Sampling Procedures for Designing Household Travel Surveys for Statewide Transportation Planning

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This paper describes sampling concepts and techniques that can be used to design household travel surveys for statewide transportation planning. Emphasis is placed on defining survey objectives in terms of the level of precision desired in estimating key variables. The need to incorporate cluster sampling treatments for trip-related variables collected in household surveys is introduced and discussed. Detailed procedures are presented for computing the minimum sample sizes of household interviews needed to accomplish survey objectives at minimum cost. A simplified method is described to account for losses in precision because of clustering. Application of the sampling techniques to an actual state travel survey design illustrates the influence of alternative levels of precision and data stratification on survey sample size. The applicability of these sampling concepts to other areas of transportation planning is discussed.

Over the next 5 to 7 years, many states expect to expand the modal and geographic scope of their statewide transportation planning programs. Such expansion has resulted in states having to collect and analyze many different types of regional, corridor, and statewide data. Many state agencies that have limited familiarity with travel surveys have been or are likely to be faced with the proglem of designing and conducting such surveys.

A problem common to both statewide and urban transportation planning is the use of rules of thumb or available funding resources as a basis for estimating survey sample sizes. Estimated sample sizes based on such factors may bear little relation to the desired level of precision of survey estimates, and they generally do not account for important sampling issues such as clustering or stratification, which influence sample size and other sampling parameters. Within the transportation planning field, little research has been done to identify potential trade-offs between sample size (and survey costs) and the selection of desired tolerance levels, confidence levels, and geographic levels for which data are needed. These factors can significantly influence survey cost. In addition, many transportation planners have limited familiarity with or experience in applying statistical sampling procedures in the design of travel surveys.

This paper focuses on sampling techniques and concepts that can be used by transportation planners to design household travel surveys (e.g., home interview) for statewide transportation planning. Such surveys could include household surveys conducted on a statewide or regional scale or for a selected geographic subarea within a state. The specific objectives of this paper are to

1. Present an overview of sampling concepts applicable to the design of household surveys for statewide transportation planning,
2. Document statistical sampling techniques to be used in household surveys to determine the sample sizes needed for estimating such commonly used variables as trip generation rates and average trip lengths, and
3. Illustrate trade-offs between survey sample sizes and alternative levels of precision as well as the effect on sample size of stratifying survey variables by geographic area and socioeconomic characteristics of households within areas.

Sample size estimates developed for a sampling plan for a statewide household travel survey in Connecticut are used to illustrate the points noted in the above objectives (1). Although nonsampling biases can also impact the level of precision achieved in a survey, they are treated in detail elsewhere (2) and thus are not discussed here. The research effort on which this paper is based also developed sampling procedures and survey designs for roadside and modal (intercity bus and passenger train) surveys likely to be used for statewide transportation planning (2).

SURVEY DESIGN CONCEPTS AND ISSUES

Because of budget and data constraints and lack of familiarity with sampling procedures, rigorous statistical evaluation of sample sizes and alternative survey procedures often is not performed before a travel survey is conducted. In spite of such real-world problems, it is still important to develop survey designs and sampling procedures on a sound statistical basis. Application of valid sampling procedures can strengthen a travel survey program, particularly by providing a quantitative basis for evaluating trade-offs between the scope, precision, coverage, and cost of a travel survey. Application of statistical sampling procedures and concepts makes it possible to design travel surveys that, within available funding resources, provide data at the required levels of precision.

Preparation of a Survey Design

The first and most critical step in developing any type of travel survey design is to specify the survey objectives. Survey objectives must be clearly and specifically defined in the design process. One expert in survey design has suggested (3) that survey objectives should

1. Specify how the survey results will be used in the decision-making process;
2. Identify the variables of interest, the content and extent of the survey population, and the classification that will be used to analyze the results (e.g., trip purpose, socioeconomic groupings);
3. Identify desired or minimum levels of precision and the geographic areas for which such precision is to be maintained;
4. Specify how the variables are to be measured, coded, and processed; and
5. Identify how the data will be analyzed.

