# Accuracy and Tolerances of Weigh-in-Motion Systems

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**A systematic study of in-motion weighing of some 800 trucks that were selected from the traffic stream on I-10 near Seguin, Texas, yielded data sets that were analyzed to define the attainable accuracy within which wheel, axle, axle-group, and gross-vehicle weights could be estimated by a properly calibrated in-pavement weigh-in-motion system. Each truck that was weighed passed successively over the Radian weigh-in-motion system transducers at high (±50 mph), intermediate (±30 mph), and low (≤10 mph) speed and then stopped on a special axle/wheel reference scale for successive static weighing of each wheel. Tolerances for a 95 percent confidence level were derived after the system had been calibrated to yield a zero mean of differences in the weigh-in-motion wheel weight estimates and the corresponding static wheel weights. The concept of use tolerances, which allow for the probable error in both the static weight measurement and the weigh-in-motion weight estimate, is presented. Tolerances for high-speed weigh-in-motion, intermediate-speed weigh-in motion, and low-speed weigh-in-motion scales at the experimental site are tabulated.**

Although weigh-in-motion (WIM) systems have been operational for two decades, the accuracy with which static vehicle loads can be estimated at high, intermediate, and slow traffic speeds when compared with static scale measurements has not been systematically investigated or documented for mixed traffic. Previous studies *(1, 2)* have addressed the accuracy of the Texas WIM system by analyzing data sets from test trucks. With the static weighing technique *(3)*, the overall accuracy of a WIM system is determined not only by the accuracy with which force measurements can be made by the system, but also by the signal-processing technique and by how the system is used. The systematic bias in weight estimates made by a WIM system can be reduced significantly, and the variability can be affected somewhat, if the system is properly calibrated at each site where it is used *(4)*.

The purpose of this paper is to discuss the observed accuracy and tolerances in weight estimates associated with a Radian WIM system when about 800 trucks were weighed by the system and on special static axle/wheel scales at three different speeds in a series of field experiments in Texas. The information that is presented is a valuable resource for consideration when selecting suitable equipment for various purposes and when defining appropriate tolerances for truck-weighing operations that are conducted either for collecting statistical data or for enforcement. The concept of use tolerances is discussed, and appropriate tolerance limits for WIM scales are suggested. These values are intended to incorporate all probable errors associated with using a particular weighing device and technique so that the selected device can be used with confidence.

This paper is organized in the following order: first, a brief description of the experimenting program and the analyses of data are given. Then, the basic concept of use tolerances is presented along with some recommended tolerance limits for the WIM system used in this study.

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## EXPERIMENTAL PROGRAM

The weigh station adjacent to the eastbound lanes of I-10 at Milepost 616 east of Seguin, Texas, was selected as the experimental site for data collection. High-speed weigh-in-motion (HSWIM) scales were installed in the right-hand main lanes about 500 ft in advance of the exit-ramp gore of the weigh station. Speed over these scales averaged about 50 mph in the experiment.

Intermediate-speed weigh-in-motion (ISWIM) scales were placed in the straight section of the exit ramp 470 ft in advance of the low-speed weigh-in-motion (LSWIM) scales. The average speed over the ISWIM scales was observed to be 30 mph, and the rollover speed on the LSWIM scales was less than about 10 mph. The reference (axle/wheel) scales were placed 80 ft beyond the LSWIM scales on a straight level (longitudinal) section of the weigh station. All the WIM scales were supported by a Radian instrument system that was housed in a mobile laboratory trailer located opposite the ISWIM scales.

### Profile of the Road Surface

Gross-vehicle weight and axle-group weights can be determined in several ways. The most accurate way requires the use of a multiple-section vehicle scale using single-draft weighing, whereby all wheels on the vehicle are weighed simultaneously while the vehicle is in static equilibrium. Because of the expense involved, such a vehicle scale was not made available to determine the gross-vehicle and axle-group weights of the trucks in this study. Another way to determine gross-vehicle weight and axle-group weights is to successively weigh wheels, axles, or axle groups on axle-load scales or wheel-load weighers with all the vehicle components motionless and in exactly the same relative position to one another at the time of each weighing. Theoretically, this condition of exact positioning can best be achieved on a perfectly smooth and horizontal surface that is free of any unevenness. In reality, however, a road surface of this type is almost impossible to construct and maintain because of economic factors. Displacement of any vehicle component between or during successive weighings due to torque, braking, load-shifting, and the associated frictional forces, also causes redistribution of the gross-vehicle weight among the axles and wheels and results in inaccuracy in the gross-vehicle weight and the axle-group weights calculated by summing the successive measurements.

The existing straight, zero-grade section of the weigh station chosen for use in this study had a 3 percent cross slope to the left-hand side in the weighing lane. At the time the site was selected, the permanent axle-load scale had been installed in a shallow concrete pit with zero cross slope in the immediate vicinity of the scales. The asphalt concrete surface had been warped from the 3 percent cross slope before and beyond the shallow pit to transition to the level plane of the scale surface. This warped cross section was not shown on the plans and was not evident until construction of the reference scale pit was begun. Limited funds and time available for the study made it necessary to install the reference axle and wheel (AX/WHL) scale also at zero cross slope and to warp the adjacent surface into the 10-ft-long concrete approach aprons that were constructed before and beyond the scales. Figure 1 shows the longitudinal profile in each wheelpath at the site at the time when data collection began. The longitudinal profile at the center of the vehicle path was excellent, but the warping of the cross slope at the scale pits was a matter of concern as it could possibly have affected wheel weights adversely. The effect of the local warping of cross slope was not expected to be as pronounced on axle, axle-group, and gross-vehicle weights, however.

After the first 2 days of data taking, premixed asphalt concrete was used to replace the existing asphalt concrete surface and a weighing lane with zero cross slope before, between, and beyond the reference and the permanent scales was built. This level surface held up well under truck traffic for 2 days of data taking, but rutted considerably in the hot summer weather by the fifth day of data taking.

