Relationship Between Mainstream Cigarette Smoke "Tar" and Nicotine Yields *

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SUMMARY

The purpose of this research was to examine the relationship between mainstream "tar" and nicotine yields and refine the commonly used linear model with a positive intercept to incorporate non-linearity and product-to-product differences in filler nicotine content. "Tar" and nicotine yields are examined for a wide range of cigarettes (U.S. and international) using the Cambridge filter (CF), ISO, and the more intense MDPH, and HC smoking methods. Particularly at very low machine yields, a non-linearity is observed that can be more accurately modeled by a power law relationship, and can be further improved by incorporating the concentration of nicotine in the cigarette filler into the equation. The resultant power law relationship is the better statistical fit to the available data, avoids the physical implausibility of positive nicotine yield at zero "tar" yield and lack of dependence on filler nicotine that are inherent in the simple linear model relating nicotine yield to "tar" yield alone, and explains the non-constancy of the "tar"-to-nicotine ratio. The relationship between "tar" and nicotine can be affected by the use of very long or very short puff intervals, and, with the same tobacco blend and the same "tar" yield, longer cigarettes tend to have a slightly higher nicotine yield than shorter cigarettes. [Beitr. Tabakforsch. Int. 25 (2013) 671–684]

ZUSAMMENFASSUNG

Gegenstand dieser Forschungsarbeit war die Untersuchung des Zusammenhangs zwischen den Teer- und Nikotinausbeuten im Hauptstromrauch und die Optimierung des häufig verwendeten linearen Modells durch einen positiven Achsenabschnitt, um die nichtlinearen Unterschiede zwi-

schen den Produkten hinsichtlich des Nikotingehalts des Füllstoffs zu berücksichtigen. Die Teer- und Nikotinausbeuten werden bei einer Vielzahl von (US-amerikanischen und internationalen) Zigaretten mit dem Cambridge Filter (CF) durch die Bestimmungsverfahren ISO und die intensiveren Methoden MDPH und HC untersucht. Insbesondere bei sehr niedrigen maschinellen Ausbeuten ist eine Nichtlinearität zu beobachten, die durch eine Potenzfunktion genauer modelliert werden kann und durch Einbeziehung der Nikotinkonzentration im Zigarettenfüllstoff in die Gleichung weiter verbessert werden kann. Die sich daraus ergebende Potenzfunktion passt statistisch besser zu den verfügbaren Daten, vermeidet die physikalische Unplausibilität einer positiven Nikotinausbeute bei einer Teerausbeute von Null und die mangelnde Abhängigkeit vom Nikotin im Füllstoff, die dem einfachen linearen Modell innewohnen, in welchem die Nikotinausbeute nur zur Teerausbeute in Beziehung gesetzt wird. Zudem erklärt sie die Nichtkonsistenz des Verhältnisses von Teer zu Nikotin. Die Beziehung zwischen Teer und Nikotin kann durch die Verwendung von sehr langen oder sehr kurzen Abständen zwischen den Zügen beeinflusst werden. Mit derselben Tabakmischung und derselben Teerausbeute haben längere Zigaretten tendenziell eine leicht höhere Nikotinausbeute als kürzere Zigaretten. [Beitr. Tabakforsch. Int. 25 (2013) 671–684]

RESUME

L'objectif de cette recherche était d'étudier la relation entre le goudron du flux de fumé principal et les teneurs en nicotine et de perfectionner le modèle linéaire généralement utilisé avec une interception positive permettant d'incorporer des différences de non-linéarité et entre diffé-

rents produits dans la teneur en nicotine de la matière de remplissage. Les teneurs en goudron et en nicotine sont étudiées pour une vaste gamme de cigarettes (des USA et d'origine internationale) utilisant le filtre Cambridge (CF), le régime de fumage ISO ainsi que les régimes de fumage plus intenses du MDPH et de HC. On observe en particulier une non-linéarité à des teneurs machine très faibles, qui peut être modélisée avec plus de précision par une relation de loi de puissance et peut être encore améliorée en incorporant dans l'équation la concentration de nicotine dans la matière de remplissage de la cigarette. La relation de loi de puissance en résultant est la meilleure réponse statistique aux données disponibles, elle évite l'implausibilité physique d'une teneur en nicotine positive avec une teneur en goudron zéro et un manque de dépendance à la nicotine de la matière de remplissage qui sont inhérents dans le modèle linéaire simple n'associant la teneur en nicotine qu'à la teneur en goudron, et elle explique la non-constance du rapport du goudron à la nicotine. La relation entre le goudron et la nicotine peut être affectée par l'utilisation d'intervalles de bouffées très longues ou très courtes et, avec le même mélange de tabac et la même teneur en goudron, les cigarettes plus longues ont tendance à avoir une teneur en nicotine légèrement plus élevée que les cigarettes plus courtes. [Beitr. Tabakforsch. Int. 25 (2013) 671–684]

