Proposed Method for Calibrating Weigh-in-Motion Systems and for Monitoring That Calibration Over Time

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Calibration of weigh-in-motion (WIM) systems is a difficult process that has many limitations and problems. The problems encountered with using test trucks for calibration are documented. WIM systems often produce differing weights for individual test trucks. Furthermore, calibration achieved in this traditional manner addresses how the system is performing only on those days that tests are conducted. Actual system performance for all other days is unknown. An alternative method for calibrating a system and a method for monitoring the performance of the system on an ongoing basis are proposed. This ongoing monitoring uses an aggregation of specific types of weight data for five-axle tractor-semitrailers that are collected by the system. The results obtained from applying this procedure can also be adapted for use in editing weight data.

The Minnesota Department of Transportation (MnDOT) has been operating permanent weigh-in-motion (WIM) systems since 1981. Currently there are installations at 16 locations. The methods used to calibrate the systems and monitor that calibration have evolved over this period as experience was gained.

TRADITIONAL METHODS OF CALIBRATION

Initially, the department relied solely on one test truck for the calibration. It was a loaded two- or three-axle single-unit department dump truck. Repeated runs over the scales were made at highway speeds, and the WIM scales were calibrated to reflect the static gross weight of the truck. It was then assumed that the weights that the system collected were valid until the next time a test truck was used at the site. Because of a shortage of personnel, a great deal of time would often elapse between tests.

Various aggregations of volume and weight data collected by the system were examined on a weekly basis. Each site usually exhibited fairly predictable patterns. Some of the early weight patterns noted were the distribution of gross weight and front-axle weight of five-axle tractor-semitrailers. It was also observed that the calibration for an individual lane occasionally would drift off. This raised concerns because of the inability to use test trucks every time the occasion appeared to require it.

When test trucks were used, sometimes both two- and three-axle single-unit trucks were available. These test results showed that a system could and frequently did weigh the trucks differently. For example, the two-axle truck might register on the average 2 percent high, whereas the three-axle truck would be 3 percent low. The system would then be calibrated to an average of these readings, but there was no way to determine how well it was actually doing with trucks in the traffic stream.

In 1989 extensive tests of WIM systems were conducted in an effort to determine the simplest, most reliable method for calibrating a WIM system. A portable WIM system was set up at the site of MnDOT's permanent WIM system on I-94 east of St. Paul. Two- and three-axle test trucks were used as well as monitoring trucks in the traffic stream. The traffic stream trucks were weighed at the St. Croix weigh station, which is 3 mi upstream from the permanent WIM site. Identifying characteristics of the trucks were noted, and they were matched up when they passed the WIM site. The data reported in Table 1 represent results based on a calibration that correctly weighs five-axle tractor-semitrailer(s) in the traffic stream. These results clearly focused on the pitfalls of relying solely on test trucks for calibration. It appears that the dynamics of any specific truck are unique and can be very different from those of other trucks with the same axle configuration. Recorded weights of the test trucks and the trucks of the same axle configuration in the traffic stream often corresponded poorly. Also, dynamics constantly change, so varying results are obtained on the same route, even when the scales are close together. These circumstances make it difficult to rely on a test truck to calibrate a system. Test trucks may not be representative of the dynamic weights of the most critical trucks in the traffic stream.

TABLE 1 Results of Calibration That Correctly Weighs Five-Axle Tractor-Semitrailers in Traffic Stream

	Permanent WIM		Portable WIM	
Vehicle Type	# of Vehicles	% Deviation	# of Vehicles	% Deviation
Traffic Stream				
2 axle 6 tire	27	+ 1.7%	31	- 7.9%
3 axle single unit	17	- 3.7	19	+ 1.2
5 axle semi	208	0.0	243	0.0
Twin trailers	19	+ 5.8	19	- 7.3
Test Trucks				
2 axle 6 tire	19	+13.8	21	-10.3
3 axle single unit	9	-11.5	11	- 5.2

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OTHER EFFORTS TO ADDRESS PROBLEM

The lack of a standardized procedure for acceptance of the various types of WIM systems and performance standards led ASTM to examine this issue. ASTM conducted a study of WIM, and in 1990 it published the results (ASTM E1318-90). Its procedure for WIM acceptance involves using test trucks and randomly selecting and statically weighing trucks from the traffic stream. ASTM specifies how many trucks of each type to weigh and then calibrates the system to the average of those weights. This is unquestionably the best method. Unfortunately, however, it is impractical in most cases. One needs either a static weigh station in the immediate vicinity or portable static scales. The former situation is a rare occurrence, and the latter is time consuming, labor-intensive, and dangerous, assuming that an agency has access to portable static scales.

