Implementation of a Long-Term Bridge Weigh-in-Motion System for a Steel Girder Bridge in the Interstate Highway System

Using strain gages attached directly to the steel girders provides for a long-term monitoring system with minimal maintenance that can be readily applied to gain important information on the quantity and weights of trucks crossing a highway bridge.

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The University of Connecticut and the Connecticut Department of Transportation have implemented an extensive bridge monitoring program for the two past decades, including both short-term and long-term studies. The current research project is part of a long-term monitoring project for a group of bridges in the interstate highway network in the state of Connecticut.[1,2] The bridge studied in this article is a heavily trafficked, composite steel girder bridge. The original goal of the study on this bridge was to develop a structural health monitoring approach.[3,4]

However, based on the strain data collected after the first year, it was proposed to implement a bridge weigh-in-motion (BWIM) program using the existing monitoring system to determine the weights of trucks crossing over this bridge. The data from the BWIM system could possibly be used for research in traffic planning, pavement design, bridge rating and structural health monitoring. The data can

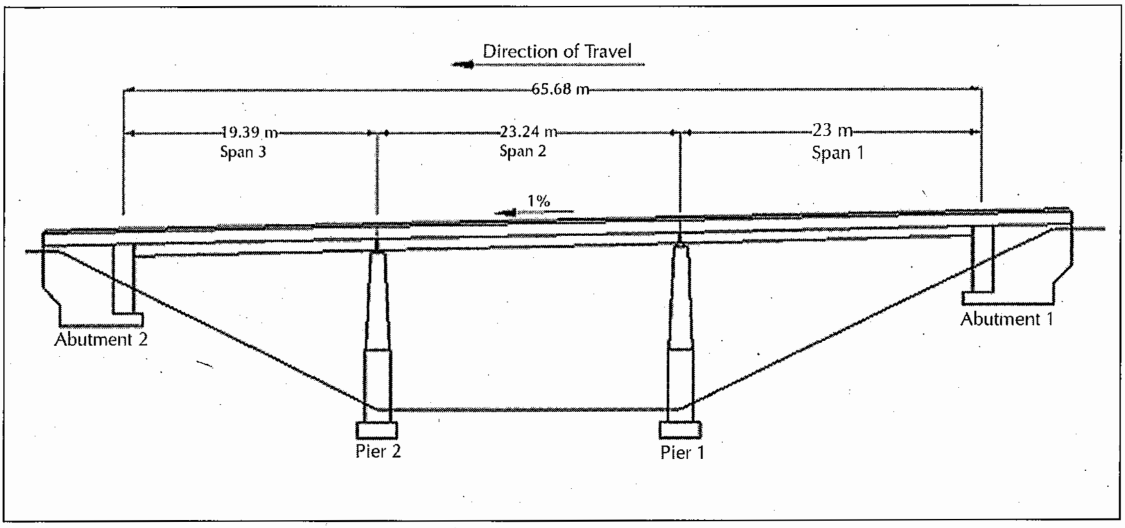

FIGURE 1. Elevation view of the subject bridge in Connecticut.

also be used to determine how many trucks crossing the bridge are overweight.

Traditional weigh-in-motion (WIM) systems use pavement-based sensors installed in the road. Typically, the durability of such WIM sensors are good; however, the surrounding pavement conditions can greatly affect their results. Other issues that can arise are truck drivers discovering the location of the sensors and avoiding them, and the issue that traditional WIM sensors need roadway closures to install the pavement-based sensors, which are dangerous and can increase traffic delays.

BWIM Advantages & Review of Studies

The BWIM concept was originally developed almost thirty years ago, but has not been as widely adopted in the United States as in Europe. It is hoped that the following research could provide the impetus to use BWIM systems on a wider scale.

The advantage of BWIM is that all instrumentation and equipment are installed under the bridge. Installation can be done with minimal lane closures for bridges that provide underside access. BWIM systems are also almost undetectable to truck drivers, and there are many possible locations for a BWIM system due to the great number of bridges suitable for BWIM installation. In addition, the dynamic truck effects are normally reduced by the relatively large inertia of the bridge.[5] The strain gages are also usually inexpensive when compared to other WIM sensors. The BWIM system implemented in this research does not require use of tube-type axle detectors placed on top of the roadway, as required by previous BWIM systems. Pavement-based sensors that are used in traditional WIM implementations are subject to harsh roadway conditions, while BWIM sensors are protected under the bridge, adding to the durability of the system. It is important to note that the one major disadvantage of BWIM is that the system must be configured to each particular bridge since superstructure type, span arrangement, number of lanes and other conditions differ at most sites.

