Simulation Results of the Highway Performance Monitoring System

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This paper covers a detailed examination of the adequacy of the Highway Performance Monitoring System (HPMS) sample for making needs estimates at the district level in Texas and recommends increases in the current sample based on the results of the examination. To test the accuracy of sample sizes, a simulation model was developed to calculate the errors of a given sample size. Since the FHWA procedure uses average annual daily traffic (AADT) to calculate the required sample size, the simulation model was used to compare the accuracy of needs estimates with the assumed accuracy using AADT. It was found that in general, the errors were larger than the assumed error range at the functional class level, but the errors decreased substantially as functional classes were aggregated. The simulation model was also used to test the usefulness of stratifying the functional classes by volume group. It was found that in most cases stratifying did improve the accuracy of the sample estimates. Further, it was found that in most cases calculating the sample at the functional class level and distributing the sample to volume groups proportionately by mileage performed better than calculating the sample at the volume group level.

The Highway Performance Monitoring System (HPMS) (*1*) was developed by the FHWA to collect data on a large sample of highway sections throughout the United States and to make estimates on the current condition of the highway system and future needs, including effects of different funding levels. For that purpose, each state was required to select a stratified random sample of highway sections and to collect several items of information on each section. They are further required to maintain and update that information with annual submittals to FHWA. The sample covers all public roads above the local functional class.

The FHWA also developed a package of computer programs to summarize and analyze the data submitted by the states. The programs provide an analysis of the current or existing condition of the highway system and a number of options that consider future needs as well as impacts of different funding limitations. The basic procedure the analysis package uses is first to estimate the current condition of the sample highway sections. Those conditions are then compared to minimum tolerable conditions. For those sections that have values falling below those minimum values, an improvement is simulated. Both the type of improvement needed and the construction cost are estimated internally within the program. If a funding limitation is imposed, then the program selects the highest ranked needed improvements until the next funding period.

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The FHWA also provided to the states a version of the analysis package for use at the state level. Since the states must collect the HPMS information anyway, it would be advantageous to make use of that data if it can successfully be adapted to the needs within Texas. That is the purpose of this study, to examine the sample and analysis package for possible adaptation and use in Texas.

One potential use of the HPMS data and analysis package for Texas is to provide information on the current condition of the highway system in Texas and estimates of future needs, similar to what is done at the federal level. Currently the Texas Department of Highways and Public Transportation (TSDHPT) compiles a document called the Strategic Mobility Plan (SMP) (*2*). This gives estimates of 20 year needs of the department and is updated every 2 years. The estimates are based on a combination of the projects submitted by the districts, which cover the anticipated needs over the next 20 years, and a computer program, which estimates aggregate rehabilitation and maintenance needs over the same 20-year period.

The HPMS has the potential to be used in combination with, or as a substitute for, the current procedure. Use of HPMS sample data would eliminate the need for submitting individual projects for estimating needs, and estimating several categories of needs together in one analysis eliminates the double counting in the current system. For example, the same highway section could have an added-capacity project submitted by the district and a pavement rehabilitation estimated with the computer program. The HPMS would eliminate that type of double counting if the improvements are needed in the same time frame, usually 5 years (which can be varied).

A disadvantage of the HPMS system is that it does not cover all construction areas TSDHPT is interested in. These include new location projects, bridges, interchanges, and routine maintenance. These would have to be handled outside the HPMS framework.

Overall, however, HPMS does seem to have a potential for providing consistent needs estimates over time. Another significant advantage is the ability to quickly and easily make estimates of the effects of changes in funding levels, something that cannot be done with the present system. This could be very beneficial when making policy and when working with the legislature in determining the required funding for TSDHPT.

This paper documents some of the work that has been done in examining the HPMS sample and analysis package for use in Texas. Extensive work has been done in examining the adequacy of the sample size and in making recommendations for increasing the sample to make needs estimates at the district level.

ADEQUACY OF THE HPMS SAMPLE

Current Sampling Procedure

The FHWA has recommended to the states the procedures that should be followed in calculating the size of the sample needed for each state, the selection of the samples, and the criteria for selecting additional samples as needed over time. The highway system is first stratified into rural, small urban, and urbanized categories. The urbanized areas can either be handled collectively or as individual areas. Currently, there are 30 designated urbanized areas in Texas that are sampled separately. Each area is broken down by functional class (excluding the local functional class) and further stratified by volume group (up to 13) within each functional class using average annual daily traffic (AADT).

