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TESTING THE ACCURACY, USEFULNESS, AND SIGNIFICANCE OF PROBABILISTIC CHOICE MODELS: AN INFORMATION THEORETIC APPROACH */

by

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ABSTRACT

Disaggregate demand models predict choice behavior on the level of the individual consumer. But testing predictions is difficult because while the models predict choice probabilities ($0<p<1$) they must be tested against observed (0,1) choice behavior. After reviewing the aggregate and disaggregate tests now in use, this paper derives an information theoretic test that provides complementary measures of "usefulness", "accuracy", and "significance". "Usefulness" compares the information provided by the model to the total entropy to measure the percent of uncertainty explained. It provides theoretic rigor and intuitive appeal to the commonly used likelihood ratio index and leads to extensions which address important practical problems. "Accuracy" is a new two-tailed normal test which determines whether the (0,1) observations are reasonable under the hypothesis that the model is a valid model. Finally, the information measure also leads to the standard chi-squared "significance" test to determine whether a null hypothesis can be rejected. Together the three-part disaggregate test provides insight to help model builders assess a probabilistic model's performance or to select a "best" model.

All tests depend on null hypotheses. This paper extends the information test to indicate the relationships among null hypotheses by allowing the model builder to test against successively more powerful hypotheses. For example, in a predictive logit model, one can quantify (1) the contribution due to knowing aggregate market shares, (2) the incremental contribution due to knowing choice set restrictions, and finally (3) the incremental contribution due the explanatory variables. Further extensions provide alternative "explainable uncertainty" measures for the case of consumer panels which observe frequency of choice rather than (0,1) choice behavior.

The tests and extensions are illustrated with empirical examples from transportation demand analysis and marketing research.

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1. INTRODUCTION

The design of successful products and services requires valid predictions of how consumers will respond to changes in product or service strategy. Recently in marketing research and in transportation planning, demand models have been developed which base their predictions on causal hypotheses which model the behavior of individual consumers (logit analysis, McFadden [19], probit analysis, Finney [3], discriminant analysis, Fisher [4], etc.). Because of their behavioral content and because of the rich, individual specific data on which these models are based, analysts expect these "disaggregate behavioral demand models" to provide accurate predictions of consumer behavior and to provide useful diagnostics which help understand the consumers' choice process. But how accurate are these models? This question, which must be answered to the satisfaction of both the analytic modeler and the marketing or transportation manager, is the subject of this paper.

Disaggregate models predict group response, e.g., the number of bus riders from zone to zone, by aggregating together predictions of how individual consumers behave (Koppelman [16]). But because of potential errors in modeling, in measurement, in estimation, and because of random influences on consumer behavior these models cannot predict with certainty. Instead for each individual, i, they predict choice probabilities. For example, in modeling choice among modes of transportation a model might predict the probability that a particular consumer will choose transit, the probability he will drive, the probability he will walk, and the probability he will not travel. The fundamental problem in testing is that while the models predict probabilities, they must be tested on observed events. In a given instance individual i either rides, drives, walks, or stays put! Suppose a model predicts that i will ride the bus with probability

.7 and i does ride the bus. To assess the validity of such a model a test must quantify how much "rightness" or "wrongness" there was in the prediction. Furthermore, if a model makes individual predictions, but for 1000 individuals, analysts need a test to indicate how well a model predicted and if necessary to select a "best" model.

2. EXISTING TESTS

The problem of testing predicted probabilities as observed events is not new and there are a number of tests now in use. Some of these tests, called aggregate tests, compare aggregate predictions, e.g., average probabilities, with aggregate statistics, e.g. market shares, while other tests, called disaggregate tests, compare individual probabilities with individual events. This section first reviews both types of tests and then discusses their relative merits.

Aggregate tests have strong intuitive appeal and are useful aids to communication between analysts and managers. Managers can internalize the meaning of these tests, compare the model to their prior beliefs, and assess the accuracy of a model in a way that can be readily communicated to others. For example, *first preference recovery*, r_1, which computes the percent of individuals that select their first preference alternative, is easy to understand and can be readily compared to chance recovery, r_c = 1/(number of alternatives), or market share recovery, $r_{ms} = \sum_j (ms_j^2)$ where ms_j = market share of product j. In most probabilistic models, maximum probabilities are substituted for first preference because choice probabilities are monotonic in preference.

Other useful aggregate tests compare predicted market shares, $\hat{ms}_j$, with observed market shares, ms_j. [$\hat{ms}_j = (1/n) \sum_i p_{ij}$, where p_{ij} is the predicted probability that i chooses j and n is the total number of individuals.] For example, *root mean square percent error* in predicted market shares, e_p, has been used by Koppelman [16] to compare aggregation methods for mode choice predictions in Washington, D.C. He reports errors in the range of 25-35%. In another example, Hauser and Urban [10] report that percent error was a better discriminator than first preference recovery between von Neumann-Morgenstern utility assessment and logit analysis (e_p=18% vs 36% while r_1=50% vs. 46%). Similar tests such as weighted percent error, mean absolute error, least square error, and weighted least square error have all been used with varying success. See Koppelman [16].

Disaggregate tests address the basic testing problem by comparing predictions and events on an individual level. These tests can discriminate between models which predict aggregate market shares well but miss the individual choice process and those which capture individual differences. For example, any logit choice model with J-1 choice specific constants (J = the number of alternatives) will predict aggregate market shares exactly on the "calibration" data, but different models within this class may be "better" than others. Disaggregate tests quantify the concept of "better".

A common test is the *log-likelihood chi-squared significance test* (Mood and Graybill [20]). In this test the probabilistic model is compared to a null model. If the null model can be formulated as a restriction (subset) on the parameters of the tested model then L = 2 log[likelihood ratio of tested model to null model] is χ^2 distributed with degrees of freedom equal to the difference in degrees of freedom between the tested model and the null model. In logit applications the most common null model is the equally likely model (all choice parameters set equal to zero) but some researchers use the market share proportional model (choice specific constants only) when a full set (J-1) of choice specific constants are used in the estimated model.

The chi-squared test can reject a null model, but it can not give an indication of how well a model predicts nor can it compare two models unless one model is a restriction of the other. The most common disaggregate test used to measure a model's predictive ability is the *likelihood ratio index* (McFadden [19]). This test, $\rho^2 = 1-L(X)/L_0$ where $L(X)$ is the log-likelihood of the tested model (explanatory variables X) and L_0 is the log-likelihood of the null model, acts like a pseudo-R^2 since $\rho^2 = 0$ when $L(X) = L_0$ and $\rho^2=1$ when the model predicts perfectly, otherwise $0 < \rho^2 < 1$. In related tests, Kendall [14] suggests a correlation coefficient similar to that for regression and Cragg [1] suggests a correlation-like coefficient. Stopher [25] uses the correlation ratio (Weatherburn [27], Neter and Maynes [21], Johnson and Leone [13]) to augment the correlation coefficient but his use requires that individuals be grouped. Results are extremely sensitive to the grouping.

Discussion: Although the aggregate tests are intuitive and aid communication between managers and analysts, they can be misleading. For example, a first preference recovery of 55% is usually good, but not in a market of two products. A recovery of 90% is usually good in a two-product market but not if one product has a market share of 95% (r_{ms} = 90.5%). Similarly, e_p is identically zero for the market share proportional null model, but $e_p > 0$ for most models which may be more realistic representations of the true choice process. (For example, most logit models without choice specific constants will not predict market shares exectly. But choice specific constants are often undesirable because they make it difficult to project a model from the "calibration" situation to a new situation. In particular if new products are introduced, there is no way to know the choice specific constant for the new product.) These restrictions on aggregate tests caution the analyst to use aggregate tests with great care. Furthermore, because aggregate tests do not address the fundamental problem of testing individual probabilities against observed events, they may not be able to discriminate between models to select the "best" model of individual choice behavior.

The disaggregate tests do address the fundamental testing problem. The chi-squared test can statistically reject properly formulated null hypotheses and the likelihood ratio index can give an R^2-like measure of the predictive ability of a probabilistic model. In many cases these tests nicely complement the aggregate tests. Disaggregate tests are not used alone because they are theoretically sensitive to the problem that $\lim_{p_{ij}\to 0} [\log p_{ij}] = -\infty$. Aggregate tests are not as sensitive to zero probabilities.

This battery of aggregate and disaggregate tests can address many problems in testing probabilistic models, but there are importance problems which this battery does not address. For example: (1) The likelihood ratio index behaves nicely at the limits $(\rho^2=0,\ \rho^2=1)$, but it does not have an intuitive interpretation between the limits. Managers need an intuitive interpretation that is naturally related to a measure of probabilistic uncertainty. (2) ρ^2 can be computed relative to any null hypothesis, L_0, but no deductive theory indicates whether that simple computation is the appropriate generalization for complex null hypotheses. (3) The choice of a null hypothesis is based on judgement. A good test should indicate which null hypothesis is best and indicate the relationship among null hypotheses. (4) The null hypothesis sets the lower bound for ρ^2, but $\rho^2=1$ may not be the appropriate upper bound. If individuals make repeated choices and if individuals do not always select the same alternative, then $\rho^2=1$ is not possible even in theory. (Perfect prediction would require different probabilities for different occasions. Such predictions are not possible without situational variables.) A theory based test should indicate how to incorporate upper bound information. Finally, (5) the chi-squared test can reject a null hypothesis but does not test the accuracy of predictions. A test of "accuracy", which can accept or reject the *tested* model, is necessary to complement the chi-squared test of "significance" and the ρ^2 test (or its generalization) of "usefulness".

These problems and others can be effectively resolved by considering probabilistic models as an information system where the predicted probabilities (or null hypotheses) represent the best information derived from the set of explanatory variables, X.

3. INFORMATION THEORY: AN INTERPRETABLE TEST OF MODEL USEFULNESS

Suppose there is a set of choice alternatives, $A=\{a_1,a_2,\ldots a_J\}$ and suppose there is a set of explanatory variables, X, which take on specific values, $\underline{X}_i$, each individual, i. Suppose that through some mathematical analysis, a conditional probability model, $p(a_j|\underline{X}_i)$, has been developed to estimate choice probabilities, $p_{ij} = p(a_j|\underline{X}_i)$, from the explanatory variables. Suppose that to test the model each individual's choice behavior, as represented by δ_{ij} , has been observed. ($\delta_{ij} = 1$ if i chooses j , $\delta_{ij} = 0$ otherwise.) This section will derive the information test for such a probabilistic model of consumer behavior. Later sections will extend the test to cases where the choice set varies and the number of choice occasions is greater than one.

