# The Efficiency of List-Assisted Random Digit Dialing Sampling Schemes for Single and Dual Frame Surveys

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## 1. Introduction

An RDD sampling design consists of two components: the sampling frame and the sampling method. The sampling frames considered here are based on the set of all possible 10 digit numbers that can be generated using the area code-prefix combinations listed in the file of all such combinations available from Bellcore, Inc. The basic frame then covers all telephone numbers in the U.S. that are working when the Bellcore file is constructed. Only about 20% (Groves and Kahn, 1979) of the telephone numbers on the full frame will reach households and, thus, drawing simple random samples from the full frame can be quite inefficient.

An RDD sampling method that has gained much popularity in recent years is the Mitofsky-Waksberg (M-W) method (Waksberg, 1978). The M-W method is a two-stage clustered sampling scheme where the first stage unit is the 100-bank (i.e., the set of 100 telephone numbers having the same first eight digits) and the second stage unit is the telephone household. To draw a sample of $n$ residential phone numbers, a sample of $m$ 100 banks is drawn as follows: first, a 100-bank is selected from the Bellcore frame with equal probability and a randomly selected telephone number is dialed. If the number is residential, it is interviewed and the 100-bank is retained. Otherwise, the 100-bank is rejected. This primary selection process continues until $m$ 100-banks are retained. At the secondary sampling stage, telephone numbers are selected within each retained 100-bank and dialed until $k$, satisfying $n = (k+1)m$, additional residential phone numbers are contacted. This procedure provides full coverage of the telephone population and can be implemented with only a list of the working prefixes in the population. Further, it results in an equal probability sample of residential phone numbers. As Waksberg (1978) observes, the M-W procedure is more efficient than simple random sampling when (a) the proportion, $t$, of primaries (usually 100-banks) that have no residential telephone numbers is large (say, $t > .50$) and (b) when the intracluster correlation (denoted by $\rho$) for the characteristic(s) of interest is not large (say, $\rho < .10$). These conditions will be discussed in greater detail subsequently.

Despite the cost efficiency of the M-W method, there are several disadvantages to the design. First, the method requires that the residential/non-residential status of each generated telephone number be determined. However, usually 5-10% of the telephone numbers in an RDD survey cannot be classified and their statuses must be imputed. This can result in calling inefficiency as well as estimation bias (Biemer, Chapman, and Alexander, 1985). Secondly, the method requires that a fixed number, $k+1$, of residential numbers be contacted in each primary. Thus, new numbers must be continuously generated throughout the survey to replace numbers which were determined to be out of scope. For surveys of limited duration, this requirement creates a number of logistical problems for the field staff. Other disadvantages of the M-W procedure are discussed in Biemer, et al. (1985). Pothoff (1987), Burkheimer and Levinsohn (1988), and Brick and Waksberg (1991) offer some solutions to these difficulties, but their remedies create additional logistical and statistical problems.

To avoid the difficulties inherent with the M-W design and its derivatives, the present paper considers two strategies for increasing the efficiency of simple random sampling from the full frame. These are (a) *frame truncation* and (b) automatic screening for nonworking telephone numbers (*autoscreening*), both of which are described below.

*Frame Truncation.* Information on the number of residential phone numbers listed in phone directories for every 100-bank represented on the Bellcore file is available through a number of commercial firms. This information can be used to identify 100-banks, 1,000-banks, or 10,000-banks (exchanges) that are likely to contain a very small total number of residential numbers. By deleting these banks of numbers from the full frame, the density of residential numbers in the remainder of the frame is increased, thus increasing simple random sampling efficiency. Let $b$ denote the bank size and let $l$ denote the deletion limit for the truncation criteria. Finally, let $F_{b,l}$ denote the frame formed by deleting from the full frame, all $b$-banks having $l$ or fewer listed phone numbers. In our study we consider banks of size $b$ = 100, 1000, and 10,000 and deletion limit, $l$ = 0, 1, 5, and 10. Such frames are referred to as *truncated frames*.

Of course, the increase in sampling efficiency from frame truncation comes at a cost: *viz.*, reduced coverage of the telephone households. However, as we shall see, the loss of coverage may not be an important consideration when viewed against the potential benefits of sampling efficiency. This may be particularly true in dual frame survey designs where the second frame achieves full population coverage but its use is quite costly. For dual frame surveys, the population not covered by the truncated frame may be covered by the second frame. Further, lower costs for the RDD survey means lower total costs for the dual frame survey.

*Autoscreening.* Autoscreening takes advantage of a new technology that uses a computer to dial numbers. After five rings, the autoscreener will automatically code and terminate calls resulting in a phone company's recorded message, data phone signals, no rings, busy signal, or no answer. In this way, a majority of the nonworking numbers in the sample can be inexpensively identified and discarded. In addition, if a person answers the phone, the answerer can be automatically transferred to an interviewer to determine whether the number has reached a business, residence, or other number. Thus, the autoscreening procedure results in phone numbers that are classified as residential, business, other working, nonworking, or status unknown. For samples of moderate to large size, the autoscreening procedure can reduce RDD costs substantially over the traditional interviewer screening method.

In a recent study, Potter, et al. (1991) "autoscreened" 4,000 numbers selected from nonworking 100-banks. About 96% of the sample numbers were classified as either "nonworking," "residential," or "nonresidential" and the remaining 4% were classified as "status unknown." Of the nonworking numbers, less than 1% were incorrectly classified. Thus, the autoscreener's error rate for identifying and classifying nonworking numbers is extremely small. This study also demonstrated that the autoscreener's non-residential and business number classifications are much less reliable - less than 50% of these classifications were correct.

Because of the high degree of accuracy in the classification of nonworking numbers, these numbers may be deleted from the sample without affecting frame coverage. The other numbers (residential, non-residential, and status unknown) then comprise the sample for the survey. If the original sample was selected by SRS, the resulting sample of residential households is also SRS. A more efficient method of handling the numbers classified as business numbers is to subsample them at say, 50%.

