

Minimizing Cost of Manual Traffic Counts: Canadian Example

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The accuracy and cost-effectiveness of short-period manual traffic counts are analyzed. Alberta's primary highway system is investigated in this study. The roads in the system under investigation are classified into four types: (a) commuter sites, (b) nonrecreational low-volume sites, (c) rural long-distance sites, and (d) recreational sites. The accuracy of short-period counts is expressed in terms of a deviation either side of the estimated volume, which defines limits of the interval in which the actual volume is most likely to be. In the tests of this study, a relative measure of deviation, namely, the coefficient of variation, is used in order to compare the variation in several sets of data for the counts of different durations and schedules. The analysis carried out in this paper illustrates clearly that the most important considerations for rationalization of short-period manual counts are (a) the type of road site being surveyed and (b) the hour-to-hour traffic variations within the same day. The month of the year, the day of the week, and the duration of counts are other significant factors that must be considered in order to devise the most efficient short-period counts.

Several types of traffic-counting programs are undertaken by roadway agencies to obtain values of average annual daily traffic (AADT) and other traffic data for their road networks. The most commonly used programs are (a) continuous counting by permanent traffic counters (PTCs); (b) seasonal counting by portable counters, where counts are taken a few times a year for periods from 48 h to 2 weeks in length; and (c) short-period counting, where manual traffic counts are undertaken for less than a day. The PTCs provide actual temporal distribution of traffic movement and the true values of AADT. The seasonal and short-period counts furnish only sample information and therefore need appropriate factoring to yield the estimates of AADT values.

In addition to the estimates of AADT, the short-period counting programs provide such important data as vehicle classification and turning movements, which are frequently required for planning and design of roads for both safety and economy purposes. The proposed study is concerned with the short-period manual counting programs.

All the provincial transportation agencies in Canada undertake short-period traffic-counting programs on an annual basis. Most of such traffic counting is carried out by students during the spring and summer seasons, which includes May, June, July, and August. The number of students hired for this purpose varies from province to province and is generally in the range of 10-20 students for the entire period.

Although it is true that the short-period manual counting is undertaken for a period of less than a day, there is a considerable difference in the actual durations and schedules adopted by the different provinces. For example, the Ministère des Transports in Quebec generally carries out 12-h (7:00 a.m. to 7:00 p.m.) and 8-h (7:00-11:00 a.m. and 3:00-7:00 p.m.) schedules, Alberta Transportation uses 12-h (7:00 a.m. to 7:00 p.m.) and 9-h (8:00 a.m. to 5:00 p.m.) schedules, and Ontario's Ministry of Transportation and Communications (MTC) employs 8-h (7:00-11:00 a.m. and 2:00-6:00 p.m.) schedules.

There are two important aspects that should be considered in relation to the short-period manual counting programs. One is that the quality of data used for planning and design purposes is a crucial factor that affects the reliability of the results.

The other is that, because collecting data is expensive, especially when considerable overtime wages are involved in 9-h or 12-h counting, the method of collection should be as cost-effective as possible.

During these times of budgetary constraints, some authorities feel that the improvement in accuracy obtained by extending a traffic count at a spot location beyond 6 h may be small. But very little scientific work has been done toward any systematic comparison between the 12-h traffic surveys and the shorter surveys in the context of the provincial or rural roads in Canada. The main objectives of this study are (a) to analyze the accuracy and cost-effectiveness of the existing programs, such as 12-h, 9-h, and 8-h counts, as compared with shorter manual traffic counts; (b) to study the influence of road type and traffic volume on the accuracy of different short-period surveys; and (c) to specify appropriate schedules of the shorter counts if they are reasonable in terms of the accuracy of the results.

BACKGROUND

Estimation of AADT from Short-Period Counts

The usual method for estimating AADT from sample counts is that advocated by the U.S. Bureau of Public Roads (BPR) in its Guide for Traffic Volume Counting Manual (1). In general, the BPR method involves (a) grouping together the PTC sites into similar patterns of monthly traffic variation, (b) determining average expansion factors for each group, (c) assigning road sections that do not have PTCs to one of these groups, and (d) applying the appropriate average expansion factor to sample counts to produce an estimate of AADT.

A commonly used form of mathematical relationship for estimating AADT from sample counts of shorter duration than 24 h is that in which the count is expanded first to 24-h volume by using an hourly expansion factor (H), second to average daily volume by using a daily expansion factor (D), and then to the annual flow by using a seasonal expansion factor (S). This formula may be expressed as follows:

$$\text{Estimated AADT} = \text{short-period volume count} \times H \times D \times S \quad (1)$$