The probability model can be viewed as an information system. In other words the "observable occurence," e.g. the attributes of the choice alternatives, provides information about "unobservable events," i.e., about the choice outcome. Thus a test uses the information measure, $I(a_j,\underline{X}_i)$, (Gallagher [5]) to quantify the information provided by $\underline{X}_i$. Formally:

$$I(a_j,\underline{X}_i) = \log \frac{p(a_j|\underline{X}_i)}{p(a_j)}$$

where $p(a_j)$ = the prior likelihood of the outcome, i.e. the event that a_j is chosen.

First observe that the information criteria provides managerially interpretable benchmarks. The first benchmark is the expected information provided by the model, $EI(A;X)$, where:

$$EI(A;X) = \sum_{\underline{X}_i \varepsilon X} \sum_j p(a_j,\underline{X}_i) \log \frac{p(a_j|\underline{X}_i)}{p(a_j)} \qquad \text{equation 1}$$

with $p(a_j,\underline{X}_i)$ the joint probability of an "observation" of $\underline{X}_i$ and an "event", a_j chosen.

Another benchmark is the total uncertainty in the system which is measured by the prior entropy, $H(A)$, where:

$$H(A) = -\sum_j p(a_j) \log p(a_j) \qquad \text{equation 2}$$

The prior entropy measures the uncertainty before "observing" $\underline{X}_i$. After observing $\underline{X}_i$ the uncertainty is reduced to the posterior entropy, $H(A|X)$, where

$$H(A|X) = -\sum_{\underline{X}_i \varepsilon X} \sum_j p(a_j,\underline{X}_i) \log p(a_j|\underline{X}_i) \qquad \text{equation 3}$$

Note that for a sample of n individuals the test can use $p(a_j,\underline{X}_i) = p(a_j|\underline{X}_i) \cdot p(\underline{X}_i)$ by setting $p(\underline{X}_i)$ = (# of times $\underline{X}_i$ occurs)/n and by setting $p(a_j)$ either equal to the observed market share fraction, ms_j, or equal to 1/(# alternatives) (equally likely model), or to any other prior belief on $p(a_j)$. For comparing $p(a_j|\underline{X}_i)$ against the market share model:

$$EI(A:X) = \sum_i \sum_j (1/n) p(a_j|\underline{X}_i) \log \frac{p(a_j|\underline{X}_i)}{ms_j} \qquad \text{equation 4}$$

and

$$H(A) = -\sum_j ms_j \cdot \log (ms_j) \qquad \text{equation 5}$$

Note that since $0 \leq ms_j \leq 1$, H(A) is positive.

The accuracy of the model can be calculated by comparing the empirical information, I(A;X), with the expected information. (More on this later.) To compute the empirical information use the δ_{ij} notation:

$$I(A;X) = (1/n) \sum_i \sum_j \delta_{ij} \log \frac{p(a_j|\underline{X}_i)}{ms_j} \qquad \text{equation 6}$$

Equations 4, 5, and 6 show that information theory can be formulated to test probabilistic models. But before this test can be used for probabilistic choice models, equations 4, 5, and 6 must be given more intuitive meanings. Consider the following theorems:

Theorem 1: The entropy of a system, is numerically equal to the information which would be observed given perfect knowledge, i.e. H(A) = I(A;perfect knowledge).

Proof: Under the assumption of perfect knowledge, $p(a_j|\underline{X}_i) = \delta_{ij}$ for all j. Thus:

$$I(A; \text{perfect knowledge}) = (1/n) \sum_i \sum_j \delta_{ij} \log \frac{\delta_{ij}}{p(a_j)}$$

Switching summations and recognizing $\delta_{ij} = 0$ if i does not choose j gives:

$$I(A;\text{ perfect knowledge}) = (1/n) \sum_j \sum_{i\varepsilon C(j)} \log \frac{1}{p(a_j)} + \sum_{i \notin C(j)} 0 \cdot \log \frac{0}{p(a_j)}$$

where $C(j)$ is the set of individuals who choose j. Since under the null hypothesis, the number of individuals who choose i is $n \cdot p(a_j)$ and since $\lim_{x \to 0} [x \cdot \log x] = 0$, this gives:

$$I(A;\text{ perfect knowledge}) = \sum_j \frac{n \cdot p(a_j)}{n} \log \frac{1}{p(a_j)}$$

$$= -\sum_j p(a_j) \log p(a_j) = H(A) \quad . \quad \blacksquare$$

Theorem 2: If the probability model is aggregately consistant with the null hypothesis, i.e. $\sum_{\underline{X}_i \varepsilon X} p(a_j, \underline{X}_i) = p(a_j)$, then the expected information is equal to the reduction in uncertainty. I.e., $EI(A;X) = H(A) - H(A|X)$.

Proof: Expanding $EI(A;X)$ as defined in equation 1 gives

$$EI(A;X) = \sum_{\underline{X}_i \varepsilon X} \sum_j p(a_j, \underline{X}_i) \log p(a_j|\underline{X}_i) - \sum_{X_i \varepsilon X} \sum_j p(a_j, \underline{X}_i) \log p(a_j)$$

The first term on the right hand side is $-H(A|X)$ as given by equation 3 and using $\sum_{\underline{X}_i \varepsilon X} p(a_j, \underline{X}_i) = p(a_j)$, the second term can be shown to be $-H(A)$ as given by equation 2. Thus

$$EI(A;X) = H(A) - H(A|X) \quad \blacksquare$$

Theorem 3: Suppose that the true choice probabilities are given by $p_{ij} = q_{ij}$, then EI(A;X) attains its maximum value for $p_{ij} = q_{ij}$.

Proof: Let $Q = \max_{p_{ij},\lambda_i} [\sum_i \sum_j (1/n)\, q_{ij} \log \frac{p_{ij}}{p(a_j)} + \sum_i \lambda_i (1-\sum_j p_{ij})]$

where the Lagrange multipliers, λ_i , have been used to incorporate the constraint that $\sum_j p_{ij} = 1$ for all i. Since q_{ij} are the true probabilities, $p(a_j, X_i) = q_{ij} \cdot$ (# of times $\underline{X}_i$ occurs)/n. when computing EI(A;X). The conditions for optimality are then $\lambda_i = (1/n)$ and $p_{ij} = q_{ij}$ and second order conditions indicate a maximum. ∎

Together theorems 1, 2, and 3 give intuitive meaning to the information measure. The entropy, H(A), is a naturally occuring measure of uncertainty in thermodynamics (Reif [23]), in statistics (Jaynes [12]), and in marketing (Herniter [11]). It measures the total uncertainty of the system and by theorem 1 it represents the maximum uncertainty that can be explained with perfect information. Furthermore, if the model is less than perfect, then the expected information represents the reduction in uncertainty due to the model. Thus, $EU^2 = EI(A;X)/H(A)$ can be used to measure the percent uncertainty explained by the model. $1-EU^2 = H(A|X)/H(A)$ gives the residual uncertainty. (Note that H(A) , and hence EU^2, depends on the null hypothesis. Since $p(a_j) = 1/J$ maximizes H(A), the equally likely null model represents maximum uncertainty or conversely minimum knowledge.)

Finally, if knowledge is limited by the explanatory variables, X, and if there are some true probabilities, q_{ij}, known only to a clairvoyant, then the best value for the expected information is attained by setting $p_{ij} = q_{ij}$. Thus the expected information is indeed an "honest reward "function" (Raiffa [22]) in the sense that the "reward" structure would force a clairvoyant to divulge the true probabilities. Note that some commonly used measures such as least squares, R^2, can be shown to be dishonest for testing probabilities against events. (A clairvoyant would maximize R^2 by setting $p_{im} = 1$ for alternative m such that $q_{im} = \max_j q_{ij}$ and $p_{ij} = 0$ for $j \neq m$.)

A problem with EU^2 is that it is computed independent of the observed data, δ_{ij}. In fact, it is the expected value of a test statistic, $U^2 = I(A;X)/H(A)$. Thus in practice, an analyst can either (1) use the empirical uncertainty explained, U^2, to measure the predictive *usefulness* of a model, or (2) use the expected uncertainty explained, EU^2 for usefulness and test the "closeness" of U^2 to EU^2. The "closeness" test can be interpreted as a test of *accuracy* and will be explained in the next section.

All that remains is to show that U^2 is the appropriate generalization of the likelihood ratio index, ρ^2. This is shown by the following theorem:

Theorem 4: If the null hypothesis is independent of i, i.e. $p_{ij}^{\circ} = p(a_j)$, then the likelihood ratio index, ρ^2, is numerically equal to the empirical percent uncertainty explained, U^2.

Proof: $\rho^2 = 1-r$ where r is the logarithm of the likelihood function for the probabilistic model, call it $L(X)$, divided by the logarithm of the likelihood function for the null hypothesis, call it L_0. Thus

$$\rho^2 = 1 - L(X)/L_0 = (L_0 - L(X))/L_0$$

Now

$$L_0 = \log \prod_{i=1}^{n} \prod_{j=1}^{J} p(a_j)^{\delta_{ij}}$$

$$= \sum_{i=1}^{n} \sum_{j=1}^{J} \delta_{ij} \log \; p(a_j)$$

Similarly

$$L(X) \;\; = \sum_i \sum_j \delta_{ij} \log p(a_j|\underline{X}_i)$$

thus

$$L_0 - L(X) = \sum_i \sum_j \delta_{ij} [\log p(a_j) - \log p(a_j|\underline{X}_i)]$$

$$= -n \; I(A;X)$$

Now since $p(a_j)$ is independent of i:

$$L_0 = \sum_{j=1}^{J} \sum_{i \varepsilon C(j)} \delta_{ij} \log p(a_j)$$

$$= \sum_{j=1}^{J} n \; p(a_j) \log p(a_j)$$

$$= -n \; H(A)$$

Thus

$$\rho^2 \;\; = -n \; I(A;X)/[-n \; H(A)]$$

$$= I(A;X)/H(A) = U^2$$

In summary, the information test, EU^2 or U^2, provides a natural measure of uncertainty and a natural intuitive managerial interpretation of uncertainty explained. Furthermore, it is an "honest" reward function and in the case of simple null hypotheses it reduces to the likelihood ratio index. Thus, EU^2 or U^2, provides the first stage of a three-stage disaggregate test. The next two sections will develop *accuracy* and *significance* tests to complement this test of *usefulness*. Section 6 will then show how this test extends naturally to successively more powerful null hypotheses and section 7 will show how to shift the upper bound when frequencies rather than single events are observed.

