Getting Better Truck Flows and Loads: Truck Weight Case Study

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Florida has 20 years of experience in running continuous weigh-in-motion (WIM) stations and currently has 13 continuous WIM stations in operation. Therefore, an exhaustive investigation of the WIM data with the purpose of determining the optimum number of WIM sites to address the needs of pavement management systems was conducted by the Florida Department of Transportation for FHWA. The study was organized according to results of specific tasks (1 through 5). Under the early tasks the WIM data were examined for seasonal patterns or other patterns for allocating a continuous WIM station to a pattern group. Florida found little or no seasonal patterns. However, Florida has decided to divide the state into seven geographic areas for WIM data collection and analysis. The basic unit of analysis was the average equivalent single-axle load (ESAL) value per truck for a day at a site. Daily ESAL values are more variable than was originally thought. Florida found that 1 week (7 days) of data collection at stable sites, two 1-week collections at moderately stable sites at semiannual intervals and four 1-week collections at unstable sites spread over the quarters of a year were recommended. The last task investigated how many WIM sites should be conducted within Florida. These results should be helpful to other states conducting a WIM program.

FHWA's Traffic Monitoring Guide (TMG) (*1*) recommends randomly collecting truck volumes and classes at 300 sites and truck weight data at 90 sites over a 3-year period. This is 100 and 30 sites, respectively, per year. A state that follows the TMG recommendations will obtain systemwide averages for four systems: (a) Interstate rural, (b) Interstate urban, (c) total non-Interstate rural, and (d) total non-Interstate urban.

Pavement management systems (PMS) and other management systems, on the other hand, need site-specific data or at least data for one site for each "long" section of highway. For example, a long section existing between the major intersections on the National Highway System would be perhaps 10 to 50 mi in rural areas and 1 to 10 mi in cities.

FHWA initiated research in late 1991 to address this problem. Hallenbeck (*2*) of the Transportation Research Center, University of Washington, Seattle, was selected to analyze truck classification data from over 20 continuous vehicle classification stations conducted by the state of Washington. Hallenbeck reported on the preliminary results at the 1993 TRB Annual Meeting (*2*). A report on the analysis of vehicle classification has been completed (*3*). In addition, a final report has been completed on how a state transportation agency would develop a data collection framework for truck volumes and truck weights for their PMS (*4*); this report will be distributed by FHWA in mid-1994.

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In late 1991, Florida Department of Transportation (FDOT) was selected to analyze truck weight data from more than 13 continuous weigh-in-motion (WIM) stations. A draft final report has been completed (*5*). This paper reports FDOT's analysis of their voluminous WIM data. The goal of truck WIM data collection and analysis is to support the estimation of 18,000-lb (8172-kg) equivalent single-axle loads (ESAL) yearly on the highways in a state's PMS.

This report is organized according to the five research subtasks as follows: (a) establishing combination truck use patterns by highway functional classification and seasonal pattern, (b) developing preliminary vehicle classification and WIM statistics, (c) investigating the short count program using both classification and WIM data, (d) determining the difference in accuracy of the annual average ESAL factor for 3S2 or combination trucks resulting from application of monthly and day-of-week factors instead of directly estimating from short counts, and (e) analyzing WIM count locations to determine the number of short counts needed for a PMS.

ESTABLISH COMBINATION TRUCK USE PATTERNS

Investigation of Strata of WIM sites

One objective of this study was to investigate a cost-effective combination of permanent and short-count WIM stations. Differences in loadings of trucks by season were explored to determine ways of using WIM data collection to account for seasonality. In addition to rural/urban and functional classification designations, a state's highways were investigated in terms of two truck use patterns: intercity and seasonal. Intercity were those routes with fairly uniform annual patterns typical of routes serving a large city. Highly Seasonal were those routes serving such areas as agriculture and forestry and connecting to shipping or processing centers. Loading differences should include the analysis of classification (volume) differences and also load (ESAL) differences.

Florida's seasonal variation is rather small and heavily influenced by less predictable factors, such as variations in the expected weather and the economic climate. Because of this probable lack of pronounced seasonality, it was determined that assignment of the state's entire network of highways to strata based on seasonality would be difficult and not useful. Other states, particularly those with severe winter weather, should have much more pronounced seasonality in their truck load factors.

Characteristics of WIM Stations in Florida

FDOT's continuous WIM (CWIM) program has been in operation for 17 years. The original Radian CWIM equipment was replaced with PAT CWIM equipment beginning in the fall of 1988. There are 13 active Florida CWIM sites whose characteristics are shown in Table 1. Florida has substantial data from seven of these sites beginning in 1991, as shown in Figure 1.

Station 9926 had incomplete data for 1991 and was eliminated. The remaining six sites were grouped into strata: (a) rural Interstate Site 9901 on I-10; (b) other rural principal arterials such as Site 9909 on US-19/98, Site 9917 on US-41, and Site 9925 on US-92; and urban Interstate Sites 9922 on I-275 and 9924 on I-110.

