# Section 5

## Truck Weight Monitoring

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# SECTION 5
# TRUCK WEIGHT MONITORING

## CHAPTER 1
## INTRODUCTION TO TRUCK WEIGHT DATA COLLECTION

The last of the primary traffic monitoring activities is truck weight data collection. Gathering truck weight data is the most difficult and costly of the three primary data collection activities. However, in many respects these data are the most important.

Data on the weight carried by trucks are used as a primary input to a number of a State highway agency's most significant tasks. For example, traffic loading is a primary factor in determining the depth of pavement sections. It is used as a primary determinant in the selection of pavement maintenance treatments. The total tonnage moved on roads is used to estimate the value of freight traveling on the roadway system and is a major input into calculations for determining the costs of congestion and benefits to be gained from new construction and operating strategies. Truck classification and weight information is also a key component in studies that determine the relative cost responsibility of different road users.

This section discusses the alternatives for collecting truck weight information. This first chapter introduces truck weight data collection technology and data collection strategies. The second chapter discusses the basic user needs for truck weight data and describes how those uses affect the data collection and summarization strategy. Chapter 3 recommends a truck weight data collection program that meets the needs identified in Chapter 2. Chapter 4 presents a variety of ways to summarize weight data. Finally, a discussion of the need for calibration of WIM devices is presented as an Appendix.

### WEIGH-IN-MOTION (WIM) DATA COLLECTION

Of all the traffic monitoring activities, WIM requires the most sophisticated data collection sensors, the most controlled operating environment (strong, smooth, level pavement in good condition), and the most costly equipment set up and calibration.[1] WIM systems are designed to measure the vertical forces applied by axles to sensors in the roadway. This measurement helps estimate the weight of those axles if the truck being weighed were stationary. The task is complicated by a number of factors, including the following:

- Each sensor "feels" the vertical force of each axle for only a brief time.
- The "weight" applied to the sensor during that time period is normally not equal to the static weight of that axle. This is because while the vehicle is

[1] An excellent introduction to WIM is provided in the reference "State's Successful Practices Weigh-in-Motion Handbook" by McCall, Bill, and Vodrazka, Walter, FHWA, December 1997.

in motion, the truck and its components bounce up and down. If the truck mass is moving upward when an axle crosses the WIM sensor, the weight applied by that axle is lower than the static value. If the truck mass is landing, the weight applied is greater than the static value.[2]

- Some sensors (strip) feel only a portion of the tire weight at any given time. Because the sensor is smaller than the footprint of the tire, the pavement surrounding the sensor physically supports some portion of the axle weight throughout the axle weight measurement.
- The tread on some tires is so well defined that very high concentrations of force are generated under those portions of the tread that are actually in contact with the ground. This is also mostly a problem for strip sensors.
- Sensors must be capable of weighing more than one axle in quick succession. That is, the scale must be able to "recover" quickly enough so that one axle weight does not affect the measurement of the following axle.
- Roadway geometry (horizontal and vertical curves) can cause shifts in vehicle weight from one axle to another.
- Vehicle acceleration or braking, torque from the drive axles, wind, the style and condition of vehicle's suspension system, and a variety of other factors can also cause shifts of weight from one axle to another.

The effects of many of these factors can be minimized through careful design of the WIM site. The site should be selected and designed to reduce the dynamic motion of passing vehicles. However, achieving these design controls requires restrictions on site selection, which means that WIM systems cannot be placed as easily or as universally as other traffic monitoring equipment.

WIM scales work most accurately when they are placed flush with the roadway. Sensors that sit on top of the roadway cause two problems with WIM system accuracy: 1) They induce additional dynamic motion in the vehicle, and 2) they can cause the sensor to measure the force of tire deformation (which includes a horizontal component not related to the weight of the axle) in addition to the axle weight. This means that permanent installation of the sensors and/or frames that hold the sensors is normally better for consistent, accurate weighing results. The use of permanently installed WIM sensors is recommended as a means of improving the quality of the data.[3]

## WEIGH-IN-MOTION EQUIPMENT CALIBRATION

Calibration of WIM equipment is also more demanding than calibration of other types of traffic monitoring equipment. WIM scale calibration must account for the vehicle dynamics at the data collection site. Because vehicle dynamics are affected by pavement roughness, the "correct" calibration value for a scale is a function of the

[2] In addition, truck components, such as shock absorbers, are also in motion affecting the axle weight at any given instant in time.
[3] This recommendation does not prevent the use of less accurate portable equipment.

pavement condition and the sensor installation at each site. Since these differ with each placement, a significant calibration effort is required each time WIM equipment is placed on the ground. If the scale is not calibrated, the static weight estimates provided by the scale can be very inaccurate, even if the scale accurately reports the vertical forces applied to its surface. The expense of calibrating portable WIM scales each time they are installed is another significant detriment to their use.

Because pavement conditions change over time, and because those changes affect WIM scale performance, even permanently installed WIM sensors need to be periodically calibrated.

To ensure that the equipment is operating effectively, the data produced must be promptly produced and analyzed. Changes in vehicle weight over time must be examined quickly to understand whether the equipment is malfunctioning, calibration is needed, or the scales are simply reflecting changes in freight movement. Software systems that allow rapid monitoring and retrieval of WIM system output are an important consideration of WIM data collection. The FHWA Vehicle Travel Information System (VTRIS) allows quick examination of WIM data. More information on WIM site requirements and WIM calibration requirements is included in Appendix 5-A.

# CHAPTER 2
# TRUCK WEIGHT USER NEEDS

Truck weight data are used for a wide variety of tasks. These tasks include, but are not limited to, the following:

- pavement design
- pavement maintenance
- bridge design
- pavement and bridge loading restrictions
- development and application of equitable tax structures
- determination of the need for and success of weight law enforcement actions
- determination of the need for geometric improvements related to vehicle size, weight, and speed
- determination of the economic value of freight being moved on roadways
- determination of the need for and effect of appropriate safety improvements.

## BASIC TRUCK WEIGHT DATA SUMMARIES

State highway agencies summarize and report truck weight data in many ways. Three types of summaries are commonly used including:

- gross vehicle weight (GVW) per vehicle (usually by vehicle class)
- axle load distribution (by type of axle) for specific vehicle types
- equivalent standard axle load[4] (ESAL) for specific vehicle types.

Basic statistics such as the GVW or ESAL for a given vehicle classification can be expressed as distributions, as mean values, or as mean values with specified confidence intervals, depending on the needs of the analysis that will use this information. Each of these summary statistics can be developed for a specific site, a group of sites, or an entire State or geographic region, depending on the needs of the analysis and the data collection and reporting procedures. The role of the traffic monitoring program is to provide the user with whichever of these data summaries is needed. The summaries can be required for any one of several levels of summarization. For example, it may be appropriate to maintain axle loading distributions for each of the FHWA heavy vehicle classes (classes 4 through 13)[5] so that these statistics are available when needed for pavement design. However, even if a more aggregated classification scheme is used, such as single-unit trucks, combination trucks, and multi-trailer trucks, the more detailed summary should be retained for WIM data. These summaries can be computed with FHWA's VTRIS software, with software supplied by the WIM system

[4] ESAL are a measure of pavement damage developed by AASHTO researchers in the 1960s that are used for pavement design by many current design procedures.

[5] See Appendix 4-C for definitions of the FHWA vehicle classes.

vendor, or with software developed specifically for use by the State highway agency as part of its traffic database.

A single statewide average statistic may not be applicable to all parts of the State. Trucking characteristics vary significantly by type of road. When a single statewide summary is not representative of all roads, it is important to collect data and maintain summary statistics for different regions or roads in the State. For example, the truck traffic in urban areas often has different truck weight characteristics than those in rural areas. Roads that serve major agricultural regions often have different loading characteristics than roads that serve resource extraction industries. Roads that serve major industrial areas within an urban area tend to carry much heavier trucks than roads that serve general urban and suburban areas. Roads that serve major through-truck movements often experience very different truck weights than roads that serve primarily local truck traffic. An effective truck weight program must identify these differences and include a data reporting mechanism to provide users with data summaries that correctly describe specific characteristics.

## TRUCK LOADING ESTIMATES

Axle load distribution tables and average gross vehicle weights per vehicle are useful statistics, but they are rarely the end product that many users need. Instead, most users are interested in total load estimates for a given period (e.g., total ESAL per year, or total number of axle loads by type and weight range in the last ten years). These statistics can be derived directly only from WIM sites. Unfortunately, because WIM equipment is expensive to install and maintain, WIM data are available at only a few locations in the State. Thus, at most road sites, these WIM data items cannot be measured directly. Instead, the data are normally computed from a summary weight data set, as previously described, and a site-specific count of volume by vehicle classification category. The WIM data are imputed to the site-specific classification count to estimate total loading.

These calculations assume that the basic weight distribution developed at available WIM sites is representative of all roads within a specified group. For example, all rural Interstates are assumed to have similar truck loading conditions. Rural Interstate loading conditions are then measured at three different WIM sites and the data combined to provide the weight distribution estimate to represent all segments in the group.

Site-specific volume counts (by classification) are used to "size" the weight distribution. That is, the site-specific classification count (adjusted for day-of-week and seasonal variation) is used to determine how many trucks of a particular type actually travel on the road. The volume by classification determines how many axles of each type are present. (For example, if a road section carries 100 Class 9 trucks in a day, it experiences approximately 100 single axles and 200 sets of tandem axles.)

Multiplying the number of trucks within a given class by the average GVW for vehicles of that class yields the total number of tons[6] applied by that class on that roadway. Adding these values across all vehicle classes yields the total number of tons carried by that road. These values can be plotted graphically, creating an image very similar to a traffic volume flow map[7] (Figure 5-2-1). The graphics are useful for both public presentations and as an information tool for decision makers. Map displays allow decision makers to graphically compare roads that carry large freight volumes with roads with light freight movements. The information can also be used to help prioritize potential road improvement projects.

Multiplying the total number of vehicles in a given class by the number of axles (by type of axle) associated with that class and by the axle weight distribution associated with that class, yields the total number of axles applied at that site by that vehicle class. Adding these weight distribution tables across vehicle classes results in the total number of axles, by weight class, applied to that roadway. This type of summary table will be one of the primary data inputs for the pavement design guide being readied by AASHTO.

The axle distribution by axle weight range can also be easily converted into equivalent standard axle loads (ESAL), the most common pavement design loading value currently used in the United States. To make this conversion, an ESAL[8] value is assigned to each axle weight category for each type of axle (single, tandem, tridem). This value times the number of axles within that weight range yields the total ESAL load for that type and weight range of axles. Summing these values across all axle types and weight ranges yields the total number of ESALs applied to that roadway (Table 5-2-1).

Finally, understanding and accounting for seasonal variations in vehicle weights is becoming increasingly important for both economic analyses and pavement design procedures. New pavement design procedures being developed and refined require traffic loading data for specific times of the year. For example, in many colder regions proposed pavement design procedures will require the average daily loading rate during the spring thaw period because the pavement will be designed to withstand loads when the roadway structure is at its weakest. Since pavement strength changes with many environmental conditions, the pavement designers are likely to require data on loads at different sites at different times during the year. If loads vary (because the numbers of trucks or the weights of individual trucks vary during the year), the traffic data collection process must be able to detect and report these differences. Otherwise, the pavement design procedures will be unreliable.

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6 Note that this value is the total tons of load carried by the roadway, not the total net tonnage of goods carried over that road (i.e., gross weight applied, not net commodity weight carried.)

7 The accuracy of these estimates is a function of the quality of the volume by vehicle classification estimate and the degree to which the GVW/vehicle value represents the trucks actually using that roadway. Like all "flow" maps, extrapolation is required to produce the map, and users should not assume high levels of precision when reading directly from such a map.