4. NORMAL DISTRIBUTION: A COMPANION TEST FOR ACCURACY

It is tempting to use EU^2 as a measure of uncertainty, but EU^2 can be easily maximized for a completely inaccurate model. (I.e. set $p_{i1} = 1$ and $p_{ij} = 0$ for $j \neq 1$.) Thus a test must be devised to compare an observed statistic, U^2, to its expected value, EU^2. Fortunately under reasonable assumptions, $I(A;X)$ is normally distributed.

Theorem 5: Suppose that the model is accurate, i.e., the observed events, δ_{ij}'s, are Bernoulli random variables with probabilities given by $p(a_j|\underline{X}_i)$, and individuals are independent. Then for large samples $I(A;X)$ is a normal random variable with mean $EI(A;X)$ and variance, $V(A;X)$, given as follows:

$$V(A;X) = (1/n)\sum_{i=1}^{n}\left\{\sum_{j=1}^{J} p(a_j|\underline{X}_i)\left[\log\frac{p(a_j|\underline{X}_i)}{p(a_j)}\right]^2 - \sum_{j=1}^{J} p(a_j|\underline{X}_i)\left[\log\frac{p(a_j|\underline{X}_i)}{p(a_j)}\right]^2\right\} \qquad \text{equation 7}$$

Proof: First recognize that

$$I(A;X) = \sum_i (1/n) \sum_j \delta_{ij} \log \frac{p(a_j|X_i)}{p(a_j)}$$

is the sum of n independent random variables. E.g. the first random variable takes on a value $(1/n) \log[p(a_j|X_1)/p(a_j)]$ with probability $p(a_j|\underline{X}_1)$. Under "reasonable conditions" this sum of independent random variables is asymptotically normal. The "reasonable conditions" require (1) that no term dominates the sum and (2) that the individual terms are not uniformly skewed (Drake [2]). Although algebraically complex, these conditions reduce to the condition that the $p(a_j|\underline{X}_i)$'s are not arbitrarily close to 1 or 0. This condition is met in any reasonable empirical probability of choice model such as the logit model. The mean and variance are then directly computed.

Thus a two-tailed test can be applied to determine whether I(A;X) is a reasonable observation from the model. If I(A;X) is statistically far from EI(A;X) reject the probabilistic model as unable to explain the empirical observations.

5. STATISTICAL SIGNIFICANCE: ITS RELATIONSHIP TO USEFULNESS AND ACCURACY

Based on section 3, the information measure provides a useful interpretation and extension of the commonly applied likelihood ratio index, and based on section 4, this measure provides a new test of accuracy which allows the analyst to accept or reject the hypothesis that the observations could have been generated by the model.

By recognizing that $L = (2n)\ I(A;X)$, a third stage can be added to the disaggregate information test. This third stage, *significance*, is simply the standard chi-square significance test reviewed in section 2. In this test, the analyst tests whether the model, the $p(a_j|\underline{X}_i)$'s, and the observations, δ_{ij}'s, are reasonable under the hypothesis that the null model is true. Too large a χ^2 statistic rejects the null model. Note that $I(A;X)$ is normally distributed in the accuracy test because only the δ_{ij}'s are random variables under the hypothesis that the *probabilistic model* is correct, while $(2n)\ I(A;X)$ is chi-squared distributed in the significance test because both the δ_{ij}'s and the $p(a_j|\underline{X}_i)$'s are random variables under the hypothesis that the *null model* is correct.

This three-part test of "usefulness", "accuracy", and "significance" is illustrated in figure 1. The model is a standard logit model without choice specific constants. The choice set consists of seven shopping centers in the suburbs north of Chicago and the explanatory variables are factor scores for each individual along six dimensions: variety, quality, atmosphere, value, layout, and parking. The dependent variable was first preference and the sample size is 99.

[Insert Figure 1 here.]

The model is overwhelmingly significant with respect to the equally likely null model, N_0, but it only explains 44% of the uncertainty. The model is clearly accurate with respect to N_0, (99% level), but less accurate with respect to the market share null model, N_1. (80% level.) Note that the accuracy test is a relative test because the null model appears in the test.

[EI(A;X) depends on $p(a_j)$.] In this application, the model was not statistically rejected, but the accuracy test relative to N_1 was one stimulus that led to further investigation. The final model, presented in Hauser and Koppelman [8], required statistical corrections for choice based sampling (Manski and Lerman [18]).

6. SUCCESSIVELY MORE POWERFUL NULL HYPOTHESES

The example in figure 1 illustrates how important null hypotheses are in the choice of a test. Fortunately the information test provides a useful generalization that helps overcome the problem of selecting a null hypothesis. To begin this discussion consider the following formal notation.

Call the equally likely null hypothesis N_0, ($p(a_j) = 1/J$) and call the market share proportional null hypothesis, N_1, ($p(a_j) = ms_j$). Using the theory introduced in equations 1 to 6, one can compute the observed information and the entropy relative to either null model. Let $I_1(A;X)$ be the observed information relative to N_1, let $H_1(A)$ be the entropy relative to N_1. (See equations 5 and 6.) Similarly let $I_0(A;X)$ and $H_0(A)$ be computed relative to N_0. (Substitute $p(a_j) = 1/J$ in equations 5 and 6.) Finally let $I_0(A;N_1)$ be the observed information of N_1 relative to N_0. (Substitute $p(a_j|\underline{X}_i) = ms_j$ and $p(a_j) = 1/J$ in equation 6.)

The first important results are that $I_0(A;N_1)$ can be more simply represented and that $I_0(A;X)$ can be computed from component parts.

Theorem 6: The incremental information of N_1 relative to N_0 is equal to the reduction in entropy in going from N_0 to N_1, i.e.,

$$I_0(A;N_1) = H_0(A) - H_1(A)$$

Proof:

$$I_0(A;N_1) = (1/n) \sum_{i=1}^{n} \sum_{j=1}^{J} \delta_{ij} \log \frac{ms_j}{(1/J)}$$

Thus:

$$I_0(A;N_1) = (1/n) \sum_{i=1}^{n} \sum_{j=1}^{J} \delta_{ij} \log ms_j - (1/n) \sum_{i=1}^{n} \sum_{j=1} \delta_{ij} \log (1/J)$$

Switching the order of the summation and noting that $\Sigma\delta_{ij}$ over i choosing j equals ms_j and that $\sum_{i=1}^{n} \sum_{j=1}^{J} \delta_{ij} = n$ yields:

$$I_0(A;N_1) = -(-\sum_{j=1}^{J} ms_j \log ms_j) + (-\sum_{j=1}^{J} (1/J) \log (1/J))$$

$$= -H_1(A) + H_0(A)$$

which completes the proof.

Theorem 7: The information relative to N_0, $I_0(A;X)$, is equal to the information relative to N_1, $I_1(A;X)$, plus the information of N_1 relative to N_0, $I_0(A;N_1)$, i.e.,

$$I_0(A;X) = I_0(A;N_1) + I_1(A;X)$$

Proof: Simlar to theorem 6.

Together theorems 6 and 7, which can be proven for any set of null hypotheses, provide very useful results. Taking N_0, the equally likely hypothesis, as the state of no knowledge one can view information as coming successively first by the hypothesis, N_1, which tells only market shares and then incrementally from the model $p(a_j|\underline{X}_i)$ for all i. Furthermore, the "no knowledge entropy", $H_0(A)$, can be viewed as being successively reduced, first to $H_1(A)$ by the market share information, N_1, and then to the estimated residual entropy, $\hat{H}(A|X)$. (Note that $\hat{H}(A|X)$ is independent of both N_0 and N_1.)

A practical advantage of theorems 6 and 7 is that while $I_0(A;X)$ may be difficult to compute, $H_0(A)$ and $I_0(A;N_1)$ are given by simple formulae. Thus $I_*(A;X)$ can be computed relative to any null hypothesis by simple addition and subtraction once $I_0(A;X)$ is known. For example:

$$H_0(A) = -\sum_{j=1}^{J} (1/J) \log (1/J) = \log J$$

$$I_0(A;N_1) = \log J + \sum_{j=1}^{J} ms_j \log ms_j$$

A point of further interest is that theorems 6 and 7 apply to the expected information measure only if $(1/n) \sum_{i=1}^{n} p(a_j,\underline{X}_i) = ms_j$, i.e. only if the model is constrained to correctly predict the market shares. Thus $I_0(A;X) - I_1(A;X)$ is only equal to $EI_0(A;X) - EI_1(A;X)$ when the predicted market shares are constrained. This is why the test of accuracy is actually a test relative to the null hypothesis.

Once the information measure is extended to test the comparison between simple null hypotheses like N_0 and N_1, the generalization is straightforward to other null hypotheses or to successively stronger models. For example, when choice specific constants were added to the model in figure 1, they explained an additional 3.1% of the uncertainty.

An important problem in practice is when the choice set varies across individuals. This problem can be addressed with the information test by selecting a null model, N_2, which assumes that the choice set and nothing else is known. This test is illustrated in a study by Silk and Urban [24] on deodorants. There were 18 brands on the market but the average size of the choice set was only 3 brands.

Define the null model, N_2, as follows:

Let J_i = the number of alternatives in individual i's choice set

then the null probabilities, p^o_{ij}, are given as

$$p^o_{ij} = \begin{cases} 1/J_i & \text{if alternative } a_j \text{ is in individual i's choice set} \\ 0 & \text{otherwise} \end{cases}$$

In the study, the explanatory variable was a ratio scaled preference measure calculated from constant sum paired comparisons (Torgenson [26]). The dependant variable was last brand purchased. The model was a one-parameter logit model linking preference to probability of choice. First preference recovery was 83%.

Relative to the equally likely hypothesis (N_0, p_j=1/18), the logit model explained 80% of the total uncertainty. But N_2 explains 62% of that uncertainty and the logit model adds only 18% to that. Thus N_2 represents a significant amount of information and is an extremely strong assumption. (In a category like deodorants where the choice set is determined more by each consumer's interest than by product availability, knowledge of everyone's choice set contains considerable preference information.)

Finally, as is shown in Figure 2, the information test can compute information as coming first from N_1 relative to N_0, then incrementally from N_2 relative to N_1, and finally from the logit model (X) relative to N_2. This can be done even though the implicit parameters for N_1 are not a subset of N_2 or of those for the logit model.

[Insert Figure 2 here.]

7. FREQUENCY OF CHOICE

A final problem that the information test can address is the problem encountered when market research data is collected from a consumer panel. In this case, observed choice is not a one-time occasion, but rather the consumer makes repeated purchases over time. Frequencies rather than (0,1) events are observed.

