

Application of In-Motion Weighing Using Instrumented Bridges

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ABSTRACT

Truck weight data are needed by several agencies within state or national highway departments. This paper contains a description of how these data can be obtained in an undetected manner at highway speeds by using instrumented highway bridge girders with a portable or semiportable bridge weigh-in-motion system. Information on the concept and accuracy is presented along with correlation data obtained with vehicles that were weighed on a static scale. Applications are outlined for planning, pavements, bridge engineering, and enforcement purposes. A discussion is presented of the inaccuracies in predicting equivalent single axle load values caused by the variability present in any weighing system.

The acquisition of truck axle and gross weight information has received considerable attention from highway engineers. These data are essential for determining the structural and maintenance requirements of bridges and pavements. In addition, accurate truck weights are important in planning and economic and enforcement surveys. The recognition that truck data are needed (in large volume, inexpensively gathered, and preferably surveying the total truck population by using an undetected weighing operation) has been well documented.

In attempting to achieve these goals, a number of studies have been performed and several approaches to performing weigh-in-motion operations have been developed. These include embedded pavement scales, pads attached to the pavement surface, and instrumented bridge girders. The first two methods are direct and easily understood in that one or both wheels of an axle produce a displacement within the scale that can be measured. One major area of concern with these techniques is that slight surface irregularities, either in the pavement section in front of the scale or even the scale "bump" itself, can cause large fluctuations in scale response. If surfaces are properly leveled and maintained, the manufacturers of pavement scales claim that accurate weight results can be obtained. In the case of pads mounted on the road surface, the bump problem is inherently present.

The third system, the bridge weigh-in-motion (WIM) system, uses instrumented girders as equivalent static scales. This approach "weighs" each axle as it crosses the entire length of the instrumented span so effects of pavement irregularities and bumps are drastically reduced, if not eliminated completely, because of the great inertia of the structure. The bridge weigh-in-motion operation thus eliminates the need for pavement resurfacing, as is common with the first two systems, solely for the purpose of obtaining high-speed WIM gross and axle weights.

BRIDGE WEIGH-IN-MOTION CONCEPT

Scale systems require that predictable displacements be induced in a member or members of the system when loaded. Because vehicle loads will be dynamic and of

short duration, the response of the system to the rapid loading must also be considered. Highway bridges are designed for such loadings.

Through mechanics, the behavior of bridges with load-carrying longitudinal girders can be readily predicted. More accurately, this behavior can be measured using a truck of known weight and dimensions. This relationship among load, load position, and response can be represented as an influence line, which is a plot of the bending moment at the location of the instrumentation as a function of a unit load moving across the bridge. It has been determined that for straight girder-slab-type bridges, the influence line can be approximated by the influence line of a single beam that has cross-sectional properties equal to the sum of the girders that constitute the bridge. In general, the weight predictions are not sensitive to the influence line shape, provided the span lengths and support locations are correct.

The WIM analysis is an inverse-type problem in that the structural response (bending moment) is measured but the live loads causing this moment must be calculated. In theory, the number of unknowns for each vehicle equals the number of axles (N) that can be determined by N different bending moments (i.e., strains) recorded for N different positions of the truck along the bridge. Because data are recorded continuously during truck passage, these redundant data effectively increase the number of separate "weighings" of the vehicle, so the results can be averaged to reduce any errors or the effect of dynamic behavior. The principle of data redundancy is extended to its logical conclusion in the statistical smoothing algorithm derived to remove the effects of bridge vibration. In effect, axle weights are found that minimize the least squares difference between the measured strain and the calculated value from the vehicle dimensions and the bridge influence line. The gross weight is then determined by summing the axle weights. Additional detail on the algorithm can be found elsewhere (1,2).

Whenever a loading is dynamic in nature, the measurement system itself may be excited resulting in transient or natural response, or both. Bridges do tend to vibrate when subject to a dynamic loading, although the magnitude varies depending on the material and geometric properties of the structure. Transient response is practically negligible because

of the relatively massive nature of the bridge--the duration of the impact is usually too small to overcome the large inertia of the structure.