The FHWA provides a formula for calculating the required sample size for the highway sections in each volume group. The formula is given below and is from Appendix G of the HPMS Field Manual (*3*). The minimum sample size is three unless there are three or fewer sections in the volume group; in such case all sections are sampled.

$$n = F/[1 + 1/N(F - 1)] \text{ with } n \geq 3 \quad (1)$$

where:

n = required sample size
F = $[(Z_\alpha)(c)/d]$
Z_α = value of the standard normal statistic for (α) confidence level (two-sided)
c = AADT coefficient of variation
d = desired precision rate
N = universe or population stratum size

The FHWA has recommended values of both Z_α and d, based on functional class, with generally higher precision and confidence levels for higher functional classes. The Texas Transportation Institute (TTI) Research Report 480-1 (*4*) shows that the current procedure can cause a problem in calculating the required sample size in some circumstances. The problem results from the use of AADT as both the variable for stratifying the highway sections and in calculating the required sample size within each of those stratified volume groups.

An example from a TRB paper on the same subject should illustrate the potential problem (*5*). The example looks at the minor arterial functional class from the Houston urbanized area. In volume group 1, from 0 to 2,499 AADT, there are 40 sections. Using Formula 1, n = 11.34. However, in volume group 5, from 15,000 to 19,999, with 154 sections, Formula 1 gives n = 0.29, which would use the minimum of 3. In the paper the reasons that this can happen are described and a procedure is recommended for eliminating the problem by calculating the required sample size at the functional class level using Formula 1 and then distributing the sample to the volume groups.

The problem with the FHWA procedure does not seem to be serious in most cases because there are not usually a large number of sections in higher volume groups where the problem is most significant. In addition, as shown in the simulation results, aggregating tends to reduce the error introduced in under sampling some volume groups. It should not affect estimates at the national level, but it could have some effect at the state level and substate level. For that reason, the sampling simulation in the next section uses the changes in the recommended procedure for testing and determining the required sample size for district level HPMS estimates in Texas.

A recent General Accounting Office (GAO) study (*6*) found the current HPMS sampling procedure to be adequate for making national needs estimates.

HPMS Sample Simulation

The objective and goal of taking a sample is that if chosen properly it can be used to represent the population being sampled subject to a known margin of error. In the case of HPMS, the sample is being used to represent the entire highway network. One of the main concerns is how well the sample represents the overall network in terms of the estimated needs over time. However, those needs are not known before the sample is selected and data are collected and analyzed.

As described previously, the size of HPMS sample is calculated using AADT, a commonly available data item on most highway sections. Since the sample size calculations and the margin of error is based on AADT, the accuracy of estimating needs is not known. In a sense, AADT is being used as a proxy for sampling purposes for other unknown items, such as needs. Although AADT may be a good proxy for some needs, it does not cover all possibilities over time. For example, AADT and 20-year needs tend to be correlated, but that correlation varies considerably, with higher correlations in rural areas than in urban areas. Therefore, it became necessary as part of this study to devise a method to determine the accuracy of various sampling rates for estimating needs.

There have been some studies that examine the accuracy and reliability of the HPMS sample in representing the highway network (*6,7*). There has also been considerable interest in the area of pavement management, to determine the sample coverage required to estimate pavement condition and rehabilitation costs (*8*). It was determined that a similar analysis could be performed on the HPMS sample in Texas.

A simulation model was developed to test several sampling rates and methods using the Texas HPMS sample data as the base of comparison. Only those samples on the state maintained highway system were used, because estimates of needs are required by TSDHPT for those highways. The sample was treated as the universe, like a district, and samples were taken from that universe. The sample sizes were calculated for this universe using the formula and procedure described in the previous section, and samples were selected randomly. The accuracy of the sample was calculated by comparing the needs estimate of the sample with the needs estimate of the universe. This procedure was repeated several times to generate an error distribution curve, giving the probability of any margin of error occurring, which could then be compared to the assumed accuracy, based on the AADT used to calculate the sample size. This was done for both 5- and 20-year HPMS needs estimates.