For each WIM site, the day-to-day variation was considerably greater than any seasonal variation. This indicates that seasonal factors are not needed by Florida to expand short counts to an annual average but that daily or 48-hr counts may need day-of-week factors to produce annual averages.

Figure 2 shows the variation over the 365 days of the year for Site 17. Note that Saturday has higher but Sunday has lower daily load factors than the weekdays. This is typical of highways used for hauling agriculture products. Other sites had different patterns.

In summary, Florida determined that there was adequate data for six of the Florida DOT CWIM sites in 1991 to use in the analyses of the remaining tasks. These six stations did not display any meaningful grouping.

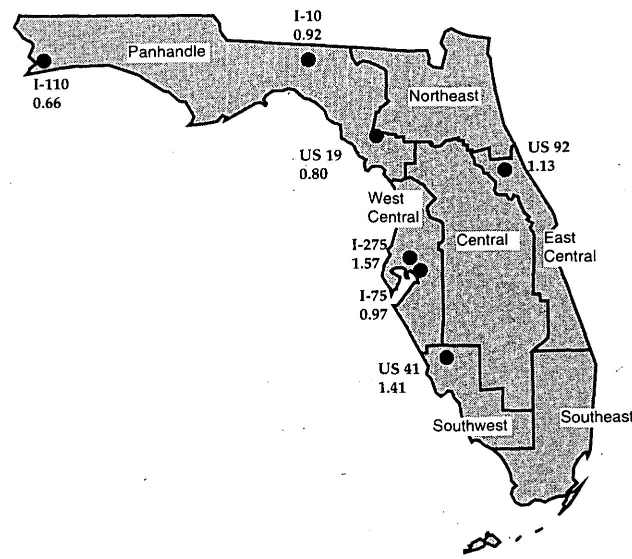

FIGURE 1 Florida stations, average load factors.

DEVELOP PRELIMINARY VEHICLE CLASSIFICATION AND WIM STATISTICS

As part of developing preliminary vehicle classification the vehicle classification data collected by WIM sites were analyzed for average daily volumes, coefficient of variance (CV), and standard deviation over the year. Individual Classes 4 through 13 of the TMG and the combined classes 1-3, 4-7, 8-10, 11-13, and 4-13 were analyzed.

The first three columns of Table 2 display this information for combined Sites 01, 09, 17, 22, and 25 for 1991. There are less than 365 days because the five major holidays were taken out so as to not bias the average daily characteristic. Further, equipment failures and other incidents that resulted in bad days were taken out. However, to be included, a station had to have data for 2 days for each weekday or 14 days minimum per month and a minimum of 2 months per quarter over the four quarters of the year. The full report contains further details on the editing. As seen in the table, the Class 9 or 5-axle tractor and single trailer was 63.9 percent of all trucks with a CV of 41.6 percent in the daily volume.

TABLE 1 Damage Factor Mean, Standard Deviation, and Coefficient of Variation by WIM Station

Station	Mean	Std. Dev.	Coef. Var.
9901	0.92209	0.08821	0.09566
9908	1.75369	1.03356	0.58937
9909	0.80457	0.10059	0.12502
9917	1.40501	0.26807	0.19080
9918	1.27461	0.28976	0.22733
9922	1.56912	0.23702	0.15105
9923	1.25626	0.24289	0.19334
9924	0.65787	0.10111	0.15370
9926	0.97530	0.12286	0.12598
9927	1.41328	0.14927	0.10562
9929	0.64974	0.23544	0.36236
9930	0.95220	0.29060	0.30519

The differences in the CV of the ESAL factor per individual truck and the CV of the average daily ESAL factor per truck class were calculated over various periods as follows. First, Florida calculated the ESAL factor per truck and the CV for each of Classes 4 through 13 of the TMG and the following combined classes: single unit, single trailers, and multitrailers. (Because of the bimodal distribution of weights around empty and loaded vehicles, the CV is expected to be large.) This was true; for example, for Class 9 trucks the mean ESAL factor for individual trucks for a day was 1.159 with a CV of 110.9 percent (see Table 2, Column 6).

Second, Florida calculated the average daily ESAL factor for each truck Class 4 through 13 of the TMG and the following combined classes: single unit, single trailer, and multitrailer. The CV of the average daily ESAL factors was calculated over the days of the year. Third, Florida compared the CV of the ESAL factor from the individual trucks within a class with the CV of the average daily ESAL factor of that class over days of the year. (The average daily ESAL factor no longer has a bimodal distribution and is expected to have a low CV.) This was true; for example, for Class 9 trucks the average daily ESAL factor compared over 360 days of the year had a CV of only 17.5 percent. Further, truck combinations with single trailers represented 73 percent of total trucks and had a CV of only 16.1 percent. Because sampling is based on the time of day, the CV of 17.5 and 16.1 percent is important (see Table 2, Column 7).

