Procedures for Measuring Regional VMT

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Detailed sampling procedures that can be used to estimate regional vehicle miles of travel (VMT) at a specified level of statistical precision are presented. These procedures were developed to reduce or eliminate problems discovered during tests of preliminary procedures in six test areas. The revised procedures account for three major sources of uncertainty in VMT estimation: (a) spatial variability, (b) temporal variability, and (c) measurement error. A relatively complex stratified sampling plan is suggested to increase the precision of estimated VMT in a cost-effective manner. Estimation methods and "default" values are suggested for key sampling parameters. An example application is provided to demonstrate how these procedures can be used to develop sampling plans for estimating regional VMT.

Transportation planning agencies are showing greater interest in measuring regional vehicle miles of travel (VMT) on an ongoing basis. Estimates of regional VMT can be useful for planning, policy assessment, environmental and energy analysis, and basic trend monitoring.

Detailed procedures for estimating VMT through the use of sampling techniques were developed to meet these needs (1). These procedures were then subjected to rigorous experimental tests in Philadelphia; Savannah, Georgia; Brevard County, Florida; Dallas-Fort Worth, Texas; Sioux City, Iowa; and the state of Rhode Island. These tests demonstrated the following major limitations of the VMT monitoring procedures: (a) The assumption of uniform system link lengths was often impractical, and the alternative procedure for treating links of varying length was inefficient; (b) no allowance was made for counts missed due to mechanical failure, vandalism, or bad weather; (c) the possible effects of measurement error were disregarded; (d) the random selection of locations and data-collection days resulted in somewhat costly and inefficient data-collection activities; and (e) no methods were provided for assessing the overall level of precision achieved when VMT estimates for geographic areas and/or facility types were aggregated to represent a larger population.

The sampling procedures described in this paper were developed to eliminate or reduce these problems. The procedures (a) permit link lengths to vary by using probability proportional to size (PPS) selection methods, (b) provide more flexibility in scheduling counts so that annual VMT can be estimated on the basis of counts concentrated over a relatively short period during a season when there is good weather to reduce the number of missed counts, (c) permit the effects of measurement error to be incorporated in the sampling plan, (d) enable counts to be scheduled evenly over the data-collection period by use of systematic rather than random selection procedures, and (e) provide ways of assessing the overall level of precision achieved when VMT estimates for geographic and/or facility-type populations are aggregated to estimate regional VMT.

SAMPLING PROCEDURES FOR REGIONAL SURVEYS

A relatively complex sampling plan is needed to estimate VMT at the regional level because (a) regional estimates are typically needed for different functional classes of highways and/or geographic subareas, (b) data collection is often performed by several different agencies, and (c) the necessarily large scope of the survey requires that the most efficient sampling methods be used.

Defining Sample Strata

The first step in developing a sampling plan is to define the stratification method. Two types of stratification apply to regional VMT estimation: reporting strata and sample strata. Reporting strata define specific populations for which VMT is to be estimated. Sample strata, on the other hand, define specific populations that are considered in the sampling plan.

A single reporting stratum can be divided into two or more sampling strata to increase the efficiency of the sampling plan. Sampling efficiency for regional VMT estimation can often be achieved by breaking reporting strata into relatively homogeneous sample strata, based either on the expected volume level (if known) or on a volume surrogate such as the number of lanes.

The local street network does not provide a very strong candidate for further stratification, since historic data on local street volumes are not likely to be available.

The arterial network offers the greatest opportunity to gain efficiency through stratification because of the wide range of volumes carried by arterials. If appropriate volumes are known, sample strata can be created, such as in 5000-vehicle/day ranges.

The potential benefits of stratifying freeway links are heavily influenced by the number of links in the system. In small- to moderate-sized freeway systems, it may be desirable to sample all links. Stratification in this case would serve no purpose.

An illustrative stratification method for estimating regional VMT is shown in Figure 1. In this example, estimated regional VMT is desired for local arterials and freeways. The reporting stratum for arterial highways has been divided into eight sampling strata to improve sampling efficiency. The reporting stratum for freeways has similarly been divided into three sampling strata based on the number of lanes.

The definition of sampling strata for estimating regional VMT is likely to be an iterative process. The initial stratification method will typically be revised after the initial sample-size estimates for each stratum are computed. As discussed below, the efficiency of the sampling plan can be increased markedly by reducing the expected range in volumes within individual sample strata.