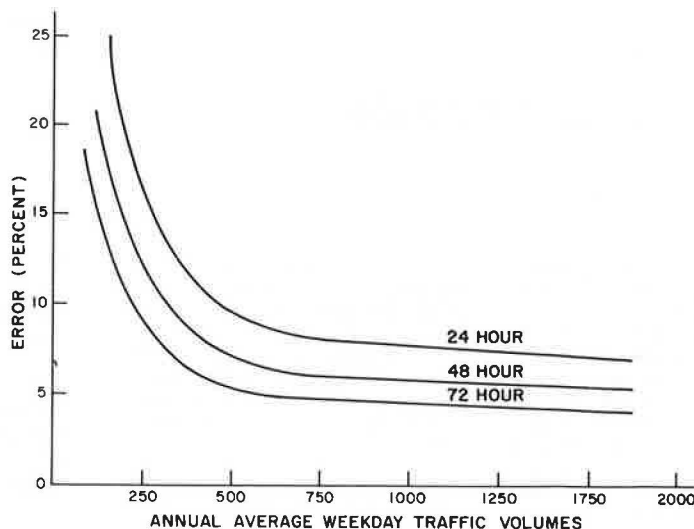
As indicated earlier, the values of average expansion factors for different groups of roads are computed from the PTC data. These factors are defined as follows:

$$\text{Hourly factor (H)} = (\text{avg volume for 24-h period}) / (\text{avg volume for particular duration of count}) \quad (2)$$

$$\text{Daily factor (D)} = [(\text{avg total volume for week}) / 7] / (\text{avg volume for particular day}) \quad (3)$$

$$\text{Seasonal factor (S)} = [(\text{total yearly volume}) / 12] / (\text{total volume for particular month}) \quad (4)$$

Figure 1. Estimation errors as function of weekday traffic volume and duration of counting.



Errors of AADT Estimates

There are four sources of error in estimating AADT at a point by using Equation 1:

1. The hourly factor at a counting site generally will not be exactly equal to the group mean;
2. The daily factor at the counting site will differ from the average daily factor for the group;
3. The seasonal factor at the site will not be exactly the same as the mean group seasonal factor; and
4. The road section on which a count is taken may have been assigned to a wrong PTC or road group; this error is assumed to be negligible (2).

The magnitude of error due to the hourly factor is generally expected to be a function of the duration and schedule of a particular short survey. However, any variation in the duration and schedule of a short-period count will not affect the errors due to the daily factor and the seasonal factor.

In the past, there have been studies to determine the effect of the duration of sample counts on the accuracy of resulting AADT estimates. The results of one such study concerning the so-called "coverage counts" (or seasonal traffic counts) were published by Petroff and Blensly (3). Commenting on Figure 1, which is adapted from the U.S. study (3), the authors write (3, p. 364):

The observation of the data presented in Figure 1 which is of utmost practical significance is that traffic counts of 24-hour duration on weekdays have a coefficient of variation of 10 percent or less when compared with the mean volume for a weekday in a given month at stations having the mean volume of about 500 vehicles per day or more. This applies usually to all months except the winter months in some of the states.... Counts of 48 hours duration improve the accuracy by 20 to 25 percent, thus raising the confidence limit from 68 percent to about 75 percent for one standard deviation of 10 percent, also extending the range of volumes down to about 300 vpd.

This translated into everyday language means that two thirds to three fourths, depending on the length of the count, of all coverage or blanket counts may be expected to have an error of about 10 percent or less when compared with the true mean weekday volume of the month during

which they were taken when volumes are 300 to 500 vehicles per day or more.

The above observations are for sample counts of one day's duration or longer in rural areas. A very limited amount of work has been reported in the literature concerning the errors of shorter-duration counts.

The study conducted by the Local Government Operational Research Unit (4) for the Department of Transport in Britain showed that a reasonably accurate estimate of AADT can usually be based on a single 16-h count. Another British study (5) on short-period counting reported:

A six-hour count in the afternoon (13:00h-19:00h or 14:00h-20:00h) on a weekday in late spring or early autumn will provide a reasonable estimate of the annual flow....

If a more accurate estimate of annual flow is required it would be better to repeat the six-hour count later in the same month rather than increase the length of counting to 16 hours. The expected accuracy from two six-hour counts is similar to that from a single 16-hour count, even though four hours less counting is undertaken.

The principal focus of this paper is to analyze the errors associated with the existing manual counting programs as used in Alberta, Ontario, and Quebec and to investigate the potential increases in the errors if shorter counts (e.g., 6-h and 4-h programs) are adopted by the provincial authorities. The study does not include the errors associated with daily and monthly expansion factors.

STUDY APPROACH

Statistical Accuracy of Short-Period Counts

The accuracy of short-period counts can be expressed in terms of deviation either side of the estimated 24-h volume, which defines limits of the interval in which the actual 24-h volume is most likely to lie. In the tests of this study, it was necessary to use a relative measure of deviation in order to compare the variation in several sets of data for counts of different durations. The coefficient of variation (CV) was used for this purpose. For a particular short-period count at a given roadway site, CV was defined as follows:

$$CV = \left\{ \frac{1}{(n-1)} \sum_{i=1}^n (X_i - \bar{X})^2 \right\}^{1/2} / \bar{X} = SD/\bar{X} \quad (5)$$

where

- X_i = i th volume count at site,
 n = total number of volume counts taken at site,
 and
 \bar{X} = average value of n volume counts.

CV, as defined in Equation 5, is the SD as a fraction (or percentage) of the mean value \bar{X} . A low value of CV, which is associated with less dispersion of individual volume data about their mean, reflects a high accuracy in estimating the actual traffic volumes.