Moses first proposed a BWIM system.[5] His concept was to use a bridge as a scale, using strain gages, to estimate the weight of trucks crossing the bridge. Moses and Ghosn extended the original algorithm to separate the weights of trucks traveling in multiple lanes by using an influence surface derived from the strain data collected during the crossing of calibration trucks in each of the bridge lanes.[6] They also used influence lines generated from field measurements to help improve the accuracy of the axle weights. Results collected from BWIM installations were used by Ghosn, Moses, *et al.* to develop methods for the reliability analysis of bridge systems, the calibration of bridge design and evaluation specifications, as well as for the safety assessment of individual existing bridges.[7-9] Ghosn and Xu modified the BWIM algorithm to calculate the dynamic amplitude of bridge vibration in addition to axle weights.[10] More recent BWIM research by Kim, Sokolik and Nowak[11] used a WIM system that utilized tape switches and infrared sensors as axle detectors to determine speed, axle spacing and the number of axles using Moses's algorithm.[5] Znidaric, Lavric and Kalin developed several algorithms to select appropriate bridges for BWIM systems, and made several additions to the BWIM algorithm to increase the accuracy of the Moses method.[12] Znidaric, Kalin, and Lavric introduced an axle-detector-free system using sensors on the underside of a bridge.[13] Gonzalez and O'Brien developed a new calibration procedure, a dynamic algorithm and a multiple sensor algorithm to deal with vehicle and bridge dynamics, as well as to improve the accuracy of BWIM.[14] Quilligan, Karoumi and O'Brien[15] implemented a method previously described by Moses and Ghosn[6] for automatically determining the influence line to include the presence of multiple vehicles on the bridge and their positions using pneumatic tubes in the road to determine the locations of two vehicles crossing. Dunne, O'Brien, Basu and Gonzalez furthered the "nothing-on-road" BWIM concept using only strain gages under the bridge to predict axle weight, vehicle spacing and vehicle velocity.[16] They also used wavelets to clarify the peaks in the data. Ojio and Yamada developed a BWIM system without axle detectors that used stringers that were installed to reinforce slabs on plate girder bridges.[17] Ojio and Yamada also developed an axle-detector-free BWIM system using strains from reaction forces and not from bending of the bridge.[18] Jacob and O'Brien reviewed the recent European developments in WIM.[19] This review also included coverage of BWIM use in Europe and the continued development of this technology. The *COST 323 Specifications* brought WIM users together and became a standardized accuracy classification method.[20] The Weighing of Vehicles in Europe (WAVE) Project, funded by the European Commission, resulted in a number of advances in WIM algorithms and sensors, as well as advances in BWIM technology.[21] O'Brien, Znidaric and Ojio discuss the latest developments and applications of BWIM as used in Europe and Japan.[22]

Description of the Bridge & Monitoring System

The bridge in this study is located in central Connecticut and carries three lanes of traffic of an interstate highway in one direction over a small river. The elevation is shown in Figure 1, the plan view in Figure 2 and a typical cross-section of the bridge is shown in Figure 3. There are eight girders numbered G1 to G8. Twenty uniaxial strain gages were installed on the web of the steel girders. Sixteen gages were placed in Span 1, located in pairs at the mid-span of each girder 2 inches below the bottom of the top flange of the girder and 2 inches above the top of the bottom flange of the girder. Four additional gages were located in Span 2. The sensors in Span 1 are used to determine weight and the sensors in Span 2 are used to determine truck speed.

The strain gages are connected to an on-site computer that is located underneath the bridge. Currently, the system is set up to record data when a vehicle weighing approximately 90 kN (10 tons) or larger crosses the bridge, using the gages on Girders G3 and G5 as triggers. The system is zeroed before each data collection session in order to take into account temperature and gage drift that occurs over time.

BWIM Algorithm Considerations

As shown in the literature review, there are several different BWIM methods. The factors that need to be taken into consideration before selecting a BWIM method include:

- pavement smoothness;
- the calibration procedure;
- the superstructure type;
- span and support conditions; and,
- bridge geometry.

The superstructure type has a large influence on what sort of BWIM data can be obtained from a bridge. A simply supported span simplifies BWIM,[5] but continuous spans have been used by Moses and Ghosn.[6,7,23] In addi-