Computing Regional VMT

An efficient way of estimating regional VMT with a sample of traffic counts is to estimate the average volume in each sample stratum, multiply the average volume by the known total mileage for the links in the stratum, and aggregate the stratum-specific VMT estimate to produce estimates for the desired reporting strata. This approach requires, however, that count locations be selected by using PPS procedures (described later). An estimate of regional VMT can be computed as

$$\overline{VMT} = \sum_{h}^{H} VMTh \qquad (1)$$

$$\overline{VMT} = MH * \overline{VOLh} \qquad (2)$$

$$\overline{VOLh} = (1/Nh) * \sum_{1}^{Nh} VOLhi \quad (3)$$

where

$\overline{VMT}$ = estimated average regional VMT during the period of interest,
H = number of sample strata,
$\overline{VMTh}$ = estimated average VMT in sample stratum h during the period of interest,
Mh = mileage of stratum h,
$\overline{VOLh}$ = estimated average volume in sample stratum h,
Nh = number of volume counts made, and
VOLhi = volume measured on count i in sample stratum h.

The above formulas assume that the reporting stratum was defined as the total region. But estimates of VMT for other reporting strata can be similarly obtained by aggregating the appropriate sample strata.

Estimating Sample Parameters

Certain key sample parameters must be estimated before the sample size required for each sample stratum can be computed. These sample parameters reflect three distinct sources of uncertainty: (a) spatial variability (variability of volume between locations), (b) temporal variability (variability of volume over time), and (c) measurement error (uncertainties due to mechanical counter errors). The specific sample parameters that correspond to these three sources of uncertainty are summarized in Table 1 and discussed below.

Spatial

Spatial variability is introduced because volume data from only a sample of links are used to estimate regional VMT. The sample parameter that accounts for spatial variability is SVOLL, the standard deviation of volume across locations.

Figure 1. Stratification method for estimating regional VMT.

REPORTING STRATA	SAMPLE STRATA
Local Streets	Local Streets
Arterials	Arterials: ADT 0-5 000
	5 000-10 000
	10 000-15 000
	15 000-20 000
	20 000-25 000
	25 000-30 000
	30 000-35 000
	>35 000
Freeways	Freeways: 4 lanes
	6 lanes
	>8 lanes

For sample strata that have been formed on the basis of expected volume ranges, the SVOLL parameter can be most easily estimated as

$$SVOLLh = (VRANGEh + 1000)/3.5 \quad (4)$$

where SVOLLh is the standard deviation of volume across locations in stratum h and VRANGEh is the range in volumes specified for stratum h. The second term in the numerator of Equation 4 is included to approximate the effects of misclassified arterial links.

For sample strata that have not been formed on the basis of expected volume levels, the SVOLLh parameter can be estimated as

$$SVOLLh = CVVOLLh * \overline{VOLh} \quad (5)$$

where CVVOLLh is the assumed coefficient of variation of volume across locations in stratum h and $\overline{VOLh}$ is the expected average volume in stratum h. Possible "default" values for CVVOLL are given in Table 1.

Temporal

Temporal variability reflects variations in volume levels over time. These can potentially include short-term and long-term effects, depending on the study design. There are three basic methods of accounting for temporal variability for annual studies:

1. Defining a short study period--A year-round average regional VMT estimate may not be needed. The estimate could represent a relatively short study period that (a) provides typical VMT patterns, (b) reduces problems caused by severe weather, and (c) permits efficient use of field personnel. Growth in VMT levels could be monitored by counting the same study period each year so that direct comparisons could be made.
2. Collecting data year round--Volume counts could be taken on randomly selected days throughout the year so as to capture any seasonal fluctuations. This would not be practical in areas with severe winter weather.
3. Applying seasonal adjustment factors--Volume counts could be taken during a relatively short period (the first method) and then adjusted with factors to represent annual regional VMT. The seasonal adjustment factors would require data from permanent automatic traffic recorders (ATRs) for each day throughout the year.

Each of these methods requires the use of a different set of temporal sample parameters.

Table 1. Regional sample parameters.

