Transportation Study Committee, under whose auspices this work was executed. We are responsible, however, for the facts and accuracy of the data presented here. The contents reflect our views and are not necessarily those of any of the participating agencies.

REFERENCES

1. D.A. Dillman. Mail and Telephone Surveys: The Total Design Method. Wiley, New York, 1978.
2. W. Wermuth. Uncertainty of Household Travel Surveys in Methodological and Measurement Contexts. In New Horizons in Travel-Behavior Research (P.R. Stopher, H. Meyburg, and W. Brög, eds.), Heath, Lexington, MA, 1981.
3. P.R. Stopher and A. Meyburg. Survey Sampling and Multivariate Analysis for Social Scientists and Engineers. Heath, Lexington, MA, 1979.
4. W. Brög and A.H. Meyburg. Consideration of Nonresponse Effects in Large-Scale Mobility Surveys. TRB, Transportation Research Record 807, 1981, pp. 39-46.
5. A.H. Meyburg and W. Brög. Validity Problem in Empirical Analyses of Non-Home-Activity Patterns. TRB, Transportation Research Record 807, 1981, pp. 45-50.
6. W. Brög and A.H. Meyburg. The Nonresponse Problem in Travel Surveys--An Empirical Investigation. TRB, Transportation Research Record 775, 1980, pp. 34-38.
7. Southeast Michigan Regional Travel Survey: Final Report 5. Schimpeler-Corradino Associates, Coral Gables, FL, June 1981.
8. K.A. Brownlee. A Note on the Effects of Nonresponse on Surveys. American Statistical Association Journal, 1957, pp. 29-32.
9. M. Young and P. Willmott. The Symmetrical Family. Panther Books, New York, 1973.
10. W.J. Goudy. Interim Nonresponse to a Mail Questionnaire: Impacts on Variable Relationships. Iowa Agriculture and Home Economics Experiment Station, Ames, Journal Paper j-8456, 1976.
11. M.N. Donald. Implications of Nonresponse for the Interpretation of Mail Questionnaire Data. Public Opinion Quarterly, Vol. 24, 1961, pp. 99-114.
12. M. Wright. Response and Non-Response to a Postal Questionnaire. Greater London Council, Res. Memorandum RM-548, 1978.
13. E.W. Waltz and W.L. Grecco. Evaluation of a Mailed Planning Survey. HRB, Highway Research Record 472, 1973, pp. 92-107.
14. D. Galin. How Reliable Are Mail-Surveys and Response Rates: A Literature Review. Journal of Marketing Research, 1975, pp. 440-453.
15. L. Kanuk and C. Berenson. Mail Surveys and Response Rates: A Literature Review. Journal of Marketing Research, 1975, pp. 454-473.
16. M.J. O'Neil. Estimating the Nonresponse Bias Due to Refusals in Telephone Surveys. Public Opinion Quarterly, Vol. 42, Summer 1979, pp. 218-232.
17. W.G. Cochran. Sampling Techniques. Wiley, New York, 1963.
18. C.H. Fuller. Weighting to Adjust for Survey Nonresponse. Public Opinion Quarterly, Vol. 38, 1975, pp. 239-246.
19. I. Wayne. Nonresponse, Sample Size, and the Association of Resources. Public Opinion Quarterly, Vol. 39, 1976, pp. 557-562.
20. D.J. Bem. Self-Perception Theory. In Advances in Experimental Social Psychology (L. Berkowitz, ed.), Academic Press, New York, 1972.
21. I.M. Sheskin, G.S. Spivack, and P.R. Stopher. The Dade County On-Board Transit Survey. Transit Journal, 1981, pp. 15-28.
22. Transit Development Program 1980-1985. Dade County Office of Transportation Administration, Miami, FL, March 1980.

Small-Sample Home-Interview Travel Surveys: Application and Suggested Modifications

PETER R. STOPHER

A method was put forward three years ago for estimating the sample sizes needed for travel surveys from information contained in earlier household surveys. The method showed that very small samples (of the order of 1000-3000 households) could be used to update trip rates and the succeeding steps of travel forecasting by using the information on standard deviations contained in 1950 and 1960 data. Despite the potentially far-reaching impacts of this method, little use appears to have been made of it. An application of the method is described that shows that, in a region of more than 1.6 million households, a sample of 2600 households was estimated as being sufficient to achieve measurement of trip rates to within ±5 percent sampling error with 90 percent confidence. After the survey had been executed, measured trip-rate variances and sample distribution were compared with those used for sample-size estimation from 1965 data. Although variances and distributions were found to have changed quite substantially, the sample was found to have produced trip-rate estimates that were within or no more than ±1.5 percent beyond the specified design sampling error. Second, it was found that the method originally put forward does not provide efficient or intuitively appealing samples for the common case of stratified trip-generation relationships. For this case, a procedure is put forward to specify the required levels of error in each stratum in such a way that account is taken of the magnitude of the trip rate and the size of the stratum. It is shown that this procedure is more efficient and that it yields more intuitively appealing sample distributions than the assumption implied by the earlier procedure of an identical percentage error for each stratum.

