A method for evaluating ink mileage in gravure printing

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ABSTRACT: Researchers have studied ink mileage curves for many years, and they have reported several models for curve fitting. Regression coefficients derived from curve fitting have been found to be very useful for comparing different inks and have been related to various properties of ink and paper. However, these models were based on experimental data from prints made on IGT and Prüfbau printability testers using offset inks. The quantity of ink transferred, and hence the amount of ink on paper, was determined by the weight difference of the printing disk before and after printing. These models have not been tested on other ink types or on commercial printing presses. The challenge has been that it is difficult to accurately measure the coat weight of gravure or flexographic ink film.

In this study, eight coated rotogravure papers were printed on a Cerutti rotogravure web press. The ink film coat weights at different tonal values were calculated from the copper (Cu) concentrations in both liquid ink and printed paper samples, which we analyzed using an atomic absorption (AA) spectrometer after digestion. The ink film coat weight and relative reflection density data were fitted by different models using OriginPro® 7.5 software. The degree of fit was determined by the sum of the squares of residuals and the distribution of residuals around zero. Both the Oittinen and Calabro-Savagnone models fitted the experimental data equally well. The regression coefficients derived from curve fitting could be related to paper properties such as surface roughness, air permeability, and pore size. We found that the saturation density D_s had higher correlations with air permeability and with pore size than with surface roughness. The parameter m, which determines the steepness of the density curve in the region of very thin film (also called density smoothness), was highly correlated with paper roughness as measured by the profilometer and at a less significant level with air permeability. The parameter n was well correlated with both profilometer roughness and air permeability.

Application: This work can be used to aid in the improvement of lightweight coated (LWC) papers to obtain high ink mileage in gravure printing.

It is important to understand how differences in paper properties affect the consumption of printing inks. An ink mileage curve is a plot of the printed optical density of an ink on a substrate as a function of ink film thickness. The optical density of a print increases from zero to a saturation value with increasing ink layer thickness on the paper. The saturation density arises from first surface reflection [1]. In practice, ink film thickness is difficult to measure, so ink film coat weight, the amount of ink in gram per square meter (gsm) of substrate, has been used to represent the ink film thickness by assuming that the ink film density varies identically for the same ink.

The mileage curve provides only qualitative information about the ink mileage characteristics of the ink. To describe ink mileage quantitatively, it is essential to fit a mathematical equation to the experimental data. The regression coefficients derived from curve fitting can be related to the properties of ink and paper [2]. Several models for curve fitting have been reported by different researchers, among them Tollenaar and Ernst [3], Kornerup et al. [4], Oittinen [5], Calabro and Mercatucci [6], Calabro and Savagnone [7], Blom and Conner [8], and MacPhee and Lind [9]. Six of these models are listed below:

Tollenaar and Ernst
$$D = D_s\,(1 - e^{-mw}) \tag{1}$$

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

Calabro and Mercatucci
$$\frac{1}{D} = \frac{1}{D_s} + \frac{1}{mw} \tag{3}$$

Calabro and Savagnone
$$\frac{1}{D} = \frac{1}{D_s} + \left(\frac{1}{mw}\right)^n \tag{4}$$

Blom and Conner
$$\frac{R}{R_p} = \frac{R_s}{R_p} + \frac{1}{mw} \tag{5}$$

Kornerup et al.
$$\frac{R_p - R_s}{R - R_s} = 1 + (mw)^n \tag{6}$$

where w is the ink film coat weight. D or R is the relative reflection density or reflectance. The subscript p or s represents paper or saturation. D_p/R_p is a constant for a certain substrate. D_s/R_s, m and n are regression coefficients. Parameter m determines the steepness of density curve in the region of very thin film and is called "density smoothness" [3]. Equations 1 and 3 result from the shapes of ink mileage curves [3, 6]. Equations 2 and 4 represent modifications to these curves by adding a power index n to the ink film thickness, which is a common practice in mathematics to obtain a better curve fit [5, 7]. Equation 6 originates from Bouguer's law with some assumptions and simplifications [4]. Equation 5 is a simplified version of Equation 6. Chou and Harbin [2] found that three-parameter equations fitted their experimental data much better than the corresponding two-parameter equations.