PROPOSED ALTERNATIVE

MnDOT's prime concern when dealing with the issue of WIM system calibration is to ensure that the weight data collected are valid. The principal thrust of this paper is to develop a system that can be used to identify those instances in which the weights are systematically off by a significant amount, defined as 4 percent at this time. There are two reasons for using 4 percent. First, the fourth-power relationship between weight and equivalent single axle loads (ESALs) means that a 4 percent difference in weight translates into a significant difference of about 16 percent when dealing with ESALs. The second reason for choosing 4 percent is that currently it is at best difficult and perhaps even impossible to achieve and especially to maintain a calibration that has a true systematic error of 3 percent or less.

After studying the calibration issue for some time, MnDOT developed a comprehensive procedure that works well, one that is being used as a manual procedure. The techniques being used concentrate on five-axle tractor-semitrailer(s), the vehicle type that has the greatest impact in terms of ESALs on Minnesota's highways. They typically contribute 70 to 90 percent of the ESALs on many of the state's trunk highways. The goal is to collect accurate weight data on them.

For the initial system calibration, a five-axle tractor-semitrailer loaded to 75 or 80 kips is used. The loaded five-axle tractor-semitrailer(s) in the traffic stream contribute the vast majority of the ESALs of all five-axle tractor-semitrailer(s). This test truck is equipped with a leaf spring suspension, which is the most common one in use. A minimum of 25 passes over the scales at highway speeds are specified after the final calibration adjustment. These runs confirm that the calibration with that vehicle is correct.

Next, the data collected on each individual lane at a site are monitored. The weight data for five-axle tractor-semitrailers are monitored in three areas:

1. Distribution of gross weight,
2. Front-axle weights, and
3. Flexible ESAL factors.

If there is a system malfunction that is severe enough, any one of these areas can indicate that there is a problem and that the data are invalid. All three are used because each plays a strong supportive role in making this determination.

DISTRIBUTION OF GROSS WEIGHT

The first area checked to determine the status of the calibration and the validity of the weight data is the distribution of

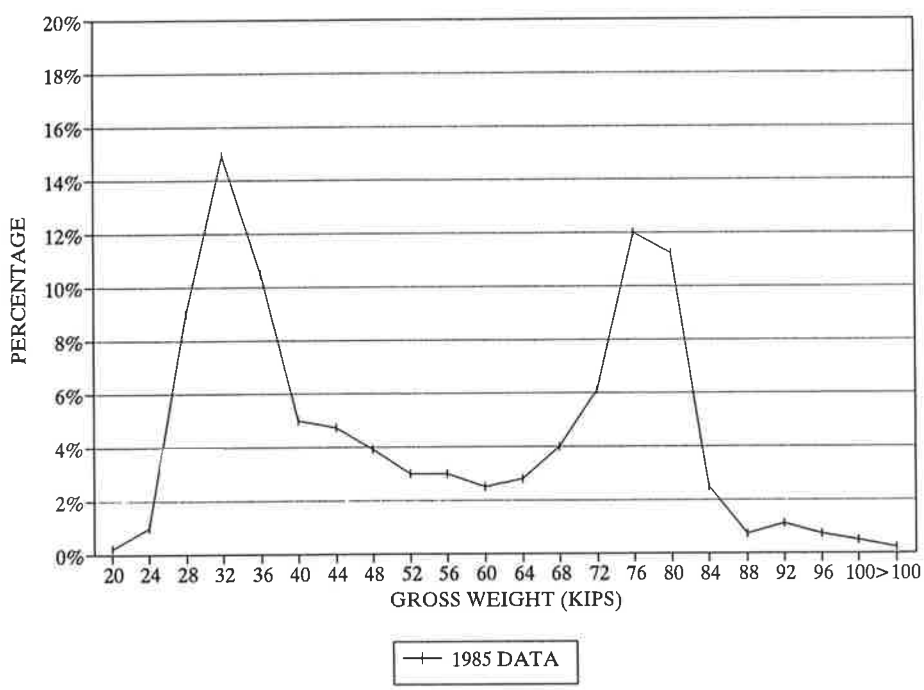

FIGURE 1 Distribution of static gross weight of five-axle tractor-semitrailers.