Many of the large urban areas of the United States are continuing in the 1980s to do transportation planning by using forecasting procedures calibrated on data collected in the 1960s. These data were generally collected by means of a random or systematic sample of households; the sampling rate was from 1 to 5 percent of the regional population. In urban areas of 100 000 population and more, this might have involved anywhere from a few thousand to 20 000 or 30 000 households in the sample. Because of the high cost of such surveys, few have been conducted since about 1972, and it is unlikely that funding will exist in the foreseeable future for such major surveys. Currently, the cost of a household interview such as that used in the 1960s data collection is anywhere from about $60 to $200; some instances of specialized data collection run well in excess of even $200. Such unit costs translate into survey costs of, perhaps, $200 000 for a small urban area of 100 000 population to several million dollars for urban areas such as New York, Chicago, and Los Angeles.

Given the age of the current primary data bases, the realities of urban growth and change of the past two decades, shifts in economic trends and patterns, and the emergence of higher fuel costs and potentially uncertain fuel supply, it is not surprising that many urban areas are concerned now to generate a new planning data base and provide the means to update or rebuild their travel-forecasting procedures. Given the tremendous costs of repeating the 1960s data collection and the dwindling of available planning funds in real dollars, the interest of many planners has turned to small samples, where "small" connotes absolute sample sizes of less than 5000 households, irrespective of urban-area size.

A major impetus was given to this direction by the work of Smith (1), which showed how to use the information collected in earlier surveys to design an efficient sample of very small size for updating travel-forecasting procedures. Smith's method uses the standard deviations obtainable from the 1960s data to compute coefficients of variation for relevant travel measures and then to compute the sample sizes needed to achieve a prescribed accuracy at specified confidence limits in new measurement of those variables. Smith showed that, for a particular scheme of trip-generation estimation, a sample size below 1000 households would achieve an accuracy of ±5 percent with 90 percent confidence for the estimation of trip rates. He then showed that this same sample size would be more than adequate to calibrate a gravity model of trip distribution and a modal-split model. Despite the significance of these findings, there appear to have been few attempts to utilize Smith's procedure since it was published. This paper reports on one such application of the formula and shows comparisons between the computations of error and sample size made from the original 1960s data and those from the new data. Although some changes in values were found, it is notable, as shown in subsequent sections of this paper, that these varying values would not have affected the sample sizes materially. The paper also describes a problem encountered with Smith's procedure and proposes a modification that should prove more useful in the future.

Table 1. AID groups identified by area type.

Area Type	Subgroup	Characteristic: Income Group	Automobiles	Household Size	Life-Cycle Group
1	14	1	0	All	3
	15	1	0	All	1,2,4,5
	18	1	1,2+	1,2	All
	19	1	1,2+	3+	All
	4	2,...,5	All	1	All
	10	2,3	All	2	All
	16	2	All	3+	All
	17	3	All	3+	All
	12	4,5	All	2,3+	2,3,4
	13	4,5	All	2,3+	1,5
2	18	1	0	1,2	All
	19	1	1,2	1,2	All
	16	2-5	All	1	All
	17	2-5	All	2	All
	6	All	0	3+	All
	8	All	1	3+	3,4
	9	All	1	3+	1,2,5
	10	1,2,3	2+	3+	All
	14	4,5	2+	3+	1-4
	15	4,5	2+	3+	5
3	10	All	All	1	All
	12	All	All	2	3,4
	13	All	All	2	1,2,5
	8	All	0,1	3+	3,4
	9	All	0,1	3+	1,2,5
	6	All	2+	3+	1-4
	7	All	2+	3+	5
4	12	1	All	1,2	All
	14	2-5	All	1	All
	15	2-5	All	2	All
	8	All	0,1	3+	2,3,4
	9	All	2+	3+	2,3,4
	6	All	0,1	3+	1,5
	10	1,2,3,4	2+	3+	1,5
	11	5	2+	3+	1,5

Notes: Symbols used in this table are defined as follows. Income group: 1 = < $4000/year, 2 = $4000 - 5999/year, 3 = $6000 - 7999/year, 4 = $8000 - 9999/year, 5 = > $10 000/year; automobiles: 0 = no automobile available, 1 = one automobile available, 2+ = two or more automobiles available; household size: 1 = one-person household, 2 = two-person household, 3 = three-person household or more; life-cycle groups: 1 = head of household <35 years, no children <18; 2 = head of household 35-65 years, no children <18; 3 = head of household 65 years or more, no children <18; 5 = head of household any age, youngest child 6-18 years.

