}{k}\left[\left(\frac{x_{max}}{x}\right)^{k} - 1\right]} \qquad (15)$$

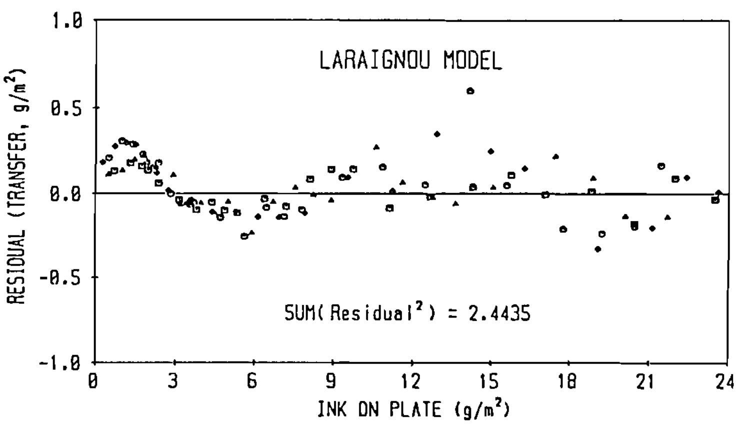
where x_{max} is the amount of input ink on the plate at maximum fractional ink transfer and y_{max} the amount of ink transferred to the paper when x is x_{max}. The parameter k is a paper constant that is independent of press conditions.

Comparison of Models

Karttunen et al. (1973) and Mangin et al. (1982) have compared various ink transfer models. They found that no model was clearly superior to the others. However, for quantitative evaluation of data, it is necessary to select one model that best fits experimental data. Figure 7 shows the sum of the square of residual errors and their distribution for various models for the same ink transfer data displayed in


WALKER-FETSKO MODEL
SUM(Residual²) = 1.4604
RESIDUAL (TRANSFER, g/m²)
1.0
0.5
0.0
-0.5
-1.0
0
3
6
9
12
15
18
21
24
INK ON PLATE (g/m²)


MODIFIED WALKER-FETSKO MODEL
SUM(Residual²) = 1.3866
RESIDUAL (TRANSFER, g/m²)
1.0
0.5
0.0
-0.5
-1.0
0
3
6
9
12
15
18
21
24
INK ON PLATE (g/m²)


LARAIGNOU MODEL
SUM(Residual²) = 2.4435
RESIDUAL (TRANSFER, g/m²)
1.0
0.5
0.0
-0.5
-1.0
0
3
6
9
12
15
18
21
24
INK ON PLATE (g/m²)