Perfect information would result from correctly predicting every choice occasion for every individual, i.e. $p_{ijk} = \delta_{ijk}$. (k indexes the choice occasion.) Unfortunately, without situational variables, probabilistic choice models predict probabilities, p_{ij}, that are independent of choice occasion. Thus $H_0(A) = I_0(A;\text{perfect information})$ is not possible even in theory.

This problem can be addressed by defining a new perfect model, P_2, such that $p_{ijk} = f_{ij}$, where f_{ij} is the observed frequency. The new entropy, $G_0(A) = I_0(A;P_2)$, then becomes the base uncertainty, and a new measure, $V_0^2 = I_0(A;X)/G_0(A)$, gives the percent of "explainable" uncertainty that is actually explained by the model. Alternatively, a figure such as figure 2 can be produced and $G_0(A)$ can be compared to $H_0(A)$ to determine the percent of unexplainable uncertainty.

Thus, in addition to indicating the relationships between the lower bounds (null hypothesis), the information test is readily extendable to indicate the relationships among the upper bounds (explainable uncertainty).

8. SUMMARY

This paper addresses the fundamental problem of testing probabilistic predictions against 0,1 observed events by deductively deriving an information theoretic test. Under standard null hypotheses this test reduces to the likelihood ratio index, ρ^2, now in common use. One advantage of the information theoretic approach is that it gives both theoretic rigor and an intuitive appeal to this hitherto heuristic measure. But the information test goes beyond that. It indicates how to extend ρ^2 to complex null hypotheses, and how to change the upper bound on explainable uncertainty. Together these extensions make clear many interesting and complex effects. For example, the contribution of choice set restrictions is quantified in figure 2.

The information test measures usefulness, but it also statistically measures accuracy. A two-tailed normal test indicates whether the information statistic is reasonable under the hypothesis that the probabilistic model is correct. This test, which is relative to the chosen null hypothesis, provides the model builder with an important diagnostic tool to assess the validity of a probabilistic model.

Finally, under the appropriate null hypothesis, $(2n)I(A;X)$ is the standard χ^2 statistic used to measure statistical significance.

Thus the information test gives a three-stage disaggregate test of usefulness, accuracy, and significance. It provides useful generalizations for existing disaggregate tests, makes possible new comparisons among models and hypotheses, and indicates the intuitive and statistical relationships among model tests. These advantages are sufficient to add this test to those tests which modelers use to select probabilistic models. To date, the test has been used to test a new ranked probability model (Hauser [6]), to test independence of irrelevant alternatives (Silk and Urban [24]), to compare various means to model consumer perceptions (Hauser and Koppelman [7]), to test the relative effects of attitudinal and engineering variables in logit models (Lavery [17], to test a bargain-value model of brand choice (Keon [15]), and to test location models for financial services.

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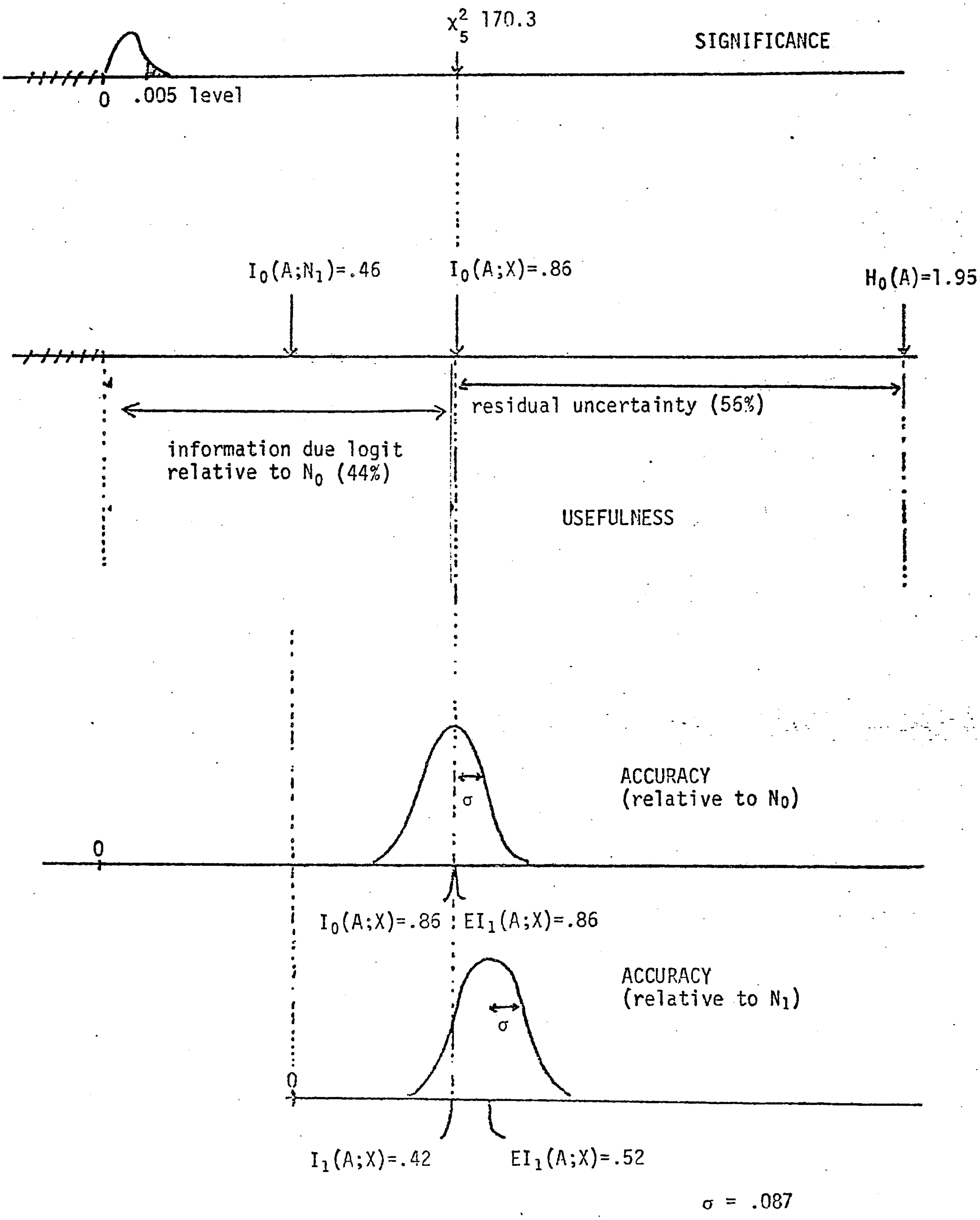

Figure 1: Honest reward/information test applied to shopping center preference prediction.

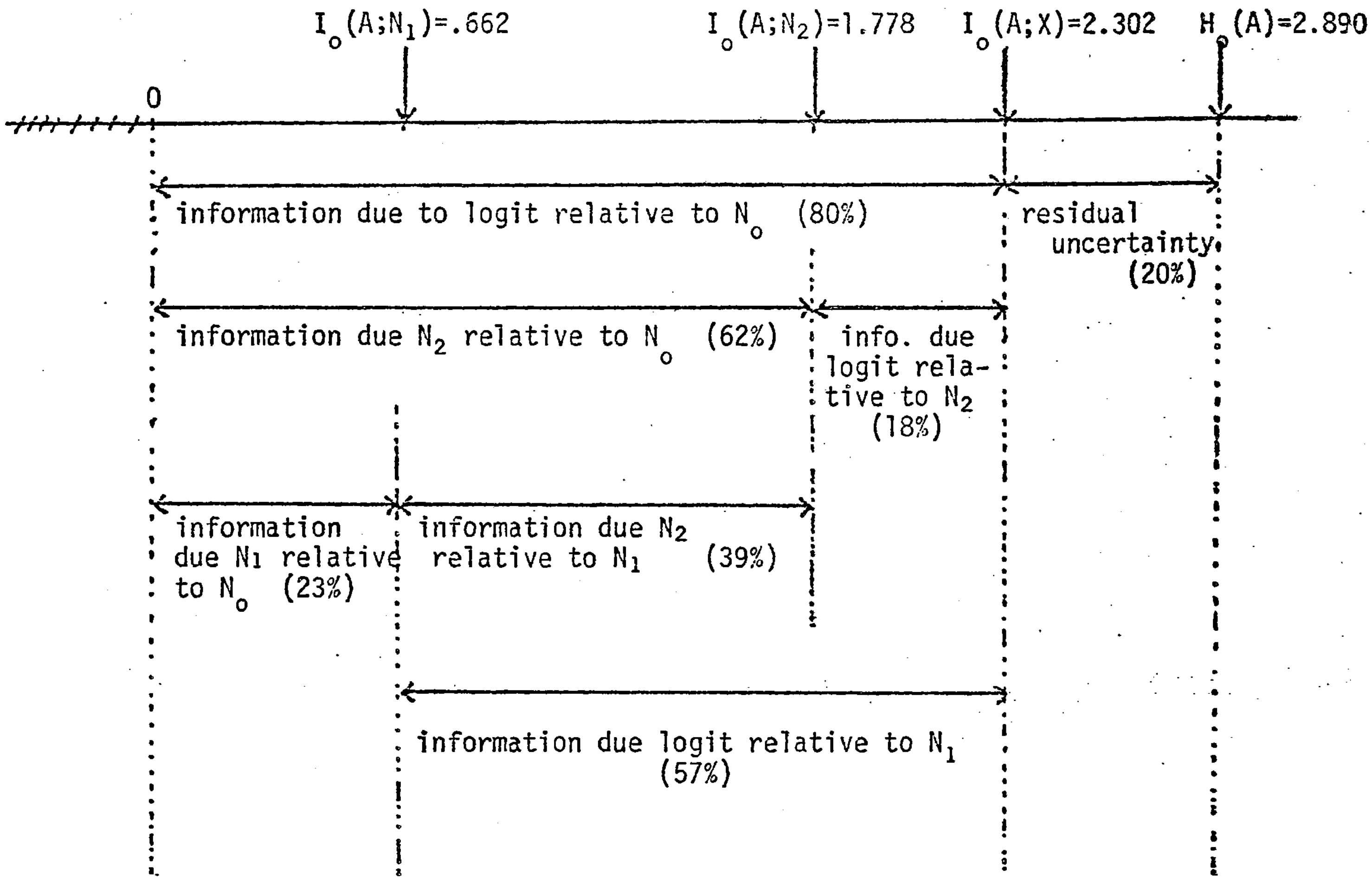

Figure 2: Information test when the choice set varies.
(Deodorant example)

DISCUSSION PAPER NO. 286

TESTING THE ACCURACY, USEFULNESS, AND SIGNIFICANCE OF PROBABILISTIC CHOICE MODELS: AN INFORMATION THEORETIC APPROACH */

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ABSTRACT

Disaggregate demand models predict choice behavior on the level of the individual consumer. But testing predictions is difficult because while the models predict choice probabilities ($0<p<1$) they must be tested against observed (0,1) choice behavior. After reviewing the aggregate and disaggregate tests now in use, this paper derives an information theoretic test that provides complementary measures of "usefulness", "accuracy", and "significance". "Usefulness" compares the information provided by the model to the total entropy to measure the percent of uncertainty explained. It provides theoretic rigor and intuitive appeal to the commonly used likelihood ratio index and leads to extensions which address important practical problems. "Accuracy" is a new two-tailed normal test which determines whether the (0,1) observations are reasonable under the hypothesis that the model is a valid model. Finally, the information measure also leads to the standard chi-squared "significance" test to determine whether a null hypothesis can be rejected. Together the three-part disaggregate test provides insight to help model builders assess a probabilistic model's performance or to select a "best" model.

