On-Site Calibration of Weigh-in-Motion Systems

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The importance of on-site calibration for weigh-in-motion systems has been illustrated by comparing weigh-in-motion weight estimates, made after calibrating the system by three different calibration-loading patterns, against corresponding wheel weights measured on a special static reference scale. Various truck types selected from the traffic on I-10 near Seguin, Texas, were included in the analysis and high, intermediate, and low speeds of in-motion weighing were considered. A pronounced improvement in the accuracy with which weights were estimated by the high and intermediate systems was achieved when six loaded five-axle tractor-trailer trucks, chosen randomly from the traffic stream, were used as the basis for calibration compared with multiple runs of the same loaded two-axle, single-unit test truck. The variability in weigh-in-motion weight estimates was not affected appreciably by the type of moving-vehicle loading that was used as the basis for calibration. Static-weight loading is recommended for low speeds of weigh-in-motion calibration, and moving-vehicle loading is recommended for practicable on-site calibration of higher-speed weigh-in-motion systems. Suggestions are offered on the types of trucks and the minimum number of wheel loads that should be used as the basis for on-site calibration.

State-of-the-art technology in in-motion weighing makes it possible to use measurements of the dynamic tire forces that are applied to the road surface by moving vehicles to estimate the weights of vehicles within certain tolerances. While the currently attainable tolerances are not considered to be acceptable for commercial weighing, they are adequate for applications of weigh-in-motion (WIM) systems for collecting statistical data and for aiding enforcement. With a WIM system, it is practicable to weigh, classify, and measure the speed of every vehicle that passes in each lane of a multilane highway during any chosen time period. Thus, virtually a 100 percent sample of traffic data for statistical purposes can be obtained, and the information can be transmitted immediately in real time, or at some future time, to locations remote from the WIM site via conventional communications networks. At present, WIM systems are applied in enforcement primarily for identifying individual vehicles that are suspected of being in violation of weight or size laws and for locating sites where relatively large numbers of probable weight, speed, or size violations occur.

The magnitude of acceptable error, or tolerance, in WIM weight estimates continues to be a matter of concern. The smallest practically attainable tolerance is, of course, the objective. A number of different factors can cause a WIM-system estimate of wheel weight to vary from the true static weight of the wheel *(1)*. Some of these factors are associated with the WIM system itself and others are related to the roadway, vehicle, and environmental conditions under which in-motion weighing is performed. For a WIM system to perform within small tolerances, the instrument system must make accurate measurements of the vertical component of the dynamic (continually changing) force that is applied to a smooth, level road surface by the tires of a moving vehicle and use these measurements as the basis for calculating an estimate of the static wheel weights. Proper force transducers and the related signal processing equipment are obviously essential components of such a system, along with the required computing power for interpreting the complex dynamic signals. A requisite for using the system is to have the roadway surrounding the transducers as nearly smooth and level as practicable.

It is well known that road surface roughness in the vicinity of WIM scales has a pronounced effect on the dynamic tire forces that result from the vehicle/road interaction *(2)*. Every vehicle will interact with the roughness differently, and vehicle speed will affect the dynamic forces to different degrees. Prevailing environmental conditions such as wind and ice can also affect dynamic wheel forces at a specific time and place, and cause variability in WIM weight estimates. Therefore, even though a particular type of WIM system meets specified performance tolerances at one particular site, it might not perform within the same tolerances at another site. Some of the variability and much of the systematic bias in WIM-system weight estimates that are due to roadway and environmental conditions can be removed or reduced by calibrating the system after it is installed at the site where it will be used. However, fundamental deficiencies in the design or operation of the WIM system itself cannot generally be overcome by calibration.

In this paper, some general concepts and techniques of on-site calibration of WIM systems are presented. The relative effectiveness of two on-site calibration techniques is demonstrated by applying the techniques to rather extensive in-motion-weighing data sets that were obtained in a series of field experiments conducted as part of the Rural Technical Assistance Program (RTAP) WIM Demonstration Program in Texas during the summer of 1984 *(3)*. Recommendations are given for practical on-site calibration of low-speed (LSWIM), intermediate-speed (ISWIM), and high-speed (HSWIM) weigh-in-motion systems.

GENERAL CONCEPTS

The load cells that are used as WIM wheel-force transducers can be calibrated individually in the factory under static load, but the response of the transducer/roadway/tire-loading system

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under dynamic loads cannot be easily evaluated in the laboratory. There is a complex interaction among the various components of this physical system that is unique for every location and vehicle load that is applied to the transducer.

A properly damped wheel-force transducer and a supporting instrument system that is capable of measuring accurately the vertical component of dynamic tire loads in the actual roadway environment are the essential hardware elements of a weigh-in-motion system. A software system that converts these dynamic force measurements into an estimate of the proportion of the gross vehicle weight that the wheel would carry if it were weighed statically must complement this hardware element for an overall WIM system to function.

A number of site-specific conditions such as road-surface roughness, grade, cross-slope near the WIM transducers, behavior of the transducer/roadway combination under dynamic load, and the speed and composition of traffic at the site affect rather significantly the overall accuracy with which a system can estimate static wheel loads. Every vehicle will interact differently; therefore, an on-site WIM-system calibration procedure is necessary if the best possible static weight estimates are to be made for the population of various vehicle types that will cross the WIM system at the site.

