A Non-Intrusive Bridge Weigh-in-Motion System for a Single Span Steel Girder Bridge Using Only Strain Measurements

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16. Abstract

This study proposes and demonstrates a non-intrusive Bridge Weigh-In-Motion (BWIM) methodology in a field study. This methodology is for a single span steel girder bridge that uses only strain measurements of the steel girders beneath the bridge deck to determine the weight and accompanying characteristics of trucks traveling over the bridge.

A brief literature review of BWIM technology is presented, followed by a description of the proposed BWIM methodology. The proposed methodology determines gross vehicle weight, speed, axle spacing, and axle weight in an automated fashion using only strain measurements.

A description is presented of the field study conducted to validate the proposed BWIM methodology. The field study used both a test truck and trucks from the traffic stream to calibrate and compare the accuracy of the proposed BWIM methodology with static measurements of weight and axle spacing collected at a weigh station located one-half mile past the bridge. The performance of the BWIM methodology is presented from a statistical perspective whereby the 95% confidence intervals are determined for the various errors in truck characteristic measurements.

The field study was made possible through the collaborative efforts of the Connecticut Department of Transportation, the Connecticut State Police, and the Federal Highway Administration.

17. Key Words
Bridge Weigh-In-Motion, Nothing-on-the-Road, weigh-in-motion WIM, traffic data collection, speed monitoring, bridge monitoring, strain measurements, steel girder bridge.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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INTRODUCTION

Bridges are critical components to the transportation system. There are close to 600,000 highway bridges in the United States, with approximately 3,700 in Connecticut (ConnDOT, 2009). It is paramount that bridge structures are kept in functional condition. Failure of a bridge can be a catastrophic event. The failure of a bridge can cause more than just structural damage, including loss of life and public loss of confidence in the transportation infrastructure. The Mianus River Bridge collapse in Greenwich, Connecticut in 1983 was tragic. The Interstate-35W bridge failure in Minneapolis on August 1, 2007, is a recent reminder of the importance of highway bridges in today's society.

Understanding the dynamic loading on a bridge can help to correctly rate and maintain bridges and the transportation infrastructure as a whole. Rating a bridge is the process of calculating the maximum load a particular bridge can safely handle either on a daily basis or for a one time loading. Live loads resulting from trucks have a more significant long-term effect on the bridge safe life than a passenger car.

Information on truck weight data is important for many functions of maintaining the infrastructure and transportation network. These functions include pavement design and maintenance, enforcement, freight movement, traffic monitoring, air quality models, determining remaining life of critical fatigue details, tracking weight limits on posted bridges, and research.

Weigh-in-motion (WIM) is the process of estimating a moving vehicle's gross weight and the portion of that weight that is carried by each wheel, axle or axle group or combination thereof, by measurement and analysis of dynamic vehicle tire forces (ASTM International, 2009). WIM systems typically use sensors installed in the pavement to determine vehicle characteristics, including gross weight, speed, axle weights, and axle spacing.

WIM systems utilize different sensor technologies, depending upon various factors including application, environment, cost, and desired accuracy (Yannis and Antoniou, 2005). The common WIM sensor technologies include piezoelectric systems, bending plates, and load cells. Quartz-piezoelectric WIM systems are used for research and enforcement applications in Connecticut (CASE, 2008). Polymeric piezoelectric sensor technologies are used by ConnDOT for FHWA data collection and support of planning and engineering applications (CASE, 2008).

There have been many initiatives that have contributed to the improvement of WIM accuracy in recent years. In Europe, the Weigh-In-Motion of Axles and Vehicles for Europe (WAVE) project was a significant advancement (WAVE, 2001). In addition, considerable work conducted under the COST (European Cooperation in Science and Technology) project 323 resulted in numerous improvements, including guidelines for WIM referred to as COST 323 Specifications (COST 323, 2002). COST 323 includes a standardized method for classifying the accuracy of a WIM system.

In the United States, there have been several initiatives that have resulted in the improvement and focus on weigh-in-motion. ASTM standard specifications E-1318 (09) "Standard Specification for Highway Weigh-In-Motion (WIM Systems with User Requirements and Test Methods)" is the primary specification used for WIM systems in the United States (ASTM International, 2009). AASHTO designated weigh-in-motion as a concept of focus technology in 2004 (http://tig.transportation.org/?siteid=57&pageid=1003, November 18, 2009). The work conducted under the FHWA-LTPP Long Term Pavement

Performance Program (LTPP) as lead to collection of research quality data through improved practices including specific installation, calibration and data validation procedures.