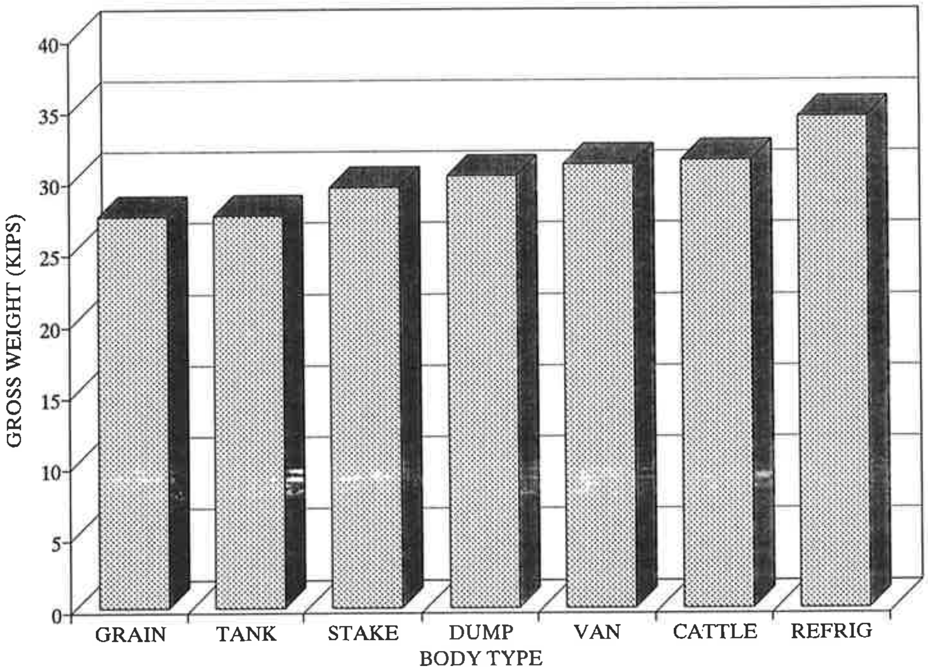

FIGURE 2 Average static weight of empty five-axle tractor-semitrailers.

the gross weight of five-axle tractor-semitrailers. It is here that the average weights of the loaded and unloaded vehicles assist in the process of separating valid and invalid weight data. This distribution should have one peak for empty vehicles at about 28 to 32 kips and another peak in the 70- to 80-kip range for loaded vehicles. This peak in the 70- to 80-kip range reflects Minnesota's gross weight limit of 80 kips. Figure 1 shows the distribution from static statewide weighing in Minnesota in 1985. These data, which represent about 3,100 vehicles, have the general pattern usually found. The gross weight figures represent the upper end of each category; for example, 32 represents those weights from 28 to 32 kips.

The type of trailers used on five-axle tractor-semitrailers varies somewhat from one area of the country to another. Figure 2 shows the static weight of empty five-axle tractor-semitrailers by body type in Minnesota. They range from a

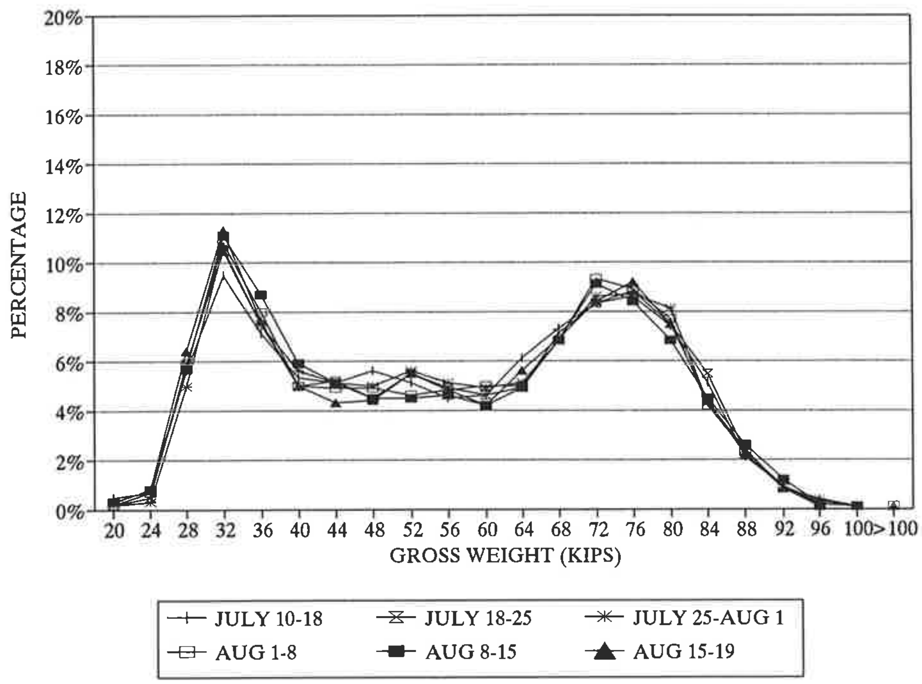

FIGURE 3 Distribution of gross weight of five-axle tractor-semitrailers on I-94: right lane, July and August.

low of 27.4 kips for trucks with grain boxes up to 34.3 kips for refrigerator trucks. The exact placement of the peak for empty trucks will depend on the type and mix of trucks that are in the traffic stream at the site. Generally, it will be close to 30 kips.