Figure 1 provides a flow diagram for the SRS/AS procedure that was considered in this work. We begin with an initial SRS sample from the chosen frame (truncated or untruncated). The next step is optional; however, we have obtained slightly greater efficiency by executing by its inclusion. It involves matching the initial sample against a file of all directory listed residential phone numbers. Like the autoscreening service, the directory phone number matching service is also available commercially. The numbers that are matched are presumed to be residential numbers and constitute part of the sample to be sent to the telephone interviewing facility. The remaining numbers are sent to the autoscreener. Following the autoscreening procedure, nonworking numbers and a random half-sample of the numbers classified as working, non-residential are discarded. The remaining numbers (residential, status unknown, and half of the working non-residential numbers) are combined with the numbers that matched the directory list to form the SRS/AS sample.

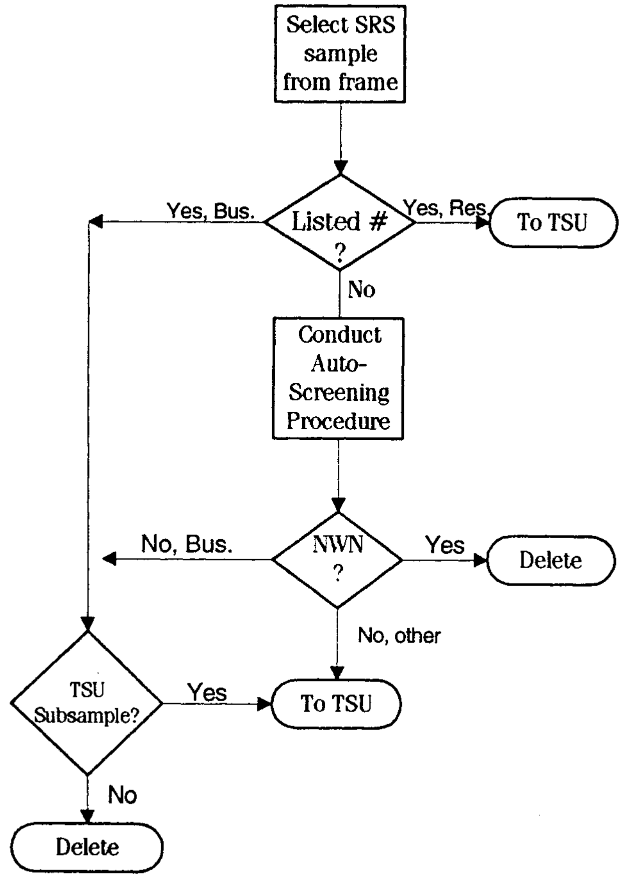


**Figure 1. SRS with Autoscreening (SRS/AS)**

Considering the sampling methods - SRS, StRS, and M-W - with and without autoscreening (the former denoted by "/AS" after the sampling method), six sampling methods can be identified. Then, combining these six methods with the 13 sampling frames - the full frame, denoted by $F_o$ and $F_{b,l}$ for $b$ = 100, 1000, and 10,000 and $l$ = 0, 1, 5, and 10 - a total of 72 sampling designs is possible. Due to the way we currently have implemented the autoscreening technology at RTI, it was not feasible to combine autoscreening with the M-W sampling method. Nevertheless, we believe the M-W/AS sampling scheme would a very efficient method and this method will be considered in a subsequent paper.

In this paper we show that, by combining frame truncation with autoscreening, the efficiency of simple random sampling (SRS) can be quite high and competitive with the M-W design. In fact, over the wide range of populations considered in our study, SRS with autoscreening (SRS/AS) cost no more and often less than the M-W procedure, regardless of whether a truncated frame or the full frame was used for both methods. We also consider the efficiency of using a stratified random sampling (StRS) design rather than a SRS. The class of stratified designs we consider are two stratum designs in which the strata are based on the density of listed telephone numbers in 100-banks. Generalizations to three or more strata are made based upon these results. Finally, we consider the efficiency of using truncated frames for dual frame surveys in which the second frame is a higher cost frame having full coverage of the target population. In particular, we examine the trade-offs between cost and variance from using the higher cost, full RDD frame compared with using a lower cost and lower coverage truncated frame

## 2. Optimization Formulas

### 2.1 RDD Optimization

To compare the alternate RDD sampling designs in our study, we modeled the minimum cost of each design for a specified level of precision in the estimator of a sample proportion. For unstratified designs, the assumed model for the total cost, $TC$, of an RDD survey was

$$TC = C_F + C_V \tag{1}$$

the sum of the fixed costs, $C_F$, plus the variable costs ($C_V$) where $C_{FIXED}$ was assumed to be equal for each design, and

$$C_V = C_p n_p + C_u n_u + C_{AS}(n_p + n_u) \tag{2}$$

where

$C_p$ = per unit cost of a productive call
$C_u$ = per unit cost of an unproductive call
$C_{AS}$ = per unit cost of autoscreening
$n_p$ = number of productive calls, and
$n_u$ = number of unproductive calls.

For sampling designs that did not use autoscreening, $C_{AS}$ was set to zero. Otherwise, the ratio $C_{AS}/C_u$ as well as $C_p/C_u$ was assumed to be the same for all survey designs.

For stratified sampling, the assumed model for $C_V$ was

$$C_V = \sum_{h=1}^{L} [(C_p n_{ph} + C_u n_{uh} + C_{AS}(n_{ph} + n_{uh})] \tag{3}$$

where $n_{ph}$ and $n_{uh}$ is the number of productive and unproductive calls respectively, in stratum $h$ and $C_p$, $C_u$, and $C_{AS}$ are as defined before.