KEY WORDS

Tobacco; cigarette; mainstream smoke; nicotine; "tar"; machine-smoking; "tar"-to-nicotine ratio

Abbreviations	
CF	Cambridge filter
MS	Mainstream
MDPH	Massachusetts Department of Public Health
HC	Health Canada
TITL	Tobacco Industry Testing Laboratory
HPHC	Harmful and Potentially Harmful Constituents
TSNA	Tobacco-specific nitrosamines
TPM	Total particulate matter
RH	Relative humidity

1. INTRODUCTION

The effects of cigarette design, ingredients, additives, and tobacco blends on the chemical, physical, and biological properties of mainstream (MS) and sidestream (SS) cigarette smoke is a major area of study (see 1–22, 65, 66). In these and many other reports, machine-smoking methods remain among the primary experimental techniques of choice even though it has been known for decades that no single method can model the various ways that humans smoke cigarettes (23–27, 66–69). In the United States, Canada, and other countries, cigarette manufacturers are required to provide MS smoke nicotine and/or "tar" yields using one of several machine-smoking methods. Those machine yields have been examined to investigate over-time trends in cigarette nicotine yields (28). In addition, machine-smoking methods are used in benchmark studies

in which MS smoke yields of various constituents are predicted based on the yields of nicotine or "tar" or carbon monoxide (5–7, 29–32). Machine-smoking methods continue to be used (see 12, 19, 28, 33–35) and continue to play a central role in both the short term and long term strategic plans of the public health community (36–38). Nonetheless, these methods are best viewed as useful complements to human-smoking exposure studies and *in vitro* or *in vivo* toxicological studies (36, 38).

Nicotine in cigarette smoke is generally related to "tar" yield in commercial cigarettes in a roughly linear manner (5–7, 29, 30, 32, 39–42). Some have refined that relationship through the incorporation of the nicotine concentration of the cigarette filler (31, 42). Researchers have proposed similar models for other smoke constituents such as tobacco-specific nitrosamines (TSNAs) and a somewhat different approach was taken by HARRIS (70). COUNTS *et al.* (6) incorporated the *weight* or the *amount* (e.g., nanograms per cigarette) of the TSNAs in the cigarette to improve the fit of the corresponding TSNAs in smoke. COUNTS *et al.* (7) and MORTON and LAFFOON (31) utilized the *concentration* of the TSNA (e.g., measured in nanograms per gram of cigarette filler). In the U.S., cigarette companies were required in 2012 by the FDA to report the weight per cigarette (not the concentration) of each of six harmful and potentially harmful (HPHC) cigarette filler constituents, including nicotine. To our knowledge no researcher has explicitly compared the relative utility of these two ways of quantifying the constituent content of the cigarette filler, i.e. weight or concentration, they have simply used or required one or the other.

The purpose of this research was to examine the relationship between nicotine yield and "tar" yield in many different machine-smoking settings and refine the commonly estimated, but implausible, linear model with a non-zero intercept. This also involves an explicit comparison of whether weight of nicotine in the cigarette or concentration of nicotine in the cigarette filler is better for use in modeling the nicotine yield of the cigarette.

2. METHODS

The four commonly used machine-smoking protocols discussed in this paper are:

1. Cambridge filter (CF; formerly also known as the FTC method) using 35 cc puffs, taken once per minute, with no blocking of the cigarette ventilation holes (43);
2. ISO using 35 cc puffs, taken once per minute, with no blocking of the cigarette ventilation holes (44, 45). There are subtle differences between the ISO and CF smoking methods, but the smoke yields are typically quite similar;
3. Massachusetts Department of Public Health (MDPH) using 45 cc puffs, taken twice per minute with 50% of the ventilation holes blocked (46);
4. Health Canada Intense (HC) using 55 cc puffs, taken twice per minute, with 100% of the ventilation holes blocked (47).

The data sets used are:

1. FTC market samples data from 1967 to 2008 (see Table 1). There were 51 market samples during that time.

Table 1. FTC/TITL market samples

Year	Date of Pickup	Market Samples	N
1967	9/67	MS #1	127
	8/67 – 1/68	MS #2	
1968	8/67 – 1/68	MS #2	137
	6/68*	MS #3	
	10/68*	MS #4	
1969	3/69	MS #5	127
	7/69	MS #6	
	12/69 – 1/70	MS #7	
1970	12/69 – 1/70	MS #7	131
	5/70 – 6/70	MS #8	
	12/70 – 1/71	MS #9	
1971	12/70 – 1/71	MS #9	134
	10/71*	MS #10	
1972	1/72	MS #11	145
	6/72	MS #12	
1973	1/73	MS #13	136
	9/73	MS #14	
1974	3/74	MS #15	148
	9/74 – 10/74	MS #16	
1975	3/75 – 5/75	MS #17	147
	8/75 – 10/75	MS #18	
1976	5/76*	MS #19	180
	11/76	MS #20	
1977	5/77 – 7/77	MS #21	167
1979	4/79	MS #23	190
	10/79 – 11/79	MS #24	
1981	3/81 – 4/81	MS #25	214
	12/81 – 2/82	MS #26	
1982	12/81 – 2/82	MS #26	225
	8/82 – 12/82	MS #27	
1983	10/83 – 1/84	MS #28	205
1986	1986*	MS #29	256
1987	1987*	MS #30	273
1988	1988	MS #31	278
1989	1989	MS #32	307

