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Fabrics for Testing the Ignition Propensity of Cigarettes[†]

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This paper reports an analysis of data from a study conducted by the cigarette industry to determine whether the fabrics used in a measurement method for cigarette ignition propensity reasonably represent the ignition behaviour of actual upholstery fabrics. A 'consistency score' is defined to evaluate objectively the relative agreement of ignition test results on various test fabrics compared with the cotton duck fabrics used in the measurement method. Particular attention is paid to those cases where the cigarettes show statistically significant differences by the chi-squared test. This analysis finds that the aggregated set of 79 industry fabrics ranks the four test cigarettes in the same order as do the three cotton duck fabrics in the measurement method. Thus, to the extent that the industry set is representative of those fabrics used in upholstery, it would be proper to use the three test fabrics as surrogates for the purpose of determining the relative ignition propensity of a cigarette. The analysis does identify six to ten fabrics that would be expected to show persistent reversals compared to the aggregate ordering; however, three-fourths of the fabrics rank the cigarettes consistently with the cotton duck fabrics.

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INTRODUCTION

Cigarette ignition of soft furnishings (upholstered furniture and bedding) has long been the leading cause of fire deaths in the United States.[1] In the 1970s, extensive effort was directed at increasing the resistance of mattresses and upholstered furniture to cigarette ignition, resulting in test methods and regulations for those products. Later, Federal legislation in 1984 and 1990 directed research efforts to determine whether the potency of the cigarette as an ignition source could be moderated. In the final report to the Congress under the Cigarette Safety Act of 1984,[2] the investigators reported that it was possible to make cigarettes with reduced ignition propensity and identified several cigarette characteristics whose adjustment could have a significant effect. They also found that ignition results from bench-scale mock-up testing agreed very well with corresponding data from experiments with full-size chairs made of the same fabrics and padding materials. However, they identified a need for a standard test method for cigarette performance that was not subject to the high variability in the fabrics and paddings used in those mockups.

Under the Fire Safe Cigarette Act of 1990, two methods for measuring cigarette ignition propensity were developed:[3,4]

- The *Mock-up Ignition Test Method* uses three types of simulated upholstery cushions, each with a different cigarette ignition susceptibility. Each assembly (substrate) consists of a top layer of one of three weights of cotton duck fabric; a cushion of a polyurethane foam, and, in the least susceptible substrate, a thin layer of thermoplastic film in between. The performance measure is whether or not the mock-up is ignited by the cigarette placed on it.
- The *Cigarette Extinction Test Method* replaces the more complex substrate with 3, 10 or 15 layers of standard cellulosic filter paper. The performance measure is whether the cigarette extinguishes before burning its full length, i.e. whether the substrate absorbs enough heat from the cigarette coal to extinguish the cigarette.

Both of these test methods were subjected to interlaboratory evaluation by nine participating organizations. The results demonstrated that both methods had values of (intralaboratory) repeatability and (interlaboratory) reproducibility comparable or superior to other standard fire tests.[3]

Subsequently, the Mock-up Ignition Method has been criticized for its use of test fabrics (cotton ducks) considered to be unrepresentative of fabrics used in the manufacture of upholstered furniture.[5] A joint venture of cigarette industry firms purchased approximately 500 upholstery fabrics and tested them using a mock-up test apparatus and procedure different form the Mock-up Ignition Method.[6] They concluded that most of the fabrics ranked cigarettes differently from the cotton duck fabrics used in the mock-up ignition test method.

The following statistical analysis of the data from Reference 5 was undertaken to investigate the strength of this conclusion. We approached this analysis with some

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uneasiness because there are many things about the conduct of the industry experiments that are not known. In particular, the conclusions from the statistical analysis are sensitive to whether or not the tests were run in a balanced design with respect to significant test conditions. For example, the interlaboratory evaluation conducted under the Fire Safe Cigarette Act of 1990 showed some evidence of ignition effects due to operator and to time-of-day (morning versus afternoon). If the experimental design for the present data were unbalanced, then some factors such as differences between operators, or between test chambers, or due to time-of-day, or to position within the test chamber or to other environmental factors would be confounded with cigarette and/or fabric differences. Such confounding would cause unresolvable ambiguity in interpreting the results. In the absence of complete information on the experiment design, our analysis in effect rests on the implicit assumption that the test conditions were completely uniform throughout, and therefore that observed differences in the results can be interpreted solely in terms of the fabric and cigarette types, plus (binomial) random variation.