In all variance formulas, we assume that the finite population correction factor is 1. For SRS, the variance formula for the sample proportion, $p$, is

$$V_{SRS} = PQ / n_p \tag{4}$$

where $P$ is the proportion in the population possessing the characteristic of interest and $Q = 1-P$.

Further, for SRS,

$$n_p = \frac{PQ}{V_0} \tag{5}$$

and

$$n_u = n_p\left(\frac{1}{H} - 1\right) \tag{6}$$

where $V_0$ is the desired variance of $p$ specified by the designer and $H$ is the proportion of productive calls in the sample (the hit rate) which must be estimated from the available data.

For StRS, the variance is

$$V_{StRS} = PQ \sum_{h}^{L} \frac{W_h^2}{n_{ph}} \tag{7}$$

where $W_h$ is the fraction of the target population in stratum $h$. Note that in this formula, the population proportion in stratum $h$, $P_h$, was assumed to be equal for all strata. This simplifying assumption does not affect the generalizability of our results. The usual formulas for optimal allocation (Cochran, 1977) yield

$$n_{ph} = \frac{W_h PQ}{\sqrt{C_h}\, V_0} \sum_h W_h \sqrt{C_h} \tag{8}$$

and

$$n_{uh} = n_{ph}\left(\frac{1}{H_h} - 1\right) \tag{9}$$

where $H_h$ is the hit rate for stratum $L$ and $C_h = (C_p/C_u + H_h^{-1} - 1)$, the per unit average cost for stratum $h$. Finally, for the variance of $p$ under M-W sampling, we used the formulas in Waksburg (1978); viz.,

$$V_{M\text{-}W} = \delta \frac{PQ}{n_p} \tag{10}$$

where $\delta$ is the design effect given by $\delta = (1+\rho k)$ and where $k$ is given by

$$k + 1 = \left[\frac{t}{\pi C_p/C_u + (1 - \pi - t)}\left(\frac{1-\rho}{\rho}\right)\right]^{\frac{1}{2}} \tag{11}$$

$\pi$ = the proportion of telephone numbers in the frame that are residential,
$t$ = the proportion of 100-banks that contain no residential numbers, and
$\delta$ = the intracluster correlation coefficient.

Finally, for M-W sampling, we computed $n_p$ and $n_u$ using Waksberg (1978) as

$$n_p = \frac{\delta PQ}{V_0} \tag{12}$$

and

$$n_u = \frac{m}{\pi}[1 + (1-t)k] - mk \tag{13}$$

where $m = n_p/(k+1)$.

2.2 Dual Frame Optimization

The objective of our study is to compare alternate dual frame designs that differ solely in the RDD sampling design component. The RDD sampling designs we consider are combinations of the 13 sampling frames and the six sampling methods discussed in Section 1. In particular, we are interested in the minimum cost of the dual frame design that satisfies specified precision criteria.

General formulas for the variance of a dual frame estimator are provided in Sirken and Cassady (1988). Their formulation makes a number of simplifying assumptions that are reasonable for most survey applications and the reader is referred to that article for a discussion of these. The cost model used for the dual frame comparisons is the following:

$$\begin{aligned} C_{DF} &= C_F n_F + C_T n_T \\ &= [C_F(1-\theta) + C_T\theta]\,n \end{aligned} \tag{14}$$

where

$C_F$ = per interview cost of the field interview,
$C_T$ = per interview cost of the RDD interview,
$n_F$ = number of households selected for interview from the field frame,
$n_T$ = number of households selected for interview from the RDD frame,
$\theta$ = proportion of the $n$ sample units selected from the RDD frame, and
$n$ = $n_F + n_T$.

This is essentially the cost model proposed by Sirken and Cassady assuming the fixed costs are constant across the alternate designs.

Consider the estimator of the population proportion, $P$, under the dual frame design. It is shown in Sirken and Cassady (1988) that

$$\begin{aligned} p_{DF} &= \hat{\alpha}\, p_{F,off} \\ &\quad + (1-\hat{\alpha})[\lambda p_{F,on} + (1-\lambda)p_T] \end{aligned} \tag{15}$$

is an unbiased estimator of $P$ with variance given by

$$\begin{aligned} Var(p_{DF}) &= \frac{PQ}{n}\Big[\frac{\alpha}{\pi_F(1-\theta)} \\ &\quad + \frac{(1-\alpha)^2\delta_T}{(1-\alpha)\pi_F(1-\theta)\delta_T + \pi_T\theta\delta_F}\Big] \end{aligned} \tag{16}$$

where

$\alpha$ = proportion of the population not on the RDD frame,
$\hat{\alpha}$ = an estimator of $\alpha$ based on the sample,
$p_{F,off}$ = field survey estimate of the proportion for households not on the RDD frame,
$p_{F,on}$ = field survey estimate of the proportion for households on the RDD frame,
$p_T$ = RDD estimator of the proportion for the households on the RDD frame,
$\lambda$ = weighting factor (see Sirken and Casady, 1988),
$\pi_F$ = field interview response rate,
$\pi_T$ = RDD interview response rate,
$\delta_F$ = field sampling design effect, and
$\delta_T$ = RDD sampling design effect.

Thus, for each dual frame design considered, we wish to determine the $\theta$ and $n$ that satisfy the following optimization problem:

$$\begin{aligned} \underset{\theta,n}{\text{Minimize}} \quad & C_{DF} = [C_F(1-\theta) + C_T\theta]\,n \\ \text{subject to} \quad & Var(p) \le V_0 \end{aligned} \tag{17}$$

where $V_0$ is a specified maximum variance.

We assume that the field interview frame completely covers the population and

$$0 < \theta < 1 \tag{18}$$

so that the coverage bias in all the dual frame estimators is zero. Thus, in what follows, the cost of the optimal dual frame design for a specified precision in the estimator of the population proportion will be the sole criterion for evaluating each dual frame design.