These models were based on experimental data from prints made on IGT or Prüfbau printability testers using offset lithographic inks. The quantity of ink transferred, and hence the amount of ink on paper, was determined by the weight difference of the printing disk before and after printing [2–9]. These models have not been tested on other ink types or on high-speed commercial printing presses. The challenge has been to find an accurate method to measure ink film coat weight in gravure or flexographic printing. In a previous study in the authors' laboratory, Serafano and Pekarovicova [10] used the weight difference of paper before and after printing to determine the ink coat weight of gravure publication papers. The solids content in solvent-based gravure ink was only about 30%, and therefore the weight of the ink film as a fraction of the variation of the substrate grammage was too small to achieve reliable results.

In this earlier work [10], the CIE L*a*b* lightness value, L*, was correlated with coat weight. L* was found to be a fairly sensitive measure for a single paper grade, but not sensitive enough for the whole palette of publication-grade papers. It was found that paper permeability, as measured by PPS porosity [11], was a useful measure for predicting gravure ink mileage [10]. This work confirmed that the speed of the printing press affects ink transfer.

In previous work by the authors, the inks were doped with a tracer, and tracer concentrations in both liquid ink and ink film were used to calculate the mass of ink transfer and hence the ink film coat weight [12, 13]. This internal tracer method can be used for all ink types, including solvent-based gravure and flexographic inks. It can also be applied to high-speed printing presses. However, adding a tracer to an ink is not convenient, and the effect of the tracer on ink performance, although minimal, still exists. In the present work, metal ions in ink pigments, specifically copper ions in cyan ink, were used for ink transfer detection. Copper is part of the cyan pigment, so it does not interfere with ink viscosity or color and can be easily determined by chemical analytical methods such as atomic absorption spectroscopy (AAS).

The objectives of this work were to: (a) use the quantitative analytical method to measure coat weight of the cyan ink film obtained on a high-speed rotogravure press, (b) find a best-fit model for the experimental data, and (c) study the effects of paper properties on the regression coefficients of ink mileage curves.

EXPERIMENTAL

Paper testing

Eight coated rotogravure papers were used in this experiment. The characteristics of the papers are reported in **Table I.** A Parker Print-Surf (PPS) Model 90 tester (Messmer Instrument) was used to measure roughness at 490 kPa with a soft backing, according to the TAPPI standard [14]. Air permeability (as determined by PPS porosity [11]) was also measured at 490 kPa. An Electronic Microgage Model 210 from EMVECO Inc. (now Lorentzen & Wettre USA, Inc.) with a spherical steel stylus having a radius of 0.001 inch, was also used for roughness measurement. Microroughness [15] was measured using a Model Autoprobe CP Atomic Force Microscope (AFM) from Park Scientific Instruments Inc. (now ThermoSpectra Corp.), with Proscan version 1.3 software. The tapping mode was used with a silicon tip (radius of the tip-end curvature was about 10 nm). Topographic data were obtained over a 20 μm × 20 μm area with a typical scanning rate of 0.5 Hz. Average pore sizes were determined by mercury porosimetry. Measurements were carried out using an Autopore IV 9500 (Micromeritics Instrument). More test details can be found in previous papers by the authors [12, 13].

Printing

The papers were printed on the pilot rotogravure web press (Cerutti Model 118) located at the Western Michigan University (WMU) Printing Pilot Plant. Researchers used commercial toluene-based coated cyan rotogravure inks (Flint Ink). The ink efflux time with Shell cup #2 was kept at 21+/- 0.5 seconds. Printing was done at 1000 ft/min with electrostatic assist (ESA) turned on. The cyan cylinder had compressed cells. The print layout contained various cyan tonal values from 25% to 100%.

Sample No.	PPS Roughness (μm)	Profilometer Roughness (μm)	AFM Roughness (nm)	Air Permeability (ml/min)	Pore Size (nm)
1	1.90	1.62	72.0	8.45	123.7
2	1.69	1.67	55.4	7.57	132.4
3	1.90	1.54	76.9	6.53	120.7
4	1.62	1.19	41.0	12.95	141.1
5	1.60	1.62	76.5	10.67	113.0
6	1.57	1.61	36.9	7.97	100.3
7	1.52	1.65	65.0	11.93	233.1
8	1.54	1.58	65.8	10.46	146.5

I. Paper characteristics.

Ink film coat weight

A known amount of liquid ink samples and certain areas of both unprinted and printed paper samples with different tonal values were digested in a mixture of nitric acid and hydrogen peroxide (1:1) by slow boiling for at least four hours. The copper (Cu) concentrations were analyzed quantitatively using a Varian Atomic Absorption (AA) Spectrometer Model AA240. The ink film coat weights at different tonal values were calculated using the equation:

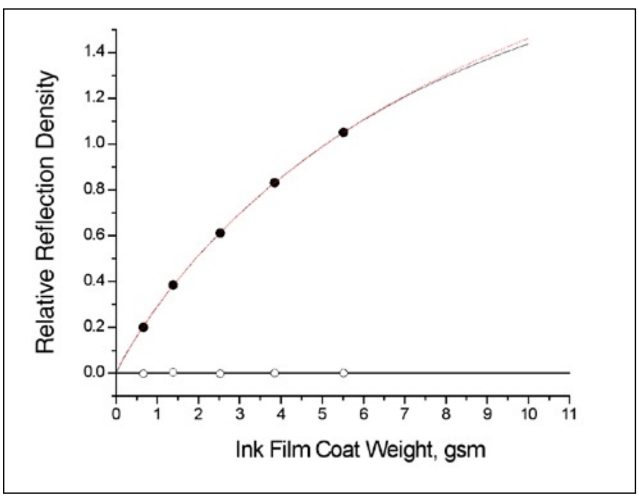
$$\text{Ink film coat weight (gsm)} = [\text{Cu in printed paper (gsm)} - \text{Cu in unprinted paper (gsm)}] / \text{Cu in ink (wt \%)} \quad (7)$$

Relative reflection density

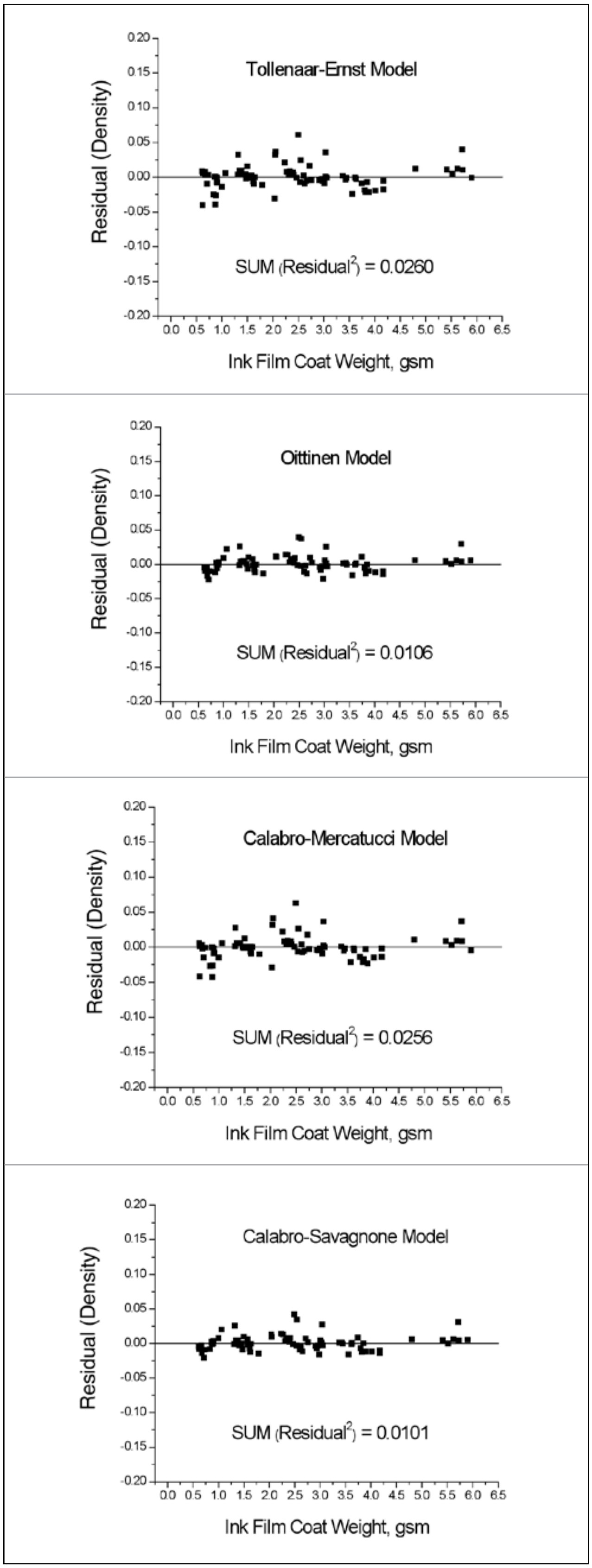
We measured the reflection densities at different tonal values with reference to the reflection density of unprinted paper using an X-Rite 530 SpectroDensitometer.