Later in June 1984, the premixed surface material was removed and replaced with hot-mixed, hot-laid asphalt concrete to form a level lane (longitudinally and transversely) approximately 400 ft long. The LSWIM scales were removed before the leveling and reinstalled afterwards. An additional 100 trucks were weighed on the AX/WHL and LSWIM scales on July 6, 1984, after leveling the surface to within about 0.02 ft for 380 ft surrounding these three scales.

### Description and Operational Features of Equipment

The nomenclature and operating features of each scale are given below in the order in which each truck passed over them. The weigh-in-motion system was supported by a four-lane Radian system that was developed especially for the study and for subsequent use in Texas for data collection.

#### High-Speed Weigh-in-Motion (HSWIM)

This scale used two flush-mounted wheel-force transducers, each 53 × 18 in. in plan dimensions, centered transversely in each wheelpath so that the tires traveled along the 18-in. dimension. Each transducer was supplied with ±1 percent maximum tolerances in electrical output signal. The analog signal was digitized and processed by a microcomputer in real time on site to convert the measured dynamic wheel force to an estimate of static wheel weight. Speed and axle-spacing computations were also made by the WIM system from inductance loop-type vehicle-presence detector signals. Thus, as a truck passed over the WIM scales, time of day, speed, axle spacing, wheelbase, wheel weights, axle weights, axle-group weights, gross-vehicle weights, bridge-formula compliance, and vehicle class were determined automatically, displayed on the video screen, and recorded on magnetic disk in digital format. Instruments for the WIM system were housed in a mobile laboratory trailer.

#### Intermediate-Speed, Weigh-in-Motion (ISWIM)

This scale was the same as HSWIM, but it was used at a slower speed (approximately 30 mph).

#### Low-Speed, Weigh-in-Motion (LSWIM)

This scale also was the same as HSWIM but each truck rolled over it at a speed of less than about 10 mph. Furthermore, on

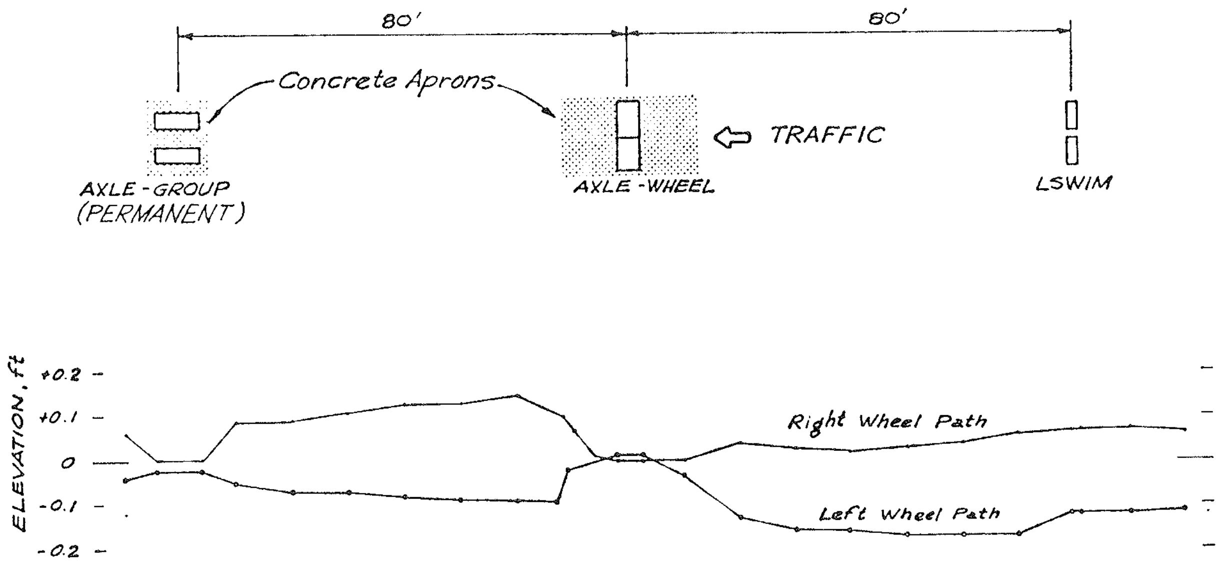


**FIGURE 1 Longitudinal profile in each wheelpath of the weighing lane at beginning of tests.**

the last day of data taking (July 6), this scale system was calibrated in place with ten 1,000-lb test blocks furnished by the Texas Department of Agriculture, Weights and Measures Section. The LSWIM scales performed within ±1 percent overall system tolerances under dead-weight loading.

### Reference Axle and Wheel Scale (AX/WHL)

This scale consisted of two scale platforms, each 4 × 6 ft in plan dimensions, arranged side-by-side and mounted flush with the road surface so that wheels rolled along the 4-ft dimension; thus, each wheel on an axle could be weighed separately when the axle was positioned on the pair of scales. The design of the scale uses all flexure types of devices to transfer forces to the levers and finally to a single strain-gauge load cell. The load-receiving surface is supported by a tabular metal frame that deflects very little under load. The manufacturer states that one part in 5,000 (0.02 percent) tolerances are attainable with the scale. Under dead-weight testing using a series of 1,000-lb test blocks, the scale always indicated correctly within the 20-lb increment that was selected for use in the study. Time of day, wheel weights, axle weights, axle-group weights, and gross-vehicle weights from these scales were printed on a hard-copy tape by a microcomputer.

### Traffic Control and Data Collection

Traffic through the weigh station was controlled by uniformed officers of the Department of Public Safety (DPS). One DPS officer and one State Department of Highways and Public Transportation (SDHPT) person were stationed approximately 2 miles upstream of the weigh station. Selected trucks were directed to stop on the shoulder by the officer; all other traffic was allowed to continue on the main lanes. A serialized identification number was attached to the front windshield of each selected truck by the SDHPT official. The trooper instructed each driver how to proceed through the weigh station and released a truck only when it could be processed at the weigh station without having to stop before crossing the LSWIM scale. The release time was coordinated via radio contact with the weigh station.