## 3. The Study Results

3.1 RDD Results

There are two sources of data for our study. First, we analyzed the call records for 1,200 phone numbers for the RDD component of a dual frame survey that is in progress in Texas and California. This RDD survey is using the SRS/AS sampling method in conjunction with two frames: $F_0$ which is being used for the first half of the study and $F_{100,0}$ which is being used for the latter half. The second source of data is a national RDD study that was conducted in 1990 using StRS and $F_0$. Here the call records for 45,000 phone numbers were analyzed to provide estimates of population hit rates and costs for national RDD studies.

Table 3.1 provides estimates of the percent of telephone numbers in Texas and California that reach residences ($\pi$ in our notation) for each of the 13 frames. With the full frame ($F_0$), $\pi$ is 18.4 percent in California and 14.3 percent in Texas. For the truncated frames in both states, $\pi$ is largest for $b$=100 and smallest for $b$=10,000. Note that for frame $F_{100,10}$, which has the highest proportion of deleted numbers, $\pi$ is more than twice as large in California and more than three times as large in Texas as for the full frame. Since the hit rates for any RDD sampling schemes are increasing functions of $\pi$, the increase in residential number density translates into reduced RDD sampling costs. Unfortunately, this cost reduction comes at the cost of reduced coverage of the population.

As shown in Table 3.1, as $\pi$ increases so does the proportion of telephone residences that are not included in the frame, denoted by $\alpha$ in our notation. For $F_{100,10}$, the coverage of the phone population is 95.4 percent in California and 93.2 percent in Texas. For a number of single frame RDD applications, the coverage bias associated with losses of coverage of these magnitudes may be intolerable no matter what the cost savings. However, the data in Table 3.1 allow the survey designer to balance survey costs with survey coverage in choosing the RDD frame.

**Table 3.1 Percent Residential, $\pi$, and Telephone Population Coverage, $1 - \alpha$, for Texas and California**

| | | STATE | | | |
|---|---|---|---|---|---|
| | | CALIFORNIA | | TEXAS | |
| | | $\pi$ | $1 - \alpha$ | $\pi$ | $1 - \alpha$ |
| Bank Size | Deletion Limit | % | % | % | % |
| 100 | 0 | 40.5 | 98.0 | 41.8 | 95.2 |
| | 1 | 41.6 | 98.0 | 43.0 | 95.2 |
| | 5 | 42.8 | 97.3 | 44.5 | 94.6 |
| | 10 | 43.4 | 95.4 | 45.9 | 93.2 |
| 1000 | 0 | 33.5 | 99.1 | 34.7 | 95.3 |
| | 1 | 35.0 | 99.1 | 36.5 | 95.3 |
| | 5 | 36.1 | 99.1 | 37.4 | 95.2 |
| | 10 | 36.7 | 98.9 | 37.9 | 95.2 |
| 10000 | 0 | 25.2 | 99.3 | 20.0 | 97.4 |
| | 1 | 25.3 | 99.3 | 20.0 | 97.4 |
| | 5 | 25.4 | 99.3 | 20.0 | 97.2 |
| | 10 | 25.6 | 99.3 | 20.2 | 97.2 |
| no deletion | | 18.4 | 100.0 | 14.3 | 100.0 |

As an example, the $F_{1000,5}$ produces a hit rate (for SRS) in California that is twice as large as that of the untruncated frame, while frame coverage loss is only 1 percent. For most single frame RDD applications, the implied cost savings would be well-worth this small risk of coverage bias. Of course, for dual frame applications, full coverage is guaranteed if the second frame has full coverage so that coverage bias is not the issue. What is important for dual frame designs is the effect of the loss of RDD frame coverage on the precision of the estimates for the telephone population. This question will be considered subsequently.

As mentioned previously, the RDD hit rate is an increasing function of the proportion, $\pi$, of residential units on the frame. For SRS, the hit rate is exactly equal to $\pi$. For SRS/AS, $\pi$ is a lower bound for the hit rate since greater dialing efficiency is realized through the autoscreening phase. For M-W designs, the hit rate is a complex function of a number of population parameters and cost components (see eq. 12 and 13). To compare the hit rates for the M-W, SRS, and SRS/AS designs, assume that: $P = .5$ and $C_p/C_u = 5$, a moderate value for this cost ratio. From the available data, we can estimate: $\pi$ and $t$, the proportion of 100-banks containing no residential numbers.

Table 3.2 provides an illustration of this comparison for California for two values of $\rho$, the 100-bank intracluster correlation coefficient. Only California is shown here to conserve space; however, these observations for California are essentially replicated in the analyses for Texas and the entire U.S. There are several things to note for this comparison:

1. For the $F_{100,l}$ frames formed by deleting 100-banks having $l$ or fewer listed numbers, $t = 0$ since this type of truncation eliminates 100-banks that contain no residential telephone numbers. As Waksberg (1978) observed, when $t = 0$ the M-W procedure will have the same efficiency as SRS. Thus, as can be seen from Table 3.2, the M-W and the SRS sampling methods have equivalent hit rates for both $\rho$-values when $b = 100$. For the larger values of $b$, the M-W procedure gains over SRS since $t > 0$.

2. The M-W procedure has higher hit rates when $\rho$ is small than when $\rho$ is large. This is because, for large $\rho$, the within 100-bank cluster size, $k$, is small (see eq. 7) and the M-W procedure requires a larger number of primaries, $m$, to achieve the optimal cost for a desired variance, $V_0$. The result is that more unproductive numbers must be dialed and, thus, a smaller hit rate is obtained.