Study Data

Since the PTCs when grouped are considered to represent the population of the group, their statistical measures of variation (such as SD and CV) are also the measures of the errors at the short-period counting sites; the latter are also samples taken out of the same population.

For the purpose of this study, Alberta's PTC data were analyzed. The PTC information for the years 1978, 1979, and 1980 were included in the study. After the reliability of the available Alberta PTC data for those years was considered, a total of 41 PTCs was selected to be used in this investigation.

Because the short-period manual traffic counting in Alberta and other provinces is carried out mainly in the spring and summer seasons, only the months of May, June, July, and August were chosen for the analysis. Computations for the CV were carried out by each day of the week for different counting schedules. The holidays, such as Victoria Day and Canada Day, were eliminated from the analysis. A number of certain other days that displayed a very unusual volume and pattern of traffic (such as that due to reconstruction of a facility) were also excluded from the study. Otherwise, it was assumed that the hourly traffic variations at study sites did not change significantly from 1978 to 1980.

Classification of Road Sites

One of the most important causes of variability in the traffic flows and the errors of AADT estimates is the nature of the road sites surveyed. Actually, it is believed that the difference between sites can be so large as to overwhelm other causes of variability in predictions. On the basis of two recent studies (6,7) on Alberta highways, the study sites were classified into four broad types according to their temporal variations in traffic flows and such other characteristics as trip purpose and trip-length distribution. These types are as follows:

1. Commuter sites, e.g., the PTC site C9 located on Highway 3 east of Lethbridge;
2. Nonrecreational low-volume (rural) sites, e.g., the PTC site C147 located on Highway 35 north of Grimshaw;
3. Rural long-distance sites, e.g., the PTC site C18 located on the Trans-Canada Highway west of Medicine Hat; and
4. Recreational sites, e.g., the PTC site C114 located on Yellowhead Highway east of Jasper National Park.

Trip purpose information for the typical examples of these classes, i.e., sites C9, C147, C18, and C114, has been provided elsewhere (6).

Selection of Study Schedules

Other important considerations in manual traffic

surveys are the duration and the schedule of counting. For a particular day, the best short period will be that which (a) has the most stable relationship with the annual flow and (b) contains the most representative and important levels (e.g., the evening peak) of traffic that occur in the course of the day.

Sample schedules in this study were selected mainly from the considerations of (a) the current practice in Canada and (b) the variability in the volumes of different duration counts in the day. According to current practice, three schedules were chosen. These are 12 h (7:00 a.m. to 7:00 p.m.), 9 h (8:00 a.m. to 5:00 p.m.), and 8 h (7:00-11:00 a.m. and 2:00-6:00 p.m.).

The CVs for continuous counts of 8 h and shorter duration were investigated for all classes of roads, as shown in Figure 2 for the rural long-distance road site C18. It became apparent that for the best results shorter manual counts would have to be carried out with their midpoints at 3:00 or 4:00 in the afternoon. However, for the purpose of detailed discussion and comparisons, some other schedules were also selected in this study. On the assumption that all manual counts would be conducted between 7:00 a.m. and 7:00 p.m., the following schedules were chosen in addition to the existing three schedules:

1. 6 h (a.m.) (7:00 a.m. to 1:00 p.m.),
2. 6 h (p.m.) (1:00-7:00 p.m.),
3. 4 h (a.m.) (7:00-11:00 a.m.),
4. 4 h (p.m.) (2:00-6:00 p.m.), and
5. 2 h (p.m.) (4:00-6:00 p.m.).

RESULTS AND DISCUSSION

Tables 1-4 contain the computed values of CVs of traffic volume recorded at the typical road sites for the selected schedules of short-period counting. The tabulations are made for each day of the week for the months of May and July. Figures 3-6 are drawn by using the data from Tables 1-4, respectively, but for the sake of simplicity of presentation and discussion, the values of CV are averaged

Figure 2. Stability of weekday volume counts: May 1978, 1979, and 1980 at rural long-distance site C18.

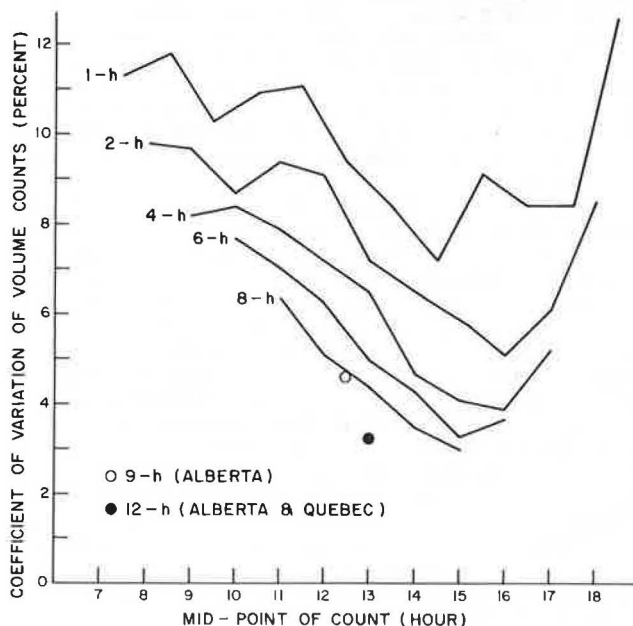


Table 1. CV of traffic volume recorded at PTC site C9 (commuter) for selected schedules of short-period counting.