* Estimated

Supplemented with PM USA data

Year	Date of Pickup	Market Samples	N
1990	3/90 – 4/90	MS #33	337
1991	3/91 – 4/91	MS #34	384
1992	2/92 – 3/92	MS #35	413
1993	2/93 – 4/93	MS #36	482
1994	1/94 – 2/94	MS #37	516
1995	1/95 – 2/95	MS #38	523
1996	1/96 – 2/96	MS #39	518
1997	1/97*	MS #40	518
1998	1/98*	MS #41	507
1999	1/99*	MS #42	526
2000	1/00*	MS #43	518
2001	1/01*	MS #44	617 [#]
2002	1/02*	MS #45	627 [#]
2003	1/03	MS #46	576 [#]
2004	1/04 – 2/04	MS #47	542 [#]
2005	1/05 – 2/05*	MS #48	428
2006	1/06 – 2/06	MS #49	421
2007	1/07 – 8/07	MS #50	517
2008	1/08 – 7/08	MS #51	531

These data were obtained from FTC Reports, TITL reports, and/or TITL spreadsheets. The market samples were assigned to years as shown in Table 1. Note that there are different conventions in different years related to the reporting of very low yield products. In several years, we only had available to us an indication that values were below some threshold (e.g., "tar" < 0.5 mg). In other years we had available to us a value, even if extremely low. We used the very low values if they were available, but omitted the small number of values listed as negative. Some additional products tested by Philip Morris USA (PM USA) for reporting to the FTC were also included as indicated in Table 1.

2. For market samples from 1981, 1995, and 1996 tobacco filler nicotine analyses for many of the products were available from internal PM USA analyses and were combined with the market sample data. For 1992, inter-

nal PM USA "tar", nicotine, and tobacco filler nicotine data were available for many products.

3. A set of 48 PM USA and Philip Morris International commercial products machine-smoked using the ISO, MDPH, and HC smoking protocols and reported in COUNTS *et al.* (7).
4. Internal product data for two PM USA products for the years 2003 and 2004.
5. A single PM USA product smoked using multiple puff profiles to give a wide "tar" range and reported in MORTON *et al.* (48).
6. The high alkaloid data from Table 1 of ST. CHARLES *et al.* (42).
7. Data generated by PM USA for reporting to the state of Massachusetts from 1997–2010 using the MDPH smoking protocol.

Only cigarettes that have been equilibrated at 60% RH are examined in this paper. This minimizes the effect of tobacco moisture on the cigarette yields. It has been shown that moisture can affect the nicotine and "tar" relationship, with drier cigarettes tending to yield more nicotine at the same "tar" yield (48–52).

3. RELATIONSHIPS BETWEEN MS SMOKE NICOTINE YIELDS AND "TAR" YIELDS

3.1 Linear relationships between MS smoke nicotine yields and "tar" yields

Figure 1 illustrates the typical relationship between MS smoke nicotine and "tar" for U.S. commercial cigarettes using the CF machine-smoking method with the data from

Market Sample #51 conducted in 2008 by the Tobacco Industry Testing Laboratory (TITL). The graph illustrates four points:

- The relationship is approximately linear;
- There are "outlier" points, i.e., cigarette products that fall outside the general relationship. In this instance, there are two "outlier" points corresponding to Eclipse cigarettes;
- The spread around the regression line increases the higher the "tar" yield. This has been noted before and has been accounted for by applying weighted regression using $1/\text{"tar"}$ as the weighting factor (see 7);
- There is a positive intercept and the products with very low "tar" yield are all below the regression line. That the low "tar" yield data points are all below the regression line indicates that the linear fit can be improved upon. We return to this point in section 3.2 below.

Figure 1. Linear relationship between MS smoke nicotine versus "tar" for U.S. commercial cigarettes in Market Sample #51 sampled and tested in 2008 using the CF machine-smoking method.

Figure 2. All market samples from 1967 to 2008. The regression equation and R^2 calculation exclude the 215 "outlier" points highlighted in the graph.