8 ESAL varies with pavement characteristics, flexible (asphalt) or rigid (Portland cement) pavement.

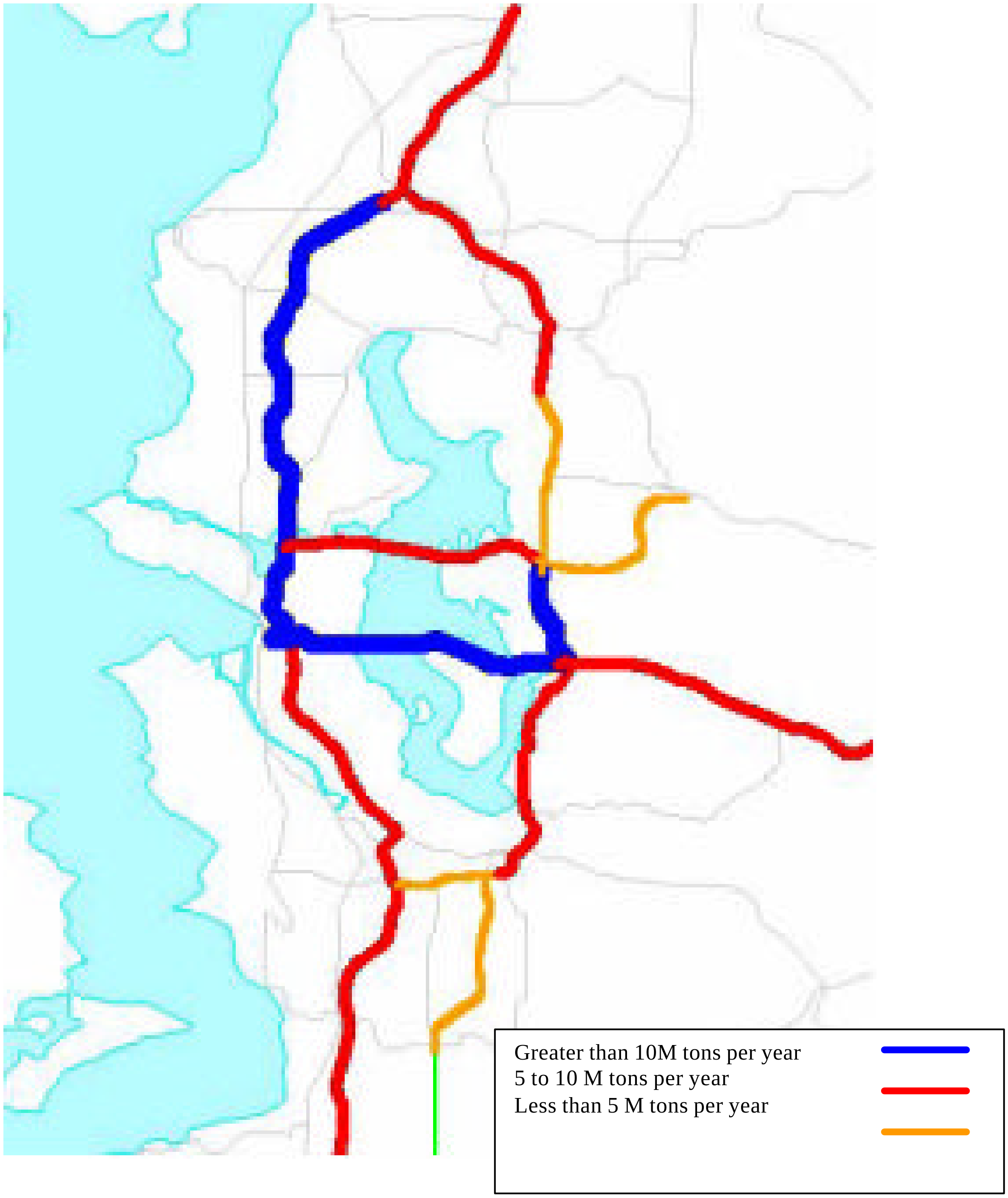


Figure 5-2-1: Example GVW Flow Map

**Table 5-2-1: Example Daily Load Distribution Table (All Vehicle Classes Combined) and Computation of Total (Flexible) ESAL Loading**

| Single Axles | | | | Tandem Axles | | | | Tridem Axles | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lower Weight Range (kgs) | Upper Weight Range (kgs) | ESAL Per Axle | Number of Axles | Lower Weight Range (kgs) | Upper Weight Range (kgs) | ESAL Per Axle | Number of Axles | Lower Weight Range (kgs) | Upper Weight Range (kgs) | ESAL Per Axle | Number of Axles |
| 0 | 1,363 | 0.000 | 5 | 0 | 2,727 | 0.001 | 4 | 0 | 5,454 | 0.001 | 0 |
| 1,364 | 1,818 | 0.001 | 7 | 2,728 | 3,636 | 0.002 | 16 | 5,455 | 6,818 | 0.006 | 0 |
| 1,819 | 2,272 | 0.003 | 51 | 3,637 | 4,545 | 0.005 | 24 | 6,819 | 8,181 | 0.014 | 0 |
| 2,273 | 2,727 | 0.007 | 31 | 4,546 | 5,454 | 0.010 | 36 | 8,182 | 9,545 | 0.027 | 0 |
| 2,728 | 3,181 | 0.014 | 37 | 5,455 | 6,363 | 0.020 | 34 | 9,546 | 10,909 | 0.048 | 0 |
| 3,182 | 3,636 | 0.026 | 75 | 6,364 | 7,272 | 0.036 | 37 | 10,910 | 12,272 | 0.079 | 0 |
| 3,637 | 4,090 | 0.044 | 99 | 7,273 | 8,181 | 0.061 | 33 | 12,273 | 13,636 | 0.126 | 0 |
| 4,091 | 4,545 | 0.071 | 97 | 8,182 | 9,090 | 0.097 | 28 | 13,637 | 15,000 | 0.191 | 0 |
| 4,546 | 5,000 | 0.108 | 78 | 9,091 | 10,000 | 0.148 | 23 | 15,001 | 16,363 | 0.278 | 0 |
| 5,001 | 5,454 | 0.158 | 56 | 10,001 | 10,909 | 0.217 | 19 | 16,364 | 17,727 | 0.393 | 0 |
| 5,455 | 5,909 | 0.224 | 40 | 10,910 | 11,818 | 0.309 | 20 | 17,728 | 19,090 | 0.539 | 0 |
| 5,910 | 6,363 | 0.310 | 22 | 11,819 | 12,727 | 0.425 | 22 | 19,091 | 20,454 | 0.722 | 1 |
| 6,364 | 6,818 | 0.416 | 16 | 12,728 | 13,636 | 0.572 | 29 | 20,455 | 21,818 | 0.947 | 0 |
| 6,819 | 7,272 | 0.547 | 16 | 13,637 | 14,545 | 0.752 | 29 | 21,819 | 23,181 | 1.217 | 0 |
| 7,273 | 7,727 | 0.706 | 13 | 14,546 | 15,454 | 0.757 | 30 | 23,182 | 24,545 | 1.537 | 2 |
| 7,728 | 8,181 | 0.894 | 13 | 15,455 | 16,363 | 1.229 | 25 | 24,546 | 25,909 | 1.912 | 1 |
| 8,182 | 8,636 | 1.115 | 11 | 16,364 | 17,272 | 1.532 | 17 | 25,910 | 27,272 | 2.346 | 3 |
| 8,637 | 9,090 | 1.371 | 10 | 17,273 | 18,181 | 1.884 | 15 | 27,273 | 28,636 | 2.843 | 1 |
| 9,091 | 9,545 | 1.664 | 7 | 18,182 | 19,090 | 2.288 | 8 | 28,637 | 30,000 | 3.408 | 0 |
| 9,546 | 10,000 | 1.999 | 6 | 19,091 | 20,000 | 2.747 | 7 | 30,001 | 31,363 | 4.046 | 0 |
| 10,001 | 10,454 | 2.376 | 5 | 20,001 | 20,909 | 3.267 | 5 | 31,364 | 32,727 | 4.763 | 0 |
| 10,455 | 10,909 | 2.801 | 3 | 20,910 | 21,818 | 3.850 | 2 | 32,728 | 34,090 | 5.563 | 0 |
| 10,910 | 11,363 | 3.275 | 1 | 21,819 | 22,727 | 4.502 | 3 | 34,091 | 35,454 | 6.453 | 0 |
| 11,364 | 11,818 | 3.804 | 1 | 22,728 | 23,636 | 5.229 | 1 | 35,455 | 36,818 | 7.441 | 0 |
| 11,819 | 12,272 | 4.390 | 1 | 23,637 | 24,545 | 6.035 | 1 | 36,819 | 38,181 | 8.534 | 0 |
| 12,273 | 12,727 | 5.039 | 1 | 24,546 | 25,454 | 6.927 | 1 | 38,182 | 39,545 | 9.740 | 0 |
| 12,728 | 13,181 | 5.756 | 0 | 25,455 | 26,363 | 7.913 | 0 | 39,546 | 40,909 | 11.070 | 0 |
| 13,182 | 13,636 | 6.546 | 0 | 26,364 | 27,272 | 8.999 | 0 | 40,910 | 42,272 | 12.532 | 0 |
| 13,637 | 14,090 | 7.416 | 0 | 27,273 | 28,181 | 10.194 | 0 | 42,273 | 43,636 | 14.138 | 0 |
| 14,091 | 14,545 | 8.371 | 0 | 28,182 | 29,090 | 11.506 | 0 | 43,637 | 45,000 | 15.900 | 0 |
| 14,546 | 15,000 | 9.419 | 0 | 29,091 | 30,000 | 12.947 | 0 | 45,001 | 46,363 | 17.831 | 0 |
| 15,001 | 15,454 | 10.567 | 0 | 30,001 | 30,909 | 14.525 | 0 | 46,364 | 47,727 | 19.942 | 0 |
| 15,455 | 15,909 | 11.824 | 0 | 30,910 | 31,818 | 16.253 | 0 | 47,728 | 49,090 | 22.250 | 0 |
| 15,910 | 16,363 | 13.197 | 0 | 31,819 | 32,727 | 18.140 | 0 | 49,091 | 50,454 | 24.769 | 0 |
| 16,364 | 16,818 | 14.696 | 0 | 32,728 | 33,636 | 20.201 | 0 | 50,455 | 51,818 | 27.514 | 0 |
| 16,819 | 17,272 | 16.331 | 0 | 33,637 | 34,545 | 22.448 | 0 | 51,819 | 53,181 | 30.503 | 0 |
| 17,273 | 17,727 | 18.111 | 0 | 34,546 | 35,454 | 24.895 | 0 | 53,182 | 54,545 | 33.753 | 0 |
| 17,728 | 18,181 | 20.047 | 0 | 35,455 | 36,363 | 27.556 | 0 | 54,546 | 55,909 | 37.283 | 0 |
| 18,182 | none | 22.149 | 0 | 36,364 | none | 30.446 | 0 | 55,910 | none | 41.111 | 0 |
| **Total ESAL by type of axle** ∑(ESAL/axle * Total Axles) | | | **169.8** | | | | **269.7** | | | | **15.6** |
| **Total ESAL** (all axle types combined) | | | **455.1** | | | | | | | | |

# CHAPTER 3
# TRUCK WEIGHT DATA COLLECTION

**The objective of the truck weight data collection program is to obtain a reliable estimate of the distribution of vehicle and axle loads per vehicle for truck categories within defined roadway groups.**

The data collection plan for truck weight accounts for:

- the statistical needs of State and federal agencies
- the capabilities and limitations of WIM equipment
- the resource constraints found at most State highway agencies
- the variability of truck weight data, as discussed in the literature and as observed in data submitted to the FHWA.

The truck weight data collection program is based on creating summary axle load distributions that can be applied with confidence and statistical precision to all roads in a State. The procedure is to group the State's roads into categories, so that each group experiences freight traffic with reasonably similar characteristics. For example, roads that experience trucks carrying heavy natural resources should be grouped separately from roads carrying only light, urban delivery loads. The truck weight data collection program is closely analogous to the permanent, continuous count programs for collecting seasonal and day-of-week pattern information for volume and vehicle classification data. The primary difference is that most of the truck weight data collection sites do not need to be operated in a continuous manner.

Within each of these groups of roads, the State should operate a number of WIM sites. These sites will be used to identify truck weight patterns that apply to all roads in the group. At least one of the WIM sites within each group should operate continuously throughout the year to measure seasonal changes in the loads carried by trucks operating on those roads. Where possible (given budget and staffing limitations), more than one location within each group should be monitored continuously to provide more reliable measures of seasonal change. The proper number of additional continuous sites is primarily a function of:

- each State's ability to supply the resources needed to monitor the sites to ensure the provision of accurate data throughout the year
- the proven need to monitor differences in seasonal weight characteristics.[9]

Performing additional vehicle weighing, both by operating more continuous WIM scales and by collecting data at more than the minimum number of scale sites, will allow a State to determine whether the initial groups selected do, in fact, carry similar truck

[9] If extensive data collection shows that a group of roads has a very stable seasonal pattern, then relatively few continuous counters are needed to monitor the pattern. However, if the State has limited data on seasonal weight patterns or if prior data collection has shown the pattern to be inconsistent, then a larger number of continuous counters may be needed.

traffic. Where new data collection shows that monitored roads do not carry traffic with loading characteristics similar to those of other roads in the group, the State will either need to create new road groups (and collect more truck weight information) or revise the existing road groups to create more homogeneous groups.

## TRUCK WEIGHT GROUP FORMATION

Truck weight road groups should be based on a combination of known geographic, industrial, agricultural, and commercial patterns, along with knowledge of the trucking patterns that occur on specific roads. Road groups or systems for truck weight data collection should: 1) be easily applied within each State, and 2) provide a logical means for discriminating between roads that are likely to have very high load factors and roads that have lower load factors (that is, between roads where most trucks are fully loaded and roads where a large percentage of trucks are either partially loaded or empty).

