ESTIMATION OF RESPONSE VARIANCES FROM INTERVIEW-REINTERVIEW SURVEYS

By

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1. INTRODUCTION

Response errors are present in survey data when the observed responses differ from the "true values" for the individuals involved. Response errors in sample-survey data may arise because of the effects of the enumerators (in personal-interview surveys), imperfections in the construction of questionnaires, or the existence of variability of respondent responses under the same survey conditions. The presence of response errors has important bearing upon the planning and analysis of sample surveys. The estimation of means for given variables and the estimation of liner regression models are two situations in which response errors in the observations require careful attention.

In the early work of the Indian Statistical Institute the importance of estimating the effect of non-sampling errors was recognised. The use of interpenetrating samples thus became an integral feature of the Institute's sample surveys [13]. The U.S. Bureau of the Census initiated post-enumeration surveys for the measurement of the effects of response errors in censuses of agriculture and business in the latter half of the nineteen forties [5]. In the earlier post-enumeration surveys a proportion of the populations involved was reinterviewed by more highly trained enumerators with a view to evaluating the biases in the census procedures. These studies led to the improvement of census and survey procedures and to the consideration of response variability. Many of the studies in applied sample-survey research considered enumerator variability and used the methods of

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the analysis of variance to estimate the variance component associated with enumerators [4, 10, 12, 15]. The paper by Hansen, Hurwitz and Bershad [8] presents some of the conceptual ideas for the response model formulations that have evolved in the U.S. Bureau of the Census. The basic response model has been discussed and applied in several publications including [9, 14, 16, 17]. The model was extended somewhat by Fellegi [6] to consider replicated responses. The U.S. Bureau of the Census publication [17] presents estimates for response variances based on a study in which sample individuals were reinterviewed. A review of these papers is presented by Battese [1].

In this paper we assume that interview and reinterview responses are obtained, under the same survey conditions, from each sample individual. Response biases are not considered in our analysis. We present estimators for the variances of the sampling deviations and the enumerator and respondent components of the response errors. Also defined are estimators for the variances of the variance-component estimators. Empirical results are presented for a survey that was conducted in 1970 by the Statistical Laboratory of Iowa State University.

2. Survey Design

A replicated survey design, in which each individual is interviewed more than once, is required in order to estimate the variances of respondent-response errors. We assume that two interviews are obtained from each individual in the sample and that the interviews are relatively close in time so that the responses can be considered measurements of the same quantities. Every enumerator conducting reinterviews is assumed to be ignorant of the initial responses obtained from the respondents that are in his reinterview assignment.

We assume that a simple random sample of $rm(m-1)$ respondents is chosen from the population of interest and m enumerators are randomly selected from a large pool of available enumerators. The sample respondents are randomly divided into $m(m-1)$ groups, each of r respondents. For convenience, these groups are referred to as "respondent groups" and are denoted by s_{ij}, $i \neq j$, $i, j=1, 2, \ldots, m$. The respondent group, S_{ij}, is a group of r respondents that is interviewed by the i-th enumerator in the first (interview) survey and by the j-th enumerator in the second (reinterview) survey. With this survey design a given enumerator does not reinterview respondents that he interviewed in the first survey, but reinterviews some respondents that were interviewed by the other $m-1$ enumerators. The i-th enumerator, thus, interviews the $(m-1)$ respondent groups, $\{S_{ij} : j=1, 2, \ldots m ; j \neq i\}$, and reinterviews the $(m-1)$ respondents groups $\{S_{ij} : j=1, 2, \ldots, m ; j \neq i\}$. This interpenetrating and replicated survey design is assumed to be applied to several statra of the population of interest.

In actual surveys it may not be possible to ensure that all respondent groups contain the same number of respondents. In Section 6 of the paper we report some of the analyses of data from an interview-reinterview survey in which respondents were selected in an area sample. For this survey the respondent groups were of approximately the same size and so appropriate modifications to the procedures of Section 3 through 5 were required.