Source of Uncertainty	Symbol	Definition	Method of Estimation	Default Value
Spatial	SVOLL	Standard deviation of volume across locations	Equation 4	CVVOLL = 0.60 (locals), 0.60 (arterials), and 0.30 (freeways)
Temporal	SVOLD	Standard deviation of volume across days within a season	SVOLD = CVVOLD * $\overline{VOL}$	Figure 2
	SVOLS	Standard deviation of volume across seasons of year	SVOLS = VRANGE/4	0
	SEADJ	Standard error of seasonal adjustment factors across automatic traffic recorders	Peat, Marwick, Mitchell and Company (2)	SEADJ = 0.05
Measurement	SEAXL	Standard error of volume counts at a single location due to assumed axle correction factors	$STR/[\sqrt{NTR} * (1 + TR)]$	STR = 0.04 or SEAXL = 0.02

Method 1

When a relatively short study period is used, the only source of variability is the day-to-day fluctuation of volumes. The sample parameter that accounts for daily (short-term) variability is SVOLD, the standard deviation of volume across days. The SVOLD parameter can be estimated as

$$SVOLDh = CVVOLDh * \overline{VOLh} \qquad (6)$$

where SVOLDh is the standard deviation of volume across days within a season in stratum h and CVVOLDh is the coefficient of variation of volume across days within a season in stratum h.

The value of the coefficient of variation can be expected to vary, depending on the duration of the counting period and the volume level. Figure 2 shows the relation between the coefficient of variation and average daily traffic (ADT). For shorter periods, such as 2-h peak periods, the coefficient of variation can be expected to fall in the following range:

$$0.05 \leqslant CVVOLDh \leqslant 0.15 \qquad (7)$$

Method 2

When volume counts are to be made throughout the year, two sources of variability should be considered: the day-to-day fluctuation of volume and the long-term shifts in volume throughout the year. The corresponding sample parameters are SVOLDh, the standard deviation of volume across days within a season, and SVOLSh, the standard deviation of volume across seasons.

The estimation of SVOLDh was discussed above. Estimating SVOLSh will require either (a) using volume data for a representative year from ATRs or from intensive counting programs at selected locations or (b) making assumptions about the probable range of seasonal shifts in volume levels. In the latter case, SVOLSh can be estimated as follows:

$$SVOLSh = VRANGEh/4 \qquad (8)$$

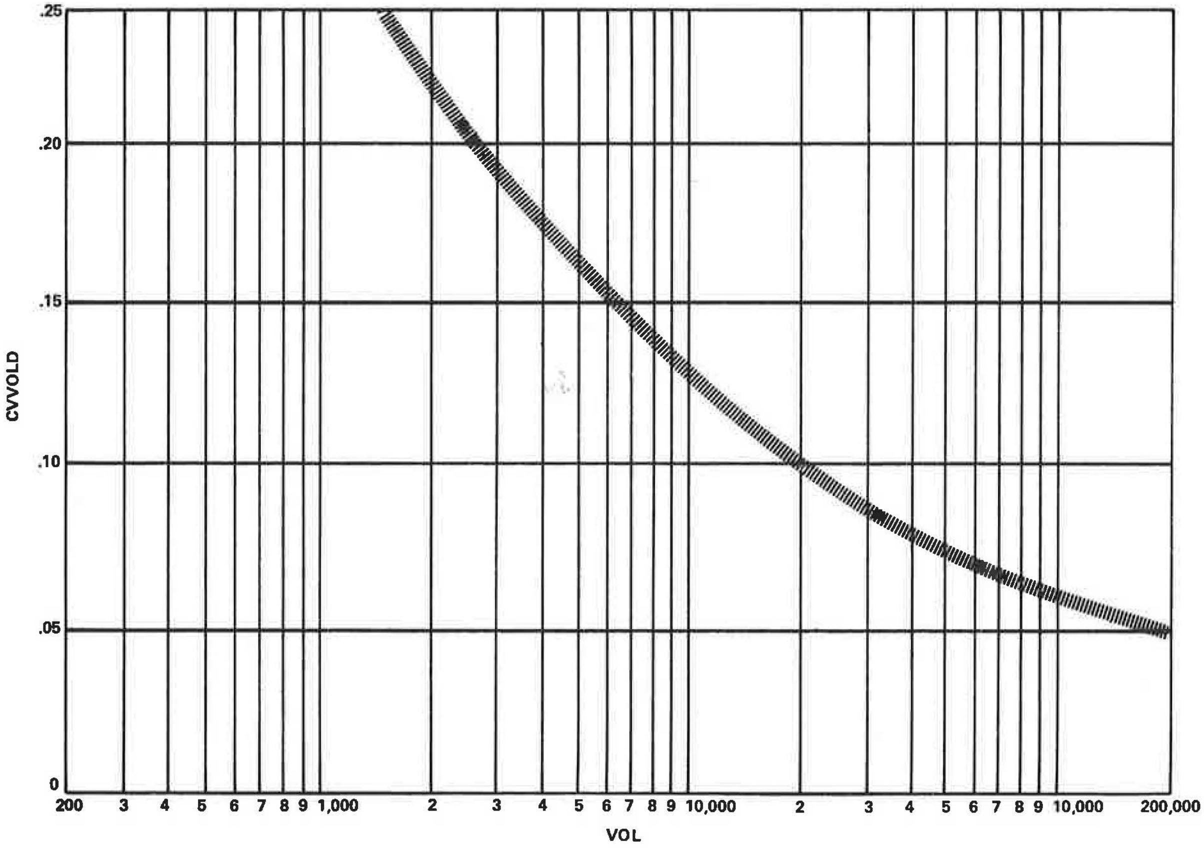
where SVOLSh is the standard deviation of volume across seasons in stratum h and VRANGEh is the approximate range of average volumes between seasons in stratum h. If no major seasonal shifts are expected, SVOLSh can be disregarded (and set at zero).