The objective of calibration is to make the weights estimated by the WIM system agree as closely as possible with the corresponding weights that would be measured by static scales. It is important to recognize that the proportion of the gross vehicle weight carried by each wheel of a vehicle changes as the vehicle moves over the road surface and stops on the static scale for weighing; thus the wheel force applied to a static scale can vary according to the relative position of the interconnected vehicle components at the time of weighing *(3)*. Perfect agreement between WIM weight estimates and static weight measurements is not expected because the quantity that is being estimated can vary with time and the position of the vehicle components when it is measured on static scales. By calibration, an attempt is made to make the mean value of WIM weight estimates agree as closely as possible with the best estimate of static weight that can be obtained feasibly in practice.

LOADING TECHNIQUES FOR CALIBRATION

Two basic types of loading can be used for on-site calibration of WIM systems: *(a)* static-weight loading, or *(b)* moving-vehicle loading. In the first type of loading for calibration, a known weight is applied to the WIM force transducer either by standard test weights (or force-reaction system) or by the wheels of a standing test vehicle. Standard test blocks provide a much more reliable reference weight than the standing test vehicle as the proportion of the gross-vehicle weight carried by any given wheel of the test vehicle changes as it moves onto the transducers and stops for weighing. In practice, however, it is sometimes difficult or expensive to use standard test blocks as a basis for calibration loading. A loaded test vehicle is usually easier to obtain for this purpose, but considerable care must be exercised in weighing each wheel of the test vehicle statically as well as in positioning the wheels on the WIM transducers. The static-weight loading technique is not generally appropriate for calibrating higher-speed WIM systems because the dynamic behavior of the moving vehicle must be considered as the vehicle interacts with the roadway surface and with the WIM transducers.

The moving-vehicle loading technique is applicable for calibrating intermediate- and high-speed in-motion weighing (ISWIM and HSWIM) systems wherein the dynamic interaction of the vehicle with the WIM system is much more pronounced. In this technique, a single test vehicle with known static wheel weights can make multiple runs over the WIM system transducers at a representative speed of traffic at the weighing site to produce a data set that defines the differences in the WIM-system weight estimates and the known static weights. Or different types of test vehicles with known wheel weights can each make multiple runs over the transducers to obtain a better representation of the various patterns of vehicle/roadway/WIM-system interaction that occur at the site. Alternatively, a single pass of several different trucks, each with known wheel weights, over the WIM system can provide a data set for determining on-site calibration settings for the WIM instrument system.

COMPARISON OF CALIBRATION LOADING TECHNIQUES

The importance of on-site calibration and the relative effectiveness of various calibration loading techniques are illustrated by the data shown in Tables 1 through 3. In these tables, summary statistical inference values from the comparison of a large number of weight estimates made by a Radian WIM system are presented after calibrating the system by three different loading techniques with the respective weights determined by weighing each wheel of the same vehicles statically on a special (two 4- × 6-ft platforms, side by side) axle-load reference scale (the AX/WHL scale). Differences in individual weight values were computed and expressed as a percentage of the reference scale weights. The mean of these percent differences is given along with another statistical value, $\hat{\mu} \pm 2\hat{\sigma}$ which defines the 95 percent confidence intervals into which an individual weight difference would probably fall if it were determined in the same way and under the same conditions that the sampled weight differences were determined.

Calibration of the WIM system for this comparative analysis involved the calculation and application of a single calibration factor (CF) that could be applied as a multiplier to the force signals from each WIM system wheel-load transducer to make the mean of the weight differences for all wheels weighed on each transducer equal zero with respect to the corresponding reference-scale weights. This mathematical adjustment was exactly equivalent to setting the calibration adjustment of the WIM instruments to a particular value in the field.

Table 1 presents information concerning the performance of the HSWIM system after it had been calibrated by three different moving-vehicle loading techniques involving a total of 60 different trucks. On June 6, 1984, the pavement surfaces surrounding the AX/WHL reference scale were warped transversely to a 3 percent cross-slope (to the left-hand side) just beyond the 10-ft-long approach aprons. The HSWIM transducers were installed in the main lanes of I-10 where the cross-slope was 2 percent to the right-hand side *(3)*. Calibration

TABLE 1 SUMMARY STATISTICS OF WIM WHEEL, AXLE, AXLE-GROUP AND GROSS VEHICLE WEIGHT ESTIMATES COMPARED WITH THE RESPECTIVE AX/WHL SCALE WEIGHTS FOR 60 TRUCKS CROSSING THE HSWIM SCALES (± 50 MPH) AFTER CALIBRATION, JUNE 6, 1984

WEIGHT ESTIMATED	STATISTICAL INFERENCE VALUE	BASIS FOR CALIBRATION OF WIM SYSTEM		
		5 RUNS OF A LOADED 2-AXLE TEST TRUCK	7 DIFFERENT LOADED 5-AXLE (3-S2) TRUCKS	60 DIFFERENT TRUCKS
WHEEL	MEAN WEIGHT, LBS AX/WHL SCALE = 4650	4950	4590	4580
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+9.3 (15.0)	+0.8 (11.2)	0.0 (10.5)
	95% CONFIDENCE RANGE $\hat{\mu} \pm 2\hat{\sigma}$	-27.7 to +46.3	-29.0 to +30.6	-27.2 to +27.2
AXLE	MEAN WEIGHT, LBS AX/WHL SCALE = 9300	9910	9180	9170
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+7.5 (9.5)	-0.3 (7.4)	-0.5 (7.4)
	95% CONFIDENCE RANGE $\hat{\mu} \pm 2\hat{\sigma}$	-13.3 to +28.3	-19.6 to +18.9	-19.8 to +18.8
AXLE-GROUP	MEAN WEIGHT, LBS AX/WHL SCALE = 13750	14660	13590	13560
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+6.4 (8.2)	-1.4 (6.1)	-1.6 (6.1)
	95% CONFIDENCE RANGE $\hat{\mu} \pm 2\hat{\sigma}$	-10.9 to +23.6	-17.5 to +14.7	-17.7 to +14.6
GROSS-VEHICLE	MEAN WEIGHT, LBS AX/WHL SCALE = 39200	41780	38720	38640
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+5.9 (6.6)	-1.8 (3.8)	-2.0 (3.8)
	95% CONFIDENCE RANGE $\hat{\mu} \pm 2\hat{\sigma}$	-3.8 to +15.6	-10.8 to +7.2	-10.9 to +7.0