When a WIM system is functioning properly, the pattern of the distribution of the gross weight repeats from week to week. Figure 3 shows six consecutive weeks of data collected in the right lane on I-94. Each data set represents approximately 5,500 five-axle tractor-semitrailers. Note that this pattern is generally similar to that in Figure 1. They both show a distinct bimodal distribution with the peaks at approximately the same locations.

SYSTEM MALFUNCTION

Sometimes WIM systems malfunction, and incorrect weight data are recorded. Figure 4 shows an example of a valid set of weight data (October 22 through 29) compared with an invalid set (December 3 through 10). Each data set represents more than 5,000 five-axle tractor-semitrailers. Note the similar patterns between the October 22–29 data and the data in Figures 1 and 3. The data in Figure 4 are from the right lane at the I-94 site, the same location as shown in Figure 3. Note that the invalid data set in Figure 4 has the highest percentage in the lightest category; it does not have the classic bimodal distribution.

Other techniques can be used to determine the validity of the December 3–10 data in Figure 4. The first is to check the volume of five-axle tractor-semitrailers for both periods. If the volume changed significantly, the observed results could be a true reflection of the actual weights on the roadway. If the volumes did not change, the data are likely to be invalid. The volumes did not change significantly in the example used here.

Further supportive evidence that the data shown in Figure 4 are invalid is shown in Figure 5. These data are from the left lane at the same site on I-94. Figure 5 shows the same period as presented in Figure 4. The patterns of both sets of data in Figure 5 are the same. Consequently, for both sets of the data in Figure 4 to be considered valid, the patterns should be very similar. They are not. There should not be such vastly different patterns in lanes that are side by side traveling the same direction. On the basis of the analyses described, the presence of a pattern such as that shown in Figure 4 indicates the likelihood of a system malfunction and not a simple drift in calibration. It requires that a technician examine the system and correct the problem. A change in calibration will not solve the problem in this case.

CALIBRATION ERRORS

Figure 6 shows data from the WIM on I-94. Both of these data sets have the desired general pattern. The problem here is that the calibration is off by about 20 percent for the October 6–16 data set. The first peak is at about 38 kips instead of 32, and the second peak is at 90 kips instead of 74. The flexible ESAL factor for July 11 through 17 was 0.90, whereas it was 1.41 for October 6 through 16. The October 6–16 data are invalid and should not be used. The calibration should be adjusted by a factor determined from an analysis of the distribution of gross weight, front-axle weights, and flexible ESAL factors. A minimum of 7,500 five-axle tractor-semitrailers are represented in each data set here.

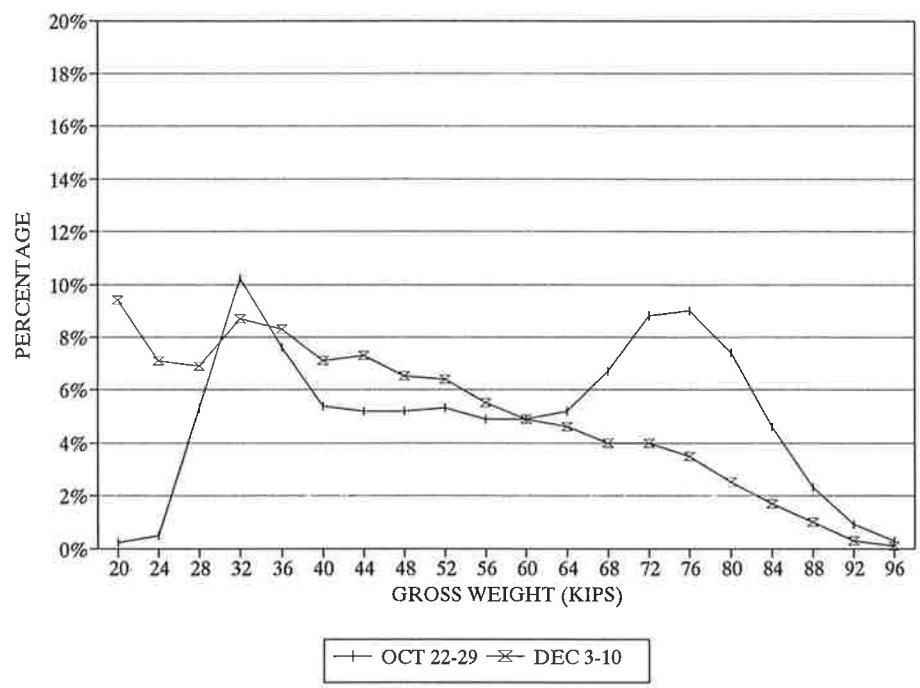

FIGURE 4 Distribution of gross weight of five-axle tractor-semitrailers on I-94: right lane, October and December.