Method 3

When ATRs are used to adjust for seasonal factors, two sources of variability should be considered: (a) the day-to-day fluctuation of volume and (b) the uncertainty in the calculated expansion factors. The corresponding sample parameters are SVOLDh, the standard deviation of volume across days within a season, and SEADJe, the standard error of the seasonal adjustment factors.

The estimation of SVOLDh was discussed above. The estimation of SEADJe will require historical count data from the ATRs and reflect the methods used to develop the corresponding seasonal adjustment factors. Although seasonal adjustment factors should ideally be available for all sample strata, most agencies will not have a sufficient number of ATRs for this purpose. In this case, the sample strata can be grouped into "aggregate" sample strata

Figure 2. Default coefficient of variations for daily volume across days.



that represent broader classifications. For example, the illustrative set of sample strata shown in Figure 1 could be regrouped into four larger strata representing (a) local streets, (b) arterials with less than 10 000 ADT, (c) arterials with more than 10 000 ADT, and (d) freeways. Corresponding seasonal adjustment factors could then be developed for these aggregate sample strata on the basis of volume data from a small number of ATRs located at "representative" locations in each of these four aggregate strata. A general discussion of the use of seasonal adjustment factors, guidelines for using current ATRs and locating new ones, and a formula for estimating SEADJe are provided elsewhere (2). If the seasonal adjustment factor will be generated from a single ATR representing a particular aggregated volume stratum e, the SEADJe parameter can be estimated as

$$\text{SEADJe} = 0.05 \qquad (9)$$

Measurement

Measurement error reflects the limitations of mechanical traffic-counting devices for counting the volume on a given day. Errors are of two types: (a) equipment errors made in counting the number of axles and (b) errors made in converting raw axle counts to traffic volume counts.

Measurement errors from equipment malfunctions are extremely difficult to incorporate in the development of a sampling plan. The effects of equipment errors can be considered negligible for sampling-plan purposes if the average error in axle counts is less than approximately 10 percent.

Measurement errors made in converting raw axle counts to volume counts should usually be considered. The major factor of uncertainty here is the percentage of vehicles with more than two axles at a particular location on the counting day. The sample parameter is SEAXL, the standard error of volume counts due to assumed axle correction factors.

If the assumed axle correction factors are developed on the basis of experience and judgment, a relatively conservative default value of SEAXLe for strata for which the axle correction factor has been judgmentally determined is

$$\text{SEAXLe} = 0.02 \qquad (10)$$

Composite Parameters

The spatial, temporal, and measurement parameters described above can be consolidated into two composite terms:

$$\text{SVIh} = (\text{SVOLLh}^2 + \text{SVOLDh}^2 + \text{SVOLSh}^2)^{1/2} \qquad (11)$$

$$\text{SVEe} = (\text{SEADJh}^2 + \text{SEAXLh}^2)^{1/2} \qquad (12)$$

where SVIh is the composite standard deviation for the internal (i.e., related to the sample size of volume counts) variability and SVEe is the composite standard error for the external (i.e., not related to the sample size of volume counts) variability.