Scaling of the influence line is done through the use of a calibration factor. This factor is obtained from a comparison of the uncalibrated weights of a test truck, as calculated from the WIM processing, with its weight obtained from a static platform scale. An average from several crossings of the test truck is used. In general, the calibration procedure is only done once for each bridge. Recalibration is not necessary for return visits as long as the transducers are installed at the same location.

The information needed to calculate axle weights includes the strain record from each load-carrying girder during the vehicle crossing and the position of each axle at each instant of strain sampling.

Girder strains are measured by reusable strain transducers that are clamped to steel girders or bolted to concrete or timber girders. These transducers have a gauge length of 3 in. and amplify the strain by a factor of five to seven. An electronic autobalancing signal conditioning system is used to maintain a proper zero output until the presence of a vehicle is detected, at which point the balancing is deactivated until the vehicle has passed.

The position of each axle with respect to time must be known during the entire truck crossing. This is accomplished by determining the vehicle velocity and axle spacings. The strain sample associated with the arrival of the steering axle on the bridge is determined so that all future samples can be related to the position of each axle if the velocity and the elapsed time are known. Traffic sensors, including tapeswitches, road tubes, radar, loop detectors, and embedded axle detectors, are used to measure vehicle velocity and axle spacings.

A more detailed approach has been developed (3) to weighing continuously all traffic on a two-lane highway including two side-by-side trucks. This WIM algorithm is a simple extension of the minimization of error method developed for single truck weighing. Just as the original method used redundant weighings to eliminate bridge and axle suspension response, multigirder strain records, if kept separate in the analysis, will provide individual lane weighings provided the influence of each girder is known. An influence surface must be used instead of an influence line. This surface represents the response of each girder to a unit load in each lane as determined from crossings of a vehicle with known axle weights. As a related development, such application is also useful to bridge engineers who need to forecast maximum bridge loads (4).

Bridge WIM systems in use today include compact enforcement screening systems, portable manned systems, and semiportable unmanned systems that operate 24 hr a day and send the data via telephone. More than 17 systems are in operation throughout the world of which 14 are in the United States. Several states have developed the systems in-house (5) as have the state of Western Australia (6) and the province of Ontario.

EXAMPLES

Figure 1 shows the procedure for obtaining vehicle axle weights. An example strain record is shown in Figure 2 as a solid line for a 3S-2 with axle spacings as shown in Figure 3. The vehicle was crossing a 32-ft simple span that was instrumented 13 ft from the beginning of the span. The resulting influence line is shown in Figure 4. The axle weights computed by the bridge WIM system are shown in Figure 3 along with the axle weights obtained on a static platform

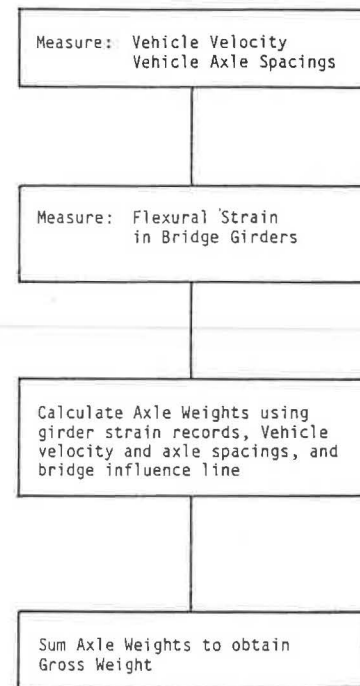


FIGURE 1 Block diagram of bridge weigh-in-motion process.

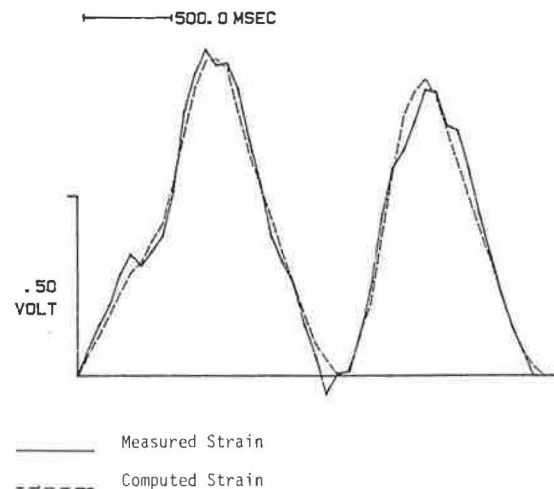


FIGURE 2 Measured and computed strains.