RESULTS AND DISCUSSION

Researchers have studied ink mileage curves for offset lithographic inks for many years. Several models for curve fitting have been reported by different researchers. These models were based on experimental data from prints made on IGT or Prüfbau printability testers using paste lithographic inks. They have not been tested on fluid ink types or on commercial printing presses. There are obvious differences in rheology, fluidity, pigmentation, and chemistry between paste offset lithographic inks with high viscosity and fluid gravure inks with low viscosity and low solids content. Ink transfer in lithography features multiple splitting of the ink film on multiple inking rollers. Thus, the ink transfer in offset lithography differs significantly from the extremely simple ink transfer in gravure from engraved cells directly onto the substrate. However, it was interesting to see whether these models, originally tailored for lithographic ink mileage curves, could be applied to the gravure printing process.



1. Ink mileage curve from sample 2 (the solid line is the curve fitted using the Oittinen model and the dotted line that fitted using the Calabro-Savagnone model).



2. Sum of squares of reflection density residuals and their distribution for various models.

The current study has established that the analytical method using copper ion in cyan pigments appears to be a practical method for measuring ink film coat weight. Digestion was extremely important to make sure all copper ions in the solid form were transferred into the liquid form, so digestion time had to be long enough to dissolve the paper samples completely.

The ink film coat weight and relative reflection density data were analyzed using the appropriate OriginPro® 7.5 nonlinear fitting routines. Equations 1 to 4 were investigated, with D_s, m, and n treated as regression variables. One example of the ink mileage curves obtained is shown in **Fig. 1**. The solid dots are experimental data for cyan ink on paper sample 2. The solid line is the nonlinear fitting result using the Oittinen model, while the dotted line represents the fit using the Calabro-Savagnone model. These two curves were indistinguishable in the range of the study data but began to separate with increasing ink film coat weight. The ink mileage curve obtained using the Calabro-Savagnone model lies above that obtained using the Oittinen model; therefore, the saturation density obtained from the Calabro-Savagnone model is higher than that obtained from the Oittinen model. The hollow dots are residual values. The residual is equal to the experimental value minus the value calculated from the fitted model. Residual values can be used to measure goodness of fit. The smaller the absolute values of the residuals, the better the curve fit.

The residual values obtained from curve fitting for all paper samples were plotted against ink film coat weight. The degree of fit of an equation to experimental data can be determined by the sum of squares of residuals and the distribution of residuals around zero. A small sum of squares of residuals and an even distribution around zero indicate a good fit. **Figure 2** compares the residual plots of four models. The comparison indicates that the three-parameter models (Oittinen and Calabro-Savagnone) fit the experimental data better than their corresponding two-parameter models (Tollenaar-Ernst and Calabro-Mercatucci), as expected. Previous studies found that the Oittinen model achieves an insufficiently good fit [2], but here it appears to give acceptable results. Both the Oittinen and Calabro-Savagnone models have a minimal sum of squares of residuals (0.0106 and 0.0101, respectively) and an even distribution of residuals around zero. Therefore, these two models were used to study the effects of paper physical properties on ink mileage characteristics.

The regression coefficients D_s, m, and n, derived from curve fitting for both models, are listed in **Table II**. Saturation density (D_s) values derived from the Calabro-Savagnone model are higher than those from the Oittinen model shown in Fig. 1.

The correlations between paper characteristics and regression coefficients for both models are shown in **Table III**.

Tollenaar and Ernst [3] reported D_s values of 0.275–0.92 for three mixtures of white letterpress ink with colored inks on three different papers. Calabro and Mercatucci [6] reported D_s values of 1.13–1.68 for eight inks on twenty newsprints. Chou and Harbin [2] reported D_s values of 1.04–1.48 for news inks on a 30-lb newsprint. Calabro and Savagnone [7] reported D_s values of 2.06–2.41 for ten offset inks on ten coated papers. Apparently, the values of saturation density (D_s) are higher on coated than on uncoated stocks. The saturation density D_s results from first-surface reflection, which is affected by the smoothness of the ink film surface. Surface roughness of an ink film is related to the ink's leveling property [16]. Calabro and Mercatucci [6] found that saturation density D_s depends on the characteristics of the ink as well as those of the paper. However, in a later study, Calabro and Savagnone [7] found that the saturation density D_s showed very poor correlation with measured ink characteristics, but they did not study the effect of paper properties. The current