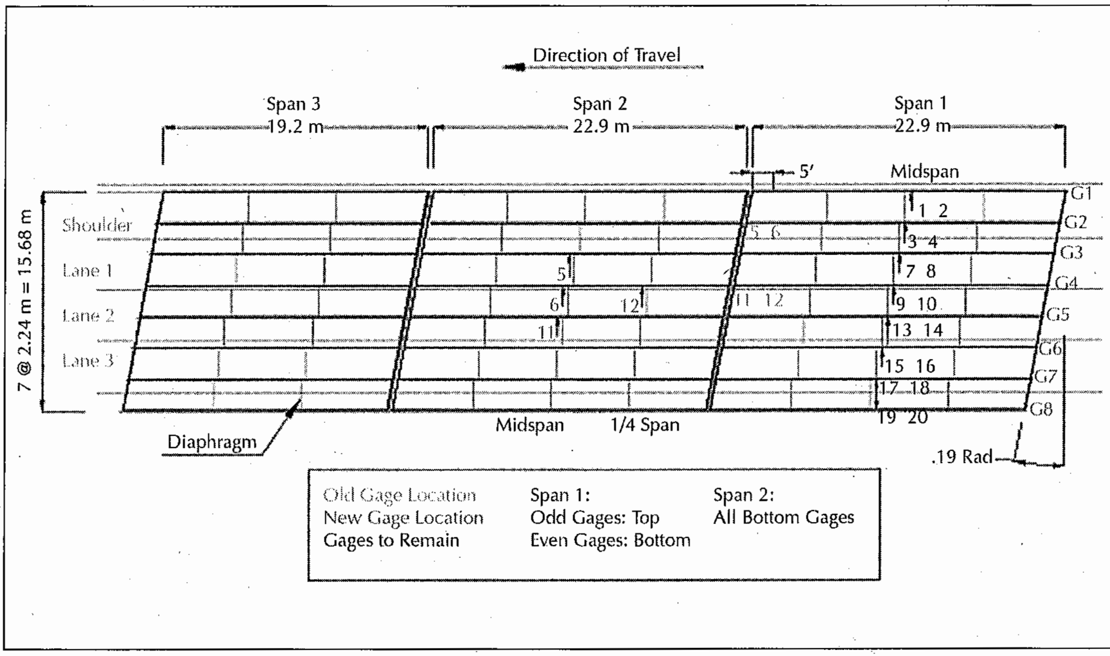

FIGURE 2. Plan view of the subject bridge showing details of the monitoring system.

tion, shorter bridges that have more flexible superstructures will have a higher strain response and are preferred for BWIM instead of longer bridges with a more rigid superstructure that will have less strain response. Znidaric, Lavric and Kalin stated that BWIM systems on bridges with a span of less than 8 meters (26 feet) will have a higher strain response and will lead to systems with higher axle accuracy, while a span between 8 to 30 meters (26 to 98 feet) will have less strain response and should provide gross vehicle weight (GVW) accurately.[12] The bridge in this project has a 22.9-meter (75-foot) long simply supported span. Therefore, the goal of this system will be to determine the GVW and, as a result, axle weights will not be determined.

Methods described by Znidaric *et al.* typically use shorter span bridges that show the peaks from all axles on the strain plot.[13] Methods by Dunne *et al.* attempted to separate peaks using wavelet transforms,[16] but since

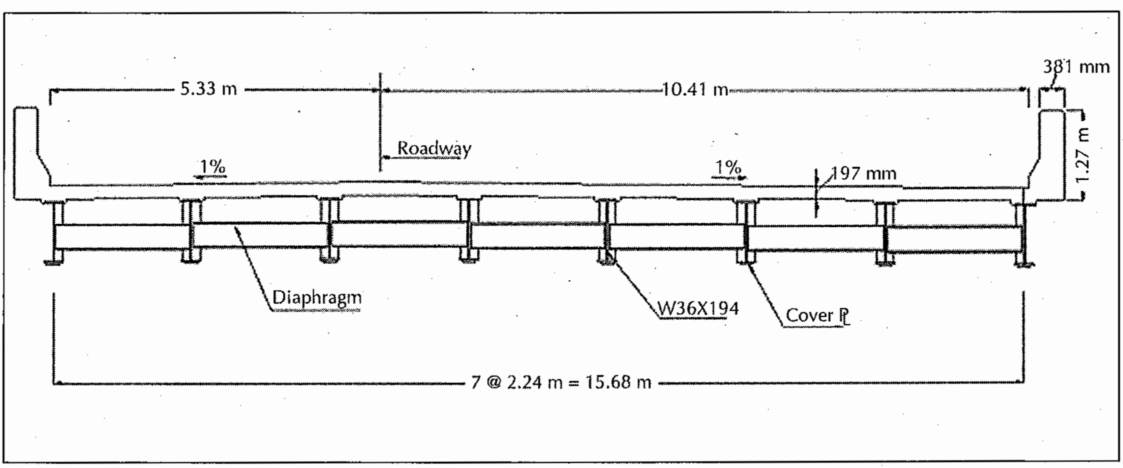

FIGURE 3. A cross-section view of the subject bridge.

some axles are being detected, this method could be tried in the future to optimize the system. Since the decision was made only to determine GVW, it was decided to use a method described by Ojio and Yamada where the individual axle peaks are not important as long as the groups of axles themselves are detected.[17] The analysis of the study bridge differs from their analysis since the study bridge's analysis used primarily the girders of the bridge, and not just stringers. The method computes the GVW by integrating the strain response curve and relates the curve using the speed to the weight of the truck using a known-weight truck to calibrate the system. The general principle is that as a load passes over a bridge at a certain speed it produces an influence area recorded by strain readings. The unknown truck weight, *GVW*, is:

$$GVW = A \bullet (GVW_C/A_C) \qquad \textbf{(1)}$$

where:

A = truck influence area for the truck crossing the bridge (see Reference 17 for the formula);

A_C = the truck influence area for the truck used to calibrate the system; and,

GVW_C = the known-weight for the truck used to calibrate the system.

The known influence area, A_C, is computed by multiplying the area under the strain plot for the known truck by the speed of the known truck. Using the known GVW_C, an unknown truck GVW can be estimated using its known influence area, A.