Table 2. Trip rates and total trips by area type.

Area Type	Trip Rate	Households (1980 estimate)	Total Trips (1980 estimate)
1	1.87	84 484	157 985
2	3.91	191 886	751 157
3	5.21	1 034 090	5 389 574
4	5.19	344 023	1 784 929
Total		1 654 483	8 083 645

PRACTICAL SAMPLE

The critical variable for sample-size determination was defined to be the household tripmaking rate. The existing trip-generation forecasting procedure consists of four linear-regression equations with the independent variables of family life cycle, income, household size, and automobile availability; stratifications to four equations are on the basis of area type. Area type was defined in terms of a combination of employment density and residential density, such that the first area type comprises zones with a high density of employment, whereas the second, third, and fourth are zones of low employment density and residential density that is high in area type 2 and declines successively to area type 4.

The decision was made to seek the same accuracy level in each area type by specifying that trip rates in each area type be estimated to within ±5 percent with 90 percent confidence. While the original trip-generation modeling from 1965 data had been done by using regression, the data were reanalyzed as rates by using the Automatic Interaction Detection (AID) procedure to select subgroups within each area type by the other independent variables. AID is essentially a clustering procedure that was used to cluster households by sociodemographic characteristics within area types. Clustering was based on the tripmaking of the households. A total of 35 clusters were identified, as given in Table 1. The 1965 average trip rates for the four area types, the populations of the four area types, and the translation of these figures into total trips are given in Table 2. By using the trip rates of Table 2, it can be seen that the trip rates in area type 1 were to be estimated to some value equivalent to 1.78-1.96 with 90 percent confidence, between 3.71 and 4.11 in area type 2, and so forth.

Smith's procedure (1) was applied within each area type and to household subgroups defined by the AID analysis. The computations for this are given in Table 3. It should be noted that, unlike the recommendations made in Smith's paper (1), a coefficient of variation (CV) of 1.0 was not assumed, but individual CVs were calculated throughout. In fact, the CVs are found to exhibit considerable variation; they range from 0.227 to 1.477, but most values are below 0.8. The procedure requires that a sample size be computed on the basis of the required accuracy at the specified confidence level by estimating a pooled CV over the identified subgroups. Subsequently, the sample size may be readjusted on the basis of the subsample size in the critical cell, where this is defined as the cell that has the largest CV. Application of the sampling procedure generates a sample size for each cell based on its contribution to the overall CV. To draw the sample in this manner, however, would require information on the cell membership of every household in the population, which is clearly not likely to be available. Rather, the sample is likely to be drawn at random, in this case from all households in an area type. Given data on the frequency with which households occurred originally in the sample within each cell, an expected sample distribution can be computed. This will usually be different from the sample distribution based on the contribution to the overall CV. This shows clearly in Table 3 when the columns "Allocated Sample" and "Expected Sample" are compared.

The initial sample sizes computed from the procedure are 610, 450, 343, and 404 households, respectively, for the four area types, which gives a total sample requirement of 1807 households. If one imposes the requirement that the critical cell (indicated by footnote a in Table 3) must be sampled at the design sample size, then the expected sample should be increased by the ratio of the allocated to expected sample for the critical cell in each area type (1). This produces the values shown in the column "Full Random Sample" and produces samples of 1157, 660, 481, and 524 for the four area types, respectively, and a total sample of 2822 households.

Although this completed the sample-size computation from a statistical standpoint, it was not considered to have defined an acceptable sample on the basis of other needs of the sampling procedure. The study region consists of multiple jurisdictions for which various planning and policy actions are expected to be done by the metropolitan planning organization (MPO). For planning based on this survey to be acceptable to the various jurisdictions, there is a need for the sample to be reasonably proportionately distributed over the jurisdictions. The expected distribution of the sample by jurisdiction (by using the eight primary jurisdictional levels) and four area types is given in Table 4 together with the percentage of the sample in each entry of the table. Table 5 notes the percentage of the population in each cell. A comparison of these two tables shows that the sample distribution is disproportionately heavy in area type 1 and jurisdiction 1.