All tests depend on null hypotheses. This paper extends the information test to indicate the relationships among null hypotheses by allowing the model builder to test against successively more powerful hypotheses. For example, in a predictive logit model, one can quantify (1) the contribution due to knowing aggregate market shares, (2) the incremental contribution due to knowing choice set restrictions, and finally (3) the incremental contribution due the explanatory variables. Further extensions provide alternative "explainable uncertainty" measures for the case of consumer panels which observe frequency of choice rather than (0,1) choice behavior.

The tests and extensions are illustrated with empirical examples from transportation demand analysis and marketing research.

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1. INTRODUCTION

The design of successful products and services requires valid predictions of how consumers will respond to changes in product or service strategy. Recently in marketing research and in transportation planning, demand models have been developed which base their predictions on causal hypotheses which model the behavior of individual consumers (logit analysis, McFadden [19], probit analysis, Finney [3], discriminant analysis, Fisher [4], etc.). Because of their behavioral content and because of the rich, individual specific data on which these models are based, analysts expect these "disaggregate behavioral demand models" to provide accurate predictions of consumer behavior and to provide useful diagnostics which help understand the consumers' choice process. But how accurate are these models? This question, which must be answered to the satisfaction of both the analytic modeler and the marketing or transportation manager, is the subject of this paper.

Disaggregate models predict group response, e.g., the number of bus riders from zone to zone, by aggregating together predictions of how individual consumers behave (Koppelman [16]). But because of potential errors in modeling, in measurement, in estimation, and because of random influences on consumer behavior these models cannot predict with certainty. Instead for each individual, i, they predict choice probabilities. For example, in modeling choice among modes of transportation a model might predict the probability that a particular consumer will choose transit, the probability he will drive, the probability he will walk, and the probability he will not travel. The fundamental problem in testing is that while the models predict probabilities, they must be tested on observed events. In a given instance individual i either rides, drives, walks, or stays put! Suppose a model predicts that i will ride the bus with probability

.7 and i does ride the bus. To assess the validity of such a model a test must quantify how much "rightness" or "wrongness" there was in the prediction. Furthermore, if a model makes individual predictions, but for 1000 individuals, analysts need a test to indicate how well a model predicted and if necessary to select a "best" model.

2. EXISTING TESTS

The problem of testing predicted probabilities as observed events is not new and there are a number of tests now in use. Some of these tests, called aggregate tests, compare aggregate predictions, e.g., average probabilities, with aggregate statistics, e.g. market shares, while other tests, called disaggregate tests, compare individual probabilities with individual events. This section first reviews both types of tests and then discusses their relative merits.

Aggregate tests have strong intuitive appeal and are useful aids to communication between analysts and managers. Managers can internalize the meaning of these tests, compare the model to their prior beliefs, and assess the accuracy of a model in a way that can be readily communicated to others. For example, *first preference recovery*, r_1, which computes the percent of individuals that select their first preference alternative, is easy to understand and can be readily compared to chance recovery, r_c = 1/(number of alternatives), or market share recovery, $r_{ms} = \sum_j (ms_j^2)$ where ms_j = market share of product j. In most probabilistic models, maximum probabilities are substituted for first preference because choice probabilities are monotonic in preference.

Other useful aggregate tests compare predicted market shares, $\hat{ms}_j$, with observed market shares, ms_j. [$\hat{ms}_j = (1/n) \sum_i p_{ij}$, where p_{ij} is the predicted probability that i chooses j and n is the total number of individuals.] For example, *root mean square percent error* in predicted market shares, e_p, has been used by Koppelman [16] to compare aggregation methods for mode choice predictions in Washington, D.C. He reports errors in the range of 25-35%. In another example, Hauser and Urban [10] report that percent error was a better discriminator than first preference recovery between von Neumann-Morgenstern utility assessment and logit analysis (e_p=18% vs 36% while r_1=50% vs. 46%). Similar tests such as weighted percent error, mean absolute error, least square error, and weighted least square error have all been used with varying success. See Koppelman [16].

Disaggregate tests address the basic testing problem by comparing predictions and events on an individual level. These tests can discriminate between models which predict aggregate market shares well but miss the individual choice process and those which capture individual differences. For example, any logit choice model with J-1 choice specific constants (J = the number of alternatives) will predict aggregate market shares exactly on the "calibration" data, but different models within this class may be "better" than others. Disaggregate tests quantify the concept of "better".

A common test is the *log-likelihood chi-squared significance test* (Mood and Graybill [20]). In this test the probabilistic model is compared to a null model. If the null model can be formulated as a restriction (subset) on the parameters of the tested model then L = 2 log[likelihood ratio of tested model to null model] is χ^2 distributed with degrees of freedom equal to the difference in degrees of freedom between the tested model and the null model. In logit applications the most common null model is the equally likely model (all choice parameters set equal to zero) but some researchers use the market share proportional model (choice specific constants only) when a full set (J-1) of choice specific constants are used in the estimated model.

The chi-squared test can reject a null model, but it can not give an indication of how well a model predicts nor can it compare two models unless one model is a restriction of the other. The most common disaggregate test used to measure a model's predictive ability is the *likelihood ratio index* (McFadden [19]). This test, $\rho^2 = 1\text{-}L(X)/L_0$ where $L(X)$ is the log-likelihood of the tested model (explanatory variables X) and L_0 is the log-likelihood of the null model, acts like a pseudo-R^2 since $\rho^2 = 0$ when $L(X) = L_0$ and $\rho^2=1$ when the model predicts perfectly, otherwise $0 < \rho^2 < 1$. In related tests, Kendall [14] suggests a correlation coefficient similar to that for regression and Cragg [1] suggests a correlation-like coefficient. Stopher [25] uses the correlation ratio (Weatherburn [27], Neter and Maynes [21], Johnson and Leone [13]) to augment the correlation coefficient but his use requires that individuals be grouped. Results are extremely sensitive to the grouping.

Discussion: Although the aggregate tests are intuitive and aid communication between managers and analysts, they can be misleading. For example, a first preference recovery of 55% is usually good, but not in a market of two products. A recovery of 90% is usually good in a two-product market but not if one product has a market share of 95% (r_{ms} = 90.5%). Similarly, e_p is identically zero for the market share proportional null model, but $e_p > 0$ for most models which may be more realistic representations of the true choice process. (For example, most logit models without choice specific constants will not predict market shares exectly. But choice specific constants are often undesirable because they make it difficult to project a model from the "calibration" situation to a new situation. In particular if new products are introduced, there is no way to know the choice specific constant for the new product.) These restrictions on aggregate tests caution the analyst to use aggregate tests with great care. Furthermore, because aggregate tests do not address the fundamental problem of testing individual probabilities against observed events, they may not be able to discriminate between models to select the "best" model of individual choice behavior.

The disaggregate tests do address the fundamental testing problem. The chi-squared test can statistically reject properly formulated null hypotheses and the likelihood ratio index can give an R^2-like measure of the predictive ability of a probabilistic model. In many cases these tests nicely complement the aggregate tests. Disaggregate tests are not used alone because they are theoretically sensitive to the problem that $\lim_{p_{ij}\to 0} [\log p_{ij}] = -\infty$. Aggregate tests are not as sensitive to zero probabilities.

This battery of aggregate and disaggregate tests can address many problems in testing probabilistic models, but there are importance problems which this battery does not address. For example: (1) The likelihood ratio index behaves nicely at the limits ($\rho^2=0$, $\rho^2=1$), but it does not have an intuitive interpretation between the limits. Managers need an intuitive interpretation that is naturally related to a measure of probabilistic uncertainty. (2) ρ^2 can be computed relative to any null hypothesis, L_0, but no deductive theory indicates whether that simple computation is the appropriate generalization for complex null hypotheses. (3) The choice of a null hypothesis is based on judgement. A good test should indicate which null hypothesis is best and indicate the relationship among null hypotheses. (4) The null hypothesis sets the lower bound for ρ^2, but $\rho^2=1$ may not be the appropriate upper bound. If individuals make repeated choices and if individuals do not always select the same alternative, then $\rho^2=1$ is not possible even in theory. (Perfect prediction would require different probabilities for different occasions. Such predictions are not possible without situational variables.) A theory based test should indicate how to incorporate upper bound information. Finally, (5) the chi-squared test can reject a null hypothesis but does not test the accuracy of predictions. A test of "accuracy", which can accept or reject the *tested* model, is necessary to complement the chi-squared test of "significance" and the ρ^2 test (or its generalization) of "usefulness".

These problems and others can be effectively resolved by considering probabilistic models as an information system where the predicted probabilities (or null hypotheses) represent the best information derived from the set of explanatory variables, X.

3. INFORMATION THEORY: AN INTERPRETABLE TEST OF MODEL USEFULNESS

Suppose there is a set of choice alternatives, $A=\{a_1,a_2,...a_J\}$ and suppose there is a set of explanatory variables, X, which take on specific values, $\underline{X}_i$, each individual, i. Suppose that through some mathematical analysis, a conditional probability model, $p(a_j|\underline{X}_i)$, has been developed to estimate choice probabilities, $p_{ij} = p(a_j|\underline{X}_i)$, from the explanatory variables. Suppose that to test the model each individual's choice behavior, as represented by δ_{ij}, has been observed. ($\delta_{ij} = 1$ if i chooses j, $\delta_{ij} = 0$ otherwise.) This section will derive the information test for such a probabilistic model of consumer behavior. Later sections will extend the test to cases where the choice set varies and the number of choice occasions is greater than one.