3. Model For Survey Responses

The survey responses for the respondents that are interviewed by the i-th enumerator and reinterviewed by the j-th enumerator are given by

$$Y_{ik1} = y_k + \beta_i + \varepsilon_{ik1}, \quad k=1, 2, \ldots, r \qquad \ldots(1a)$$

$$Y_{jk2} = y_k + \beta_j + \varepsilon_{jk2}, \quad k=1, 2, \ldots, r \qquad \ldots(1b)$$

where Y_{ik1} and Y_{jk2} denotes the interview and reinterview responses, respectively, obtained from the k-th respondent in the respondent group, S_{ij} ; y_k denotes the true value for the k-th respondent in the respondent group, S_{ij} ; β_i denotes the random effect of the i-th enumerator ; ε_{ik1} and ε_{jk2} denote the respondent-response errors that are associated with the interview and reinterview responses respectively ; and r denotes the number of respondents in the respondent group.

We assume that for each stratum the errors, β_i and ε_{ikt}, $t=1,2$, are independently distributed with zero means and variances σ^2_β and $\sigma^2_{\varepsilon_k}$,respectively, where $\sigma^2_{\varepsilon_k}$ is the response variance for the k-th respondent. We assume that β_i and ε_{ikt} are uncorrelated with the true values.* The true value, y_k, is assumed equal to the sum of a stratum mean, μ, and a "sampling deviation" e_k. The sampling deviations for all individuals in the population are assumed to have zero mean and variance σ_e^2.

We assume that the response errors, ε_{ikt}, have finite fourth moments. Further, if the population from which the sample is selected is infinite, we assume that the sampling deviations have finite fourth moments.

Our model is relatively non-parametric in that we make few assumptions about the sampling deviations and response errors. We assume that the enumerator effects are constant over time and uncorrelated with the sampling deviations or the respondent response errors. Some have conjectured that non-zero correlations may be introduced by "learning" on the part of enumerators (*e.g.*, Fellegi [6]) but no estimates for this correlation have been reported. A partial test for the presence of such a correlation is obtained by testing for an enumerator-by-time interaction. When these effects were estimated for survey data considered in Section 6 they were found to be statistically not significant. An important assumption of the model is that the response errors associated with the two responses for each respondent are independent. A partial test of this hypothesis in the case of zero-one variables is described in Battese and Fuller[2] where an example from our study fails to refute the hypothesis of independence.

Given the response model, the variance of survey responses, denoted by σ^2 is $(\overline{\sigma_\varepsilon^2}+\sigma_\beta^2+\sigma_e^2)$ where $\overline{\sigma_\varepsilon^2}$ is the mean of the respondent-response variances for the population. The covariance between the responses from two different respondents interviewed by the same enumerator is σ_β^2, given that the correlation between different sampling deviations in a finite population is ignored. Further, it is readily verified that, under the response model (1*a*, *b*) and the specified sampling scheme, the variance of the average of the responses in a given stratum is

*This model is appropriate for variables of the zero-one type if the "true value" is the mean for the population of responses for that individual. This is somewhat different representation from that generally given for the zero-one case (*e.g.* [8]).

$$\text{Var}(\bar{Y}\ldots)=\sigma^2\{1+\rho_e+[2r(m-1)-1]\,\rho_\beta\}/2rm(m-1) \quad \ldots (2)$$

where $\rho_e=\sigma_e^2/\sigma^2$, $\rho_\beta=\sigma_\beta^2/\sigma^2$ and m denotes the number of enumerators in the stratum. This equation demonstrates that enumerator effects can account for a large proportion of the variance if the enumerator workloads are relatively large. If the survey design did not require reenumeration of respondents but specified that all the m enumerators interview $2r(m-1)$ different respondents, then the variance of the stratum mean is reduced by the exclusion of ρ_e from (2). Without reenumeration of sample respondents, however, it is impossible to individully estimate the variances of the sampling deviations and the respondent-response errors.