The speed of the truck must be determined in order to calculate the influence area. When a truck passes over the bridge, peaks can be seen in the strain readings where groups of axles are present. If the peaks are found at two different strain gage locations a known distance apart, the time between peaks is known and the speed can be determined. For determining speed, trucks in Lane 1 use Gages 8 and 5, while Lane 2 uses Gages 11 and 14. An example strain plot used for speed determination can be seen in Figure 4. Figure 4 shows the strain response for a typical truck in Lane 2 using Gages 11 and 14. The plot shows two peaks for readings in the two different spans. Using the first peaks from Gage 14 and Gage 11, the time is calculated using the known distance between the gages. In the example, the truck is moving at approximately 97 kilometers per hour (60 miles per hour). The area under strain versus time plot is then determined for Span 1 and then multiplied by the speed to determine the influence area.

As noted, this method requires known-weight truck data for calibration. Two different known-weight trucks passed in Lanes 1 and 2 at a speed slightly below the speed limit for this bridge. The truck layouts and weights are shown in Figure 5. Truck 1 is a shorter truck that was measured statically to be 309 kN (35 tons). Truck 2 is a longer truck that was measured statically to be 275 kN (31 tons). Multiple passes were used for each truck at a constant speed and the pass only counted if there were no other trucks on the bridge. The data collected with the known-weight truck runs showed good consistency with respect to speed and peak strain values. For Truck 1, there were seven useable passes in Lane 1 and eight useable passes in Lane 2. Due to mechanical vehicle difficulties with Truck 2, there were only two useable passes in Lanes 1 and 2. Therefore, it was determined to use five passes from Truck 1 to calibrate the system and then the remaining passes from Truck 1 and all the passes from Truck 2 to validate the accuracy of the system.

The influence area for Truck 1 in both lanes was determined for five different runs in Lanes 1 and 2. The strain response is taken from Gage 8 for Lane 1 and Gage 14 for Lane 2. An example strain versus time plot used to calculate the influence area for Truck 1 in Lane 1 (Gage 8) can be seen in Figure 6, where the shaded area is computed and then multiplied by the speed in order to acquire the known influence area, A_C. The accuracy of the BWIM method was tested by determining the weights of the other known-weight truck passes. The weights of the Truck 1 and Truck 2 passes that were not used in the calibration calculation were determined using the BWIM method and then compared to their actual val-

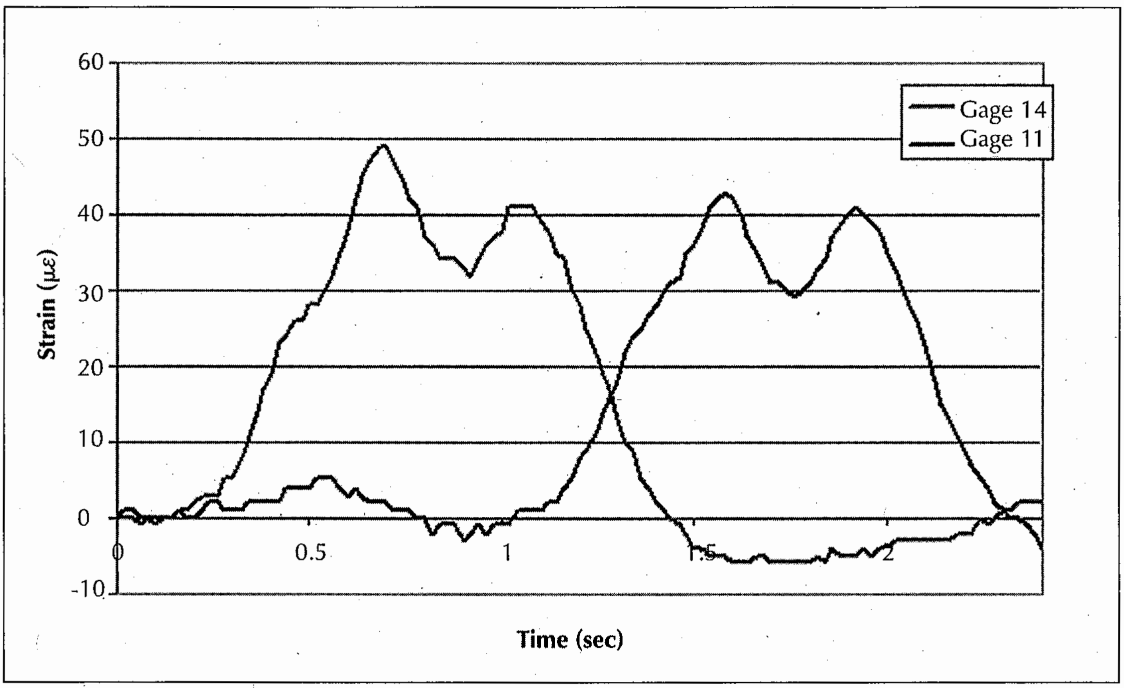

FIGURE 4. Strain versus time for a typical truck for Gages 14 and 11.