All of these procedures are necessary to develop a sampling plan for a travel survey. Inaccuracy or incompleteness in any of these areas could reduce the usefulness and possibly the precision of survey data.

Selecting a final set of survey objectives and a final sampling plan is likely to be an iterative process. One or more of the initial survey objectives may have to be modified to develop a feasible design, given the financial and staff resources and time deadlines of the study.

Factors Influencing Sample Size

The required sample size in a survey is related to (a) the desired level of precision of survey estimates, (b) the variance of characteristics of interest within the population, (c) the size of the population to be sampled, and (d) the procedure used to select the samples. The influence of the first three factors on sample size is shown by the following equation for estimating the sample size of a simple random sample without replacement (4):

$$n_0 = [t^2_{(1-\alpha/2)} s^2/d^2] / \{1 + (1/N)[t^2_{(1-\alpha/2)} s^2]/d^2\} \qquad (1)$$

where

- n_0 = number of households to be sampled to estimate the mean of the sample at a specified level of precision;
- $t_{(1-\alpha/2)}$ = Student's t-value at level of confidence $(1 - \alpha)$;
- s = standard deviation of the sample observations about the sample mean;
- d = acceptable difference ($\pm$) between the sample mean and the population mean (tolerance level); and
- N = total number of elements in the population.

Level of significance (α) means that the sample estimate will fall outside the specified tolerance level with a probability (α). Assuming a symmetrical distribution of the sample estimate about the mean, this implies that an observation will lie above the range with a probability ($\alpha/2$). Therefore, for a given level of confidence ($1 - \alpha$, where α is the level of significance), the Student's t-value for $1 - \alpha/2$ should be used in Equation 1. This corresponds to a two-tail t-value.

The term level of precision here consists of the variables (d) and (α) in the above equation. For example, if a state wishes to estimate the average number of automobile driver trips per household for all households within the state, one possible level of precision is that the estimate be within $\pm$10 percent of the population mean 95 percent of the time. The choice of a 95 percent confidence level indicates that, for the use to which the estimate will be put, a 1-in-20 chance of the mean trip-rate estimate from the sample lying outside a 10 percent tolerance level of the true value is acceptable. The level of precision specified for a survey estimate does not account for nonsampling errors that may affect survey estimates.

As shown in later sections, the selection of d and a confidence level, i.e., $1 - \alpha$, has a substantial influence on the required survey sample size, which is directly proportional to the level of confidence specified in the survey and inversely proportional to the acceptable error range of the sample mean. The variance (s^2) of sample observations about the sample mean also has a direct relation to sample size. As the variance of the characteristic to be sampled increases, the required sample size will also increase for a given level of precision.

Equation 1 also illustrates the important condition that, as the size of the population to be sampled (N) increases, its influence on the required sample size decreases and becomes negligible if N is large relative to n. Because the sampling fraction in most statewide household travel surveys is typically smaller than 1 percent, a simplified equation that consists only of the numerator [$n_0 = (ts/d)^2$] can usually be used with little or no loss in accuracy. The above relationships between sample size and tolerance levels, confidence levels, sample variance, and population size are applicable to sampling procedures other than those for a simple random sample.

Implicit in the equation is the specification of a geographic area for which the desired survey estimates are required, i.e., the areal unit of analysis. The selection of a geographic area for which data are to be obtained is likely to have a major impact on the number of samples required in the survey and thus on survey cost. For many variables, the sample size required to estimate the mean or the proportion of elements with a particular characteristic at a specified level of precision is likely to be similar at the regional and county levels to that required at the state level. This has potentially significant implications for the cost of conducting statewide surveys.

Sampling Techniques for Household Surveys

In many conventional statewide and urban household travel surveys, households in the sample are typically considered to have been selected by simple random samples. However, many of these surveys are, in total or in part, cluster samples. As noted by Kish (3), "sample elements are the units for which information is sought." In a cluster sample, each sample unit contains more than one sample element; in an element sample each sample unit contains only one sample element.