The International Society for Weigh-In-Motion (ISWIM) is an international society comprised of researchers, manufacturers and end users of WIM technology (ISWIM, 2007). ISWIM was established to support multiple aspects of WIM, including advances in WIM technologies, standardization of WIM technologies, a more widespread use of WIM, and the applications of WIM data.

Despite these best efforts to improve the standard practices, there are challenges associated with use of current WIM technologies. The common challenge for all of the types of WIM sensors is their placement in the road surface. The majority of technologies require sensors that are embedded in the pavement and require pavement cuts or some form of excavation. Other systems that place or adhere sensors on the pavement present different challenges. Both methods require working in the lanes of traffic. This makes the WIM systems both dangerous and costly to install and maintain. Pavement smoothness is a critical factor for in-pavement (and on-pavement) WIM systems to produce accurate results. This is necessary to minimize the influence of vehicle dynamics. It is difficult to build and maintain pavements that are sufficiently smooth throughout the WIM approach and installation.

Bridge weigh-in-motion (BWIM) is an alternative to traditional WIM. BWIM uses the response of a bridge to determine WIM data. BWIM has potential to produce similar results as traditional WIM, while overcoming the challenges associated with sensors in the pavement. BWIM is potentially less sensitive to vehicle dynamics than traditional WIM. BWIM was first proposed by Moses in the 1970’s (Goble, et al., 1976; and Moses, 1979).

Recent advances in sensor technology and data acquisition hardware and software capabilities can allow for improvements in the accuracy and application of BWIM.

This study proposes an automated BWIM methodology made possible by use of state-of-the-art bridge monitoring sensor and data acquisition technologies. A literature review of existing BWIM technology was first conducted. The proposed methodology utilizes strain sensors that are mounted underneath a single-span steel-girder bridge. A test vehicle was used as the control for calibration. A field study was conducted to validate the BWIM methodology recording bridge strain measurements of reference truck traffic traveling on an in-service Connecticut Interstate. The trucks are then measured at a nearby weigh station. The strain data is processed to determine the gross vehicle weight, axle spacing, axle weights, and speed of individual trucks crossing the bridge. The accuracy of the proposed BWIM results is evaluated.

LITERATURE REVIEW

The concept of bridge weigh-in-motion was proposed over 30 years ago (Goble, et al., 1976; Moses, 1979). An initial BWIM system was developed in 1979 that required sensors both on the pavement and beneath the bridge. The pavement sensors were used to determine vehicle speed and axle spacing. Strain sensors located beneath the bridge were used to compare strain time histories to calculated influence lines from a model of the bridge. A field test of this system reported that the gross vehicle weight of the calibration truck from twelve crossings generated an 11% error for a 95% confidence interval. It demonstrated that truck weight predictions from strain measurements were feasible (Moses, 1979). Subsequent BWIM methods continued to be based on influence lines. These methods require an inverse matrix solution to produce individual axle weights (Snyder and Moses, 1985). This innovative system was groundbreaking for bridge weigh-in-motion. The drawbacks included that determining the influence lines for an in-service bridge can be challenging and requires an accurate model of the bridge structure. Additionally, sensors located in the pavement can be a safety issue for installation and maintenance. This system was not easily implemented.

In 1999, O'Brien (O'Brien, et al., 1999) made the transition from requiring an actual influence line for each bridge to only needing a theoretical influence line for bridge WIM. This simplified the testing process as the theoretical influence line is scaled up or down depending upon the calibration truck results.

A more recent procedure to determine gross vehicle weight requires no estimation of influence lines, but instead consists of integrating the strain response data, adjusting for speed, and using a calibration factor identified from a test truck to determine gross vehicle weights (Ojio and Yamada, 2002). In a 2006 field test, this method was employed to demonstrate feasibility of BWIM on a multi-span steel girder bridge in Connecticut (Cardini and DeWolf, 2009). Cardini and DeWolf illustrated that BWIM can be achieved using an existing bridge monitoring system.

