TRUCK FLOWS AND LOADS FOR PAVEMENT MANAGEMENT

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16. ABSTRACT

This report describes procedures state departments of transportation can use to determine the location and frequency of their truck monitoring activities. The objective of the recommended procedures is to help a state design a program that cost-effectively meets its needs for truck data within its overall pavement management structure. If the data are collected and used properly, they should provide a much more effective pavement design and management process than is currently available, thereby increasing the reliability of pavement designs; decreasing overall pavement construction, maintenance, and rehabilitation costs; and improving a state's ability to manage its pavement infrastructure.

This summary report discusses

- the procedures required to determine the number and distribution of permanent, automatic vehicle classification (AVC) and weigh-in-motion (WIM) devices within a state,
- a system for using the data gathered with these devices to adjust data from short duration vehicle classification and WIM counts to better estimate average annual conditions,
- the appropriate length of short duration AVC and WIM counts required to develop annual average estimates of travel within specified levels of precision, and
- research performed in Florida and Washington that illustrates the variability of vehicle classification and truck weight data that states can expect to find on their roads.

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TRUCK FLOWS AND LOADS FOR PAVEMENT MANAGEMENT

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington State Transportation Commission, Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

This report recommends procedures state departments of transportation can use to determine the location and frequency of their truck monitoring activities. The objective of the recommended procedures is to help a state design a program that cost-effectively meets its needs for traffic data within its overall pavement management structure. If the data are collected and used properly, they should provide a much more effective pavement design and management process than is currently available, thereby increasing the reliability of pavement designs; decreasing overall pavement construction, maintenance, and rehabilitation costs; and improving a state's ability to manage its pavement infrastructure.

This report discusses

- the procedures required to determine the number and distribution of continuous, automatic vehicle classification (AVC) and weigh-in-motion (WIM) devices within a state,
- a system for using the data gathered with these devices to adjust data from short duration vehicle classification and WIM counts to better estimate average annual conditions,
- the appropriate length of short duration AVC and WIM counts required to develop annual average estimates of travel within specified levels of precision, and
- research performed in Florida and Washington that illustrates the variability of vehicle classification and truck weight data that states can expect to find on their roads.

The recommendations presented in this report are based on a series of analyses performed with WIM data from Florida and WIM and vehicle classification data from Washington. In addition, the results of other published WIM data analyses have been incorporated into the recommended system design. The technical reports for this projects should be reviewed if more details are required on the recommendations presented in this report. [1,2]

VARIABILITY IN TRUCK TRAVEL PATTERNS

The analyses performed by Florida and Washington showed that different states are subject to different truck travel patterns. Some states (and even some portions of some states) are subject to truck travel that varies throughout the year. Other states have fairly stable truck volumes, with little variation from season to season. In some states, truck volume and weight patterns are fairly consistent for all roads in the state. In other states, truck volume and weight patterns vary considerably among roads and among geographic areas.

The key to determining (and thus improving) the accuracy of pavement loading estimates is in determining the variability inherent in the data and then measuring how much of that variation is accounted for by the data available for making an estimate. This section examines the variability found in the volumes and weights of trucks in Florida and Washington.

These two states discovered differing amounts of variability in the trucking patterns in their states. In general, Florida had more stable truck patterns than Washington. However, even within Florida, a considerable amount of variation was apparent.

SITE SPECIFIC VARIATION

Variation in both truck weights and truck volumes can be present in four major areas:

- time of day,
- day of week,
- season of the year, and
- geographic location.

Time of Day Variation

The time of day variation is usually accounted for in both WIM and vehicle classification estimates by collecting data for 24-hour periods. Neither the Florida nor

Washington analyses explored these within-day variations because the data used for these analyses incorporated data collection through the day. However states that use counting programs of less than 24-hour days and adjust these partial-day counts to represent 24-hour totals must understand that truck traffic varies throughout the day and that truck time-of-day patterns are different than automobile patterns.

Day of Week

Day of week variations differ from state to state, and from site to site within a state. The analysis of Washington vehicle classification data showed that truck volumes on Tuesdays, Wednesdays, and Thursdays were statistically the same. For some roads, truck traffic on Mondays and Fridays was also similar to that on Tuesdays through Thursdays. In other locations, Mondays and/or Fridays were statistically different. At almost all sites, Saturdays and Sundays experienced different traffic patterns than those of weekdays. (In addition, Sundays were different than Saturdays at most sites.)

The study also found that truck volume day-of-week patterns were not similar to automobile day-of-week patterns. Finally, the day-of-week patterns for many truck types differed as well. For example, in Washington, many sites experienced such a large drop in heavy truck traffic over the weekend that the average monthly weekday traffic volume for large trucks for all 12 months of the year was greater than average annual conditions. (In other words, if trucks were counted on any given weekday during the year, the number of trucks counted times 365 would exceed annual truck traffic on that road.) If the annual estimation process does not account for day-of-week changes such as the decrease in truck volumes observed in Washington, those annual estimates will include significant errors. Consequently, the prediction of annual average conditions must account for the different traffic levels that are present on different days of the week.

Season of the Year

Truck patterns also change by season in some locations. Florida DOT examined the seasonal patterns of WIM data within Florida and concluded that little seasonal

variation was present in that state. A brief analysis of Washington data showed a considerable amount of seasonal variation among the WIM patterns at ten sites in Washington. The different results of these two analyses is not surprising. The presence of seasonal variation within a state is a direct result of the types of commodities trucks carry in that state and the movement patterns of those commodities. Common sense predicts that roads in different parts of the country will experience a variety of truck travel patterns, and indeed seasonal differences have also been observed in examinations of WIM data in Minnesota and Pennsylvania.

For example, in south central Washington, a considerable increase in both truck volumes and average damage factor per truck type occurs in the late summer and early fall as a result of agricultural movements. Florida also has agricultural commodity movements, but the greater diversity of crops and year-round growing season in Florida have resulted in a more continuous truck movement throughout the year, rather than the peaked pattern found in south central Washington.

However, the late summer/early fall peak movement described above is not found west of the Cascade mountain range, because this section of the state is more urban. Furthermore, in the rural areas of the western portion of the state, the truck volume patterns are very different than those found in south central Washington.

Geographic Location

It is also possible to find two roads near each other that have very different truck patterns. For example, roads impacted by heavy through truck traffic movements may have very different truck volume patterns than roads that carry primarily local traffic.

In Florida, the DOT determined that most Principal Arterials in the Panhandle region followed similar vehicle weight patterns. Of the four WIM sites in that group of roads, three of the sites had a mean damage factor for single trailer trucks of between 0.66 and 0.68. However, the fourth site had an average damage factor of 1.75. Differences of

this size can be caused by the location of specific facilities (e.g., a gravel pit), the nature of truck hauls on a specific facility, or the presence of other mitigating factors.

These findings support the generally held belief that truck volume and weight patterns are heavily influenced by factors such as weather (particularly where weather requires the imposition of load restrictions), the type of truck hauls that use a road, the local industrial base, the amount of through-traffic present on a road, and a number of other factors. As a result, the truck patterns that any state or any site within a state will experience will vary according to local conditions. The truck patterns in one state may bear very little relation to those in a neighboring state, and thus each state will need to investigate the variation of truck travel on its own highway system.

GROUP MEAN VARIATION

One of the findings of both the Washington and Florida studies was that the mean for a group of related sites can be significantly different than the actual value for a specific site or route. For example, in Florida, the mean damage factors (computed as ESALs/vehicle) for 3S2 trucks for I-75 at four sites were computed as 0.97, 1.31, 1.34, and 1.57. Similar variability in damage factors per vehicle was found in the Washington WIM data; average damage factors at three WIM sites on I-5 ranged from 0.825 to 1.75.

The variability described above illustrates the importance of determining and accounting for the variability in truck characteristics (volumes, vehicle classifications, and weights) found in all states. For example, the use of the smallest damage factor in determining pavement design for the highest damage factor location will lead to premature failure of the pavement. Use of the largest damage factor for a smaller damage factor location will result in substantial over-design of the pavement structure. Even the use of the mean for the four sites will result in over-design of the pavement at one location and premature failure at the other.

This variability in damage factors can be accentuated by different proportions of vehicles within the different vehicle classes. For example, in the Washington data, the

proportion of 3S2 trucks in the traffic stream ranged from 2.5 percent at one site to 20 percent at another site. Even within the stream of trucks itself, the proportion of specific types of trucks varied. At some Washington urban sites, single trailer trucks made up less than 20 percent of the total truck traffic. At other (rural) Washington sites, single trailer trucks made up as much as 75 percent of the total truck traffic.