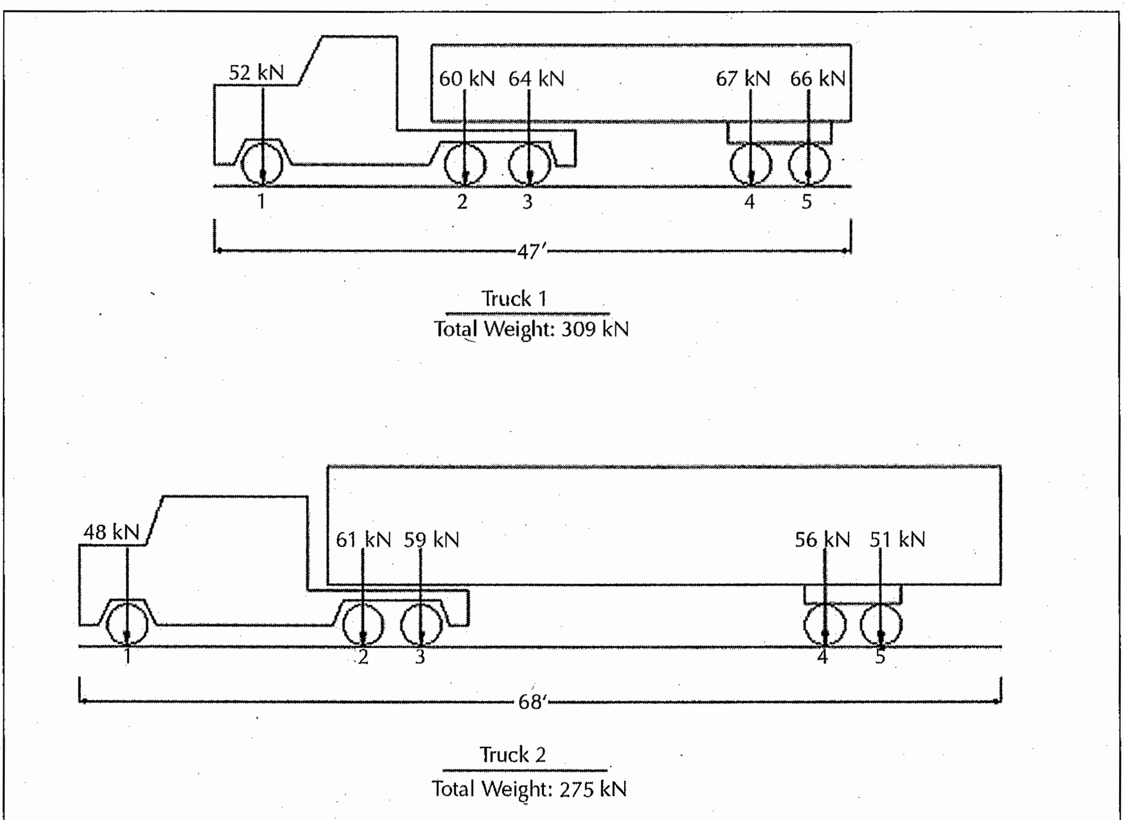

FIGURE 5. Known-weight truck layouts.

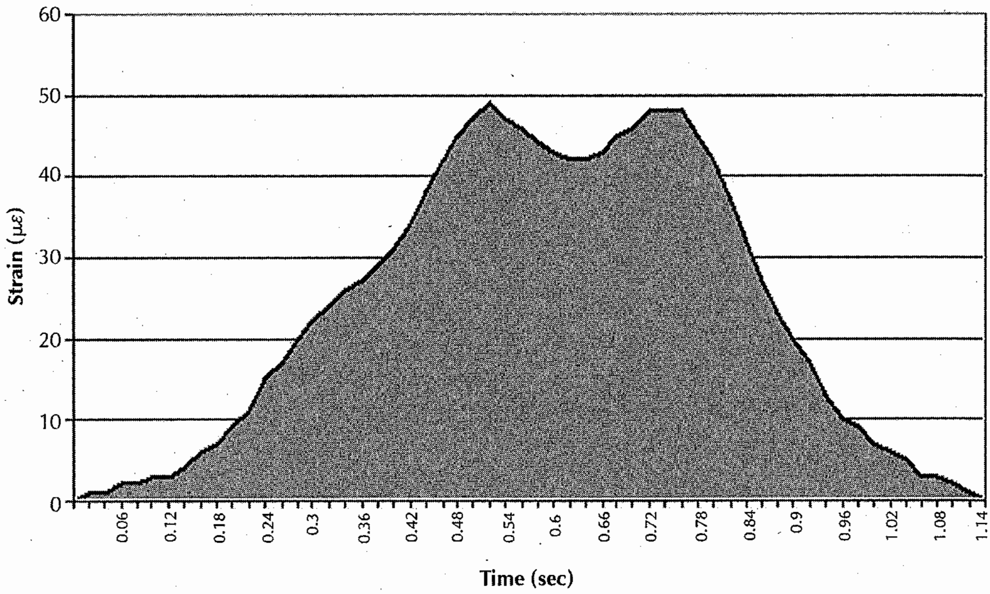

FIGURE 6. Strain versus time plot for Truck 1 in Lane 1 (data from Sensor 8).

ues. As seen in Tables 1 and 2, the error is less than 5 percent for any truck in either lane. It is assumed that this calibration is good until the global condition of the bridge changes due to deterioration.