BWIM methodologies have adopted a non-intrusive approach whereby no sensors are placed in the pavement – Non-intrusive is also known as Nothing-On-the-Road (NOR) or Free-of-Axle Detector (FAD). The non-intrusive method eliminates the use of pneumatic tubes or tape switches in the travel lanes. Neural network-based methods are also employed to remove the need for intrusive devices on the roadway. A comparison study between three types of neural network systems used for classifying trucks passing over a bridge was conducted by Flood (2000). The study demonstrated the viability of using neural networks for truck classification using the Federal Highway Administration (FHWA) system. More recent testing, conducted by Chatterjee, et al. (2006), uses a wavelet-based approach to analyze the strain signals, which can also produce vehicle speed, axle spacing, axle weights, and gross vehicle weights. Truck speeds for Cardini and DeWolf (2007) were manually calculated in their non-intrusive application by examining the time delay between the peak strain responses of multiple adjacent spans.

The SiWIM system is the result of research conducted in Slovenia on BWIM (Žnidarič, et al., 2002). SiWIM is a commercially available BWIM system that has been deployed extensively for short-term BWIM applications.

The most recent application of BWIM in the United States was in Alabama using a commercially available SiWIM BWIM system. The application of the SiWIM system in Alabama was the focus of a recent FHWA-funded research project between the Alabama Department of Transportation and the University of Alabama – Birmingham (UTCA, 2007). The results of this testing are not yet available in open literature.

The literature indicates many applications where the need to determine the weights of moving vehicles from bridge weigh-in-motion is useful. Examples of these include prescreening, bridge rating, and health monitoring. Notably, Nyman and Moses (1985) applied BWIM data to structures to design a bridge prescreening tool. More recently, the portable SiWIM system has been used in Slovenia and France as a prescreening tool for temporary weight enforcement. Ghosn, et al. (1986) used BWIM to assist in bridge rating and evaluation. Similarly, Swan and Fairfield (2008) implemented a BWIM system to monitor the condition of the bridge involved in testing.

PROPOSED BWIM METHODOLOGY

The proposed methodology uses strain measurements on a slab-on-girder highway bridge to determine gross vehicle weight, speed, axle spacing, and axle weights. This method does not require development of a bridge model or influence line. The unique aspect of the proposed BWIM method in this study is the non-intrusive calculation of truck characteristics for a single span highway bridge using only strain measurements of the steel girders beneath the bridge. The proposed method builds on the theory for determining gross-vehicle weight from the work of Ojio and Yamada (2002) and the findings of Cardini and DeWolf (2002). The strain sensors are located on the steel girders beneath the bridge and are non-intrusive (i.e. no sensors in the pavement). The bridge used for testing has just one span and can be assumed to behave as a simply supported beam. While this approach neglects the spatial behavior of the multi-lane bridge, examining girders located directly under the lanes of travel allows for the simply supported beam assumption. Vehicle loads are applied to the bridge by the truck axles and can be modeled as a group of point loads moving across the simply supported beam at fixed spacing and constant speed.

A schematic of the simply supported beam is shown in Figure (Fig.) 1.

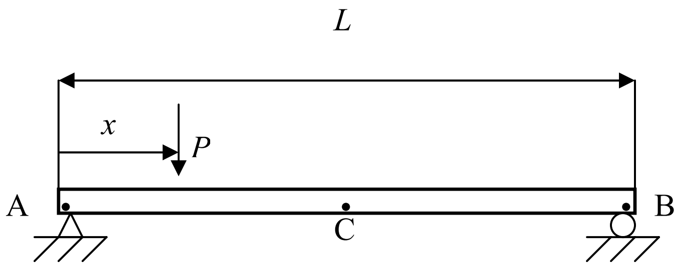

Figure 1: Simply supported beam with point load representing a single span bridge with axle loading.

The largest internal moment for a point load moving over a simply supported beam occurs at midspan, C. The influence line for the moment at the midspan shows the variation of the moment due to the application of a unit load at various distances along the length of the beam. The influence line for the moment at the middle of the span (mid-span) and the corresponding equations are shown in Fig. 2 and Equation (Eq.) (1) (AISC, 2005).