Month	Counting Schedule (h)	CV of Recorded Traffic Volume (%)						
		Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.
May	12	2.7	1.4	1.3	1.3	1.4	2.2	2.0
	9	3.0	2.1	2.5	2.0	2.4	3.1	2.2
	8	2.8	1.7	2.0	1.8	1.7	2.1	3.6
	6 (a.m.)	7.2	2.6	2.9	2.6	2.0	3.7	4.8
	6 (p.m.)	2.7	1.7	2.3	2.0	2.1	2.1	2.9
	4 (a.m.)	9.6	3.3	4.3	4.4	2.8	3.5	8.3
	4 (p.m.)	2.8	2.1	2.4	2.1	2.8	2.6	3.0
	2 (p.m.)	3.6	2.5	4.3	3.4	2.5	2.3	3.8
	2 (p.m.)	3.6	2.5	4.3	3.4	2.5	2.3	3.8
July	12	2.9	1.1	1.2	2.1	2.1	2.3	4.1
	9	2.7	1.4	1.3	3.1	2.5	2.5	5.1
	8	3.2	3.5	2.1	3.6	2.9	3.3	5.2
	6 (a.m.)	6.0	3.0	3.6	3.5	3.3	2.6	9.1
	6 (p.m.)	2.4	1.4	1.8	2.2	1.9	2.8	3.3
	4 (a.m.)	7.9	6.3	5.1	4.8	5.0	3.7	13.4
	4 (p.m.)	3.4	2.3	2.1	3.8	2.6	3.6	3.9
	2 (p.m.)	4.4	2.6	3.2	2.9	3.8	4.4	4.0
	2 (p.m.)	4.4	2.6	3.2	2.9	3.8	4.4	4.0

Table 2. CV of traffic volume recorded at PTC site C147 (nonrecreational low volume) for selected schedules of short-period counting.

Month	Counting Schedule (h)	CV of Recorded Traffic Volume (%)						
		Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.
May	12	2.5	2.5	2.2	1.8	3.6	3.4	3.0
	9	6.5	5.6	3.2	3.4	5.9	5.2	4.3
	8	7.3	1.8	2.8	1.5	4.5	4.1	4.9
	6 (a.m.)	14.8	9.5	4.6	4.9	6.8	4.0	7.7
	6 (p.m.)	5.2	4.0	4.8	4.1	3.3	5.1	4.2
	4 (a.m.)	23.8	8.3	6.5	6.3	7.2	5.1	14.1
	4 (p.m.)	10.7	4.4	5.5	5.7	6.6	6.7	7.1
	2 (p.m.)	11.5	9.2	6.6	8.9	8.4	6.6	10.8
	2 (p.m.)	11.5	9.2	6.6	8.9	8.4	6.6	10.8
July	12	4.3	2.7	3.2	2.5	2.4	2.0	3.2
	9	6.7	4.4	4.5	3.6	3.6	2.4	3.7
	8	6.3	5.4	4.1	2.9	2.7	3.0	4.6
	6 (a.m.)	11.6	6.6	5.2	3.8	3.3	4.1	5.4
	6 (p.m.)	4.4	3.3	4.3	3.3	3.7	5.0	4.4
	4 (a.m.)	14.9	10.8	6.6	4.9	4.6	7.3	10.1
	4 (p.m.)	4.6	5.6	5.7	3.7	3.6	6.0	6.0
	2 (p.m.)	5.1	8.8	6.0	6.2	8.6	3.8	8.7
	2 (p.m.)	5.1	8.8	6.0	6.2	8.6	3.8	8.7

for the weekdays and the results for May and July are plotted in these figures. It may be mentioned here that the results for the months of June and August are omitted because of their close similarity to the results of May and July, respectively.

The following presentation of results and discussion is made by taking the examples of the typical road sites C9, C147, C18, and C114. But it should be noted that the computations of CV were also made for the remaining 37 sites and the results obtained at those sites were similar to their respective typical sites.

Examination of Figures 3-6 reveals several important facts that are common to each type of road site. One observation is that the CV for a 12-h schedule is smaller than those for other schedules. Therefore, the 12-h schedule can be expected to provide the most accurate estimates of traffic statistics. Another striking observation from these figures is that Alberta's 9-h short-period schedule produces higher values of CV as compared with the 6-h (p.m.) schedule in a great majority of cases. Actually, the results, such as those shown in these figures, indicate that many times even the 4-h (p.m.) schedule can provide as good an estimate of volume as does the 9-h schedule. It may also be noted from the values of CV that the 8-h schedule yields better results than the 9-h schedule. The results for the 8-h schedule are generally similar to those of the 6-h (p.m.) schedule.

Table 3. CV of traffic volume recorded at PTC site C18 (rural long distance) for selected schedules of short-period counting.