Figure 2 shows the data from 13,027 data points from the 51 market samples conducted from 1967 to 2008. The majority of the data shows a similar pattern to that observed with Figure 1. The linear regression across the entire time period is very similar to that found in 2008. Additionally, we see a small collection of data points with nicotine yields below the general population. The lowest of the data points correspond to products using de-nicotinized tobaccos such as the PM USA product Next. Other data points below the population consist of products, such as Sano, Domino, Vogue, Mapleton, and others, that were either blended to be low nicotine or used partially de-nicotinized tobaccos. The regression line in the graph does not include the 215 “outlier” data points highlighted in the graph.

The equations relating “tar” and nicotine from year-to-year are generally similar, though the small year-to-year differences (not shown) are statistically significant. The year-to-year variation was taken into account by fitting a random coefficients model to the data (see 53, 54). As noted above, the scatter around the line tends to increase at higher yields and this was accounted for through the use of weighted regression using $1/\text{“tar”}$ as the weighting factor. The resulting fitted equation is:

$$\text{Nicotine} = 0.066 \times \text{“tar”} + 0.087 \quad [1]$$

The weighted R^2 for the model is 0.956.

Figure 3 shows “tar” and nicotine yields from 48 PM USA and Philip Morris International products each tested under ISO, MDPH, and HC smoking protocols. The linear equation shown with the data is equation [1] and is very close to the equation that would be fitted to this data set. This shows that the relationship fit under CF or ISO conditions extrapolates reasonably well to more intense smoking conditions. Though not shown here, this also holds true with products in the so-called MASSACHUSETTS BENCHMARK STUDY (29).

Each of the previous graphs showed many different products machine-smoked either using a single protocol or using three different protocols. We next examined data from MORTON *et al.* (48), in which a single product is smoked in 16 different ways (see Table 2). The intent was to generate similar “tar” yields using three different puff volumes by changing the interpuff interval (and in two instances by removing the product from the smoking machine after a designated number of puffs). The interpuff interval is defined here as the time from the start of one puff until the start of the next puff.

Table 2. MS smoke nicotine and “tar” yields for a U.S. commercial cigarette using machine-smoking methods with a 2-s puff and inter-puff intervals and puff volumes as listed.

Puff volume	Puff interval	“Tar” (mg/cig)	Nicotine (mg/cig)
35 cc	130 s	6	0.4
	60 s	11	0.8
	35 s	16	1.2
	19 s	22	1.5
	9 s [#]	31	1.7
55 cc	166 s	7	0.4
	92 s	12	0.8
	61 s	16	1.1
	39 s	21	1.5
	23 s	30	2.0
70 cc	180 s (2 puffs)*	4	0.3
	180 s (3 puffs)*	7	0.4
	106 s	13	0.8
	67 s	17	1.2
	44 s	24	1.6
	28 s	30	2.0

[#] Excluded from the calculation of the regression equation shown in Figure 4

* Removed from the smoking machine after the designated number of puffs

Figure 3. Data from COUNTS *et al.* (7). Reference line is equation [1]. The regression fit to the data is $y = 0.091 + 0.066x$, $R^2 = 0.968$. The regression fit is not shown on the graph because it is difficult to distinguish from equation [1].

Figure 4. U.S. commercial cigarette machine-smoked with a 2-s puff interval at 35 cc, 55 cc, or 70 cc puff volume and at various interpuft intervals. The regression line excludes data using 35 cc puff volume at the shortest puff interval and is graphed with a solid line. The dashed line is equation [1]. Data source is MORTON *et al.* (48). The excluded points are the four points drawn with open circles near 30 mg/cigarette "tar" yield.

Figure 4 shows the nicotine vs. "tar" relationship for the data values resulting from the 16 different sets of puffing parameters. With respect to nicotine yield, the four replicates at the highest "tar" yield condition using 35 cc puffs are somewhat below the other data points with similar "tar" yields and are not included in the calculation of the regression equation. Equation [1] is also plotted for reference (the dashed line in the graph).

The regression equation in Figure 4 is similar to equation [1], but also shows some interesting differences.

1. The intercept in the regression is not statistically significantly different from zero;
2. The nicotine yields associated with the data points under 10 mg "tar" yield are below equation [1].

We postulate that the highest "tar" yield points using 35 cc puffs and the lowest "tar" yield points are below equation [1] because of the pattern of nicotine deposition after a puff. In GREEN *et al.* (50), it is shown that following a puff the area immediately behind the firecone is partially depleted of nicotine, the region from 4 to 8 mm behind the firecone has a somewhat elevated nicotine concentration, presumably because of nicotine condensing onto the tobacco behind the firecone, and the concentration is gradually lower further down the rod.