From the politics of MPO planning, this is not acceptable. Therefore, several changes were made to the sample sizes based on the statistical sample and jurisdictional concerns.

The first adjustment made was to reduce the size of the sample for area type 1. The required sample here almost doubled in size when the critical cell was considered, although this cell generates very few of the regionwide trips. It was determined that accepting the expected sample of 24 households would increase the error at 90 percent confidence from ±5 percent to ±7.5 percent. This was felt to be acceptable in light of the very large increase needed otherwise in this sample size and its implication for the entire sample distribution.

The second adjustment was based on the selected method of sampling. Smith's procedure is based on the assumption that a simple random sample is selected. The sampling procedure used in this case, however, was a three-stage sampling procedure by using zones, blocks, and households as the sampling units for the three stages. Multistage sampling provides considerable gains in sampling accuracy and inexpensiveness when a full enumeration of the final sampling units does not exist but increases the sampling error over that of simple random sampling of the final-stage units (2,3). To calculate the sampling error for the multistage procedure, it would be necessary to know the standard deviations of trip rates by zone and by block. This information was not available and could not be computed readily at the time of sampling, so precise sampling errors could not be computed. To allow for the increased error, an across-the-board arbitrary increase of 10 percent was applied to the sample sizes. Given the importance of area type 3, by virtue of both its trip rate and the proportion of households, it was decided to add a further 95 households to this sample, distributed proportionately over all jurisdictions. This brought the total sample to 620 in area type 3. Finally, 50 households were removed from area type 2 and added to area type 4 to be distributed over all jurisdictions except 1. These sample-size changes were decided on as being politically or judgmentally desirable and were not based on statistical analysis. A summary of these changes is given in Table 6, and Table 7 gives the final designed sample.

RESULTS OF SURVEY SAMPLE EXECUTION

In execution, a total of 2706 interviews were conducted, of which 2446 were considered to be sufficiently complete for analysis, including data on the independent variables for trip-rate analysis. Some of the 2446 sampled households had an estimated income based on data on area type, available vehicles, and number of workers. The distribution of the achieved sample by area type and jurisdiction is shown in Table 8. Comparisons of this table with Table 7 show that a fairly good approximation to the design sample was achieved, with the exception of area types 1 and 2 in jurisdiction 1. The samples in these localities proved to be quite problematical due to urban renewal and localities of high unemployment.

Table 9 gives the computations of sample size given the trip rates and their standard deviations as actually measured in the survey. The sample sizes attained were in all cases close to or in excess of those required for ±5 percent error at 90 percent confidence, despite the changes in critical cells and the general shifts in CVs.

On the basis of this use of the procedure for sample estimation, after the elapse of more than 15 years, it appears that the sample sizes estimated are perfectly adequate and sufficiently robust to provide acceptable accuracy, even where trip-rate measures have not been very stable. Furthermore, even though quite small sample sizes are generated, these are proved adequate to measure trip rates to the required level of accuracy. Through this method, a major cost saving is realized. In 1965, the TALUS survey sampled 4 percent of the region's households. With the increased region and population, which totaled more than 1.65 million households in 1980, the same sampling rate would have required a sample of 66 000 households. At $100 per interview, the survey would have cost $6 600 000, $6 300 000 more than this survey. A problem does arise, however, in that specifying the level of accuracy in terms of trip rates appears to be inadequate with respect to accuracy of trip estimation. This issue is discussed at greater length in the remainder of this paper.

APPROPRIATE SPECIFICATION OF ACCURACY

In the case study described in this paper, the regional population of households was stratified first into four area types. Subsequently, the same percentage error was specified for each area type, notwithstanding the major differences in subpopulation size and the variations in trip rates present across the area types. This process led to domination of the sample by area type 1, even though this area type produces only 1.95 percent of regional trips. To achieve the required 5 percent accuracy in this stratum, 1157 sample households were needed out of a statistically computed total sample of 2822 households for the four strata. In other words, 41 percent of the sample was required to measure 1.95 percent of the regional trip total. This situation arises for several reasons. First, because there are few households in this area type, the simple random sample from 1965 located few households in this stratum (4.5 percent or 523 out of a sample of

Table 3. Sample-size calculations for all four area types.