INVESTIGATE SHORT-COUNT PROGRAM

Investigation of the short-count program analyzed the vehicle classification and weight data to determine an appropriate and effective short-count duration. The first step was to determine the optimum duration and frequency of short counts to provide vehicle classification counts using six durations (1, 2, 3, and 7 days, and 2 and 3 weekdays plus a 2-day weekend) and five-count frequencies (once every 3 years and 2 years, and once, twice, and four times per year) in all possible combinations. The second step was to repeat the first step to develop the average daily damage

(ESAL) factors. The analysis was performed by randomly sampling the year's data and drawing up to 30 sample periods for each period length and frequency per year. The 2-day, 2- or 3-weekday and 2-weekend days, and 7-day periods at various frequencies during the year are of special interest. The mean and CV were calculated for each period. The CV was plotted against the cost in a figure similar to that of the TMG (*1*, p. 3-3-3).

Florida based the average annual damage factor on the mean of all days. Florida found that for both truck volumes and weights, the CV decreases as sample duration and frequency increases. There are three conclusions relevant just to truck weights. First, for highways with more than 200 trucks per day in the critical lane, to obtain truck damage factors with a 95 percent probability of being accurate to within 10 percent of the true mean, 7-day surveys twice a year, approximately 6 months apart, are necessary. Second, for highways with less than 200 loads (or trucks) per day in the critical lane, to obtain truck damage factors with a 95 percent probability of being accurate to within 10 percent of the true mean, 7-day surveys four times a year, approximately 3 months apart, are necessary. If a state can accept an 85 percent probability of being within 10 percent, 7-day surveys twice a year at 6-month intervals will suffice. Third, for highways with less than 100 loads (or trucks) a day in the critical lane, FDOT minimum designs exceed the expected loadings. See Figure 3 for partial results.

A conclusion relevant to truck volumes only is that truck volumes are more variable than truck damage factors. The only sampling plan that allows a 95 percent probability of estimating truck volumes within 10 percent of the annual average is 7-day surveys four times a year at 3-month intervals. See Figure 4 for partial results.

DETERMINE ACCURACY IMPROVEMENT

The purpose of this next task was to determine whether ESAL accuracy can be improved by applying monthly or day-of-week adjustment factors to collected data. This task was accomplished in three steps: (a) estimate annual average ESAL factors directly from short counts (i.e., use the results of Task 4); (b) determine accuracy improvement from using monthly and day-of-week factors for ESALs; and (c) compare the results between the unfactored and factored data.

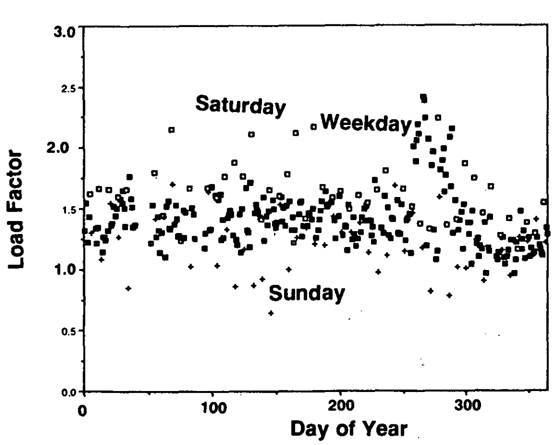

FIGURE 2 Daily load factors over 1991: Site 17, US-41.

Florida found some differences between factored and unfactored data, but the differences are not statistically significant. Since applying adjustment factors requires significant additional time and work and has not been shown to provide significant improvement in accuracy, Florida had decided that no adjustment factors (monthly or day-of-week) would be applied to the weight data. [The opposite was true in Washington, as discussed by Hallensbeck and O'Brien (*4*).]

Generally Florida found a lack of seasonality or other monthly patterns to the ESAL (weight) data. This diminishes the argument for continuous WIM stations. However, Florida's recommended data collection over 7 days covers the variability over the days of a week, and data collection two to four times a year covers the large general variability and some of the seasonal variability.

ANALYZE AVAILABLE WIM COUNT LOCATIONS

Analyzing WIM count locations develops a rationale and a sampling framework to predict ESALs on any individual section for a PMS. State highway agencies do not find it cost-effective to conduct WIM measurements on all highway sections, making it desirable to use average values from a substratum of the highway system. The procedures for determining sample size for truck weight (ESAL per truck) are discussed in the TMG; however, the data used were limited and collected before the 1982 legislation that authorized twin trailer trucks nationally. This research was to define the number of sample sites needed, especially for a PMS.