3. The SRS/AS hit rate is the highest among the three methods. As mentioned previously, the SRS/AS hit rate cannot be smaller than that for SRS. The degree to which additional calling efficiency can be gained from autoscreening depends upon the proportion of nonworking numbers that can be identified electronically. Based upon our analysis of Texas, California, and the entire U.S., the gains shown in the table for California are typical of what can be expected for SRS/AS for state and national RDD surveys.

4. Based upon these hit rates, we expect that SRS/AS will be more efficient than SRS without autoscreening. We also expect that SRS/AS will compete very well with the M-W procedure. Note that without truncation, the SRS/AS hit rate and

the M-W hit rate for small $\rho$ are almost equal. Recall, however, that the SRS/AS is an unclustered design producing estimates with design effects of 1 while the clustered M-W method will have design effects larger than 1. Thus, the M-W procedure will require a larger number of interviews to achieve the same variance as the SRS/AS design. Still, the SRS/AS design incurs an additional cost for autoscreening that is not incurred with the M-W design. Thus, the comparison of the SRS/AS and the M-W designs will be quite sensitive to what is assumed for $C_{AS}$ and $\rho$, especially when the full RDD frame is used.

For the next set of comparisons, we compared cost of conducting a single frame RDD survey using M-W, SRS, and SRS/AS designs under a wide range of survey conditions. In these comparisons, $C_F$, $C_p$, and $C_u$ were assumed to be equal for all three designs. $C_p/C_u$ varied in the range of 2 to 20; $C_{AS}$ was set to 0 for the M-W and SRS without autoscreening. For SRS/AS we estimated $C_{AS}/C_u$ to be .17 based upon our recent experience. Finally, we considered sample sizes ranging from 400 to 10,000 residential phone numbers.

**Table 3.2 Hit Rates for the Alternate Designs**

| | | CALIFORNIA | | | | |
|---|---|---|---|---|---|---|
| | | $t$ | $H$ for SRS | $H$ for SRS /AS | $H$ for M-W $\rho$ = 0.02 | $H$ for M-W $\rho$ = 0.1 |
| | | | % | % | % | % |
| Bank Size | Deletion Limit | | | | | |
| 100 | 0 | 0.0 | 40.5 | 53.5 | 40.5 | 40.5 |
| | 1 | 0.0 | 41.6 | 54.1 | 41.6 | 41.6 |
| | 5 | 0.0 | 42.8 | 54.8 | 42.8 | 42.8 |
| | 10 | 0.0 | 43.4 | 54.9 | 43.4 | 43.4 |
| 1000 | 0 | 17.7 | 33.5 | 48.9 | 37.2 | 34.1 |
| | 1 | 14.3 | 35.0 | 50.1 | 37.3 | 35.5 |
| | 5 | 12.3 | 36.1 | 50.9 | 38.1 | 36.1 |
| | 10 | 11.4 | 36.7 | 51.2 | 38.6 | 36.7 |
| 10000 | 0 | 38.7 | 25.2 | 42.0 | 34.2 | 30.6 |
| | 1 | 38.5 | 25.3 | 42.2 | 34.3 | 30.1 |
| | 5 | 38.2 | 25.4 | 42.3 | 34.3 | 30.2 |
| | 10 | 37.8 | 25.6 | 42.6 | 34.4 | 30.3 |
| no delete | | 56.1 | 18.4 | 34.0 | 33.3 | 25.6 |

Figure 2 presents a comparison of the three designs for the State of Texas setting $C_p/C_u$ = 5; C.V (coefficient of variation) = .01 (i.e., approximately, 10,000 interviews), and all other parameters set to the same values as in Table 3.2. These results, which are typical of the results produced from these analyses, may be summarized as follows:

1. There is little efficiency to be gained from using a deletion limit greater than $l = 0$ whatever the value of $b$. Since higher values of $l$ will reduce frame coverage, selecting a truncated frame with $l > 0$ is not justified on the basis of these data.

2. The use of frame truncation can result in a considerable reduction in costs. For this sample size, using $F_{100,0}$ instead of $F_0$ saves \$46,000 for the SRS design and at least \$15,000 for the M-W design depending on the value of $\rho$. For the SRS/AS, the cost savings was approximately \$18,000.

3. For all 13 frames considered, the SRS/AS design is the most efficient RDD design. However, the reduction in cost over the M-W designs was only a few thousand dollars.

4. Considering the $F_{b,0}$ frames under the SRS/AS design, there is only a slight increase in cost (about \$2,000) going from $b$ = 100 to $b$ = 1,000. There is a much larger jump in cost (about \$7,000) in going from $b$ = 100 to $b$ = 10,000. These cost increases need to be weighed against the coverage improvement advantages of less frame truncation.

Finally, we considered the potential gains in efficiency from stratification where the stratum definitions are based upon the number of listed phone numbers in a 100-bank. We confine ourselves to a simple two-stratum design where Stratum 1 is the set of all 100-banks having $q$ or fewer listed phone numbers and Stratum 2 is the complementary set; i.e., the set of all 100-banks having $q$ + 1 or more listed numbers. The stratifier $q$ may defined optimally if the call records from a previous RDD survey is available. To find the optimal $q$, we set $q = l + 1$, the lowest value possible for truncated frames, and compute the cost of the RDD survey under optimal allocation to the two strata. Here, we can estimate the hit rates for the two strata using the available data. This process is repeated for $q$ = $l$+2, $l$+3, and so on, stopping when the $q$ with the lowest cost is found. Tucker, Casady, and Lepkowski (1993) consider much more complicated stratum definitions as well as more than three strata. However, because of its simplicity, stratification schemes such as the one considered here are often used in practice.