scale. The dashed line in Figure 2 is the strain record computed from the axle weights determined by the bridge WIM system and the bridge influence line (Figure 4). The differences between the two plotted curves in Figure 2 can be attributed to the dynamic response of the bridge to the vehicle crossing. The dynamic response is effectively filtered in calculating the axle weights. It should be noted that the shape and magnitude of a strain record are dependent on vehicle velocity, axle spacing, and axle weights as well as the bridge influence line. Consequently, the shape of the strain record has the dominant role in determining axle weights as opposed to peak strain magnitudes--a common misconception.

A correlation between a bridge WIM system and a static scale of random traffic has been performed by the Iowa Department of Transportation and Bridge Weighing Systems, Inc. (7). The results are given in Tables 1 and 2 for gross vehicle weight and rear

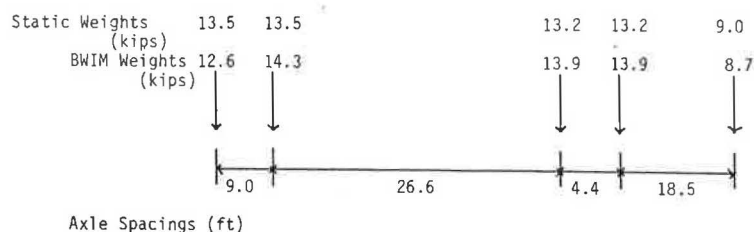


FIGURE 3 Vehicle axle spacings and weights.

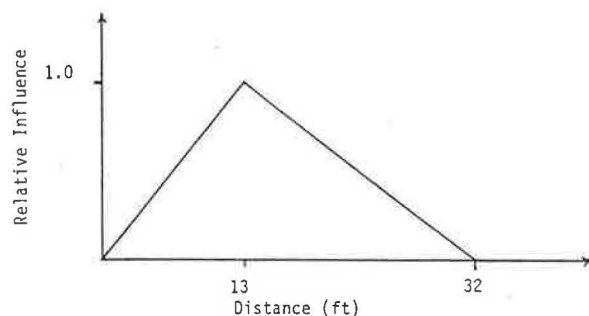


FIGURE 4 Bridge influence line.

TABLE 1 Gross Vehicle Weight Comparison

Observation	Static Scale (kips)	Bridge WIM (kips)	Difference (%)
1	25.5	26.0	2.0
2	25.6	24.8	-3.1
3	25.8	24.9	-3.5
4	28.0	27.0	-3.6
5	31.4	29.7	-5.4
6	32.5	34.3	5.5
7	32.7	30.5	-6.7
8	35.0	36.6	4.6
9	39.8	40.2	1.0
10	40.3	41.4	2.7
11	46.1	44.8	-2.8
12	47.4	48.2	1.7
13	48.3	46.5	-3.7
14	49.3	47.4	-3.9
15	57.2	56.5	-1.2
16	57.7	58.3	1.0
17	64.2	61.2	-4.7
18	66.8	66.3	-0.7
19	67.0	68.6	2.4
20	70.1	66.5	-5.1
21	70.9	72.8	2.7
22	71.0	71.8	1.1
23	71.2	72.2	1.4
24	73.8	72.7	-1.5
25	75.1	77.5	3.2
26	75.2	75.8	0.8
27	75.2	77.2	2.7
28	76.3	76.8	0.7
29	76.4	77.6	1.6
30	76.9	78.5	2.1
31	77.3	79.9	3.4
32	77.4	77.1	-0.4
33	79.5	77.7	-2.3
34	79.5	82.3	4.8
Total (average percentage)	1,946.4	1,950.6	(-0.2)

tandem weight, respectively. A plot of the gross vehicle weight results is shown in Figure 5. The following standard deviations were calculated by Iowa DOT for 34 vehicles: steering axle, 1.3 kips; drive tandem, 1.7 kips; rear tandem, 1.1 kips; and gross weight, 1.7 kips. The coefficient of variation (COV) is defined as the ratio of the standard devia-