BWIM Development Issues

A sample period of a mainline traffic stream was used to study potential problems in applying the BWIM system on this bridge. The system was only designed to provide BWIM data for the middle and right lanes, which are the only lanes trucks may legally use on this bridge. Since there is a left-hand on-ramp approximately 2.4 kilometers (1.5 miles) upstream from the bridge, there is a possibility that trucks will not be able to get over from the left lane to the legal lanes before they cross the bridge in heavy traffic situations. Using a randomly selected day, only 0.08 percent of trucks were found traveling in the left lane, which equaled four trucks out of about 4,800; therefore, it was determined acceptable to omit Lane 3 from the study. If these weights are desired in the future, known-weight data would be needed for Lane 3.

TABLE 1.
Predicted Weights vs. Actual Weights for Lane 1

Truck	Predicted Weight (kN/tons)	Actual Weight (kN/tons)	GVW Error from Static Weight (%)
Truck 1	314.7/35.4	310.3/34.9	1.4
Truck 1	321.0/36.1	310.3/34.9	3.5
Truck 2	285.2/32.1	275.2/30.9	3.7
Truck 2	277.7/31.2	275.2/30.9	0.9

TABLE 2.
Predicted Weights vs. Actual Weights for Lane 2

Truck	Predicted Weight (kN/tons)	Actual Weight (kN/tons)	GVW Error from Static Weight (%)
Truck 1	316.9/35.6	310.3/34.9	2.2
Truck 1	318.7/35.8	310.3/34.9	2.7
Truck 2	271.7/30.5	275.2/30.9	-1.2
Truck 2	266.7/30.0	275.2/30.9	-3.1

Determining the weights of multiple trucks on the bridge at the same time is an important issue. Since the span length of the bridge is 66 meters (217 feet), it is possible that trucks traveling close together can have the back axles of one truck on the bridge and the front axles of another truck on the bridge. There are also trucks that travel side by side, and staggered, that create problems separating events. Figure 7 shows an example of two closely staggered trucks in Span 1 — the first truck is in Lane 2 and has its peak in Gage 14; the second truck is in Lane 1 and has its peak in Gage 8. The issue is that the first truck's strain readings are influenced by the second truck, and the first truck strain does not return to zero until well after the second truck is off. Moses and Ghosn developed an algorithm to separate the weights of such trucks;[6] however, there were insufficient data to determine an influence surface and implement the algorithm into this study (it is hoped that such an implementation can be done in the future). The occurrence of these events is not frequent, but they do happen; however, this study will omit these events at this time. The other rare event that will be omitted from this study is a truck crossing between lanes (most likely changing lanes) on this bridge.

BWIM Results

Results from a typical weekday (a 24-hour period of data) were used. A combined histogram GVW screening can be seen in Figure 8. This histogram uses weights from Lanes 1 and 2. As shown in the figure, there are two peaks: one at the 126 to 150 kN (14 to 17 ton) range, and one at the 326 to 350 kN (37 to 39 ton) range. It is possible that the 126 to 150 kN (14 to 17 ton) range is either loaded box trucks (two-axle) or un-loaded semi-trucks (five-axle). The 326 to 350 kN (37 to 39 ton) range could possibly be loaded semi-trucks (five-axle). These peaks are typical for a weekday and only show a slight change in range for different weekdays (for example, the first peak varies between the 101 to 125 kN [11 to 14 ton] range and the 176 to 200 kN [20 to 22.5 ton] range). There are days when there are more trucks in the higher peak than the lower peak. It should also be noted that typically only about 8 percent of trucks exceed 355 kN (40 tons). Trucks above this range would be permit trucks, or, on occasion, trucks that are overloaded.

Figure 9 shows a plot of the truck GVW versus time for the same set of 24-hour data. This plot shows the large variation in truck weights. At this time, there is no pattern that corresponds to times when heavier or lighter trucks cross the bridge. Due to the fact that only the GVW can be determined by this system, plotting the trucks by truck class is not possible since the number of axles is not determined for each truck.

Statistics for this same typical day are shown Table 3. As seen in the table, the average speed in Lane 1 (the right lane) is slightly less than the average speed in Lane 2 (the middle lane), which is expected. The peak strain averages for each lane are very close to 37 $\mu\varepsilon$. There is also a considerable difference in the