The sample parameters SVOLSh and SEADJe are optional and will depend on the method of incorporating temporal fluctuations, as follows:

1. If the VMT estimate will be based on field data collection over a relatively short study period and will not be adjusted to represent travel throughout the year, SVOLSh and SEADJe should be disregarded (i.e., set to zero in the formula).
2. If the VMT estimate will be based on field data collection throughout the entire year, SVOLSh should be estimated and SEADJe should be disregarded.
3. If the VMT estimate will be based on the combination of field data collection over a relatively short study period and seasonal adjustment factors from permanent ATRs, SVOLSh should be disregarded and SEADJe should be estimated.

Computing the Sample Size

The sample size of traffic-counting sessions needed for each sample stratum will reflect the desired level of precision, estimated sample parameters, and the stratification method used. The relation between the reporting stratum and the component sample strata is particularly important. Two basic situations can be considered: (a) single reporting stratum and multiple sample strata and (b) multiple reporting strata and multiple sample strata.

Single Reporting Stratum and Multiple Sample Strata

Multiple sample strata will usually be created for arterial and freeway systems to increase efficiency. If a single sample stratum is used, the same equation applies. For example, the reporting stratum could represent all arterial streets and the sample strata could represent arterial streets of particular volume levels.

The number of link days of data collection that will be needed to reliably estimate the VMT in reporting stratum r can be computed as

$$\text{Nr} = \left(\sum_{h}^{H} \text{Mh} * \text{SVIh}\right)^2 \Big/ \left[(\text{DVMTr}^2/\text{Z}^2) + \sum_{h}^{H} (\text{Mh}^2 * \text{SVIh}^2/\text{NPOPh}) - \sum_{e}^{E} (\overline{\text{VMTe}}^2 * \text{SVEe}^2)\right] \qquad (13)$$

where

Nr = number of volume counts required in reporting stratum r;
H = number of sample strata in reporting stratum r;
DVMTr = acceptable difference between the estimated VMT in reporting stratum r and the true value;
Z = normal variate for the specified level of confidence, two-tailed test (i.e., as represented in standard tables);
NPOPh = population of links in same stratum h;
E = number of aggregate sample strata for purposes of reflecting external errors that cannot be affected by the sample size for volume counts; and
$\overline{\text{VMTe}}$ = anticipated VMT in aggregated sample stratum e.

The inclusion of the sample parameters SVOLSh and SEADJe in computing SVIh and SVEe will, as before, depend on the method of accounting for temporal variability, as discussed earlier.

The sample size for reporting stratum r can be allocated among the H sample strata as follows:

$$\text{Nh} = \text{Nr} * \text{Mh} * \text{SVIh} \Big/ \left(\sum_{h}^{H} \text{Mh} * \text{SVIh}\right) \qquad (14)$$

The computed number of counts for each sample stratum can generally be rounded so that the desired number of counts for the reporting stratum is achieved. Although the VMT estimate for the reporting stratum can be computed with a minimum of one count per sample stratum, a minimum of two counts per sample stratum will permit the precision of the VMT estimate for the reporting stratum to be computed after the results of the counting program are available.

Multiple Reporting Strata and Multiple Sample Strata

The second case that must be considered occurs when more than one study objective must be met through the counting program. In this case, more than one reporting stratum must be considered in the sampling plan. For example, the counting program could be designed to provide VMT estimates as predetermined levels of statistical precision for (a) all arterial highways in each of the three counties of the region, (b) all arterial highways in the region, and (c) all highways in the region (i.e., including local streets, arterials, and freeways). The sampling plan would therefore need sample sizes that would permit all of these estimates to be made at the desired levels of precision.

In general, the sampling plan will be built around the minimum sample sizes specified for each sample stratum from the "controlling" objective. The controlling objective is that which requires the largest sample size for a given sample stratum. For example, the sample size of counts for the reporting strata corresponding to the arterial highways in each country may be large enough that the estimates of VMT for all arterial highways in the region may be achieved as well. In this case, the sample sizes needed for the county-specific VMT estimates are controlling. But, if a lower precision had been specified for the county-specified VMT estimates, the sample size needed for the estimate for all regional arterials may have been controlling. In each case, the precision desired for the VMT estimates for the controlling objective will be attained and the precision desired for the other objectives will probably be higher than desired.