For this analysis, we considered the additional efficiency to be gained from stratification when using SRS

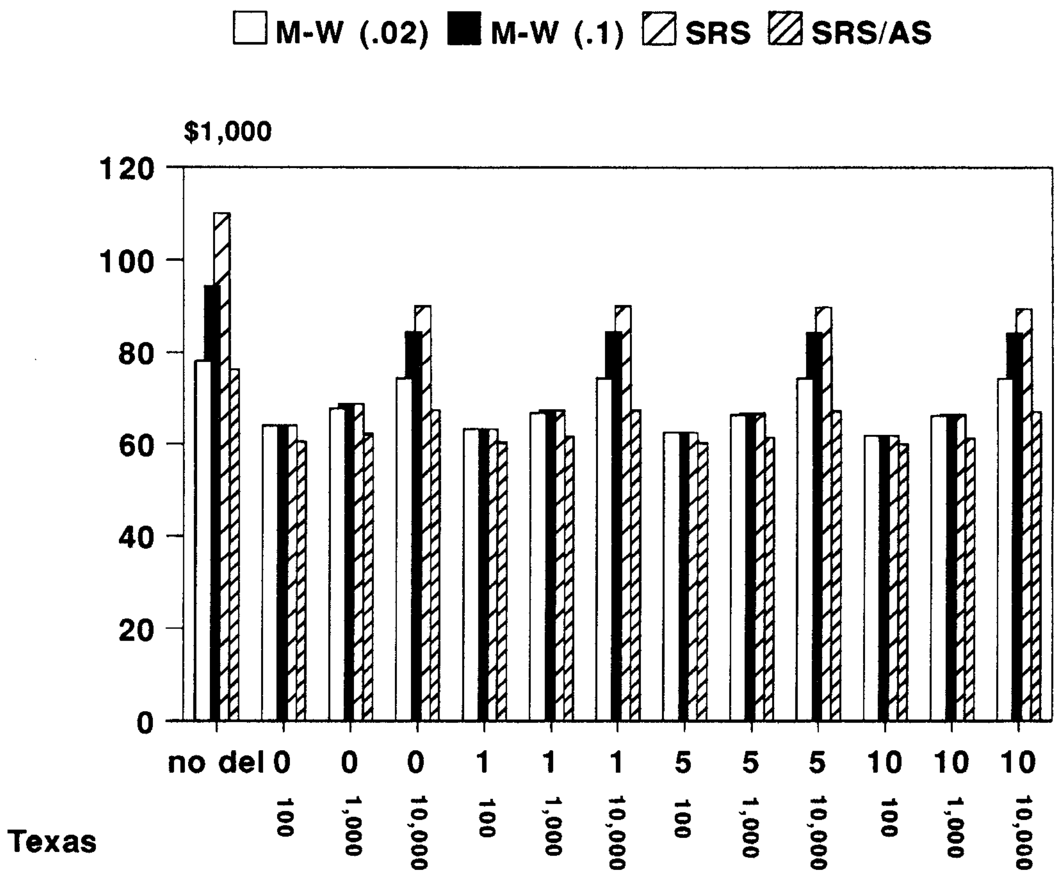


**Figure 2. Cost of Alternative Sampling Designs for Texas: $C_p/C_u$ = 5 and C.V. = .01**

(with or without autoscreening) and truncated frames. Our results are summarized in Figure 3 which compares SRS and StRS for truncated frames with $b$ = 100 as well as for the full frame. When used with the full frame, $F_0$, StRS substantially increases RDD sampling efficiency. However, there is little to be gained from this type of stratification when used in conjunction with the truncated frames.

Although the data needed to compare StRS with StRS/AS is not available for our analysis, we can infer from Figure 3 that cost of StRS/AS would not differ appreciably from SRS/AS when applied to truncated frames. Further, for the full frame, we do not expect the gains in efficiency using StRS/AS over SRS/AS that are illustrated in the figure for StRS and SRS. Since SRS/AS eliminates a large proportion of the nonworking numbers, we speculate that the comparison between StRS/AS and SRS/AS for $F_0$ will be very similar to the comparison of StRS and SRS for the truncated frames shown in the figure. Thus, for sampling designs using truncated frames and/or autoscreening, the simple stratification considered here does not gain enough efficiency to compensate for the additional complexity for data analysis brought about by the differential weighting of the sample.

3.2 Dual Frame Results

Finally, we consider the efficiency of the RDD sampling designs in the context of a dual frame survey where the second frame (area frame or address frame) requires a more expensive mode of interview (eg. face to face interviewing). We further assume that the second frame covers the entire target population. One might speculate that the use of truncated RDD frames would be very efficient in a dual frame design for two reasons. First, coverage bias is not a concern for the RDD survey since the second frame has full coverage. Thus, one could consider much higher levels of truncation (and more efficient RDD designs) than could be considered in the single frame case. Secondly, the precision of the nontelephone component of the dual frame estimator decreases as the proportion of households in the nontelephone population decreases. Therefore, in some situations, using an RDD frame that excludes a larger proportion of the population may actually improve the precision of the dual frame estimator.

Regarding the use of truncated frames in a dual frame survey, two points should be noted. First, if we define the "telephone population" as all households covered by the RDD frame, the telephone population may