The task involves analyzing WIM data, calculating the CV of ESALs per truck per day for the Class 9 or single trailer combination trucks and the optimum sample size. Heavy volumes and routes having a high proportion of trucks in one season should be emphasized in allocating samples. The premise was that CWIM stations will provide monthly and day of week factors. The factors can be used to factor the sample site data to annual average day and also can be used with special data collection sites for project development or special analysis.

The data comprised the mean, standard deviation, and CV for damage factors at 13 stations. The data for all except Station 9925 are contained in Table 1. The mean damage factors for these sites ranged from a low of 0.64974 for Site 9929 to a high of 1.56912 for Site 9922. The CV for the factors ranged from a low of 9.6 percent for Site 9901 to a high of 59 percent for Site 9908.

Cluster Analysis

Clustering in its purest scientific form was presented in the TMG and a recent paper by Arizona DOT (*6*). A dendrogram or scatter plot of data was inspected and suggested three major clusters. The first was only one station, Station 9908, that stands apart from the others with the highest CV in damage factor values (approximately 59 percent). The second cluster contains Stations 9917, 9918, 9922, 9923, 9925, and 9927. The third cluster contains Stations 9901, 9909, 9924, 9926, 9929, and 9930.

The grouping scheme that emerged from the clustering analysis brought together under the same umbrella urban Interstate, rural non-Interstate and rural Interstate roadways. This scheme deviates significantly from what conventional wisdom on roadway classi-

TABLE 2 Daily Volumes and Load Factors for Sites 01, 09, 17, 22, and 25 Combined

Class of Trucks	Description of Trucks	Days *	Total No. of Trucks	Classification	Truck Weight	Cumulative
				Ave. Daily Vol.	Daily Load	Ave. Daily L.F.
				No. C.V. S.D.	No. C.V. S.D.	No. C.V. S.D.
04	Buses	360	21,672 (1.3%)	60 37.2 22.4	0.354 75.3 0.27	0.355 15.0 0.05
05	2-axle single unit	360	277,524 (16.9%)	771 43.8 337.4	0.392 191.60.75	0.372 17.6 0.07
06	3-axle single unit	360	82,110 (5.0%)	228 47.4 108.1	1.002 158.3 1.59	0.931 33.4 0.31
07	4-axle single unit	306	14,458 (0.9%)	47 67.1 31.7	2.914 55.0 1.60	2.720 25.1 0.68
08	<4-axle single trailer	360	151,758 (9.2%)	422 50.6 213.5	1.284 166.2 2.13	1.158 30.9 0.36
09	5-axle single trailer	360	1,051,737 (63.9%)	2,992 41.6 1,214	1.159 110.9 1.29	1.214 17.5 0.21
10	6+-axle single trailer	352	5,367 (0.3%)	15 58.2 8.9	0.942 108.0 0.02	0.908 44.0 0.40
11	5-axle multi-trailer	356	33,862 (2.1%)	95 40.8 38.9	1.587 82.9 1.32	1.641 17.2 0.28
12	6-axle multi-trailer	354	6,850 (0.4%)	19 54.3 10.5	0.646 107.7 0.70	0.672 39.2 0.26
13	7+ multi-trailer	272	749 (0.0%)	3 62.0 1.7	1.933 79.5 1.54	1.931 62.8 1.21
04-07	Single Units	360	395,764 (24.0%)	1,099 43.6 479.7	0.609 185.7 1.13	1.031 96.7 1.00
08-10	Single trailers	360	1,208,862 (73.4%)	3,358 41.9 1,406	1.174 120.9 1.42	1.213 16.1 0.20
11-13	Multi-trailers	356	41,461 (2.5%)	117 41.7 48.8	1.438 89.6 1.29	1.494 18.5 0.28
04-13	All classes	360	1,646,087 (100%)	4,573 40.8 1,864	1,045 131.6 1:38	1.148 71.5 0.82

*Equipment failures result in missing days. The full report discusses editing procedures.

fication dictates. As implied above, the analyses are a necessary, but not sufficient, determinant of WIM station grouping. Hence Florida concluded that the final grouping schedule must depend on other than purely scientific criteria including, but not limited to, "expert" judgment, particularly knowledge of the various stations.

Recommended Grouping Scheme

Next, Florida investigated a pseudoscientific clustering procedure based mainly on geography and the knowledge of the damage factor distribution within the state. These two factors played a pivotal role in Florida's efforts to group the WIM stations once the number necessary for each cluster had been determined.