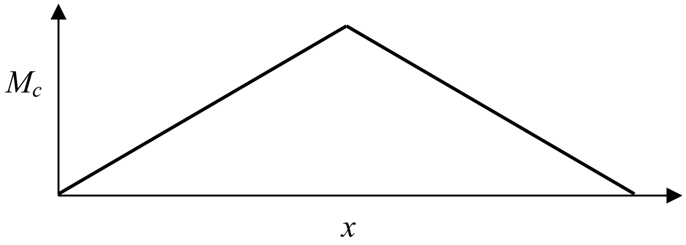

Figure 2: Influence line for moment at the mid-span of a simple beam.

$$M_c = \begin{cases} \dfrac{Px}{2} & 0 < x < \dfrac{L}{2} \\ \dfrac{PL}{2}\left(1 - \dfrac{x}{L}\right) & \dfrac{L}{2} < x < L \end{cases} \tag{1}$$

where M_c is the internal moment at point C, P is the magnitude of the point load, x is the distance from A to the location of the point load, and L is the total length of the beam.

The internal moment at a cross-section results in a stress distribution that can be described by

$$\sigma = \frac{Mc}{I} \tag{2}$$

where σ is the stress, M is the internal moment, c is the distance from the sensor location to the centroid of the cross-section, and I is the moment of inertia of the cross-section. While the moment may not be available as a measurement, the strain at the midspan cross-section is an available measurement in bridge monitoring. The strain in Eq. (2) can be written as a function of the moment using Hooke's Law ($\sigma = E\varepsilon$) such that

$$\varepsilon = \frac{Mc}{EI} \tag{3}$$

where ε is the strain and E is the modulus of elasticity. Substituting Eq. (1) into Eq. (3) gives

$$\varepsilon_c(x) = \begin{cases} \dfrac{Pcx}{2EI} & 0 < x < \dfrac{L}{2} \\ \dfrac{PcL}{2EI}(1 - \dfrac{x}{L}) & \dfrac{L}{2} < x < L \end{cases} \tag{4}$$

Assuming the point load travels at a constant speed, v, over the bridge, distance can be converted into time, t, as $x = vt$. The strain at midspan C from Eq. (4) can be rewritten as a function of time as

$$\varepsilon_c(t) = \begin{cases} \dfrac{Pcvt}{2EI} & 0 < t < \dfrac{L}{2v} \\ \dfrac{PcL}{2EI}(1 - \dfrac{vt}{L}) & \dfrac{L}{2v} < t < \dfrac{L}{v} \end{cases} \tag{5}$$

The first time derivative of the strain measurement is

$$\frac{d\varepsilon_c}{dt}(t) = \begin{cases} \dfrac{Pcv}{2EI} & 0 < t < \dfrac{L}{2v} \\ -\dfrac{Pcv}{2EI} & \dfrac{L}{2v} < t < \dfrac{L}{v} \end{cases} \tag{6}$$

If discrete samples of the strain are measured, at time interval Δt, the second time derivative of the strain measurement can be written as

$$\frac{d^2\varepsilon_c}{dt^2}(t) = \begin{cases} \dfrac{Pcv}{2EI\Delta t} & t = 0 \quad and \quad \dfrac{L}{v} \\ -\dfrac{Pcv}{EI\Delta t} & t = \dfrac{L}{2v} \\ 0 & elsewhere \end{cases} \tag{7}$$

The strain and its associated time derivatives are illustrated in Fig. 3 as functions of time.