The method of determining the minimum sample sizes needed for each sample stratum is therefore likely to be iterative in nature. The sample sizes should first be computed for each objective individually. These initial sample sizes should then be adjusted as needed so that all objectives can be achieved. The precision of an estimate of VMT for any reporting stratum made up of more than one sample stratum can be computed as follows:

$$\mathrm{DVMTr} = \mathrm{Z} * \left[\sum_{h}^{H} (\mathrm{Mh}^2 * \mathrm{Fh} * \mathrm{SVIh}^2/\mathrm{Nh}) + \sum_{e}^{E} (\overline{\mathrm{VMTe}}^2 * \mathrm{SVEe}^2)\right]^{1/2} \quad (15)$$

$$\mathrm{Fh} = (\mathrm{NPOPh} - \mathrm{Nh})/\mathrm{NPOPh} \quad (16)$$

where Fh is the finite population correction factor.

The effect of the finite population correction factor is only approximated in the above equation, but it should be sufficiently accurate for practical applications. This term is likely to be important only when relatively small strata are sampled at a relatively high rate, as will typically occur for sample strata that represent freeways.

The precision of an estimate of VMT for a reporting stratum that represents a single sample stratum can be computed as

$$\mathrm{DVMTr} = \mathrm{Z} * [(\mathrm{Mh}^2 * \mathrm{Fh} * \mathrm{SVIh}^2/\mathrm{Nh}) + (\mathrm{VMTh}^2 * \mathrm{SVEe}^2)]^{1/2} \quad (17)$$

Selecting the Sample

The locations for volume counts should be chosen by using PPS methods to avoid possible biases. The sample of locations can be selected in two steps: (a) identify candidate links by using either random or systematic selection procedures (in the latter case, considerable caution must be used) and (b) select the sample of locations from the candidates by incorporating the length of the links in the procedure. Thus, for example, if a link included in the initial selection is twice as long as another link also included in the initial selection, the first link should have twice the probability of being included in the final sample of locations.

Once the count locations have been identified, a day must be chosen for each location. Sampling of days may be performed randomly, or some systematic process may be used. The advantage of systematic selection is the control it offers to ensure that the demand for personnel and equipment is spread out over the study period. It must be realized, however, that any departure from random selection must be carefully considered to make sure that no systematic bias is introduced. Either way, sampling should be carried out with replacement.

EXAMPLE

Assume that a planning agency wants to estimate regional VMT for each of three reporting strata: (a) local streets within ±25 percent, (b) arterials within ±5 percent, and (c) freeways within ±5 percent. A 95 percent level of confidence is specified, which indicates that the agency is willing to face a 1-in-20 chance that a given VMT estimate will fall outside the indicated range.

Further assume that the data-collection effort will be conducted over a three-month period and that the agency plans to monitor VMT during the same period in future years to identify trends. The agency will judgmentally specify the proportion of multiple-axle vehicles for local streets, for arterials with less than 10 000 ADT, for arterials with greater than 10 000 ADT, and for freeways. To improve efficiency, the agency will further stratify arterial and freeway links on the basis of either anticipated volume or number of lanes. The characteristics of the highway network are summarized in Table 2. The assumed average link lengths are 0.5 mile for arterials and 0.25 mile for local streets and freeways.

These assumed network characteristics can then be translated into sampling parameters by using the formulas and default values discussed previously. Table 3 illustrates the calculation of parameters needed to compute the sample size. Because the study will be conducted over a relatively short time period, the composite standard deviation for the internal variability reflects two terms: (a) standard deviation across locations (SVOLLh) and (b) standard deviation across days (SVOLDh). The corresponding composite standard error for the external variability represents only the effects of the assumed axle correction factors. This term is assumed to be unnecessary for freeways because

Table 2. Example network characteristics.

Sample Stratum	Mileage (Mh)	Link Population (NPOPh)	Average Volume (VOLh)	VMTh	TRe
Local streets	400	1600	500	200 000	0.02
Arterials (ADT)					
<5000	40	80	2 500	100 000	0.06
5000-10 000	70	140	7 500	525 000	
10 000-15 000	40	80	12 500	500 000	0.10
15 000-20 000	30	60	17 500	525 000	
20 000-25 000	10	20	22 500	225 000	
25 000-30 000	10	20	27 500	275 000	
Freeways					
4 lanes	30	120	40 000	1 200 000	0.15
6 lanes	20	80	80 000	1 600 000	

Table 3. Example worksheet.