Cell	CV_i	F_i	F_iCV_i	W_i	Allocated Sample	Expected Sample	Full Random Sample
Area type 1							
14	0.426	0.171	0.0728	0.097	59	104	204
15	0.678	0.237	0.1606	0.214	130	145	284
18	0.787	0.079	0.0622	0.083	51	48	94
19	0.743	0.044	0.0327	0.044	27	27	53
10	0.828	0.114	0.0944	0.126	77	70	137
16	0.884	0.118	0.1043	0.139	85	72	141
4	0.527	0.081	0.0427	0.057	35	49	96
17	0.865	0.054	0.0467	0.062	38	33	65
12	1.200	0.064	0.0768	0.102	62	39	76
13[a]	1.477[a]	0.039	0.0576	0.077	47[a]	24[a]	47
			0.7508		610	610	1197
Area type 2							
18	0.271	0.099	0.0268	0.042	19	45	66
19	0.460	0.074	0.0342	0.053	24	33	48
16	0.283	0.057	0.0161	0.025	11	26	38
17	0.549	0.215	0.1181	0.183	82	97	142
6	0.526	0.050	0.0264	0.041	18	23	34
8	0.772	0.153	0.1179	0.183	82	69	101
9	0.863	0.138	0.1191	0.185	83	62	91
10	0.833	0.066	0.0554	0.086	39	30	44
14	0.842	0.081	0.0681	0.106	48	36	53
15[a]	0.944[a]	0.066	0.0627	0.097	44[a]	30[a]	44
			0.6446		450	450	660
Area type 3							
10	0.268	0.057	0.0154	0.027	9	20	28
12	0.460	0.043	0.0195	0.035	12	15	21
13	0.458	0.178	0.0814	0.145	50	61	86
8	0.593	0.199	0.1182	0.210	72	68	95
9	0.227	0.120	0.0274	0.049	17	41	58
6	0.705	0.209	0.1471	0.261	90	72	101
7[a]	0.795[a]	0.194	0.1541	0.274	94[a]	67[a]	94
			0.5631		343	343	481
Area type 4							
12	0.357	0.089	0.0317	0.052	21	36	47
14	0.320	0.028	0.0090	0.015	6	11	14
15	0.401	0.191	0.0764	0.125	50	77	100
8	0.578	0.173	0.0998	0.163	66	70	91
9	0.726	0.209	0.1515	0.248	100	84	109
6[a]	0.788	0.092	0.0728	0.119	48[a]	37[a]	48
10	0.764	0.082	0.0628	0.103	41	33	43
11	0.787	0.137	0.1074	0.176	71	55	71
			0.6114		404	404	524

[a]Critical cell.

Table 4. Initial sample distribution by jurisdiction and area type.

	Area Type									
	1		2		3		4		Total	
Jurisdiction	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent
1	661	23.4	566	20.0	110	3.9	2	0.1	1339	47.0
2	199	7.0	80	2.8	140	5.0	89	3.2	508	18.0
3	132	4.7	9	0.3	104	3.7	192	6.8	437	15.5
4	51	1.8	0	0	89	3.2	59	2.1	199	7.0
5	95	3.4	7	0.2	24	0.8	45	1.6	171	6.1
6	12	0.4	0	0	4	0.1	53	1.9	69	2.4
7	8	0.3	0	0	8	0.3	44	1.6	60	2.1
8	0	0	0	0	2		40	1.4	42	1.5
Total	1158	41.0	662	23.4	481	17.1	524	18.5	2825	100.0

Table 5. Percentages of population by area type and jurisdiction.

Jurisdiction	Area Type 1	2	3	4	Total
1	2.9	9.9	14.3	0.1	27.2
2	0.9	1.4	18.3	3.5	24.1
3	0.6	0.2	13.6	7.6	22.0
4	0.2	0	11.5	2.3	14.0
5	0.4	0.1	3.1	1.8	5.4
6	[a]	0	0.5	2.1	2.6
7	[a]	0	1.1	1.7	2.8
8	0	0	0.3	1.6	1.9
Total	5.1	11.6	62.5	20.8	100.0

[a]Less than 0.1 percent.

Table 6. Adjustments to statistical sample by area type.

Area Type	Adjusted Sample from Smith's Procedure	Reduction in Area Type 1 Sample	Adjustment for Multistage Sampling	Adjustment for Area Type 2,3,4 Samples
1	1157	610	680	680
2	660	660	725	675
3	481	481	525	620
4	524	524	575	625
Total	2822	2275	2505	2600

Table 7. Distribution of final sample.

Jurisdiction	Area Type 1	2	3	4	Total
1	388	578	141	2	1109
2	117	82	181	106	486
3	78	9	135	229	451
4	30	0	114	71	215
5	56	7	31	54	148
6	7	0	5	63	75
7	5	0	11	53	69
8	0	0	3	48	51
Total	681	676	621	626	2604

Table 8. Distribution of executed sample.