Geographical Differences

Different parts of a state have different types of agriculture, industry, mining, or other activities and have related differences in

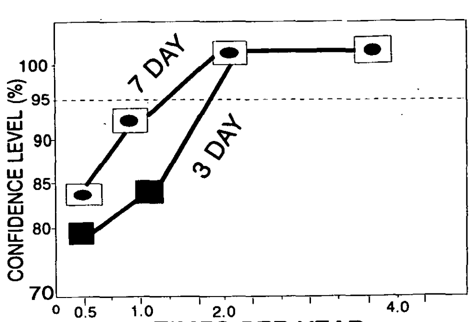

FIGURE 3 Truck ESALs, Station 01.

truck weights. In the case of Florida, there are differences in population characteristics that may be reflected in geographic differences in truck weights. For example, the northern end of the state tends to be less populated, and it also was on the way to the more populous southern end of the state. Thus North Florida may have more long-haul trucking than local trucking, compared with South Florida. The key question in this regard is whether the region involved is sufficiently large and uniform to make truck weight measurements at any one part of an area representative of the entire area.

For tourism purposes, the state of Florida was divided into seven main regions. A cursory inspection of damage factors registered at existing weighing sites revealed the presence of homogeneous configurations of damage factor values, which can be grouped by regions approximating those established for tourism purposes. Florida's efforts resulted in seven clusters of seven geographic regions and an eighth cluster composed of the four major Interstate highway systems. The regions and the Interstate highway systems are as follows. Region 1 (Northwest Panhandle) includes Station 9924 on I-110, SHRP 4100 on SR-85, SHRP 4108 on US-98, SHRP 4096 on SR-20, and 9908 on US-319.

Region 2 (northeast) includes SHRP 4105 on SR-9A and SHRP 3997 on US-17.

Region 3 (east) includes SHRP 4138/4000 on US-92, SHRP 4059/4109 on US-1, SHRP 1370 on SR-407, SHRP 4102/4101 on SR-528, SHRP 4107 on SR-70, and, SHRP 1030 on US-1.

Region 4 (central) includes only Station 9918 on US-27.

Region 5 (west) includes SHRP 3996 on US-19 and Station 9927 on US-92.

Region 6 (southwest) includes Station 9917 on US-41 and SHRP 4099 on SR-884.

Region 7 (southeast) includes Station 9930 on US-1, SHRP 1060 on SR-878, and SHRP 4103 on SR-836.

This grouping includes some stations that are greatly different. For example, WIM 9908 in Region 1 at 1.7537 and SHRP 4059/4109 at 0.6997 in Region 3 have damage factors that are greatly different from those of the other stations in their group. As time permits, these stations should be investigated with respect to the reason for the large difference.

Interstate highways are known to differ from other highway types in both the amount and the kind of traffic they carry and to have relatively uniform characteristics along their lengths. Therefore, each of the four major Interstate highways in the state is placed into a separate category for the purpose of this study. The first is I-4, a highway that runs east to west connecting I-95 at Daytona to I-75 at Tampa. No WIM station is located on this highway. The closest WIM station is on SR-546 (Memorial Boulevard in Lakeland). This station registered a mean damage factor of 1.4133 with a CV of 10.6 percent. This damage factor is associated with I-4 for the purpose of the analysis in this report. The second Interstate highway is I-10. Three weighing stations, with mean damage factor values ranging from 0.8805 to 0.9221, are located on this highway. The third highway is I-75, which has four weighing stations having mean damage factors ranging from 0.9753 to 1.5691. The last highway is I-95, which has three weighing stations having mean damage factors of 0.9424, 1.0069, and 1.2563, respectively.

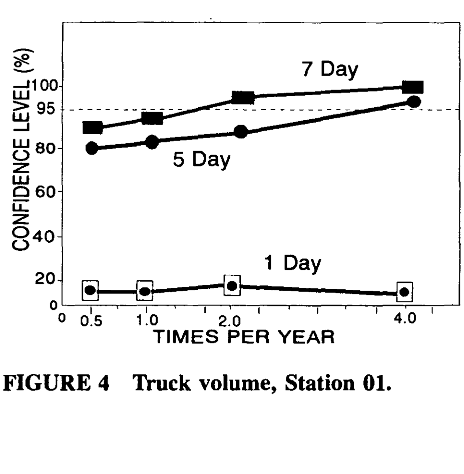

FIGURE 4 Truck volume, Station 01.

Separating principal arterial and minor arterial highways by region is both logical and intuitively appealing to Florida, where experience reveals that principal arterial highways mainly handle the intercity movement of goods, whereas the minor arterials mostly handle farm-to-market traffic. For example, in the northern part of the state, the minor arterial highways are used mostly by trucks transporting timber from the forests to wood processing mills, whereas the principal arterial highways handle mostly traffic that carries non-raw material from one city to another.

The following 16 groups include the regional, Interstate, and functional classification categories and provide a reasonable framework for possible regional damage factor differences for the study:

1. Panhandle principal arterial,
2. Panhandle minor arterial,
3. Northeast principal arterial,
4. Northeast minor arterial,
5. East central principal arterial,
6. East central minor arterial,
7. Central principal arterial,
8. Central minor arterial,
9. West central principal arterial,
10. West central minor arterial,
11. Southeast principal arterial,
12. Southeast minor arterial,
13. Interstate 4,
14. Interstate 10,
15. Interstate 75, and
16. Interstate 95.