Three different groups of precision rates were tested in the simulation model. The precision rates recommended by FHWA for statewide sampling and for individual urbanized areas were used along with a lower precision rate I developed for testing. The three groups of precision rates are presented in Table 1. The precision rates specify the probability that the sample mean will fall within a specified range. For example, if a 90-5 precision is specified, it means that the sample mean AADT will be within ± 5 percent of the universe mean AADT 90 percent of the time. If a sample were drawn 100 times from the universe, the sample mean AADT would be expected to be within 5 percent of the universe mean 90 times.

A sample size was calculated for each precision rate on all the functional classes; Formula 1 was used to calculate the required sample size. These numbers are presented in Table 2. The estimated needs for all the HPMS sections were used as the basis of comparison in calculating the sample errors. For example, in rural class 1, there is a total of 176 HPMS sections. For the statewide precision rate, 142 of those sections need to be sampled. Sections were randomly selected, without replacement, until 142 of the 176 total had been selected. Selection without replacement was used so that the same section could not be in the sample more than once.

After the samples were selected, the 5- and 20-year costs were summed and then expanded to represent all the sections, using the ratio of the universe mileage to sample mileage as the expansion factor. That is the same process used in the HPMS analytical package. The samples were not stratified by volume group during this part of the simulation; stratification is tested in the next section. The error then can easily be calculated by taking the difference between the expanded sample cost and the universe cost and dividing by the universe cost. This was repeated 350 times to give a distribution of the errors. The number of replications, 350, was chosen because the distribution seemed to stabilize at about that point in testing of the simulation model and the distribution changed very little with higher replications. Some examples of the simulation results are shown in Figures 1 to 6. The complete set of graphs is contained in TTI Research Report 480-2F (*9*).

Each of the figures depicts the accuracy range along the horizontal axis, which is based on the calculated percent sample error previously described. The vertical axis gives the percentage of the 350 samples that fall within that range of accuracy. For example, in Figure 1, rural functional class 1, the top line represents the error distribution with the statewide precision rates. About 82 percent of the samples were within 5 percent of the 20-year needs estimate for all the sections in the universe and about 98 percent were within 10 percent of the universe amount. None of the samples was more than 15 percent off.

TABLE 1 PRECISION RATES USED IN SAMPLE SIMULATION

Functional Class	FHWA Statewide Precision Rates[1]	FHWA Individual Urbanized Area Rates[1]	Lower Precision Rates
Rural			
1 - Interstate	90 - 5	80 - 10	70 - 10
2 - Principal Arterial	90 - 5	80 - 10	70 - 10
3 - Minor Arterial	90 - 10	80 - 15[2]	70 - 15
4 - Major Collector	80 - 10	70 - 15	60 - 15
5 - Minor Collector	80 - 10	70 - 15	60 - 15
Small Urban and Urbanized			
1 - Interstate	90 - 5	80 - 10	70 - 10
2 - Other Freeway	90 - 5	80 - 10	70 - 10
3 - Principal Arterial	90 - 5	80 - 10	70 - 10
4 - Minor Arterial	90 - 10	80 - 15[2]	70 - 15
5 - Collector	80 - 10	70 - 15	60 - 15

[1] FHWA rates taken from Appendix F, HPMS Field Manual (3). The first number in each entry of the table is the confidence interval and the second number is the precision or range of error for that confidence level.

[2] Precision rates changed from those recommended in HPMS Manual to make them consistent with statewide rates. The recommended precision rate is 70 - 15.

TABLE 2 SUMMARY OF SAMPLE SIZES USED IN HPMS SIMULATIONS

Functional Class	Total Number of HPMS Sections	Sample Size Simulation: Statewide Precision Rate	Individual Urbanized Rate	Lower Precision Rate	Stratifying by Volume Group Simulation
Rural					
1 - Interstate	176	142	69	52	92
2 - Principal Arterial	437	355	174	132	171
3 - Minor Arterial	165	112	60	45	53
4 - Major Collector	173	139	94	76	74
5 - Minor Collector	162	111	63	48	66
All	1113	859	460	353	456
Small Urban					
1 - Interstate	42	38	27	23	31
2 - Other Freeway	25	23	18	18	20
3 - Principal Arterial	264	184	69	49	98
4 - Minor Arterial	57	49	36	30	36
5 - Collector	8	7	6	6	8
All	396	301	156	124	193
Urbanized					
1 - Interstate	148	112	48	35	60
2 - Other Freeway	167	137	69	52	86
3 - Principal Arterial	442	291	100	71	97
4 - Minor Arterial	147	97	51	37	48
5 - Collector	15	13	11	10	14
All	919	650	279	205	305
Statewide	2428	1810	895	682	954