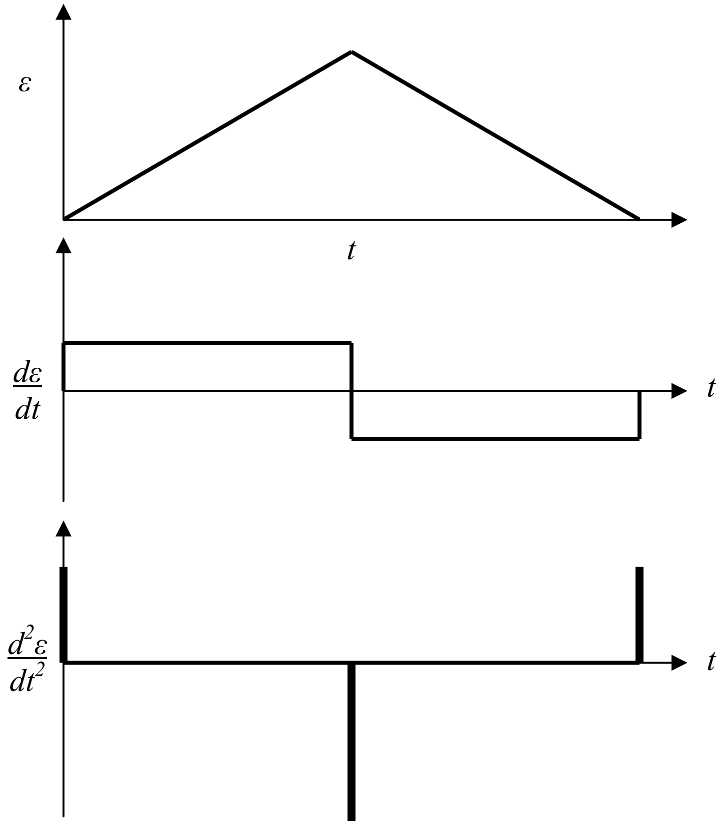

Figure 3: The strain and associated derivatives of a simply supported beam with a moving point load.

The strain at any location along the length of the beam will take the same form as in Eq. (5), with reduced amplitude. As such, the subscript *c* denoting the strain at the mid-span of the beam can be dropped. Furthermore, the strain due to any magnitude point load will take the same form amplified by the relative magnitude of the point load. Superposition can be used to account for more than one axle (point load) such that the strain and associated derivatives can be written as:

$$\varepsilon = \sum_{n=1}^{N} \varepsilon_n (t - t_n) \tag{8}$$

$$\frac{d\varepsilon}{dt} = \sum_{n=1}^{N} \frac{d\varepsilon_n}{dt} (t - t_n) \tag{9}$$

$$\frac{d^2\varepsilon}{dt^2} = \sum_{n=1}^{N} \frac{d^2\varepsilon_n}{dt^2} (t - t_n) \tag{10}$$

where N is the number of axles (point loads), ε_n is the strain for an individual axle, and t_n is the time between when the first axle enters the bridge and the n$^{\text{th}}$ axle reaches the midspan of the bridge. Fig. 4 depicts the effect of multiple point loads as it illustrates the theoretical influence line and associated derivatives for a typical five-axle truck traveling over a 26.0 m (85.3 ft) span at 25.0 m/s (55.9 mph). For the purpose of generating Fig. 4, the weights of axles one through five are estimated for this example to 45.0 kN, 60.0 kN, 60.0 kN, 70.0 kN, and 70.0 kN (10.12 kips, 13.49 kips, 13.49 kips, 15.74 kips, and 15.74 kips), respectively. The corresponding distances between axles are 3.60 m, 1.35 m, 7.40 m, and 1.20 m. The dashed peaks in the first plot represent the strain from each individual axle load. The varying heights of these peaks are a result of the magnitude of the point loads. The summation of the strain caused by all five axles produces the larger peak (solid line). The shape is unique to the axle spacing and relative weights.