TABLE 2 SUMMARY STATISTICS OF WIM WHEEL, AXLE, AXLE-GROUP, AND GROSS VEHICLE WEIGHT ESTIMATES COMPARED WITH THE RESPECTIVE AX/WHL SCALE WEIGHTS FOR 61 TRUCKS CROSSING THE HSWIM SCALES (± 50 MPH) AFTER CALIBRATION, JUNE 11, 1984

WEIGHT ESTIMATED	STATISTICAL INFERENCE VALUE	BASIS FOR CALIBRATION OF WIM SYSTEM		
		5 RUNS OF A LOADED 2-AXLE TRUCK (2D)	6 DIFFERENT LOADED 5-AXLE (3-S2) TRUCKS	61 DIFFERENT TRUCKS
WHEEL	MEAN WEIGHT, LBS AX/WHL SCALE = 5400	5740	5510	5350
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+7.2 (10.9)	+3.0 (9.0)	0.0 (8.4)
	95% CONFIDENCE RANGE $\hat{\mu} \pm 2\hat{\sigma}$	-17.5 to +31.9	-20.3 to +26.3	-22.3 to 22.3
AXLE	MEAN WEIGHT, LBS AX/WHL SCALE = 10800	11470	11010	10690
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+7.2 (9.2)	+2.9 (7.1)	-0.1 (6.6)
	95% CONFIDENCE RANGE $\hat{\mu} \pm 2\hat{\sigma}$	-11.8 to +26.2	-15.4 to +21.2	-17.8 to +17.7
AXLE-GROUP	MEAN WEIGHT, LBS AX/WHL SCALE = 17000	18040	17320	16820
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+6.1 (7.8)	+1.8 (5.7)	-1.1 (5.6)
	95% CONFIDENCE RANGE $\hat{\mu} \pm 2\hat{\sigma}$	-9.5 to 21.7	-13.1 to +16.8	-15.7 to +13.4
GROSS-VEHICLE	MEAN WEIGHT, LBS AX/WHL SCALE = 49600	52650	50540	49080
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+5.8 (6.4)	+1.6 (4.0)	-1.3 (3.8)
	95% CONFIDENCE RANGE $\hat{\mu} \pm 2\hat{\sigma}$	-3.8 to +15.4	-7.6 to +10.8	-10.6 to +7.6

of the HSWIM scales attempted to make the WIM-estimated weight values agree with the static weights determined on the AX/WHL scale under these conditions. A pronounced improvement in the agreement of the mean weights was made when seven loaded five-axle tractor-semitrailer (3-S2) trucks were used as the basis for calibration compared with five runs of a loaded two-axle single-unit test truck. When differences in the static weights and the WIM weight estimates for all 60 trucks in the data set were taken as the basis for calibration, the resulting mean WIM-estimated weights were virtually the same as those obtained from using the differences from seven loaded 3-S2 trucks as the basis for calibration. The variability in weight differences about the means, as indicated by the 95 percent confidence range, was not affected significantly by the calibration loading technique.

Information about HSWIM weight estimates and corresponding reference-scale weights for 61 trucks on June 11, 1984, is shown in Table 2. The road surface surrounding the

TABLE 3 SUMMARY STATISTICS OF WIM WEIGHT ESTIMATES COMPARED WITH THE RESPECTIVE AX/WHL SCALE WEIGHTS FOR 86 TRUCKS CROSSING THE LSWIM SCALES (< 10 MPH) AFTER CALIBRATION, JULY 6, 1984

WEIGHT ESTIMATED	STATISTICAL INFERENCE VALUE	BASIS FOR CALIBRATION OF WIM SYSTEM		
		STANDARD 1000 LB TEST WEIGHTS	7 DIFFERENT LOADED 5-AXLE (3-S2) TRUCKS	86 DIFFERENT TRUCKS
WHEEL	MEAN WEIGHT, LBS AX/WHL SCALE = 5180	5190	5200	5140
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+1.0 (6.5)	+1.0 (6.0)	0.0 (6.0)
	95% CONFIDENCE RANGE $\hat{\mu} + 2\hat{\sigma}$	-16.4 to +18.4	-15.2 to +17.2	-16.0 to +16.0
AXLE	MEAN WEIGHT, LBS AX/WHL SCALE = 10350	10,390	10350	10290
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+0.9 (4.7)	+0.9 (4.7)	-0.1 to (4.7)
	95% CONFIDENCE RANGE $\hat{\mu} + 2\hat{\sigma}$	-12.3 to +14.1	-12.2 to +14.1	-13.1 to 13.0
AXLE-GROUP	MEAN WEIGHT, LBS AX/WHL SCALE = 15700	15750	15760	15600
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+0.2 (3.9)	0.2 (3.8)	-0.8 (3.9)
	95% CONFIDENCE RANGE $\hat{\mu} + 2\hat{\sigma}$	-10.6 to +10.9	-10.5 to +10.9	-11.4 to +9.8
GROSS-VEHICLE	MEAN WEIGHT, LBS AX/WHL SCALE = 44180	44320	44340	43900
	MEAN OF DIFFERENCES, % (MEAN OF ABSOLUTE DIFFERENCES)	+0.4 (2.6)	0.4 (2.6)	-0.6 (2.6)
	95% CONFIDENCE RANGE $\hat{\mu} + 2\hat{\sigma}$	-6.0 to +6.7	-5.9 to +6.8	-6.8 to +5.7