When released by the trooper, each truck traveled in the right-hand lane of I-10, passed over the HSWIM scale at about 55 mph, exited, and passed over the ISWIM scale at approximately 30 mph. Each truck was then stopped approximately 20 ft in advance of the LSWIM scale and the driver was instructed to roll slowly over the LSWIM scale and stop with the front axle on the AX/WHL scale. Another trooper instructed the driver to release the brakes after stopping each axle on the AX/WHL scale and wait for weighing. A weight reading was taken only after no appreciable change in the indicated weight was observed.

## ANALYSIS OF WIM DATA

The sum of the vertical forces exerted on a perfectly smooth and level road surface by the perfectly round and dynamically balanced rolling wheels of a vehicle (i.e., an ideal vehicle) at a constant speed in a vacuum is exactly equal to the gross weight of the vehicle. In reality, these ideal conditions do not exist. However, if the deviations from the ideal are small, static weight estimates of acceptable precision and accuracy for certain purposes can be obtained from samples of dynamic wheel force. The field data collected in the experimental program are representative of actual truck traffic conditions under normal road and environmental conditions. The data sets are analyzed to determine mainly the accuracy with which static wheel, axle, axle-group, and gross-vehicle weights can be estimated from dynamic wheel forces measured with a properly calibrated WIM system at three different speeds. Axle weight and axle-group weight have been taken as the sum of all wheel weights for the particular axle or axle group under consideration, and gross-vehicle weight has been computed as the sum of all axle and axle-group weights on a truck or truck-trailer combination.

Graphical and statistical methods, including regression techniques, are used here for the comparison and correlation analysis of the data sets. Static weights that are used as a basis for comparison were obtained from the AX/WHL scale. This scale was accurate under dead-weight testing and weighed a test truck that made more than 60 runs over the scales very consistently throughout the 6 days of data-taking sessions. Because the number of trucks weighed was large and the mix of truck types in the sample was similar to the mix in the total traffic stream, the sample can be considered representative of the population of trucks that would be weighed in practice.

Three different data sets, one each taken on June 6 and 11, 1984, over all three WIM scales, and a third set taken on July 6, 1984, only over the LSWIM scale, are analyzed and presented in the following sections.

### Graphical Representation

In the graphical approach, the weight data from the static weighings are plotted on the horizontal axis, labeled AXLE/WHEEL SCALE, and the corresponding weight for each vehicle as estimated by the WIM system at each speed is plotted along the vertical axis (labeled WIM SCALE) in each figure. Bounds of +10 percent and −10 percent difference in the WIM-estimated weight and that obtained from the static AX/WHL scale are shown as divergent sloping lines in each figure. Dot-dash lines on these figures indicate the legal weight limits. In another graphical approach the relative difference in the WIM-estimated weight, which is calculated and expressed as a percentage of the weight measured by the reference scale, is plotted against that of the corresponding reference weight.

### Statistical Procedures

Statistical tests of normality *(5, 6)* indicate that the frequency of relative differences in WIM-estimated weights can be considered to be normally distributed; therefore, by applying the properties of a normal frequency distribution, certain inferences can be drawn from analysis of the data sets. The sampled data are considered to be representative samples drawn from a large parent population.

For further analysis of the data, in order to examine the relationship between the WIM estimates of the static weights and the respective weights from the AX/WHL scale numerically, a linear regression analysis is used. For each data set, the regression is performed on the WIM-estimated weights against the corresponding observed weights from the static scale. Although the obvious purpose of this analysis is to determine the accuracy and precision, on the average, associated or attainable with WIM systems for predicting the true weights from samples of dynamic wheel forces, the equations are derived by using weights measured from the AX/WHL (reference) scale to predict weights from the WIM scales. This is necessary because, in a normal regression equation $y = b_0 + b_1x$, the predictor or independent variable $x$ is assumed to be virtually error free, whereas the response or dependent variable $y$ is not. Thus, weight determined from the reference scale is taken as the predictor variable $x$ in developing the needed regression equation. The fitted straight line, in essence, provides a calibration curve for the WIM scales, related to the static weight data from the reference scale. The problem of estimating true weight from a WIM system measurement of dynamic force is called in statistics the inverse regression problem and is fully documented in studies by Halperin *(7)* and Ostle and Mensing *(8)*. So the equation for a given $y$, namely $y_0$, may be inverted, or solved for the inverse estimate of $x$, by solving the following equation for $x_0$

$$y_0 = b_0 + b_1x_0,$$

namely

$$x_0 = (y_0 - b_0)/b_1$$

so that force measurements from the WIM scales can be used to estimate the static weight that would be expected to result from weighing on the reference scale.

Results of the regression analysis are tabulated for axle-group and gross-vehicle weights in the following paragraphs. These regression equations were developed for each WIM scale—LSWIM, ISWIM, and HSWIM—used in the experiment. For cases in which it is known or in which it has been found empirically that the standard deviation of the untransformed response $y$, $\sigma_y$, say, is a function of the mean value, $\mu = E(y)$, a natural-log transformation of the data is used in the analysis. The coefficient of variation (c.v.), which is a measure of the precision with which true weight can be estimated by the equation, is computed for each equation. As previously explained, the coefficients are computed on the basis of the reference scale weight being the predictor variable; therefore, small inaccuracies can result from applying the coefficients to the inverted equations. These inaccuracies, however, cannot possibly be large because of the relatively small scatter in the untransformed or transformed weight information. The c.v.'s can be treated as standard deviations of the relative difference in weights. That is, true weights estimated by the regression equations from weight measurements by the WIM scales will yield estimates within ($\pm 2 \times$ the coefficient of variation) of the actual weight values approximately 95 percent of the time (i.e., within the 95 percent confidence limits). The regression coefficient or the slope of the line, on the other hand, is the measure of correlation or agreement between the WIM estimates of the static weights and the corresponding measurements from the AX/WHL scale. A slope of 1.0 and a c.v. equal to zero percent would result if perfect agreement existed between the two sets of weight readings.