In the Florida WIM data, the proportion of 3S2s in the truck traffic ranged from 19 percent at one site to 84 percent at another site. Florida and Washington urban areas normally experience a considerably higher proportion of small trucks, and rural areas normally experience a higher proportion of larger trucks. As a result of these differences in vehicle mix, the average damage factor per truck can differ from site to site, even if the average damage factor per truck type does not. Remember that the average damage factor per truck of each type can also change, as noted earlier.

It is because of the variety of ways in which truck volumes and loads vary over time and from site to site that accurately predicting loads is a difficult task. Recommendations for accounting for this variation are presented in the remainder of this report.

RECOMMENDED DATA COLLECTION SYSTEM

Because of the potential for variation in the number and types of trucks, as well as in the damage each truck causes, site specific data collection is the best method for gathering accurate truck volume and weight data for pavement design and management. Unfortunately, the cost of collecting these data is high, and the collection of data at all sites is not realistic. WIM data, in particular, are difficult to collect. The reasons are that the collection of accurate loading data requires pavement conditions that are not present in many roadways and that the sensors needed for WIM data collection are not easily placed in the pavement.

Therefore, the basic data collection methodology recommended in this report is to collect site specific data whenever possible and to supplement these data with data collected at continuously operating sites at a more limited number of locations. The continuously collected data provide an understanding of truck travel variation over time, while the short-term data supply the geographic distribution needed for a state's pavement management system.

This recommended system for determining vehicle loadings for a state's pavement management system does not change the basic philosophy underlying the computation of pavement loadings in most states. The recommended system still computes total load by using vehicle classification counts to estimate the volume of vehicles by class, and WIM data to estimate the average damage factor by vehicle class. The primary change for most states is the adjustment of truck volumes and loading for variation in truck travel by day of the week and/or season of the year.

Unfortunately, there is no simple formula for determining the "optimum" number and distribution of long- and short-term data collection efforts. Each state must develop these numbers by balancing its need for information against the resources required to collect that information. The number and distribution of counts required by a large state

with diverse traffic characteristics will be very different from those required by a small state with homogenous traffic characteristics.

The data collection program is designed to produce two types of estimates, site specific values and "system" or "group" means. Note that the definition of a "system" or "group" will vary from state to state. For most applications, site specific estimates are better than system means. However, as indicated earlier, the collection of site specific estimates is often unrealistic because of limited resources, and where this occurs, system means must be used.

SITE SPECIFIC DATA

The first recommendation for improving loading estimates is to use data specific to each pavement site whenever possible. Research has shown that truck loading rates (both the number and weight of trucks) can vary considerably from road to road, even within a specific geographic area. The collection of either (or both) vehicle classification counts or weigh-in-motion data at a site for which loading rates are being computed will dramatically improve the accuracy of the loading rate estimates used for pavement management system analyses and pavement design. The more site specific loading information collected at a site, the better will be the annual load estimates.

AVERAGED DATA

Because traffic data collection, particularly WIM data collection, is expensive, in many cases, little or no site specific data will be available for developing pavement loading rates. Where site specific information is not available, values for "similar" roadways must be used.

The use of "similar" roadway values for estimating the number of trucks on a road is highly discouraged for actual pavement design. These values should only be used for network level estimates when the cost of data collection prohibits the collection of site specific data.

However, the use of "similar" roadway values for estimating vehicle weights is often necessary because of the difficulty and cost of placing and operating portable WIM equipment. Where site specific WIM data are not available to provide damage factors for the trucks that are using the road, average damage factors for other "similar" roads must be used. When these average damage factors are developed, the best estimate is the mean damage factor per truck type for a sample of roads that are assumed to carry similar truck traffic.

The accuracy of these "similar road" estimates is dependent on each state's ability to define "similar" roads. Having roads that are truly alike

- reduces the variability of truck characteristics between roads in each group,
- improves the state's ability to measure the true population mean for that group of roads, and
- reduces the differences between the specific site in question and the true group mean.

These issues are explored later in this paper.

DESIGN OF A CONTINUOUS DATA COLLECTION PROGRAM FOR VEHICLE CLASSIFICATION AND WEIGHT

The design of the long-term (i.e., continuous) data collection system for both vehicle classification and truck weights (leading to damage factor estimates) relies on a combination of both statistics and professional judgment. Few (if any) states have sufficient amounts of vehicle classification or truck weight data to accurately describe the true population of truck patterns for all roads in their state. Thus, some professional judgment is needed to make the assumptions that drive the statistical equations used by this methodology.

As described above, both the vehicle classification and weigh-in-motion data collection programs need to account for all four types of variation in truck travel patterns. To eliminate errors from time-of-day variation, the recommended data collection process uses 24-hour truck traffic counts and average daily damage factors. In order to perform quality control checks, the authors recommend collecting data as hourly volumes by vehicle classification and either individual vehicle weight records or hourly summaries of vehicle volumes and weights. After the quality control checks, these data should be aggregated into 24-hour totals (class data) or averages (damage factors per vehicle class).

To account for both day-of-week and seasonal variation in vehicle classification and truck weight data, the data collection program should have some sites that collect data year-round (at least for a few years). Besides helping to determine the types of seasonal and day-of-week patterns, these continuous stations provide the data necessary for estimating the number of data collection counts required to provide annual estimates at a given level of accuracy.

ORGANIZATION OF THE CHAPTER

As indicated above, to supply information on seasonal and day-of-week variations, it is necessary for a state to collect both vehicle classification and truck weight

data from a series of permanent, continuously operating sites. WIM sites are more expensive to install and operate than continuously operating vehicle classifiers. In addition, technological limitations often limit the ability of a state to locate WIM scales. (WIM sensors should be placed in road sections that are flat and where the pavement is in good condition.) The cost and siting requirements of WIM scales limits both the potential places scales can be placed, and the total number of sites that can be instrumented. However, permanent, continuously operating WIM sites also serve as permanent, continuously operating vehicle classification sites, reducing the need for that kind of site.

Because WIM equipment is more difficult to site, the author recommends that WIM equipment be sited prior to siting vehicle classification equipment. Those sites should then automatically be subtracted from the total number of sites required for supplying vehicle classification data. Similarly, both continuously operating WIM and vehicle classification equipment can supply the information collected by continuously operating traffic volume data recorders (often called ATRs), reducing the number of ATRs needed by a state or supplementing the available data. Thus a permanent, continuously operating WIM device serves three purposes, a WIM scale, a vehicle classifier, and a traffic counter.

Because of this "nesting" of WIM and vehicle classification sites, the subject of determining the number and location of continuously operating WIM sites will be addressed prior to that for vehicle classification sites. The reliance on "nesting" of volume, class, and weight data collection sites reduces the total amount of equipment needed to collect this information, and lowers the total cost of equipment, maintenance, and operation of this portion of the data collection process.

NUMBER OF CONTINUOUSLY OPERATING WIM SITES NEEDED

The number of continuously operating sites that are needed within each state will vary from state to state, depending on the variability of truck traffic in the state and the

accuracy with which the state wishes to estimate average damage factors and other group statistics. The greater the variability of truck patterns is within a state (either seasonal or geographic), the greater is the number of sites required. The more homogeneous the truck traffic is, the smaller is the number of continuously operating sites required.

Step 1 - Create Groups of Roads

The first step in determining the number of continuously operating sites necessary for both vehicle classification and truck weight is to divide the state into basic groups of roads that the DOT believes contain reasonably homogeneous truck populations and patterns. (This must be done with professional judgment, based on the information available to the state DOT.) In Florida, these road groups were defined by both geography and functional classification of road. (Florida developed 18 groups. Four of these were individual interstate highways; the remaining were seven geographic areas split into principal and minor arterials.)

These groups of roads do not have to be the same for vehicle classification and truck weights. That is, the state may aggregate roads into one set of groups for truck volume patterns and a different set of groups for truck weights. Both of these groupings may be different from the roadway groupings used to factor volume counts. (Note that the same sites may be used, they are just grouped differently for classification than for weights.)