AX/WHL reference scale had already been leveled with premixed asphalt paving material. A different group of trucks was weighed, but again, a noticeable improvement in the agreement between mean weight values occurred when five-axle tractor-semitrailer (3-S2) trucks were used for calibration loading rather than multiple runs of the same loaded two-axle test truck. Slight improvement over the 3-S2 truck loading resulted from taking all 61 trucks in the data set as the basis for calibration. The range in variability of the weights was slightly less on this day than it was on June 6, 1984, when the road surfaces beyond the reference scale approach slabs were warped to a 3 percent cross-slope.

The information in Table 3 pertains to weight measurements on 86 trucks that were weighed on the low-speed weigh-in-motion (LSWIM) scales on July 6, 1984. On this day, the adverse cross-slope in the pavement surfaces beyond the level approach aprons to the reference scale had been removed and the LSWIM scales had been reinstalled in the leveled surface. Thus, no adverse performance of either the static reference scale or the LSWIM scale can be attributed directly to an uneven surface. It can be seen from the tabulated values that the mean difference in weights from the LSWIM system was 1.0 percent or less for all calibration techniques including dead-weight test blocks. Variability in the percentage differences, as indicated by the 95 percent confidence range, systematically increased from about ±6 percent for gross-vehicle weights to about ±16 percent for wheel weights.

Overall, this comparison indicated that a much better HSWIM or ISWIM system calibration (not included here) was achieved with loaded tractor-semitrailer (3-S2) trucks than with multiple runs of a loaded two-axle (2D) single-unit test truck. The sample of trucks for these data sets contained approximately 60 percent 3-S2 types of trucks, which was representative of the normal kind of truck mix in the traffic stream at the experimental site. As indicated earlier, LSWIM system calibration was best achieved with the static-weight loading technique.

WIM WEIGHT ESTIMATES FOR TWO TRUCK TYPES

Data from the WIM demonstration project that was referenced previously have also been analyzed to study the performance of a high-quality in-pavement WIM system with respect to the consistency of the weight estimates that were produced for two different truck types. These data were taken from the Radian WIM system after the system had been calibrated on site with calibration loading provided by multiple runs of a loaded two-axle, single-unit test truck. Calibration settings on the system were not changed throughout the 2 weeks of data-taking during the project; therefore, the calibration settings in effect at the time when the selected data set was taken are not necessarily the best possible ones. Nevertheless, the data for the two truck types are comparable as the WIM-system operation was the

TABLE 4 SUMMARY STATISTICS OF WIM WEIGHT ESTIMATES COMPARED WITH RESPECTIVE REFERENCE (AX/WHL) SCALE WEIGHTS FOR TRUCKS CROSSING WIM SCALES AT LOW (< 10 MPH), INTERMEDIATE (30 MPH), AND HIGH (50 MPH) SPEEDS. FIVE RUNS OF THE SAME TWO-AXLE SINGLE UNIT

WEIGHT	STATISTICAL INFERENCE VALUES	WEIGHTS FROM WHEELS ON LEFT SIDE			WEIGHTS FROM WHEELS ON RIGHT SIDE		
		LSWIM	ISWIM	HSWIM	LSWIM	ISWIM	HSWIM
WHEEL	MEAN WIM WEIGHT, lbs	5890	5590	5140	5875	5835	5635
	MEAN REFERENCE-SCALE WEIGHT, lbs	5610	5610	5610	5835	5835	5835
	MEAN OF DIFFERENCES, %	+3.6	-1.6	-7.4	+0.5	-1.1	-2.7
	STANDARD DEVIATION IN DIFFERENCES, ± %	3.8	5.6	6.7	2.9	5.4	4.2
GROSS	MEAN WIM WEIGHT, lbs	11780	11180	10280	11750	11670	11265
	MEAN REFERENCE-SCALE WEIGHT, lbs	11225	11225	11225	11670	11670	11670
	MEAN OF DIFFERENCES, %	+4.9	-0.4	-8.4	+0.7	0.0	-3.4
	STANDARD DEVIATION IN DIFFERENCES, ± %	1.7	4.9	3.3	2.9	4.4	2.8

SINGLE PASS OF 6 DIFFERENT 5-AXLE TRACTOR-SEMITRAILERS

WEIGHT	STATISTICAL INFERENCE VALUES	WEIGHTS FROM WHEELS ON LEFT SIDE			WEIGHTS FROM WHEELS ON RIGHT SIDE		
		LSWIM	ISWIM	HSWIM	LSWIM	ISWIM	HSWIM
WHEEL	MEAN WIM WEIGHT, lbs	7655	7815	7040	8305	8315	8300
	MEAN REFERENCE-SCALE WEIGHT, lbs	7650	7650	7650	7860	7860	7860
	MEAN OF DIFFERENCES, %	+0.1	+2.0	-8.1	+5.2	+6.0	+6.2
	STANDARD DEVIATION IN DIFFERENCES, ± %	9.3	8.0	7.1	10.5	6.3	9.5
AXLE-GROUP	MEAN WIM WEIGHT, lbs	12755	13025	11730	13840	13860	13835
	MEAN REFERENCE-SCALE WEIGHT, lbs	12750	12750	12750	13100	13100	13100
	MEAN OF DIFFERENCES, %	-0.8	+0.6	-8.8	+3.7	+5.7	+6.8
	STANDARD DEVIATION IN DIFFERENCES, ± %	8.0	7.5	5.5	10.0	5.5	8.3
GROSS	MEAN WIM WEIGHT, lbs	38265	39075	35190	41515	41570	41505
	MEAN REFERENCE-SCALE WEIGHT, lbs	38255	38255	38255	39310	39310	39310
	MEAN OF DIFFERENCES, %	+0.1	+2.2	-8.0	+5.7	+5.7	+5.6
	STANDARD DEVIATION IN DIFFERENCES, ± %	2.5	4.0	2.1	3.6	4.1	4.3