## Gross-Vehicle Weights

Figures 2, 3, and 4 illustrate the variability that was observed in gross-vehicle weight estimates for 61 trucks when each truck was weighed at three different speeds (low ≤ 10 mph, intermediate = approximately 30 mph, and high = approximately 50 mph) on June 11, 1984, by three properly calibrated WIM scales. Each graph illustrates the relationship between the WIM

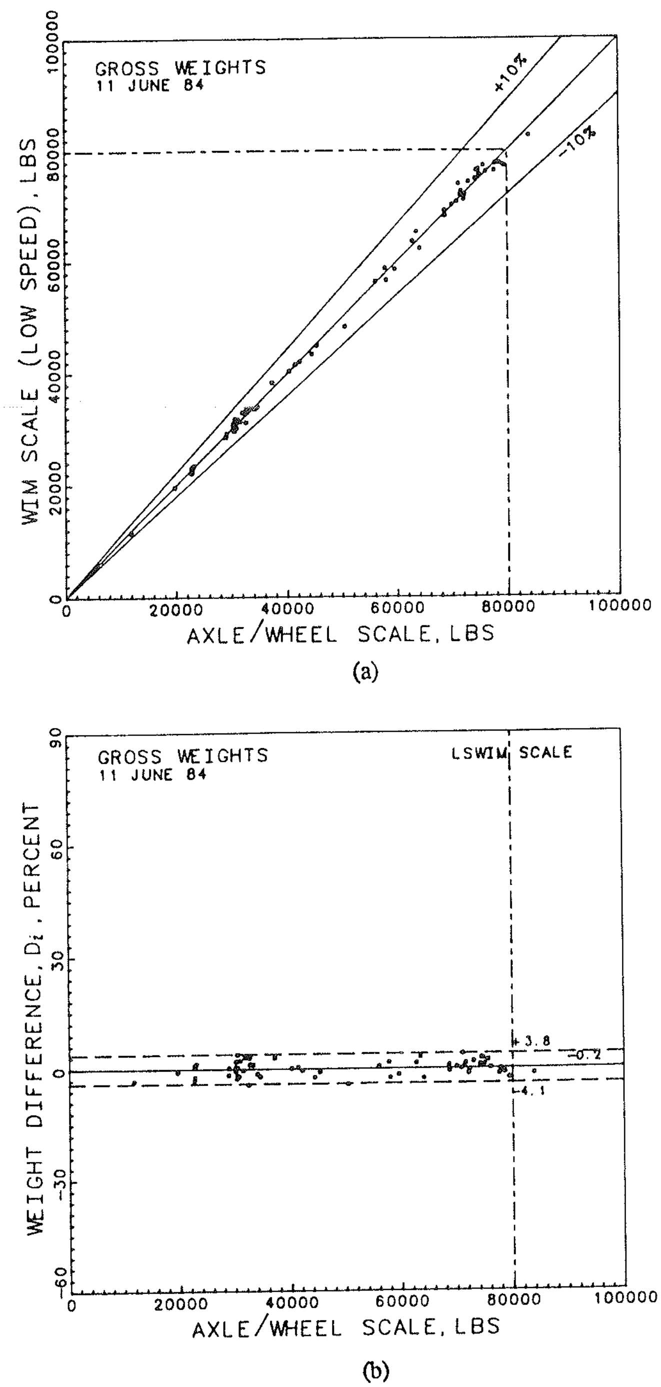


**FIGURE 2 Gross-vehicle weight estimates for 61 trucks crossing the LSWIM scale *(a)* at less than 10 mph versus weights summed from the AX/WHL scale and *(b)* percent difference in gross-vehicle weight estimates from the LSWIM scale with reference to the static weights.**