The more alike the roads are in a group, the fewer are the data collection points that will be needed within that group to accurately estimate the mean population statistics for that group. The more diverse the roads within each of those groups, the more data collection points will be needed. At the same time, generally, when more groups are present, more total sites are needed to measure mean values within a given level of precision. (The best rule of thumb for selecting groups is that if a large group can be divided into two or more smaller groups that have much lower internal variability the large group should be split. Using statistics to determine whether two groups of sites are

statistically different is a good method of determining whether two groups of roads should be aggregated together or left separate.)

Some states may have only one group (all roads in the state). Other states may have a large number of groups, needed to track a number of different travel patterns. If Florida's estimates of truck weight variability are representative of the variability typically found in the nation, between 5 and 15 sites will be needed per group to develop mean damage factors for each group to achieve a precision level of ± 10 percent, 95 percent of the time within that group.

Step 2 - Determine Homogeneity of Groups

Once the state has developed initial road groups, it must determine whether the roads in the group really have similar travel patterns. To do this, the state must examine the patterns observed in the available data. For example, for truck weights, are the mean damage factors for 3S2 trucks (or single trailer trucks) roughly the same? Plot the daily damage factors for these vehicles over time (see Figures 1 and 2) and compare the plots for different sites within each group. If the travel patterns observed in these plots are similar, then the groups are relatively homogenous. If they are not, refine and retest the road groupings.

There are no statistical absolutes that dictate how "tight" a group must be (i.e., how little variation between sites it must have). For damage factors per truck, the authors suggest calculating the average annual damage factor for either the 3S2 (FHWA Class 9) or single trailer truck categories (FHWA Classes 8, 9, and 10 combined) for each site, and using this as the decision making variable. If other truck classes cause a greater proportion of road damage for that group of roads, use that most important vehicle class.

The average annual damage factor at each site must incorporate any differences that exist between weekday and weekend loading rates, as well as variations throughout the year. These values are most commonly developed by averaging a year of data, although samples of data from a year can be used instead, with some loss of precision.

Figure 1. Load Factors at Site 01 in Florida

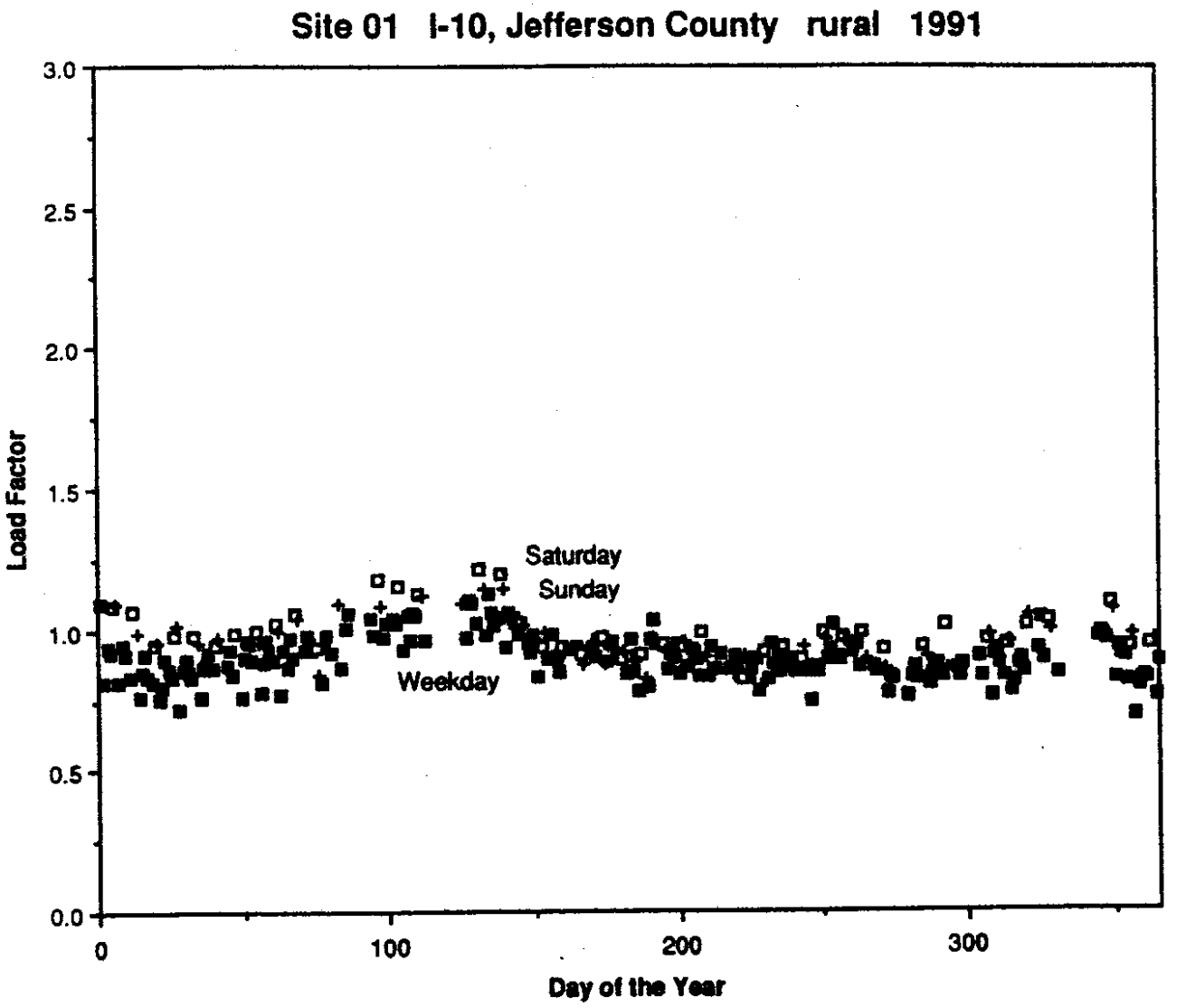
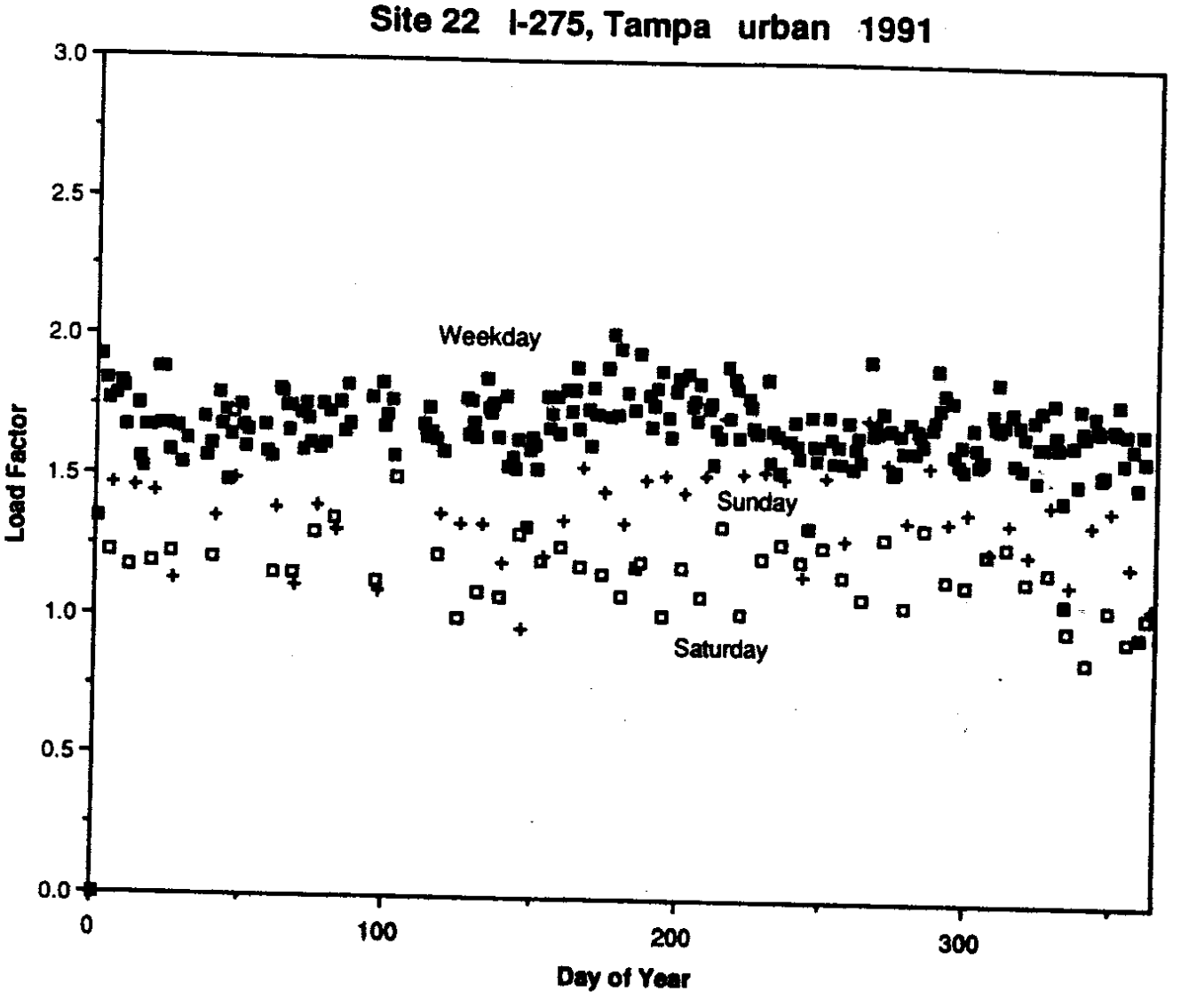