same throughout the session (June 11, 1984). The road surface surrounding the AX/WHL reference scale was level on this day. Judgment about the possible consequences of using only one type of truck for calibration loading can perhaps be improved by studying this data set.

Summary statistical inference values about the relationships among WIM weight estimates and the corresponding static weights from the reference (AX/WHL) scale are presented in Table 4. In computing these values, the weights of wheels on each side of the trucks were considered separately. Each truck passed successively over the HSWIM, ISWIM, and LSWIM transducers in each wheelpath at the approximate speed shown in the table heading before stopping for sequential weighing of the wheels on each axle by the reference scale. An arithmetic mean was calculated for the reference-scale weights and for the WIM-estimated weights for wheels, axle groups, and gross on each side of the truck for each scale. Next, the difference in the reference-scale weight and the WIM-estimated weight was calculated and expressed as a percentage of the reference-scale weight. An arithmetic mean of these differences was then calculated along with the standard deviation and shown in the table. It is pointed out here that the mean of the differences may be numerically different from the difference of the means. The mean of differences, in this analysis, indicates the average amount by percent by which the individual WIM-estimated weights differed from the corresponding reference-scale weights. The standard deviation in differences indicates the percentage range about the mean into which approximately 68 percent of the weight/weight estimate differences would be expected to fall in a normally distributed population of observations. In this data set, the number of observations is too small to test for normality adequately, but other experience with similar, larger samples indicates that the differences tend to be normally distributed. Thus, the magnitude of the standard deviation in differences can be viewed as a measure of the expected variability scatter in the observed differences.

The left-side LSWIM scale indicated slightly higher weight estimates, on average, than the reference scale for the two-axle truck but nearly the same weight estimates, on average, for the six five-axle trucks. Scatter in the weight differences, as indicated by the standard deviation, is much larger for the six different five-axle trucks than for the two-axle truck. The right-side LSWIM scale gave virtually the same average weights for the two-axle truck but considerably heavier average weight estimates for the five-axle trucks. The pattern and magnitude of scatter are similar to those for the left-side LSWIM values. It is interesting to note that the largest standard deviation (10.5 percent) in the differences was for wheels on the five-axle trucks on the right-side LSWIM scale.

The left-side ISWIM scale produced quite small means of differences for both types of trucks. All values were within ±2 percent. The standard deviation in the differences ranged between 4 and 8 percent. The right-side ISWIM scale, however, had very small means of differences for the two-axle truck, but values of about +6 percent for the five-axle trucks. The standard deviation of the samples ranged between 4.1 and 6.3 percent for all trucks weighed on this scale.

The mean of differences from the left-side HSWIM scale for both truck types ranged between −7.4 and −8.8 percent. This is the most consistent pattern of differences for both truck types in the data set. The standard deviation in the weight differences from this scale also followed a consistent pattern. The right-side HSWIM scale, on average, underestimated weights for the two-axle truck by about 3 percent and overestimated weights for the six different five-axle trucks by about 6 percent. The standard deviation in the differences for the five-axle trucks was nearly double that for the two-axle truck.

In interpreting these observations, it is important to remember that data from three different WIM systems are presented in Table 4. Each system incorporated transducers and associated instrumentation for each wheelpath (left side and right side). These instruments can be adjusted (calibrated) individually to increase or decrease proportionally the magnitude of the weight estimate within a range of settings provided on the instruments. The calibration settings were not optimized for the particular trucks that have been selected for analysis. The road-surface conditions surrounding every transducer might have been slightly different, thereby affecting the dynamic behavior of each truck wheel that crossed the transducer in a different way.

The relative effects of using only one type of truck, say, the two-axle, single-unit, for calibration loading can be appraised by making a rough estimate of the proportional change in the weight estimates for the five-axle tractor-semitrailers that could be expected if the WIM-system calibration were adjusted to make the mean of differences for the two-axle, single-unit wheel weights equal zero. This would result in the left-side LSWIM scale's underweighing the five-axle units by about 4 percent, and would make the right-side LSWIM scale overweigh these units by about 5 percent. The ISWIM scales would tend to overweigh the left side of the five-axle trucks by about 4 percent and the right side by about 7 percent. The left-side HSWIM scales at this site would probably weigh the five-axle units correctly, and the right-side scales would tend to overweigh these units by about 9 percent. These relationships suggest that the dynamic behavior of the wheels on the five-axle, tractor-semitrailer trucks was different from that for the wheels on the two-axle, single-unit truck at the time that the wheel-force sample was taken by the WIM system. The left-side HSWIM scale weight estimates were least affected by the type of truck, and the right-side HSWIM scale weight estimates were most affected. This points out the need to consider each side of the truck separately in calibrating a WIM system on site. The data set also reflects the fact that the trucks observed were not symmetrically loaded side to side (see Mean Reference-Scale Weight, Table 4). The left side of the two-axle, single-unit test truck was nearly 4 percent lighter than the right side, and the left side of the six five-axle, tractor-semitrailers averaged almost 3 percent lighter than the right side when weighed statically on the reference scale.