Jurisdiction	Area Type 1	2	3	4	Total
1	348	465	139	0	952
2	98	73	170	90	431
3	73	23	156	219	471
4	33	0	166	72	271
5	41	13	38	37	129
6	11	0	0	61	72
7	13	0	16	50	79
8	0	0	0	41	41
Total	617	574	685	570	2446

Table 9. Calculations of sample sizes based on survey results.

Cell	CV_i	F_i	$F_x CV$	W_i	Optimal Sample	Expected Sample	Full Sample	Executed Sample	Design Sample
Area type 1									
14	0.652	0.238	0.155	0.181	144	188	296	147	117
15	1.313	0.066	0.087	0.102	80	52	82	41	161
18	1.061	0.149	0.158	0.185	146	118	186	92	54
19	1.352	0.107	0.145	0.170	134[a]	85[a]	134[a]	66[a]	30
10	0.585	0.089	0.052	0.061	48	70	110	55	78
16	0.720	0.109	0.079	0.092	73	86	136	67	80
4	1.245	0.070	0.087	0.102	81	55	87	43	55
17	0.318	0.028	0.009	0.010	8	22	35	17	37
12	1.112	0.044	0.049	0.057	45	35	55	27	44
13	0.341	0.100	0.034	0.040	31	79	125	62	27+
			0.855		790	790	1246	617	683
Area type 2									
18	1.038	0.099	0.103	0.141	82	58	97	57	67
19	1.217	0.064	0.078	0.106	62[a]	37[a]	62[a]	37[a]	50
16	0.742	0.206	0.153	0.208	122	121	203	118	39
17	1.066	0.037	0.039	0.053	31	22	37	21	145
6	0.651	0.054	0.035	0.048	28	32	54	31	34
8	0.875	0.061	0.053	0.072	42	36	60	35	103
9	0.622	0.099	0.062	0.084	49	58	97	57	93
10	0.899	0.117	0.104	0.141	83	68	114	67	45
14	0.397	0.171	0.068	0.093	54	100	168	98	55
15	0.430	0.092	0.040	0.054	32	54	90	53	45[a]
			0.735		585	586	982	574	676
Area type 3									
10	0.825	0.162	0.134	0.218	89	66	95	113	35
12	0.807	0.215	0.174	0.283	116	88	126	150	27
13	0.773	0.079	0.061	0.099	41	32	46	55	111
8	0.857	0.099	0.085	0.138	57[a]	40[a]	57[a]	69[a]	124
9	0.427	0.262	0.112	0.182	74	107	153	183	75
6	0.410	0.052	0.021	0.034	14	21	30	36	130
7	0.245	0.113	0.028	0.046	19	46	66	79	120
			0.615		409	410	573	685	621
Area type 4									
12	0.726	0.205	0.149	0.253	95	77	118	117	56
14	0.912	0.179	0.163	0.277	103[a]	67[a]	103[a]	102[a]	18
15	0.520	0.107	0.056	0.095	36	40	61	61	120
8	0.656	0.084	0.055	0.093	35	32	49	49	108
9	0.747	0.037	0.028	0.048	18	14	21	21	131
6	0.402	0.249	0.100	0.170	64	93	143	143	58[a]
10	0.289	0.073	0.021	0.036	13	27	42	42	51
11	0.252	0.068	0.017	0.029	11	26	40	40	86
			0.589		375	376	577	570	626

[a]Critical cell.

Table 10. Constant-magnitude error by area type.

Area Type	Avg Trip Rate	90 Percent Confidence Limit of Sampling-Error Value	Percent
1	1.87	±0.244	±13.0
2	3.91	±0.244	±6.24
3	5.21	±0.244	±4.68
4	5.19	±0.244	±4.70

Table 11. Z^2/E^2 and sample size by stratum.

Area Type	Percent Error Required	Z^2/E^2	$\overline{CV}_i$	n
1	13.0	160.1	0.7508	90
2	6.24	695.0	0.6446	289
3	4.68	1235.5	0.5631	392
4	4.70	1225.0	0.6114	458
Total	–	–	–	1229

Table 12. Comparisons of sample and population.