The probability model can be viewed as an information system. In other words the "observable occurence," e.g. the attributes of the choice alternatives, provides information about "unobservable events," i.e., about the choice outcome. Thus a test uses the information measure, $I(a_j,\underline{X}_i)$, (Gallagher [5]) to quantify the information provided by $\underline{X}_i$. Formally:

$$I(a_j,\underline{X}_i) = \log \frac{p(a_j|\underline{X}_i)}{p(a_j)}\quad .$$

where $p(a_j)$ = the prior likelihood of the outcome, i.e. the event that a_j is chosen.

First observe that the information criteria provides managerially interpretable benchmarks. The first benchmark is the expected information provided by the model, $EI(A;X)$, where:

$$EI(A;X) = \sum_{\underline{X}_i \epsilon X} \sum_j p(a_j,\underline{X}_i) \log \frac{p(a_j|\underline{X}_i)}{p(a_j)} \qquad \text{equation 1}$$

with $p(a_j,\underline{X}_i)$ the joint probability of an "observation" of $\underline{X}_i$ and an "event", a_j chosen.

Another benchmark is the total uncertainty in the system which is measured by the prior entropy, $H(A)$, where:

$$H(A) = -\sum_j p(a_j) \log p(a_j) \qquad \text{equation 2}$$

The prior entropy measures the uncertainty before "observing" $\underline{X}_i$. After observing $\underline{X}_i$ the uncertainty is reduced to the posterior entropy, $H(A|X)$, where

$$H(A|X) = -\sum_{\underline{X}_i \epsilon X} \sum_j p(a_j,\underline{X}_i) \log p(a_j|\underline{X}_i) \qquad \text{equation 3}$$

Note that for a sample of n individuals the test can use $p(a_j,\underline{X}_i) = p(a_j|\underline{X}_i)\cdot p(\underline{X}_i)$ by setting $p(\underline{X}_i)$ = (# of times $\underline{X}_i$ occurs)/n and by setting $p(a_j)$ either equal to the observed market share fraction, ms_j, or equal to 1/(# alternatives) (equally likely model), or to any other prior belief on $p(a_j)$. For comparing $p(a_j|\underline{X}_i)$ against the market share model:

$$EI(A:X) = \sum_i \sum_j (1/n) p(a_j|\underline{X}_i) \log \frac{p(a_j|\underline{X}_i)}{ms_j} \qquad \text{equation 4}$$

and

$$H(A) = -\sum_j ms_j \cdot \log (ms_j) \qquad \text{equation 5}$$

Note that since $0 \leq ms_j \leq 1$, H(A) is positive.

The accuracy of the model can be calculated by comparing the empirical information, I(A;X), with the expected information. (More on this later.) To compute the empirical information use the δ_{ij} notation:

$$I(A;X) = (1/n) \sum_i \sum_j \delta_{ij} \log \frac{p(a_j|\underline{X}_i)}{ms_j} \qquad \text{equation 6}$$

Equations 4, 5, and 6 show that information theory can be formulated to test probabilistic models. But before this test can be used for probabilistic choice models, equations 4, 5, and 6 must be given more intuitive meanings. Consider the following theorems:

Theorem 1: The entropy of a system, is numerically equal to the information which would be observed given perfect knowledge, i.e. H(A) = I(A;perfect knowledge).

Proof: Under the assumption of perfect knowledge, $p(a_j|\underline{X}_i) = \delta_{ij}$ for all j. Thus:

$$I(A;\ \text{perfect knowledge}) = (1/n) \sum_i \sum_j \delta_{ij} \log \frac{\delta_{ij}}{p(a_j)}$$

Switching summations and recognizing $\delta_{ij} = 0$ if i does not choose j gives:

$$I(A;\text{ perfect knowledge}) = (1/n) \sum_j \sum_{i \in C(j)} \log \frac{1}{p(a_j)} +$$

$$\sum_{i \notin C(j)} 0 \cdot \log \frac{0}{p(a_j)}$$

where $C(j)$ is the set of individuals who choose j. Since under the null hypothesis, the number of individuals who choose i is $n \cdot p(a_j)$ and since $\lim_{x \to 0} [x \cdot \log x] = 0$, this gives:

$$I(A;\text{ perfect knowledge}) = \sum_j \frac{n \cdot p(a_j)}{n} \log \frac{1}{p(a_j)}$$

$$= -\sum_j p(a_j) \log p(a_j) = H(A) \quad . \quad \blacksquare$$

Theorem 2: If the probability model is aggregately consistant with the null hypothesis, i.e. $\sum_{\underline{X}_i \varepsilon X} p(a_j,\underline{X}_i) = p(a_j)$, then the expected information is equal to the reduction in uncertainty. I.e., $EI(A;X) = H(A) - H(A|X)$.

Proof: Expanding $EI(A;X)$ as defined in equation 1 gives

$$EI(A;X) = \sum_{\underline{X}_i \varepsilon X} \sum_j p(a_j, \underline{X}_i) \log p(a_j|\underline{X}_i) - \sum_{X_i \varepsilon X} \sum_j p(a_j,\underline{X}_i) \log p(a_j)$$

The first term on the right hand side is $-H(A|X)$ as given by equation 3 and using $\sum_{\underline{X}_i \varepsilon X} p(a_j,\underline{X}_i) = p(a_j)$, the second term can be shown to be $-H(A)$ as given by equation 2. Thus

$$EI(A;X) = H(A) - H(A|X) \quad \blacksquare$$

Theorem 3: Suppose that the true choice probabilities are given by $p_{ij} = q_{ij}$, then EI(A;X) attains its maximum value for $p_{ij} = q_{ij}$.

Proof: Let $Q = \max_{p_{ij},\lambda_i} \left[\sum_i \sum_j (1/n)\, q_{ij} \log \frac{p_{ij}}{p(a_j)} + \sum_i \lambda_i (1-\sum_j p_{ij})\right]$

where the Lagrange multipliers, λ_i , have been used to incorporate the constraint that $\sum_j p_{ij} = 1$ for all i. Since q_{ij} are the true probabilities, $p(a_j, X_i) = q_{ij} \cdot$ (# of times $\underline{X}_i$ occurs)/n. when computing EI(A;X). The conditions for optimality are then $\lambda_i = (1/n)$ and $p_{ij} = q_{ij}$ and second order conditions indicate a maximum. $\blacksquare$

Together theorems 1, 2, and 3 give intuitive meaning to the information measure. The entropy, H(A), is a naturally occuring measure of uncertainty in thermodynamics (Reif [23]), in statistics (Jaynes [12]), and in marketing (Herniter [11]). It measures the total uncertainty of the system and by theorem 1 it represents the maximum uncertainty that can be explained with perfect information. Furthermore, if the model is less than perfect, then the expected information represents the reduction in uncertainty due to the model. Thus, $EU^2 = EI(A;X)/H(A)$ can be used to measure the percent uncertainty explained by the model. $1-EU^2 = H(A|X)/H(A)$ gives the residual uncertainty. (Note that H(A) , and hence EU^2, depends on the null hypothesis. Since $p(a_j) = 1/J$ maximizes H(A), the equally likely null model represents maximum uncertainty or conversely minimum knowledge.)

Finally, if knowledge is limited by the explanatory variables, X, and if there are some true probabilities, q_{ij}, known only to a clairvoyant, then the best value for the expected information is attained by setting $p_{ij} = q_{ij}$. Thus the expected information is indeed an "honest reward function" (Raiffa [22]) in the sense that the "reward" structure would force a clairvoyant to divulge the true probabilities. Note that some commonly used measures such as least squares, R^2, can be shown to be dishonest for testing probabilities against events. (A clairvoyant would maximize R^2 by setting $p_{im} = 1$ for alternative m such that $q_{im} = \max_j q_{ij}$ and $p_{ij} = 0$ for $j \neq m$.)

A problem with EU^2 is that it is computed independent of the observed data, δ_{ij}. In fact, it is the expected value of a test statistic, $U^2 = I(A;X)/H(A)$. Thus in practice, an analyst can either (1) use the empirical uncertainty explained, U^2, to measure the predictive *usefulness* of a model, or (2) use the expected uncertainty explained, EU^2 for usefulness and test the "closeness" of U^2 to EU^2. The "closeness" test can be interpreted as a test of *accuracy* and will be explained in the next section.

All that remains is to show that U^2 is the appropriate generalization of the likelihood ratio index, ρ^2. This is shown by the following theorem:

Theorem 4: If the null hypothesis is independent of i, i.e. $p_{ij}^{\circ} = p(a_j)$, then the likelihood ratio index, ρ^2, is numerically equal to the empirical percent uncertainty explained, U^2.

Proof: $\rho^2 = 1-r$ where r is the logarithm of the likelihood function for the probabilistic model, call it $L(X)$, divided by the logarithm of the likelihood function for the null hypothesis, call it L_0. Thus

$$\rho^2 = 1 - L(X)/L_0 = (L_0 - L(X))/L_0$$

Now

$$L_0 = \log \prod_{i=1}^{n} \prod_{j=1}^{J} p(a_j)^{\delta_{ij}}$$

$$= \sum_{i=1}^{n} \sum_{j=1}^{J} \delta_{ij} \log \; p(a_j)$$

Similarly

$$L(X) \; = \sum_i \sum_j \delta_{ij} \log p(a_j|\underline{X}_i)$$

thus

$$L_0 - L(X) = \sum_i \sum_j \delta_{ij} [\log p(a_j) - \log p(a_j|\underline{X}_i)]$$

$$= -n \; I(A;X)$$

Now since $p(a_j)$ is independent of i:

$$L_0 = \sum_{j=1}^{J} \sum_{i \varepsilon C(j)} \delta_{ij} \log p(a_j)$$

$$= \sum_{j=1}^{J} n \; p(a_j) \log p(a_j)$$

$$= -n \; H(A)$$

Thus

$$\rho^2 \; = -n \; I(A;X)/[-n \; H(A)]$$

$$= I(A;X)/H(A) = U^2 \qquad \blacksquare$$

In summary, the information test, EU^2 or U^2, provides a natural measure of uncertainty and a natural intuitive managerial interpretation of uncertainty explained. Furthermore, it is an "honest" reward function and in the case of simple null hypotheses it reduces to the likelihood ratio index. Thus, EU^2 or U^2, provides the first stage of a three-stage disaggregate test. The next two sections will develop *accuracy* and *significance* tests to complement this test of *usefulness*. Section 6 will then show how this test extends naturally to successively more powerful null hypotheses and section 7 will show how to shift the upper bound when frequencies rather than single events are observed.