4. Estimation Of Variance Components

We define transformations of the survey responses to obtain uncorrelated observations that can be used to estimate the variance components. Given the two survey responses from each respondent we consider the difference between the first ahd second responses

$$\underset{ijk}{\overset{(1)}{Z}} \equiv Y_{ik1}-Y_{ik2}$$

$$=(\beta_i-\beta_j)+(\varepsilon_{ik1}-\varepsilon_{jk2}) \quad \ldots (3a)$$

and the sum of the first and second responses

$$\underset{ijk}{\overset{(2)}{Z}} \equiv Y_{ik1}+Y_{jk2}$$

$$=2\mu+(\beta_i+\beta_j)+2e_k+(\varepsilon_{ik1}+\varepsilon_{jk2}) \quad \ldots (3b)$$

for each individual, $k=1, 2, \ldots, r$, in the $m(m-1)$ respondent groups, S_{ij}, $i\neq j=1, 2, \ldots, m$, in each stratum.

Using the observations in (3a) we use least-squares regression to estimate the linear model

$$\underset{ijk}{\overset{(1)}{Z}} = \sum_{t=1}^{m-1} \underset{ijkt}{\overset{(1)}{\psi}} C_t+(\varepsilon_{ik1}-\varepsilon_{jk2}) \quad \ldots (4)$$

$$k=1, \ldots, r;$$

$$i\neq j=1, \ldots, m,$$

where the parameters, C_t, are contrasts among the enumerator effects in a given stratum; and $\underset{ijkt}{\overset{(1)}{\psi}}$ is the value of the coefficient of C_t that corresponds to the observation $Z^{(1)}_{ijk}$. With four enumerators in a stratum ($m=4$) we define the normalized orthogonal contrasts,

$$(\beta_1-\beta_2)/\sqrt{2},\ (\beta_3-\beta_4)/\sqrt{2} \text{ and } (\beta_1+\beta_2-\beta_3-\beta_4)/2.$$

We estimate the average respondent-response variance by

$$\hat{\bar{\sigma}}^2_\varepsilon = \frac{1}{2}\, MS^{(1)} \qquad \ldots(5)$$

where $MS^{(1)}$ denotes the residual mean square from a regression fit of model (4) that combines data from all statra, The variance of this estimator is not estimated by use of normal theory because the assumption that the errors, $\varepsilon_{ik1}-\varepsilon_{jk2}$, in the regression model (4) are normally distributed appears inappropriate for many survey variates. Given that the fourth moments of the response errors, ε_{ikt}, exist, it follows that the variance of the squares of the residuals, $\varepsilon_{ik1}-\varepsilon_{jk2}$, exist. Therefore, a consistent estimator for the variance of our estimator (5) for $\bar{\sigma}^2_\varepsilon$ is

$$\hat{\text{Var}}\,(\hat{\bar{\sigma}}^2_\varepsilon) = \frac{\Sigma\left[\left(\tilde{\varepsilon}^{(1)}_{ijk}\right)^2 - \hat{\bar{\sigma}}^2_\varepsilon\right]^2}{[2p\,(m-1)(rm-1)]^2} \qquad \ldots(6)$$

where the $\tilde{\varepsilon}^{(1)}_{ijk}$ denote the estimated residuals obtained from the regression fit of model (4) ; the summation in the numerator of the variance estimator is over all estimated residuals, $\tilde{\varepsilon}^{(1)}_{ijk}$; and $p\,(m-1)$ $(rm-1)$ denotes the degrees of freedom for the residual mean square, $MS^{(1)}$, given that p is the number of strata in the survey.