Table 1 gives a list of typical variables collected in household surveys and identifies the type of sample associated with each variable. In examples 1 and 2, the sample element (the unit for which information is sought) is the household. Specifically, the number of person trips produced and the number of automobiles owned by the household are of interest. The sampling units are the same as the sample elements, i.e., households, which indicates that element sampling procedures such as the simple random sample should be used to estimate required sample sizes. In example 3, the sample elements are person trips. Each sampling unit (household) thus potentially contains more than one sample element. Therefore, cluster sampling procedures should be applied to estimate sample sizes for trip-related variables. Examples 4 through 6 illustrate other variables that should be treated as cluster sampling problems.

Table 1. Variables in element and cluster samples.

Example	Type of Sample	Sampling Unit	Sample Element	Variable
1	Element	Households	Households	Person trips per household
2	Element	Households	Households	Automobiles owned per household
3	Cluster	Households	Person trips	Average length of person trip
4	Cluster	Households	Person trips	Proportion of person trips by purpose
5	Cluster	Households	Automobile driver trips	Average length of automobile driver trip
6	Cluster	Households	Automobile driver trips	Average automobile occupancy

Estimating minimum sample size for cluster samples is more complex. A factor commonly used to simplify the estimation of sample size for cluster or other complex samples is the design effect. According to Kish (3), the design effect (D) is "the ratio of the actual variance of a sample to the variance of a simple random sample of the same number of elements." This factor is calculated as follows:

$$D = \mathrm{var}(\bar{y})/[(1 - f)s^2/n] \quad (2)$$

where

- $\mathrm{var}(\bar{y})$ = variance of the sample mean calculated for a particular sampling procedure such as cluster sampling,
- f = proportion of elements in the population that are sampled (called the sampling fraction),
- s^2 = sample variance of a simple random sample (i.e., $s^2 = \Sigma(y_i - \bar{y})/(n - 1)$ about the sample mean, and
- n = number of elements sampled.

The denominator in Equation 2 is the variance of the mean of a simple random sample.

The design effect provides a means of accounting for the effects of clustering on sample size. Kish (3) suggests the following approach, which uses the design effect and the sample size for a simple random sample to estimate sample size for complex problems such as cluster samples:

$$n = n_0 D \quad (3)$$

where

- n = number of elements to be sampled to estimate the sample mean at a specified level of precision in a cluster sample,
- n_0 = number of elements to be sampled to estimate the sample mean at a specified level of precision for a simple random sample, and
- D = design effect as defined above.

The significance of this concept is illustrated in the following example. Data collected in a Kentucky statewide household survey gave a mean trip length of 16 km (9.94 miles) and a sample standard deviation (s) of 34.4 km (21.3 miles). The required sample size to estimate mean trip length within ±10 percent (d) at a 90 percent level of confidence for a simple random sample was

$$n_0 = [t^2_{(1-\alpha/2)}s^2/d^2] = (1.645)^2\,(21.3)^2/[(0.10)(9.94)]^2 = 1250 \text{ trips} \quad (4)$$

However, based on an analysis of survey results, the actual variance of mean trip length for a cluster sample was estimated to be 2.39 times as large as the variance of the sample mean trip length, assuming a simple random sample of trips (D = 2.39). Therefore, estimating the mean trip length at the same level of precision specified above would require sampling almost 3000 trips, as estimated below:

$$n = n_0 D = 1250 \text{ trips} \times 2.39 = 2995 \text{ trips} \quad (5)$$

TECHNIQUES FOR ESTIMATING SAMPLE SIZES

The following discussion of simple random sampling and cluster sampling formulas presents formulas for two illustrative categories of variables that are of general interest to practicing transportation planners: (a) person-trip generation rates stratified by trip purpose, geographic area, and socioeconomic characteristics of households; and (b) average lengths of person trips stratified by purpose and geographic area.