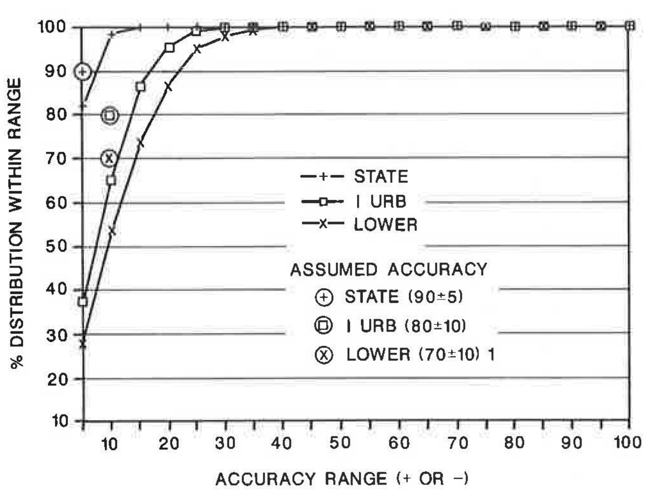

FIGURE 1 Results of HPMS simulation, testing sample size—20-year needs, rural functional class 1. ***Note*****: State, statewide precision rate; I URB, individualized rate; Lower, lower precision rate.**

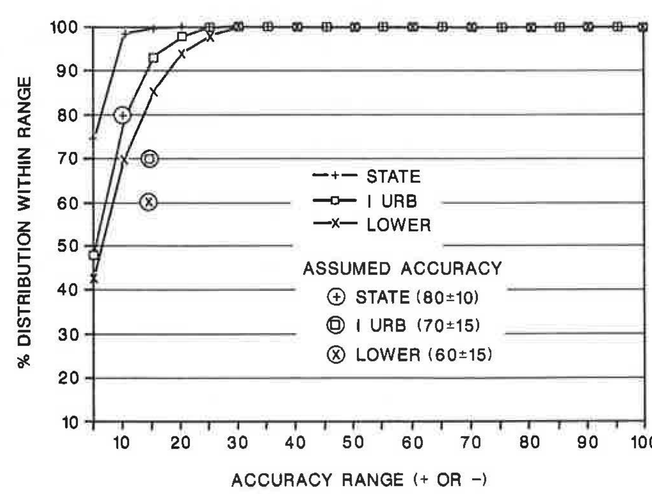

FIGURE 2 Results of HPMS simulation, testing sample size—20-year needs, rural functional class 4.

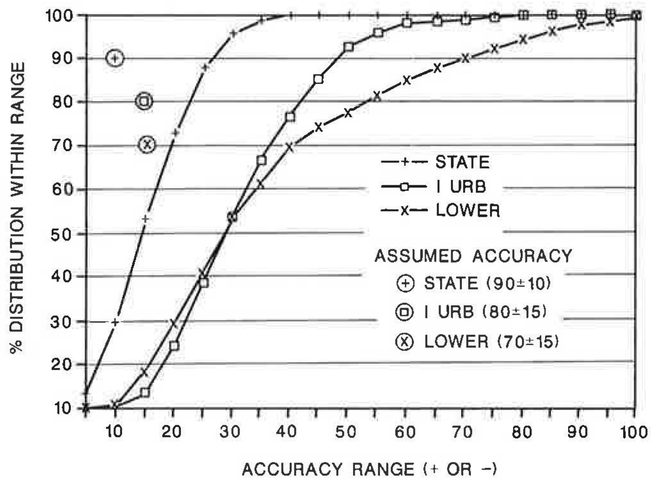

FIGURE 3 Results of HPMS simulation, testing sample size—20-year needs, urbanized functional class 4.