Sample Stratum	SVOLLh	SVOLDh	SVIh	SVEe	Mh * SVIh[a]	Mh^2 * $SVIh^2$/NPOPh[a]	$VMTE^2$ * $SVEc^2$[a]
Local streets	300	150	335	0.02	134 000	11.2	16
Arterials (ADT)							
5000	1 714	500	1 785	0.02	71 400	63.7	15.7
5000-10 000	1 714	1050	2 010		140 700	141.4	
10 000-15 000	1 714	1500	2 278	0.02	91 120	103.8	93.0
15 000-20 000	1 714	1838	2 513		75 390	94.7	
20 000-25 000	1 714	2250	2 828		28 280	40.0	
25 000-30 000	1 714	2475	3 011		30 110	45.4	
Subtotal	-	-	-		437 000	489.0	1.087
Freeways							
4 lanes	12 000	3000	12 369		371 070	1147.4	
6 lanes	24 000	5200	24 557		491 140	3015.2	
Subtotal	-	-	-		862 210	4162.6	-
Total					1433 210	4662.8	1.103

[a] Column scaled by 10^{-6}.

manual rather than machine counts are assumed to be needed for the high-volume freeways in this example.

The sample size of volume counts needed to meet the specific study objectives can then be computed as shown below. The first step is to estimate the acceptable error of the VMT estimate for each reporting stratum (DVMTr) by factoring the anticipated VMT value by the specified relative error. For example, the value for local streets is 50 000 (computed as 0.25 * 200 000). The sample size required for each reporting stratum can then be computed by using Equation 13.

The resulting sample sizes are as follows: For local streets (±0.25),

$$VMTr = 400 * 500 = 200\ 000.$$
$$DVMTr = 0.25 * 200\ 000 = 50\ 000.$$
$$Nr = (400^2\ \&\ 335^2)/\{(50\ 000^2/2^2) + [(400^2 * 335^2)/1600] - (200\ 000^2 * 0.02^2)\} = 29.$$

For arterials (±0.05),

$$VMTr = 2\ 150\ 000.$$
$$DVMTr = 0.05 * 2\ 150\ 000 = 107\ 500.$$
$$Nr = (437\ 000)^2/[(107\ 500^2/2^2) + (489\ 000\ 000) - (1\ 087\ 000\ 000)] = 84.$$

For freeways (±0.05),

$$VMTr = 2\ 800\ 000.$$
$$DVMTr = 140\ 000.$$
$$Nr = (862\ 210)^2/[(140\ 000^2/2^2) + (4\ 162\ 600\ 000)] = 82.$$

These counts--29 for local streets, 84 for arterials, and 82 for freeways--add up to a total of 195. The counts for the last two reporting strata are then allocated to the component sample strata by using Equation 14. Although it is not shown here, the resulting precision of a regional VMT estimate made on the basis of these sample sizes and allocations could be computed by using Equation 15 as a 3.2 percent realistic error. The precision of the regional VMT estimate would thus be considerably better than the precision of the VMT estimates for the individual functional class strata.

CONCLUSIONS

This paper has presented cost-effective methods for estimating regional VMT. These methods use relatively complex sampling procedures to avoid possible biases, account for major sources of uncertainty, and minimize the data-collection effort required to estimate VMT at a specified level of statistical confidence. The following conclusions can be made.

1. The detrimental effects of missed counts due to severe seasonal weather can be reduced by scheduling the data-collection effort over a relatively short period in a season with temperate weather conditions. Long-term trends in VMT can then be assessed either by counting during the same period in succeeding years or by using seasonal adjustment factors from representative ATR locations.
2. More efficient data-collection activities can be achieved by using systematic rather than random selection of data-collection days and by concentrating the data-collection effort over a relatively short period.
3. Measurement error can affect the precision of a VMT estimate and should thus be considered in the sampling plan when traffic-counting machines are used. Although minor errors made by an individual machine in counting axles will not seriously affect the overall VMT estimate, the application of assumed axle correction factors to convert raw axle counts to volume counts can affect the overall VMT estimate. These effects can be considered whether the axle correction factors are based on vehicle classification counts or on experience and judgment.
4. The precision of VMT estimates for different aggregations of geographic area and/or functional class strata can be considered in the sampling plan. Estimates of VMT for aggregate strata will tend to be more precise than those for the corresponding individual strata.
5. Useful estimates of regional VMT at specified levels of statistical precision can be achieved at relatively low cost through the use of efficient sampling procedures.

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