Figure 2. Load Factors at Site 22 in Florida



Once the average annual damage factor for each site has been computed, calculate the mean and standard deviation of these values for all sites within each roadway group. The standard deviation of this factor provides an initial measure of "how good" or "tight" a group is.

Step 3 - Determine the Number of Sites Required

These two values are also necessary for determining the number of sites that are required for each group of roads to meet desired levels of precision. The following equation is used to determine the number of sites required:[1]

$$n = \left[\frac{t * COV}{d}\right]^2 \qquad [1]$$

where

n	=	the number of sites required
t	=	the Student's t statistic for n-1 degrees of freedom
COV	=	the coefficient of variation for the damage factors within the sample, and
d	=	the desired precision or allowable error expressed as a fraction of the mean damage factor

Thus, the greater the precision or the coefficient of variation of the damage factors that is desired, the larger is the number of data collection points required.

Several significant assumptions are made when this formula is used. These are described below.

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1 Equation 1 can alternatively be written as:

$$n = [\,(Z)(\sigma) / d\,]^2$$

where: n = the number of sites required
Z = the Z-score associated with the desired level of confidence
σ = the standard deviation of the group damage factors, and
d = the desired precision or allowable error expressed in damage factor units (ESALs)

Use of this equation is justified by the Central Limit Theorem when the number of sample sites selected exceeds 30. This formula will require slightly fewer sites than Equation 1 to achieve a given level of precision. However, if fewer than 30 sites are used to calculate the coefficient of variation, the distribution of those sites is often not normally distributed, and the Z statistic does not accurately predict the distribution of the population as a whole.

Assumption 1 The first is that the damage factors within each roadway group are normally distributed about the mean value. If they are not normally distributed, this equation is inappropriate.

Assumption 2 The second assumption is that the limited number of sites available for calculating the standard deviation of the damage factor are representative of the population of roads incorporated in the group. This second assumption causes the error associated with damage factor calculations to be underestimated. Often only two or three WIM sites exist in any one roadway group. As a result, these sites must represent many roads that experience a variety of truck travel characteristics. For example, if the two or three WIM sites present have similar damage factors, the above equation will indicate that few sites are needed to estimate the mean value. Error will result if some of the roads in the group actually have much different damage factors. An example is the Florida Panhandle area described earlier. If the site with a damage factor of 1.75 were not present, the truck damage factors for the roads in the panhandle would appear to have very little variability. By adding this one specific station, the expected variability within the Panhandle would increase dramatically, and the number of sites needed to estimate the true mean damage factor would increase accordingly. The opposite type of error can occur when most roads in a group have similar characteristics, but the roads selected for weighing contain highly variable characteristics. In this case, the number of sites needed will be over-estimated. This type of error often occurs with WIM data because the cost of WIM data collection limits the geographic distribution that can be achieved with the available resources. Because WIM data collection is limited, it is usually difficult to accurately determine these values.

Assumption 3. The third assumption of Equation 1 is that the damage factors used in the calculation are the "true" mean damage factors for each site. That is, this equation assumes that the damage factor used for each site has no error associated with it. (The WIM device is assumed to have operated correctly for 365 consecutive days.)

However, if data are not available for an entire year, additional error is associated with this equation for which the statistical theory used to derive the equation does not account. This additional error can not be easily calculated. If the damage factors from each site are reasonably accurate and the estimates used contain no bias, this error is small. However, if the data do contain bias, this error can be significant.

In the Florida WIM data analyses, Florida DOT determined that annual average damage factors for sites with "heavy" seasonality can be estimated within ± 10 percent with 95 percent confidence (for a particular site) if four, week-long WIM counts are conducted during the year. These four counts should be spread equally throughout the year. At Florida sites, which have moderate seasonality, this level of precision can be obtained with two, week-long WIM counts. If there is no discernible seasonality, one, week-long count is sufficient. These estimates need further testing in other states.

Assumption 4. The final assumption required to use Equation 1 is that the precision being measured is actually the error associated with calculating the mean for the roadway group. Equation 1 calculates this error. However, when this estimate is applied to a specific site there are two sources of error. The first source of error is the calculation of the mean value for the group. (This is the value given in Equation 1 as "d", given the above assumptions.) However a second, much larger error is the error associated with applying a mean value to a specific geographic location (i.e., the geographic variability).

The site at which the mean value is applied is really only one of many sites within the roadway group. This group of sites has a diverse group of damage factors. That group of damage factors forms a distribution about the true mean for the group (an estimate of which is calculated above). The actual damage factor for the site at which the mean is applied can fall anywhere within that distribution. Without site specific information, its location within the distribution can only be predicted as being within a given number of standard deviations of the population mean. For example, the true value for the site in question will be within one standard deviation of the mean 68 percent of the

time if the group of roads has a normal distribution. The value of this standard deviation is the same as that used in Equation 1.

The number of samples computed in Equation 1 has no impact on the precision of the mean value as it is applied to an unsampled specific site. The lack of effect that sample size has on the precision of the mean value at a specific point is a result of the geographic variation in truck patterns and the lack of site specific information, not the size of the sample taken to predict the mean population value. The only way to improve the precision of damage factor estimates at a specific site is to collect WIM data at that site. Data collected at the site in question have no geographic component of variability (although they do have seasonal and day of week variability).

NUMBER OF CONTINUOUSLY OPERATING VEHICLE CLASSIFICATION SITES NEEDED

The same process can be repeated for vehicle classification estimates if the value predicted for vehicle classification is a mean for a group of roads. Unfortunately, pavement engineers rarely need the mean volume or mean percentage of trucks for a group of roads. Instead they need the volume of trucks (or the percentage of trucks) by vehicle class at a specific site. As a result, the mean volume for a group of roads is considerably less useful than the mean daily damage factor per truck for those roads.

In most cases, truck volume estimates are based on site specific or nearly site specific vehicle classification counts. This site specific counting is the most important aspect of pavement loading estimation, because the volume and type of trucks at a site is much more variable than the load per vehicle, and plays such an important role in the determination of total loading. (Sometimes these counts are too old and/or too far away from the site being investigated, but that is a different problem.) Because these counts are taken at the site in question (or at least close to the site in question) little or no error is associated with the geographic component of variability. However, the use of short

duration counts to estimate average annual conditions is still subject to errors caused by seasonal and day-of-week fluctuations in truck volumes.

Thus, roads still need to be grouped to assist in estimating seasonal and day-of-week truck volume fluctuations. Using average patterns obtained from road groups to adjust site specific counts is one way to reduce the impact of seasonal and day-of-week fluctuations, and improve the accuracy of annual traffic loading estimates. Because truck volumes are normally more variable than damage factors per truck, a larger number of continuously operating classifiers is generally needed than continuously operating WIM scales.

As with the application of average damage factors per truck two sources of error are associated with the application of average seasonal and day-of-week adjustment factors. The first source of error is prediction of the average seasonal adjustment factor. The second source of error is the difference between a specific site and the mean of the group of roads to which it is assigned.

Guidance for developing groups of roads, determining the number of data collection sites that should be operated for each group of roads, and computing and applying seasonal factors on the basis of these groups is provided below.

The "classic" process for determining the roads that should be grouped together and then determining the accuracy of the specific adjustment factors developed for those roads is similar to that for truck damage factors described earlier in this document.

