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

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Abstract: This technical paper discusses the implementation of a long-term bridge weigh-in-motion system for use in determining gross vehicle weights of trucks crossing steel girder bridges. The system uses strain data to determine truck weights using an existing structural health monitoring system installed on a interstate highway bridge. The applied system has the advantage of not using any axle detectors in the roadway; and instead all analyses are performed using strain gauges attached directly to the steel girders, providing for a long-term monitoring system with minimal maintenance. Long-term data has been used to demonstrate that this method can be readily applied to gain important information on the quantity and weights of the trucks crossing the highway bridge.

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Introduction

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 (DeWolf et al. 2006; Olund et al. 2006). The bridge studied in this technical paper is a heavily trafficked, composite, steel girder bridge (Chakraborty and DeWolf 2006). The original goal of the study on this bridge was to develop a structural health monitoring approach (Cardini and DeWolf 2009; Cardini 2007). 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 the trucks crossing over this bridge.

Traditional weigh-in-motion (WIM) systems use pavement-based sensors installed on the road. Typically, the durability of such WIM sensors are good. However, the surrounding pavement conditions can greatly affect their results. Other issues are that trucks can discover the location of the sensors and take steps to avoid them, and traditional WIM sensors need roadway closures to install the pavement-based sensors. The BWIM approach used in this study and others has several advantages over WIM systems. BWIM systems are harder to detect since they are installed under the bridge and do not require placement of sensors directly into the pavement. The BWIM system implemented in this research does not require use of axle detectors placed on top of the roadway, as required by previous BWIM systems or the pavement-based sensors that traditional WIM uses. This provides for long-term monitoring without maintenance. The data from WIM and BWIM studies can be used for research in traffic planning, pavement design, bridge rating, and structural health monitoring. The data can also be used for identifying overweight trucks.

BWIM Advantages and Review of Studies

The BWIM concept was originally developed almost 30 years ago, but has not been widely adopted in the United States. It is hoped that the following research will 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. This can be done without lane closures for bridges with underside access. BWIM systems are also almost undetectable to truck drivers, and there are many possible locations for a BWIM system due to the number of bridges. Also, the dynamic truck effects are normally reduced by the relatively large inertia of the bridge (Moses 1979). The strain gauges are also usually inexpensive when compared to other WIM sensors. The major disadvantage of BWIM is that the system must be configured to each bridge since superstructure type, span arrangement, number of lanes, and other conditions differ at most sites.

Moses (1979) first proposed a BWIM system. His concept was to use a bridge as a scale, using strain gauges, to estimate the weight of trucks crossing the bridge. Moses and Ghosn (1983) extended the original algorithm to separate the weights of trucks traveling in multiple lanes by using an influence surface derived from the strain date collected during the crossing of calibration trucks in each of the bridge lanes. They also used influence lines

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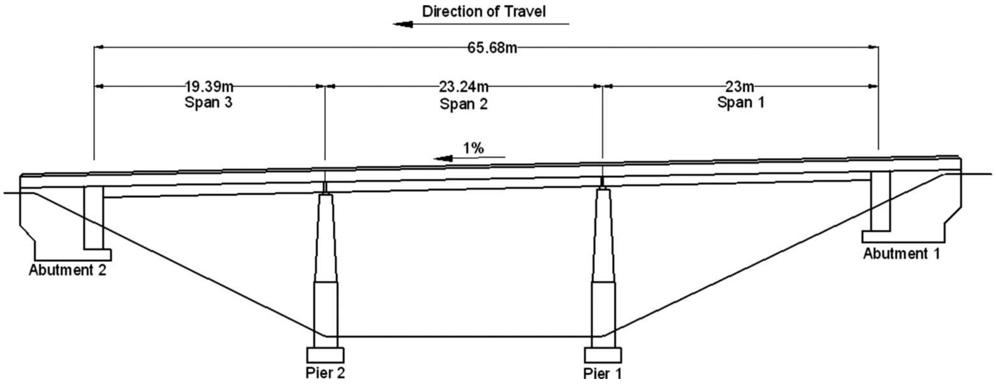