The assumed precision rates are also shown on each figure when applicable. The cross with a circle around it at 90-5 in Figure 1 is the statewide precision rate used to calculate the sample size. The simulated error is somewhat below the assumed precision rate, but not by much. The other precision rates miss by more. For example, the lower precision rate assumes 70 percent of the samples will be within 10 percent of the actual amount, but only 54 percent are in that range in the simulation. The rate does go over 70 percent at the 20 percent range, but doesn't reach 100 percent of the distribution until about a 50 percent range of accuracy.

Much better results are shown in Figure 2, rural functional class 4, in terms of the accuracy of the simulation versus the assumed precision. In each case, the simulated accuracy is much higher than the assumed precision. For example, the assumed statewide precision is 80-10, whereas the simulated results give about 98 percent of the distribution within 10 percent of the actual value.

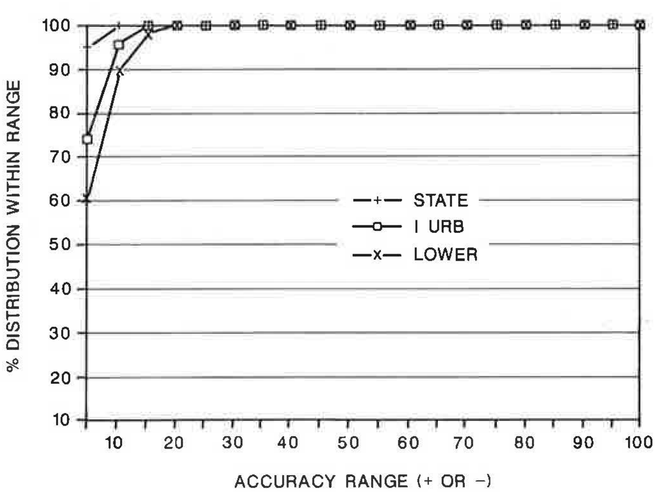

FIGURE 4 Results of HPMS simulation, testing sample size—20-year needs, all rural functional classes.

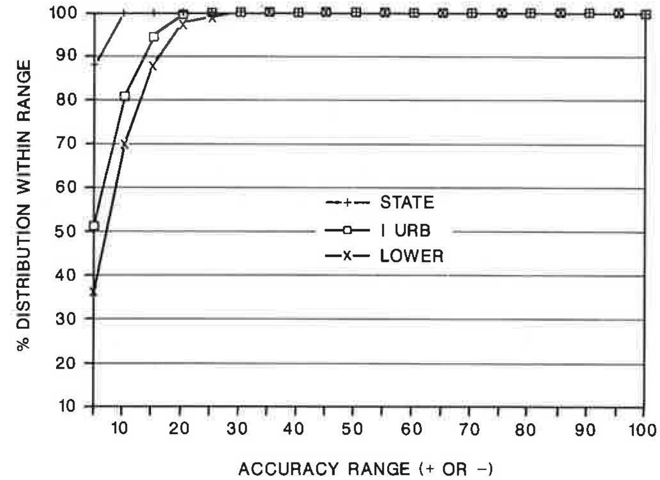

FIGURE 5 Results of HPMS simulation, testing sample size—20-year needs, all urbanized functional classes.

At the other extreme, the results of urbanized functional class 4 are shown in Figure 3. Here the errors are much larger than was assumed in calculations of the sample sizes. For example, the statewide precision rate assumes 90 percent of the distribution will be within 10 percent of the actual amount, but only about 30 percent of the distribution is within that range. At the lowest precision rate there are some samples that have an error greater than 100 percent.

Fortunately, aggregating substantially reduces the errors for individual functional classes. The combined functional classes in the rural area are depicted in Figure 4. The assumed precision rates are not shown because they vary by functional class. The statewide precision rate gives about 96 percent of the samples within 5 percent and 100 percent within 10 percent. Even the lower precision rate has 90 percent of the samples within 10 percent and 100 percent within 20 percent.