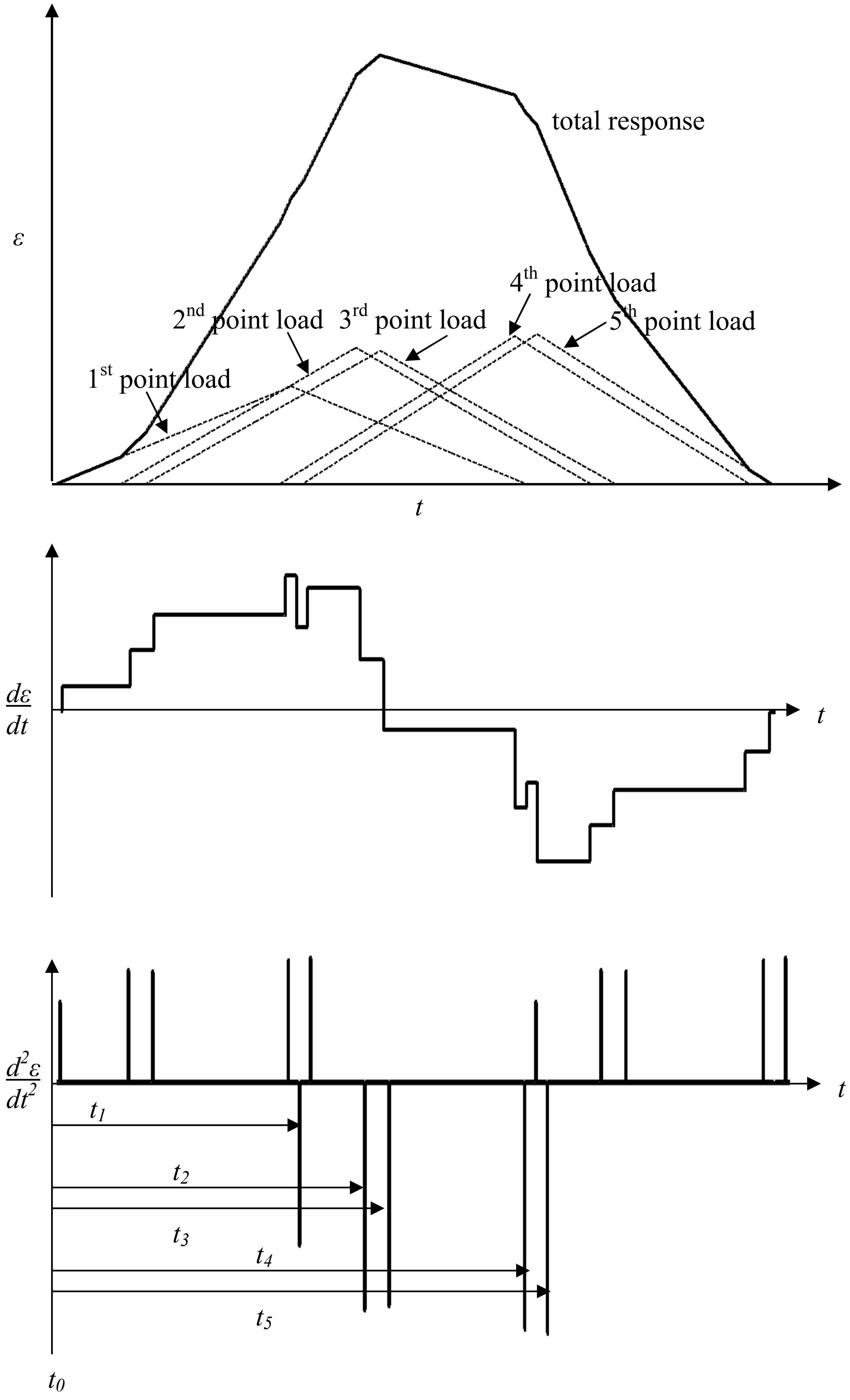

Figure 4: Theoretical response wave and associated derivatives as functions of time.

The second (4B) and third (4C) plots in Fig. 4 represent the first and second derivatives of the strain with respect to time. It should be noted that at other measurement locations on the beam the general shape of the strain and derivatives of strain only change in amplitude. The peak values in strain occur when the axle crosses the midspan, regardless of the measurement location on the length of the beam.

Calculating the vehicle speed is the first and a vital step to calculating the gross vehicle weight, axle spacing, and axle weights. This study uses only strain measurements from sensors underneath the bridge to determine the vehicle speed. The second derivative of the strain exhibits impulses when the axle loads enter the span, cross the middle of the span, and exit the span. The first five positive peaks (Figure 4) correspond to the times when the five axles enter the span. The five negative peaks correspond to the times t_1 through t_5 when each axle passes over the middle of the span. The final five positive peaks and the final recorded time correspond to the times when each axle exits the span. It should be noted that the negative peaks of the second derivative (Figure 4B) correspond to the axles passing over the middle of the span are twice as large as the positive peaks corresponding to the axles entering and leaving the bridge.

Truck speed is determined from the time it takes the first-axle to pass two fixed points, specifically the initial point (start) on the bridge deck and mid-span of the bridge. The strain gauge records the time the time it takes the first axle to reach the mid-span of the bridge and the distance traveled in this time is known. As such, speed is determined as half the span length, $L/2$, divided by time t_1. The equation to calculate the truck's speed is

$$v = \frac{L}{2(t_1)} \tag{11}$$

where v is the speed of the truck (m/sec), L is the length (m) and t_1 is the time it takes for the first axle of the truck to travel from the start of the bridge to the mid-span.