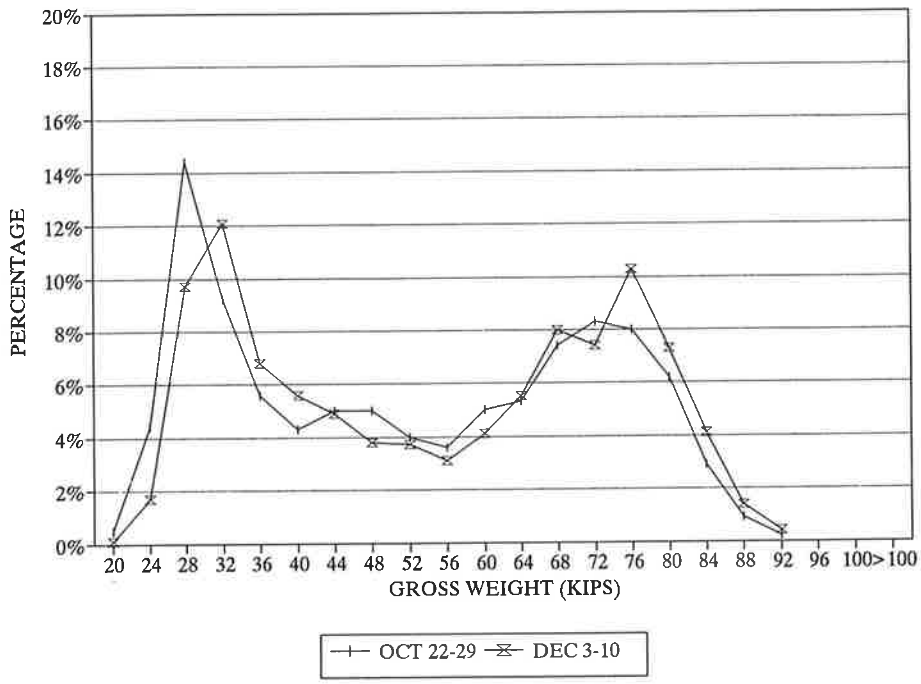

FIGURE 5 Distribution of gross weight of five-axle tractor-semitrailers on I-94: left lane, October and December.

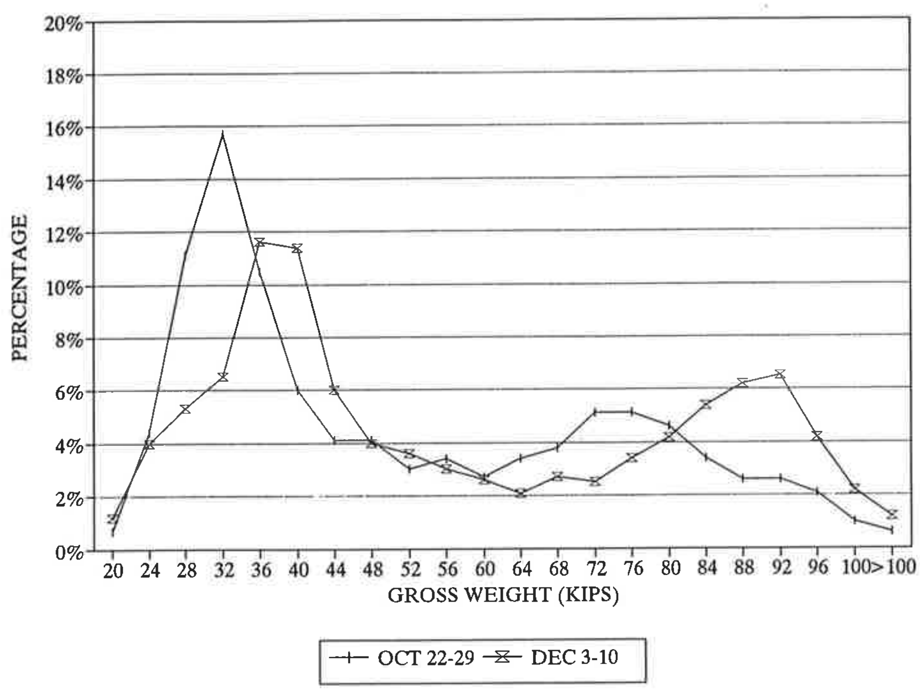

FIGURE 6 Distribution of gross weight of five-axle tractor-semitrailers on I-94: both eastbound lanes, October and December.