Person-Trip Generation Rates

The general formula for estimating the minimum sample size of completed interviews needed to estimate the average number of person trips of purpose (p) per household at a desired level of precision, if a simple random sample of households is selected within each geographic area of interest (e.g., state, county, or traffic zone), is as follows:

$$n_p = [t^2_{(1-\alpha/2)}(s_p^2/d_p^2)]/\{1 + (1/N)[t^2_{(1-\alpha/2)}s_p^2/d_p^2]\} \quad (6)$$

where

- n_p = number of completed household interviews required to estimate the person-trip generation rate for trip purpose (p) for the geographic area of interest,
- $t_{(1-\alpha/2)}$ = value of Student's t-statistic for level of confidence $(1 - \alpha)$;
- s_p = estimated standard deviation of the person-trip generation rate for trip purpose (p) for the geographic area of interest,
- d_p = acceptable error (or difference) between the estimated person-trip generation rate for trip purpose (p) and the true trip generation rate for purpose (p) for the geographic area of interest, and
- N = total number of households in the geographic area of interest.

Average person-trip generation rates by trip purpose and corresponding standard deviations can be estimated by using the computer program XCLASS in the Federal Highway Administration (FHWA) urban transportation planning battery and the results of previously conducted household travel surveys. The total number of households (N) in each geographic area can be estimated from secondary sources such as the 1970 census.

Transportation planners often wish to estimate person-trip generation rates by trip purpose for households stratified by household income, automobile availability, or other socioeconomic variables. The formula for calculating required sample sizes to estimate such trip generation rates is essentially the same as above except that n_p, s_p, d_p, and N must be redefined as follows:

- n_{ph} = number of completed household interviews with characteristic (h) (e.g., one automobile required to estimate the person-trip generation rate for trip purpose (p) for households with characteristic (h) for the geographic area of interest,
- s_{ph} = estimated standard deviation of the person-trip generation rate for trip purpose (p) for households with characteristic (h) for the geographic area of interest,
- d_{ph} = acceptable error (or difference) between the estimated person-trip generation rate for trip purpose (p) and the true trip generation rate for purpose (p) for households with characteristic (h) for the geographic area of interest, and
- N_h = total number of households with characteristic (h) within the geographic area of interest.

The FHWA program XCLASS can again be used to estimate person-trip generation rates and standard deviations about the rates by trip purpose and type of household for each geographic area of interest.

Average Person-Trip Lengths by Town Class

As previously noted, the procedures for estimating required sample sizes for measuring average person-trip lengths at a given level of precision are analogous to but more complex than those for measuring trip generation rates. The formula for estimating the minimum sample size of households to estimate the average trip length for person trips of purpose (p) at a desired level of precision within each geographic area of interest is

$$n_p = D_p/\bar{x}_p \{[t^2_{(1-\alpha/2)}(s_p^2/d_p^2)]/[1 + (1/N)t^2_{(1-\alpha/2)}(s_p^2/d_p^2)]\} \quad (7)$$

where

- n_p = number of completed household interviews required to estimate the average person-trip length for trips with purpose (p) for the geographic area of interest,
- D_p = computed design effect for trip purpose (p),
- $\bar{x}_p$ = person-trip generation rate for trip purpose (p) for the geographic area of interest,
- $t_{(1-\alpha/2)}$ = value of Student's t-statistic for level of confidence $(1 - \alpha)$,
- s_p = estimated standard deviation of the average person-trip length for trips of purpose (p) for the geographic area of interest,
- d_p = acceptable error (or difference) between the estimated average and the true average trip length for person trips of purpose (p) for the geographic area of interest, and
- N = total number of households within the geographic area of interest.

The above formula differs from the single random formula in that the design effort (D_p) compensates for the clustering of trips made by sampled households and the average person-trip generation rate for purpose (p) (i.e., $\bar{x}_p$) is included in the formula to estimate sample size in terms of households, not trips. The average trip length for person trips of purpose (p) and the standard deviations (s_p) about the average trip lengths can be estimated by using the XCLASS program.