Step 1 - Calculate Seasonal and Day-of-Week Adjustment Patterns

The first step is to calculate the seasonal and day-of-week adjustment patterns for all sites within a state that have the appropriate data. (Sites to be used in this effort must have continuously operating WIM or vehicle classifier equipment functioning for at least one year.) To simplify the factor process, the day-of-week and seasonal adjustment patterns should be combined into one factor. In Washington, a short count taken on a weekday is divided by a seasonal factor that is the ratio of Monthly Average Weekday

Traffic (MAWDT) for the month in which that count was taken divided by the Average Annual Daily Traffic (AADT). A weekday is assumed to be any 24 consecutive hours of counting between noon Monday and noon Friday. The math for this factoring process is shown in Equation 2:

$$\text{AADT (by class)} = \frac{\text{24-hour weekday short count}}{\text{(MAWDT/AADT)}} \qquad [2]$$

Where more than one weekday of data is available, the daily counts are averaged before they are divided by the MAWDT / AADT ratio. Therefore, in Washington the seasonal pattern to be computed in this early step are the 12 monthly ratios of MAWDT / AADT.

Step 2 - Create Groups of Roads

The next step is to use professional judgment to initially estimate how roads in the state should be grouped so that each site within a group experiences relatively similar truck volume patterns. These road groups may be very different from both the traditional volume seasonal factoring groups and the damage factor groups discussed above. They may even vary for different classes of trucks.

As with the damage factor road groups, each state may divide itself into different road groups on the basis of state specific criteria. The most common criteria used are geographic location, functional classification of roadway, and some measure of recreational activity. A measure of economic activity (e.g., Whether it is a farming area or a coal mining area) may also be needed to describe the expected truck volume patterns. However, the factors that are important in one state for differentiating truck volume patterns may be very different from those that are important in another state.

Step 3 - Determine Homogeneity of the Groups

Using the seasonal/day-of-week patterns for all available sites, it is possible to determine the acceptability of these initial road groups by computing the mean and standard deviation of the monthly factors for each month for each proposed group of roads. Performing these computations, will make apparent the fact that variability of

truck travel is much higher than automobile travel variability. The analyses performed with Washington data showed that peak season adjustment factors for many truck types were routinely around 1.6 for the ratio of MAWDT/AADT, with adjustment factors greater than 2.0 for highly variable sites. For sites where volumes of trucks were low (e.g., sites with average daily volumes of less than 50 vehicles in a particular truck class) factors considerably larger than 2.0 were occasionally present. Similar adjustment factors for automobiles were rarely higher than 1.3 or 1.4, with adjustment factors of 1.6 or 1.8 for extreme recreational routes.

Because truck adjustment factors tend to be quite high (and sometimes quite variable from year to year or from vehicle class to vehicle class) the standard deviation of the monthly seasonal factors within the proposed road groups is likely to be high, particularly in comparison to the standard deviation for automobile seasonal factors. The higher is the standard deviation of these factors, the greater is the number of data collection sites needed to estimate the mean monthly factors for each group of roads within a given level of precision. (It is assumed that each of these sites is a permanent data collection device, collecting data year-round.)

Step 4 - Determine the Number of Sites Required

As with truck damage factors, the number of sample sites needed to compute the mean group factor can be computed with the following formula:[2]

$$n = \left[\frac{t * COV}{d}\right]^2 \qquad [3]$$

where

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[2] As with Equation 1, when more than 30 sites are present within each factor group, this equation can also be expressed as

$$n = [\,(Z)(\sigma)\,/\,d\,]^{\,2}$$

where: n = the number of sites required
Z = the Z-score associated with the desired level of confidence
σ = the standard deviation of the monthly seasonal factors for the group, and
d = the desired precision or allowable error expressed as a fraction of AADT.

n	=	the number of sites required
t	=	the Student's t statistic for n-1 degrees of freedom
COV	=	the coefficient of variation for the seasonal factors for the group, and
d	=	the desired precision or allowable error expressed as a fraction of the mean seasonal factor for the group.

The value for n <u>includes</u> the WIM locations computed in the previous section, so long as those sites collect vehicle classification data throughout the year. When calculating the number of sites, note that each month of the year will have a different mean and standard deviation for each road group. (That is, there will be 12 different means and standard deviations for each road group.) In addition, each vehicle classification for which a factor is computed will have a separate set of 12 monthly means and standard deviations.

To simplify the computational process, the sample size selected should be based on the accuracy of the most important truck classification, (usually single trailer trucks or FHWA Class 9 vehicles) during either the worst month of the year (so that the precision achieved for all months is at least as good as the sample design indicates) or the most variable month for which traffic data are routinely collected.[3] For example, if no short duration traffic counts are taken in December, January, or February because of snow, the variability of seasonal factors during these months does not need to be considered when determining the appropriate sample size for the factor group.

<u>Precision of the seasonal factor versus precision of the factor's application.</u> As with the damage factor calculations presented earlier, this equation only computes the precision of the mean monthly factor for a group. This is not the same as the precision associated with applying these factors to a specific site. Furthermore, the precision of applying a given monthly factor to a specific site can be estimated using the standard deviation of the factor for the group. That is, there is approximately a 90 percent chance

[3] The "true" accuracy of each of the volume estimates by vehicle class will differ by class and by month.

that the true adjustment factor lies within two standard deviations of the true mean adjustment factor. This error is not impacted by the sample size used to compute the group mean factor. This is the primary reason why no "group factoring" approach to adjusting short duration truck volume estimates will achieve high levels of precision in the estimation of truck AADTs when even moderate levels of variability are present within a factor group. (Note that the accuracy of the annual estimates is still improved by factoring. The errors associated with these estimates are simply larger than commonly requested for traffic volume counts.)

Adjust the factor groups as necessary. If the standard deviation within a factor group is too high to either allow use of a moderately low sample size for calculating mean group factors, or produce the precision levels needed when applying those factors, some adjustment of the road groups may be necessary. As with the truck damage factors, the variability of factors within groups can sometimes be decreased by defining more groups. This process can decrease the number of sites needed to estimate each group factor mean within a given level of precision and increase the precision of each of those estimates when they are applied to specific sites. However, the increase in the number of groups usually requires a corresponding increase in the number of sites needed because group factors are needed for more groups. (For example, with six factor groups, an average of 10 sites per group (for a total of 60 sites) might be needed to achieve a specific level of precision. By redefining roads into eight groups, the lower variability might allow the same level of precision with an average of eight sites per group. However, 64 sites would be required for the state.)

When factor groups are developed, states should look critically at their initial assumptions of traffic patterns. Both Washington and Florida were occasionally surprised at the truck patterns observed in their data. In many cases increases in precision (and decreases in the required sample sizes) can be obtained by simply reassigning some roads from one factor group to another, rather than by redefining the entire factor group.

However, the groups selected must include some type of explanatory mechanism or roadway characteristic that defines the group. Without a good explanatory mechanism, the assignment of short counts to factor groups becomes too subjective; leading to significant bias errors.

Seasonal factors decrease bias even for groups with high variability. Guidance on how "tight" a factor group should be can also be obtained by examining the value of the mean factor being computed. If the mean factor (assumed to be MAWDT/AADT) for a vehicle class for a month is 1.6, this represents a 60 percent adjustment to the short count to estimate AADT. This adjustment is extremely large, and thus even if the adjustment is inexact, a significant improvement in the accuracy of the annual estimate will result from its application.

For example, if the standard deviation of the mean factor is 0.15, there is a 90 percent chance that the true adjustment factor at any specific site will lie between 1.3 and 1.9. If we assume that the actual adjustment for the site in question is at the extreme for this range (1.9), the application of the factor of 1.6 still reduces the error of the annual travel estimate considerably. This is illustrated below.

Short count = 100 vehicles per day

Estimated Seasonal Factor = 1.6

Actual AADT = 52

Actual Seasonal Factor = (100 / 52) = 1.9

Estimated AADT Using Short Count and Estimated Factor = 100 / 1.6 = 62.5 = 62

Error Without Factoring = (100 - 52) / 52 = 92 percent

Error After Factoring = (62 - 52) / 52 = 19 percent

Thus, while factoring with an imprecise group mean may still leave a considerable error, when the factors applied are large, the resulting annual estimates are still considerably more accurate after factoring than before.