In summary, this analysis seems to suggest, as does the one presented in the previous section, that the vehicle types used for calibration loading should be proportioned so that they are representative of the mix of truck types that are expected at the WIM site. At least some consideration must be given to whether the calibration-loading trucks should incorporate tandem-axle groups. It appears that trucks with this axle arrangement interact with the WIM system differently from trucks without tandem axles.

COMPUTATION OF CALIBRATION FACTORS

A procedure for calculating a multiplier, or CF, is then developed that can be applied to the wheel force signals in a WIM system to adjust the mean of the expected differences in the WIM weight estimates and the corresponding static weights to zero for a particular site. Differences in WIM weight estimates and measured static weights for a representative sample of vehicle types selected for calibration loading at each site provide the basis for deriving the required CF. A statistical analysis of the wheel weights for a large group of trucks that were selected from the normal traffic stream indicated that there was a significant difference in the loads carried on the left- and right-side wheels of an axle (discussed in the next section). The computational procedure for CFs, therefore, uses left- and right-side wheel-weight data sets separately. Differences can be calculated for wheel weights by using the following equation:

$$D_i = (W_i - W_{o,i})/W_{o,i} \qquad (4\text{-}1)$$

where

D_i = difference in the individual wheel weight estimated by the WIM system and that measured by the static scale expressed as a fraction of the corresponding wheel weight measured by the static scale,

W_i = wheel weight estimated by the WIM system for observation i, and

$W_{o,i}$ = wheel weight measured by the reference scale for observation i.

The average relative difference is

$$\bar{D} = \frac{1}{n}\sum_{i=1}^{n}[(W_i - W_{o,i})/W_{o,i}] = \frac{1}{n}\sum_{i=1}^{n}\left[\left(\frac{W_i}{W_{o,i}}\right) - 1\right] \qquad (4\text{-}2)$$

where n = number of observations.

For a given sample of wheel weight data, the value of this average relative difference, for left or right wheels, or both, will fall into one of the following categories:

$\bar{D} = 0$, meaning that it is not necessary to perform an on-site calibration.

$\bar{D} \neq 0$; in this case, on-site calibration is needed. The CFs can be computed from calibration-loading wheel-weight data. Note that CFs may be different for each transducer.

For the second category, a CF can be derived using a set of wheel weight data, as follows. The value of $\bar{D}$ equals the required adjustment to the wheel-weight estimate, a, thus,

$$\bar{D} = \frac{1}{n} \sum_{i=1}^{n} \left[\left(\frac{W_i}{W_{o,i}} \right) - 1 \right] = a \qquad (4\text{-}3)$$

This expression (4-3) can also be stated as

$$\frac{1}{n} \sum_{i=1}^{n} \left(\frac{W_i}{W_{o,i}} \right) = 1 + \bar{D} \qquad (4\text{-}4)$$

where $\bar{D}$ is not equal to zero (i.e., $\bar{D} = a$).

In order for $\bar{D}$ to fall into the first category previously mentioned (i.e., $\bar{D} = 0$, so that, on the average, WIM-estimated weights will not be different from static weights), the right-hand side of the expression (4-4) must equal 1.0. Both sides of the expression can be multiplied by $1/(1 + \bar{D})$. This puts the expression for $\bar{D}'$, the mean of differences in adjusted weight estimates and corresponding static weights, in the form:

$$\bar{D}' = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{W_i}{W_{o,i}} \right) \left(\frac{1}{1 + \bar{D}} \right) - 1 = 0 \qquad (4\text{-}5)$$

The multiplier, $1/(1 + \bar{D})$, is the CF that can be applied to WIM wheel-weight estimates to make the average difference in the estimates and the respective static weights equal zero. The CF is simply computed as the reciprocal of the value of $\bar{D}$ (as derived from the data set for each wheel-force transducer, separately) increased by one. This calibration adjustment can be made directly to the force signals from each transducer in the WIM-system instruments or applied to the estimated weights computed by the system.

DISTRIBUTION OF AXLE WEIGHTS ON LEFT- AND RIGHT-SIDE WHEELS

The weight on an axle is usually assumed to be distributed approximately equally between the right and left wheels of the axle; therefore, the gross weight of the truck is assumed to be approximately equally shared by the wheels on the right and left sides of the truck. This assumption is frequently made in analyzing truck-weight data for pavement design and other purposes and is sometimes used for estimating axle loads after the wheels on only one side of a truck have been weighed either statically or dynamically. For example, in Texas, the practice of collecting statistical truck-weight data for many years involved weighing only the right wheels of selected vehicles on a wheel-load weigher and doubling this value for axle weights.

Because the design of pavement and bridge structures is based to a significant extent on the analysis of stress in the structures caused by loads applied to the road surface by the individual wheels of a moving vehicle, wheel-weight data are fundamental. In some pavement design procedures, however, simplifying assumptions that account only for axle loads are made. In order to satisfy the design information needs of all users, a code-specified WIM system should estimate both wheel weights and axle weights for each vehicle. In addition, because the most significant uncontrollable vehicle factor affecting in-motion weighing is tire condition, and because all axle loads are not equally distributed among the wheels of an axle, there is a need for weighing all individual wheels on both sides of a vehicle. Furthermore, weighing on both sides reduces the chance of losing weight data on a truck completely when one of the two WIM system transducers malfunctions. One operable transducer can provide wheel-weight data and serve as a basis for estimating axle loads with some degree of reduced reliability.