Grouping Analysis Using TMG-Based Method

Essentially the TMG bases the number of permanent annual traffic recorders (ATRs) on the number of groups of highways and the CV of the data within each group. The TMG estimates that, provided the data in question exhibit a CV of from 10 to 15 percent, five to eight ATRs were required for each group. As shown below, the higher the CV, the larger the number of required number of ATRs. The following equation, which can be used to estimate the number of permanent counters, is provided in TMG (p. 3-2-7).

$$D = Ts \times \mathrm{CV}/\sqrt{n} \tag{1}$$

where

D = precision interval expressed as a decimal,
Ts = value of Student's T-distribution with $1 - d/2$ level of confidence and $n - 1$ degrees of freedom, and
CV = coefficient of variation.

Solving for the number of degrees of freedom, the equation becomes

$$n = (Ts \times CV/D) \quad (2)$$

This equation is indeterminate because the value n occurs on both sides of the equation; the value of Student's T is dependent on n. To use this equation additional data were required. Since Task 3 showed that two weighing surveys of 1-week duration taken approximately 6 months apart should provide sufficient accuracy and precision, the data from the seven WIM stations not used in the previous analysis (because of insufficient data coverage for the entire year) were processed to provide damage factors.

Truck weight data collected in 1991 for the Strategic Highway Research Program General Pavement Study sections in Florida were examined for use in this task. Twenty locations had 1 week of weight data collected during December 1991. The TMG model was applied to these data. It showed that 157 WIM stations were required to attain the 95-10 precision level to be distributed as given in Table 3.

Although the number of WIM stations (157) is statistically and mathematically sound, that number is expensive. It was necessary to seek a strategy that is capable of generating fewer, yet adequate, WIM stations for Florida.

Alternative Methods Based on Measures of Central Tendency

TMG page 3-2-8 specifies that samples be selected in compliance with a precision level of 10 percent and a 95 percent confidence (95-10) "for each individual seasonal group excluding recreational groups where no precision requirement is specified." On the basis of this compliance level, the following model, which incorporates this precision level and has as its core an important measure of central tendency, namely standard deviation, was developed:

$$n = \left[\frac{(Z)(\sigma)}{\delta}\right]^2 \quad (3)$$

where

n = optimum sample size,
Z = Z-score associated with desired confidence level,
σ = population standard deviation, and
δ = desired precision or allowable error.

The following values were given:

Population mean = 1.0728,
Z = 1.96,
σ = 0.28004, and
δ = 10 percent of population mean, or 0.1 × 1.07281 = 0.1073

Substituting in Equation 3 presented above:

$$n = \{(1.96 \times 0.28004)/0.1073\}^2 = 26.127, \text{ or } 26 \text{ sites} \quad (4)$$

Upon arriving at 26 as the optimum sampling size, it was necessary to determine the number of sites required for each of the seven regions by roadway classification (principal versus minor arterial) and the four Interstate highways. This problem was resolved by testing two stratified sample-based methods.

One method uses truck daily vehicle miles of travel (TDVMT) comprising the following three steps. (a) Existing sites were grouped by region. (b) Then the TDVMT for each group were computed. (c) Finally, the number of sites necessary for each category was calculated. The proportion of the optimum number of sites assigned to any given region was equivalent to that region's total TDVMT as a proportion of the total TDVMT for all sites combined. This process ensured that roadways or segments thereof experiencing high truck activity were adequately represented in the sample. After rounding to the closest whole number where fractions of a site were computed, the total number of sites required was found to be 32 subdivided as follows: Interstate highways, 15; principal arterial, 10; and minor arterial, 7. To understand how these sites were subdivided by region it is necessary to see the full report.

The other is a damage factor-based method that also has three steps: (a) existing sites were grouped by functional class of high-

TABLE 3 WIM Site Distribution Based on TMG Model

Cluster or Group	C.V.	Ts	n
I-4	0.000	*	5
I-10	0.070	2.920	4
I-75	0.098	2.353	5
I-95	0.133	1.943	7
Panhandle Principal Arterial	0.222	1.761	15
Panhandle Minor Arterial	0.178	1.833	11
North Florida Principal Arterial	0.167	1.860	10
North Florida Minor Arterial	0.125	2.015	6
East Central Florida Principal Arterial	0.282	1.717	23
East Central Florida Minor Arterial	0.125	2.015	6
Central Florida Principal Arterial	0.167	1.860	10
Central Florida Minor Arterial	0.000	*	6
West Central Florida Principal Arterial	0.156	1.895	9
West Central Florida Minor Arterial	0.000	*	6
Southeast Florida Principal Arterial	0.182	1.812	11
Southeast Florida Minor Arterial	0.000	*	6
Southwest Florida Principal Arterial	0.191	1.796	12
Southwest Florida Minor Arterial	0.091	2.353	5
TOTAL			157

* indicates that no Ts value was available and that the n is of an adjacent region.

way; (b) the damage factors for each group were computed; and (c) the number of sites necessary for each category was calculated as a proportion of the extent to which its mean damage factor deviates on the average from the population mean. It also came up with an optimum of 26 sites. In evaluating 26 stations, no WIM station was required for minor arterial roads in the north or east region, or for principal arterial roads in the north, west, or southeast region. This made no sense, according to FDOT. Thus, where this was the case, the region was automatically awarded one station. For this reason the total number of sites required is again 32 instead of 26.