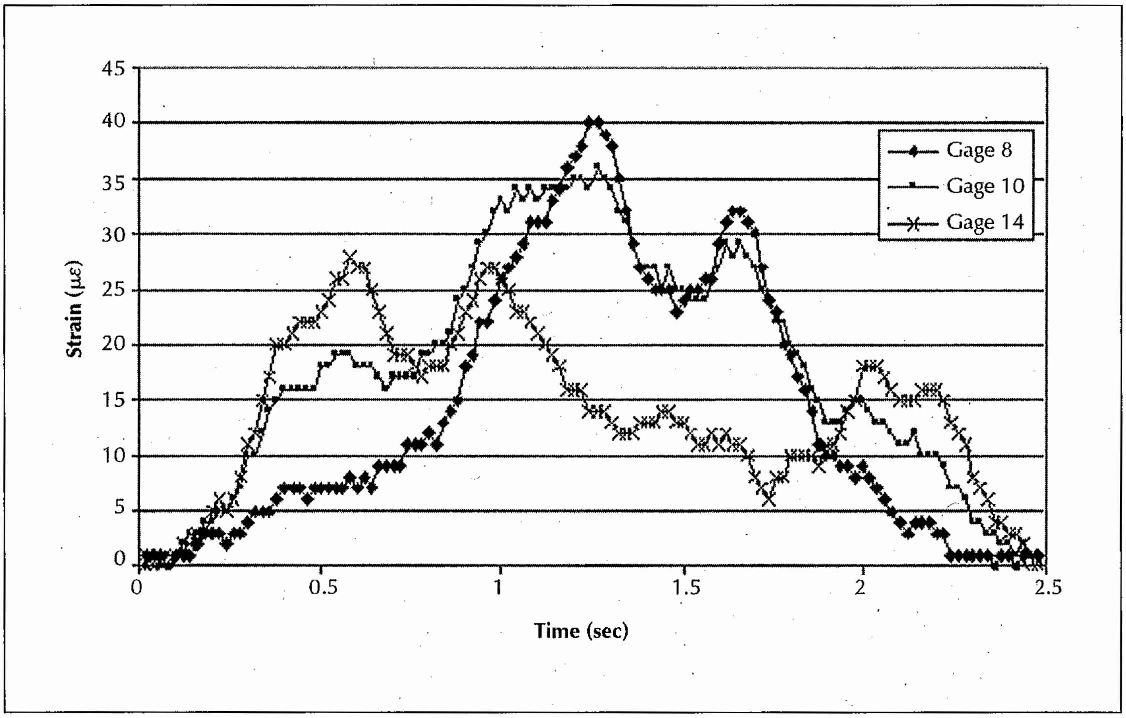

FIGURE 7. Strain versus time for Gages 8, 10 and 14 showing staggered trucks in different lanes.

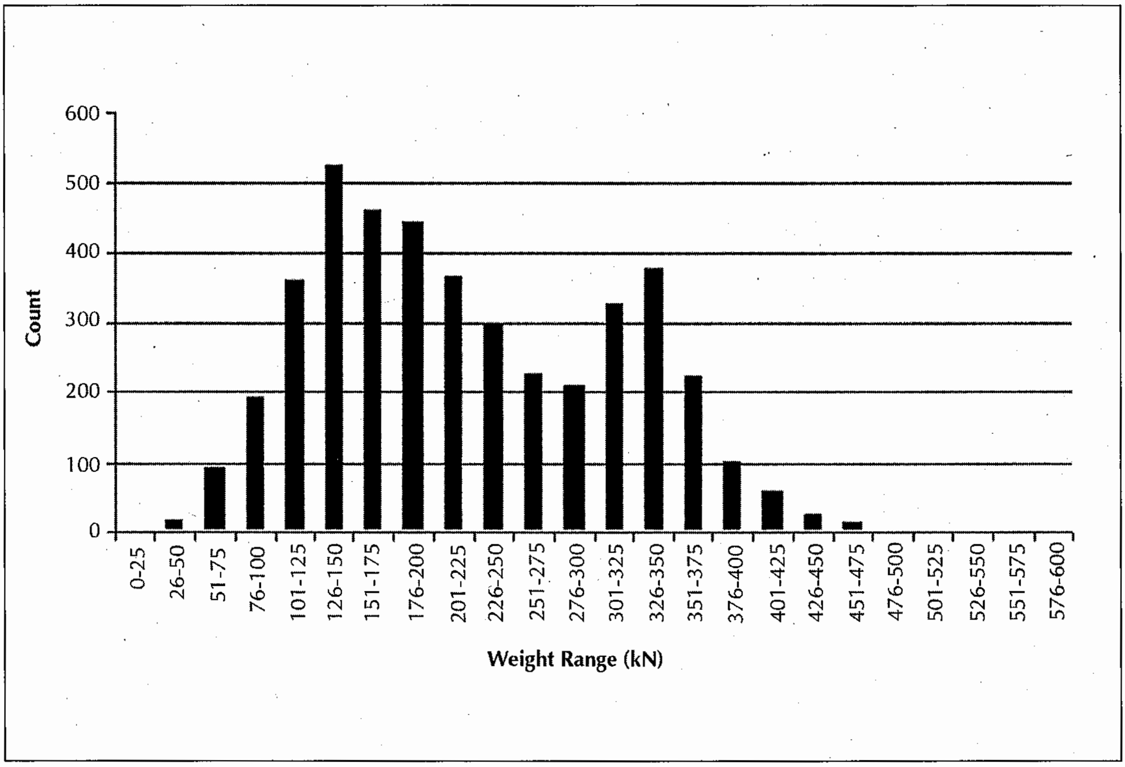

FIGURE 8. Histogram of truck weights for a typical weekday in 5 kip increments.