Analysis of the wheel-weight data set that was obtained on July 6, 1984, from the special static AX/WHL scale (described previously) indicated that the total weight carried on a tandem axle group (on five-axle tractor-semitrailer trucks of the 3-S2 type) was not equally distributed among all four wheels in the group. Furthermore, this analysis indicated that differences between individual wheel weights and the mean weight of all wheels in the tandem axle sets on the semitrailers were larger than the differences for wheels in the drive-trandem axle groups. By examining this same set of wheel-weight data, a comparison was made of the static wheel weights on the left and right sides of 100 trucks. Data for this comparison are presented graphically in Figure 1.

As shown in Figure 1*a*, individual wheel weights are represented by plotting the left wheel weights against those on the right side of the same axle. This graph clearly indicates that the assumption of equal wheel weights on an axle is not valid, as most of the plotted points do not lie exactly on the 45 degree sloping line of equality. Another form of graphical representation of the data (see Figure 1*b*), indicates the relative difference in the left-wheel weight as a percentage of the right-wheel weight. The right wheel was selected arbitrarily as the reference wheel. It may be noted from Figure 1*b* that, on average, the left-side wheels on these trucks were 3.7 percent heavier than the right-side wheels and that the percent difference in the left-side wheel weight compared with the respective right-side wheel weight on the same axle ranged from 42 percent less to 60 percent more. The results of the Shapiro-Wilk W test *(4, 5)* indicate that these percentage differences can, for statistical analysis purposes, be considered to be normally distributed; therefore, statistically based inferences can be drawn about the probability of wheel weight differences exceeding certain magnitudes due to chance alone. The statistical interpretation of the information shown in Figure 1*b* indicates that, for this population of trucks, 5 percent of the relative differences in the left-side and right-side wheel weights on an axle can be expected to lie outside the −18.1 and +25.4 percent levels. Another statistical test on this data set indicated that the mean value of left-side wheel weights was significantly different from the mean value of right-side wheel weights at a 1 percent confidence level. A greater difference than that observed in the mean values would be expected to occur due to chance alone only once in 100 observations; therefore, it can be concluded that the left-side wheel loads were in fact heavier than the right-side wheel loads for this population of trucks on the average.

Further statistical tests were performed to determine whether there was a statistically significant difference in the average

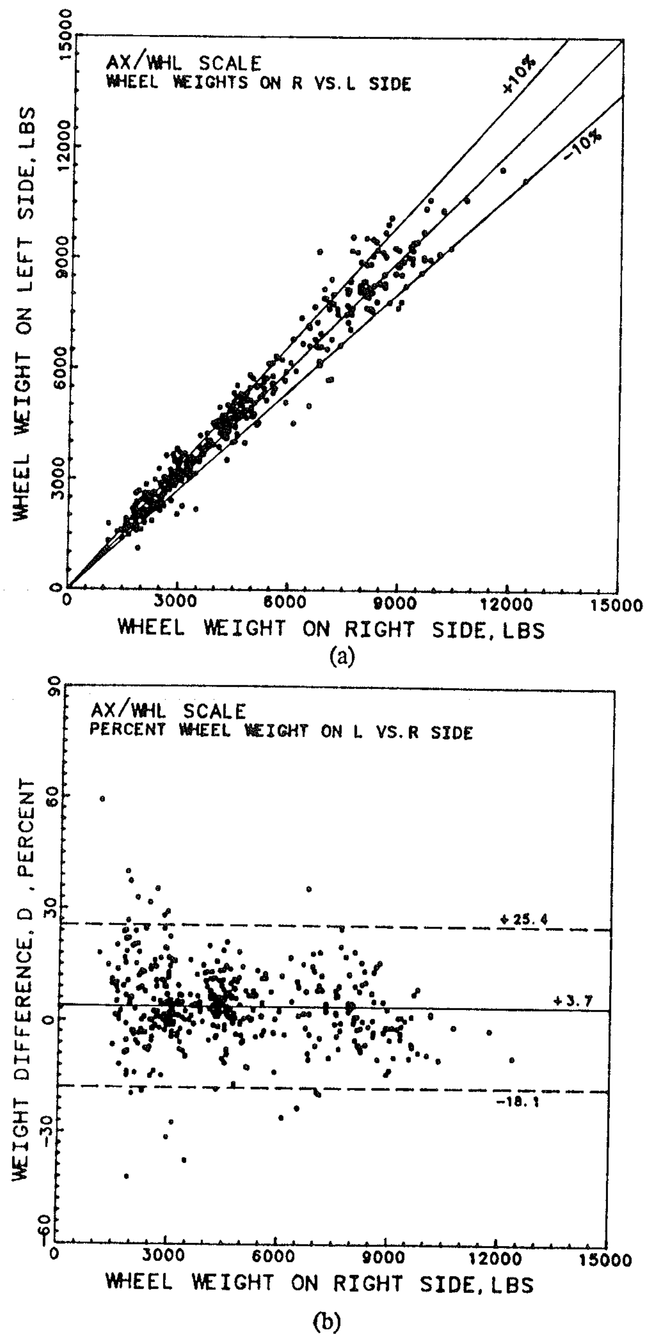

FIGURE 1 ***(a)* Comparison of the weight of the wheels on the same axles on 100 trucks weighed simultaneously on the AX/WHL scale, *(b)* Percent difference in left-side wheels with reference to right-side wheels.**

side-to-side loading of axle groups and in the proportion of the gross vehicle weight carried on the wheels on each side of the trucks. Results of this analysis are summarized in Table 5. The tests indicate that there was a statistically significant difference in the average side-to-side loading of trucks when considering individual axles, axle groups, or gross vehicle weight.