INDUSTRY DATA

Aspects of the industry study are reported in References 5 and 6. Samples of 500 fabrics were obtained from shops in the Greensboro, NC, area with the goal of surveying upholstery fabrics that are in wide use and representative of materials commonly found in residences. Each fabric was tested for ignitability with an experimental cigarette of high ignition propensity. All of the ignitable fabrics were either 100%, or nearly 100%, cellulosic in fibre content. In Reference 6, it is stated that 145 of the 500 fabrics were ignitable by the test cigarette, and of these, 127 were 100% cellulosic. A copy of these data (Set 1) was provided to the Consumer Product Safety Commission in 1993. Reference 5 states that, among the 500 fabrics tested, there were 113 cellulosic fabrics that gave ignitions with the same test cigarette. A copy of these data (Set 2) was provided to the National Institute of Standards and Technology in 1994 by an official in the cigarette industry.[7]

The industry group then selected four different experimental cigarettes and tested each on the ignitable cellulosic fabrics. The test apparatus and procedure are described in Reference 6. Six replicate tests were performed for each of the four cigarettes on each of the 113 fabrics. For some fabrics, all four cigarettes either ignited the substrates all of the time or none of the time. Table 1 summarizes the two industry reports of their ignition data. The source of the second set of data has stated that Set 2 should be used for further analyses. Our comparison of the two data sets indicates that the fabrics in Set 2 comprise a subset of those in Set 1.

The authors of Reference 5 assigned each of the 113 ignitable fabrics to one of three groupings—'Duck-Like', 'Duck-Unlike', or 'Balance'— based on the fabric weight, porosity and content of sodium and potassium ions. The 'Duck-Like' grouping consisted of 21 fabrics that contained high levels of alkali metal ions, coupled with high weight and below average porosity. The 'Duck-Unlike' grouping included those 24 fabrics containing relatively low levels of alkali metal ions and having a low weight and no restrictions on porosity. The 'Balance' group contained the remaining 68 fabrics.

Table 1. Summary of the two industry data sets

	Data set 1	Data set 2
Total number of fabrics represented	145	113
Number of fabrics with at least one ignition and one non-ignition for test cigarettes	101	79

The industry data show that the 'Duck-Like' fabrics ranked the ignition propensities of the four test cigarettes in the same order as did the cotton ducks. By contrast, the larger set of 'Duck-Unlike' fabrics, in aggregate, ranked the same four cigarettes quite differently. The authors concluded that the mock-up ignition test method 'provides a measure of cigarette propensities that is not representative of those found on commercial fabrics' and 'its adoption as a definitive test for ranking cigarettes can lead to erroneous conclusions.' (Reference 5, pp. 81, 82)

The physical interpretation of this result is uncertain. Both groupings of fabrics were predominantly cellulosic; thus the fuel chemistry is similar. Most of the oxygen needed for ignition is available from the air above the fabric;[8] an industry analysis of the permeability of the fabric weave to air has shown it to be of secondary effect on the ignition process.[9]

The following analysis of the industry 500 fabric study is not based on any groupings of the fabrics, but focuses directly on the ignition propensity results. This analysis was undertaken to obtain an independent evaluation of the extent to which fabrics show inconsistent ignition behaviour in these data.