Whereas the number 32 may be statistically logical, it is not intuitively appealing. Certainly not even the most innovative sampling design will guarantee the fair representation of the entire state by only 32 sites. More directly, Florida believes that 32 WIM stations are far too few for a state as large as Florida. Thus, Florida deemed it necessary to seek more reasonable strategies. Two closely related strategies were considered.

Separate Groups for Interstate, Principal Arterial, and Minor Arterial Highways

The relevant highways were divided into three distinct groups, namely, minor arterial (MA), principal arterial (PA), and major Interstate (MIS). Then, Equation 3 was modified such that σ equals the strata standard deviation instead of the overall population standard deviation.

Finally, Equation 3 was applied to the damage factor data contained in each of the three groups. As an example, Florida determined the adequate sample size for all minor arterial highways. The following data are given:

$Z = 1.96$

$\sigma = 0.27250$

$$\delta = 10 \text{ percent of population mean} = 0.1 \times 1.07281 \quad (5)$$

Therefore,

$$n = \{(1.96 \times 0.2750)/0.1 \times 1.07281)\}**2 = 24.99 \quad (6)$$

On the basis of the formula, the optimum number of WIM stations required for MA highways is 25. Likewise, the number of stations required for PA and MIS highways was calculated to be 33 and 20, respectively. The total number of sites required therefore is 78 (i.e., 25 + 33 + 20).

The number of sites required for each subgroup or stratum was computed with the aid of the following equation:

$$AD = \frac{1}{N} \sum|\overline{X}_i - \overline{X}_p| \quad (7)$$

where

AD = average deviation,
X_p = population mean, and
X_i = mean of strata 1, 2, . . ., n.

Florida found that some strata contain two sites or less. In this case, especially where the stratum contains only a single site or two sites with identical values, average deviation results are meaningless. This problem was dealt with by employing the average deviation values for adjacent strata. This was the case, for instance, with MA roads in the north and east regions and PA roads in the west. The adjustments resulted in 18 more sites being added to the 78. Thus, on the basis of this strategy, the recommended sample size is 96. Table 4 shows the distribution of the 96 sites. Figure 1 shows how Florida is divided into seven regions.

Reflecting on Alternative Sampling Methods

The first sampling strategy was based on the TMG and generated 6 to 8 WIM sites in each of the 18 strata, resulting in 157 sites. Florida rejected 157 sites because it was too costly for the available resources. The second sampling strategy combined the 18 strata into one statewide stratum and found that only 32 sites are necessary. Although 32 sites could be a fallback position, Florida believes that 32 sites do not adequately cover the state, that is, fulfill the need for data by region and functional class of highway. The last sampling method was based on the three highway classes (MIS, PA, and MA) and determined that 96 WIM sites would provide the 95-10 precision level for the three highway classes and could be allocated to the 18 strata, resulting in more than one site per strata.

An examination of the data reveals little statistically significant difference between the functional groups, but the damage factors differ significantly by region. Thus, an alternative strategy was to select samples on the basis of the regional distribution of damage factors. The steps involved in the sample selection process are the same as those discussed above, except that intraregional differences (e.g., minor versus principal arterial roads) are ignored. When adjustments were made for regions with only one observation, the adjusted sample size was found to be 59. Another strategy resulted in 77 sites.

Reflecting on Central Tendency-Based Strategy

A fundamental objective of the study reported here was to devise strategies capable of improving cost-effectiveness and precision in WIM programs. Cost-effectiveness is essentially the principal rationale for suggesting that samples of highway segments instead of entire highway segments be surveyed. Ideally, optimal precision can be attained by recording damage factors and related data for entire highway segments within the state. Such a stratagem is, however, unrealistic given its enormous cost vis-à-vis the fact that resources (financial and otherwise) are finite. Further, Florida contends that 157 sites are too many given the resources that are available to the state.

However, if cost-effectiveness constituted the only concern, Florida would have settled for the lowest number of samples (32) which was arrived at earlier. Certainly cost-effectiveness was not the only concern. Florida contends that 32 sites cannot adequately cover a state as large as Florida, which has 67 counties. To ensure that precision was not sacrificed for the sake of cost-effectiveness, precision was built as a principal component into the sampling model presented above. In so doing, a delicate balance was struck between cost-effectiveness and precision, which were important objectives of the task.