Fig. 1. Elevation view

generated from field measurements to help improve the accuracy of the axle weights. The results of BWIM studies were used by Moses et al. (1985), Ghosn and Moses (1986), and Ghosn et al. (1986) to develop methods for the reliability analysis of bridge systems, the calibration of bridge design, and evaluation specifications, as well safety assessments of individual existing bridges. Goshn and Xu (1988) modified the BWIM algorithm to calculate the dynamic amplitude of the bridge vibration in addition to the axle weights. More recent BWIM research by Kim et al. (1996) used a WIM system that used tape switches and infrared sensors as axle detectors to determine speed, axle spacing, and the number of axles, using the algorithm of Moses (1979). Znidaric et al. (2002b) developed several algorithms to select appropriate bridges for BWIM systems, and several improvements to the BWIM system algorithms to increase the accuracy of the Moses method. Znidaric et al. (2002a) introduced an axle-detector free system using sensors on the underside of the bridge. Gonzalez and O'Brien (2002) developed a new calibration procedure, a dynamic algorithm, and a multiple sensor algorithm to deal with vehicle and bridge dynamics and improve the accuracy of BWIM. Quilligan et al. (2002) implemented a method previously described by Moses and Ghosn (1983) for automatically determining the influence line to include the presence of multiple vehicles on the bridge and their position using pneumatic tubes in the road to determine the locations of two vehicles crossing. Dunne et al. (2005) furthered the nothing-on-road BWIM concept, using only strain gauges under the bridge to predict axle weight, spacing, and vehicle velocity. They also used wavelets to clarify the peaks in the data. Ojio and Yamada (2002) developed a BWIM system without axle detectors using stringers installed to reinforce slabs on plate girder bridges. Ojio and Yamada (2005) also developed an axle-detector-free BWIM system using strains from reaction forces and not from bending of the bridge. Jacob and O'Brien (2005) reviewed the recent European developments in WIM. This also includes BWIM in Europe and continued development of this technology. The COST 323 specifications (COST 323 1999) brought WIM users together and became a standardized accuracy classification method. The Weighing of Vehicles in Europe (WAVE) (Jacob 2002) project, funded by the European Commission, resulted in a number of advances in WIM algorithms and sensors, and BWIM technology. Obrien et al. (2008) discussed the latest developments and applications of BWIM as used in Europe and Japan. This paper also references earlier work on Weighing-in-motion of Axles and Vehicles for Europe (WAVE), a large research and development project in Europe.

Description of the Bridge and Monitoring System

The bridge is located in Connecticut and carries three lane traffic of the interstate highway system over a small river. The elevation

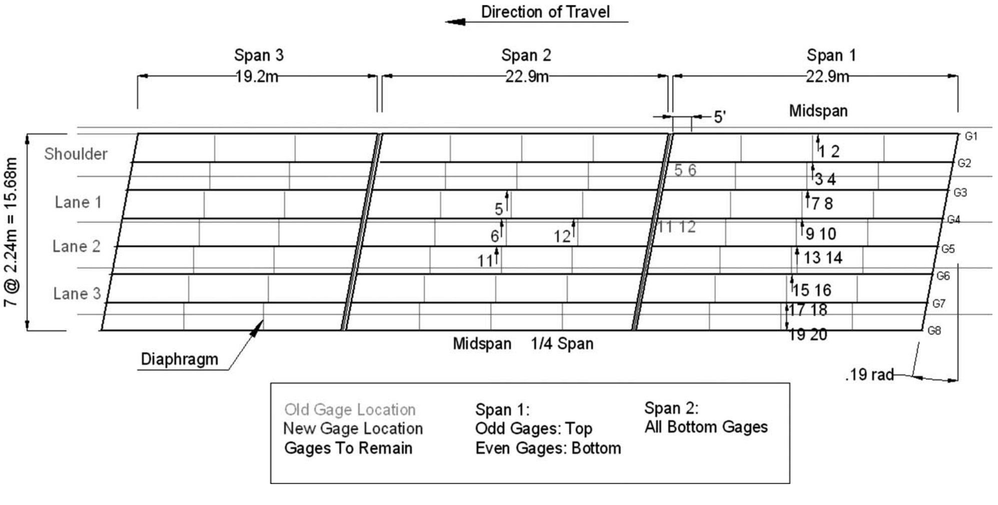

Fig. 2. Plan view showing monitoring detail

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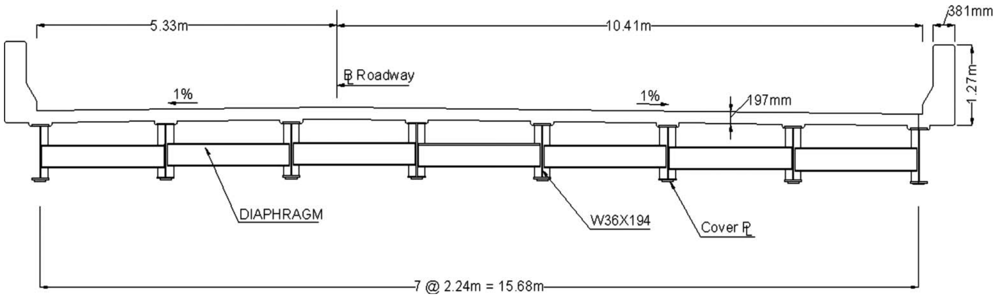