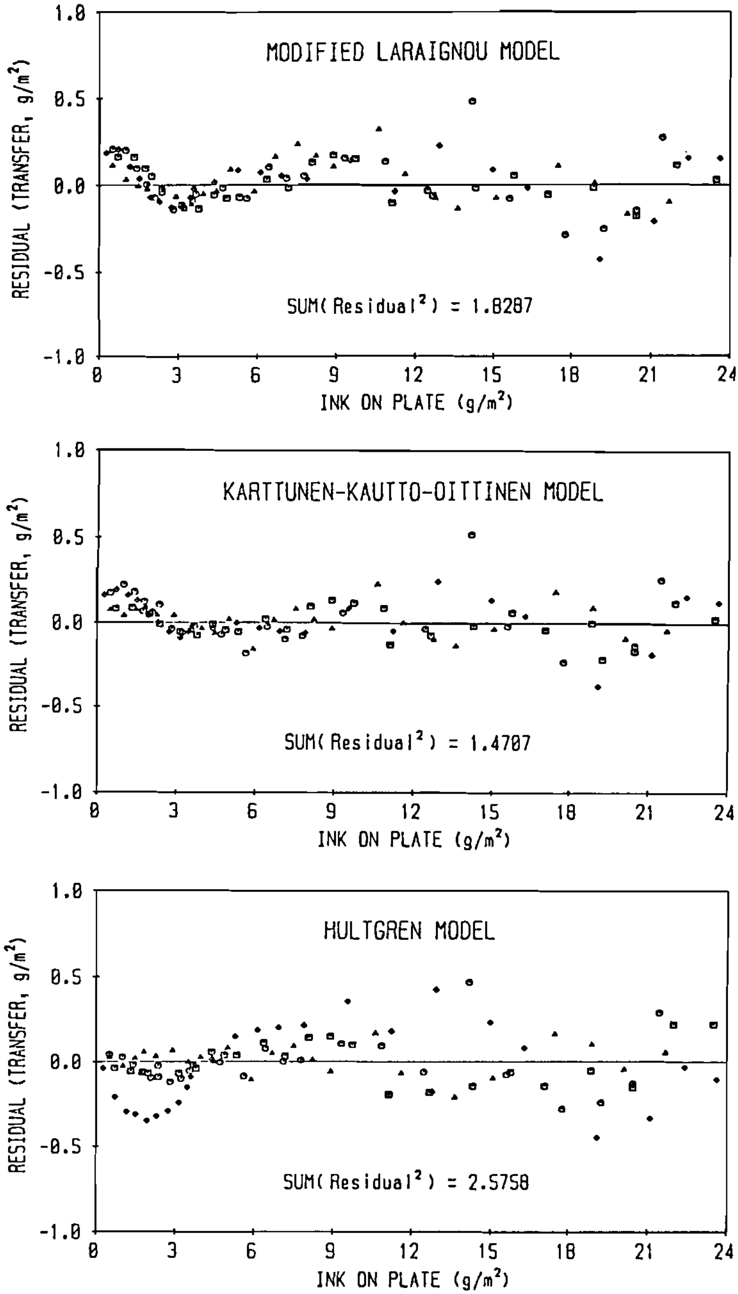


Figure 7. Sum of the square of residual errors and their distribution for various ink transfer models.

Figure 6a. The uneven distribution of residual errors, especially at low, practical inking levels, indicates that none of the models reviewed here is a perfect fit from the statistical viewpoint. The sum of the square of residuals for the modified Walker-Fetsko equation is slightly lower than the others and was therefore selected for evaluating ink transfer characteristics.

Effect of Printing Conditions

Effect of printing speed on ink transfer for the magenta ink obtained with the Prufbau Printability Tester at a line pressure of 252 N/cm is shown in Figure 8. The effect of printing pressure on ink transfer at a printing speed of 3 m/s is illustrated in Figure 9. Parameters characterizing ink transfer behavior of the magenta ink as a function of printing speed and force are summarized in Table III.

Table III. Parameters characterizing transfer behavior of the magenta ink as a function of printing conditions.

Speed	Force	b	f	k	n
0.5	252	8.10	0.356	0.710	0.810
3.0	252	5.80	0.164	0.472	0.985
6.0	262	6.95	.0003	0.573	1.250
0.5	126	3.86	0.408	0.520	0.880
3.0	131	4.54	0.175	0.401	1.106

The data in Table III indicates that the splitting coefficient f decreases with increasing printing speed. The splitting coefficient is nearly zero at the speed of 6 m/s and may become zero at higher speeds. The implication is that the Hultgren model may be better than the others for describing ink transfer behavior of this particular ink-paper combination at higher printing speeds.

Table III data also show that the splitting coefficient decreases with increasing printing pressure, but to a lesser extent. It has been proposed that the asymmetric ink film splitting may be due to shear thinning of the ink close to the

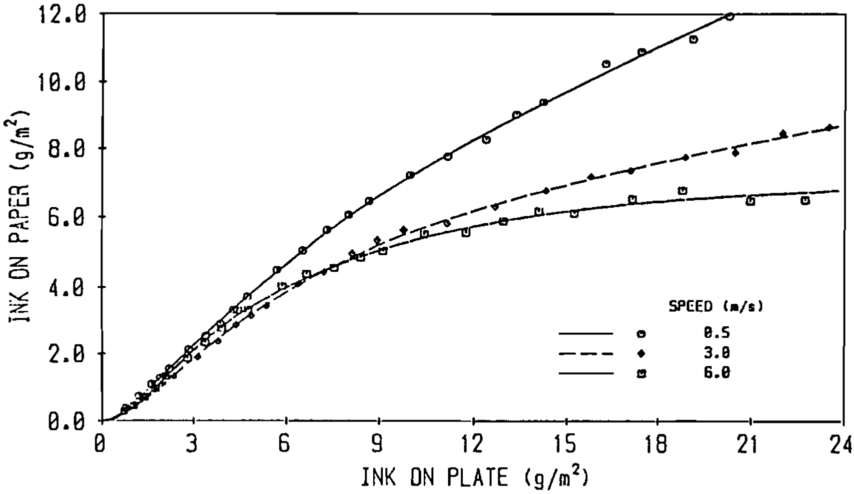


Figure 8. Effect of printing speed on ink transfer for the magenta ink.