TABLE 2 Rear Tandem Weight Comparison

Observation	Static Scale (kips)	Bridge WIM (kips)	Difference (%)
1	6.6	6.4	-3.0
2	8.1	8.2	1.2
3	8.2	8.2	0.0
4	8.6	8.8	2.3
5	8.9	10.2	14.6
6	9.8	10.6	8.2
7	10.2	9.4	-7.8
8	11.0	10.4	-5.5
9	11.0	11.8	7.3
10	14.0	13.8	-1.4
11	15.0	16.2	8.0
12	17.3	16.2	-6.4
13	17.4	15.6	-10.3
14	21.4	20.6	-3.7
15	21.9	21.8	-0.5
16	25.7	26.1	1.6
17	26.0	26.6	2.3
18	28.4	28.0	-1.4
19	29.0	27.2	-6.2
20	30.4	28.2	-7.2
21	30.7	31.4	2.3
22	31.8	33.4	5.0
23	32.0	31.6	-1.3
24	32.0	32.6	1.9
25	32.6	29.8	-8.6
26	32.8	31.8	-3.0
27	33.4	31.2	-6.6
28	33.6	32.8	-2.4
29	33.6	34.0	1.2
30	34.0	34.0	0.0
31	34.2	31.8	-7.0
32	34.2	34.6	1.2
33	36.0	36.9	2.5
34	36.2	36.0	-0.6
Total (average percentage)	796.0	786.2	(-0.7)

tion to the mean and has been determined from the ratio of the bridge WIM values to the static scale values for each vehicle. These standard deviations result in the following COVs: front axle, 14.4 percent; drive tandem, 6.4 percent; rear tandem, 5.4 percent; and gross weight, 3.2 percent. Note that the COV of the front axle correlation has the largest COV and the lowest mean value.

APPLICATIONS

The data obtained by bridge WIM are useful to agency planning, pavement, bridge, and enforcement divisions. The data are available in one-to-one correlation or in histogram form. Most important is the tail of the spectrum representing the heavier vehicles. This should be unbiased data because the weighing operation is undetected by drivers. The data can be presented by vehicle classification; time of day; day of the week; and, with the portable manned system, body type or some other visual classification. Table 3 gives axle-weight data in histogram form. The system stores axle and gross weights to the nearest 100 lb.

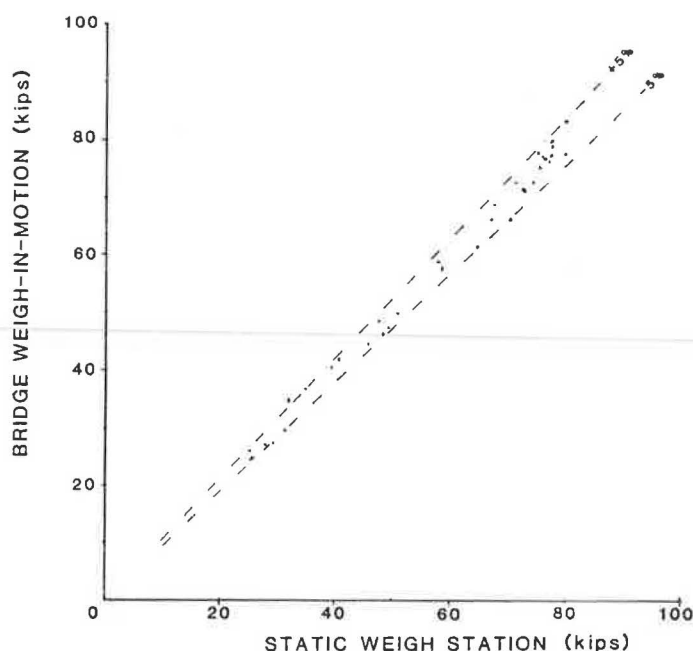


FIGURE 5 Gross weight correlation.

Given the required pavement parameters, the system also calculates equivalent single axle load (ESAL) values, also known as 18-kip equivalents, needed by pavement groups. In addition, ESALs can be separated by lane, which is important because driving and passing lanes do receive different loadings and therefore exhibit different wear. Moses and Ghosn (3) reported ESAL values 4.2 times greater in the driving lane of the Ohio Turnpike than in the passing lane. The Ohio Turnpike Commission has reported that, at the time of resurfacing, the driving lane required at least 80 percent of the base repair cost.