In addition, States should incorporate into their truck weight grouping process knowledge about specific types of heavy trucks, so that roads that carry those heavy trucks are grouped together, and roads that are not likely to carry those trucks are treated separately. For example, roads leading to and from major port facilities might be treated separately from other roads in that same geographic area, simply because of the high load factor that is common to roads leading to/from most port facilities.

Figure 5-3-1 illustrates the reason why roads should be stratified into road groups. It shows the distribution of tandem axle weights for Class 9 trucks from three different truck weight sites. Each of these three sites exhibits a very different set of loading conditions, ranging from heavily loaded to very lightly loaded. Use of loading information from one of these sites at either of the other two sites would result in very poor load estimates. The average flexible ESAL per tandem axle at the heavily loaded site is 0.66, while the moderately loaded site has a flexible ESAL per tandem axle of 0.35, and the lightly loaded site has an ESAL per tandem axle of 0.19. Thus, use of the "heavy" load distribution at the "lightly" loaded site would result in an overestimation of actual loading rates by a factor of over 3.

The key to the design of the truck weight data collection effort, and the use of the data that results from that process, is for the highway agency to be able to successfully recognize these differences in loading patterns, and to collect sufficient data to be able to estimate the loads that are occurring under these different conditions.

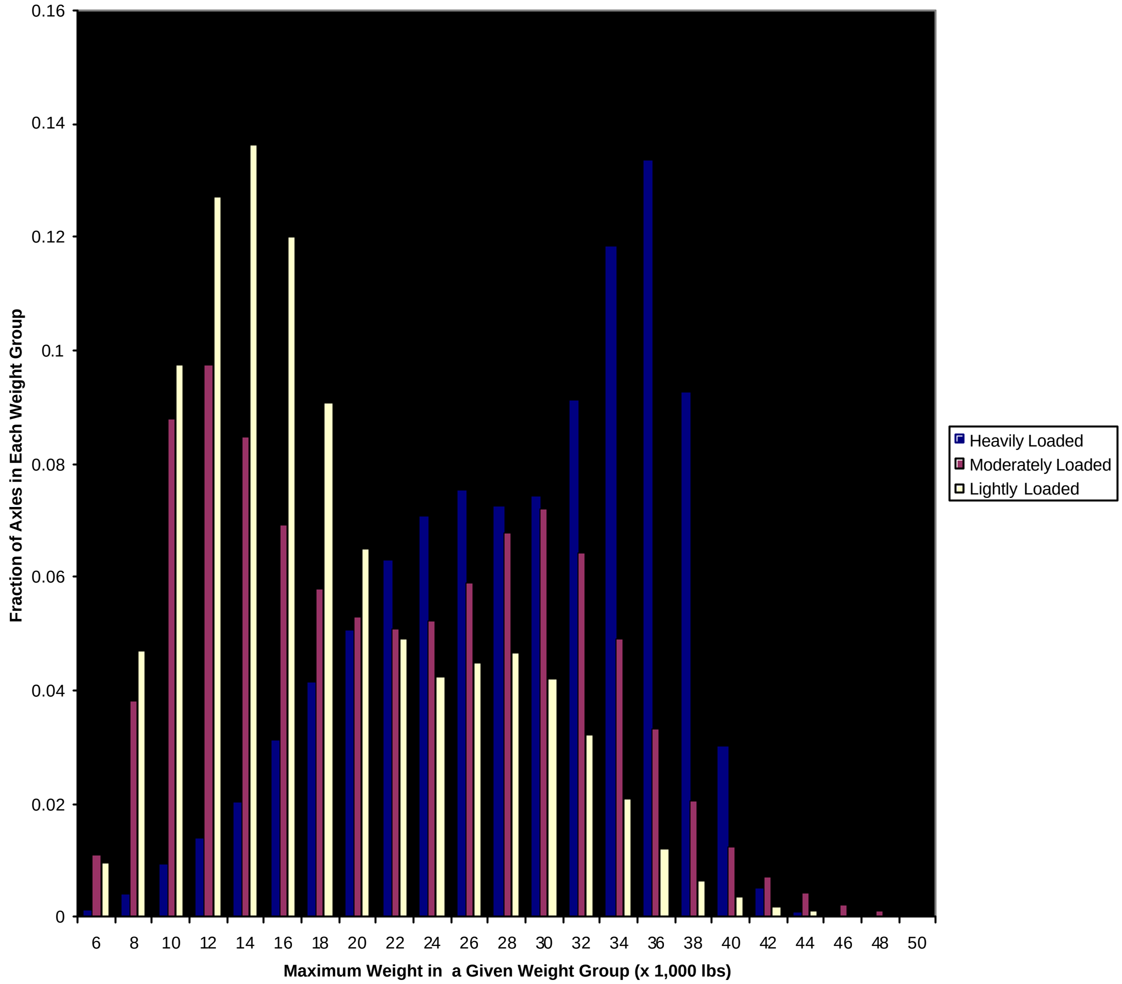


**Figure 5-3-1: Tandem Axle Load Distributions At Three Sites With Different Loading Conditions. The Case For Truck Weight Road Groups**

Australia recently proposed a similar grouping technique in the chapter on traffic data collection in its pavement design guide.[10] In the Australian guide, 25 different truck loading patterns are identified nationwide. These patterns are structured both by type of trucking movement, and the infrastructure linkages being served. The Australian's use the following categories of haul activities:

- General Freight
- General Freight in a Heavy Vehicle Increased Mass Permit Environment
- Predominately Industrial
- Quarry Products

[10] Update of the AUSTROADS Pavement Design Guide – Traffic Design Chapter, Final Draft Working Document, September 1998.

- Predominately Farm Produce
- Live-Stock
- Logging Products

To further aid in classifying any given road section to one of the truck loading patterns, the Australian guide also provides a simplified description of what types of links a given roadway provides (e.g., the road connects a major port to other regional cities). "Characterizations" of the trucking patterns used include the following:

- Long-haul, inter-capital
- Long-haul inter-capital at remote sites
- Inter-regional within state/territory or nearby region
- Near town and/or where local freight movement occurs
- Developing area
- Entering and exiting port/loading sites
- Entering and exiting capitol city

This report does not recommend specific roadway grouping criteria. The Australian system has significant merit, can be applied fairly easily, and requires only a modest understanding of the traffic on a given highway. However, the Australian groupings are not directly applicable to U.S. roads because our economy and geographic distribution of cities are considerably different. Instead, States should consider creating similar styles of roadway groups that are characterized by industrial/roadway traits that fit their economic infrastructure. For example, States may want to differentiate among roads affected by specific types of industrial or agricultural activity (such as areas that grow wheat or areas that support steel manufacturing).

It may also be reasonable to start with a less detailed truck weight stratification than used by the Australians. In fact, unless extensive State data suggest the need for a more definitive grouping process, it is recommended that initial groups be based on a much more simplistic approach. This simplistic approach would then be improved (as needed) over time as more weight data are collected and analysis carried out.

Where more detailed information is not available, the initial grouping of roads into truck weight categories should be based on the percentage of through-trucks that exist on a roadway and distinct geographic regions within a State that can be associated with specific types of economic activity. The vehicle classification data provide much information as to what types of trucks are found on which roads. Other factors that can/should be used to differentiate roads into truck weight groups may include the following:

- The presence of agricultural products that create specific loading patterns and are carried in specific types of trucks. For example, wheat growing areas might need to be grouped separately from those that grow cherries because these two products have different densities, different weights on a truck and because their harvest and hauling seasons are different.

- The types of industrial areas, such as resource extraction operations that ship large amounts of material by truck. For example, coal truck traffic roads may be grouped separately from roads that experience few coal trucks.
- The distance over which the trucks are likely to travel. For example, roads where trucks deliver cargo over long distances across multiple States, or roads with truck travel between cities within a region where drivers can make a round trip in one day, or roads with truck travel within a general urbanized area where drivers make multiple trips in a day. Trucks traveling longer distances are more likely to be full, and thus heavier, than trucks operating within half a day of their base, which are likely to be full leaving their depot but are often empty when returning.
- Urban or rural roads, because urban areas often have considerably higher numbers of partially loaded trucks and trucks that travel empty after unloading at urban destinations. Note that some roads functionally classified as "rural" that are located between two large cities (say within 300 km or 180 miles of each other) may experience urban rather than rural trucking patterns because trucks routinely make day-trips between those cities, traveling full in one direction and empty in the other.

A State may also be interested in discriminating between roads because of the industrial activity they serve. For example, roads leading into and out of major seaports may experience far heavier traffic (higher load factors) than other roads in the same area. Much information can be extracted from existing truck weight databases and planning programs to determine logical and statistical differences that can be accounted for in the formation of truck weight groups.

As an example of a weight factor group, Washington State developed five basic truck loading patterns as part of a study to determine total freight tonnage carried by all State highways. These five groups were defined as

Group A - serves major statewide and interstate truck travel. These routes are the major regional haul facilities
Group B - serves primarily intercity freight movements, with minor amounts of regional hauling. These routes also serve as produce transfer routes, serving rail and barge loading facilities.
Group C - serves farm to market routes and regional commerce.
Group D - serves suburban industrial activity.
Group E - serves primarily local goods movement and specialized products.

A starting point for developing truck weight groups is shown in Table 5-3-1. The example begins with the groups identified in the vehicle classification section. The truck loading groups defined should be coordinated with the vehicle classification groups identified in section 4. Differences in the two sets of groups are likely since the groups are defined to meet different purposes (seasonal differences in volume and loading variation). However, they both reflect truck travel characteristics that are directly related. A similar group definition will greatly simplify the understanding and applicability of the patterns. The groups will need further redefinition over time as information is gained.

**Table 5-3-1: Example Truck Loading Groups**[11]

| Rural | Urban |
|---|---|
| Interstate and arterial major through-truck routes | Interstate and arterial major truck routes |
| Other roads (e.g., regional agricultural with little through-trucks) | Interstate and other freeways serving primarily local truck traffic |
| Other non-restricted truck routes | Other non-restricted truck routes |
| Other rural roads (mining areas) | Other roads (non-truck routes) |
| Special cases (e.g., recreational, ports) | |

The number of groups selected is a key consideration because of the impact on the number of WIM installations needed. The higher the number of groups, the higher the number of WIM sites needed. For large States with an established base of WIM sites, a higher number of groups is appropriate. For small States with limited number of WIM installations, smaller numbers of groups should be tried. Since the character of trucking patterns does not change at State boundaries, pursuing the establishment of regional groups in combination with neighboring States could serve to reduce the individual State level of effort required while still providing the basic information needed.

Given the fact that much needs to be learned, starting the process with a small number of groups seems very reasonable. This can be accomplished by defining the truck loading groups as would be appropriate if WIM resources were not a constraint. The groups can then be combined and aggregated until the number of groups dwindles down to the appropriate number given the currently available WIM sites. In some cases, groups could be formed with smaller number of WIM sites than recommended and then WIM installations added in the future as resources become available. It is very likely that the study of truck patterns will highlight the need for additional WIM installations in the future.

[11] These are examples. Each State highway agency should select the appropriate number and definition of truck groups based on its economic and trucking characteristics.

## TESTING THE QUALITY OF SELECTED TRUCK WEIGHT GROUPS

Just as with the formation of groups used for factoring volume and classification counts, the initial formation of truck weight groups must be reviewed to determine whether the road segments grouped together actually have similar truck weight characteristics. Examining available data from the existing truck weight sites is the first step. A substantial amount of judgment is required since the data is likely to be limited to that currently available from existing WIM sites.

For example, a State highway agency may find that in one group of roads, the class 9 trucks all have similar characteristics, but the class 11 truck characteristics are very different from each other. By changing the road groups, it may be possible to classify roads so that all class 9 and 11 trucks within a road group have similar characteristics. More likely it will not be possible to form homogenous groups for different truck classes, and trade-offs will have to be made. The type of vehicle considered the most important should be given priority.

The trade-offs can be made based on the relative importance of each weight statistic to the data user. In many cases this is simply a function of determining the relative importance of different truck statistics. For example, if 95 percent of all trucks are in class 9, then having truck weight road groups that accurately describe class 9 truck weight characteristics may be more important than having road groups that accurately describe class 11.

## DETERMINING THE PRECISION OF ESTIMATES FROM TRUCK WEIGHT GROUPS

An estimate of the "precision" of the mean of a variable that any truck weight road group will provide can be found by computing the standard deviation when computing the mean statistic for that variable (refer to equation 3-3). For example, the precision of the mean gross vehicle weight for a Class 9 truck within a truck weight group can be estimated while computing the mean GVW per Class 9 truck from all of the WIM sites within that group. The standard deviation of the estimate and the number of sites provide an approximate measure of the accuracy of the mean of the group.