Using the observations in (3*b*) we use least-squares regression to estimate the linear model

$$Z^{(2)}_{ijk} = 2\mu + \sum_{t=1}^{m-1} \psi^{(2)}_{ijkt}\, C_t + (2e_k + \varepsilon_{ik1} + \varepsilon_{jk2}), \qquad \ldots(7)$$

$$k=1, 2, \ldots, r\ ;$$

$$i \neq j = 1, 2, \ldots, m,$$

where $\phi^{(2)}_{iikt}$ is the coefficient of the contrast C_t for the observation $Z^{(2)}_{ijk}$. The residual mean square, $MS^{(2)}$, from the regression fit of model (7), that cambines data from all starta, estimates $\left(4\sigma^2_e + 2\bar{\sigma}^2_\varepsilon\right)$. We thus estimate the variance of the sampling errors by

$$\hat{\sigma}^2_e = \tfrac{1}{4}\,[MS^{(2)} - MS^{(1)}]. \quad \text{.. (8)}$$

The variance of this estimator,

$$\text{Var}\left(\hat{\sigma}^2_e\right) = \frac{1}{16}\,[\text{Var}\,(MS^{(2)}) + \text{Var}\,(MS^{(1)})],$$

is estimated by first estimating Var (MS^2) by using the squares of the estimated residuals from the regression fit of model (7) as in (6).

From the estimated regressions for models (4) and (7), we obtain two sets of uncorrelated estimators for the contrasts among the enumerator effects. The estimated contrasts obtained in the separate regressions involving models (4) and (7) ore uncrrelated if the numbers of respondents in the respondent groups are the same. We combine the two estimators for the contrasts into a single estimator

$$\hat{C}_t = \frac{\left\{\dfrac{\hat{C}^{(1)}_t}{\hat{V}^{(1)}_t} + \dfrac{\hat{C}^{(2)}_t}{\hat{V}^{(2)}_t}\right\}}{\left\{\dfrac{1}{\hat{V}^{(1)}_t} + \dfrac{1}{\hat{V}^{(2)}_t}\right\}} \quad \text{...(9)}$$

where $\hat{C}^{(1)}_t$ and $V^{(1)}_t$ are the estimates for the contrast, C_t, and the variance of the estimator for the contrast obtained from the regression fit of model (4) ; and $\hat{C}^{(2)}_t$ and $\hat{V}^{(2)}_t$ are the estimates for the contrast, C_t, and the variance of the estimator for the contrast obtained from the regression fit of model (7). The square of the estimated contrast, $\hat{C}_t$, estimates the variance of the enumerator effects plus the variance of the estimator defined by (9). We estimate variances of the squares of the combined contrasts of (9) on the basis of normal theory. Because the errors in the contrasts are weighted averages of a large number of observations, by the Central Limit Theorem, they should be approximately normally distributed. The variance of $\hat{C}_t^2$ is then initially estimated by

$$2\left[\frac{1}{\hat{V}_t^{(1)}}+\frac{1}{\hat{V}_t^{(2)}}\right]^{-2}$$

The variance component, σ_β^2, is thus estimated by the weighted regression of the observations

$$\hat{C}_t^2-\left[\frac{1}{\hat{V}_t^{(1)}}+\frac{1}{\hat{V}_t^{(2)}}\right]^{-1},$$

on a column of ones. If the estimated variance component, $\hat{\sigma}_\beta^2$, is positive, the variance of the $\hat{C}_t^2$ observations is estimated by

$$2\left\{\hat{\sigma}_\beta^2+\left[\frac{1}{\hat{V}_t^{(1)}}+\frac{1}{\hat{V}_t^{(2)}}\right]^{-1}\right\}^2$$

and the regression is re-computed with these new weights.

While the estimation of sampling and non-sampling variances is useful for making decisions about survey designs and the estimation of variances of statistics of the mean type, those interested in more detailed analyses of survey observations may require additional information. For example, for the estimation of regression relationships among survey variates, information is often required on the correlation structure of the response errors. The existence of response errors in the survey observations may imply that the errors-in-the-variables bias of least-squares estimators should seriously be considered. Fuller [7] defines several errors-in-variables models and presents approximately unbiased estimators for the parameters in each of the linear models. An illustration of the computations that are involved when the response errors in the variates of the model are uncorrelated si presented in Warren et al [18].