THIS STUDY

The purpose of this analysis was to investigate the relationships among the reported ignition propensities of four selected cigarette types (designated as 528, 525, 508, and 506) as measured across the wide variety of fabrics in the industry 500 fabric study. In particular, the relative ignition propensities were measured in terms of the number of ignitions out of six trials of each cigarette type on each fabric. The industry data set contains results for 113 different fabrics. Of these, the results for 34 fabrics did not produce cigarette rankings because in these cases all four cigarettes either ignited the fabric 100% of the time (23 fabrics) or 0% of the time (11 fabrics). Thus, we consider a reduced data set consisting of the outcomes (number of ignitions in 6 trials) from 316 tests (4 cigarettes on each of the remaining 79 fabrics). This reduced data set is shown in Table 2.

Testing for between-cigarette differences

To avoid trying to interpret differences in ignitions that are not statistically significant, we computed, for each fabric, the chi-squared (χ^2) statistic appropriate for testing the hypothesis that the ignition propensities of the four cigarettes are equal. Since the experiments were based on a small number of tests (6 for each cigarette and fabric combination), the differences in the observed ignitions were not statistically significant for about half of the fabrics. However, the χ^2 test did indicate a significant difference between cigarettes (at the 5% level) for 41 of the 79 fabrics. The results shown in Table 2 are listed in decreasing order of the χ^2 statistic, so that fabrics showing the nost significant differences between the four cigarettes appear near the top of the table. Fabrics for which the cigarettes differ significantly at the 5% level of significance (i.e. $\chi^2 > 7.81$) are marked with a single asterisk (*). Those which also detect differences at the 1% level of significance (i.e. $\chi^2 > 11.34$) have a double asterisk (**).

If there were no real differences in ignition propensity among the four test cigarettes, one could expect that purely random variation would cause the χ^2 test to produce 'false positive' conclusions (that significant differences exist at the 5% level of significance) for about 5% of the 79 fabrics (i.e. four fabrics). The fact that 41 such cases were observed implies that real differences do exist among the cigarettes, and that this conclusion is not compromised by statistical considerations related to multiple comparisons or multiple testing. Similar conclusions follow from the results of the χ^2 test at the 1% level of significance. Under the null hypothesis that these four test cigarettes are truly equal, only one fabric (i.e. 1% of 79) would be expected to yield $\chi^2 > 11.34$, compared with 28 which were observed. Thus, it is reasonable to proceed with the data analysis on the assumption that these four test cigarettes are showing real differences in ignition propensity and not just random variation.

Testing for statistical interaction

Interaction is present in a statistical model whenever the difference (in some metric) in the ignitability of two cigarettes changes depending on the fabric used. Two major types of interactions are possible. In the first, the rank ordering of the cigarettes' ignition propensities is the same on all fabrics, but the magnitude of the differences varies. An example of this would occur if cigarette type A is more likely than cigarette type B to ignite all fabrics, but type A is twice as likely as type B to ignite fabric X and 3 times as likely to ignite fabric Y. The second type of interaction involves 'reversals'. A reversal would be indicated if, for example, cigarettes of type A consistently showed higher ignitability than type B on some fabrics, but that order was reversed, with type A lower than type B, on other fabrics. For purposes of this investigation, we will consider that an interaction is important only if it affects the direction, and not just the magnitude, of a difference in ignitability.

It is a straightforward matter to conduct a statistical test for general interaction between fabric type and cigarette type based on the data in Table 2. The result of performing such a test* is that the null hypothesis of zero interaction is strongly rejected ($p < 0.001$). Thus, we conclude some type of interaction between fabric type and cigarette type is clearly indicated by the data in Table 2.

Identifying 'reversals'

Given the conclusion that some type of interaction exists between cigarette type and fabric type, the next issue is to distinguish whether the cigarettes and fabrics indicate a reversal phenomenon. While there is no standard statistical approach to address this specific type of question, we have used a simple and practical approach that seems adequate for present purposes.