As would be expected, the combined urbanized area, shown in Figure 5, is not as high as the combined rural area, but the

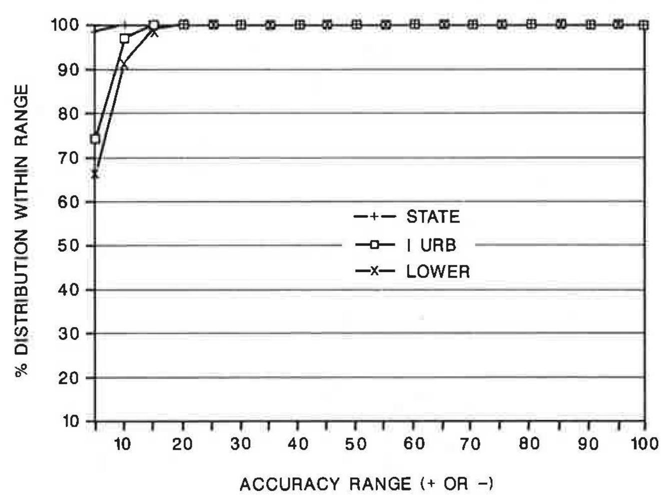

FIGURE 6 Results of HPMS simulation, testing sample size—20-year needs, all statewide functional classes.

improvements are substantial. The statewide precision rate gives about 88 percent of the samples within 10 percent and 100 percent within 10 percent. The lower precision rate gives about 88 percent within 15 percent and 100 percent within 30 percent.

The combined statewide distributions are shown in Figure 6. The statewide precision rate is very high, with 100 percent of the distribution within 10 percent. The other two are somewhat lower, but still very high, with both above 90 percent at the 10 percent accuracy level.

There appears to be considerable increases in the accuracy levels when functional classes are combined, even if the accuracy of individual functional classes is not very high.

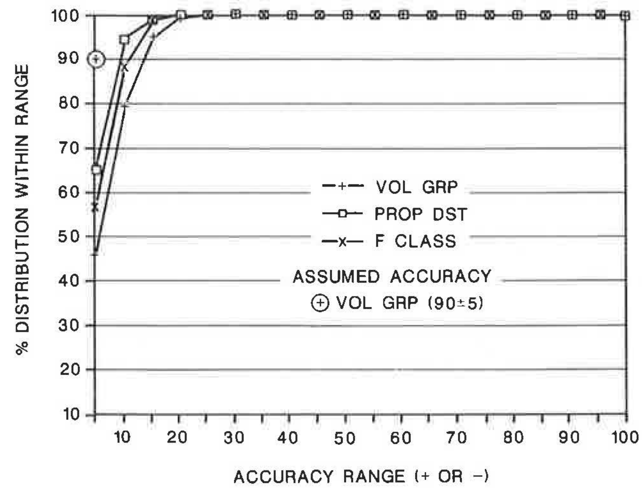

FIGURE 7 Results of HPMS simulation, testing volume group stratification—20-year needs, rural functional class 1.

Stratification by Volume Group

One common way to improve the accuracy of the sample is to stratify it into more homogenous groups. The HPMS sampling procedure attempts to do this by stratifying functional classes by volume group. The objective is to reduce the required number of samples for a given precision rate. One reason for that was to reduce the data-collection burdens on the states when the HPMS sample data was originally collected. Stratification does not necessarily improve the accuracy of the sample and it can actually make it worse, though it generally helps.

In an effort to determine the usefulness of stratifying the HPMS sample by volume group using AADT, the simulation model was used to test two stratification strategies. The first is the current technique recommended by FHWA. The HPMS sections are stratified by AADT volume group and then the required sample size for each volume group is calculated using Formula 1. In the second method the same AADT volume group stratification is used, but the sample is distributed proportionately by mileage to the volume groups. The functional class level of sampling, presented in the previous section, is also used in this stratification simulation as the basis of comparison. The functional class sample is not stratified at all, so it can be compared with the previous graphs.

A summary of the sample sizes used in the volume group simulation is given in Table 2. A complete set of sampling rates by volume group used in the simulation is contained in TTI Research Report 480-2F (*9*).

For these HPMS sections, the sample size calculated at the volume group level using the statewide precision rate gives roughly the same sample size as using the individual urbanized precision rate at the functional class level. For example, the statewide total in Table 2, the sample for individual urbanized rate is 895, compared to 954 for the volume group stratification. Of course, the sample sizes for some functional classes vary considerably, influencing the accuracy of individual functional classes.