RECOMMENDATIONS

The following recommendations concerning the calibration of WIM systems are based on an evaluation of the previously described data sets and on other experience with the installation and operation of weigh-in-motion systems. Consideration is given to the practicability, safety, and expense of conducting this essential operation on site and under traffic. The need for using wheel weights rather than axle, axle-group, or gross-vehicle weights as the basis for calibration loading has been pointed out.

TABLE 5 SUMMARY STATISTICS FOR LEFT AND RIGHT WHEEL WEIGHTS FROM AX/WHL SCALE

STATISTIC	WHEEL WEIGHT	AXLE GROUP WEIGHT	GROSS VEHICLE WEIGHT
Average Right, Lbs	4719	7213	20340
Average Left, Lbs	4841	7398	20863
Mean Difference, Lbs	121.4	185.6	523.4
Standard Deviation of Differences	483.1	642.3	1328.2
Size of Sample	431	282	100
Z-Value	5.22*	4.82*	3.94*
+ Mean Relative Error, %	+3.67	+3.41	+2.73
+ Absolute Mean Relative Error	8.40	6.72	5.37
+ Standard Deviation for Relative Error	10.88	7.97	6.23

* Significant at 95% Confidence Level
+ Weights on the Left With Reference to Right-Side Weights

Before on-site calibration, the inherent limits on the performance capability of each new commercial WIM system configuration should be established under as nearly ideal site conditions as possible via a nationally recognized type-approval program so that each WIM-system user is not required to duplicate this extensive effort. Basic defects or deficiencies in the design or operation of a WIM system cannot be overcome by calibration. On-site calibration can be used, however, to compensate partially for the systematic (biasing) effects of certain local conditions, such as unevenness in the road surface, on WIM-system estimates of vehicle weights.

An accurate determination of the loads that are to be used as the basis for calibrating a WIM system is obviously necessary. If standard dead-weight test blocks are used, these must be of known quality. Likewise, if a force-reaction system (e.g., ram and load cell) is used, the accuracy of the indicated force must be known. If vehicle loading is used, the proportion of the gross-vehicle weight carried by each wheel of the calibration-loading vehicle while its components are in the same attitude as when applying force to the WIM-system transducers must be known. Experience has shown *(3)* that the proportion of gross-vehicle weight that is carried by each individual wheel changes as the wheels move over the road and stop on the scales for weighing and that elevating or lowering the wheel during weighing also causes a load transfer. These effects must be recognized when determining the static wheel weights that will be referenced as the loads used for calibrating a WIM system.

The most practical way to measure the individual wheel weights on vehicles that will be used for on-site calibration loading of a WIM system is with wheel-load weighers. These devices are portable and are designed especially to measure wheel loads. Good equipment and proper use of the equipment are both mandatory if accurate measurements are to be obtained. Because all wheels of the vehicle need to be in the same horizontal plane at the time of weighing, multiple (4 or 6 preferred) wheel-load weighers and suitable blocking are required for operating efficiency on a smooth, level surface. Low-profile wheel-load weighers that support dual tires are easier for the vehicle to mount and cause less difficulty when the wheels on the active weighing surfaces are aligned. The lower height also reduces the amount of displacement of vehicle components during the static wheel-weighing process. Alternatively to wheel-load weighers, certain configurations of portable, or fixed, axle-load scales can be used to measure individual wheel loads. It is generally not feasible to weigh individual wheels on a vehicle scale.

LSWIM (< 10 mph) scales should be calibrated against static reference loads. These loads may be applied by standard test weights, a force-reaction system, or the wheels of a standing vehicle. In any case, the range in applied loads should cover the expected-use range (e.g., 1,000–15,000 lb) of interest and include a sufficient number of increments to evaluate the linearity of the system.

ISWIM (±30 mph) and HSWIM (±50 mph) systems should be calibrated with moving-vehicle loads at the time of initial installation and periodically thereafter whenever the local conditions change appreciably. The individual wheel weights of the calibration-loading vehicles must be known. The types of calibration-loading vehicle should be representative of the types of vehicles that are to be weighed at the site. Tandem-axle vehicles seem to interact with the WIM site-specific condition differently from vehicles with only single axles; therefore, the calibration-loading vehicles should have tandem-axle sets if a significant number of tandem-axle weights are to be estimated by the WIM system. If a large proportion of any particular vehicle type is expected (e.g., five-axle, tractor-semitrailers), this vehicle type should be included among the calibration-loading vehicle types. If a single calibration-loading vehicle is to be used, it should have tandem axles. Most heavy axle loads are carried on multiple-axle groups (tandems, triples, and so on); these are loads of critical interest from both the statistical data and the enforcement viewpoint.

A minimum of 30 wheel loads (e.g., 10 passes of three-axle vehicles or 6 passes of five-axle vehicles) should be used as the basis for final adjustment of the mean of the difference in static weight and the corresponding WIM weight estimate to zero for each wheel-force transducer. Preliminary adjustment may be based on fewer loads.

SUMMARY

The importance of on-site calibration of WIM systems has been illustrated by comparing the results of WIM weight estimates made after calibrating the system by various techniques against weights measured on an accurate static reference scale. Mixed truck types were included in the analysis, and high, intermediate, and low speeds were considered. A pronounced improvement in the accuracy with which weights are estimated by the HSWIM and ISWIM systems is achieved when six or seven loaded five-axle, tractor-trailer trucks chosen randomly from the traffic stream are used as the basis for calibration compared with multiple runs of a loaded two-axle, single-unit test truck. The variability in WIM weight estimates is not affected appreciably by the type of moving vehicle used for calibration. A static-weight calibration basis has been found to be adequate for LSWIM calibration.

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