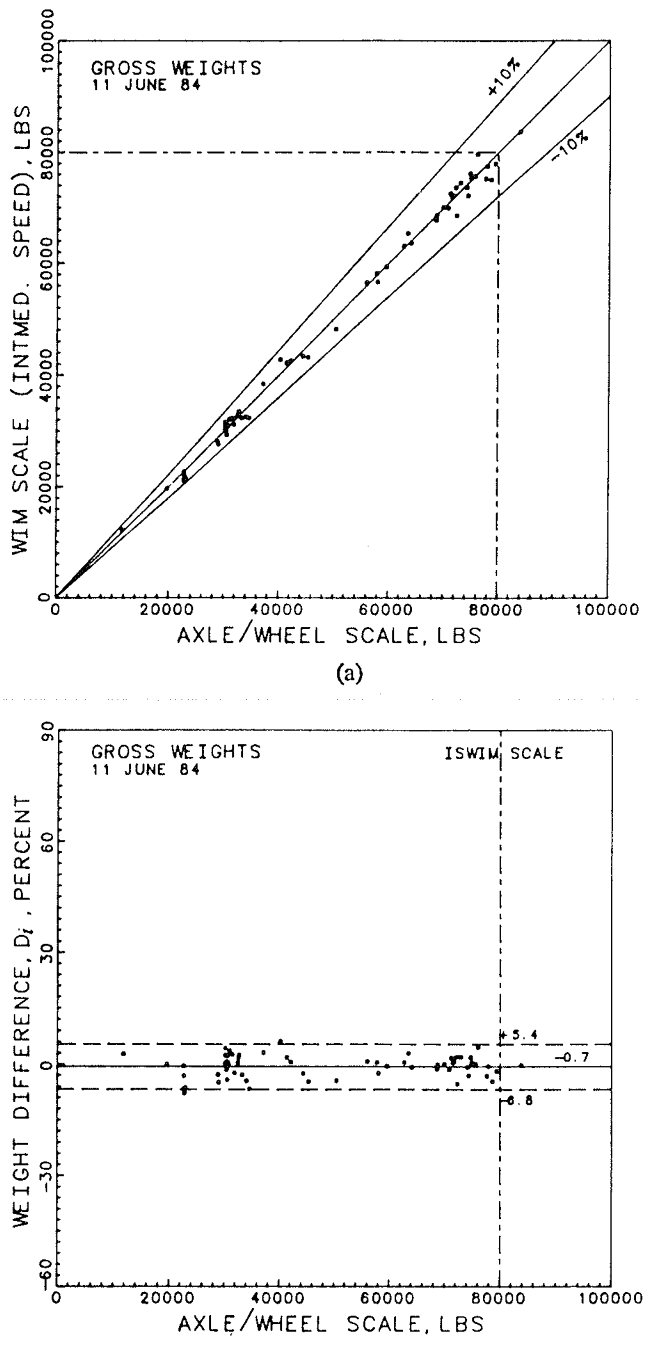


**FIGURE 3 Gross-vehicle estimates for 61 trucks crossing the ISWIM scale *(a)* at about 30 mph versus weights summed from the AX/WHL scale and *(b)* percent difference in gross-vehicle weight estimates from the ISWIM scale with reference to the static weights.**

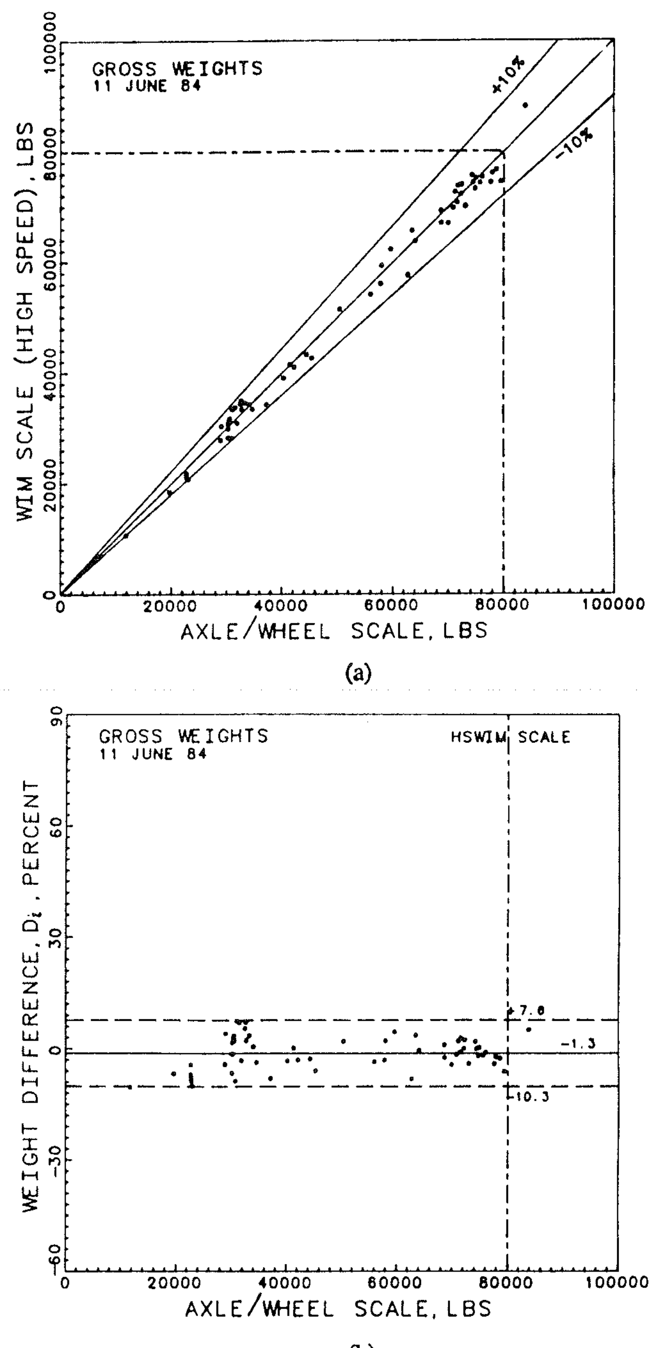


**FIGURE 4 Gross-vehicle weight estimates for 61 trucks crossing the HSWIM scale *(a)* at about 55 mph versus weights summed from the AX/WHL scale and *(b)* percent difference in gross-vehicle weight estimates from the HSWIM scale with reference to the static weights.**

system weight estimates and the corresponding weights from the AX/WHL reference scale. The static gross-vehicle weight that was used for reference was taken as the sum of the weights of all axles on the vehicle after each axle was weighed in sequence on the static AX/WHL scale. Careful examination of each of the data sets was made to check for abnormalities in weight data and a few (fewer than five) extreme outlying points were removed with discretion from the data sets. Implications such as a tire partially or fully off the WIM scale guided this process.

As shown in these figures, if there were perfect agreement between the two weights, all the plotted points would lie exactly on the 45° line of equality. The pattern of data points shown in these three figures indicates that there was a small but consistent increase in the range of gross-vehicle weight difference as the speed of the vehicles being weighed by the WIM system increased. For all three scales, the data points are clustered rather evenly with small scatter about the 45° line of perfect agreement. The gross-vehicle weights from the