Also, referring to Figure 5, it appears that the calibration was off for the October 22–29 period. The peaks are slightly offset. The flexible ESAL factor for October 22 through 29 was 0.77, whereas it was 0.88 for December 3 through 10. The calibration should be adjusted by a factor determined from an analysis of the distribution of gross weight, front-axle weights, and flexible ESAL factors. Approximately 1,500 five-axle tractor-semitrailers are represented in each data set here.

FRONT-AXLE WEIGHTS

The second area that may be analyzed to determine the status of the calibration and the validity of the weight data is front-axle weights. The distribution of front-axle weights should repeat in a predictable manner at each site for a group of five-axle tractor-semitrailers. The distribution may be grouped into three categories, with the weights in kips.

Gross Weight Range	*Average Weight*
Less than 32.0	8.5
32.0–70.0	9.3
More than 70.0	10.4

These are average values that do not always apply to a specific site. However, the pattern that exists at each site should be consistent. The weights recorded for front axles vary to some degree depending on the vendor that produced the system.The important point here is not the weights that are noted but the pattern that is recorded by the system being studied. A minimum of 30 vehicles probably should be weighed in each group to be considered valid.

Figure 7 shows front-axle weights as recorded for individual weeks over an extended period. These data were also taken from the right lane on I-94. Note that each of the respective three weights were steady over an extended period. Then the weights began to show a large amount of deviation. It is interesting that the last value in January was lower than it should have been in the group of less than 32 kips and higher than it should have been in the group of more than 70 kips. The system was weighing some trucks too light and others too heavy. The weights in December indicate invalid data.

MnDOT's systems now contain an optional feature that provides an automatic system recalibration. This recalibration procedure is based on an aggregation of the observed weights of the front axles of five-axle tractor-semitrailers in the three weight ranges previously discussed. This procedure is being monitored to determine if it performs satisfactorily.

FLEXIBLE ESAL FACTORS

The third data set that may be analyzed to determine the status of the calibration and the validity of the weight data is flexible ESAL factors. Either rigid or flexible factors can be used in the evaluation. As was mentioned, these factors are sensitive to changes in the weights because of the fourth-power relationship between weight and ESALs. The approximate range for these values must be determined for each lane. These values are obtained by noting what the system produces after it has been properly calibrated.

Generally the ESAL factors for each individual day—particularly weekdays—are examined. Weekday ESALs tend to be quite stable. That is not necessarily true for weekends. Figure 8 shows weekday data from October to mid-December for the right lane on I-94. Data from this lane are shown in

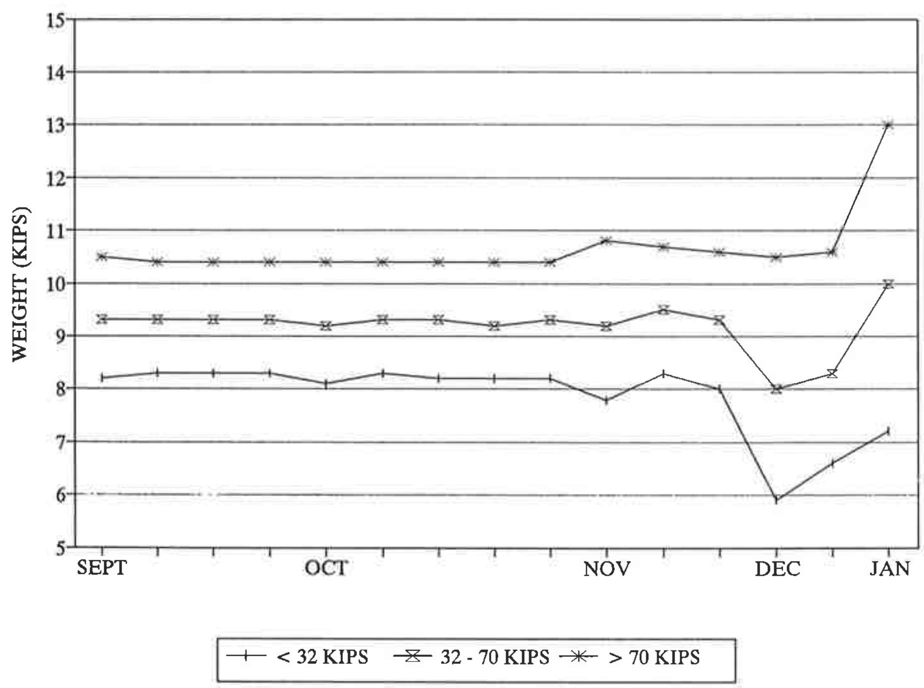

FIGURE 7 Front-axle weights of five-axle tractor-semitrailers on I-94: right lane, by gross weight range.