In addition, the estimated AADT will be unbiased. That is, some AADT estimates (after factoring) will be slightly greater than the true AADT and some will be smaller than the true AADT. If factors are not applied, most truck AADT estimates for sites within a group will be on one side of the true estimate. (For example, in Washington, weekday counts of combination and double trailer trucks during almost any month of the year at almost any site over-estimate the AADT for those vehicle types (see Figure 3).

In the Washington analyses, it was not possible to develop truck factor groups that routinely produced estimates of truck volume AADTs within ± 10 percent 95 percent of the time. When factor groups were developed with the above techniques, the AADT estimates significantly improved; however, the high level of variability in the truck volumes prevented the researchers from reaching the desired levels of precision.

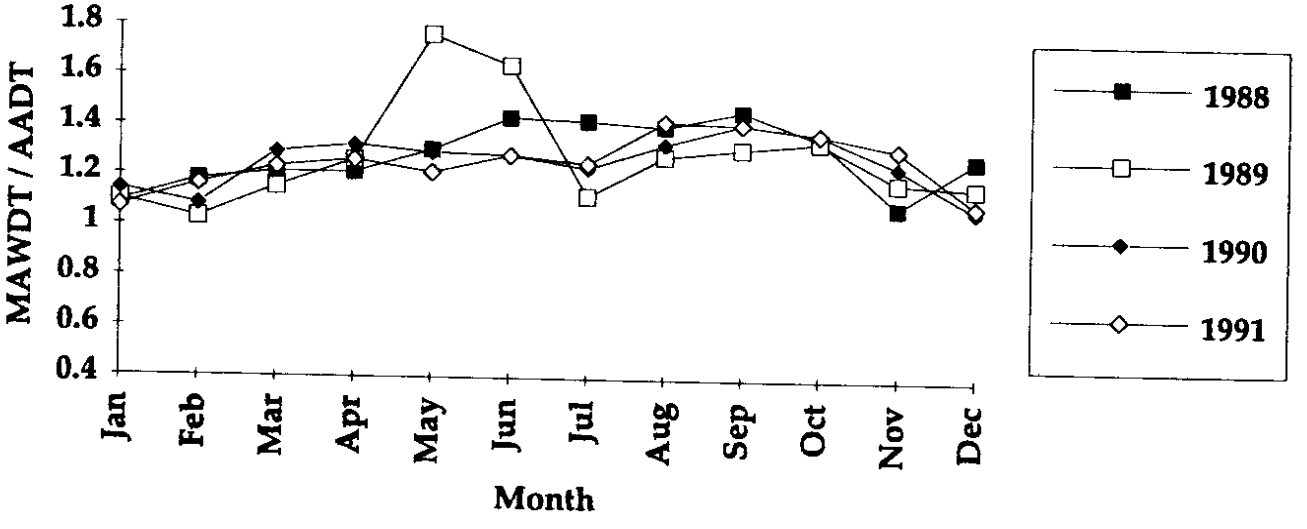
TWO TECHNIQUES FOR INCREASING ACCURACY

To address these limitations, two alternative techniques were developed and tested to improve the truck AADT estimates. The most accurate of these alternatives (and the only one to come close to estimating AADTs within ± 10 percent 95 percent of the time) was to collect truck volume counts four times per year (i.e., quarterly), with each count lasting one week. These 28 days of counts were then averaged to produce the AADT estimate. Week-long counts were selected to account for the differences in day-of-week volumes. Four of these counts were required to account for the seasonal differences in truck volumes.

While this methodology provided the most accurate of the AADT estimates, it was also the most expensive method tested and is an unreasonably costly approach for meeting most truck AADT requirements. However, where accuracy of truck AADT estimates is very important, this approach is better than all of the factoring approaches tested.

Figure 3

Ratio of Average Monthly Weekday to Average Annual Travel For Larger Combination Vehicles On Interstate 5 At Marysville



A second factoring approach that Washington tested also worked slightly better than the more traditional approach described above. This approach used a multi-linear regression calculation to develop monthly seasonal factors. While this approach produced slightly better AADT estimates, it is considerably more complex than the traditional approach described above, and not all states will be comfortable with it. Both of these techniques are discussed below.

An Alternative To Vehicle Classification Factoring

The difficulties the Washington state project team experienced in developing and applying traditional factoring approaches to truck volumes led to the exploration of other rational methods for estimating annual traffic volumes on the basis of short-duration counts. The most basic method for estimating traffic volumes is to count vehicles at multiple times during the year at the same location and then average the counts.

The advantage of this method is that counts from different times of the year reflect the various volume patterns that occur during the year and result in a balanced estimate of high and low volume periods. A secondary benefit is that the analysts no longer need to

- determine factor groups;
- allocate individual roadway segments to specific factor groups; and
- develop, maintain, and apply seasonal factors by truck category.

Testing the Method

The initial test of the multiple count technique was to collect data four times during the year for one week during each counting session. Approximately three months passed between counts. Traffic counts collected during weeks that contained holidays were not used in the analysis. Annual average volumes by class were developed by computing simple averages from the 28 days of data present in each sample site.[4]

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[4](The Washington tests were performed using four vehicle classes based on total vehicle length. The classes roughly correspond to vehicle types as follows: Bin 1 = cars, Bin 2 = single unit trucks, Bin 3 = single trailer trucks, Bin 4 = double trailer trucks. Specific length limits for these bins are given on page 38 of this report.

A summary of the results of these tests is shown below.

Table 1. Average Error of Annual Traffic Estimates Based on Four, Week Long, Vehicle Class Counts

	Bin 1	Bin 2	Bin 3	Bin 4
Mean Error	0.029	0.038	0.045	0.042
Standard Deviation	0.023	0.026	0.038	0.035
Maximum Error	0.077	0.084	0.157	0.118

These results were better than the results obtained by computing annual volumes with seasonal factors developed from a specific site and applied only to that site (See Reference 2). More importantly, Table 1 shows that this system provided estimates of annual traffic within 10 percent almost 90 percent of the time for each of the four length bins. (The mean plus two standard deviations was 7.4 percent for Bin 1, 9.0 percent for Bin 2, 12.1 percent for Bin 3, and 11.1 percent for Bin 4. The mean would drop to 6 percent for Bin 1, 8 percent for Bin 2, 7 percent for Bin 3, and 9 percent for Bin 4 if the sites with the largest variations were dropped from the calculations.)

The errors associated with the multiple count approach were roughly 1.4 to 2.0 times better than the errors associated with the calculation and application of site-specific seasonal factors. Furthermore, the error associated with factoring short counts was underestimated because no error associated with computing group factors or assigning a site to a group was included.

Limitations To This Method

There were three primary drawbacks to calculating annual average truck volumes on the basis of multiple counts. The first was the difficulty in obtaining the staffing resources necessary for collecting seven consecutive days of vehicle classification data four times per year for each roadway section of interest. The second drawback was the need to collect classification data for all seven days of the week. The problem was that

the potential for the portable axle sensors, used by the classifiers, to come loose before the end of the scheduled count increased dramatically as the duration of the count increased. The final drawback was the cost of collecting the required number of counts.

Variations of the Method

A test to reduce the count program to two week-long counts per year, spaced six months apart, produced mixed results. The accuracy of the annual estimates decreased for roughly three quarters of the sites tested when the number of counts included in the annual estimate calculation was reduced from four to two. However, a quarter of the sites actually provided better annual estimates when based on two weeks of data than on four weeks of data. This greater accuracy occurred when the two-week periods were more representative of the full year's traffic patterns than the four-week periods.

A test with a cycle of three counts per year was also conducted. For this test, three week-long counts were conducted four months apart. The results mirrored those of the two-count period experiment, described above. In each of these cases, a full week of data still had to be collected to account for the differences in traffic between weekdays and weekends.

Another alternative counting approach would be to reduce the duration of the traffic counts used. This counting approach would reduce the likelihood that axle sensors would fail during the count and would lower the cost of data collection.. Traffic counts would be shortened if counts were taken during the weekdays only (as most traffic counts currently are). The axle sensors would then only be on the ground for three to four days, greatly reducing the chance that a sensor would be dislodged.

This approach was tested by counting three consecutive weekdays, four times each year. Each of the weekday estimates was then factored to represent the average annual condition; the 12 counts were then averaged. The results of this test were quite respectable, although this technique requires that the day-of-week pattern within each factor group be stable. In most cases, mean errors for the annual estimates ranged from 1

percent to 5 percent, with standard deviations near 5 percent. Thus, under this "best case" scenario, this counting approach provided annual estimates that were as accurate as those provided by the four-week long counts. Whether this technique was actually accurate depends on how "tight" the factor group was and how well a specific site was assigned to its factor group.