An example of this computation is shown below. In the example, assume that a State has determined that all rural Interstate roads have similar truck weight characteristics based on seven WIM sites. Statistics from those WIM sites are shown in Table 5-3-2. On the basis of these data, it can be assumed that all rural Interstate roads in the group have a mean gross vehicle weight of 25,000 kg for class 9 trucks. Each class 9 truck can also be assumed to apply an average of 1.63 ESAL.[12]

[12] When comparing ESAL values between sites, the ESAL computations assume the same pavement type and structure. All ESAL examples in this document are computed assuming flexible pavements.

The precision of the group mean, referred to as the standard error of the mean, can be estimated with 95 percent confidence as approximately[13] plus or minus 1.96 times the standard deviation divided by the square root of the number of sites.

**Table 5-3-2: Example of Statistic Computation for Precision Estimates**

| Site | Mean Class 9 GVW | Mean Class 9 ESAL |
|---|---|---|
| 1 | 23000 kg | 1.64 |
| 2 | 26000 kg | 1.72 |
| 3 | 29000 kg | 1.84 |
| 4 | 21000 kg | 1.45 |
| 5 | 21000 kg | 1.34 |
| 6 | 25000 kg | 1.65 |
| 7 | 28000 kg | 1.78 |
| **Group Mean** | **25000 kg** | **1.63** |
| **Group Standard Deviation** | **3200 kg** | **0.18** |
| **Coefficient of Variation** | **0.13** | **0.11** |

In the above example, note that the coefficient of variation for the two statistics (GVW/vehicle and ESAL/vehicle) are different, even though both variables come from the same set of vehicle weights. Each statistic computed for a truck weight group is likely to have different statistical reliability because of the different levels of variation found in axle weights, GVW, and the various other statistics computed from weight records.

To complicate matters further, each statistic has a different level of precision for each different vehicle class. Thus, the precision of the ESAL/vehicle value for Class 9 trucks will be different than that of the ESAL/vehicle value for Class 11 trucks.

In sampling applications, increasing the number of samples increases the precision of the mean estimate being computed. Thus, increasing the number of WIM sample locations within a given truck weight group will improve the precision of the mean value computed within a weight group. This is an important result when calculating system-level summary variables, such as annual ton-kilometers.

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[13] This is a relatively crude approximation. The value 1.96 should be used only for sample sizes of 30 sites or more. A more statistically correct estimate would use the Student's *t* distribution, which for six degrees of freedom (seven weigh sites) is roughly 2.45.

Increasing the number of WIM sites will improve the system-wide averages for each group. However, increasing the sample size only marginally improves the precision of estimates used as default values for loading rates on specific roadway sections. When a mean value of a distribution is assumed to be the "best" estimate of a value at a specific point, the variability of that estimate is measured by the standard deviation of the distribution. The error bounds can only be reduced by creating truck weight groups that have tighter distributions, or by taking site-specific WIM counts. Taking site-specific measurements ensures that the data apply directly to the site in question. This is why site-specific vehicle classification counts are requested for most pavement design projects since they provide the only cost-effective method for obtaining the accuracy needed at a specific location. Unfortunately, because portable WIM data is difficult to collect accurately, it is very difficult to obtain site-specific values for truck weights.

## DETERMINING THE NUMBER OF WIM SITES PER GROUP

The precision calculations can be used to determine how many WIM systems should be included within each truck weight group. The State highway agency should determine what statistic it wants to use as the key to the analysis, select how precisely it wishes to estimate that statistic, and compute the number of WIM locations needed to obtain the desired degree of confidence.

The first step involves several decisions. The State highway agency should determine whether the truck weight groups will be developed to produce mean statistics within each group with a given level of precision (e.g., the mean ESAL/class 9 truck for rural interstates is 1.56 $\pm$ .15 with 95 percent confidence).

This decision primarily affects the grouping process. If the intention is to develop precise mean values for the group as a whole, the key tends to be the number of data collection locations included in each group. If the intention is to develop good default values for individual sites, the key to the grouping process is to have more and very homogenous groups (groups in which truck weights are very similar for all sites within the group, making standard deviations very small). States that emphasize predicting mean values for groups will have fewer groups but larger numbers of data collection sites within each group, whereas States that emphasize site-specific estimates will have more truck weight groups but fewer sites within each group.

The second decision that affects the grouping process is the selection of the statistic to be the basis for the precision estimates. Because the precision of each statistic will vary, the State should select a single statistic to use as its benchmark. Normally, this means selecting a specific vehicle classification and a specific weight variable. The recommended statistics for use in selecting sample sizes are either the mean ESAL[14]/class 9 trucks or better the mean GVW for class 9 trucks. Class 9 trucks are recommended

[14] ESAL varies with pavement characteristics, thus the ESAL formulation used for this purpose should be a generic formulation using default pavement characteristics.

because they are the most common throughout the country, and they tend to carry a high percentage of the loadings on most major roads.

The two most likely weight variables that can be used are the average gross weight (by class) and the average ESAL per vehicle (by class). Both measures are acceptable statistics for this purpose. GVW is easily understood by technical and non-technical people and does not change. It is reasonably well correlated to pavement damage and is commonly used as a measure of the size of commodity movements. ESAL are a much better measure of pavement damage than GVW. However, ESAL are not easily converted to measures of commodity flow, and current pavement research is not emphasizing their use in the design process.

The next decision is how precise to estimate the target statistic. Precision levels are normally stated in terms of percentage of error within a given level of confidence (e.g., the GVW/vehicle estimate is within $\pm$15 percent with 95 percent confidence). Decreasing the size of the acceptable error or requiring higher levels of confidence both increase the number of samples required. Conversely, accepting lower levels of precision and/or confidence allows smaller sample sizes and lower data collection costs.

Selecting the acceptable level of error is an iterative process. First, the desired target precision is selected. Next, the variability of data in the truck weight groups is examined. This examination may result in either the need to collect more data or to adjust the assignment of roads within truck weight groups. If the State can not meet the initially selected precision levels (either because it can not create sufficiently homogenous groups or because it can not collect data at enough sites), the desired precision levels have to be relaxed to reflect the quality of the estimates that can be obtained. The last step is to compute the number of weighing locations needed to meet the desired precision level. The number of WIM sites within a group is estimated as:

$$n = (t_{(a/2)})^2 (C^2) / (D^2) \qquad (5\text{-}1)$$

where: n = the number of samples taken (in this case, the number of sites in the group),
$t$ = the Student's $t$ distribution for the selected level of confidence ($\alpha$) and appropriate degrees of freedom (one less than the number of samples, n),
$\alpha$ = the selected level of confidence,
C = the coefficient of variation (COV) for the sample as a proportion,
D = the desired accuracy as a proportion of the estimate.

This equation can be manipulated to solve for any variable. COV (the ratio of the standard deviation to the mean) is usually computed from available truck weight data. D is selected as part of the previous step (see above). The number of sites, n, can be computed after selecting the value for alpha ($\alpha$) and looking up the appropriate term for $t_{\alpha/2}$ with n-1 degrees of freedom. Similarly, if n is given, it is possible to solve directly for the value of $t_{\alpha/2}$ and thus $\alpha$. The example given below illustrates the basic process of comparing sample size with the precision levels each sample size achieves.

Table 5-3-3 shows the same truck weight statistics used in Table 5-3-2, except two additional weigh sites have been added. These two sites experience heavy vehicle weights and, consequently, have increased the mean values for GVW/vehicle and ESAL/vehicle for the group.

**Table 5-3-3:**
**Statistics Used For Sample Size Computation**

| Site | Mean Class 9 GVW | Mean Class 9 ESAL |
|---|---|---|
| 1 | 23000 kg | 1.64 |
| 2 | 26000 kg | 1.72 |
| 3 | 29000 kg | 1.84 |
| 4 | 21000 kg | 1.45 |
| 5 | 21000 kg | 1.34 |
| 6 | 25000 kg | 1.65 |
| 7 | 28000 kg | 1.78 |
| 8 | 35000 kg | 2.01 |
| 9 | 34000 kg | 1.95 |
| **Group Mean** | **27000 kg** | **1.71** |
| **Standard Deviation** | **5100 kg** | **0.22** |
| **Coefficient of Variation** | **0.19** | **0.13** |
| **Standard Error of Mean** | **1700** | **0.07** |

Using this table, the following facts can be determined:

- The average GVW of Class 9 trucks for this group is 27,000 kg.
- This estimate is $\pm$ 3,900 kg with 95 percent confidence (1700 multiplied[15] by 2.31).

Increasing the number of WIM stations included in the sample to 15 sites (and assuming that those stations do not change the standard deviation of the sample) would change the standard error of the mean to 1300 kg. (5100 divided by the square root of 15). This would improve the confidence in the mean value of the GVW/vehicle estimate for the truck weight group to 27,000 kg $\pm$ 2,800 kg with 95 percent confidence.

The improvement comes from two sources. The first is the increased precision in the mean value provided by the increase in the number of samples. The second is the decrease in the value of $t_{\alpha/2}$ used to compute the multiplier in the confidence interval by having a greater sample size upon which to perform the statistical computation.

Table 5-3-4 shows the effect of different sample sizes and confidence intervals estimates of the group mean. Note that increases beyond about six sites in the group sample size has only a marginal effect on the precision of the group mean.

**Table 5-3-4**
**Example Effects of Sample Size on the Precision of GVW Estimates**

| Number of Weigh Sites[16] | Mean Value | Precision of the Mean Value Itself (Standard Error ) | |
|---|---|---|---|
| | | 80% Level of Confidence[17] | 95% Level of Confidence[18] |
| 3 | 27,000 kg | $\pm$5600 kg | $\pm$12800 kg |
| 5 | 27,000 kg | $\pm$3500 kg | $\pm$6400 kg |
| 9 | 27,000 kg | $\pm$2400 kg | $\pm$3900 kg |
| 15 | 27,000 kg | $\pm$1800 kg | $\pm$2800 kg |
| 30 | 27,000 kg | $\pm$1200 kg | $\pm$1900 kg |
| 60 | 27,000 kg | $\pm$850 kg | $\pm$1300 kg |
| 90 | 27,000 kg | $\pm$700 kg | $\pm$1100 kg |

[15] This table uses the Student's *t* distribution for 8 degrees of freedom because of the small number of sample sites within the truck weight road group.

[16] This table uses the Student's *t* distribution because of the small number of sample sites in the group.

[17] The value of $t_{\alpha/2}$ for each sample size using the Student's *t* distribution for a two-tailed confidence interval of $\alpha$ = 80% ($t_{.1}$) is as follows: n = 3, $t_{\alpha/2}$ = 1.886, n = 5, $t_{\alpha/2}$ = 1.533, n = 9, $t_{\alpha/2}$ = 1.397, n = 15, $t_{\alpha/2}$ = 1.345, n = 30, $t_{\alpha/2}$ = 1.282.

[18] The value of $t_{\alpha/2}$ using the Student's *t* distribution for a two-tailed confidence interval of $\alpha$ = 95% ($t_{.025}$) is: n = 3, $t_{\alpha/2}$ = 4.303, n = 5, $t_{\alpha/2}$ = 2.776, n = 9, $t_{\alpha/2}$ = 2.306, n = 15, $t_{\alpha/2}$ = 2.145, n = 30, $t_{\alpha/2}$ = 1.960.

If tighter confidence intervals are deemed necessary, it is always possible to modify the truck weight road groups. Looking at Table 5-3-3, it is apparent that sites 8 and 9 have much higher loads than the remaining seven sites. If these sites are removed from the truck weight group, the computed standard deviation of the GVW per vehicle computed for sites in the group drops from 5100 kg to 3200 kg. This has a dramatic impact on the precision of the estimates computed for the group.

Table 5-3-5 shows the precision level of the truck weight group after removal of these sites. However, note that in order to remove these two sites from the truck weight road group, they must represent some identifiable set of roads. For example, they could be located on the State's only north/south rural Interstate, while the remaining seven sites are on east/eest interstates. Thus the "rural Interstate" truck weight grouping could be divided into two separate truck weight groupings, "rural east/west Interstate" and "rural north/south Interstate."

**Table 5-3-5:**
**Example Effects of Sample Size and Confidence Interval on Precision of GVW Estimates for the Revised Truck Weight Group**

| Number of Weigh Sites[19] | Mean Value | Precision of the Mean Value Itself (Standard Error ) 80% Level of Confidence[20] | 95% Level of Confidence[21] |
|---|---|---|---|
| 3 | 25,000 kg | ±3,500 kg | ±8000 kg |
| 5 | 25,000 kg | ±2,200 kg | ±4000 kg |
| 9 | 25,000 kg | ±1,500 kg | ±2500 kg |
| 15 | 25,000 kg | ±1,100 kg | ±1800 kg |
| 30 | 25,000 kg | ±800 kg | ±1200 kg |
| 60 | 25,000 kg | ±500 kg | ±800 kg |
| 90 | 25,000 kg | ±400 kg | ±700 kg |

The key to correctly creating these truck weight groups is that sites should only be removed from a truck weight group when they can be readily identified with a specific set of roads that experience those loads. All of those roads need to be moved to the new truck weight group.