TABLE 1 SUMMARY STATISTICS OF WIM GROSS-VEHICLE WEIGHTS AS COMPARED AND CORRELATED WITH THE AX/WHL SCALE WEIGHTS FOR SPEEDS AND TIMES SHOWN

| DATE | SPEED AT WIM SCALES | STATISTIC | | | | |
|---|---|---|---|---|---|---|
| | | MEAN WEIGHT, LBS | MEAN OF DIFFERENCES (MEAN OF ABSOLUTE DIFFERENCES), % | 95% CONFIDENCE RANGE, $\hat{\mu} \pm 2\hat{\sigma}$, % | REGRESSION ANALYSIS | |
| | | | | | SLOPE | C.V.* |
| June 11, 1984 n = 61 | LSWIM (10 mph) | 49570 (49600)+ | -0.2 (1.6) | -4.1 to +3.8 | 1.00003 | 2.0 |
| | ISWIM (30 mph) | 49310 | -0.7 (2.4) | -6.8 to +5.4 | 0.99494 | 2.8 |
| | HSWIM (55 mph) | 49080 | -1.3 (3.8) | -10.3 to +7.6 | 0.99054 | 3.8 |
| June 6, 1984 n = 60 | LSWIM (10 mph) | 38870 (39200)+ | -1.3 (2.8) | -7.8 to +5.2 | 0.99344 | 2.6 |
| | ISWIM (30 mph) | 39000 | -0.8 (2.8) | -7.7 to +6.1 | 0.99729 | 3.2 |
| | HSWIM (55 mph) | 38640 | -2.0 (3.8) | -10.9 to +7.0 | 0.98803 | 4.0 |
| July 6, 1984 n = 86 | LSWIM (10 mph) | 43900 (44180)+ | -0.6 (2.6) | -6.8 to +5.7 | 0.99174 | 2.8 |

* Coefficient of Variation, %
\+ Reference Scale Mean Weight

HSWIM scales are, on the average, 1.3 percent lower than the respective static weights. Several light trucks produced large negative weight differences in terms of percentage; these had a rather large influence on this mean value. Although the dynamic effects of vehicle/road/WIM-system interaction on these gross-vehicle weights tend to be greater at higher speeds, virtually all the WIM estimates of gross-vehicle weights at high speed differed less than 10 percent from the observed static gross-vehicle weights (see Figure 4).

Results of the regression analysis, along with the statistical inferences drawn from the sample distribution of the relative difference in gross-vehicle weights, are summarized in Table 1. A linear regression equation (with zero intercept) was developed for each of the three WIM scales used in the experiment. The regression coefficient (i.e., slope of the line) and c.v. are also presented in this table. The slope and the coefficient of variation for each regression equation are measures of the accuracy with which estimates of static gross-vehicle weight can be predicted by the equation. It can be concluded, for example, that approximately 95 percent of the weight observations would produce estimates of static weight from HSWIM scales that would be within [±2 (c.v.) = ±2 (3.8 percent) = ±7.6 percent] of the actual values of the static gross-vehicle weights. The respective accuracies for the LSWIM and ISWIM scales are ±4 and ±5.8 percent. Or, without using a regression equation, gross-vehicle weights can be predicted with 95 percent confidence within ±4.0, ±6.0, and ±9.0 percent for trucks running over the scales at speeds of 10, 30, and 55 mph, respectively [see the confidence bands in Figures 2*(b)*, 3*(b)*, and 4*(b)*, respectively].

The value of the slope of the regression line, on the other hand, is a good indication of how well the static gross-vehicle weights are predicted by the estimated weights from the sampled dynamic wheel forces by the WIM scales. For the HSWIM scale, for example, the value of the slope of the regression line is 0.99054. This figure is very close to 1.0 and it implies that, on the average, the system makes accurate predictions of gross-vehicle weights. The respective values for LSWIM and ISWIM, respectively, are 1.00003 and 0.99494. Again these numbers are very close to 1.0, indicating that a small improvement in predictive accuracy can, on the average, be achieved by applying the regression technique. The confidence bands are reduced slightly.

The observed differences in the WIM-estimated gross-vehicle weights and the comparable static weights cannot be attributed entirely to WIM system error or to inaccuracy in the WIM system. Part of the difference comes from the redistribution mechanism of the gross-vehicle weight among the axles on the vehicle as it moves into different positions and stops for successive weighing of each axle on the static reference scale. This redistribution, which is governed to a large extent by the interaction of the vehicle with the road surface, the scale, and the atmosphere, occurs continually as the vehicle moves over the WIM system scales. Additionally, the dynamic behavior of the various interconnected vehicle components contributes to the magnitude of this difference at the time of weighing. The static gross-vehicle weights calculated from the reference (AX/WHL) scale are not without error because of the method of successive weighing that was used.

## Axle-Group Weights

The total weight on a group of closely spaced axles is important in the engineering design of pavement and bridge structures and also in enforcement weighing. The WIM and AX/WHL scales indicated the weight of each wheel. Axle-group weights were calculated from these scales by summing the weights of all wheels on the axles in the group.

The calculated values for all axle-group weights, when each axle was weighed on LSWIM, ISWIM, and HSWIM scales, indicated that there was a small but consistent increase in the range of axle-group weight differences as the speed of the vehicles being weighed by the WIM scales increased. Statistical tests indicate that the relative difference in axle-group weights computed from the WIM estimates with reference to those from the AX/WHL scale, are normally distributed in a

TABLE 2 SUMMARY STATISTICS OF WIM AXLE-GROUP WEIGHTS COMPARED AND CORRELATED WITH AX/WHL SCALE WEIGHTS FOR SPEEDS AND TIMES SHOWN

| DATE | SPEED AT WIM SCALES | STATISTIC | | | | |
|---|---|---|---|---|---|---|
| | | MEAN WEIGHT, LBS | MEAN OF DIFFERENCES (MEAN OF ABSOLUTE DIFFERENCES), % | 95% CONFIDENCE RANGE, $\hat{\mu} \pm 2\hat{\sigma}$ % | REGRESSION ANALYSIS | |
| | | | | | SLOPE | C.V.* |
| June 11, 1984 n = 178 | LSWIM (10 mph) | 16990 (17000)+ | -1.0 (3.7) | -10.0 to +8.0 | 1.00594 | 4.0 |
| | ISWIM (30 mph) | 16900 | -0.7 (3.8) | -10.6 to +9.2 | 0.99538 | 4.4 |
| | HSWIM (55 mph) | 16820 | -1.1 (5.6) | -15.7 to +13.4 | 0.99052 | 6.7 |
| June 6, 1984 n = 171 | LSWIM (10 mph) | 13640 (13750)+ | -1.9 (4.8) | -13.4 to +9.7 | 0.99962 | 5.0 |
| | ISWIM (30 mph) | 13690 | -0.8 (4.6) | -12.6 to +11.0 | 0.99888 | 5.4 |
| | HSWIM (55 mph) | 13560 | -1.6 (6.1) | -17.7 to +14.6 | 0.98754 | 6.7 |
| July 6, 1984 n = 242 | LSWIM (10 mph) | 15600 (15700)+ | -0.8 (3.9) | -11.4 to +9.8 | 0.99934 | 4.3 |