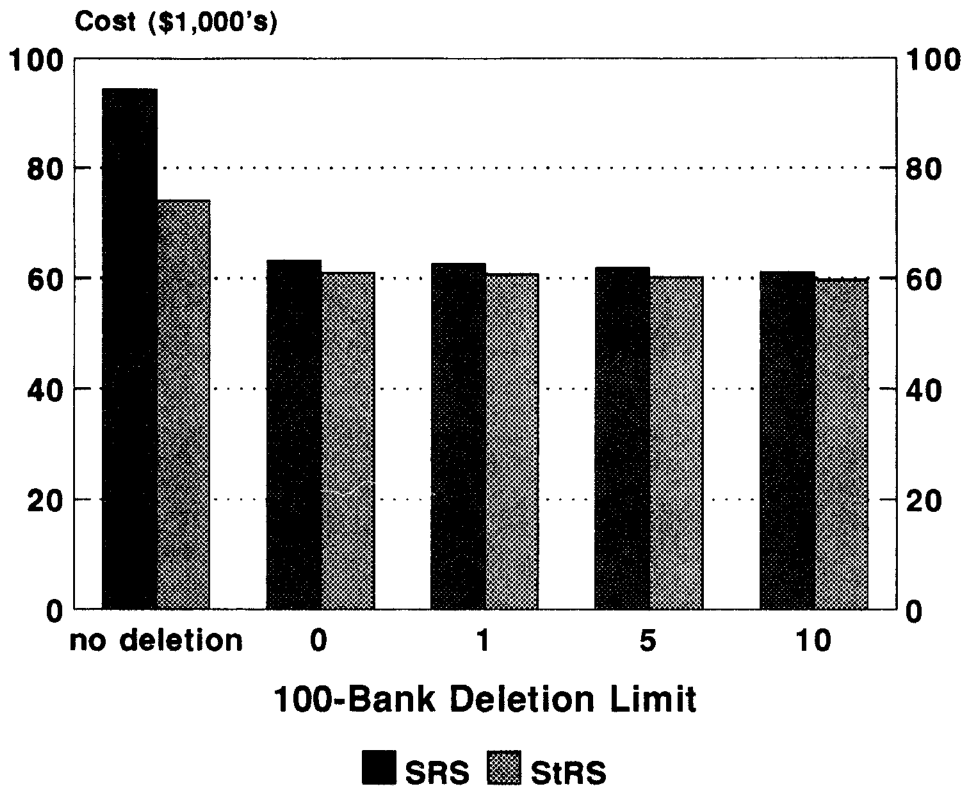


**Figure 3. Comparison of SRS and StRS for the U.S. : $n_p = 10{,}000$ and $C_p/C_u = 5$**

change according to the frame selected. Secondly, the use of truncated frames in a dual frame survey requires that we obtain the phone number (or at least the *b*-bank number) of the household in the field survey so that we can later determine whether the household is on the RDD frame. In the results that follow, we assume that frame membership can be accurately determined for each household. Further, we only consider the efficiency of optimal dual frame designs where the allocation of resources to the two frames is determined by minimizing the variable cost of the dual frame survey subject to a specified desired level of precision as described in Section 2.

The dual frame optimization formulae in Section 2 contain a number of parameters associated with either the telephone frame or the field frame. Of particular interest in the present analysis is the effect of RDD costs and frame coverage on dual frame efficiency. Consistent with our analyses of RDD single frame efficiency, we let $P = .5$, assume the RDD sample design effect, $\delta_T$, is 1, and considered optimal designs for achieving a C.V. of .01 for the estimator of $P$. For the remaining parameters, we assume the values that were assumed in Sirken and Cassady (1988). Thus, we assume $\delta_F = 1.3$, $\pi_T = .80$, and $\pi_F = .95$. The variable costs, $C_T$ and $C_F$ and the RDD noncoverage rate, $\alpha$, were varied systematically within a practical range of values. Finally, for each case considered, the sample allocation parameter, $\theta$, was set to its optimum value.

Figure 4 shows the relationship of RDD cost and coverage to the total dual frame survey cost for optimal dual frame designs. In this graph, $(1 - \alpha)$, plotted on the *x*-axis, varies in the range of 70% to 100% coverage of the telephone population, the range observed for the 13 frames in our study. On the *y*-axis is the cost ratio, $C_{DF}(F_{b,l})/C_{DF}(F_0)$, where the numerator is the dual frame cost using a truncated RDD frame with coverage $(1 - \alpha)$ and the denominator is the dual frame cost using the full RDD frame. Finally, the curves on the graph represent the relationship between the $C_{DF}$ ratio and the frame coverage for alternate assumptions regarding the relative cost of using a truncated frame. Each curve corresponds to a particular value of the ratio $C_T(F_{b,l})/C_T(F_0)$; i.e, the ratio of the RDD cost per interview using a truncated frame to the RDD cost using the full frame. The lower curve corresponds to a value of this cost ratio of 60% - that is, the RDD cost per interview using the truncated frame is 60% of the cost per interview using the full frame; the middle curve, 80%; and the top curve, 100%, that is no cost savings for the RDD survey by using the truncated frame. The horizontal line represents the point on the *y*-axis at which it is equally efficient to use a truncated frame for the dual

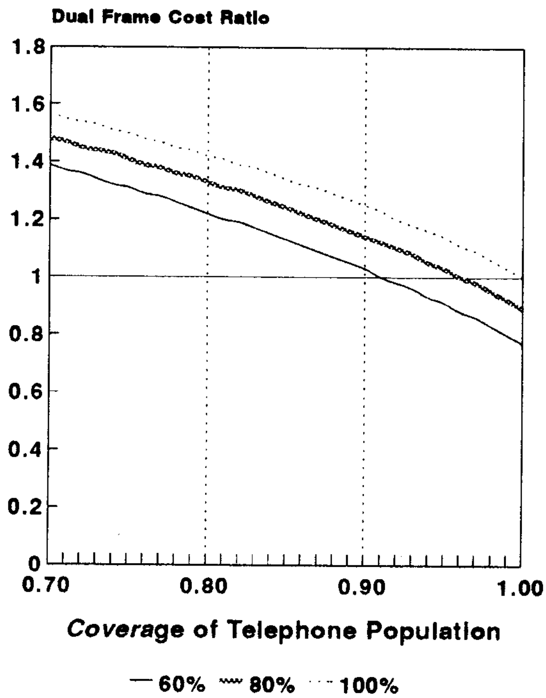


**Figure 4. Ratio of Dual Frame Cost Using $F_{b,l}$ to Dual Frame Cost Using $F_0$: $C_F / C_T = 4$**

frame survey as it is to use the full frame; that is, $C_{DF}(F_{b,l})/C_{DF}(F_0) = 1$.