19 This tables uses the Student's *t* distribution because of the small number of sample sites within the truck weight road group.

20 The value of $t_{\alpha/2}$ for each sample size using the Student's *t* distribution for a two-tailed confidence interval of $\alpha$ = 80% ($t_{.1}$) is as follows: n = 3, $t_{\alpha/2}$ = 1.886, n = 5, $t_{\alpha/2}$ = 1.533, n = 9, $t_{\alpha/2}$ = 1.397, n = 15, $t_{\alpha/2}$ = 1.345, n = 30, $t_{\alpha/2}$ = 1.282

21 The value of $t_{\alpha/2}$ for each sample size using the Student's *t* distribution for a two-tailed confidence interval of $\alpha$ = 95% ($t_{.025}$) is as follows: n = 3, $t_{\alpha/2}$ = 4.303, n = 5, $t_{\alpha/2}$ = 2.776, n = 9, $t_{\alpha/2}$ = 2.306, n = 15, $t_{\alpha/2}$ = 2.145, n = 30, $t_{\alpha/2}$ = 1.960

From the above examples, it is possible to see that changing the number of sites included in a truck weight road group has three effects:

- It changes the computed sample standard deviation for the group (which serves as the estimate of the standard deviation for the entire road group).
- It changes the denominator used to computed the standard error, the statistic used to determine "how well" the mean value computed from that group of roads estimates the mean value for the population being sampled.
- It changes the value of $t$ used to compute the size of the confidence interval applied to estimates produced for that group.

In general, the more sites included in a group, the better the estimates produced by that group, although the benefit of adding sites decreases as the number of sites within a group increases. The effect of using the Student's $t$ distribution to compute confidence intervals means that a significant decrease in the value of $t$ can be obtained by simply adding locations up to a sample size of six. A sample size of six sites has a 10 percent smaller confidence interval at the 95 percent level of confidence than a sample size of five sites, all other things being equal. Beyond six sites, the benefits gained by adding sites begin to decrease quickly. More than six sites in a group may be appropriate, particularly if the State is unsure of its truck weight patterns.

**Based on this analysis, six sites per group are recommended.** The exception to the six-site rule is for truck weight road groups that contain very few roads. These will tend to be specialty roads (e.g., roads leading into and out of gravel pits) that have unusual loading conditions but that are not applicable to many other roads in the State.

If improvements in precision are needed beyond what affordable increases in sample size will achieve, the primary option is to change the make-up of the truck weight groups, i.e., create new subsets of roads that will serve as the truck weight groups. If this change produces a significant decrease in the standard deviation that offsets the increase in $t_{\alpha/2}$ caused by the lower sample size, then the State will benefit from an improvement in the precision of its weight estimates along with a smaller data collection sample size.

## DETERMINING THE NUMBER OF DAYS THAT SHOULD BE COUNTED AT A GIVEN WIM SITE

All of the statistics discussed above start with the critical assumption that each WIM site in a truck weight group produces an accurate estimate of vehicle weights for that location, so that the mean value calculated for the group is accurate. The "accuracy" assumed for the data provided by each WIM scale is not just that the scale weighs the passing trucks correctly but that those weight estimates are representative of weights at that site throughout the year.

For WIM sites where less than a year of data are collected, the assumption is that the time period measured gives an accurate measurement of weights for the entire year.

If the weight data collection period is only 24 or 48-hours long, it assumes that there is no day-of-week difference in the loading condition of trucks passing the site (that is, that trucks traveling on weekends carry the same distribution of payloads as trucks traveling on weekdays), as well as the hypothesis that there are no seasonal differences in truck loading patterns.

At some WIM sites in some States, extensive data collection has shown that these assumptions are quite reasonable. (Butler 1993) At other sites and in other States these assumptions are incorrect (Hallenbeck and Kim 1993). Where truck weights are not stable across days of the week or seasons, the weight monitoring effort has to be extended to account for these differences. For example, the count duration may be extended from two days to seven days to incorporate day-of-week differences. Seasonal differences can be detected and incorporated in the annual estimates by collecting data at each site more than once per year, such as once per quarter.

It is also possible to factor data collected during short duration WIM sessions on the basis of findings from permanent, continuous WIM sites, much like the seasonal adjustments recommended for volume and vehicle classification counts. For example, if one data collection site is operated continuously, the information learned about seasonal patterns from that one site can be applied to other weight data collected within that truck weight group. This step requires the assumption that all sites within the truck weight group experience the same seasonal variation. This process is doable for summary statistics, such as GVW, if sufficient data is available, but it becomes more mathematically complex to seasonally adjust axle weight distribution tables. As seasonality analysis for total volume and vehicle classification data have shown, a large database is needed to identify and quantify temporal variation patterns.

If two or more continuous sites are present in a truck weight group, the seasonal adjustments for both sites can be averaged before being applied to the data collected at the short duration sites. However, if the seasonal adjustments for those sites are significantly different, it is likely that the truck weight road group consists of more than one truck weight pattern. In these cases, splitting the truck weight road group into two or more new groups could be considered.

To date, little work has been published on the seasonal differences in axle weight distributions found in the nation's truck fleet, let alone on the weight characteristics of particular trucking movements found in individual States. However, these seasonal and day-of-week weight changes can have dramatic effects on the selection of the pavement designs that rely on them. The collection and analysis of continuous data collection is the easiest method to begin to understand the temporal variation.

The key for the weight data collection program is to measure and account for both day-of-week and seasonal differences in vehicle weights within each truck weight group. The only way to do this adequately is to have each WIM station providing continuous WIM data, unless analysis has shown that temporal variability is not present. For States with large numbers of continuous WIM stations, there may exist sufficient stations to populate the groups. For smaller States facing resource limitations, the installation of many continuous WIM sites is not an option. **The general recommendation is that each truck weight group should have at least one[22] permanent WIM device collecting continuous data.** This site should be maintained in a calibrated condition, and the data obtained from it should be used to determine whether significant differences exist between vehicle weights (by vehicle class) for different days of the week and different seasons of the year.

The remaining sites within a group can have either short duration counts or additional continuous counts. As with vehicle classification and volume counting, a minimum of 48 hours is recommended. Weight data have been shown to vary by time of day, day of week, weekdays and weekends. As with vehicle classification and volume counts, it is acceptable to use different data collection periods as needs and constraints allow. Because of differences in weekday and weekend vehicle weights, the data collection program should be designed to cover those differences and account for them when statistics are produced. Counts taken for a period of one week eliminate the need for day-of-week adjustment, allow the equipment and traffic conditions to stabilize, provide data verification capabilities, and identify weekday/weekend differences in average weights. **A monitoring period of seven continuous days is recommended for all WIM sites that do not provide continuous data.**

Short duration WIM measurements should be collected with permanently mounted sensors because permanent[23] sensors can be mounted flush to the road surface, providing a more accurate weight measurement. Use of permanently mounted sensors also allows data collection periods to be lengthened at relatively little additional cost.

Portable sensors although not completely ruled out, introduce accuracy issues that may compromise the validity of the data. Organizations using portable WIM sensors, must carefully ensure that the data collected is sufficiently accurate to meet user needs.

## WIM SITE INSTALLATION BY LANE AND DIRECTION OF TRAVEL

There are many issues to consider when installing WIM sites. Current installations range from full coverage for all lanes and directions of travel to the LTPP standard of a single lane in one direction. Some of the issues that should be reviewed when selecting the number of lanes of WIM to install include: available funding, the cost of installation, program objectives to be met, the design of current installations in the State, the trade-offs between obtaining more complete coverage at each site versus less coverage at each site but getting more sites covered, prior experience with WIM equipment, the type of equipment being installed, equipment installation options, specific site characteristics, truck volumes present at the roadway being monitored, use of the scale for or influence

[22] Preferably more than one

[23] Permanent sensors include sites where the sensors are permanently installed but only used periodically; sites where the sensors are installed permanently but the electronics removed from the roadside when not in use, and sites where semi-permanent sensor frames are permanently installed but the actual sensors replaced with a "dummy" scale when not in use.

from nearby enforcement activities, the ability to perform maintenance on equipment at that site, and the ability to perform calibration of the scales.

Analyses of available WIM data have shown that significant differences in loads by direction of travel often occur. The collection of WIM data in at least one lane in each direction of travel at each site allows a clear assessment of directional differences in weights and loadings.

WIM differences by travel lane are generally less significant and difficult to generalize, although previous analyses have shown that the outside lanes tend to carry heavier vehicles. More analysis of current installations is needed before a determination of the cost-effectiveness of covering several lanes at some of the WIM sites or at all sites can be made.

A WIM site covering all lanes and direction of travel provides the most accurate data collection coverage. **At least one continuous WIM station in each weight group should provide WIM coverage for all or a minimum of two travel lanes in each direction.** This will allow future pavement design analysis to cover most possibilities. For multi-lane facilities, covering two lanes in each direction provides the most cost-effective alternative. If all lanes are not monitored by WIM scales, each WIM site should have, at a minimum, a short classification count by direction and travel lane in order to measure truck travel in the lanes not being monitored with WIM. Continuous classification in those lanes may even be preferable.

**For new WIM site installations, at least one lane in each direction of travel is recommended.** Additional lane/direction installations at current sites, such as LTPP sites, depend on many other considerations and should be made based on careful analysis including the examination of vehicle classification data at each site to determine cost-effectiveness. The VTRIS package allows these types of analyses by direction and lane for both vehicle classification and WIM data.

## SITE SELECTION

Most WIM systems also provide counts of vehicle volume by classification and total volume. Consequently, most WIM data collection locations can also provide volume and vehicle classification count data that can take the place of counts required to meet the needs discussed in Sections 3 and 4. Unfortunately, for a variety of technical reasons, WIM data cannot be collected on all roadway sections. Physical constraints on many road sections prevent the collection of accurate weight data. In addition, most States do not have the resources to collect weight data at more than a modest number of locations. Finally, most States already have a significant investment in WIM sites, either as part of their existing truck weight monitoring program or as part of the Long Term Pavement Performance project (LTPP).

Each State should begin to apply the procedures discussed with its existing WIM data collection sites. As a result of the study the addition of sites may become necessary. As existing sites require attention because of failure of the pavement surrounding the WIM sensors or failure of the WIM equipment itself, the need for that WIM station or site should be reevaluated. Sites that are still necessary should be reinstalled. If that site is no longer needed or if other higher priority locations exist, the WIM equipment should be moved to another site.

**New WIM Site Selection Criteria**

The selection of new WIM sites should be based on the needs of the data collection program and the site characteristics of the roadway sections that meet those needs. The needs of the data collection program include, but are not limited to, the following:

- the need to obtain more vehicle weight data on roads within a given truck weight roadway group
- the need to collect data in geographic regions that are poorly represented in the existing WIM data collection effort
- the need to collect data on specific facilities of high importance (e.g., Interstate highways or other National Highway System routes)
- the need to collect data for specific research projects or other special needs of the State
- the need to collect weight information on specific commodity movements of importance to the State.

However, just because a roadway section meets some or all of the above characteristics does not make it a good WIM site. With current technologies, WIM systems only accurately weigh trucks when the equipment is located in a physical environment that meets specific criteria. Thus, States should place WIM equipment only in pavements that allow for accurate vehicle weighing. While individual equipment vendors may require slightly different pavement characteristics to achieve specified results, in general all WIM sites should have the following[24]:

- smooth, flat (in all planes) pavement
- pavement that is in good condition and that has enough strength to adequately support axle weight sensors
- vehicles traveling at constant speeds over the sensors
- access to power and communications (although these can be supplied from solar panels, and through various forms of wireless communications).

In addition, there should be sufficient truck traffic at the site to justify the installation of a WIM data collection site. The actual sites can be selected randomly or

[24] An excellent reference for learning about WIM site requirements is ASTM Standard E-1318, Highway Weigh-in-Motion (WIM) Systems With User Requirements and Test Method.

judgmentally (using the previous list of criteria) from sites that meet all of the site requirements.

Smooth, strong pavement is needed to reduce the effect of vehicle dynamics. Although placing multiple sensors in series (Cebon 1999) can significantly reduce the error that vehicle dynamics produce in individual weight measurements, placement of WIM sensors on smooth, flat pavements that reduce vehicle dynamics significantly improves WIM accuracy, regardless of the equipment used.