Fig. 3. Cross-sectional view

is shown in Fig. 1, the plan view in Fig. 2, and a typical cross section of the bridge is shown in Fig. 3. There are eight girders numbered G1 to G8. Twenty uniaxial strain gauges were installed on the web of the steel girders. Sixteen were placed in the first span, located in pairs at the midspan of each girder, one 2 in. below the bottom of the top flange of the girder, and one 2 in. above the top of the bottom flange of the girder. There are four additional gauges 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 gauges are connected to an on-site computer located underneath the bridge. Currently the system is set up to record data when a vehicle weighing approximately 90 kN or larger crosses the bridge, using the gauges on Girders G3 and G5 as triggers. The system is zeroed before each data collection session in order to remove temperature and gauge drift, which occurs over time.

Bridge Weigh-In-Motion 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 (Moses 1979), but continuous spans have been used by Moses and Ghosn (1981, 1983) and Moses et al. (1985). Usually shorter bridges have more flexible superstructures than longer bridges. Their higher strain response makes them preferred for BWIM, as opposed to longer bridges, which can have a more rigid superstructure, with smaller a strain response. Znidaric et al. (2002b) stated that BWIM systems on bridges with a span less than 8 m will have a higher strain response and will lead to systems with higher axle accuracy, while a span between 8–30 m will have less strain response and should provide GVW accurately. The bridge in this project has a 22.9 m simply supported span. Therefore, the goal of this system will be to determine the gross vehicle weight (GVW) and axle weights will not be determined.

Methods described by Znidaric et al. (2002a,b) usually use shorter span bridges that show the peaks from all axles on the strain plot. Methods by Dunne et al. (2005) attempted to separate peaks using wavelet transforms, but since some axles were being detected this method could be tried in the future. Since the decision was made only to determine GVW, it was decided to use a method described by Ojio and Yamada (2002) where the individual axle peaks are not important as long as the groups of axles are detected. The analysis of this bridge differs from their analysis by using the primarily loaded girders of the bridge, and not 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

$$\mathrm{GVW} = A \cdot \frac{\mathrm{GVW}_C}{A_C} \tag{1}$$

where A [Ojio and Yamada (2002) for formula]=truck influence area for the truck crossing the bridge; A_C=truck influence area for the truck used to calibrate the system; and GVW_C=known weight for the for the truck used to calibrate the system. The known influence area, Ac, 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 get the influence area. When a truck passes over the bridge, peaks can be seen in the strain readings where groups of axles are. If the peaks are found at two different strain gauge 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 Gauges 8 and 5, while Lane 2 uses Gauges 11 and 14.

An example strain plot used for speed determination can be seen in Fig. 4. The figure shows the strain response for a typical truck in Lane 2 using Gauges 11 and 14. The plot shows two peaks for readings in the two different spans. Using the first peaks from Gauges 14 and 11, the time is calculated using the known