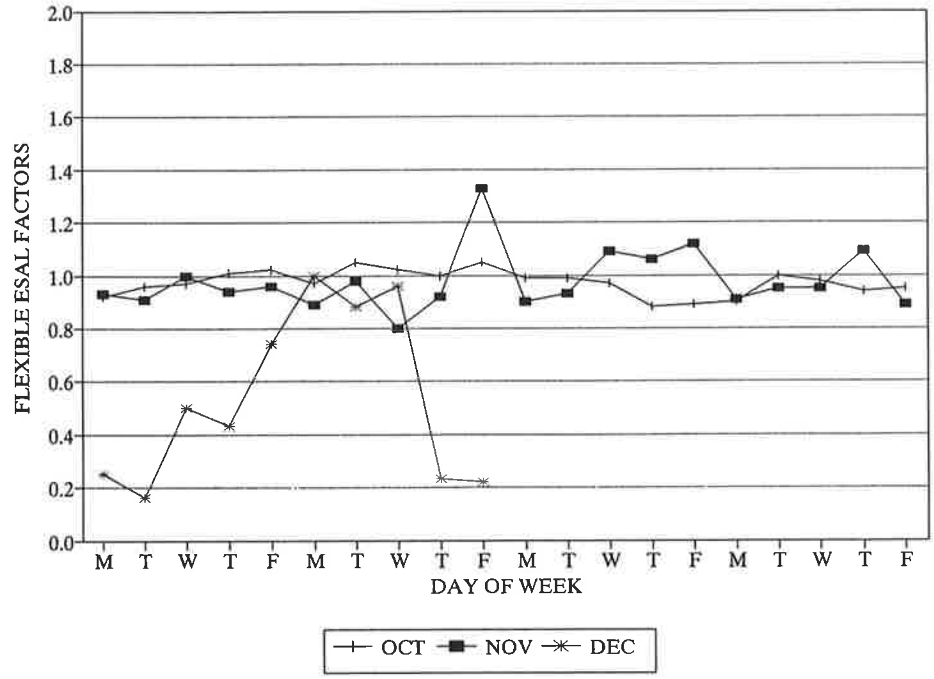

FIGURE 8 ESAL factors for five-axle tractor-semitrailers on I-94: right lane.

Figures 3, 4, and 7. It becomes evident after viewing these data that the valid factors should be in the area of 0.90 to 1.05. Approximately 900 five-axle tractor-semitrailers per day are represented here.

Figure 9 shows weekday data for the left lane on I-94. These data cover the same period as those shown in Figure 8. The pattern is consistent and generally falls in the 0.70 to 0.90 range. There are no drastic deviations as observed in Figure 8. These data are valid, as was also determined for Figure 6. Approximately 200 trucks a day are represented here.

SUMMARY OF PROCEDURE AFTER INITIAL CALIBRATION

The following steps outline how to conduct an analysis of WIM data to determine the status of the calibration and the