The design effect is the ratio of the variance of the mean trip length, computed by using clustered sampling assumptions, to the variance of the mean (assuming selection of a simple random sample of trips). The design effect for a cluster sample of person trips derived from a simple random sample of households within each geographic area of interest is computed from the following:

$$D_p = \mathrm{var}(r_p)/\mathrm{var}(r_p)_0 \quad (8)$$

in which

$$r_p = y_p/x_p = \sum_j^n y_{pj} \Big/ \sum_j^n x_{pj} \quad (9)$$

$$\mathrm{var}(r_p) = [(1 - f)/x_p^2]\,[n/(n - 1)]\left\{\left[\left(\sum_j^n y_{pj}^2 - y_p^2\right)\Big/n\right] + r_p^2\left[\left(\sum_j^n x_{pj}^2 - x_p^2\right)\Big/n\right] - 2r_p\left[\sum_j^n y_{pj} \times x_{pj} - (y_p \times x_p)\Big/n\right]\right\} \quad (10)$$

$$\mathrm{var}(r_p)_0 = \{(1 - f)/[x_p(x_p - 1)]\}\left(\sum_k^x y_{pk}^2 - y_p^2\right)\Big/x_p \quad (11)$$

where

- D_p = computed design effect for purpose (p) for the geographic area of interest,
- $\mathrm{var}(r_p)$ = variance of the mean person-trip length for purpose (p) under cluster sampling assumptions,
- $\mathrm{var}(r_p)_0$ = variance of the mean person-trip length for purpose (p) under simple random sampling assumption,
- r_p = average trip length for person trips of purpose (p) for the geographic area of interest,
- y_p = total kilometers recorded in the sample for the geographic area of interest for person trips of purpose (p),
- x_p = total person trips of purpose (p) recorded in the sample for the geographic area of interest,
- y_{pj} = total kilometers recorded for all person trips of purpose (p) made by household (j) in the geographic area of interest,
- x_{pj} = total number of person trips of purpose (p) made by household (j) in the geographic area of interest,
- f = proportion of survey households sampled in the geographic area of interest,
- n = number of households sampled, and
- y_{pk} = total distance for trip (k) of purpose (p) in the geographic area of interest.

APPLICATION OF SAMPLING PROCEDURE

The sampling procedures were used to design a sampling plan for a statewide household travel survey for the Connecticut Department of Transportation (ConnDOT). The key variables to be estimated in the survey included (a) household person-trip generation rates stratified by town class, trip purpose, and socioeconomic characteristics of households and (b) average person-trip length stratified by town class and trip purpose. The term town class refers to the stratification of the 169 Connecticut towns into three classes based on residential development and transit use and level of service.

Rather than attempting to specify desired levels of precision to be achieved before determining sample size, ConnDOT suggested three tolerance levels (5, 10, and 25 percent) and three confidence levels (68, 90, and 95 percent) for which sample size estimates were to be developed. Sampling parameters were computed from a Connecticut statewide travel survey conducted in 1964.

Figure 1 shows, for a statewide simple random sample, the number of completed household interviews required to estimate the average number of person trips per household at various levels of confidence and tolerance. It can be seen in the figure that the choice of confidence and tolerance levels greatly influences the required sample size. The analysis also showed that far fewer completed interviews are required to estimate statewide person-trip generation rate than are required to estimate average person-trip length at comparable levels of precision. For example, only 216 completed interviews are required to estimate the true statewide person-trip generation rate within ±10 percent of the estimated rate at a 90 percent level of confidence, but 460 completed interviews are required to estimate the average statewide person-trip length at the same level of precision. These sample sizes represent, respectively, 0.02 and 0.05 percent of the

Figure 1. Simple random sample sizes for estimating statewide person-trip generation rate at various confidence and tolerance levels.