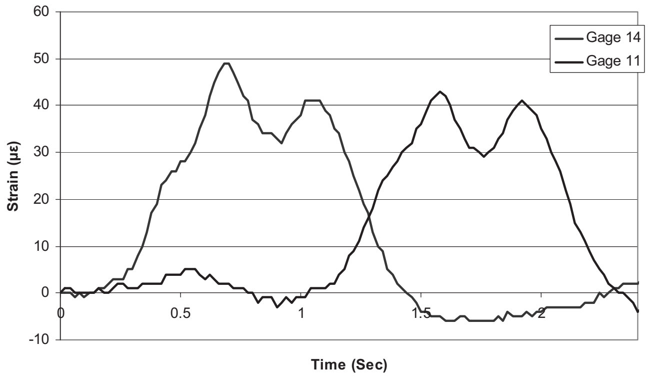

Fig. 4. Strain versus time for a typical truck for Gauges 14 and 11

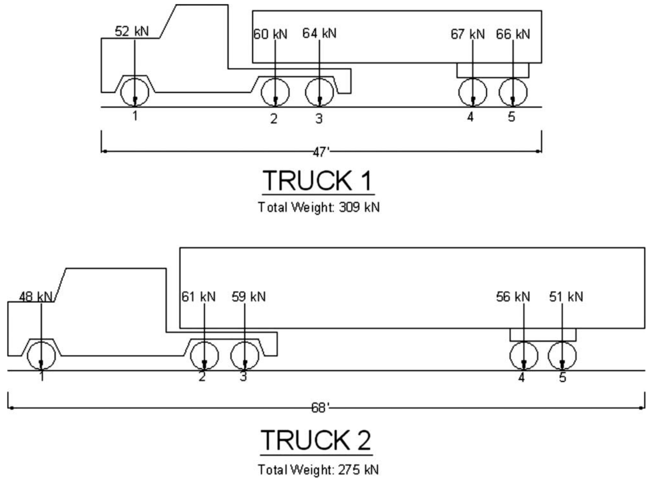

Fig. 5. Known-weight truck layouts

distance between the gauges. In the example the truck is moving at approximately 97 kmh. 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 layout and weight are shown in Fig. 5. Truck 1 is a shorter truck that was measured statically to be 309 kN, Truck 2 is a longer truck that was measured statically to be 275 kN. Multiple passes were used for each truck at 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 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 Gauge 8 for Lane 1 and Gauge 14 for Lane 2. An example strain versus time plot used to calculate the influence area for Truck 1 in Lane 1 (Gauge 8) can be seen in Fig. 6, where the shaded area is computed and then multiplied by the speed to get 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 values. As seen in Tables 1 and 2, the percent error is less than 5% for any truck in either lane.

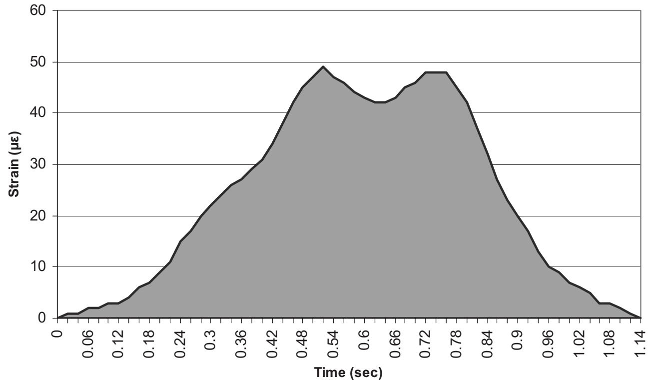

Fig. 6. Strain versus time plot for Truck 1 in Lane 1 (Sensor 8)

Table 1. Predicted Weights versus Actual Weights for Lane 1

Truck	Predicted weight (kN)	Actual weight (kN)	GVW % error from static weight
Truck 1	314.7	310.3	1.4%
Truck 1	321.0	310.3	3.5%
Truck 2	285.2	275.2	3.7%
Truck 2	277.7	275.2	0.9%

Bridge Weigh-In-Motion Development Issues

A sample period of 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 onramp approximately 2.4 km 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% of trucks were found traveling in the left lane, which equaled four trucks out of about 4,800, and 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.

Determining weights of multiple trucks on the bridge at the same time is an important issue. Since the span length of the bridge is 66 m, 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. Fig. 7 shows an example of two closely staggered trucks in Span 1, the first truck is in Lane 2 and has its peak in Gauge 14; the second truck is in Lane 1 and has its peak in Gauge 8. The issue is that the first truck's strain readings are influenced by the second truck, and the first truck's strain does not return to zero until well after the second truck is off. Moses and Ghosn (1983) developed an algorithm to separate the weights of such trucks but there were not sufficient data to determine an influence surface and implement the algorithm into this study. The occurrence of these events is not frequent and for this study it is considered acceptable to omit these events. The other rare event that will be

Table 2. Predicted Weights versus Actual Weights for Lane 2

Truck	Predicted weight (kN)	Actual weight (kN)	GVW % error
Truck 1	316.9	310.3	2.2%
Truck 1	318.7	310.3	2.7%
Truck 2	271.7	275.2	−1.2%
Truck 2	266.7	275.2	−3.1%

omitted from this study is a truck crossing between lanes (most likely changing lanes) on this bridge.