For very short puff intervals, it is likely that there is not adequate time for the cigarette to smolder through the region of depleted nicotine prior to the next puff. This is likely to be the case for the very short interpuft interval associated with the highest yield data values with 35 cc puffs. Under static burn conditions, a cigarette smolders approximately 5 mm per minute (PM USA unpublished results; similar results are given in 55). Following a puff, a cigarette resumes visible smoldering within about 15 to 20 s (56, 57). So, for very long puff intervals the cigarette is likely to smolder beyond the region of maximum nicotine concentration prior to the next puff. This was likely to be the case for each of the data points with "tar" yield below 10 mg and possibly for some of the 55 and 70 cc puff volume points above 10 mg "tar" yield. If the concentra-

tion of nicotine in the vicinity of the puff is less, it would be expected that the nicotine yield would be somewhat lower at the same "tar" yield, consistent with the pattern seen in Figure 4.

3.2 Refinements to the linear relationship between CF nicotine and "tar" yields

As noted above, most linear regressions of nicotine and "tar" yields result in a positive intercept. Equation [1] and similar regression equations are not consistent with the low CF or ISO "tar" yield data, since the low machine-yield cigarettes consistently have nicotine yields below the regression line. Since the tobacco blends used in very low yield products often have somewhat higher nicotine concentration, the low yield points would be expected to be above, not below the regression line, if the relationship were truly linear. Additionally the non-zero intercept in most of these equations implies, implausibly, nicotine yield approaching a positive value as the "tar" yield approaches zero.

Due to the low yield products falling below the regression line, the magnitude of the intercept varies depending on the manner in which the line is estimated and, in particular, on the relative weight given to the data points at very low "tar" yield. Equation [1] is estimated using 1/"tar" weighted regression which weights the low yield products more heavily than the higher yield products and, correspondingly, results in a smaller intercept. An unweighted regression using the same data gives an intercept of 0.15, almost twice that seen in equation [1].

In a recent manuscript ST. CHARLES *et al.* (42) argued for a linear relationship with a positive intercept as being the *correct* model, not just a convenient and simple approximation. If one fits a linear equation using the data given for the eight "high alkaloid" products in Table 1 of ST. CHARLES *et al.* (42), an intercept of 0.051 results and the regression has a root mean squared error of 0.024. Though the linear fit to these data from ST. CHARLES *et al.* (42) has

a very high R^2 , a power law fit, going through zero, as described below, is better still with a root mean square error of 0.011, less than half that of the linear fit.

ST. CHARLES *et al.* (42) rationalized the seemingly implausible positive intercept with the observation that sometimes negative "tar" yields can be observed. When an inherently positive quantity is calculated by subtraction, it is possible to obtain negative calculated values. Total particulate matter (TPM) is intended to be the particulate phase yield of a cigarette and its calculation can be thought of as the per cigarette weight difference in the Cambridge filter pad before and after smoking. For very low yield products, water already present on the Cambridge filter pad prior to smoking can be driven off during smoking, resulting in a negative calculated TPM, and ultimately to a negative calculated "tar". Difficulties in the measurement of very low yields can also result from analytical variability in the determination of water on the Cambridge pad and variation in the determination of weight (58). Though a negative TPM or "tar" yield is not physically meaningful, we understand that it can happen analytically when a value is calculated by subtraction. More generally, we recognize the

difficulties inherent in measuring very low smoke yields. Nonetheless, as we show below, a non-linear equation with a zero intercept better fits the available data in addition to being more physically plausible.

Some researchers have proposed non-linear relationships between MS smoke nicotine and "tar" yields for improved fit of the data. ROEMER *et al.* (59) used a power function to fit nicotine yield as a function of "tar" yield under ISO conditions, and the same functional form was utilized in COUNTS *et al.* (7). Fitting a power function to the data used to generate equation [1] gives

$$\text{Nicotine} = 0.121 \times (\text{"tar"})^{0.811} \quad [2]$$

The weighted R^2 for this model is 0.966. As found here, the value of the exponent is generally estimated to be in the vicinity of 0.8, consistent with the observation that the relationship between "tar" and nicotine is concave down. After excluding the low alkaloid "outlier" points from the market samples shown earlier, Figure 5 shows the market sample data points together with equations [1] and [2].

Figure 5. Market samples from 1967 to 2008 excluding 215 "outlier" points. Equations [1] and [2] are shown for comparison. Both fits were calculated excluding 215 "outlier" points.

Table 3. R^2 values for linear and power function models used to predict CF nicotine using data for U.S. commercial cigarettes. The regressions are weighted using "tar"⁻¹ as the weighting factor.

Independent variable	R^2 for linear fit			
	1981	1992	1995	1996
CF "tar"	0.973	0.964	0.955	0.965
CF "tar" × concentration of nicotine in tobacco	0.989	0.964	0.973	0.979
CF "tar" × weight of nicotine in tobacco	0.972	0.932	0.948	0.958
R^2 for power function fit				
CF "tar"	0.991	0.984	0.979	0.985
CF "tar" × concentration of nicotine in tobacco	0.997	0.984	0.993	0.995
CF "tar" × weight of nicotine in tobacco	0.993	0.975	0.988	0.992

We see that the power law curve better captures the low yield behavior and overall has a better correlation. It is also consistent with the non-constancy in the "tar"/nicotine ratio discussed in Section 3.4. However, being simply an empirical fit to the data, it should not be extrapolated outside the range used to estimate the equation.