Some examples of the simulation results of stratification are shown in Figures 7 to 11. Rural functional class 1 is presented in Figure 7. All three lines are below the assumed precision of 90-5, with the proportional distribution performing the best. Surprisingly, the unstratified functional class distribution is higher than the volume group calculated distribution. In this case, the calculation of sample size by volume group actually was worse than if no stratification at all had been done.

A somewhat different result for rural, functional Class 3 is shown in Figure 8. In this class the highest accuracy is the volume group calculation with the stratified proportional distribution higher at most levels of accuracy than the unstratified distribution.

As was the case with the simulation results of the previous section, the errors tend to be much larger in the urban areas (Figure 9), but decline substantially as functional classes are combined (Figures 10 and 11).

In general, stratification improved the overall accuracy of a given sample. This can be seen in the combined statewide distributions in Figure 11. Both stratification strategies give a substantial improvement at the 5 percent and a lesser improvement at the 10 percent level. In most cases, the proportional stratification improved the sample accuracy as compared to the volume group calculated accuracy, although that

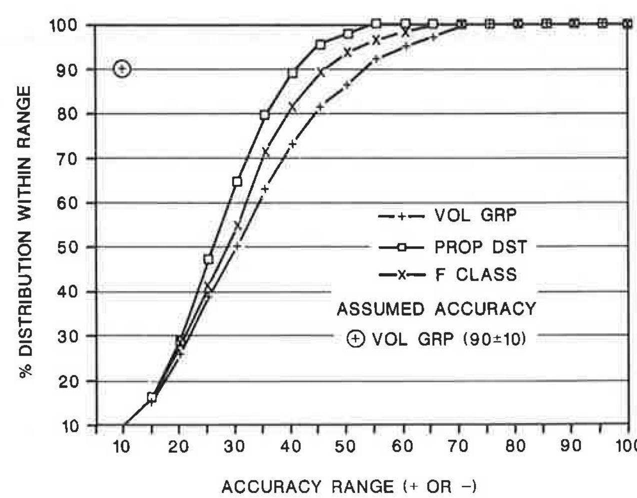

FIGURE 8 Results of HPMS simulation, testing volume group stratification—20-year needs, urbanized functional class 4.

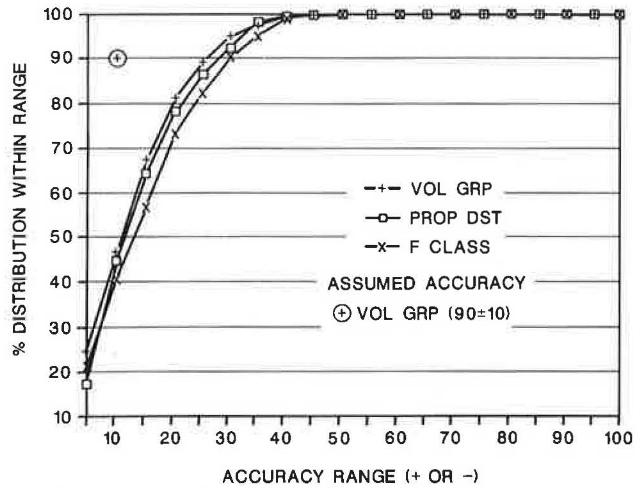

FIGURE 9 Results of HPMS simulation, testing volume group stratification—20-year needs, rural functional class 3.

is not always the case, and many times the difference is very small. However, the benefits of stratification that FHWA anticipated when stratifying the HPMS sample by volume group are very small. The same sort of accuracy can be obtained by a simple proportional stratification.