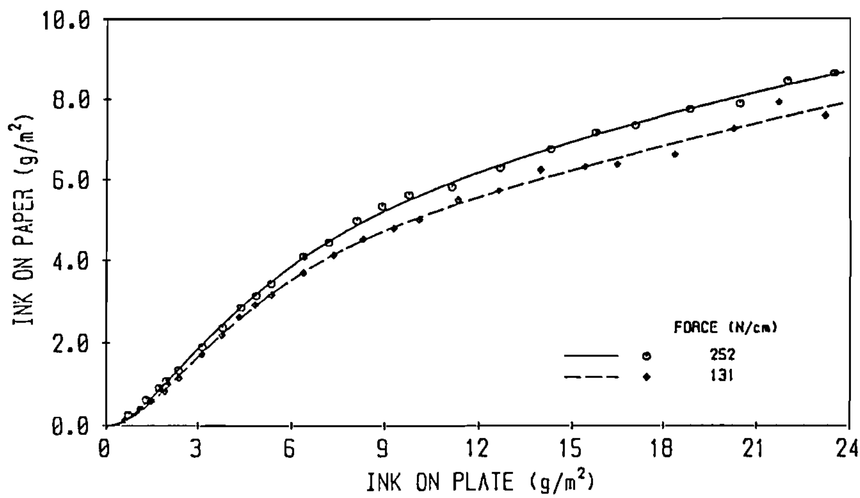


Figure 9. Effect of printing force on ink transfer for the magenta ink.

paper surface (Taylor and Zettlemoyer, 1958), the micro-roughness at the surface of paper (De Grace and Mangin, 1984), or due to the presence of entrained air at the ink-paper interface (De Grace and Mangin, 1988). Either mechanism may initiate cavitation close to the paper surface for the subsequent ink film splitting. There is, at present, no conclusive mechanism for this apparent asymmetric ink film splitting.

Printing conditions affect the immobilization capacity b in a more complicated way (De Grace and Mangin, 1984). The amount of ink pumped into the pores or recessed area of the paper increases with increasing printing pressure. The volume of surface pores and voids available for immobilizing ink, however, probably decreases with pressure due to the increased compression of the paper. The hydraulic pressure within the ink film increases with printing speed, but the time available for immobilizing ink decreases. So, the immobilization capacity depends on the properties of ink and paper as well as on the printing conditions. For the magenta ink and newsprint combination used in this study, the immobilization capacity is minimal at an intermediate printing speed and increases with increase in printing pressure, especially at lower printing speed. This may account for the slightly higher ink transfer at 6 m/s than that at 3 m/s at low inking levels.

The trend for the printing smoothness constant k is similar to that for the immobilization capacity. The power index n increases with speed but decreases with pressure. The current experimental results are insufficient for a more complete correlation of ink transfer parameters with printing conditions.

Detailed discussions about the mechanism of ink transfer are beyond the scope of this paper and will not be presented here. It is also not appropriate to attempt quantitative correlations of ink transfer characteristics with the properties of inks and paper based on these limited experimental results.

CONCLUDING REMARKS AND IMPLICATIONS

Figure 10 shows a schematic ink mileage curve from which corresponding windows for the ink film thickness can be considered. The width of thickness window is critical to print quality and process control. If the window of interest is located close to the saturation density, the ink film thickness window will be so wide, e to f in Figure 10, that it is very easy to run the press. However, an excessively thick film can inadvertently be run on the plate without a noticeable difference in the optical density of the printed image. The consequences are excess dot gain, poor print contrast, and severe print through.

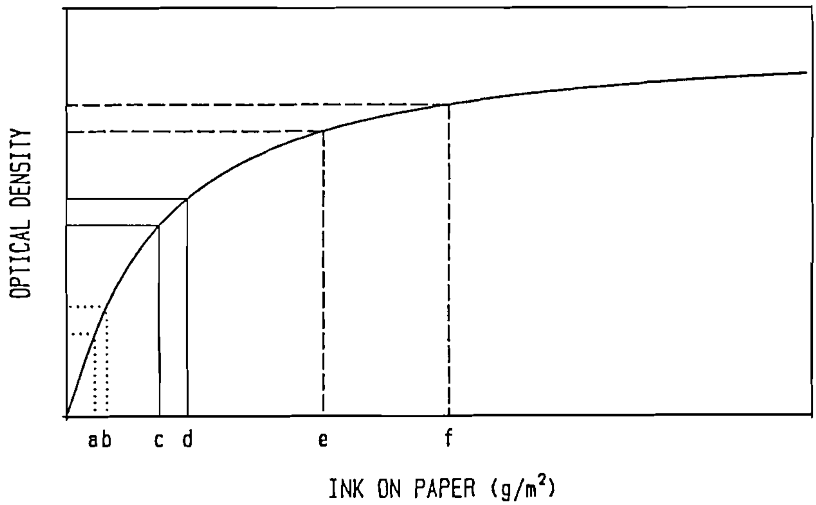


Figure 10. Schematic ink mileage curve showing target optical density ranges and their corresponding ink film thickness ranges.