Though the correlations using "tar" yield alone as the predictor variable are generally quite good, there is still product-to-product variation around the regression lines, as can be seen in Figure 1 and other products that appear to not fit the relationship. Not surprisingly, it has been found that information related to the nicotine content of the cigarette filler often helps to explain portions of that variation (31, 42). However, it is somewhat uncommon to have filler nicotine information in conjunction with "tar" and nicotine yields. So we merged historical data for four years combining CF "tar" and nicotine yield data with tobacco filler nicotine data available from internal testing conducted at PM USA. The data sets represent a broad picture of the 1981, 1992, 1995 and 1996 U.S. commercial cigarettes.

Both MORTON and LAFFOON (31) and ST. CHARLES *et al.* (42) used the concentration of nicotine in the cigarette filler in conjunction with the "tar" yield of the cigarette to help explain the nicotine yield. COUNTS *et al.* (7) used a similar model to explain nitrosamine yields. However COUNTS *et al.* (6) used the total amount of the nitrosamine in the cigarette to aid in the estimation of the corresponding nitrosamine in the smoke. The authors have found many experienced tobacco scientists who believe that the total amount of the constituent in the cigarette would better explain the corresponding smoke yield than would the concentration. For those reasons we explicitly compare the two ways of expressing the cigarette nicotine content, concentration (e.g., mg of nicotine per gram dry weight of tobacco) and amount (e.g., mg per cigarette).

Table 3 reports the proportion of the variance of CF nicotine yield explained by six alternative predictors. Three are linear functions of CF "tar", of CF "tar" times the concentration of nicotine in the cigarette tobacco, and of CF "tar" times the weight of nicotine in the cigarette tobacco. Three are power functions using the same x-variables. Of course, analogous equations can be employed for machine-smoking methods other than the CF method. For reference, we include parameterized versions of equations [1] and [2] as well.

$$\text{MS smoke nicotine} = a + b \times \text{"tar"} \quad [1]$$

$$\text{MS smoke nicotine} = a \times \text{"tar"}^b \quad [2]$$

$$\text{MS smoke nicotine} = a + b \times \text{"tar"} \times \text{concentration of nicotine in tobacco} \quad [3]$$

$$\text{MS smoke nicotine} = a + b \times \text{"tar"} \times \text{weight of nicotine in tobacco} \quad [4]$$

$$\text{MS smoke nicotine} = a \times (\text{"tar"} \times \text{concentration of nicotine in tobacco})^b \quad [5]$$

$$\text{MS smoke nicotine} = a \times (\text{"tar"} \times \text{weight of nicotine in tobacco})^b \quad [6]$$

All the regressions shown in Table 3 use a regression weighting factor of "tar"⁻¹. In all the linear functions "a" and "b" represent the intercept and slope, respectively. In the power functions equations [2], [5] and [6], there is no intercept, "a" is a scaling factor, "b" is the exponent, and

the parameters are fitted using non-linear regression, employing SAS/STAT® Version 9.1 (60).

Greater than 95% of the variance in the CF nicotine and "tar" data is explained with a linear fit considering "tar" alone. Even so, in each case, the fit improves substantially when non-linearity is taken into account with a power function. It is informative to examine the unexplained variance, $1 - R^2$, which is often reduced by a factor of more than two. The unexplained variance is related to the prediction error associated with the regression equation. For example, using the 1981 data set, $1 - R^2$ changes from $1 - 0.973 = 0.027$ using a linear fit to $1 - 0.991 = 0.009$ using a power function fit. Using the variable "tar" $\times$ nicotine concentration in tobacco" generally improves the fit further (though makes no difference for the 1992 data) and always does better than using "tar" $\times$ weight of nicotine in tobacco", which often performs worse than "tar" alone.

Nicotine smoke yield under MDPH machine-smoking conditions and tobacco filler nicotine content are also measured for selected brand families for reporting to the Commonwealth of Massachusetts and the State of Texas. Nicotine machine-smoke yield has been reported since 1997 using the MDPH machine-smoking protocol. Moisture of the filler was also internally available for the years 1998 – 2010 and was approximated for 1997 assuming 11.75% tobacco moisture, the average in 1998. That allowed the calculation of the dry weight nicotine concentration. In Table 4, the regression models for smoke nicotine for the PM USA Marlboro and Basic brands reported to Massachusetts and Texas are summarized using "tar" alone as an explanatory variable, using "tar" times tobacco dry weight nicotine concentration, and "tar" times nicotine amount. The regressions were calculated each year and overall.