The second derivative of the strain (Figure 4 B) provides the times when each of the remaining axles pass over the mid-span of the bridge; t_2, t_3, t_4 and t_5. The product of time difference between these times and the calculated speed provides the truck's axle spacing, d_n. The equation for axle spacing is

$$d_n = v(t_{n+1} - t_n), \qquad n = 1,2,\ldots,N\text{-}1 \tag{12}$$

where d_n is the distance between the n-1 and n^{th} axles, and t_n is the time it takes for the n^{th} axle to reach the mid-span of the bridge after the truck first enters the bridge, and N is the total number of axles on the truck.

Gross vehicle weight is determined from the method of Ojio and Yamada (2002). The *response wave* is the strain response of the bridge to a truck traveling over the bridge. The response wave can be defined mathematically as the strain at a specific location of the bridge due to multiple point loads traveling over the bridge. The response wave is written as

$$\varepsilon(x) = \sum_{n=1}^{N} P_n f(x - x_n) \tag{13}$$

where P_n is the weight, or magnitude, of the nth axle, assumed to be a point load P, x_n is the distance between axles, and $f(x - x_n)$ is the influence line of the simply supported beam as defined as $f(x) = \begin{cases} \dfrac{cx}{2EI} & 0 < x < \dfrac{L}{2} \\ \dfrac{cL}{2EI}\left(1 - \dfrac{x}{L}\right) & \dfrac{L}{2} < x < L \end{cases}$.

The influence area, A, of a single truck passing over the bridge is defined as

$$A(x) = \int_{-\infty}^{\infty} \varepsilon(x)dx \tag{14}$$

Substituting Eq. 13 into Eq. 14 and rearranging slightly gives

$$A = \sum_{n=1}^{N} P_n \int_{-\infty}^{\infty} f(x - x_n)dx \tag{15}$$

Recognizing that the Gross Vehicle Weight (GVW) can be written as

$$GVW = \sum_{n=1}^{N} P_n \tag{16}$$

allows Eq. (15) to be simplified as

$$A = GVW \sum_{n=1}^{N} \int_{-\infty}^{\infty} f(x - x_n)dx \tag{17}$$

For trucks with the same axles configuration the term in the summation is a constant, such that

$$\alpha = \sum_{n=1}^{N} \int_{-\infty}^{\infty} f(x - x_n)dx \tag{18}$$

This constant α can be substituted into Eq. (17) and written as

$$\frac{A}{GVW} = \alpha \tag{19}$$

If the GVW of test truck is known, the GVW of any second truck can be determined knowing that

$$\frac{A_k}{GVW_k} = \frac{A_u}{GVW_u} \tag{20}$$

where A_k and GVW_k are the calculated area and reference gross vehicle weight for a test truck of *known* weight, and A_u and GVW_u are the calculated area and gross vehicle weight for a truck with *unknown* weight.

Equation (20) can be arranged so that

$$GVW_u = \frac{A_u}{A_k} GVW_k \tag{21}$$

The ratio of GVW_k to A_k is defined as the calibration constant β where

$$\beta = \frac{GVW_k}{A_k} \tag{22}$$

that the GVW of the unknown truck is then determined as

$$GVW_u = A_u \beta \tag{23}$$

where A can be written in terms of ε(t), again where $x = vt$, and written in discrete form such that

$$A(t) = v \int_{-\infty}^{\infty} \varepsilon(t) dt = \frac{v \Delta t}{N} \sum_{i=1}^{N} \varepsilon(i \Delta t) \tag{24}$$

where Δt is the discrete sample time of the strain measurement, and N is the total number of measurements needed for the truck to cross the bridge. It should be noted that the method of Ojio and Yamada (2002) does not incorporate the dynamic effects of the bridge response in the calculation of GVW.