4. NORMAL DISTRIBUTION: A COMPANION TEST FOR ACCURACY

It is tempting to use EU^2 as a measure of uncertainty, but EU^2 can be easily maximized for a completely inaccurate model. (I.e. set $p_{i1} = 1$ and $p_{ij} = 0$ for $j \neq 1$.) Thus a test must be devised to compare an observed statistic, U^2, to its expected value, EU^2. Fortunately under reasonable assumptions, $I(A;X)$ is normally distributed.

Theorem 5: Suppose that the model is accurate, i.e., the observed events, δ_{ij}'s, are Bernoulli random variables with probabilities given by $p(a_j|\underline{X}_i)$, and individuals are independent. Then for large samples $I(A;X)$ is a normal random variable with mean $EI(A;X)$ and variance, $V(A;X)$, given as follows:

$$V(A;X) = (1/n)\sum_{i=1}^{n}\left\{\sum_{j=1}^{J} p(a_j|\underline{X}_i)\left[\log\frac{p(a_j|\underline{X}_i)}{p(a_j)}\right]^2 - \sum_{j=1}^{J} p(a_j|\underline{X}_i)\left[\log\frac{p(a_j|\underline{X}_i)}{p(a_j)}\right]^2\right\} \qquad \text{equation 7}$$

Proof: First recognize that

$$I(A;X) = \sum_i (1/n) \sum_j \delta_{ij} \log \frac{p(a_j|X_i)}{p(a_j)}$$

is the sum of n independent random variables. E.g. the first random variable takes on a value $(1/n) \log[p(a_j|X_1)/p(a_j)]$ with probability $p(a_j|\underline{X}_1)$. Under "reasonable conditions" this sum of independent random variables is asymptotically normal. The "reasonable conditions" require (1) that no term dominates the sum and (2) that the individual terms are not uniformly skewed (Drake [2]). Although algebraically complex, these conditions reduce to the condition that the $p(a_j|\underline{X}_i)$'s are not arbitrarily close to 1 or 0. This condition is met in any reasonable empirical probability of choice model such as the logit model. The mean and variance are then directly computed.

Thus a two-tailed test can be applied to determine whether I(A;X) is a reasonable observation from the model. If I(A;X) is statistically far from EI(A;X) reject the probabilistic model as unable to explain the empirical observations.

5. STATISTICAL SIGNIFICANCE: ITS RELATIONSHIP TO USEFULNESS AND ACCURACY

Based on section 3, the information measure provides a useful interpretation and extension of the commonly applied likelihood ratio index, and based on section 4, this measure provides a new test of accuracy which allows the analyst to accept or reject the hypothesis that the observations could have been generated by the model.

By recognizing that L = (2n) I(A;X), a third stage can be added to the disaggregate information test. This third stage, *significance*, is simply the standard chi-square significance test reviewed in section 2. In this test, the analyst tests whether the model, the $p(a_j|\underline{X}_i)$'s, and the observations, δ_{ij}'s, are reasonable under the hypothesis that the null model is true. Too large a χ^2 statistic rejects the null model. Note that I(A;X) is normally distributed in the accuracy test because only the δ_{ij}'s are random variables under the hypothesis that the *probabilistic model* is correct, while (2n) I(A;X) is chi-squared distributed in the significance test because both the δ_{ij}'s and the $p(a_j|\underline{X}_i)$'s are random variables under the hypothesis that the *null model* is correct.

This three-part test of "usefulness", "accuracy", and "significance" is illustrated in figure 1. The model is a standard logit model without choice specific constants. The choice set consists of seven shopping centers in the suburbs north of Chicago and the explanatory variables are factor scores for each individual along six dimensions: variety, quality, atmosphere, value, layout, and parking. The dependent variable was first preference and the sample size is 99.

[Insert Figure 1 here.]

The model is overwhelmingly significant with respect to the equally likely null model, N_0 , but it only explains 44% of the uncertainty. The model is clearly accurate with respect to N_0 , (99% level), but less accurate with respect to the market share null model, N_1 . (80% level.) Note that the accuracy test is a relative test because the null model appears in the test.

[EI(A;X) depends on $p(a_j)$.] In this application, the model was not statistically rejected, but the accuracy test relative to N_1 was one stimulus that led to further investigation. The final model, presented in Hauser and Koppelman [8], required statistical corrections for choice based sampling (Manski and Lerman [18]).

6. SUCCESSIVELY MORE POWERFUL NULL HYPOTHESES

The example in figure 1 illustrates how important null hypotheses are in the choice of a test. Fortunately the information test provides a useful generalization that helps overcome the problem of selecting a null hypothesis. To begin this discussion consider the following formal notation.

Call the equally likely null hypothesis N_0, $(p(a_j) = 1/J)$ and call the market share proportional null hypothesis, N_1, $(p(a_j) = ms_j)$. Using the theory introduced in equations 1 to 6, one can compute the observed information and the entropy relative to either null model. Let $I_1(A;X)$ be the observed information relative to N_1, let $H_1(A)$ be the entropy relative to N_1. (See equations 5 and 6.) Similarly let $I_0(A;X)$ and $H_0(A)$ be computed relative to N_0. (Substitute $p(a_j) = 1/J$ in equations 5 and 6.) Finally let $I_0(A;N_1)$ be the observed information of N_1 relative to N_0. (Substitute $p(a_j|\underline{X}_i) = ms_j$ and $p(a_j) = 1/J$ in equation 6.)

The first important results are that $I_0(A;N_1)$ can be more simply represented and that $I_0(A;X)$ can be computed from component parts.

Theorem 6: The incremental information of N_1 relative to N_0 is equal to the reduction in entropy in going from N_0 to N_1, i.e.,

$$I_0(A;N_1) = H_0(A) - H_1(A)$$

Proof:

$$I_0(A;N_1) = (1/n) \sum_{i=1}^{n} \sum_{j=1}^{J} \delta_{ij} \log \frac{ms_j}{(1/J)}$$

Thus:

$$I_0(A;N_1) = (1/n) \sum_{i=1}^{n} \sum_{j=1}^{J} \delta_{ij} \log ms_j - (1/n) \sum_{i=1}^{n} \sum_{j=1} \delta_{ij} \log (1/J)$$

Switching the order of the summation and noting that $\Sigma\delta_{ij}$ over i choosing j equals ms_j and that $\sum_{i=1}^{n} \sum_{j=1}^{J} \delta_{ij} = n$ yields:

$$I_0(A;N_1) = -(-\sum_{j=1}^{J} ms_j \log ms_j) + (-\sum_{j=1}^{J} (1/J) \log (1/J))$$

$$= -H_1(A) + H_0(A)$$

which completes the proof.

Theorem 7: The information relative to N_0, $I_0(A;X)$, is equal to the information relative to N_1, $I_1(A;X)$, plus the information of N_1 relative to N_0, $I_0(A;N_1)$, i.e.,

$$I_0(A;X) = I_0(A;N_1) + I_1(A;X)$$

Proof: Simlar to theorem 6.

Together theorems 6 and 7, which can be proven for any set of null hypotheses, provide very useful results. Taking N_0, the equally likely hypothesis, as the state of no knowledge one can view information as coming successively first by the hypothesis, N_1, which tells only market shares and then incrementally from the model $p(a_j|\underline{X}_i)$ for all i. Furthermore, the "no knowledge entropy", $H_0(A)$, can be viewed as being successively reduced, first to $H_1(A)$ by the market share information, N_1, and then to the estimated residual entropy, $\hat{H}(A|X)$. (Note that $\hat{H}(A|X)$ is independent of both N_0 and N_1.)

A practical advantage of theorems 6 and 7 is that while $I_0(A;X)$ may be difficult to compute, $H_0(A)$ and $I_0(A;N_1)$ are given by simple formulae. Thus $I_*(A;X)$ can be computed relative to any null hypothesis by simple addition and subtraction once $I_0(A;X)$ is known. For example:

$$H_0(A) = -\sum_{j=1}^{J} (1/J) \log (1/J) = \log J$$

$$I_0(A;N_1) = \log J + \sum_{j=1}^{J} ms_j \log ms_j$$

A point of further interest is that theorems 6 and 7 apply to the expected information measure only if $(1/n) \sum_{i=1}^{n} p(a_j,\underline{X}_i) = ms_j$, i.e. only if the model is constrained to correctly predict the market shares. Thus $I_0(A;X) - I_1(A;X)$ is only equal to $EI_0(A;X) - EI_1(A;X)$ when the predicted market shares are constrained. This is why the test of accuracy is actually a test relative to the null hypothesis.

Once the information measure is extended to test the comparison between simple null hypotheses like N_0 and N_1, the generalization is straightforward to other null hypotheses or to successively stronger models. For example, when choice specific constants were added to the model in figure 1, they explained an additional 3.1% of the uncertainty.

An important problem in practice is when the choice set varies across individuals. This problem can be addressed with the information test by selecting a null model, N_2, which assumes that the choice set and nothing else is known. This test is illustrated in a study by Silk and Urban [24] on deodorants. There were 18 brands on the market but the average size of the choice set was only 3 brands.

Define the null model, N_2, as follows:

Let J_i = the number of alternatives in individual i's choice set

then the null probabilities, p^o_{ij}, are given as

$$p^o_{ij} = \begin{cases} 1/J_i & \text{if alternative } a_j \text{ is in individual i's choice set} \\ 0 & \text{otherwise} \end{cases}$$

In the study, the explanatory variable was a ratio scaled preference measure calculated from constant sum paired comparisons (Torgenson [26]). The dependant variable was last brand purchased. The model was a one-parameter logit model linking preference to probability of choice. First preference recovery was 83%.

Relative to the equally likely hypothesis $(N_0, p_j=1/18)$, the logit model explained 80% of the total uncertainty. But N_2 explains 62% of that uncertainty and the logit model adds only 18% to that. Thus N_2 represents a significant amount of information and is an extremely strong assumption. (In a category like deodorants where the choice set is determined more by each consumer's interest than by product availability, knowledge of everyone's choice set contains considerable preference information.)

Finally, as is shown in Figure 2, the information test can compute information as coming first from N_1 relative to N_0, then incrementally from N_2 relative to N_1, and finally from the logit model (X) relative to N_2. This can be done even though the implicit parameters for N_1 are not a subset of N_2 or of those for the logit model.

[Insert Figure 2 here.]

7. FREQUENCY OF CHOICE

A final problem that the information test can address is the problem encountered when market research data is collected from a consumer panel. In this case, observed choice is not a one-time occasion, but rather the consumer makes repeated purchases over time. Frequencies rather than (0,1) events are observed.