In each year except 1997 the regressions are improved by including tobacco nicotine concentration over using "tar" yield alone. The differences in the regressions from year-to-year are statistically significant ($p < 0.0001$), even restricting the products in the regression to those common to all years, and likely reflect a combination of temporal variation in the analytical methods and year-to-year variation in tobaccos and other materials. However, the curvature to the relationship of "tar" and nicotine is less important in the range of "tar" yields produced by smoking under MDPH conditions and the curvature is not statistically significant in any of the years 1997–2010.

Nicotine concentration is likely to be more helpful beyond using "tar" yield alone the greater the product-to-product filler nicotine differences and the more accurately those differences are measured. Indeed if the differences in the filler nicotine concentrations from one product to another are minimal, the measurement error involved in determining the nicotine concentrations can make the predictions incorporating the measured nicotine concentration worse than using "tar" yield alone. This may be the explanation for why "tar" alone was a better predictor in 1997 than a model including tobacco filler nicotine. In 1997 PM USA testing was only required of products from the Marlboro brand family which had relatively similar tobacco blends. One of the reasons that the relationship between "tar" and nicotine yields is so good is because most of the cigarette products in the U.S. marketplace are similarly constructed

Table 4. Regression of MDPH machine-smoked nicotine yields against "tar" yield, against "tar" yield times tobacco nicotine concentration, and "tar" yield times nicotine amount for PM USA Marlboro and Basic cigarette products reported to MDPH or TX-DSHS. In 1997 nicotine reporting was required for the Marlboro brand family, but not the Basic brand family. Nicotine concentration is measured in dry weight percent and nicotine amount is measured in milligrams.

Year	"Tar" alone			"Tar"*nicotine concentration			"Tar"*nicotine amount		
	Int.	Slope	R ²	Int.	Slope	R ²	Int.	Slope	R ²
1997	0.124	0.065	98.3%	0.190	0.030	87.9%	0.611	0.0035	89.5%
1998	0.146	0.061	91.7%	0.143	0.032	96.9%	0.582	0.0034	93.7%
1999	0.169	0.062	95.0%	0.151	0.033	96.9%	0.557	0.0036	92.6%
2000	0.077	0.066	91.8%	0.095	0.032	98.5%	0.548	0.0033	94.4%
2001	0.127	0.065	89.8%	0.129	0.031	95.6%	0.422	0.0038	95.7%
2002	0.150	0.068	92.8%	0.127	0.032	96.9%	0.470	0.0038	94.2%
2003	0.156	0.068	94.0%	0.137	0.033	97.5%	0.504	0.0040	93.7%
2004	0.133	0.067	96.1%	0.137	0.033	97.7%	0.457	0.0042	95.1%
2005	0.114	0.065	92.0%	0.131	0.033	95.2%	0.437	0.0042	93.1%
2006	0.114	0.063	88.7%	0.136	0.032	95.1%	0.425	0.0041	90.5%
2007	0.093	0.063	82.8%	0.119	0.031	94.1%	0.409	0.0041	90.8%
2008	0.127	0.062	84.6%	0.091	0.031	95.8%	0.475	0.0037	89.6%
2009	0.137	0.062	85.1%	0.080	0.032	94.6%	0.480	0.0039	90.6%
2010	0.060	0.067	79.6%	0.134	0.033	96.1%	0.420	0.0044	92.9%
Overall	0.141	0.064	86.2%	0.144	0.032	93.9%	0.513	0.0038	89.4%

"American Blend" cigarettes. If marketplace blends were more different from one another, the relationship between "tar" and nicotine would be much looser.

As noted above, some researchers have used weight of the associated tobacco constituent to aid in the prediction or explanation of the corresponding smoke constituent. More commonly the concentration of the constituent has been used. The results in Tables 3 and 4 indicate that concentration is preferable to weight. The next example illustrates that, though preferable, nicotine concentration even in conjunction with "tar" yield is not complete.

It is commonplace within a brand family to have product pairs of differing length, such as a "king size" and a "100's," with the same tobacco blend and similar "tar" yields. In this case, there is typically more cigarette filler in the longer cigarette, and, therefore, more total nicotine. If the products use the same filler, the nicotine concentrations will be the same, and, if nicotine concentration together with "tar" yield were the complete explanation of the nicotine yield, then one would expect the nicotine yields to be the same if the "tar" yields are the same.

Figure 6. A comparison between the CF nicotine yields of a King Size and 100's cigarettes. The two products have the same tobacco blend and similar "tar" yields. The regression lines are used to adjust for the small "tar" yield differences using an analysis of covariance. The 4% difference in nicotine yield is much smaller than the 19% weight difference, but is statistically significant ($p < 0.0001$).