The following is an illustration of the interpretation of the graph. Recall from Table 3.1 that the coverage of the telephone population in Texas using the $F_{0,100}$ frame is 95%. We therefore locate .95 on the $x$-axis. Now, for this coverage rate, we see from the graph that the RDD cost ratio, $C_T(F_{100,0})/C_T(F_0)$ must be no larger than 80% to achieve greater efficiency in the dual frame design by using $F_{0,100}$ instead of $F_0$. That is, we must be able to reduce the RDD cost per interview by at least 20% using the truncated frame to achieve the same dual frame efficiency as using the full frame. Since our previous analysis indicated that the RDD cost using $F_{0,100}$ was approximately 80% of the corresponding cost using $F_0$, we may conclude that there would be little or no cost savings from using $F_{0,100}$ for a dual frame survey in Texas under these assumptions.

Note that the dual frame cost is a decreasing function of telephone frame coverage and an increasing function of the RDD cost per interview. Note further that the cost of a field interview, $C_F$, is 4 times the cost of a telephone interview, $C_T$. The relationship depicted in Figure 4 changes somewhat if $C_F$ increases relative to $C_T$. In fact, as the relative cost of the field interview increases, the point at which these curves intersect the line $C_{DF}(F_{b,l})/C_{DF}(F_0) = 1$ moves to the right. Thus, higher coverage rates are demanded for the truncated frame to compete with the full frame: as field costs increase, the optimal sample design strategy allocates more sample units to the RDD frame and, thus, the less expensive, truncated frame becomes less efficient than the more expensive, but higher coverage, full frame.

## 4. Conclusions

In summary, we investigated the relative efficiency of four sampling methods - SRS, SRS/AS, StRS, and M-W - in combination with 13 sampling frames - $F_0$, and $F_{b,l}$ for b = 100, 1000, 10000 and $l$ = 0, 1, 5, 10 - both for a single frame RDD survey and also a dual frame survey. Using data from RDD surveys in Texas, California, and the entire U.S., we estimated the cost of a single frame RDD survey for a wide range of telephone variable costs and frame characteristics. We also investigated the efficiency of using truncated frames in a dual frame survey in which the allocation of sample to the two frames is determined optimally.

From these analyses, the following conclusions can be drawn:

1. When applied to $F_0$, the untruncated Bellcore frame, SRS/AS is at least as efficient as the M-W sampling scheme and when $t$ is less than 50%, is usually more efficient than M-W. Further, SRS/AS offers the added advantage of unclustered samples.

2. When applied to $F_{b,l}$, the truncated frames, SRS/AS is more efficient than the M-W method. This result is due to two factors. First, for truncated frames, the value of $t$ is usually less than about 40%. As Waksburg (1978) observes, the M-W method loses much of its advantage over SRS when $t$ is less than 50%. Secondly, the clustering of the M-W samples further reduces the efficiency of the design compared with SRS.

3. StRS with two strata substantially increased the efficiency of RDD when applied to $F_0$. However, for sampling designs using truncated frames, the increase in efficiency using StRS was quite small. The gains are also expected to be small for designs using autoscreening regardless of the frame used, although these designs were not evaluated in this study.

4. Frame truncation is not always efficient in dual frame surveys. A major determinant in the

decision to use a truncated frame is the cost of an RDD interview in relation to the cost of a field interview. When the ratio, $C_F/C_T$, is large (say, 10 or more), it is usually more efficient to use $F_0$ than $F_{b,1}$. This is because, under an optimal allocation design, the larger the ratio, $C_F/C_T$, the higher is the allocation to the RDD frame. As the allocation to the RDD frame increases, it becomes more important (in terms of estimator precision) to increase frame coverage than to decrease frame costs.

## REFERENCES


Biemer, P.P., Chapman, D.W., and Alexander, C.F. (1985). "Some Research Issues in Random-Digit-Dialing Sampling and Estimation," *Proceedings of the First Annual Research Conference of the U.S. Census Bureau*, U.S. Bureau of the Census, pp. 71-86.

Brick and Waksberg (1991). "Avoiding Sequential Sampling with Random Digit Dialing," *Survey Methodology*, Vol. 17, No. 1, pp. 27-42.

Burkheimer, G.J. and Levinsohn, J.R. (1988). "Implementing the Mitofsky-Waksberg Sampling Design with Accelerated Sequential Replacement," in *Telephone Survey Methodology*, New York, John Wiley and Sons.

Cochran, W.G. (1977). *Sampling Techniques*. New York. John Wiley and Sons.

Groves, R.M. and Kahn, R.L. (1979). *Surveys by Telephone: A National Comparison With Personal Interviews*, New York, Academic Press.

Potter, F., McNeill, J.J., Williams, S.R., and Waitman, Melodie A. (1991). "List-Assisted RDD Telephone Surveys," *Proceedings of the American Statistical Association, Section on Survey Research Methods*, pp. 117-122.

Potthoff, R.F. (1987). "Some Generalizations of the Mitofsky-Waksberg Technique for Random Digit Dialing," *Journal of the American Statistical Association*, Vol. 82, No. 398, pp. 409-418.

Sirken, M. G. and Casady, R.J. (1988). "Sampling Variance and Nonresponse Rates in Dual Frame, Mixed Mode Surveys," in *Telephone Survey Methodology*, New York, John Wiley and Sons.

Tucker, C., Casady, R.J., and Lepkowski, J. (1993). "A Hierarchy of List-Assisted Stratified Telephone Sample Design Options," in *1993 Proceedings of the American Statistical Association, Section on Survey Research Methods, Volume II*, pp. 982-987.

Waksberg, J. (1978). "Sampling Methods for Random Digit Dialing," *Journal of the American Statistical Association*, Vol. 73, No. 361, pp. 40-46.