The TMG does not specifically endorse or recommend any particular method for determining the number and locations of ATRs. This is because decisions generally are based on local conditions. Hence, a method that may be deemed suitable for Florida may not necessarily be suitable for another state. The main reason for walking through the various procedures and methods that were explored before arriving at what Florida considers to be an appropriate method for determining the number and location of WIM sites in Florida is to provide the reader with a wide array of methods to choose from should the need arise. As implied earlier, some of the methods that may be considered inappropriate for Florida may be useful elsewhere.

In arriving at the decision to utilize the damage factor by functional class sampling strategy and hence 96 sites, a number of factors—some of which were other than mathematical and statistical—were taken into account. Florida noted for instance that, based on local data, the TMG model failed to provide the 95-10 condition stipulated in the TMG. Florida also noted that a cluster analysis in its purest mathematical form is of little or no use in grouping the state's CWIM and portable WIM sites and associated damage factor values. Florida further observed that the utility of other more rigorous methods tailored along the lines of the TMG model was significantly diminished by their inability to generate a sizable number of locations. These observed phenomena are plausibly attributable to the rather small sample size dealt with in the study. It is possible that where a larger sample size is available or for other possible reasons, some of the strategies considered and rejected in the case of Florida may find utility elsewhere.

CONCLUSION

The 96 WIM sites appear to be the best choice in being affordable and meeting the stipulated precision level. On the basis of known truck travel behavior, truck weights, and the resulting pavement damage factors, Florida believes 96 sites can be reasonably distributed throughout the state and are adequate to generate sample damage factors for the 18 groupings by region and functional class of highway in accordance with the 95-10 precision level recommended by the TMG. Florida does not contemplate adding more than a few more continuous WIM stations to the 13 continuous WIM stations now available. Therefore, it is likely that most of the 96 stations would be operated 1, 2, or 4 weeks per year depending on the importance and stability of the truck flows at the station. In one aspect this would be similar to the 90 WIM sites recommended by the TMG over a 3-year period. In another aspect

TABLE 4 Projected Number of WIM/SHRP Sites by Region and Highway Class

Region	Class.	Dam. Fact.	AD	AD/ADtot	Stations		
					M.A.	P.A.	HWYS
Panhandle	M.A.	0.6512					
		0.6657	0.4143	0.1285	7		
	P.A	0.6579					
		0.6809					
		1.7537					
		0.6579	0.1352	0.0419		5	
North	M.A.	0.9935	0.0793	0.0246	4		
	P.A.	0.9560					
		0.9642	0.1127	0.0350		4	
East	M.A.	1.1203					
		1.0652	0.0199	0.0062	4		
	P.A.	1.1349					
		0.6997					
		1.3581					
		1.1455	0.0118	0.0036		5	
Central	M.A.	1.2986	0.2258	0.0700	4		
	P.A.	1.2746	0.2018	0.0626		7	
West	M.A.	1.4133	0.3405	0.1056	6		
	P.A.	0.9300	0.1429	0.0443		5	
S.W.	M.A.	1.2986	0.2258	0.0700	4		
	P.A.	1.4050	0.3322	0.1031		11	
S.E.	M.A.	0.8961	0.1767	0.0548	3		
	P.A.	0.9522					
		1.0986	0.0474	0.0001		2	
I-4		1.4133	0.3405	0.1056			9
I-10		0.8845					
		0.8540					
		0.9221	0.1860	0.0577			5
I-95		0.9424					
		1.0069					
		1.2563	0.0043	0.0013			5
I-75		1.3139					
		0.9753					
		1.3391					
		1.5691	0.2265	0.0703			6
Mean:		1.0728			32	39	25
Std. Dev.:		0.2800					
ADtot:		3.2235					
				Opt. Size	78	TOTAL:	96

it is different because of the length of data collection, i.e., 1 to 4 weeks instead of 2 days per year.

RECOMMENDATIONS

In future work, assuming that stratification by region and functional class is able to group highways with similar damage factors and reduce the number of samples required, then the overall population mean damage factor of 1.0728 should not be used in Equation 3, but the mean damage factor for each stratum will be used in determining the sample size of the stratum. Further, the size of the TDVMT reflects the importance of a highway and should be used to allocate the 96 sites in a manner similar to that done earlier for the 32 sites.

Because of the large variability in damage factors among sites and those adjacent to each other, it is recommended that project WIM data be collected for the design of a major improvement.

Ultimately, the decision on how to group WIM stations in any state or locale falls under the purview of professionals who should use their experience and judgment. In this case, geographic region is the underlying common attribute by which the sites are grouped. Although Florida finds a purely scientific clustering procedure unsuitable, it is possible that another state may find it otherwise.

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