Area Type	Percent of Population	Percent of Percentage Sample	Percent of Absolute Sample
1	5.1	41.0	10.1
2	11.6	23.4	24.3
3	62.5	17.0	31.5
4	20.8	18.5	34.1

11 512 usable household records). Thus, the means and standard deviations were estimated from very small samples. (All but one of the 13 cells had samples less than 90 and that one exception had a sample size of 123. Among the other area types, with a total of 33 cells, the smallest sample size was 47 and the next was 138. The remaining cells ranged from 150 to 1125 households.)

Second, area type 1 was defined only in terms of high employment density. The zones occur mainly in central business districts (CBDs) and outlying business districts (OBDs) and exhibit wide variations in residential characteristics. Trip rates varied by cell from 0.27 to 5.15; the mean was 1.87. Variations in the other trip rates were generally markedly smaller. Thus, area type 1 households constitute a diverse group of households in terms of tripmaking and are inaccurately measured because of the small sample size. Third, although the initial sample size estimation is close to the sample sizes of the other area types (610 compared with samples between 343 and 450), one cell--the critical cell--in area type 1 has a very small frequency of occurrence but a large CV. It serves to double the sample size to 1157. This also should be seen in the context that this cell is responsible for 0.08 percent of the region's tripmaking.

The basic problem identified by this case study is that the sample trip rates bear no relation to the planning units of measurement, for which sampling is really designed. Given that trip rates are the units that will be estimated and about which standard deviations and means are known from previous surveys, the primary issue becomes one of how to weight the trip rates so that the samples drawn are in reasonable relation to the impact of the rates on estimation of travel volumes. This problem arises only under the circumstances that some form of stratification or segmentation takes place and samples are to be estimated independently for each stratum or segment. Complication is added by the fact that a unique set of sampling rates cannot be obtained from the equation for the sampling error for a stratified sample with variable sampling fraction, unless some relationship is prespecified between the sampling rates or stratum sampling errors.

First, consider the effects of the stratification used in this case. If one applies the estimating procedure for a stratified sample with variable sampling fraction, the sampling error for the regionwide average trip rate can be computed. The estimation is made from the following:

$$\text{s.e.}(\bar{y}) = (\sum_i g_i{}^2 n_i s_i{}^2/\hat{N}^2)^{1/2} \tag{1}$$

where

$\text{s.e.}(\hat{\bar{y}})$ = sampling error of $\hat{\bar{y}}$,
g_i = expansion factor for stratum i,
n_i = sample size in stratum i,
s_i = standard error of $\bar{y}_i$, and
$\hat{N}$ = estimated total population = $\Sigma_i g_i n_i$.

The estimated standard errors of the stratum trip rates are ±2.113, ±1.083, ±1.198, and ±1.220, respectively. By using the original sample sizes from Smith's procedure shown in Table 4, the sampling error is ±0.0364.

The weighted average trip rate is 4.886, so the error at 90 percent confidence is ±1.22 percent. By using the adjusted samples shown in Table 7, this sampling error reduces to ±0.0323 and a 90 percent confidence bound of ±1.09 percent. Clearly, by specifying ±5 percent error in each stratum, the error over all strata is much less than ±5 percent, as expected. It is interesting to note that the reduced sample in area type 1 is outweighed by the increases in area types 3 and 4.

As a means to define more appropriate sample sizes for a stratified sample, consider specifying an error on the weighted average trip rate. If one specifies a requirement of ±5 percent error on the average trip rate of 4.886, this represents an error of ±0.244. Now, suppose that this error in the rates is specified for each stratum. This means that, irrespective of stratum, any given household will have the same probability of a misprediction of given magnitude. The reason for choosing this definition of error is that it means that tripmaking by each household is estimated to the same absolute level of accuracy. Thus, in looking at any group of trips, such as those in a corridor, on a specific facility, or those in a subarea, all of the trips in the group will have been estimated to the same level of accuracy, irrespective of the type of household that generated the trips. It implies also that one is less interested in household trip rates per se but is more interested in numbers of trips by some grouping geographically or modally.

In this case study, the effect of this is to specify the trip rates and 90 percent confidence limits on error (see Table 10). This is markedly different from the constant percentage error, which at 5 percent generates absolute errors of ±0.094, ±0.196, ±0.261, and ±0.260, respectively. Again, the implications of this are that with many more households in area types 3 and 4 than in 1 and 2, the absolute error in trips will be higher than with the specification shown in Table 9.

Applying these new sampling errors produces different values of Z^2/E^2 for each stratum (see Table 11). It can be seen that the sample sizes are markedly different from those obtained from the constant percentage error sample. If these individual samples are then allocated across the cells of each area type as before, an increase in sample size is required for the critical cell of each area type, which increases the four samples to 176, 424, 550, and 594, respectively, and requires a total of 1744 households. This is noticeably smaller than the 2822 generated from the percentage sample. Consider also the percentages of the sample and population in each area type for this procedure compared with the previous one, as given in Table 12. The new sample's percentages bear a more logical relationship to the population than those of the original sample.