Table 2. Average Error of Annual Traffic Estimates Based on Four, 3-Day Long, Factored, Vehicle Class Counts

	Bin 1	Bin 2	Bin 3	Bin 4
Mean Error	0.013	0.037	0.021	0.049
Standard Deviation	0.035	0.055	0.047	0.047

However, note that much of the accuracy of this method was due to the averaging of the four counts, rather than to the accuracy of the adjustment factors. The error within the individual estimates of annual conditions (prior to their averaging) was often over 20 percent. (This is equivalent to use of a single 24-hour factored count.) However, these errors were normally distributed about an error of 0.00. Thus, when points were averaged (12 points were averaged to obtain a single annual estimate), the mean value for each site was often quite good, even though the individual data points used to make that estimate did not accurately replicate the annual conditions.

Another alternative method to account for differences in weekday/weekend travel without counting for seven days at a time would be to count the weekend[5] and only one weekday. That weekday could be either before or after the weekend. The one weekday counted (either Thursday or Tuesday) would then be used as a surrogate for the missing two weekdays. Removing 2 weekdays from the count (i.e., counting Thursday through Monday, or Friday through Tuesday) decreased the method's accuracy. This decrease

[5](Mondays and Fridays are considered weekends for this analysis, because Monday and Friday truck traffic volumes were often different from Tuesday through Thursday traffic volumes. For sites where Monday or Friday traffic were consistent with Tuesday through Thursday volumes, the length of these counts could be shortened.

ranged from 1 percent or 2 percent at sites with stable vehicle classification volumes, and from 6 percent to 10 percent at sites with unstable vehicle classification volumes.

Regression Analysis Approach To Seasonal Factoring

A second alternative to the classic seasonal factoring approach, regression analysis, was also explored using Washington data. The regression approach to developing factor groups is initially similar to the analysis process described in the main body of this report. However, professional judgment is used not to define groups of roads but to define the road characteristics that differentiate the road groups. These characteristics can include geographic area, total volume of vehicles (or volume by class), functional class, and presence of recreational travel, among others.

A dummy variable is then assigned to each of these characteristics for each of the sites for which seasonal factors are available. The dummy variable has a value of 1 (positive) or 0 (negative) for each site for each input variable except volume. The input value for volume in the test is the monthly average weekday traffic for a particular vehicle classification, expressed in units of 1,000s for vehicle Bins 2, 3, and 4, and in units of 10,000 vehicles for Bin 1.

In the regression approach tested for this project, monthly factors for each year for each counter site are not used to compute the factor groups; instead, a time series-based approach called Decomposition is used to calculate a single set of monthly adjustment factors at each continuously operating counter site on the basis of the monthly adjustment factors for multiple years of data at that site. (Essentially, instead of calculating the factor groups for a specific year, and then determining if these groups are stable over multiple years, the Decomposition method incorporates all years of data into one grouping analysis.) A reference that describes the Decomposition approach is "Forecasting, Methods and Applications," by Spyros Makritakis, Steven Wheelwright, and Victor McGee, 1983.

Once the independent variables (the dummy variable described above) and dependent variables (the monthly seasonal factors) are ready, a standard, multi-linear regression analysis can be used to determine which variables significantly affect the computation of the seasonal factors and the coefficients for those variables. Note that it is not necessary to use the same variables to compute the seasonal factor for the month of March as are used to compute the factor for June. Table 3 illustrates this fact by showing the 12 seasonal adjustment equations for length bin 2.

An interesting difference between the regression approach and the "classic" approach is that the concept of a "group of roads" has no meaning in the regression approach. Each road is classified as its own group, with that group defined by the actual characteristics of the road. This means that a unique seasonal factor is computed for each site for each month.

The primary benefits to using the Decomposition method are that the method

- automatically accounts for missing values,
- discounts the presence of extreme data points, and
- reduces the impact of moderate to large year-to-year and site-to-site variability, which is a problem for the lower volume vehicle classes.

The drawback to this technique is that it is computationally and intellectually more complex than computing simple group averages. This complexity may cause problems for the DOT staff responsible for implementing and maintaining the factoring process.

The test if this approach revealed one advantage: it provided a direct computation of whether specific input variables had an effect on the seasonal factor "grouping" for a highway. (If an input variable was useful, it improved the predictive capability of the regression equation. If an input variable did not improve the predictive nature of the equation, it was discarded.) Thus, the final regression equation indicated those criteria that were important for defining a "factor group," although no specific "group" was identified as such. This result made the assignment of specific, short-duration traffic

Table 3
Seasonal Adjustment Equations From Washington Regression Analysis For Length Bin 2[1]

January	63.01 + 22.3*Urban + 13.9*Collec - 7.8*Part - 22.1*Central + 22.2*Recart - 19.5*Receast - 7.9*Agr + 31.9*Hrv - 12.2*R90 + 8.7*Vol
February	65.32 + 15.2*Urban + 32.4*Collec + 15.7*Mart - 7.9*Central -15.9*Rec +13.3*Recart - 13.9*Agr + 13.8*Hrv + 12.4*Volume
March	105.6 + 10.6*Urban - 33.7*Mart - 23.8*Central - 28.5*Rec + 20.4*Reccent - 27.15*Agr - 14.3*I90 - 8.5*Volume
April	97.2 + 13.6*Urban - 45.5*Mart - 9.1*Part - 22.1*Rec + 24.4*Recart + 9.5*Receast - 7.0*Agr + 50.0*Hrv - 6.5*R90
May	105.4 +11.7*Urban - 10.9*Ec + 4.8*Reccent + 21.7*Hrv + 13.3*R90
June	114.2 - 19.0*Macol + 12.0*Recart - 13.3*Reccent + 25.6*Hrv - 10.4*I5 + 8.5*Volume
July	121.1 + 64.1*Mart + 11.2*Part + 36.9*Rec - 10.0*Receast - 33.6*Recec + 8.5*I90 + 5.7*Volume
August	136.9 + 43.5*Mart + 12.3*Part - 12.1*Ec + 25.9*Rec - 22.7*Recec - 13.9*Hrv + 8.5*I90
September	128.7 - 46.0*Collec - 6.6*Reccent + 11.1*Hrv - 14.0*Uru - 8.0*I90
October	114.6 - 11.0*Part + 14.8*East - 24.5*I90
November	82.6 + 14.4*Urban - 9.0*Mart - 8.3*Part - 23.3*Central -11.6*Rec +12.9*Recart +20.2*Reccent + 27.0*Hrv - 5.5*I90
December	54.7 + 21.1*Urban + 16.8*Macol - 26.3*Central + 7.5*Recart - 6.8*Receast + 15.5*Reccent + 26.0*Hrv +15.1*Uru - 10.0*R90 + 14.7*Volume

where: Part = principal arterial, Mart = minor arterial, Collec = collector, Macol = minor arterial or collector, East = eastern Washington (WA), Central = central WA, Ec = if eastern or central WA, Rec = recreational route, Agr = an agricultural route, Recart = if recreational and an arterial, Reccent = if recreational and in central WA, Receast = if recreational and eastern WA, Recec = if recreational and eastern or central WA, Hrv = high pproportion of RVs, Volume = bin 2 traffic count in units of 1000, I90 = if Interstate 90, R90 = if a rural section of I-90,

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1 This seasonal adjustment factor is used to convert weekday counts of Length Bin 2 traffic to estimates of annual average Length Bin 2 loadings. The seasonal factor is applied using the following formula: Count / Seasonal Factor = Annual Estimate

counts to "factor groups" easy and reduced the error associated with assigning specific locations to specific "factor groups."

On the other hand, too few continuously operating vehicle classification counter sites were available to determine the true input variables needed to compute seasonal factors, and thus, the end results were biased by the data available.

The results of this technique, while somewhat better than those for the "classic" approach described in the main body of this paper were still not impressive. The R-squared coefficients for the groupings of stations were not high. Twelve R-squared values were computed for each vehicle bin (one R-squared value per month). Table 4 summarizes these values.