To identify easily and objectively which fabrics show evidence of a reversal in the behaviour of the four cigarettes, we found it convenient to define a numerical criterion called the 'consistency' score for each fabric. This consistency score is defined so that it takes positive values when the numbers of ignitions for the four test cigarettes are generally in the same order as the total ignitions for all tests, which was $525 > 528 > 508 > 506$. For brevity, we refer to this ordering as the 'aggregate ordering'. The consistency score takes negative values when the results tend to be reversed, compared to the aggregate ordering. For each fabric, the value of the score is calculated as follows: select two cigarettes from the four tested, and compute the difference in the number of ignitions, carrying out the subtraction according to the aggregate ordering. Then sum these differences over all such pairs. The result is as follows:

$$\begin{aligned}\text{Consistency} = &(X_{525} - X_{528}) + (X_{525} - X_{508})\\ &+ (X_{525} - X_{506}) + (X_{528} - X_{508})\\ &+ (X_{528} - X_{506}) + (X_{508} - X_{506})\end{aligned}$$

where, e.g. X_{525} is the number of ignitions for cigarette 525 on a given fabric. This definition of a consistency score coincides with the linear component of the trend in the ignitions which would be estimated using orthogonal polynomials.[12] This means that if the four cigarettes are assigned ranks in the order (525, 528, 508, 506), and if numbers of ignitions are fit by regression as a linear function of the ranks, then the slope of that function is the consistency score.

'Reversals' and statistical significance

Study of the results in Table 2 yields the following summary of the relation between the consistency scores and the χ^2 values.

Table 3 shows that 77% of the fabrics (61 out of 79) indicate general agreement with the aggregate ordering shown at the bottom of Table 2, which is

$$525 > 528 > 508 > 506$$

In the aggregate ordering, the total ignitions for cigarettes 525 and 528 were nearly equal (292 and 319 out of 474, or 62 and 67%). This outcome is quite similar to the ordering of these same cigarettes tested on the cotton

* A simple test for interaction was conducted by using analysis of variance (ANOVA) on the ignition counts in Table 2, after first transforming the raw counts by the Freeman–Tukey version of the angular transformation.[10] In the resulting two-way table with one observation per cell, the test for interaction was performed using Tukey's one-degree-of-freedom test for additivity.[11]

Table 2. Summary of results for 79 fabrics yielding at least one ignition and one non-ignition with test cigarettes