Conversely, if the window is located near the lower end, for instance a to b, the ink film thickness window will be so narrow that it is extremely difficult to run the press at consistent print quality. Any variation in the thickness of ink film on the plate due to the fluctuation of pressroom or press conditions will result in a significant and unacceptable change of printed optical density. And, the printed ink film is so thin as to cause linting and picking of weak papers.

It appears that the optimum window for target optical density should be somewhere between the two extremes, for example c to d, so that high quality print can be produced without difficulty.

It is fortunate to learn that printing conditions have a negligible influence on the mileage characteristics of an ink. This makes the press control much less complicated. A press control engineer only needs to implement a predetermined ink curve to the press that adjusts ink input when the printing conditions change. For example, the percent ink transfer generally decreases with increasing printing speed. As the press speed increases from the makeready to production speed, the ink key settings or the fountain roller speed or both should be increased according to the ink curve. This will maintain a constant delivery of ink to the paper and hence a consistent optical density of printed images.

Because a thicker ink film is required on the plate at higher speeds to achieve the target density, a good mileage ink is definitely desired for high speed presses to enhance print quality.

The percent ink transfer increases with increasing printing pressure. This infers that a thinner ink film is needed on the plate to produce the target optical density at higher pressures and print quality is expected to be better. However, excessively high pressure may cause severe wear to the plate. It may also force substantial ink vehicle to drain into the pores of the paper and aggravate print through. Since it is much more difficult to change the impression force of a press than the speed, the printing pressure is seldom changed during printing to enhance ink transfer.

Both ink mileage and ink transfer characteristics are also important to ink trapping, one of the key elements to a successful color reproduction in the wet multi-color printing. Theoretically, satisfactory ink trapping can be achieved by printing process colors in a sequence of reducing ink tack. However, many exceptions have been encountered. To resolve those deviating cases with the theory, one needs to know how tack is measured and what factors affect the tack reading.

Stefan (Scarlett and Eldred, 1984) observed that the force or tack needed to split a thin film of Newtonian fluid between two parallel plates is governed by the following equation.

$$F = \frac{\eta v A}{t^3} \qquad (16)$$

where η = viscosity of the Newtonian fluid.
v = velocity of separation of the two plates.
A = area of the plates.
t = thickness of the fluid between the plates.

It is noted from Stefan's equation that tack is inversely proportional to the cubic power of ink film thickness. Any minor change of ink film thickness in the printing nip will cause a large change of tack. In general, a fixed volume of ink, regardless of its identity, is used in tack measurement on an inkometer. That is, the ink film thickness term in Eq. 16 is a constant rather than a variable. The SNAP committee recommends dry ink target densities of 0.90, 0.90, 0.85, and 1.05 for cyan, magenta, yellow, and black with a tolerance of ±0.05. The ink film thickness on the paper needed to achieve the target optical density can be calculated from Eq. 4, which can in turn be used in Eq. 10 to calculate the required ink film thickness on the printing roller. The ink film thicknesses on the paper and on the plate that are needed to result in the target optical densities at a printing speed of 3 m/s and a line pressure of 252 N/cm are listed in Table IV. The difference in the ink film thickness on the roller between cyan and magenta inks may result in more than 200% variation in the tack, according to Eq. 16. Moreover, the thickness of the ink film in the roller nip is about 24 micrometers for the tack measurement on an electronic inkometer from Thwing-Albert Instrument Co., which is more than one order of magnitude thicker than the ink films listed in Table IV. These observations account for the failure of predicting color sequence on the basis of the inkometer readings.

Table IV. Calculated ink film thicknesses on the paper and the plate that result in SNAP's target optical densities for the process colors.

Ink	Target Density	Thickness on Paper	Thickness on Plate
Black	1.05	0.93	1.47
Cyan	0.90	0.94	1.43
Magenta	0.90	1.15	1.91
Yellow	0.85	1.12	1.82

In conclusion, to predict the performance of a particular ink-paper-press system from laboratory results, one needs to correlate the printing conditions of the printability tester with those of real presses. Then, an ink curve can be programmed for the press to correctly regulate ink input as the printing conditions change. The thickness of ink film on the plate to achieve a desired optical density can also be calculated. By applying an ink film of that thickness to the inkometer, the measured tack will become meaningful for setting proper color sequence in the wet multi-color printing.

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