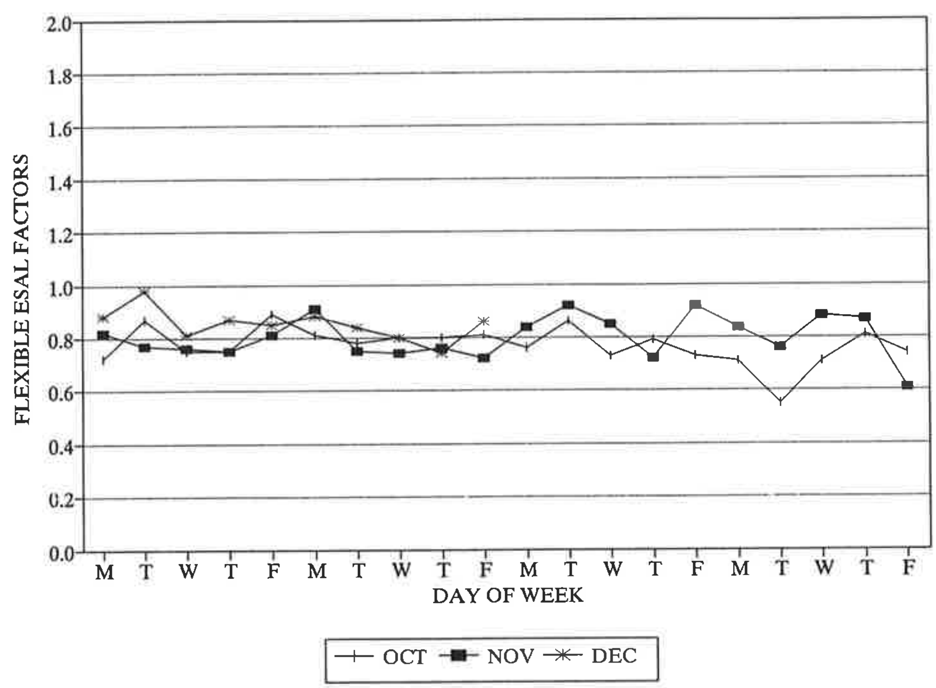

FIGURE 9 ESAL factors for five-axle tractor-semitrailers on I-94: left lane.

validity of the data. They also suggest an application in the process of editing weight data. The analysis examines the distribution of gross weight, front-axle weight, and flexible ESAL factors for five-axle tractor-semitrailers. It also contains guidelines for determining whether the weight data are valid. When an analysis indicates that the calibration is incorrect, a recalibration should be done on the basis of the percentage indicated by the outlined procedures. When there is a system malfunction, recalibration should not be done. The system should be examined and repairs should be made. These procedures follow the initial calibration of the system. The application is on an individual-lane basis.

1. Determine whether the distribution of the gross weight is logical. The first peak in the bimodal distribution should be between 28 and 32 kips, and the second peak should be between 70 and 80 kips. Many states have legal limits that are greater than 80 kips; this means that the second peak will occur at a different location, but the first peak should remain at about 30 kips. If the peaks are where they belong, the system is properly calibrated.

If a shift in the peaks has taken place, determine if the volume of trucks has changed appreciably from the number that regularly uses that lane. If the volume did change, it might explain the shift in distribution of weight. If the number has not changed, and if both peaks have shifted in the same direction and they are off by 4 percent or more, the data should be considered invalid. This indicates the need for recalibration. If both peaks are off by 4 percent or more and they have shifted in opposite directions, the data should also be considered invalid. In this second circumstance, do not consider recalibration, because such data indicate a system malfunction.

2. Determine the proper front-axle weights for each of the three gross weight categories. These are the values that the system produces, assuming that the basic calibration check described in Step 1 has been completed. Then monitor the values in each of the three categories. If a change is occurring, check the volume of vehicles passing through the system as described in Step 1 to determine if that might be the cause of the change.

If the weights in at least two of the three categories are shifting in the same direction and they pass beyond a specified point—for example, 4 percent—the system should be considered to be out of calibration and the data collected during this period invalid. This shift in weights indicates the need for recalibration. Also, if one value shifts 4 percent in one direction and another value shifts 4 percent in the other direction, the data are invalid. Do not consider recalibration because this type of action indicates a system malfunction.

3. Determine the average flexible (or rigid) ESAL factor for weekdays by using the values calculated from weight data collected by the properly calibrated system. Then set up the acceptable range of factors. Coordinate this range with what was deemed acceptable in the other two areas being monitored. For example, when 4 percent is used in those areas, approximately 16 percent should be used here. If values are observed outside the range, check to see if the volume of vehicles changed as described in Step 1. The data are invalid for any days that fall outside those values. For those stations collecting either continuous or a significant amount of weight data, assume that Saturday and Sunday are valid as long as the adjacent weekdays are valid.

4. Compile the results of the analysis of the three measures discussed. Determine whether the data are valid. If they are valid, continue to collect data with the system and use the data in the desired analysis. If they are invalid, the system requires either recalibration or repair. Recalibrate the system if at least two of the three areas indicate that this is needed, or repair the system if at least two of the three areas indicate that this is needed. These three measures all complement one another. They serve as cross checks in determining whether the weight data are valid.

5. Apply the results of the analysis to the WIM site data editing process. This step is a vital supplement to standard editing techniques that focus on the validity of individual vehicle records. Such standard editing techniques cannot detect the types of problems that have been discussed here.

CONCLUSIONS

There is a practical, effective method that can be used to calibrate a WIM system and monitor that calibration over time. This method uses predictable patterns of five-axle tractor-semitrailer weight data. The distribution of the gross weight data provides the best vantage point to determine its overall validity. This is a key part of the process. The other two measures—front-axle weight and flexible ESAL factors—are also important. Any one or two of these items can function independently, but they work best when used together. These indicators can also be used to identify and edit out invalid weight data.

ACKNOWLEDGMENT

The author gratefully acknowledges the contributions made to this report by Roberta Casey, George Cepress, Mark Flinner, and Morris Gildemeister of MnDOT.

Publication of this paper sponsored by Committee on Vehicle Counting, Classification, and Weigh-in-Motion Systems.