Perfect information would result from correctly predicting every choice occasion for every individual, i.e. $p_{ijk} = \delta_{ijk}$. (k indexes the choice occasion.) Unfortunately, without situational variables, probabilistic choice models predict probabilities, p_{ij}, that are independent of choice occasion. Thus $H_0(A) = I_0(A;\text{perfect information})$ is not possible even in theory.

This problem can be addressed by defining a new perfect model, P_2, such that $p_{ijk} = f_{ij}$, where f_{ij} is the observed frequency. The new entropy, $G_0(A) = I_0(A;P_2)$, then becomes the base uncertainty, and a new measure, $V_0^2 = I_0(A;X)/G_0(A)$, gives the percent of "explainable" uncertainty that is actually explained by the model. Alternatively, a figure such as figure 2 can be produced and $G_0(A)$ can be compared to $H_0(A)$ to determine the percent of unexplainable uncertainty.

Thus, in addition to indicating the relationships between the lower bounds (null hypothesis), the information test is readily extendable to indicate the relationships among the upper bounds (explainable uncertainty).

8. SUMMARY

This paper addresses the fundamental problem of testing probabilistic predictions against 0,1 observed events by deductively deriving an information theoretic test. Under standard null hypotheses this test reduces to the likelihood ratio index, ρ^2, now in common use. One advantage of the information theoretic approach is that it gives both theoretic rigor and an intuitive appeal to this hitherto heuristic measure. But the information test goes beyond that. It indicates how to extend ρ^2 to complex null hypotheses, and how to change the upper bound on explainable uncertainty. Together these extensions make clear many interesting and complex effects. For example, the contribution of choice set restrictions is quantified in figure 2.

The information test measures usefulness, but it also statistically measures accuracy. A two-tailed normal test indicates whether the information statistic is reasonable under the hypothesis that the probabilistic model is correct. This test, which is relative to the chosen null hypothesis, provides the model builder with an important diagnostic tool to assess the validity of a probabilistic model.

Finally, under the appropriate null hypothesis, $(2n)I(A;X)$ is the standard χ^2 statistic used to measure statistical significance.

Thus the information test gives a three-stage disaggregate test of usefulness, accuracy, and significance. It provides useful generalizations for existing disaggregate tests, makes possible new comparisons among models and hypotheses, and indicates the intuitive and statistical relationships among model tests. These advantages are sufficient to add this test to those tests which modelers use to select probabilistic models. To date, the test has been used to test a new ranked probability model (Hauser [6]), to test independence of irrelevant alternatives (Silk and Urban [24]), to compare various means to model consumer perceptions (Hauser and Koppelman [7]), to test the relative effects of attitudinal and engineering variables in logit models (Lavery [17], to test a bargain-value model of brand choice (Keon [15]), and to test location models for financial services.

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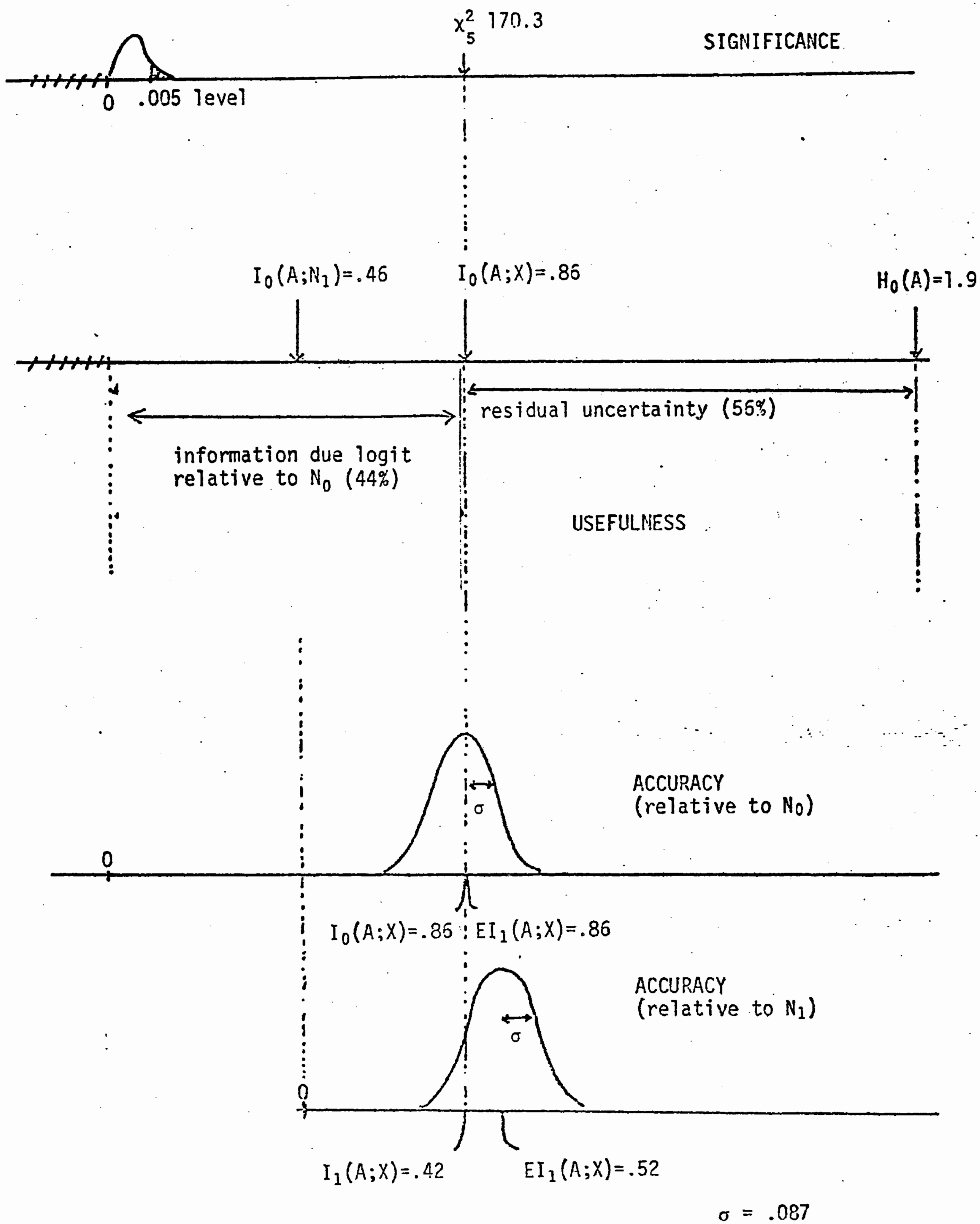

Figure 1: Honest reward/information test applied to shopping center preference prediction

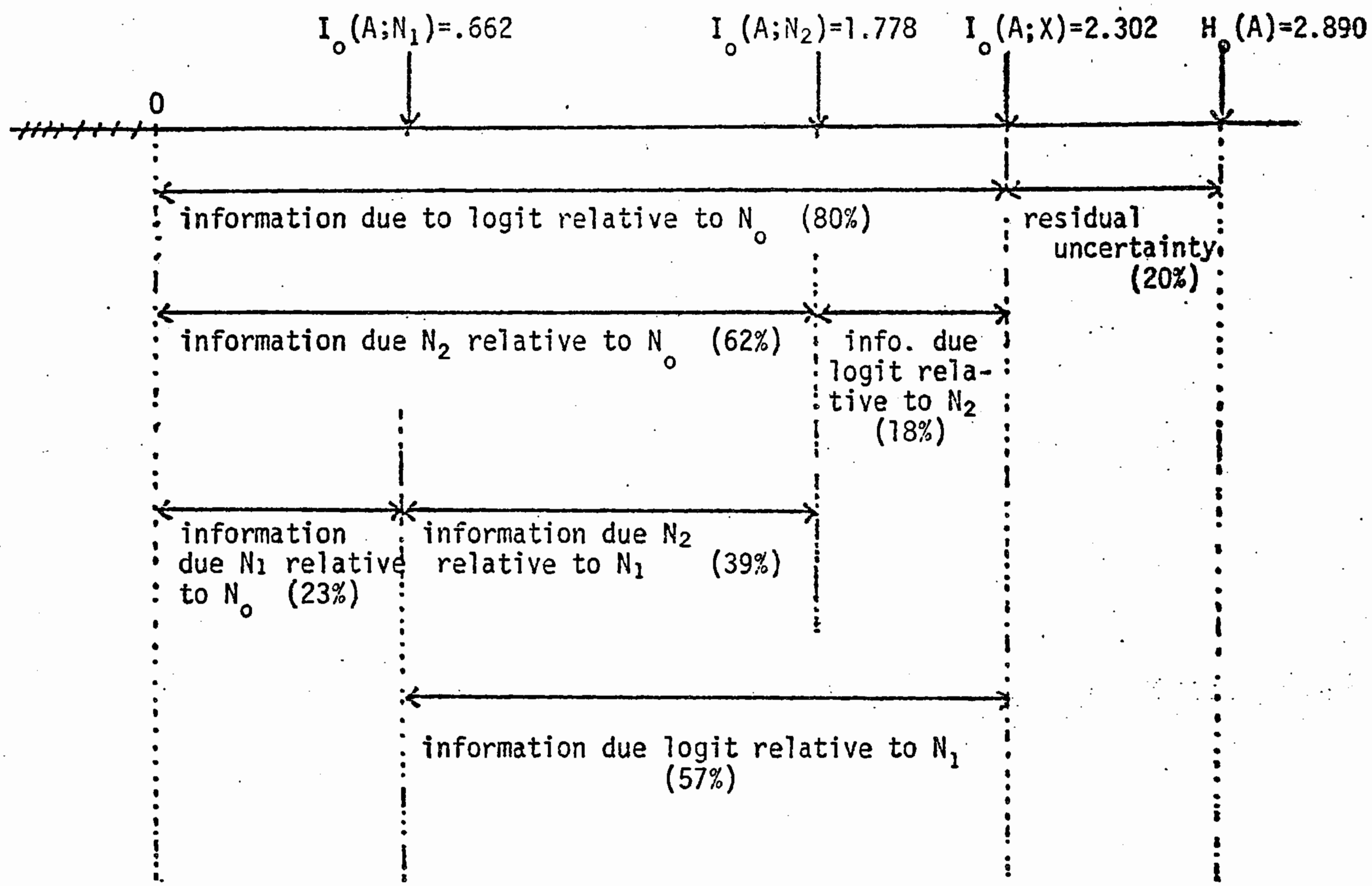

Figure 2: Information test when the choice set varies. (Deodorant example)