Month	Counting Schedule (h)	CV of Recorded Traffic Volume (%)						
		Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.
May	12	2.7	2.8	2.2	2.5	3.0	3.4	2.7
	9	4.1	2.3	3.6	3.5	4.0	4.0	3.7
	8	3.1	2.9	2.5	3.0	3.5	4.2	3.2
	6 (a.m.)	11.7	3.3	3.3	2.8	5.1	8.4	5.3
	6 (p.m.)	6.8	3.0	2.7	3.5	3.0	3.2	5.0
	4 (a.m.)	15.4	4.2	3.8	2.8	5.2	9.7	8.3
	4 (p.m.)	7.0	3.2	3.1	3.9	4.1	3.0	6.6
	2 (p.m.)	8.5	7.0	5.3	7.3	6.7	4.3	8.7
	2 (p.m.)	8.5	7.0	5.3	7.3	6.7	4.3	8.7
July	12	2.2	2.0	2.0	1.9	2.5	1.8	2.2
	9	3.2	3.0	3.3	2.7	3.6	2.3	2.6
	8	2.0	2.6	2.2	2.3	2.6	3.1	2.4
	6 (a.m.)	2.5	3.1	3.3	2.5	3.9	3.5	3.6
	6 (p.m.)	3.6	1.7	3.5	2.9	3.1	2.6	3.9
	4 (a.m.)	5.5	3.2	4.8	3.5	4.6	5.2	5.5
	4 (p.m.)	4.1	3.1	4.2	3.2	3.2	3.6	4.0
	2 (p.m.)	5.6	3.5	4.5	3.2	3.9	3.9	3.4
	2 (p.m.)	5.6	3.5	4.5	3.2	3.9	3.9	3.4

Table 4. CV of traffic volume recorded at PTC site C114 (recreational) for selected schedules of short-period counting.

Month	Counting Schedule (h)	CV of Recorded Traffic Volume (%)						
		Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.
May	12	7.6	6.1	6.0	5.6	3.9	6.2	7.1
	9	13.0	8.8	8.9	8.0	5.7	8.6	11.2
	8	9.3	7.9	8.3	7.5	6.9	6.6	9.7
	6 (a.m.)	23.6	11.2	9.1	7.4	7.4	13.0	12.1
	6 (p.m.)	9.3	7.8	5.7	6.8	5.7	8.7	8.8
	4 (a.m.)	37.5	21.0	16.5	11.7	14.0	17.9	21.0
	4 (p.m.)	10.8	8.0	6.5	8.6	6.7	9.5	10.9
	2 (p.m.)	14.2	8.9	9.5	10.8	6.8	8.8	11.7
	2 (p.m.)	14.2	8.9	9.5	10.8	6.8	8.8	11.7
July	12	4.1	2.6	4.0	3.2	2.7	5.9	2.7
	9	5.7	4.9	5.8	6.1	4.1	8.6	4.1
	8	7.0	5.6	5.9	5.5	5.0	8.6	5.9
	6 (a.m.)	12.8	15.2	12.3	12.3	8.5	18.4	10.9
	6 (p.m.)	4.5	6.1	3.7	4.4	4.4	3.6	4.3
	4 (a.m.)	25.9	29.8	19.0	19.7	18.0	27.7	19.8
	4 (p.m.)	5.3	5.7	4.6	4.0	4.5	4.2	3.9
	2 (p.m.)	7.8	9.5	7.4	7.9	6.3	9.5	7.1
	2 (p.m.)	7.8	9.5	7.4	7.9	6.3	9.5	7.1

Figures 3-6 also indicate clearly that the morning hours are not very appropriate for short-period counting. For example, the values of CV for the 6-h (a.m.) and 4-h (a.m.) schedules are considerably higher than the values for the 6-h (p.m.) and the 4-h (p.m.) schedules, respectively. In fact, it should be noted that a short-period count of 2-4 h in the late afternoon will provide the same accuracy of data as a 6-h count in the morning.

Prior to examining the effect of road sites on the accuracy of short-period counts, let us consider the influence of traffic volume (or AADT) on the expected values of CV. Figure 7 presents the average values of CV as a function of AADT. Smooth hand-fitted curves in the figure are drawn from the scatter of CV statistics for all 41 study sites for the weekdays of May to August. The X-axis in the figure is the average AADT for 1978, 1979, and 1980--the years for which PTC data are analyzed in this investigation.

These curves clearly indicate that the errors in estimated volumes are expected to be less for the road that carries large volumes of traffic. However, it can also be noted that beyond a certain critical range of AADT, the errors are not likely to decrease significantly with further increase in traffic volume. For example, this critical range of AADT from Figure 7 is (a) 2000 for the 12-h schedule, (b) 3000 for the 6-h (p.m.) schedule, and (c) 4000 for the 2-h (p.m.) schedule.

There is one important factor to be considered in relation to the effect of road sites on the accuracy of counts. It is that, in general, different classes of road sites carry different amounts of traffic volume. For example, commuter sites located near large population centers are likely to carry much heavier traffic volumes as compared with other road sites, which by their nature serve primarily such specific purposes as long-distance farm-to-market or highly recreational trips. The average

AADT values for the four typical road sites of this analysis are 8800 for C9, the commuter site; 1180 for C147, the nonrecreational low-volume site; 3500 for C18, the rural long-distance site; and 2055 for C114, the recreational site.