HPMS Sample Size Recommendation for Texas

As a result of the simulation results, and taking into account the requirement to estimate needs at the district level, the TSDHPT advisory committee for this project decided to substantially increase the HPMS sample size in Texas. It was decided that estimates were not required at the functional class level within districts, so the errors estimated with the simulation model at the area level were acceptable. The recommended sample represents about a 133 percent increase in the on-system HPMS sample in Texas. The recommended

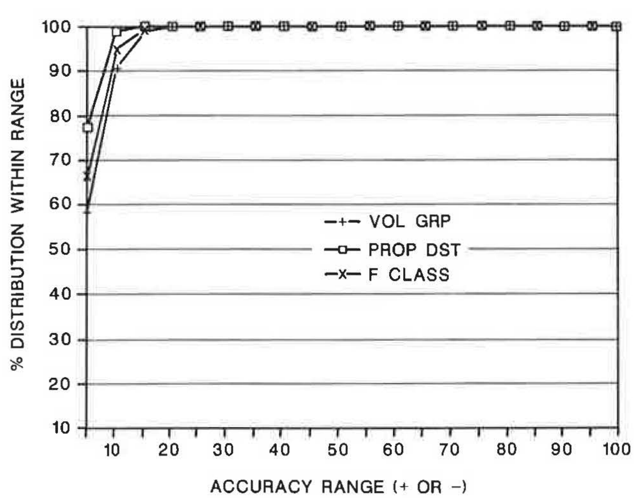

FIGURE 10 Results of HPMS simulation, testing volume group stratification—20-year needs, all urbanized functional classes.

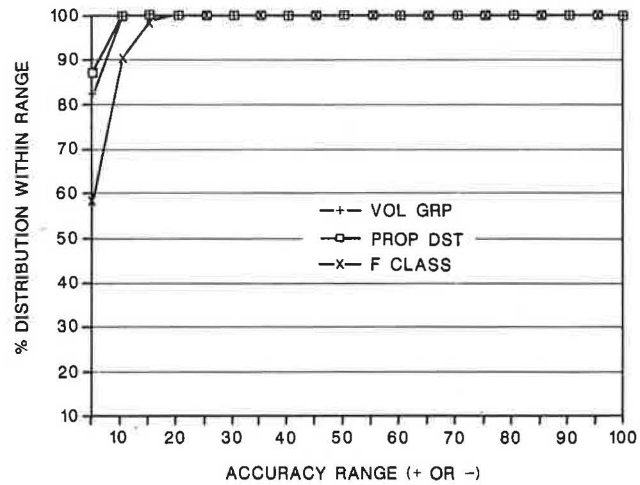

FIGURE 11 Results of HPMS simulation, testing volume group stratification—20-year needs, all statewide functional classes.

sample sizes were calculated at the functional class level by district, with proportional distribution of samples within volume groups. The individual urbanized precision rates were used for the urban area and the lower precision rates, presented in Table 1, were used for the rural and small urban areas. The lower precision rates were used for the rural area because the simulation results indicated satisfactory accuracy levels with that precision rate. The small urban areas constitute a very small proportion of the estimated statewide needs, so the lower precision rates were also used for that category. There was also a concern to keep the increase in sample sizes as low as possible because it would entail a significant data-collection burden for the districts, and the small increase in the accuracy of the estimates would not justify the increased data-collection costs.

CONCLUSION

The HPMS sample data and analytical package offer an opportunity for Texas to make estimates of future needs in a consistent and comprehensive fashion that is not available at the present time. In addition, it provides a tool for estimating the effects of different funding levels on the condition of the highway system and the motorists using the highways. This method should be very valuable in the future.

One of the biggest areas of concern with the HPMS is the sample. Anytime a sample is used to represent a larger population, in this case the highway network, there is a legitimate concern that the sample may not accurately represent the population for estimating those unknown elements from the population. In the case of HPMS, the sample is based on AADT, a commonly used and widely available data item for highways. However, one of the principal items of interest is not the input AADT, by itself, but how it affects, along with the other data items, the estimated needs in the output. For that reason a simulation model was developed to determine how good a sample, based on AADT accuracy, is in estimating needs.

The results of the simulation showed that in general the needs accuracy is not as high as assumed when the sample size for individual functional classes is calculated. But when aggregating over functional classes, the accuracy significantly improves, which suggests that for highly aggregated needs estimates the sample is probably not introducing much error. In other words, the sample is accurately representing the overall highway network. However, more caution should be exercised when making estimates at lower levels of aggregation.

The recommended increases in the HPMS sample for use in Texas represent the results from the simulation model, as well as the need to stratify the sample to the district level. The increased sample will provide adequate coverage for district level needs estimates, and because it is far above the minimum required sample from FHWA, should pose no problems for reporting purposes to the FHWA.

ACKNOWLEDGMENT

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