Given the response model (1*a*, *b*) for each variate in the survey, the covariances between the respondent-response errors are estimated with use of the estimated residuals obtained by fitting the linear model (4). The covariance matrix is estimated by dividing the sum-of-squares-and-products matrix of the residuals by twice the residual degrees of freedom. The difference between the sum-of-squares-and-products matrix of the estimated residuals for model (7) and the sum-of-squares-and-products matrix of the estimated residuals for model (4), divided by four times the residual degrees of freedom, estimates the covariances matrix of the sampling deviations in the survey variates.

5. Empirical Results

In 1970 the Statistical Laboratory of Iowa State University conducted a survey of Iowa farmers in which two responses were obtained from each sample respondent. The purpose of the survey was to estimate the response variances of some of the major variates involved in the June Enumerative Survey of the U.S. Department of Agriculture. This survey is a personal-interview farm surveyconducted during early June each year in forty-eight states to estimate land use, crop acreage, livestock numbers and farm labour in the United States. About 1350 enumerators are involved in the collection of these data. In the 1972. June Enumerative Survey 360 area segments were drawn within Iowa and thirty-five field enumerators personally interviewed on an average of sixty farm operators.

The 1970 interview-reinterview survey involved drawing an area sample of farmers within each of three geographic areas (strata) in Iowa. Four enumerators ($m=4$) were assigned to each of these three strata ($p=3$). Within each strata there were thus twelve respondent groups. The farmers selected in the survey were interviewed by two different enumerators, one month apart, according to the design presented in Section 2. A total of 262 farmers were interviewed twice and the average number in a respondent group was about seven. More details of the survey, together with earlier analysis of the data, are presented in. [3]

The average responses and the ertimates for the variance components for the thirteen variates investigated are presented in Table 1. About half of the estimated variates of the enumerator effects are positive, but none are significantly larger than their estimated standard errors. We recognize, however, that our survey involved few enumerators and the enumerator variances are estimated with less than nine degrees of freedom. For all thirteen variates the estimated variance of enumerator effects is less than the estimated variance of respondent-response errors which is estimated with about two hundred and fifty degrees of freedom. The enumerator component of all the variates, except "idle acres", is estimated to be less than one percent of the total variance. For the thirteen variates the average ratio of the estimated variance of enumerator effects to the total variance is only 0.0015. However, it is not believed that enumerator effects contribute equally to the variability of variates in a survey. Interviewer effects may be larger for variates having a high degree of complexity or ambiguity.

The average of the estimates for the multiple, $[1+(\bar{n}-1)\,\rho_\beta]$, by which the variance of strata mean responses is increased due to enumerator effects with the enumerator workloads, $\bar{n}$, of twenty-one and sixty are 1.030 and 1.089, respectively. The enumerator workloads of twenty-one and sixty approximate those for each trial of our survey and for the Statistical Reporting Service's June Enumerative Survey in Iowa. For some of the acreage and livestock items enumerator effects contribute to a large proportion of the variance of average responses when workloads are as large as those of the June Enumerative Survey in Iowa.

Hurley, et al. in their study of enumerator variance in the 1959 Census of Agriculture[11], considered some variables similar to those in this study. Their results are presented in terms of coefficients of variation for the respose variance of totals of average-sized clusters. By assuming that the clusters were of equal size, the relative enumerator variance for a cluster total, v^2, [11, p. 102] is expressed in terms of the enumerator variance by

$$v^2=\frac{\tilde{\sigma}^2_\beta}{(\bar{x})^2} \qquad \ldots(10)$$

where $\bar{x}$ denotes the average volue per farmer. The estimates for enumerator variances obtained from the results of Hurley, et al. [11] and Equation (10) are presented with the estimates from our study in Table 2. The variate "acres in the place" in [11] is compared with "acres operated" in our study. Except for "acres of corn", the estimated enumerator variances from the two studies are of similar magnitude even though the size of the farm operations in 1970 was significantly greater than in 1959.