The effect of road types on estimated errors of counting can be deduced by referring back to Figures 3-6. It is evident that the values of CV or the errors of estimation are functions of the location of short-period counts. As generally expected, the

Figure 3. CVs of traffic volumes: weekdays of May and July in 1978, 1979, and 1980 at commuter site C9.

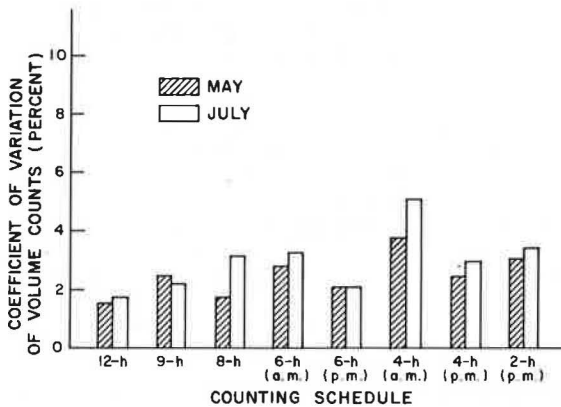


Figure 4. CVs of traffic volumes: weekdays of May and July in 1978, 1979, and 1980 at nonrecreational low-volume site C147.

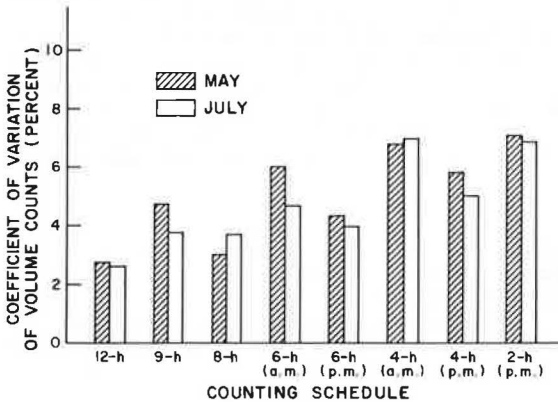


Figure 7. CVs of traffic volumes: weekdays of May, June, July, and August in 1978, 1979, and 1980; averages of all study sites.

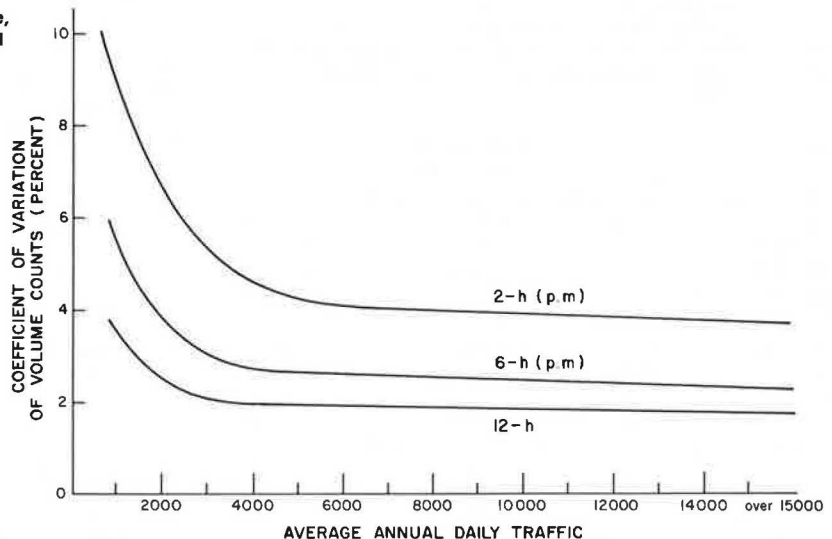


Figure 5. CVs of traffic volumes: weekdays of May and July in 1978, 1979, and 1980 at rural long-distance site C18.

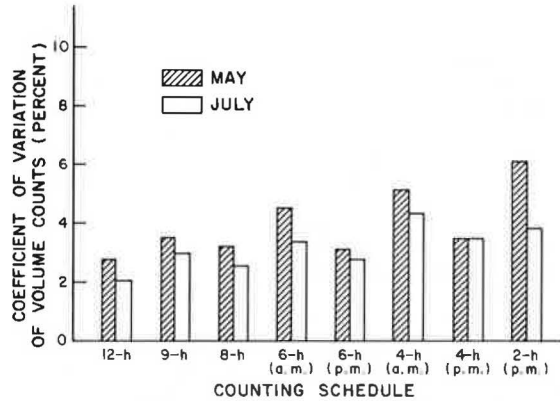
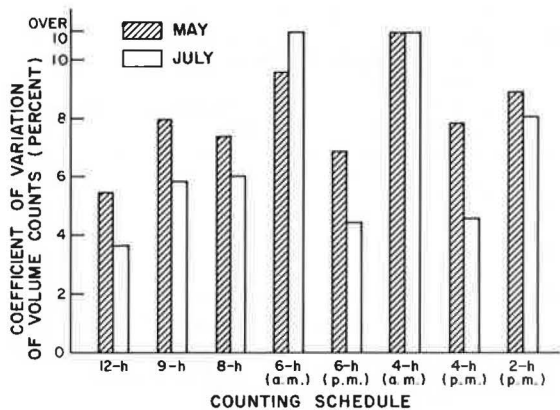


Figure 6. CVs of traffic volumes: weekdays of May and July in 1978, 1979, and 1980 at recreational site C114.



lowest errors are observed in the case of commuter site C9 and the highest in the case of recreational site C114. The values of CV in those figures also suggest that the 2-h (p.m.) schedule at a commuter site, or the 4-h (p.m.) schedule at a rural long-distance site, or the 6-h (p.m.) schedule at a non-recreation low-volume site are all likely to produce the same accuracy as would the 12-h schedule at a recreational site.