Pavement strength can affect sensor accuracy. Weight estimates produced by strip sensors (such as piezo-cables) that are embedded directly into pavements are often affected by changes in pavement strength caused by changes in environmental conditions (e.g., spring thaw periods). A decrease in pavement strength invariably decreases system accuracy. Therefore, WIM sensors should only be placed in strong pavements that are not subject to significant changes in structural response during different seasons. Similarly, WIM sensors begin to become inaccurate as soon as pavements start to rut. In most cases, installations in pavements likely to rut are a poor investment of limited data collection funds.

The requirement for constant vehicle speed (which limits the use of WIM equipment in many urban and suburban areas where routine congestion occurs) is primarily due to the fact that braking and acceleration causes shifts in load from one set of axles to another. This shifting causes "inaccurate" comparison of WIM estimates against static loads.

The availability of power and communications allows extended operation of the WIM equipment. While this is not as crucial for sites intended for short duration WIM counts, the availability of power allows the collection of longer duration WIM measurements. This is particularly helpful for research studies intended to confirm or refute the ability of short duration counts to meet the accuracy needs of the data collection plan. It also allows the WIM site to be used as a continuous classifier or ATR even while weight data are not being collected.

## Integrating the WIM Sites with the Remaining Count Program

Even with all of the constraints described above, most of the existing sites can be used to meet a given weight data collection need. When exploring alternative sites, the "deciding vote" can often be cast by examining how well these alternative sites fit within the existing State traffic monitoring program.

Sites selected for WIM data collection should be located within HPMS volume sample section, if at all possible. If two alternative sites exist to meet a specific need and one is already an HPMS sample site, it should be given priority over the alternative (all other factors being equal). If neither site falls on an HPMS sample section, the selected WIM site should become an HPMS sample section the next time the HPMS sample is revised. The HPMS volume and classification data should be collected at the same time as the WIM data, using the same equipment where practical. This reduces the staffing and resources needed to collect these HPMS data and directly ties the different data items.

## TOTAL SIZE OF THE WEIGHT DATA COLLECTION PROGRAM

The recommendations discussed above lead to the conclusion that the size of the weight data collection program will be a function of the variability of the truck weights and the accuracy and precision desired to monitor and report on those weights.

For a small State that has only two basic truck weight road groups, the basic recommendation would be for a minimum of about 12 weighing locations and two to four continuously operating weigh-in-motion sites. The number of locations could be further reduced if the State worked with surrounding States to collect "joint" vehicle weight data. A larger state with diverse trucking characteristics might have as many as 10 or 15 distinct truck weight road groups, and thus 60 to 90 WIM sites, with a corresponding increase in the number of continuously operating WIM locations. Most States will be between the two extremes presented, and the number of weighing locations should fall somewhere between 12 and 90 locations.

# CHAPTER 4
# TRUCK WEIGHT DATA SUMMARIZATION

WIM data collection provides a number of important summary statistics. These statistics are computed both from individual vehicle weight records and from the axle weight summary distributions that are developed from the scales. The following statistical summaries should be routinely computed and used by States:

- the average number of specific axle groups (i.e., the number of single, tandem, and triple axles) per vehicle for each vehicle (truck) class
- the average number of axles (total) per vehicle for vehicle classes that do not have constant numbers of axles
- the average weight distribution for each type of axle for each vehicle class used by the State highway agency for pavement design.

The AASHTO 2002 Pavement Design Guide (being developed under NCHRP Project 1-37, and currently in draft form) uses inputs of axle load distributions and volumes by vehicle classification to determine the traffic load inputs to the design process. One important input variable that the State highway agency needs to compute and use in that process is the average number of axles (by type of axle) found in each vehicle type. For example, if the state uses the 13 FHWA vehicle classes, it needs to track how many of the 7+axles in Class 13 trucks are single axles and how many are tandem axles. These factors are easily computed as part of the load distribution process. All valid axle weights are counted (by type) for a given vehicle class, and that total is divided by the total number of vehicles weighed in that class. This yields the average number of axles within each axle type for that vehicle class.

The second category of statistical summaries allows the State highway agency to produce a more accurate axle correction factor from vehicle classification data. Several of the FHWA 13 vehicle classes do not contain specifically defined numbers of axles on each vehicle. Class 7 allows four or more axles per single unit truck. Class 8 allows four or fewer axles. Class 10 allows six or more, and class 13 allows seven or more axles per truck. Individual vehicle weight records allow the computation of more precise measures of the mean number of axles per vehicle for each of these types of truck classes.

The NCHRP Project 1-37 draft pavement design guide is designed to allow engineers to account for variation in both traffic load and material properties as environmental conditions change. This allows State highway agencies to account for the effects of spring load restrictions and seasonal changes in commodity flows as part of the pavement design process. However, to take advantage of these new design capabilities, the State highway agency must have the data that describe these load changes.

These data come from collecting and summarizing data from continuously operating WIM sites at different times of the year. Ideally, the State highway agency should create axle weight distribution tables by vehicle class for each period when axle weight distributions change. These axle load distribution tables (by vehicle class) can then be read directly into the new Pavement Design Guide software, where they supply the load information needed to complement vehicle classification volume data collected on different roads.

When analyzed, WIM data will also determine whether changes in axle load distributions occur by season of the year. These changes can (and should) then be used in the pavement design process to improve the reliability of the pavement designs. Seasonal WIM data for each truck road group should be analyzed, since each road group may exhibit different seasonal patterns. This process can result in a considerable number of axle load distribution tables (one per vehicle class, per season, per road group). While this may seem like an excessive amount of data summarization, it is necessary to understand the nature of and account for truck loading patterns in the design process. In addition, by automating the collection and reporting of WIM data, the resources required to perform these tasks can be minimized.

State highway agencies also need to compute axle distribution tables for each vehicle classification scheme the agency intends to use in the pavement design procedures. At a minimum, axle load distribution tables for each of the ten FHWA heavy vehicle categories (Classes 4 – 13) should be used. In order to use a more aggregated vehicle classification scheme (such as the four category scheme "cars, single unit trucks, combination trucks, and multi-trailer trucks"), axle load distribution tables and axle frequency tables for these vehicle classes must be developed. These tables identify how many axles of each type (singles, tandems, tridems, quads) are present on average for each truck class, and what the axle load frequency distribution is for each of those axle types.

In addition to these primary analyses, individual vehicle records from WIM data collection allow a variety of specialized analyses. For example, they can be used to monitor changes in axle spacing configurations that result from changes in vehicle size and weight regulations. Similarly, changes in the relative proportion of specific vehicle configurations that fall within the more generalized vehicle classifications can be examined. For example, what specific vehicle types are classified within the FHWA Class 13 category? This latter analysis is particularly important for summary vehicle classification categories (e.g., "multi-trailer trucks") when limited other data exist with which to monitor the changing composition of vehicles within aggregated classes.

Finally, individual vehicle records serve as an excellent data resource that can be manipulated for a variety of research and planning purposes. For example, with WIM from most types of scales, changes in overall vehicle lengths over time can be examined. This has implications for roadway geometric design and the need for new roadway design standards. Another example is that with some scales, individual vehicle records can be used to monitor the variation in loads between axles in a tandem. Scale data can also be used for a variety of economic studies (fraction of unloaded trucks) and as an independent measure of the effectiveness of applied enforcement strategies. Note that because of the effects of vehicle dynamics, WIM data cannot be used directly to measure the number of over-weight and/or illegally loaded trucks. However, under controlled conditions WIM data can be used to determine changes in the presence of overloaded vehicles. Controlled conditions include the fact that the scale is well calibrated, changes in pavement roughness do not occur during the study, and scale by-pass efforts can either be measured or controlled for. State highway agencies are thus encouraged to collect and store these data in a manner that allows them to be retrieved and used as easily as possible.

# APPENDIX 5-A
# WIM EQUIPMENT ISSUES

This appendix discusses two key issues concerning the use of WIM equipment and data. Both subjects deal with ensuring that the data being collected represent, to the highest degree possible, the vehicle weights being experienced by the roadways. These two subjects are 1) the calibration of WIM equipment and 2) the monitoring of the data reported by WIM systems as a means of detecting drift in the calibration of weight sensors.

## WIM SENSOR CALIBRATION

The FHWA strongly encourages State highway agencies to allocate resources to the calibration of their WIM systems. Calibration of WIM sensors is especially important, because even small errors in vehicle weight measurements caused by poorly calibrated sensors result in significant errors in estimated pavement damage when those axle weights are used in pavement design analyses. Traditional pavement damage calculations use a formula developed as part of the original AASHO Road Test. This formula is a fourth order polynomial. Its is often simplified by stating that damage from a single axle can be computed from the following rule:

$$\text{Damage} = (\text{axle weight in pounds} / 18{,}000 \text{ pounds})^4$$

Figure 5-A-1 shows the general effects of scale calibration error that result from the use of this formula. In this graphic, the X-axis is the percent error in the axle weight, while the Y-axis is the corresponding error in ESAL values. Although the effect of scale drift varies somewhat from site to site, the basic trend is that every 1 percent error that a scale is <u>under</u>-calibrated results in slightly more than a 3 percent under-estimation of the true ESAL value.[25] ESAL computed for heavy axles are affected more by calibration drift than ESALs computed for light axles. So the ESAL error for a site with mostly heavy axles is greater than the error for a site with mostly light axles. Every 1 percent <u>over</u>-estimation in axle weight represents a 4.5 percent over-estimation of ESAL values. Thus, even an over-calibration of merely 10 percent would result in a 45 percent error in estimated damage.

Unfortunately, at this time, an inexpensive WIM calibration system has not been developed. The NCHRP has twice attempted to create improved, lower cost, WIM calibration techniques (Cunagin 1993; Papagiannakis 1995). In both cases, the practices developed have failed to be widely adopted, primarily because of their cost and complexity. Unfortunately, this does not remove the need for WIM system calibration. In addition to the techniques developed by NCHRP, a number of other techniques are

[25] WIM Scale Calibration: A Vital Activity for LTPP Sites, FHWA-RD-98-104, July 1998.

used to ensure that the equipment is initially calibrated and then remains in calibration. These techniques tend to be less robust than the NCHRP procedures, but they provide a process that has a more acceptable balance between the accuracy of the WIM calibration effort and the resources needed to perform it.

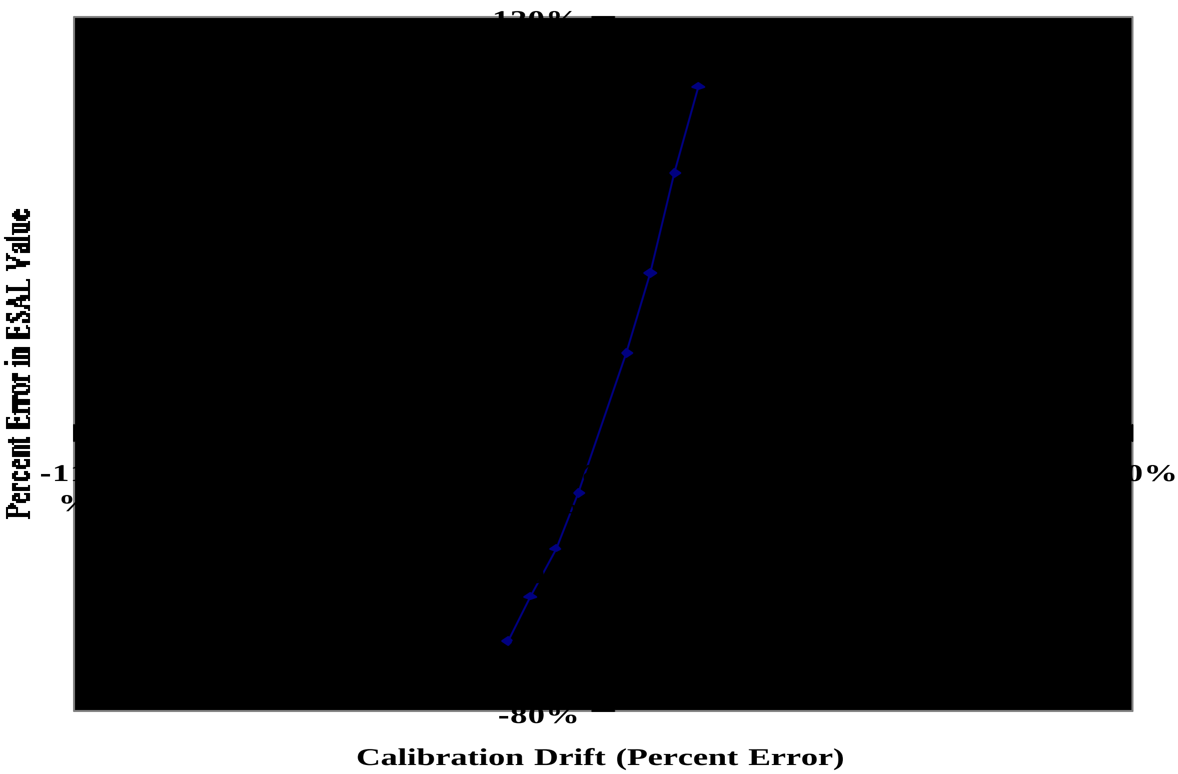


**Figure 5-A-1: Effect of Weigh-in-Motion Scale Calibration Drift on the Accuracy of ESAL Calculations**

The most common of these approaches is to make multiple passes over the WIM scale with one or more test trucks of known (measured) weight. The scale's performance is then compared with the known weights, and adjustments are made to the scale's calibration as necessary (McCall and Vodrazka 1997; Long-Term Pavement Performance Project 1998). Additional passes are then made to confirm that the performance of the scale has improved to the level of accuracy desired.