To illustrate, two years of PM USA internal production monitoring data are examined for a commercial king size and 100 mm cigarette. The two products were both smoked for CF "tar" and nicotine 65 times over the two year time period. The tobacco blend and thus the nicotine concentrations were the same for the two products. By target weight, the 100 mm cigarette had about 19% more tobacco and therefore about 19% more total nicotine in the tobacco.

Over the two year period there would be variation in the tobaccos and other materials and long-term analytical variation in the determination of "tar" and nicotine yields. However, the two products were sampled and tested at the same time points, so tobacco and analytical method variation are balanced between the two products. When looking for subtle differences, it is very important that product differences not be confounded with temporal or other effects and maintaining balance in those factors achieves that goal.

The data are graphed in Figure 6, and, when adjusted for the slight CF "tar" yield differences using "tar" as a covariate in the comparison, the CF nicotine yields were 0.86 mg/cig and 0.83 mg/cig for the 100 mm and the king size cigarette, respectively. The nicotine yield difference is much less than the 19% weight difference, but is still statistically significantly different from zero ($p < 0.0001$). This is consistent with the observation above that concentration of nicotine in the cigarette blend is more effective than amount of nicotine in the cigarette in explaining smoke nicotine yields. However it is also a reminder that equations such as [3] or [5] are just convenient empirical approximations and not complete explanations. Though not shown here, we have examined the phenomenon over several product pairs and several years and the phenomenon of longer cigarettes resulting in higher nicotine yields (holding "tar" yield and tobacco blend constant) has been found consistently.

4. THE "TAR"-TO-NICOTINE RATIO

The ratio of CF "tar" to nicotine is graphed in Figure 7 for the 2008 U.S. commercial cigarettes and the ratio is seen to increase with "tar" yield. The relationship shown in Figure 7 is typical of that found for the largely American blend U.S. commercial cigarette market in other years. This phenomenon has long been known and its potential impact on smoker exposure was discussed in GORI and LYNCH (61).

The non-constant "tar" to nicotine ratio is consistent with any number of "tar" and nicotine relationships. For example, using a relationship similar to that shown in equation [2] gives

$$\text{"Tar"}/\text{nicotine} = \text{"tar"}/(0.12 \times \text{"tar"}^{0.81}) = \text{"tar"}^{0.19}/0.12$$

which is an increasing function of "tar". A similar power law relationship was found when the nicotine concentration of the tobacco filler was incorporated.

The reason both for the non-linearity of the "tar" and nicotine relationship and the non-constancy of the "tar" to nicotine ratio may relate, among other potential factors, to nicotine's eluting more readily from the cigarette filter or the tobacco itself than most other particulate phase compounds as shown in CURRAN and KIEFER (62) and discussed in NORMAN (63). This may have a proportionately greater effect with lower yield or longer cigarettes.

Another possible explanation could be the effect of ventilation. NORMAN (64) showed that ventilation reduces cigarette nicotine yield proportionately less than "tar" yield. Low yield cigarettes typically have high ventilation. Similarly for a 100 mm cigarette to have a comparable "tar" yield to that of a king size cigarette, it typically has a higher ventilation. In the example shown in Figure 6, the ventilation of the 100 mm cigarette was 28% and the king size ventilation was 23%.

Figure 7. Relationship between the ratio of "tar" to nicotine versus "tar" for 2008 U.S. commercial cigarettes from Market Sample #51 using the CF machine-smoking method. The Eclipse cigarettes were excluded from the graph as outliers.

5. SUMMARY AND CONCLUSIONS

Machine smoking methods are incorporated in regulatory requirements in the U.S., Canada, and around the world, and have served for decades as useful tools to investigate the mechanisms of tobacco smoke formation and to evaluate the effect of ingredients and cigarette design on smoke formation and MS smoke yields.

For multiple data sets comprising commercial cigarettes from 1967–2010 and CF, ISO, MDPH, and HC smoking regimens, we find that the data are typically well fit by the linear relationship given by equation [1]. However, we did find a number of refinements to that model and circumstances under which it may not apply:

- We found that very low yield products tend to have ISO or CF yields below the regression line. A power law fit to the data is a simple approach accounting for this non-linearity.
- Denicotinized or otherwise reduced nicotine products fall below the regression line.
- Very short or very long intervals between puffs may give results below equation [1].
- Utilizing the nicotine concentration in conjunction with the "tar" yield improves the prediction of the corresponding nicotine yields. We did illustrate, however, that nicotine concentration alone, even in conjunction with the "tar" yield, does not completely account for the corresponding nicotine yield. For example, with the same tobacco blend and the same "tar" yield, a 100 mm cigarette showed a roughly 4% higher nicotine yield than its king size counterpart.
- The ratio of "tar" to nicotine yield is an increasing function of "tar" yield. The power law equation is consistent with the observed non-constant "tar" to nicotine ratio.

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