* Coefficient of Variation, %
\+ Reference Scale Mean Weight

TABLE 3 SUMMARY STATISTICS OF WIM AXLE WEIGHTS COMPARED AND CORRELATED WITH THE AX/WHL SCALE WEIGHTS FOR SPEEDS AND TIMES SHOWN

| DATE | SPEED AT WIM SCALES | STATISTIC | | |
|---|---|---|---|---|
| | | MEAN WEIGHT, LBS | MEAN OF DIFFERENCES (MEAN OF ABSOLUTE DIFFERENCES), % | 95% CONFIDENCE RANGE, $\hat{\mu} \pm 2\hat{\sigma}$, % |
| June 11, 1984 n = 280 | LSWIM (10 mph) | 10800 (10800)+ | -0.1 (4.6) | -11.8 to +11.7 |
| | ISWIM (30 mph) | 10740 | -0.1 (5.5) | -14.7 to +14.6 |
| | HSWIM (55 mph) | 10690 | -0.1 (6.6) | -17.8 to +17.7 |
| June 6, 1984 n = 253 | LSWIM (10 mph) | 9220 (9300)+ | -0.6 (5.3) | -13.9 to +12.7 |
| | ISWIM (30 mph) | 9250 | -0.5 (5.5) | -14.6 to +13.7 |
| | HSWIM (55 mph) | 9170 | -0.5 (7.4) | -19.8 to +18.8 |
| July 6, 1984 n = 367 | LSWIM (10 mph) | 10290 (10350)+ | -0.1 (4.7) | -13.1 to +13.0 |

\+ Reference Scale Mean Weight

statistical sense. Therefore, some important statistical inferences were developed from analysis of the three data sets mentioned previously; these are tabulated in Table 2. These statistics can be interpreted to indicate that accuracies of about ±9, ±10, and ±14 percent can be expected when comparing LSWIM, ISWIM, and HSWIM estimates of axle-group weights with the corresponding weights from the static reference scale, respectively, at 95 percent confidence level. Or, using the regression equation estimates just described, axle-group weights can be predicted at the same level of confidence within ±8.0, ±8.8, and ±13.4 percent.

### Axle and Wheel Weights

Summary statistics for axle and wheel weights are given in Tables 3 and 4, respectively. These results further support the fact that the distribution of weight among the axles of a vehicle changes as the vehicle moves over the road surface and stops for successive weighing of axles and wheels on static scales.

## TOLERANCES

### Concept

In dealing with weight measurements, a distinction should be made between accuracy and precision. Accuracy is the degree of conformity of a measurement to a standard or to a true value. Precision, on the other hand, refers to the exactness with which a measurement is made. A measurement can be precise without necessarily being accurate. Errors in precision are generally random or accidental and can therefore be explained by applying appropriate statistical concepts and techniques. Errors in

TABLE 4 SUMMARY STATISTICS OF WIM WHEEL WEIGHTS COMPARED AND CORRELATED WITH THE AX/WHL SCALE WEIGHTS FOR SPEEDS AND TIMES SHOWN

| DATE | SPEED AT WIM SCALES | STATISTIC | | |
|---|---|---|---|---|
| | | MEAN WEIGHT, LBS | MEAN OF DIFFERENCES (MEAN OF ABSOLUTE DIFFERENCES), % | 95% CONFIDENCE RANGE, $\hat{\mu} \pm 2\hat{\sigma}$, % |
| June 11, 1984 n = 560 | LSWIM (10 mph) | 5400 (5400)+ | 0.0 (8.7) | -21.8 to +21.8 |
| | ISWIM (30 mph) | 5370 | 0.0 (6.8) | -17.8 to +17.8 |
| | HSWIM (55 mph) | 5350 | 0.0 (8.4) | -22.3 to +22.3 |
| June 6, 1984 n = 506 | LSWIM (10 mph) | 4610 (4650)+ | 0.0 (8.8) | -22.6 to +22.6 |
| | ISWIM (30 mph) | 4630 | 0.0 (8.1) | -21.3 to +21.3 |
| | HSWIM (55 mph) | 4580 | 0.0 (10.5) | -27.2 to +27.2 |
| July 6, 1984 n = 734 | LSWIM (10 mph) | 5140 (5180)+ | 0.0 (6.0) | -16.0 to +16.0 |

+ Reference Scale Mean Weight

accuracy are usually systematic and can frequently be minimized or eliminated by adjustment or calibration of a properly designed weighing device that has good precision. In using a weighing device that has systematic errors that cannot be eliminated by calibration, the systematic errors combine with the random errors to determine the overall accuracy with which weight can be measured by the device.

In recognition of the fact that errorless performance of mechanical or electromechanical equipment is unattainable, tolerances are established to define the range of inaccuracy within which such equipment will be allowed to perform and still be approved for official use in a jurisdiction. The U.S. Department of Commerce, National Bureau of Standards, has set out code requirements [*NBS Handbook 44* (1986)] for static scales (but not yet for WIM scales) in official use for the enforcement of traffic and highway laws or for the collection of statistical information by government agencies. Acceptance tolerances are defined in the code and are applied to new or newly reconditioned or adjusted equipment. Maintenance tolerances, which are generally twice the acceptance tolerances, are applied to the equipment that has been in service for some time; these tolerances define the maximum variation in accuracy that will be permitted when the equipment is tested against an official standard. The official standard for verifying the performance of static scales is a set of standard test weights of known value.