Several variations to this basic approach exist. These variations usually involve the use of additional vehicles, the performance of test runs at different speeds, or the performance of test runs under different environmental conditions (usually different temperatures). All of these variations have merit. The benefits gained from a specific variant depends somewhat on the specific scale technology being used, the types of environmental conditions that occur at the site while the scale is operating, the type of pavement in which the scale sensors are installed, and the structural response of that pavement.

Test trucks have the distinct advantage of being relatively easy to use and only modestly expensive. In most cases, the most common variant of this technique increases the number of passes performed, and increases the quality of the scale calibration operating under commonly experienced conditions. This improves scale calibration, but also slightly increases calibration costs.

**The drawback to the use of test trucks is the fact that use of a single vehicle (or even two vehicles) to calibrate a scale can create bias in the calibration**, and thus additional steps are needed to ensure the accuracy of the calibration effort. One common method for testing for scale bias is to examine summary outputs from the scale and compare those outputs against known weights (e.g., legal load limits) for trucks commonly found in the road.

Bias in the calibration when a single test truck is used comes from the fact that each truck has its own unique dynamic interaction with a given road. Calibration of a scale to a specific vehicle's dynamic performance (motion) is acceptable when the motion of that vehicle is representative of the traffic stream. Unfortunately, a single test truck is hardly representative of the traffic stream and the calibration effort actually forces the scale to weigh most vehicles inaccurately.

Why this occurs can be explained with a picture. Figure 5-A-2 shows how the force of a truck (or any given truck axle) varies as it moves down the road as a result of the interaction between the vehicle's suspension system(s) and the road's roughness. The vehicle's dynamic motion causes the weight felt by the road to change from location to location. The goal of the WIM calibration effort is to measure this varying force at a specific location (Point A in Figure 5-A-2) and relate it to the truck's actual static weight. To do it, the scale sensor needs to be able to measure the weight actually being applied at Point A, and correct for the bias associated with the fact that at Point A, the truck is actually producing more force than it does when the truck is at rest (because it is in the process of landing as it bounces down the road).

By using a test truck, these two tasks can be performed in one pass. The truck is driven over the scale several times, and the weights estimated by the scale are compared to actual static values. The scale's sensitivity is then adjusted until the weight estimated by the scale equals the known static weight of the truck/axle.

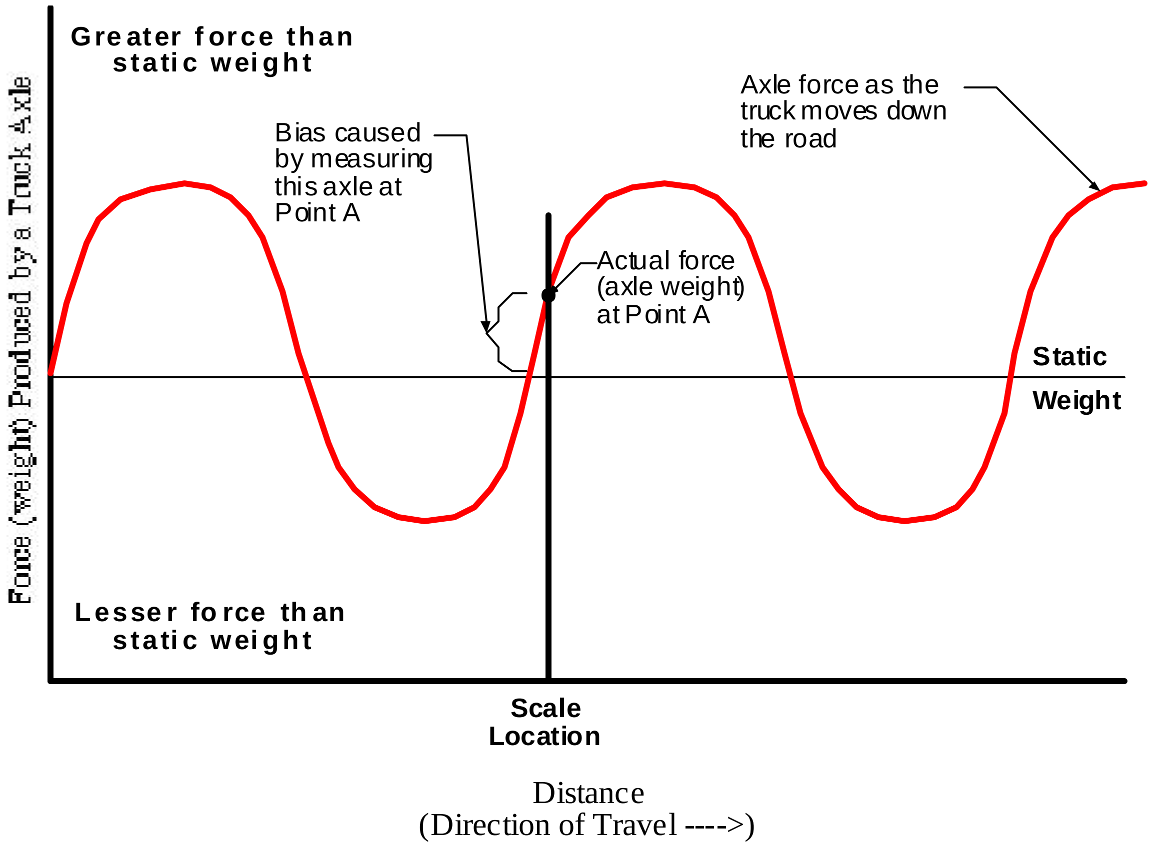


**Figure 5-A-2: Variation of Axle Forces with Distance and the Consequential Effect on WIM Scale Calibration**

The problem with this technique comes from the fact that each truck has a different dynamic motion. When the test truck has a different set of dynamics than the other trucks using that road, the scale is calibrated to the wrong portion of the dynamic curve (Point B shown in Figure 5-A-3). If the scale is calibrated to the dynamic motion of the test truck, it will cause the scale to overestimate the weights associated with the majority of trucks on that road.

To solve this problem there are five basic approaches:

- A scale sensor can be used that physically measures the truck weight for a long enough time period to be able to account for the truck's dynamic motion (this is true of the bridge weigh in motion system approach where the truck is on the "scale" the entire time it is on the bridge deck).
- Multiple sensors can be used to weigh the truck at different points in its dynamic motion either to average out the dynamic motion, or to provide enough data to predict the dynamic motion (so that the true mean can be estimated accurately).
- The relationship of the test truck to all other trucks can be determined. This is often done by mathematically modeling the dynamic motion of the

truck being weighed in order to predict where in the dynamic cycle it is when it reaches the scale.

- More than one type of test truck can be used in the calibration effort (where each test truck has a different type of dynamic response) in order to get a sample of the vehicle dynamic effects at that point in the roadway.
- Independent measurement can be used to ensure that the data being collected are not biased as a result of the test truck being used.

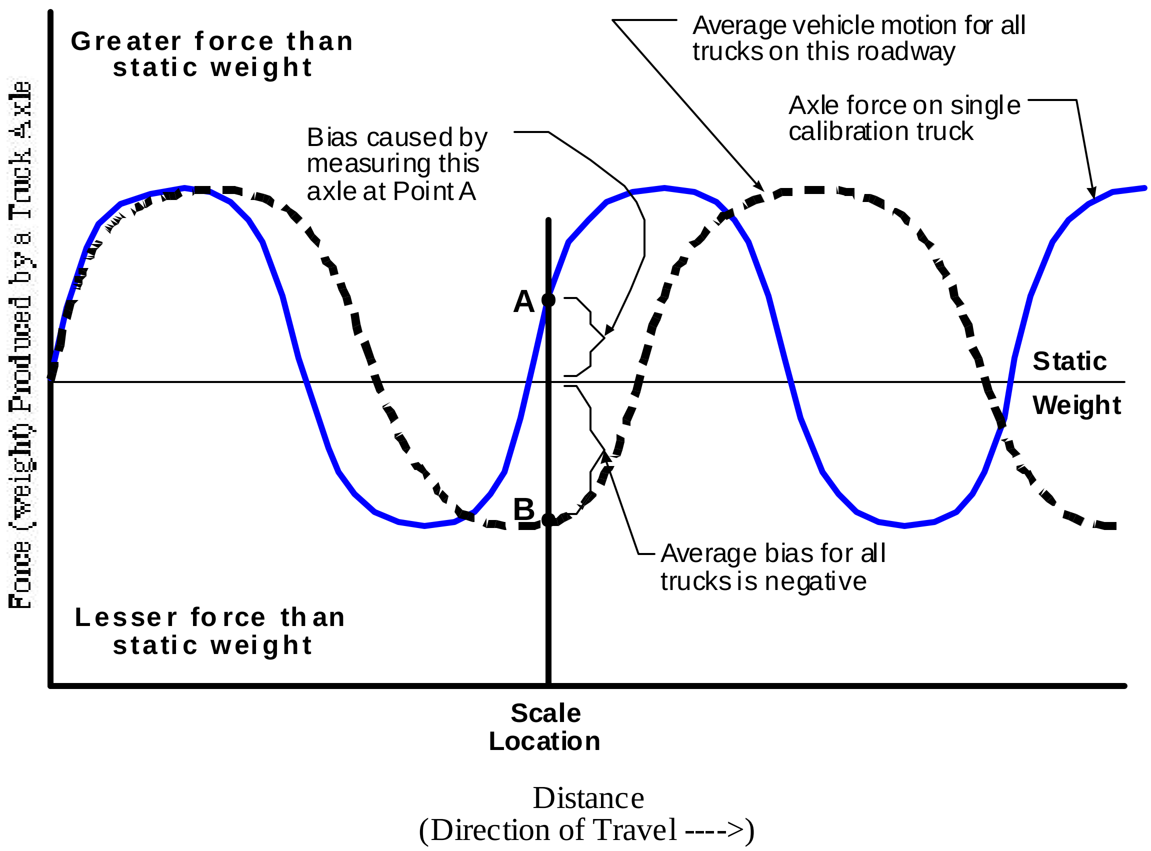


**Figure 5-A-3: Variation of Axle Forces with Distance and the Consequential Effect on WIM Scale Calibration**

The first of these techniques results in a series of other difficult technical problems that result in other accuracy problems. The use of multiple sensors is encouraged from a technical perspective, but most States dislike the added capital costs associated with this technique, although theoretically, it has the best long-term chance of success.

The third technique has strong theoretical backing. However, it is very difficult to perform in the field, both because it requires extensive knowledge about the test truck (dynamic response is not easily/inexpensively measured in the field) and because it requires more technical knowledge than most data collection crews possess.

The FHWA LTPP project recommends the use of multiple test trucks. These trucks should have suspensions typical of the type carrying loads on that road. This allows the calibration process to average between the dynamic relationships that are measured for the different trucks. This technique was selected as a compromise between the simplicity and low cost of using only one test truck and the increased confidence but higher cost of scale calibration performed with larger numbers of trucks.

The technique used by California DOT and presented in the Best Practices Handbook (McCall and Vodrazka 1997; Long-Term Pavement Performance Project 1998) uses independent measures to confirm the scale's performance and reduce the chance for bias. One of these measures is developed by varying the speed of the vehicle crossing the scale. This changes both the period during which the vehicle's tires are in contact with the scale and the dynamic motion of the truck. Another measure is to compare the scale's weight outputs with those of expected truck weights. Specific classes of vehicles in California, primarily the FHWA classes 9 and 11 vehicles, have consistent weight characteristics that can be used to confirm the accuracy of the scale's calibration. However, it is necessary for the individual performing the calibration to understand these characteristics as they apply to that specific WIM site in order to use these factors. That is, unusual truck loading patterns caused by local economic forces (e.g., the presence of a natural resource mining site) can cause trucks passing that scale to exhibit unusual loading characteristics.