Fabric number	Number of ignitions in 6 trials[7]				Consistency score	χ^2 test of significance	Fabric grouping[7]
	Cig. 528	Cig. 525	Cig. 508	Cig. 506			
140	6	6	0	0	−24	24.0**	Duck-Like
147	6	6	0	0	24	24.0**	Duck-Like
148	6	6	5	0	19	20.0**	Balance
24	0	6	1	0	17	20.0**	Balance
68	6	6	2	0	22	18.5**	Duck-Like
155	6	6	4	0	20	18.0**	Balance
283	6	6	4	0	20	18.0**	Duck-Like
64	0	0	6	2	−12	18.0**	Balance
34	6	6	3	0	21	17.6**	Balance
42	6	6	3	0	21	17.6**	Duck-Like
6	1	0	6	5	−20	17.3**	Duck-Unlike
40	6	5	1	0	20	17.3**	Duck-Like
66	6	6	5	1	16	15.1**	Duck-Like
26	1	5	6	6	−8	15.1**	Balance
37	6	6	2	1	19	14.8**	Duck-Like
57	6	2	1	0	11	14.8**	Balance
38	3	6	0	1	18	14.4**	Balance
19	6	6	6	2	12	14.4**	Balance
414	0	0	0	4	−12	14.4**	Balance
1	6	6	4	1	17	13.5**	Duck-Like
78	6	6	4	1	17	13.5**	Balance
150	2	5	0	0	17	13.5**	Balance
70	6	6	3	1	18	13.5**	Duck-Like
407	3	2	0	6	−9	12.6**	Duck-Unlike
74	6	6	2	2	16	12.0**	Duck-Like
239	6	6	2	2	16	12.0**	Balance
264	1	0	5	1	−7	11.9**	Duck-Unlike
7	4	5	0	1	16	11.7**	Balance
349	0	4	0	1	9	10.9*	Balance
399	1	0	5	2	−10	10.5*	Duck-Unlike
287	0	1	5	2	−8	10.5*	Duck-Unlike
131	3	5	0	1	15	10.5*	Duck-Like
105	6	6	3	2	15	10.3*	Duck-Like
46	6	6	6	3	9	10.3*	Duck-Like
87	6	6	6	3	9	10.3*	Duck-Like
107	6	6	6	3	9	10.3*	Duck-Unlike
103	3	0	0	0	3	10.3*	Balance
77	0	0	4	2	−10	9.8*	Duck-Unlike
135	1	6	3	3	7	8.6*	Duck-Unlike
302	1	4	1	0	12	8.0*	Duck-Like
401	0	1	4	1	−4	8.0*	Duck-Unlike
49	1	5	2	1	11	7.6	Duck-Unlike
234	2	4	6	2	2	7.5	Duck-Unlike
276	4	4	3	0	13	7.2	Balance
499	6	6	5	3	10	7.2	Duck-Unlike
447	2	1	4	5	−14	6.7	Duck-Unlike
136	6	6	6	4	6	6.5	Duck-Unlike
286	0	0	0	2	−6	6.5	Balance
445	6	6	6	4	6	6.5	Balance
146	2	0	0	0	2	6.5	Duck-Like
110	2	5	1	2	10	6.2	Duck-Unlike
151	4	2	2	0	8	6.0	Balance
120	3	5	4	1	11	5.9	Duck-Like
289	3	3	6	5	−9	5.4	Duck-Unlike
67	5	5	3	2	11	4.8	Duck-Like
356	2	0	0	2	−4	4.8	Balance
65	0	1	3	1	−3	4.8	Balance
86	6	6	5	4	7	4.2	Duck-Like
247	4	3	4	6	−9	3.8	Balance
108	3	4	2	1	10	3.4	Balance
389	4	3	3	1	7	3.2	Balance
9	6	6	6	5	3	3.1	Balance
83	6	6	6	5	3	3.1	Balance

Table 2. Continued

Fabric number	Number of ignitions in 6 trials[7] Cig. 528	Cig. 525	Cig. 508	Cig. 506	Consistency score	χ^2 test of significance	Fabric grouping[7]
85	6	6	6	5	3	3.1	Balance
90	6	6	6	5	3	3.1	Balance
127	6	6	6	5	3	3.1	Balance
129	6	6	6	5	3	3.1	Duck-Like
238	6	6	6	5	3	3.1	Balance
295	6	6	6	5	3	3.1	Balance
341	6	6	6	5	3	3.1	Balance
426	0	1	0	0	3	3.1	Balance
260	0	0	1	0	−1	3.1	Balance
293	4	5	6	4	1	2.8	Duck-Unlike
252	6	5	5	4	4	2.4	Balance
44	1	2	3	1	1	2.2	Duck-Unlike
391	1	0	1	0	0	2.2	Balance
50	1	0	1	1	−3	1.1	Duck-Unlike
169	1	2	1	1	3	0.8	Balance
4	3	4	4	3	2	0.7	Duck-Unlike
Totals	292	319	259	165			

* Denotes values of χ^2 that are statistically significant at the 5% level of significance.
** Denotes values of χ^2 that are statistically significant at the 1% level of significance.

duck fabrics, which was reported in Reference 5 as

$$525 = 528 > 508 > 506$$

with cigarettes 525 and 528 tied. We refer to this as the 'cotton duck ordering' for brevity. In view of the tie in the cotton duck ordering, the consistency score defined above, which measures consistency of an individual fabric with the aggregate ordering, should be modified to measure consistency with the cotton duck ordering. This can be achieved by simply eliminating the difference between cigarettes 525 and 528 from the original definition, yielding

Modified consistency score

$$= (X_{525} - X_{508}) + (X_{525} - X_{506}) + (X_{528} - X_{508}) + (X_{528} - X_{506}) + (X_{508} - X_{506})$$

For the data in Table 2, this modified consistency score and original consistency score agree in that they both produce negative values (indicating reversals) for exactly the same subset of fabrics. That is, the two versions of the consistency score both classify the fabrics in the same way with respect to reversals and non-reversals. Therefore, the summary shown in Table 3 applies equally to the aggregate ordering and to the cotton duck ordering.