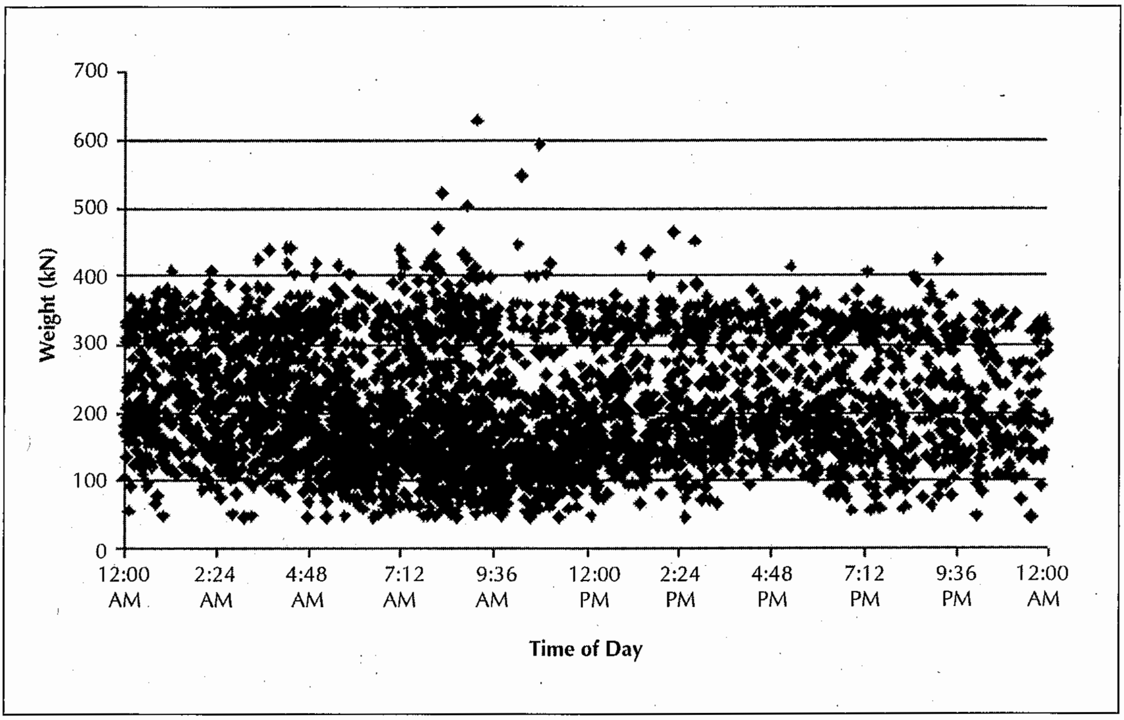

FIGURE 9. Weight versus time of day for a typical weekday.

volume of trucks in Lanes 1 and 2. The majority of trucks crossing this bridge use Lane 2. This is most likely due to the right-hand on-ramp immediately before the bridge since trucks typically move over to Lane 2 to let traffic merge, and from trucks that move over from the left-hand entrance ramp 2.4 kilometers (1.5 miles) before the bridge to Lane 2. The table also provides information on the amount of trucks that were missed by the BWIM program. These missed trucks typically occurred when it was not possible to determine the speed or when there were several trucks on the bridge at the same time. It is hoped to increase this accuracy and detect these trucks in the future by applying some of the methods described by Moses and Ghosn with more known weight testing and possibly adding sensors to the bridge.[6]

Approximately twelve 24-hour data collection periods have been analyzed by the BWIM program. It is usually impractical to start a day of recording at midnight, so most 24-hour periods start in the morning and then are stopped the next morning to create a 24-hour period. A weekend period of 48 hours (midnight Saturday to midnight Sunday) has also been analyzed. Additional BWIM results are contained in a separate study.[4]

Conclusions

A readily applied, reliable strain-based monitoring system can be used for a long-term BWIM program. The BWIM system is a feasible alternative to traditional WIM in that it has the advantage that the system is non-intrusive — *i.e.,* it is not necessary to install sensors in the roadway pavement. The data produced by this BWIM system can be used in research for traffic planning, load rating and structural health monitoring.

Data collected with multiple passes of two test trucks have demonstrated that there is consistency in the BWIM evaluations. The large amount of data studied for normal truck crossings did not indicate any significant discrepancies due to wide variations in trucks and their speeds. In addition, the system determines the number of trucks that cross the bridge per day. The BWIM data produced by this system has shown patterns in truck GVWs. It has also shown that, for this bridge,

TABLE 3.
Average Values from a Typical Weekday

Values	Lane 1	Lane 2	Combined
Speed (kph/mph)	108/67	112/70	111/69
Weight (kN/tons)	248/28	206/23	222/25
Peak Strain ($\mu\varepsilon$)	36	37	37
Number of Truck Events	2,084	4,162	6,246
Number of Truck Weights Determined	1,716	2,727	4,443
Number of Truck Weights Missed	368	1,435	1,803
Missed (%)	18	34	29
Trucks/hour	87	173	260

approximately 8 percent of the trucks are overweight.

In summary, the proposed BWIM system is being used successfully to determine the volume of trucks crossing the bridge, their GVWs, the lanes used by the trucks and the number of overload trucks.

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