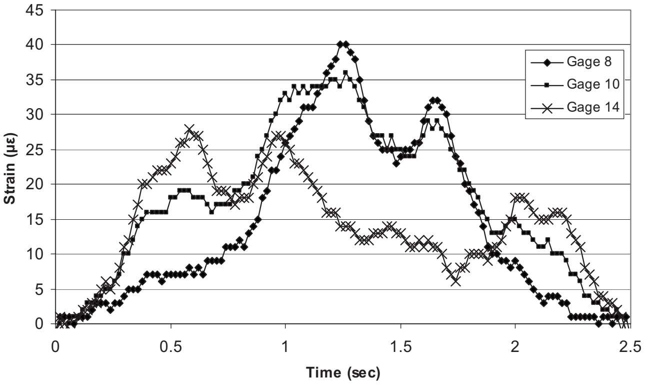

Fig. 7. Strain versus time for Gauges 8, 10, and 14 showing staggered trucks in different lanes

Bridge Weigh-In-Motion Results

Results from a typical weekday (a 24-h period of data) are shown. A combined histogram of GVW is shown in Fig. 8. This histogram uses weights from Lanes 1 and 2. As shown in the figure, there are two peaks, one at the 126–150 kN range, and one at the 326–250 kN range. It is possible that the 126–150 kN range is either loaded box trucks (two axles) or unloaded semitrucks (five axles). The 326–250 kN could be possibly loaded semitrucks (five axles). 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 101–125 kN range and the 176–200 kN range). There are some other days where there are more trucks in the higher peak than the lower peak. It should also be noted that typically only about 8% of trucks exceed 355 kN. Trucks above this range would be permitted trucks, or on occasion trucks that are illegally overloaded.

Fig. 9 shows a plot of the truck GVW versus time, for the same set of 24-h 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.

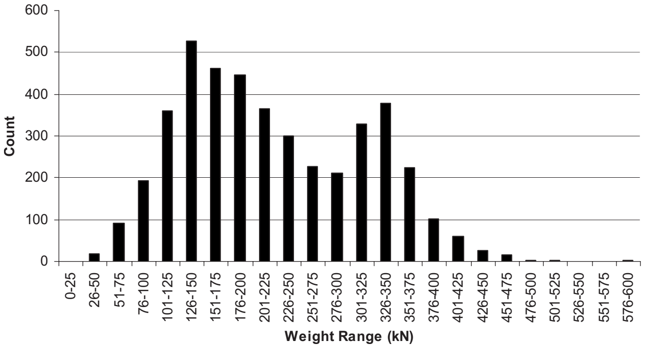

Fig. 8. Histogram of truck weights for a typical weekday in 25 kN increments

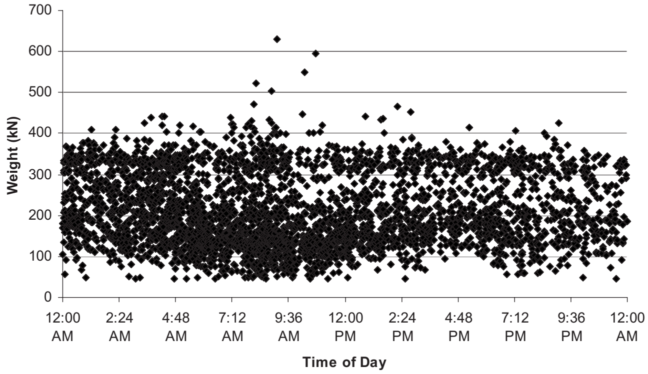

Fig. 9. Weight versus time of day for a typical weekday

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 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 km before the bridge to Lane 2. The table also gives the amount of trucks that were missed by the BWIM program. The missed trucks typically occur when it was not possible to determine the speed or when there were several trucks on the bridge at the same time.

Approximately 12 24-h 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-h periods start in the morning when the recording is started and then is stopped the next morning to create a 24-h period. A weekend period of 48 h (midnight Saturday to midnight Sunday) has also been analyzed. Additional BWIM results are contained in the thesis by the primary writer (Cardini 2007).

Conclusions

This paper describes the implementation of a readily applied reliable strain based monitoring system for use as a long-term BWIM system for a multigirder interstate bridge in Connecticut. The BWIM system is a feasible alternative to traditional WIM in that it has the advantage that the system is nonintrusive, i.e., it is not necessary to install sensors in the roadway pavement. The

Table 3. Average Values from a Typical Weekday

Values	Lane 1	Lane 2	Combined
Speed (kmh)	108	112	111
Weight (kN)	248	206	222
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
Percent missed (%)	18	34	29
Trucks/hour	87	173	260

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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 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 gross vehicle weights. It has also shown that for this bridge, approximately 8% of trucks are overweight.

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

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