The ESAL value for an axle or axle group in-

creases with approximately the fourth power of the axle or group weight. Thus, even though an axle weighing system shows no bias (i.e., the mean value measured is the true mean of the population), the ESAL values obtained will be greater than the true ESAL values of the truck population. For example, if a population of n axles weighing 18 kips is measured by a system with no bias and a known COV and no skew, the data will be evenly distributed about the measured mean of 18 kips; that is, there will be as many axles weighed at 16 kips as there are at 20 kips (the average of 16 and 20 is 18). However, the sum of the ratios of the axle weights to 18 kips raised to the fourth power will not be equal to n

TABLE 3 Axle Weight Histogram for Bridge Weigh-in-Motion System^a

DISTRIBUTIONS BY AXLE WEIGHT															
FRONT				SINGLE				TANDEM				TRIPLE			
	#	%	SUM%		#	%	SUM%		#	%	SUM%		#	%	SUM%
TOTAL	75	100.0	100.0	TOTAL	74	100.0	100.0	TOTAL	92	100.0	100.0	TOTAL	1	100.0	100.0
0 5	10	13.3	86.7	0 5	13	17.6	82.4	0 10	21	22.8	77.2	0 15	0	.0	100.0
5 6	6	8.0	78.7	5 6	5	6.8	75.7	10 12	4	4.3	72.8	15 18	0	.0	100.0
6 7	7	9.3	69.3	6 7	6	8.1	67.6	12 14	7	7.6	65.2	18 21	0	.0	100.0
7 8	12	16.0	53.3	7 8	5	6.8	60.8	14 16	2	2.2	63.0	21 24	0	.0	100.0
8 9	21	28.0	25.3	8 9	7	9.5	51.4	16 18	6	6.5	55.5	24 27	0	.0	100.0
9 10	12	16.0	9.3	9 10	2	2.7	48.6	18 20	6	6.5	50.0	27 30	0	.0	100.0
10 11	6	8.0	1.3	10 11	5	6.8	41.9	20 22	4	4.3	45.7	30 33	0	.0	100.0
11 12	0	.0	1.3	11 12	4	5.4	36.5	22 24	9	9.8	35.9	33 36	1	100.0	.0
12 13	1	1.3	.0	12 13	3	4.1	32.4	24 26	5	5.4	30.4	36 39	0	.0	.0
13 14	0	.0	.0	13 14	6	8.1	24.3	26 28	10	10.9	19.6	39 42	0	.0	.0
14 15	0	.0	.0	14 15	7	9.5	14.9	28 30	5	5.4	14.1	42 45	0	.0	.0
15 16	0	.0	.0	15 16	3	4.1	10.8	30 32	11	12.0	2.2	45 48	0	.0	.0
16 17	0	.0	.0	16 17	3	4.1	6.8	32 34	1	1.1	1.1	48 51	0	.0	.0
17 18	0	.0	.0	17 18	3	4.1	2.7	34 36	1	1.1	.0	51 54	0	.0	.0
18 19	0	.0	.0	18 19	2	2.7	.0	36 38	0	.0	.0	54 57	0	.0	.0
19 20	0	.0	.0	19 20	0	.0	.0	38 40	0	.0	.0	57 60	0	.0	.0
20 21	0	.0	.0	20 21	0	.0	.0	40 42	0	.0	.0	60 63	0	.0	.0
21 22	0	.0	.0	21 22	0	.0	.0	42 44	0	.0	.0	63 66	0	.0	.0
22 23	0	.0	.0	22 23	0	.0	.0	44 46	0	.0	.0	66 69	0	.0	.0
23 24	0	.0	.0	23 24	0	.0	.0	46 48	0	.0	.0	69 72	0	.0	.0
23100	0	.0	.0	23100	0	.0	.0	46200	0	.0	.0	69300	0	.0	.0
KIPS				KIPS				KIPS				KIPS			

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times the ESAL of the mean of the population. The ratio of 16 to 18 kips raised to the fourth power is 0.62. Similarly, the ratio of 20 to 18 kips to the fourth power is 1.52. The average of 0.62 plus 1.52 is 1.07 rather than 1.00.