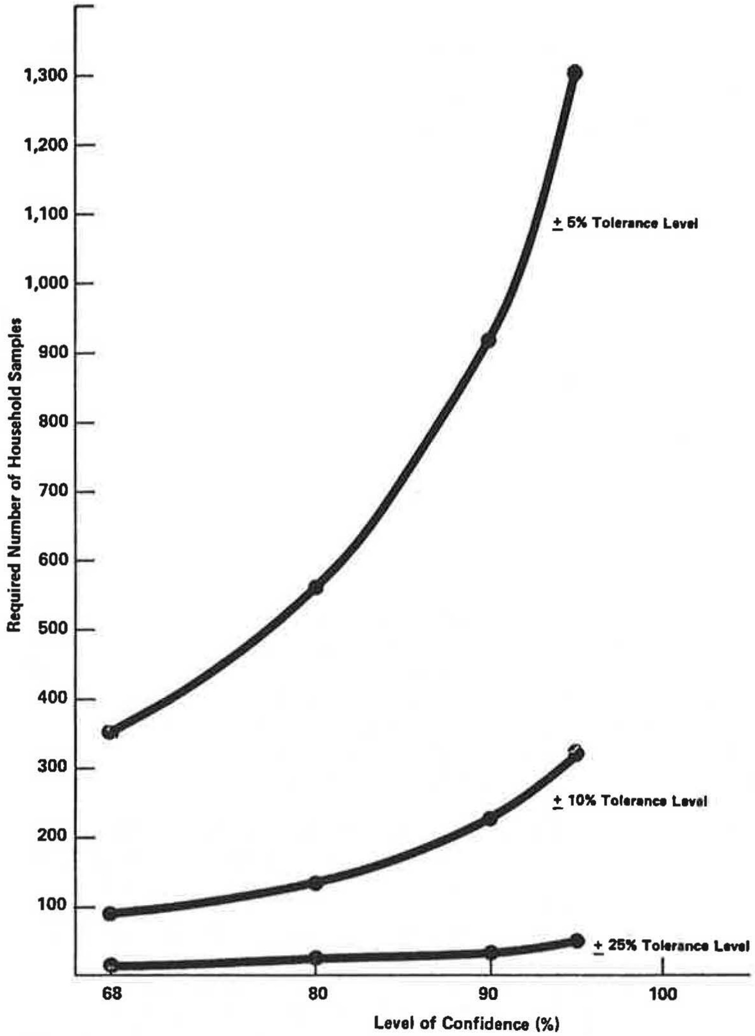

Table 2. Sample size required to estimate survey variables for households stratified by automobile ownership and tolerance levels.

	Tolerance Level About Mean (%)					
	±5		±10		±25	
Variable	Completed Interviews	Total Sample	Completed Interviews	Total Sample	Completed Interviews	Total Sample
Home-based work person trips per household						
0 automobile	1 889	23 037	523	6 378	84	1024
1 automobile	660	1 473	165	368	30[a]	67[a]
2 automobiles	638	1 623	159	405	30[a]	76[a]
≥3 automobiles	379	4 922	95	1 234	30[a]	390[a]
Home-based nonwork person trips per household						
0 automobile	2 674	32 610	746	9 098	124	1512
1 automobile	1 114	2 487	279	623	46	103
2 automobiles	733	1 865	183	466	30[a]	76[a]
≥3 automobiles	607	7 883	157	2 039	30[a]	390[a]
Non-home-based person trips per household						
0 automobile	12 172	148 439	2693	32 841	509	6207
1 automobile	2 184	4 875	979	2 185	157	350
2 automobiles	3 935	10 013	1447	3 683	232	590
≥3 automobiles	928	12 052	327	4 247	52	675

Note: Data are for town class 2 at a 90 percent level of confidence.

[a]Minimum of 30 samples required.

Table 3. Sample size required to estimate survey variables for households stratified by household size and income.