Because all sample sizes were increased to produce the minimum required sample in the critical cell, the final sample of 1744 households will produce a smaller error than the specified ±5 percent of the weighted average trip rate. By using the estimation for a stratified random sample with variable sampling fraction, the sampling error is found to be ±0.035, which produces a 90 percent confidence limit on the error of ±1.18 percent. This is slightly less than the ±1.22 percent error obtained from the 2822 sample. An interesting comparison can be obtained to the achieved sample of 2446 with its distribution among the area types. This sample provides a sampling error of ±0.0313, which is ±1.05 percent at 90 percent confidence. Because of the changed distribution imposed in design and further shifted in execution, this sample produced a smaller error on overall trip rates than the statistically designed sample based on a ±5 percent error. The greater efficiency of the absolute-value-based sample is shown by increasing that sample of 1744 households to 2446 with the same proportionate distribution as in the 1744 sample. In that case, the error on the overall weighted trip rate is ±0.0296, which gives a 90 percent confidence limit of ±1.00 percent. This shows that the absolute-value sample is more efficient than the percentage-based sample as well as being more reasonable on the basis of prediction of trip volumes. Similarly, increasing the sample size to 2822 reduces the sampling error yet further to ±0.93 percent at 90 percent confidence.

CONCLUSION

The sample-size estimation procedure developed by Smith (1) has been shown to produce an adequate sample for updating trip-generation rates from previous years' surveys. Despite changes in the distribution of households over the relevant cells, the sample produced trip-rate estimates that were within ±1.5 percent of the required 90 percent confidence limit on sampling error, even though the executed sample was about 6.5 percent short of the design sample and more significant shortfalls of 10 and 15 percent occurred in area types 1 and 2. The method appears robust enough to be able to handle the realities of real-world survey execution and changes in population distribution over the elapse of 15 years.

The case study used here also shows that this procedure for sample estimation may need to be used as only the initial estimate of sample size and distribution. Political and jurisdictional realities are likely to require that the sample sizes be changed and augmented to satisfy other requirements than purely statistical ones. Nevertheless, judicious changes should not threaten the statistical reliability of the sample, if these changes are made with the goals of the sampling clearly in mind.

Finally, this case study shows that the sample is likely to be estimated inappropriately if the trip-generation procedure is based on stratification and sample sizes estimated independently in each stratum. In this case, independent estimation can lead to domination of the sample by a stratum of households that has a low trip rate and that may represent a very small proportion of regional households. In this case, this was found to happen, so that a stratum containing 5.1 percent of regional households and producing 1.95 percent of regional trips was estimated to require 41 percent of the sample. The need was identified, therefore, to determine a more rational basis for specifying the permissible sampling error than the direct extension of Smith's procedure, which leads to specifying a constant percentage error for all strata.

The proposed modification for stratified sampling is to estimate the permissible error as an absolute number (fraction) of trips per household and then calculate this as a fraction of the mean trip rate in each stratum. This procedure has been shown to generate a smaller sample requirement than that by using a constant percentage error and to provide a distribution of the sample by stratum that is intuitively more appealing. In this case, the low trip-rate stratum requires 10 percent of the sample instead of 41 percent, which seems much more reasonable for the stratum's contribution to trip totals and to probable error. Furthermore, the resulting sample in this case is smaller and has a smaller overall error than the sample generated from a constant relative error. Comparing the overall weighted trip-rate error between the absolute-error method and the relative-error method, one finds that the absolute-error method reduces the sampling error by almost 25 percent or reduces the required sample size by 38 percent.

ACKNOWLEDGMENT

I would like to thank staff at the Southeastern Michigan Transportation Authority and the Southeastern Michigan Council of Governments for the use of data from the 1965 Detroit Regional Transportation and Land Use Study (TALUS) and the 1980 regional travel survey that provided the case study material for this paper.

REFERENCES

1. M.E. Smith. Design of Small-Sample Household-Interview Travel Surveys. TRB, Transportation Research Record 701, 1979, pp. 29-35.
2. F. Yates. Sampling Methods for Censuses and Surveys. Charles Griffin and Sons, London, 1965.
3. P.R. Stopher and A.H. Meyburg. Survey Sampling and Multivariate Analysis for Social Scientists and Engineers. Heath, Lexington, MA, 1979.