Even though the volume of traffic, particularly when AADT is less than 2000, may have some effect on the accuracy of counts (Figure 7), it is believed that the difference in the accuracy of counts at various sites is due primarily to trip-purpose characteristics at the site being surveyed. The work-business trips are considered to be less variable from day to day as compared with the social-recreational trips. A good example in this respect is to compare the results for the C147 low-volume rural site and those for the C114 recreational site. Even though site C147 has a lower value of AADT, its results are more accurate as compared with those of site C114. This difference can be attributed to the trip-purpose characteristics. The social-recreational components of trip purpose for C147 and C114 during the summer weekdays are 22 and 75 percent, respectively (6).

A formal analysis of variance pertaining to the effects of days, months, and their possible interactions with different road types was not carried out in this study. However, the study results such as those included in Tables 1-4 and Figures 3-6 seem to indicate that (a) there is no effect of weekdays on the accuracy of counts and (b) the months have some interaction with the nature of the sites surveyed. It is apparent that site C18 (rural long distance) and site C114 (recreational) are expected to produce the most accurate estimates during the months of July (and August) when the tourist-recreational travel is at peak levels in Alberta. In contrast, the other two sites seem to provide better results during May (and June) when the work-business trips are still at their normal levels.

CONCLUSIONS

The analysis carried out in this paper illustrates clearly that the most important considerations for rationalization of short-period manual counts are (a) the type of road site being surveyed and (b) the hour-to-hour traffic variations within the same day. The month of the year, the day of the week, and the duration of the counts are other significant factors that must be considered in order to design the most efficient schedules of short-period counts. The following specific conclusions are drawn from this investigation of 41 PTC sites in the province of Alberta:

1. For the counts of 8 h or less on weekdays, a period with a midpoint at 3:00 or 4:00 p.m. is expected to provide the most accurate volume estimates for each class of road. An additional advantage of including this period is that peak-hour turning movements and vehicle classification can still be observed because such a counting period generally includes the evening peak of traffic volume.

2. The accuracy of short-period counts is a function of the nature of road sites surveyed. The greatest accuracy is expected for commuter sites and the least in the case of highly recreational sites. In fact, the values of CV computed for the study sites of this investigation indicate that the 2-h (p.m.) schedule at a commuter site, the 4-h (p.m.) schedule at a rural long-distance site, or the 6-h (p.m.) schedule at a nonrecreational low-volume site

are all likely to produce the same accuracy as would the 12-h schedule at a recreational site.

3. There seems to be some interaction between the type of road surveyed and the month of counting. For example, recreational roads produce more reliable traffic estimates in the months of July and August when tourist-recreational travel is at peak levels. In contrast, commuter sites provide better information during May and June.

4. The 9-h schedule as currently used in Alberta produces less accurate volume estimates compared with the 6-h (p.m.) schedule in a great majority of cases. Actually, the results indicate that many times even the 4-h (p.m.) schedule can provide as good estimates of volume as does the 9-h schedule. The accuracy of the 8-h schedule as used in Ontario is generally similar to that of the 6-h (p.m.) schedule.

5. The traditional 12-h surveys yield the most accurate estimates of 24-h volume. The differences in the accuracy of the 12-h schedule and the carefully selected 6-h (p.m.) schedule are (a) 0-1 percent at commuter and long-distance rural sites and (b) 1-2 percent for nonrecreational low-volume sites and recreational sites. However, since the overtime wage rules in Canada increase the personnel cost of the 12-h count to nearly three times that of a shorter 6-h count, the traditional 12-h surveys are less cost-effective than the 6-h (p.m.) surveys. Actually, in many cases, even the 4-h (p.m.) schedules could be considered reasonably accurate and cost-effective.

6. Another conclusion of this study is the effect of AADT on the accuracy of short-period counts. In general, the errors in volume are expected to be less for the roads that carry large volumes of traffic. But beyond a certain critical range of AADT, the errors are not likely to decrease significantly with further increase in traffic volume. For example, this critical range of AADT appears to be 2000 for the 12-h survey, 3000 for the 6-h (p.m.) survey, and 4000 for the 2-h (p.m.) survey.

The findings of this research provide a better understanding of the factors that affect the accuracy of estimating traffic volumes. It is hoped that with this better understanding, agencies will be able to design and schedule more cost-effective short-period traffic-counting programs without any loss in accuracy.