Variable	Household Income Class (1964 dollars)					
	0 to 4999		5000 to 6999		≥7000	
	Completed Interviews	Total Sample	Completed Interviews	Total Sample	Completed Interviews	Total Sample
Home-based work person trips per household						
1-person households	720	8 000	58	2 762	281	16 529
2-person households	696	8 700	95	1 727	121	834
3- and 4-person households	291	6 326	130	1 831	107	421
≥5-person households	252	14 000	149	4 382	125	744
Home-based nonwork person trips per household						
1-person households	555	6 167	242	11 524	195	11 471
2-person households	338	4 225	271	4 927	170	1 172
3- and 4-person households	198	4 304	206	2 901	170	669
≥5-person households	197	11 500	203	5 971	151	899
Non-home-based person trips per household						
1-person households	2671	29 678	813	38 714	387	22 765
2-person households	1111	13 888	1052	19 127	452	3 117
3- and 4-person households	801	17 413	671	9 451	1829	7 201
≥5-person households	1288	71 556	918	27 000	464	2 762

Note: Data are for town class 2 at a 90 percent level of confidence.

estimated 933 050 households in Connecticut.

The table below and Tables 2 and 3 give data showing the influence of stratifying households by geographic area and socioeconomic characteristics. These tables, which were developed for suburban towns in Connecticut (town class 2), are based on an assumed 90 percent level of confidence and the indicated tolerance levels.

The following table shows the number of completed household interviews required to estimate the average person-trip generation rates and trip lengths by trip purpose within town class 2 at a 90 percent level of confidence (a minimum of 30 samples was required):

Variable	Completed Interviews at Tolerance Levels of ±5%	±10%	±25%
Person trips per household			
Total	883	221	35
Home-based work	712	178	30
Home-based nonwork	1098	273	44
Non-home-based	6084	1521	243
Average trip length			
Home-based work	1656	414	66
Home-based nonwork	2256	564	90
Non-home-based	6536	1633	261

Approximately the same number of completed interviews were estimated to be needed in each of the other town classes in the state. The sample size estimates for average trip length in each town class were developed on the basis of design effects computed from the 1964 Connecticut statewide household survey. Design effects for the three town classes ranged between 1.7 and 2.1 for home-based work trips, between 2.8 and 3.7 for home-based nonwork trips, and between 2.9 and 3.8 for non-home-based trips.

Tables 2 and 3 (1) give sample sizes of households for estimating person-trip generation rates for town class 2 for households stratified by automobile ownership and household size and income, respectively. These tables give both the estimated number of completed interviews for households having given socioeconomic characteristics and the total number of households that would have to be sampled to locate the required number of households having the indicated socioeconomic characteristics. For example, if 200 completed interviews were required to estimate a person-trip generation rate for households of five or more persons in a particular income group, and if such households represented 10 percent of all households in this town class, a total of 2000 households would have to be randomly sampled to locate 200 households having the desired characteristic.

These tables illustrate two of the important considerations in designing a household travel survey.

1. The stratification of households into detailed geographic or socioeconomic strata may require that, if households are randomly sampled, a large number of households (i.e., total samples) be contacted to locate households having the desired characteristics. Screening households may help to reduce survey costs if specific types of households must be sampled.
2. The sample size estimates also show that substantial numbers of completed interviews are required in each data stratification. Depending on the approach, substantially more than 30 completed interviews may be required for each data stratification if person-trip generation rates are to be measured at ±5 or ±10 percent tolerance levels at a 90 percent level of confidence.

CONCLUSIONS

This paper presents an approach that may be used to determine the sample size needed to achieve specific objectives in a household travel survey. The following points are of particular importance.

1. Computation of minimum sample size should be based on the attainment of specific survey objectives. These objectives should be translated into the desired level of precision to be achieved in estimating individual survey variables.
2. Stratifying survey variables by geographic region or household characteristics can result in a substantially larger sample size. In many cases the minimum sample size needed to develop a statewide estimate will be approximately the same as that for a single subarea.
3. Trip-related survey variables must generally be treated by using cluster sampling procedures in a household survey. The design-effect correction factor should be used to account for the impact of clustering in computing sample size. Failure to use this procedure in determining sample size may result in travel

information that is insufficient to achieve survey objectives or in unnecessarily high survey costs.

4. Although the sampling approach described was developed in support of statewide transportation planning needs, these procedures are equally applicable to urban and regional household travel surveys.

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