Paper Sample No	Oittinen Model			Calabro-Savagnone Model		
	D_s	m	n	D_s	m	n
1	2.039	0.161	0.900	3.135	0.308	0.928
2	1.943	0.161	0.921	3.028	0.300	0.946
3	2.741	0.123	0.891	4.472	0.305	0.906
4	1.469	0.284	1.240	2.024	0.543	1.320
5	2.000	0.168	0.906	2.968	0.322	0.944
6	2.253	0.137	0.901	3.520	0.285	0.925
7	1.511	0.189	1.097	2.064	0.355	1.180
8	2.358	0.140	0.847	3.374	0.294	0.888

II. Regression coefficients of Oittinen and Calabro-Savagnone models.

	Oittinen Model			Calabro-Savagnone Model		
	D_s	m	n	D_s	m	n
PPS Roughness	0.458	-0.264	-0.283	0.547	-0.176	-0.334
Profilometer Roughness	0.332	-0.797	-0.731	0.335	-0.913	-0.706
AFM Roughness	0.366	-0.439	-0.452	0.341	-0.419	-0.428
Air Permeability	-0.775	0.780	0.731	-0.853	0.719	0.777
Pore Size	-0.561	0.289	0.489	-0.599	0.225	0.541

III. Correlation matrix of regression coefficients of Oittinen and Calabro-Savagnone models.

work has determined that saturation density D_s has higher correlations with air permeability and pore size than with surface roughness, as shown in Table III. Ink absorption plays a more important role in leveling of solvent-based gravure inks than in leveling of viscous paste offset inks.

The parameter m, or "density smoothness", determines how fast the ink mileage curve approaches the saturation density as ink film thickness increases. Tollenaar and Ernst [3] reported that m was correlated with the degree of contact between the ink film and the paper. Calabro and Savagnone [7] found that m was correlated mainly with smoothness, gloss, and absorption. The current study has shown that m is highly correlated with paper roughness as measured by the profilometer, and at a less significant level, with air permeability.

Calabro and Savagnone [7] found that the ink film coat weight exponent n showed good correlations with ink rheological variables such as viscosity, yield value, and tack, and with ink optical properties such as the absorption coefficient and the fineness of grind of the pigment. In the current study, n was best correlated with profilometer roughness and air permeability, so it was found to be affected by paper properties as well as ink properties.

Pauler [17] also pointed out the importance of ink penetration in determining the shape of the ink mileage curve and proposed a model to study the effect of different paper structures on ink penetration. Permeability and pore size are the main factors affecting ink penetration and therefore also affect ink mileage characteristics.

CONCLUSIONS

The models that were used to fit laboratory results for offset inks were tested for various rotogravure ink/paper/press settings. It was found that both the Oittinen and Calabro-Savagnone models fitted the experimental data much better than other models, as evidenced by minimal sum of squares of residuals and their even distribution around zero. These two models were used to study ink mileage characteristics. The regression coefficients derived from curve fitting were compared and related to paper properties. The saturation density D_s had higher correlations with air permeability and pore size than with surface roughness. The density smoothness m was well correlated with paper roughness as measured by the profilometer, and at a less significant level with air permeability, while the parameter n was well correlated with both profilometer roughness and air permeability.

Ink characteristics and printing conditions are also important in determining ink mileage curves. However, they were kept constant at this stage of research. The ultimate goal is to enable an ink mileage curve to be programmed so that the press can adjust ink input and printing conditions as substrates change. **TJ**

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INSIGHTS FROM THE AUTHORS

Ink mileage is important for both paper manufacturers and printing companies, but none of the existing methods is accurate or convenient for everyday use. The method proposed here uses chemical analysis instead of weight difference to determine the amount of ink transferred onto paper. Moreover, previous methods can be applied only to offset printing and on laboratory-scale printability testers, but this method can be applied to all printing processes and on high-speed commercial presses.

The most challenging aspect of this research was the chemical analysis, figuring out how to digest inks and papers into liquids to measure ion concentrations. The method used here was developed with the help of chemists.

Paper mills can use the method developed in this research to evaluate the ink mileage of their papers and to modify their papers to achieve higher ink mileages. The next step in this research will be to move beyond the effect of paper properties on ink mileages to study the impact of ink properties and press conditions, which also play important roles.

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