Another independent measure that is often used for scale calibration is the front axle of the FHWA class 9 trucks. This measure can be used, but only where the State actually understands the axle weights found on the specific road that contains the scale. It has been found that as truck configurations and weights change, the weight on the front axle of these trucks varies considerably. Changes in truck configuration that are as simple as moving the King Pin[26] connection on a tractor can cause significant differences in mean front axle weight ($\pm$10 to 15 percent) on any given truck. Without having an independent measure of the actual axle front weights present at a site, use of this technique can force the scale's calibration to drift away from the appropriate calibration factor rather than improving the quality of the scale's calibration. However, where this technique is used properly, it can improve scale accuracy.[27]

[26] The King Pin is the main connection between the tractor and the semi-trailer it is pulling. On most tractors, the connection point for the King Pin can be moved by as much as two feet. The closer the pin is set to the vehicle's cab, the better the gas mileage (because of decreased air resistance) but the rougher the ride on the driver. Thus, on rough roads, these connections tend to be set further back, while on smooth roads the connections are closer to the cab.

[27] For some types of sensors, other factors such as changes in sensor sensitivity due to changing ambient temperatures and changes in sensor sensitivity due to changes in pavement response caused by changing environmental conditions are attempted using this technique. The effectiveness of the technique is a function of its application by individual equipment vendors, the characteristics of each individual sensor installation, and the nature of the traffic crossing the installation.

## MONITORING OF WIM DATA OUTPUT

The use of front axle weight for calibration purposes is as much a monitoring function as it is a calibration function. The FHWA's LTPP program and several States have concluded that one of the best methods for obtaining valid truck weight data is to carefully calibrate the WIM equipment, then use a comparison of scale output and expected truck volume and weight statistics to indicate when a scale's calibration or classification accuracy is drifting.

If a measure being tracked changes, then the staff investigate the change. The key is to limit the time spent examining "good data" while concentrating the limited staff time on review of "questionable" results and the repairs needed to fix malfunctioning equipment. If the monitored change can be independently verified as being true, the new pattern is included as an "expected" pattern for that site. When that "new" pattern re-appears at a later date, it then does not need to be investigated further.

The most common statistics applied to monitor the "health" of a WIM scale follow:

- the front axle weight of five-axle, tractor semi-trailer trucks
- the gross vehicle weight distribution of five-axle, tractor semi-trailer trucks
- the spacing of tandems axles on five-axle, tractor semi-trailer trucks
- traffic volumes for various vehicle classes, with particular emphasis on the percentage of vehicles that fall within each FHWA vehicle classification.

### Front Axle Weights of Five-Axle, Tractor Semi-Trailer Trucks

For most roads, the mean front axle weight for these trucks should remain fairly constant. Most statistical tests of this value examine a rolling average of the last 100 front axle weights for vehicles of this configuration. If this mean value changes by more than a given amount (usually determined as a function of the variability of that statistic on that road), then the scale calibration is suspected of drifting.

As noted above, several factors can affect the front axle weight statistic. Among the most important of the factors that should be taken into account when examining changes in front axle weight statistics are the following:

- the total gross weight of the vehicle (more vehicle weight generally raises the front axle weight)
- the spacing between the front axle and the drive tandems on the tractor (generally, the greater the distance between the first and second axles, the lower the front axle weight)
- the roughness of the road (in general, the rougher the road, the lower the front axle weight that can be expected)

- State-specific weight laws and truck characteristics (which have a variety of effects, but often result in significantly different mean front axle weights for roads in different States).

Each of these factors has spawned improvements in the front-axle monitoring concept. One improvement is to track front-axle weights by basic gross vehicle weight category. Another is to monitor front-axle weight relative to axle spacing. A third is to ensure that site specific conditions are accounted for in initially setting the target front-axle weight against which gathered data will be compared.

It is also important to note that the 100 consecutive vehicles must be weighed within a timeframe in which the scale calibration is not expected to change in order to use this mechanism for calibration testing. For example, this statistic is often used as a self-calibration adjustment for piezo-electric cable WIM systems. It is designed to adjust the scale's calibration factor as the temperature changes. Temperature affects both the sensitivity of the piezo-cable itself and the structural response of the roadway that supports that cable.

When truck volumes are high relative to changes in temperature (for example, when over 100 of these trucks an hour cross the scale, and temperatures do not change more than 10 degrees during that hour), then all vehicles being included within any given set of 100 consecutive trucks can be considered to have been weighed under the same relative conditions, and in most cases, the calibration check represents an excellent measure of the scale's need for calibration adjustment.

However, if that scale experiences only five Class 9 trucks per day, it takes 20 days for the scale to observe 100 vehicles. The temperature conditions during those 20 days can be dramatically different for each of the 100 different measurements. In this case, computing a calibration adjustment designed to account for temperature changes is inappropriate, since the conditions under which the adjustment was calculated were not stable. This specific condition has caused many States to disconnect this feature on their scales. In many cases that is the correct decision. However, as noted above, there are situations where this feature does improve a scale's calibration.

## Gross Vehicle Weight Distributions of 5-Axle Tractor Semi-Trailer Trucks

This technique was originally developed by the Minnesota DOT and was later adopted by the LTPP program (Hallenbeck 1994). The participating agency must be able to produce a histogram plot of the gross vehicle weights of class 9 trucks (mostly five-axle tractor semi-trailer trucks). LTPP uses a 4,000-lb. increment for creating the histogram plot, but a State highway agency may use any weight increment that meets its own needs.

The logic underlying the process is based on the expectation of finding consistent peaks in the GVW distribution at each site. Most sites have two peaks in the GVW distribution. One represents unloaded tractor semi-trailers and should occur between

28,000 and 36,000 pounds. This weight range has been determined from data collected at static scales around the country and appears to be reasonable for most locations. The second peak in the GVW distribution represents the most common loaded vehicle condition at that site. It varies somewhat with the type of commodity commonly being carried on a given road and each State's weight limits for five-axle trucks. Generally, the loaded peak falls somewhere between 72,000 and 80,000 lb.

For most sites, the location of these peaks within the GVW histogram remains fairly constant, although the height of the two peaks changes somewhat over time as a result of changing volumes and/or percentages (depending on whether the participating agency is plotting volume or percentage on the vertical axis of the frequency distribution; either will work) of loaded and unloaded vehicles. The reviewer must examine this distribution and decide whether the vehicle weights illustrated represent valid data or the scale either is not correctly calibrated or is malfunctioning. This is easily done when the current graph can be compared with graphs produced from data collected at that site when the scale was known to have been operating correctly.

**Both Peaks Shifted**

If a plot shows both peaks shifted from their expected location in the same direction (that is, where both peaks are lighter than expected or heavier than expected), the scale is most likely out of calibration. The participating agency should then recalibrate that scale at that site and collect new data.

**One Peak Shifted**

If a plot shows one peak correctly located but another peak shifted from its expected location, the site should be reviewed for other potential scale problems (such as a high number of classified but not weighed vehicles or scale failure during the data collection session). Additional information on that site may also be needed to determine whether the scale is operating correctly. Information that can be very useful in this investigation includes the types of commodities carried by class 9 trucks using that road and the load distribution obtained from that scale when it was last calibrated. For example, it might be discovered that a cement plant is just down the road from the WIM scale, and the loaded, five-axle cement trucks are routinely exceeding the 80,000-pound legal weight limit. This might result in acceptance of a loaded peak at that site that exceeds the normal 80,000-pound upper limit for the loaded peak.

If additional information indicates the presence of scale problems, the scale should be recalibrated. If scale calibration shows that the no calibration shift has occurred, this new pattern should be catalogued so that it is accepted in the future. For example, it is possible for shifts in the commodities carried to occur. These shifts can cause the loaded peak to shift, without changing the unloaded peak.

**Number of Vehicles Heavier than 80,000 Pounds**

A second check can be performed with the class 9 GVW frequency distribution by examining the number (and/or percentage) of vehicles that are heavier than the legal limit for the State. It is particularly important to look at the number and percentage of class 9 vehicles that weigh more than 100 kips. If the percentage of overweight vehicles (particularly vehicles over 100,000 lb.) is high, the scale calibration is questionable, although some jurisdictions routinely allow these weights and thus would not question the results. This check must be done with knowledge of a specific State's weight and permitting laws, as well as knowledge of the types of commodities carried by trucks operating on that road.

The 100,000 lb. check is particularly useful in detecting when piezo-electric scales begin to fail, since these scales often generate an almost flat GVW distribution when they begin to malfunction. An axle weight data set produced by such a scale results in an extremely large (and inaccurate) ESAL computation for a given number of trucks. It is also highly unusual for the class 9 trucks to carry such heavy loads. In most cases, trucks legally carrying these heavy weights are required to use additional axles, and they are thus classified as class 10 (or higher) and do not appear in the class 9 GVW graph. While illegally loaded five-axle trucks may be operating at the site in question, most illegally loaded trucks do not exceed the legal weight limit by more than several thousand pounds, and the number (or percentage) of these extremely high weights is usually fairly low. Thus, it is assumed that high percentages of extremely heavy class 9 trucks are a sign of scale calibration or operational problems. On the other hand, if a participating agency routinely permits much higher loads to be carried on five-axle trucks, this check may not be useful.

In either case (scale problems or extreme numbers of overloaded trucks), State personnel should investigate the situation. If the data are valid, notes to this effect should be written and maintained in the calibration file, so that future reviewers are aware of this site's unusual travel characteristics.

## Changes in Tandem Axle Spacings

The mean axle spacing of drive tandems on tractors of class 9 trucks are fairly constant. As a result, several States monitor this statistic to determine whether WIM scale sensors are working correctly. The scale's measurement of this statistic is a function of the scale's ability to accurately measure speed. Speed determination is crucial in several aspects of the axle weight computation process. Thus if the scale is unable to accurately measure speed, it is highly likely that it is not correctly measuring axle weights. Similarly, if the scale cannot accurately measure speed, it will be apparent in the mean distance reported between axles 2 and 3 of three-axle tractors on class 9 trucks.

## Changes in Measured Truck Volumes

This last category of monitoring data consists of comparing expected truck volumes by vehicle classification with expected volumes for those classes. Two different measures are effectively tracked. One is the total volume of trucks by classification. The other is the percentage of trucks within each classification.

Routinely monitoring the total volume of trucks at a WIM site is good, not only because it can provide a key indicator of scale error, but because it will show when significant changes in truck flows are occurring. Analysis performed with LTPP truck volume data show that at many sites, dramatic changes in truck volumes can occur, even on major truck routes, such as rural Interstates. On lower volume roads, 100 percent changes in class 9 truck volumes are not necessarily an indicator of scale malfunction, but knowing that such an increase (or decrease) in truck volume has occurred is critical to understanding the performance of that roadway and the expected lifespan of that roadway's pavement.

On the other hand, some dramatic changes in truck volumes, especially on high volume truck routes, are often an indication of malfunctioning data collection equipment. Malfunctioning axle detectors can result in both the undercounting of axles (resulting in the under-estimation of large truck volumes), and over counting of axles (one common condition is called "ghost axles"), resulting in the over-estimation of large truck volumes. Similarly, a malfunctioning loop detector can cause two cars to be called one truck, or can cause one truck to be split into two or more cars.

Simply monitoring summary truck volumes, such as average daily or even average weekly or monthly volumes allows the detection of changes as they occur. When significant changes occur, independent measures can be used (for example a short manual count, or a call to a local DOT office to confirm the presence of large new truck volumes) to determine the validity of the data. Data that are invalid can then be discarded. Data that are valid can then be stored and used with confidence later.

Monitoring truck percentages (i.e., the percentage of truck volumes within each vehicle classification) is another excellent tool for detecting equipment failures. When sensors fail, trucks are often misclassified. For example, the loss of one axle normally converts a class 9 vehicle into a class 8 vehicle. Thus, a significant shift in truck percentages from class 9 to class 8 is an indicator of possible equipment error.

Monitoring truck percentages and truck volumes is very beneficial. However, it is only truly useful if the State highway agency performs these checks frequently, promptly investigates abnormal conditions, and repairs or removes malfunctioning data collection equipment. Without this prompt follow-up it can be difficult to determine whether abnormalities discovered are caused by real equipment problems or are the result of changes in local traffic conditions. Quality information results from the continuous data collection, improvement, and verification of the data provided.

## APPENDIX 5-B
## FREQUENTLY ASKED QUESTIONS

Should WIM data be collected only on smooth and flat pavements?

WIM data is needed to address pavement design and other uses involving all types of pavement. Data collection mechanisms that provide quality data are needed under all conditions. Indeed the dynamic forces that vehicles apply to the pavement may increase as the quality of the pavement decreases. Research and equipment activities under the auspices of the traffic monitoring program must continue under a variety of roadway conditions. However, under current equipment constraints, the collection of WIM data based on calibrated equipment and comparable to static weight data may only be possible on smooth and flat pavement. The TMG emphasizes the collection of quality WIM data at permanent installations in flat and smooth pavement to insure the quality and veracity of the resulting WIM data. The limited WIM data at these sites is then expanded based on specific road groups and detailed classification data to apply WIM estimates to the complete roadway system. Extended information on these issues is available from ASTM or the LTPP program.

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