TABLE 1

Average values and estimated variance components for variates from the 1970 interview-reinterview survey*

Variate	$\bar{Y}$	$\hat{\bar{\sigma}}^2_\epsilon$	$\hat{\sigma}^2_\beta$	$\hat{\sigma}^2_e$
Acres operated	297.8	480.4 (172.5)	12.8 (11.6)	33399.5 (5913.8)
Acres rented	165.5	1468,0 (608.3)	51.1 (32.2)	25643.6 (2703.5)
Acres of corn	112.6	137.0 (37.3)	2.9 (3.1)	11570.2 (2789.2)
Acres of soyabeans	49.8	86.1 (35.8)	0.8 (1.8)	3325.7 (877.5)
Acres of permanent pasture	33 2	456.6 (116.6)	−5.6 (7.3)	2070.0 (845.2)
Acres of hay	19.8	299.5 (217.8)	−1.2 (4.3)	321.5 (206.3)
Idle acres	19.9	274.1 (174.5)	14.6 (10.2)	312.0 (218.8)
Cattle and calves	101.4	1101.0 (486.8)	−6.9 (18.3)	50345.3 (23616.7)
Breeding hogs	26.5	213.6 (114.9)	4.4 (5.5)	842.5 (157.2)
Marcy-May farrowings	13.5	61.9 (23.9)	−1.3 (1.0)	288.1 (75.4)
June-August ferrowings	8.6	33.0 (8.2)	− 0.4 (0.5)	166.4 (28.6)
Chickens (units of ten)	14.4	29.90 (10.18)	2.15 (1.66)	2718.52 (1684.50)
Non-family workers, 1962	3.05	5.62 (1.32)	−0.01 (0.08)	7.96 (1.81)

*The estimated standard errors are given below the estimates for the variance components.

Our results indicate that the respondent-response errors are a particularly important source of total variability of responses. For all thirteen variates the estimated average respondent-response variances are greater than their estimated standard errors. Almost all of these estimated variances are significantly greater than zero. For variables such as "acres of permanent pasture", "acres of hay" and "idle acres" confusion associated with the definition of these concepts may be responsible for the large response variability. The large respondent-response error variances for variates such as sow farrowings in previous quarters and labour use in the previous year may be due to poor recall or guessing on the part of the respondents. The incidence of such response variability may indicate the need for better questions or the introduction of alternative definitions or concepts.

The correlations between the respondent-response errors for the thirteen variates are presented in [3]. A large number of the estimated correlations were found to be significantly different from zero. The use of the sample estimates of the response variances and covariances to obtain approximately unbiased estimators for the parameters in linear models is discussed by Fuller. [7]

TABLE 2

Estimates for enumerator variances from two farm surveys

Variate	*The 1959 Study**			*The 1970 Study***	
	$\bar{x}$	v	$\tilde{\sigma}^2_\beta$	$\bar{Y}$	$\hat{\sigma}^2_\beta$
Acres in the place	119.2	0.035	17.4	297.8	12.8 (11.6)
Acres of corn	31 9	0.096	9.4	112.6	2.9 (3.1)
Acres of soyabeans	11.8	0.060	0.5	49.8	0.8 (1.8)
Number of cattle	14	—	—	101.4	—6.9 (18.3)
Number of chickens	144	—	—	144.2	214.6 (166.0)

*These values are from Hurley, et al. [11] in which negative estimates for the relative variances, v, were omitted.

**These values art for this study and are taken from Table 1.

SUMMARY

A simple components-of-variance model, involving enumerator effects, sampling deviations and respondent-response errors, is defined for the analysis of data from personal-interview surveys containing both initial interview and reinterview responses. Estimators for the variances of enumerator effects and sampling deviations and the average of the respondent-response variances are defined. The estimation of variances of the variance-component estimators is also considered. Empirical results are given for some of the variates on which data was collected in a survey of Iowa farm operators.

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