Table 4. R-Squared Coefficients For Regression-Based Factor Calculation in Washington

	Bin 1	Bin 2	Bin 3	Bin 4
Mean R-squared	0.900	0.826	0.810	0.735
Standard Deviation	0.066	0.205	0.137	0.158
High R-squared	0.975	0.981	0.956	0.955
Low R-squared	0.787	0.287	0.457	0.476

Table 4 shows that the R-squared values were highest for Bin 1, with an average of 0.9 and individual R-squared values ranging from 0.975 to 0.787. They were lowest for Bin 4, with an average of 0.735 and individual R-squared values ranging from 0.955 to 0.476.

Because automobile travel was the most stable both among sites and from year to year, it was not surprising that Bin 1 provided the most accurate regression results. The results of the analysis of seasonal factors for the three truck classes were reasonably similar. Each truck classification showed reasonably good R-squared values for most months; however, each classification had at least one month for which the variability in the monthly factors was simply too large for the factoring process to account for accurately.

OTHER ISSUES

Distribution of Counts Within a Group

One question that is unanswered by the discussions above is how to distribute counts between sites within a group of roads. A variety of techniques are available for this task. From a statistical stand-point, the best method for distributing the count locations is to use a random sample.

Because WIM data collection requires good pavement conditions (smooth pavement, no horizontal or vertical curves, etc.), the number of locations at which WIM can be installed will be limited. It is appropriate to select randomly among these potential locations.

The problem with truly random distribution of a small number of sites within a group of roads is that such a distribution may not account for the geographic diversity within a group. That is, if the "group" is the entire state, and all of the count locations are in the southern end of the state, no data will indicate whether the northern end of the state experiences different truck traffic conditions. This lack of diversity in the selection of sites can also apply to other stratifications (e.g., functional class, volume of road). The limited number of continuously operating WIM and vehicle classification counters and thus the lack of diversity in the sample makes it very easy to create.

Therefore, it is acceptable for the state to use some professional judgment in selecting data collection sites so that sites within a group are distributed roughly in proportion to the presence of roads that contain a particular characteristic within a factor group. For example, if 40 percent of truck VMT is in the northern half of the state, roughly 40 percent of the WIM sites should be in the north. However, caution must be exercised when deviating from random site selection, because subjective selection of data collection sites can also bias the data being collected (for example, towards the truck characteristics experienced on high volume truck routes, and away from lower volume routes).

A careful mix of random site selection mixed with prudent professional oversight will help ensure that states are able to detect the types of travel patterns that exist. A good rule to use when either distributing sites or checking the distribution of existing sites, is that sites should be located in rough proportion to their contribution to truck VMT in the state. That is, if interstates are responsible for 50 percent of truck VMT they should have roughly 50 percent of the sites being distributed. This same philosophy can be extended towards geographic areas (as illustrated above), or other stratifications of interest to the state.

Axle Correction Factors

The Washington vehicle classification analysis found that axle correction factors are highly variable from site to site, as well as from month to month. Weekday and weekend axle correction factors also differ significantly.

In general, at all sites, the axle correction factor measured for weekdays was higher than that measured on weekends. In addition, the difference in axle correction factors among sites was more significant than the difference between axle correction factors from one month to the next. However, the difference in axle correction factors between weekdays and weekends was often as large the difference among sites.

A single-axle correction factor for all seven days predicts too many trucks operating during the weekends and not enough during the weekdays. This prediction results in the underestimation of vehicles on the weekend and the overestimation of vehicles on the weekdays. To avoid these problems, the states should use axle correction factors that are consistent with the axle counts being factored. For example, only data from weekdays from a continuously operating vehicle classification counter should be used to compute axle correction factors that will be applied to weekday counts.

Number of Vehicle Classes That Should Be Used

In most cases, aggregated vehicle classifications should be used to develop seasonal factors. The analysis of Washington classification data showed that several of

the FHWA vehicle classifications contained such a small percentage of vehicles, that for moderate and lower volume roads, the volume patterns for these classes often became unstable. (That is, small changes in volumes within some classes caused extreme changes in seasonal, temporal, and day-of-week patterns. This made it difficult to determine consistent travel patterns within these vehicle classes.)

The authors of the Washington report conclude that from four to six vehicle classes should be used for seasonal factor development for moderate and lower volume roads. Use of a smaller number of vehicle classifications results in some loss of precision (i.e., it is not possible to distinguish how travel patterns for two FHWA classes that fit within a single aggregated class differ), but results in a more stable set of adjustment factors. This results in a better estimation of loading patterns and therefore total loads. Many states maintain equipment that can classify vehicles by total length using two induction loops (for example, speed monitoring equipment). While total length does not provide a precise measure for differentiating vehicles by class, it does allow states to develop a reasonable picture of the volume of vehicles in the basic categories of passenger cars, small commercial trucks, single trailer trucks, and multi-trailer trucks. For many pavement analyses these categories are sufficient. Table 5 illustrates the bounds used for length categories used by Washington and Idaho.

Table 5
Washington and Idaho Vehicle Length Classifications

	State	Minimum Length	Maximum Length
Bin 1	Washington		26 feet
	Idaho		20 feet
Bin 2	Washington	26 feet	39 feet
	Idaho	20 feet	40 feet
Bin 3	Washington	39 feet	65 feet
	Idaho	40 feet	70 feet
Bin 4	Washington	65 feet	115 feet
	Idaho	40 feet	148 feet

Besides the loss of precision, the primary disadvantages of using the vehicle length classes are the facts that FHWA vehicle classification categories do not fit cleanly into vehicle length categories, and that states tend to use different length classification boundaries; (see below) making it more difficult to compare travel patterns and trends between states.[6]

The exceptions to this recommendation are high volume interstate and principal arterial routes, where sufficient volumes are present within each of the FHWA categories to calculate stable adjustment factors for all 13 FHWA classifications.

Combining Group Means To Obtain Statewide Estimates

The methodologies described above develop mean estimates of various attributes for each group of roads defined by a state. A state may be interested in determining the statewide mean damage factor per truck or mean damage factor for each truck type. Unless the state uses a single truck weight factor group for the entire state, this value must be obtained by combining the damage factors from each group. (If the state uses a single group of roads as its sample basis, that one group mean is the mean for the state.)

Where more than one group exists, two alternative approaches can be used to estimate the statewide average. The better of these two techniques weighs the mean damage factor from each group of roads by the proportion of statewide truck travel that occurs within that group. To compute this statewide mean, analysts must know the annual vehicle miles of travel for trucks within each group of roads; these estimates can be used to weight the damage factors from each group. This computation can be expressed as follows:

$$SDF = \sum_{0}^{n} \left(\frac{DF_i * VMT_i}{\sum_{0}^{n} VMT_i} \right) \qquad [4]$$

[6] The technical report for this project [2] provides more information and analysis on this subject.

where

SDF = the statewide mean damage factor,

VMT_i = the VMT for that truck class in region i,

DF_i = the damage factor for that truck class for region 1, and

n = the number of regions in the state.

This approach assumes that all roads in a group have statistically similar damage factors and then weights the group means on the basis of their contribution to statewide travel. It is most accurately applied when truck VMT is known for individual classes of trucks so that the statewide mean damage factors can be computed separately for each truck class.

Where VMT by factor group is not available, the second aggregation technique is to compute the average daily damage factor for each weigh station in the state and then either calculate a straight average of those values or average the damage factors by using a weighting factor equal to the proportion of average daily volume (by truck class) at each site divided by the total volume for that class for all sites combined.

The straight average assumes that the selected WIM sites are equally representative of statewide travel, regardless of volume. (That is, it assumes that the volume of trucks on a road is not a good estimate of how "representative" that site is of damage factors within the state.) The weighted average assumes that "a truck is a truck," regardless of where it is weighed and that each truck weighed should be treated equally. Insufficient information is available to prove or disprove any of these assumptions.

REFERENCES

1 Getting Better Truck Flows and Loads for Pavement Management, Task B Final Report: Truck Weight Case Study, by Jack Butler, Manager, Transportation Statistics Office, Florida Department of Transportation, August 1993.

2 Getting Better Truck Flows and Loads for Pavement Management, Task A Final Technical Report: Vehicle Classification Case Study, by Mark E. Hallenbeck and Soon-Guam Kim, Washington State Transportation Center, September 1993.

3 Summary of Truck Loading Patterns In Washington State, by Mark E. Hallenbeck and Soon-Guam Kim, Washington State Transportation Center, September 1993.

4 Getting Better Truck Flows and Loads: Truck Weight Case Study, by Philip Hazen, FHWA, and Richard Reel, Ambe Njoh, and Gordon Morgan, Florida DOT, presented at TRB Annual Meeting, January 1994.