It can be shown that any axle weighing system that has no bias but does have some variation (as all do) will overestimate the total ESAL values for a given population. The amount by which the ESAL estimate is greater than the true value will be dependent on the COV of the weighing system. Table 4 gives the value of the increase in the ESALs for different COVs. The bridge WIM method has a COV of 6 percent on tandem weights that corresponds to a 3.2 percent increase in total ESAL values. Moses and Ghosn (3) reported increases in total ESALs of less than 5 percent compared with a static platform scale. It should be kept in mind that static weighing does have some variation depending on the scale used and the speed of the weighing operation. Moses and Ghosn (3) have reported higher COVs with repeatability of the same truck on static scales than with a bridge WIM operation. Note that the values in Table 4 will change with any bias in the weighing system results.

TABLE 4 Ratio of Predicted ESAL Values to Actual ESAL Values Versus Coefficient of Variation

COV (%)	$E(R^4)^a$	COV (%)	$E(R^4)^a$
2	1.004	15	1.203
4	1.014	20	1.360
6	1.032	25	1.563
8	1.058	30	1.810
10	1.090	50	3.250

^a $E(R^4)$ = Predicted total ESAL/Actual total ESAL.

Other factors contribute to inaccurate ESAL values at a weighing site. One such factor is the bypassing of the weighing operation by heavy or overweight vehicles. A correlation was performed between a bridge WIM system and a static scale on I-90 in northeastern Ohio. The static scale was 17 mi upstream from the bridge WIM site. Axle weights were collected at both sites along with visual hauling information and vehicle identification numbers. A study of the data revealed substantially different populations. For example, five heavy vehicles carrying rolls of steel were observed and weighed at the bridge site, but no steel haulers had passed through the weigh station. There is a four-lane limited access highway that could serve as a bypass route for vehicles heading east out of Cleveland, from which vehicles would enter I-90 between the static scale and the bridge WIM site. Using this bypass would add 10 to 15 min to driving time. The ESAL values from the loading spectra indicate a 63 percent increase in the average ESAL per vehicle from 1.21 at the static scale to 1.97 at the bridge WIM site.

The bridge WIM system also checks compliance with the bridge formula as well as with regulations peculiar to a particular state. Noncomplying vehicles are reported in a series of six tables useful in examining the effectiveness of an agency's enforcement effort, or to determine where and when enforcement activity is needed. Because the system is portable, traffic on smaller routes may be weighed to determine the presence of heavy vehicles bypassing a static weigh station.

Another application of the bridge WIM system results from the direct measurement of bridge girder strains. Strain records can be analyzed to obtain lateral distribution factors, maximum stresses, and impact, all of which are important in evaluating and rating bridges. In addition, the bridge response can be measured for the relatively rare event of two heavy vehicles crossing the structure simultaneously. The measured bridge load spectra can replace conservative AASHTO rating recommendations in a reliability or probabilistic approach for a rational and consistent evaluation (4).

SUMMARY

The bridge WIM concept used in practice today has been described. The variety of applications for which the data can be used has been discussed. The ease with which the system can be moved from site to site and the relatively low cost of obtaining measurements at new sites (the scale, or bridge, is already in place) make the bridge WIM operation an attractive means for obtaining the large amounts of data needed. In addition, the weighing operation is not noticed by passing vehicles so the data obtained are unbiased. Weighing can be performed in most weather conditions and at night with no danger to highway personnel.

The relationship presented for estimating the error associated with cumulated ESAL values demonstrates the need for pavement groups to either obtain accurate load spectra or realize the possible error in the WIM equipment used to gather the data. For example, there are several systems in use with COVs of 25 percent or greater, which could result in much higher ESAL values on surveyed routes.

Bridge WIM system results can be used by bridge departments for rating and evaluating structural safety, bridge life, and posting limits. Analyzing the structural response to random traffic may identify critical elements and assist in identifying inspection intervals.

Many bridges could be instrumented in an enforcement screening program providing enforcement personnel with "probable cause" for weighing suspect vehicles. Because the system is not detected by drivers, reliable surveys can be done efficiently to evaluate the effectiveness of an existing enforcement program.

ACKNOWLEDGMENT

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