Thus, about three-fourths of the fabrics showing differences in the cigarette industry 500 fabric study rank these four cigarettes in general agreement with the ordering obtained on cotton duck fabrics in the mock-up ignition test method. Interestingly, as Table 3 shows, this fraction holds quite consistently whether one considers all fabrics, or only the subset of fabrics showing significant differences in ignitions at the 5% level of significance (those with $\chi^2 > 7.81$), or only those significant at the 1% level (those with $\chi^2 > 11.34$). The remaining fabrics, which amount to about one-fourth of each of the groups in Table 3, show evidence of reversal in the observed patterns of ignitions.

The degree of consistency or inconsistency with the aggregate ordering is further examined in Fig. 1. The figure displays a histogram of the positive consistency scores (shown in the top portion of the plot) along with a histogram of the negative scores. (shown inverted in the bottom portion of the plot.) Recall that positive consistency scores indicate general agreement with the results for cotton duck, and negative scores indicate reversals. The 41 fabrics that significantly discriminate among the four test cigarettes at the 5% level of significance are represented by filled squares.

Three notable patterns in the figure are (1) there are substantially more fabrics with positive consistency

Table 3. Relation of consistency scores and significant χ^2 values from Table 2

	Consistency scores that do not indicate reversals: Number	Percent	Consistency scores that indicate reversals: Number	Percent	Total fabrics
All fabrics	61	77%	18	23%	79
Fabrics with $\chi^2 > 7.81$ ($p < 0.05$)	31	76%	10	24%	41
Fabrics with $\chi^2 > 11.34$ ($p < 0.01$)	22	79%	6	21%	28

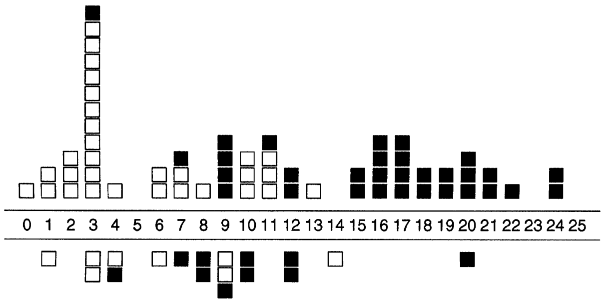

Figure 1. Consistency scores for the 79 fabrics in Table 2.

scores than negative scores; (2) the positive scores tend to be larger in magnitude than the negative ones; and (3) considering only the fabrics that significantly discriminate among the test cigarettes, the first two patterns are still evident.

CONCLUSIONS

As mentioned at the end of the Introduction, meaningful conclusions from this data analysis depend implicitly on details about the statistical design of the industry study that are not known to us. However, on the assumption that those unknowns do not affect the results of this analysis, we can summarize the results as follows:

- These four cigarettes differ in ignition propensity. Therefore, these test cigarettes constitute a set that can reasonably be used to evaluate the equivalency of fabrics.
- The aggregated set of 79 fabrics ranked the four cigarettes in the same order as did the cotton duck fabrics. Thus, to the extent that this set of fabrics is representative of those used in soft furnishings, it would be proper to use the cotton ducks as surrogates for the purpose of determining the relative ignition propensity of a cigarette type. A recent, complementary analysis by Hirschler[13] arrives at the same conclusion.
- About three-fourths (61) of the 79 fabrics in Table 2 yield rankings of the test cigarettes that are consistent with the rankings observed using cotton duck fabrics.
- About 6–10 of the 79 fabrics in this study would be predicted to show persistent reversals, compared to the aggregate ordering, if extended testing of ignition behaviour were conducted. These are the fabrics showing statistically significant differences in ignition behaviour as well as negative consistency scores.

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