### Use Tolerances

In-motion weighing involves two processes: *(a)* sampling a dynamic tire force, and *(b)* using the sampled force to estimate the corresponding portion of the gross-vehicle weight that this tire would carry if weighed statically. Neither of these processes, nor the corresponding measurement of static tire force, can be performed without error. Therefore, not only basic tolerances, which protect the interests of both the users of the information obtained by WIM systems and the manufacturer of the system, but also use tolerances are needed. Use tolerances account for both the inherent variability in the physical phenomenon being estimated (i.e., static wheel force) and the accuracy with which a WIM system can possibly and practically perform each of the two processes mentioned above. As with static scales, the overall accuracy of a WIM system is determined partly by the accuracy that is attainable by the system itself and partly by how the system is used *(3)*. A number of site-specific conditions such as road profile, cross slope near the WIM transducers, interaction of the transducer/roadway system under dynamic load, and vehicle factors affect the overall accuracy of an installed WIM system.

The importance of on-site calibration for WIM systems is discussed by Lee et al. *(4)*. However, the inherent variability in weight data due to factors such as torque in the vehicle drive train, dynamic behavior of the various interconnected vehicle components, friction, and other factors, cannot be completely accounted for, even by a properly calibrated system. Therefore, use tolerances that recognize such variability must be used when interpreting and applying WIM-estimated weights for enforcement or for statistical data-collection purposes.

In the regression analysis already mentioned, it is assumed that the reference weight $x$ (i.e., the predictor variable) is not subject to random variation, but that the WIM estimate $y$ (the response variable) is. The regression model $y = \beta_1 x + e$ is considered in the analysis because the nonzero intercept term is physically difficult to explain and justify. Because the actual observed value of $y$ varies about the true mean value with the unknown variance $\sigma^2$, a predicted value of an individual observation, which is given by $y = b_1 x$, has greater variation than $\sigma^2$. This means that a prediction interval for the particular outcome of a weight reading from the WIM scale can be defined. A prediction interval is one that contains $y$ with a desired level of confidence. A one-sided (upper band width) 95 percent prediction interval for $y$ at a fixed value $x$ can be constructed. The use tolerance for a given data set is then determined by subtracting the value of $x$ (the reference weight) from the predicted value of the weight plus its upper prediction interval. The results from the regression models are given in Table 5.

TABLE 5 USE TOLERANCES FOR AXLE-GROUP AND GROSS-VEHICLE WEIGHTS FOR THE WIM SCALES (95 PERCENT CONFIDENCE LEVEL)

| SPEED | AXLE-GROUP WEIGHT TOLERANCE (LBS) | GROSS-VEHICLE WEIGHT TOLERANCE (LBS) |
|---|---|---|
| LSWIM (< 10 mph) | +1100 (-1350 to +1350)* | +1650 (-2050 to +1950) |
| ISWIM (< 35 mph) | +1100 (-1550 to +1350) | +2000 (-3050 to +2450) |
| HSWIM (< 55 mph) | +1700 (-2400 to +2050) | +2650 (-4300 to +3250) |

* Two-Tailed 95% Confidence Limits to Show Upper and Lower Limits of Tolerances

To apply the use tolerances to estimated weights from a particular WIM device, the user may calculate a probable minimum weight by subtracting the applicable tolerance value (e.g., at 95 percent confidence) from the WIM-estimated weight. He can then be sure that there is only a 5 percent probability that the estimated weight would be less than that calculated if it were measured on the reference scale. For example, a tandem-axle group weight is estimated by an LSWIM scale at 35,500 lb. The probable minimum weight would be 35,500 − 1,100 = 34,400 lb (see Table 5). An enforcement officer using the LSWIM system could charge that the axle-group weight was in violation of the 34,000-lb legal limit and be sure that there was only 1 chance in 20 that it would weigh less than 34,400 lb if weighed on the accurate reference scale.

## SUMMARY

Statistical analysis of the performance of the Texas WIM system at different speeds indicates that a properly calibrated system can produce the following results compared with the respective weights from the AX/WHL reference scale (see Table 6).

TABLE 6 TOLERANCE VALUES FOR A CALIBRATED WIM SYSTEM

| Speed at WIM Scale | Statistical Inference | Gross-Vehicle Weight (% difference) | Axle-Group Weight (% difference) |
|---|---|---|---|
| LSWIM | Mean of differences | −0.2 | −1.0 |
| (10 mph) | range for 95% | +3.8 to −4.1 | +7.9 to −10.0 |
| ISWIM | Mean of differences | −0.7 | −0.7 |
| (30 mph) | range for 95% | +5.4 to −6.8 | +9.2 to −10.6 |
| HSWIM | Mean of differences | −1.3 | −1.1 |
| (55 mph) | range for 95% | +7.6 to −10.3 | +13.4 to −15.7 |

These values imply that tolerances of about ±4 percent, ±6 percent, and ±9 percent would be appropriate when interpreting LSWIM, ISWIM, and HSWIM estimates of the gross-vehicle weight from the static reference scale, respectively, if the WIM-estimated weight is expected to be within the chosen tolerance value for 95 out of 100 vehicle weighings. Likewise, tolerances of about ±9 percent, ±10 percent, and ±14 percent should be applied to WIM-estimated axle-group weights for the same level of confidence.

The results of these analyses also indicate that the performance of this WIM system is adequate for use *(a)* in gathering weight data at high speeds for statistical information, *(b)* as a means of sorting overweight trucks in enforcement programs, and *(c)* in weighing trucks at low speeds for legal evidence of weight-law violation (compared with the performance of the static axle-load scales and wheel-load weighers that are being used at the present time in enforcement programs). It is also concluded that the use tolerances for the properly calibrated LSWIM and ISWIM systems are lower than the corresponding use tolerances for all the static weighing devices *(4)* utilized in the field study.

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