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REFERENCES

1. Guide for Traffic Volume Counting Manual. Bureau of Public Roads, U.S. Department of Commerce, 1965.
2. R.R. Bodle. Evaluation of Rural Coverage Count Duration for Estimating Annual Average Daily Traffic. Bureau of Public Roads, U.S. Department of Commerce, Highway Planning Technical Rept. 5, 1966.
3. B.B. Petroff, and R.C. Blensly. Improving Traffic-Count Procedures by Application of Statistical

- cal Method. HRB Proc., Vol. 33, 1954, pp. 362-375.
4. Annual Traffic Multipliers for Use in COBA. Local Government Operational Research Unit, Department of Transport, London, England, 1978.
5. G. Phillips. When to Mount a Traffic Count. Traffic Engineering and Control, Vol. 21, No. 1, 1980, pp. 4-6.
6. S.C. Sharma and A. Werner. Improved Method of Grouping Provincewide Permanent Traffic Counters. TRB, Transportation Research Record 815, 1981, pp. 12-18.

7. S.C. Sharma. Toward a Standard Functional Classification of Provincial Roads in Canada. Presented at 1981 Roads and Transportation Association of Canada Annual Conference, Winnipeg, Canada, 1982.

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Tandem Toll Booths for the Golden Gate Bridge

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Many toll plazas are constrained in width by buildings or other physical barriers. These barriers may make the cost of adding toll lanes prohibitive. One method for increasing the capacity of a toll facility without increasing its width is to use tandem toll booths. A tandem toll booth consists of two toll takers in a single toll lane both serving alternating sets of vehicles simultaneously. The capacity of tandem toll booths is calculated with time-space diagrams and the cumulative headway distributions of vehicles at a conventional toll booth. The capacity depends on the maximum of two random variables, which correspond to the service times at the two booths, and is found by taking the product of their cumulative headway distributions. Adjacent tandem toll booths were found to increase the capacity of the Golden Gate Bridge toll plaza by about 15 percent, and batch tandem toll booths increase capacity by 25 percent or more. Thus, tandem toll booths would eliminate the queueing that now exists during the morning commute period without the cost of expanding the toll plaza's width.

The Golden Gate Bridge is the primary transportation link between Marin County, California, and the City of San Francisco. Each day 100 000 vehicles traverse the six-lane 2-mile span, 20 000 of which travel in each commute period. The bridge is operated by the Golden Gate Bridge, Highway, and Transportation District and is financed by user fees. Tolls are collected in the southbound direction at the south (San Francisco) end of the bridge.

In February 1981 the bridge board of directors approved an increase in the automobile toll from \$1.00 to \$1.25. Soon afterward, it became evident that the toll plaza could no longer accommodate peak-period traffic. Queues extended as far back as 4 miles; occasionally delays were up to 30 min. Predictably, many motorists were upset and the new toll became the subject of media scrutiny.

The ability of a toll facility to accommodate large traffic flow depends on two factors: the number of servers (toll takers) and the service time per vehicle. The Golden Gate solution to the queuing problem was to reduce the service time per vehicle. Delay had increased with the \$1.25 toll because more motorists needed change and because some motorists folded their dollar bill around their quarter (which caused the toll taker to spend extra time sorting money). The added delay caused the \$1.25 toll to be rescinded in July 1981. The toll was eventually replaced by a split toll of \$1.00 from Sunday through Thursday and \$2.00 on Friday and Saturday. Since that time the number of complaints has dropped considerably, but the equity of the split toll has been questioned. Clearly, the split toll was not motivated by traditional pricing con-

siderations but simply by the need to reduce service time while maintaining revenue.

The alternative approach of increasing the number of servers was perceived to be infeasible in the short run. The peculiar geography of the facility meant that adding toll lanes would require relocation of the entire toll plaza at a cost of \$16 million (1). Other ideas, such as building separate toll facilities for the different bridge lanes, would also be capital intensive.

The purpose of this paper is to demonstrate the consequences of adding toll booths to existing lanes in series rather than adding toll lanes in parallel. The unit of study will be a pair of toll takers serving a single traffic lane. Such a unit, which we call a tandem toll booth, can potentially increase the per-lane throughput, or capacity, and may obviate the need for increasing the width of the toll facility. When the width of a toll facility is physically constrained (by buildings or other barriers), as is the case with the Golden Gate Bridge, tandem toll booths may be cost efficient. Because the length of the toll plaza is also restricted, this paper focuses on tandem-toll-booth strategies that are not greatly affected by the distance between the upstream and downstream toll takers. Although other strategies (such as staggered toll plazas for different lanes or the alternating-toll-booth strategy, described by Rubenstein in another paper in this Record) might increase capacity more, queuing can be nearly eliminated at the Golden Gate Bridge without resorting to these capital-intensive alternatives.

We next describe how to calculate the capacity of tandem toll booths and then report on a case study at the Golden Gate Bridge.

PER-LANE CAPACITY

Single Toll Booths

Before the operation of a tandem toll booth is explained, a single toll booth will be considered. Let the service position be the location of a vehicle when it pays its toll and let the waiting position be the location of the following vehicle in line (Figure 1). Furthermore, let vehicles be numbered 0, 1, 2, ... beginning from the vehicle in the service position.