As part of this study, the axle weights are then determined from the GVW and strain measurements. For this methodology the point loads, P_n, are assumed to be equivalent to the axle weights. Distributing the GVW into axle weights is done by recognizing that the amplitude of $\frac{d^2 \varepsilon}{dt^2}$ is directly proportional to the axle load, P_n, where:

$$\frac{d^2\varepsilon}{dt^2}(t_n) = -\frac{P_n cv}{EI\Delta t} \tag{25}$$

If the constant $\Gamma = -\frac{cv}{EI\Delta t}$ is defined, then

$$\frac{d^2\varepsilon}{dt^2}(t_n) = P_n\Gamma \tag{26}$$

The sum of this quantity over all axles results in

$$\sum_{n=1}^{N}\frac{d^2\varepsilon}{dt^2}(t_n) = \sum_{n=1}^{N} P_n\Gamma = GVW \times \Gamma \tag{27}$$

Dividing Eq. (26) by Eq. (27) gives

$$\frac{\frac{d^2\varepsilon}{dt^2}(t_n)}{\sum_{n=1}^{N}\frac{d^2\varepsilon}{dt^2}(t_n)} = \frac{P_n\Gamma}{GVW \times \Gamma} = \frac{P_n}{GVW} \tag{28}$$

As such the n^th axle weight, P_n, can be calculated as

$$P_n = \left[\frac{\frac{d^2\varepsilon}{dt^2}(t_n)}{\sum_{n=1}^{N}\frac{d^2\varepsilon}{dt^2}(t_n)}\right] \times GVW \tag{29}$$

As such, the gross vehicle weight, speed, axle spacing, and axle weights are determined in this section from the time history measurement of the strain using Eqs. (21), (11), (12), and (29), respectively. In particular, the unique aspects of the methodology proposed in this study are the calculation of speed and axle weight from the second time derivative of the strain measurement.

The BWIM methodology produces calculated speed, GVW, axle spacing and axle weight data. These BWIM results will be referred to as BWIM-speed, BWIM-GVW, BWIM-axle spacing and BWIM-axle weight.

FIELD STUDY VALIDATION OF BWIM METHODOLOGY

Field testing to validate the proposed BWIM methodology took place on November 20, 2008. The field study was set up to collect bridge response data both for multiple passes of a test truck of known-weight, speed and configuration, and bridge response data and static weights and measurements for trucks from the traffic stream. The test truck results were used to both calibrate and validate the BWIM system. The BWIM results for the trucks from the traffic stream were then correlated to measured weights from the static scale and axle spacing measured from still digital photos at a static weigh station. The static weigh station is located a half mile north of the bridge and is operated by the Connecticut State Police. Data sets of traffic stream data were collected according to a coordinated effort with the State Police for intervals of when the weigh station was open. In all, eight sets of truck data were collected for a total of 163 passes from the traffic stream. A statistical analysis was conducted to quantify the performance of the BWIM system and identify the 95% confidence intervals of the various measurements. The change in temperature, as measured on the surface of the steel bridge girders, was less than 8^{o} F over the course of the testing. As such, the effect of temperature on the strain measurements is neglected. This chapter describes the main components of the field study, namely the highway bridge, static scale, bridge monitoring system, and the characteristics of the truck traffic used for the field study.

Highway Bridge

The bridge used in this research is located on Interstate 91 (I-91) Northbound over Baldwin Avenue in Meriden, Connecticut. The bridge, denoted Bridge Number 03051, was built in 1964. The bridge was inspected on August 12, 2008, three months prior to the field data and received a sufficiency rating of 96 out of 100. The sufficiency rating indicates a bridge's sufficiency to remain in service, where 100 is entirely sufficient. The formula for the sufficiency rating (FHWA, 1995) is used to determine if a bridge is eligible for Federal funding eligibility for maintenance, rehabilitation, or replacement (e.g. a bridge with a sufficiency rating of 80 or less is eligible for Federal bridge rehabilitation funding; and a sufficiency rating of 50 or less is eligible for Federal bridge replacement funding). The Meriden Bridge is sufficient to remain in service and furthermore meets desired conditions for the BWIM field study, including proximity to a permanent weigh station, a smooth approach, access to install sensors, and little skew. Truck flow during testing remained steady and averaged over 200 trucks each hour. Figure 5 displays the location of the highway bridge relative to the weigh station, and Fig. 6 shows the road surface of the bridge.

The bridge's layout and geometry are of importance. Since it is the feasibility of BWIM being assessed, it is important to select a structure with a simple layout and a noncomplex geometry for initial testing. A flat, short, straight, and single span steel girder bridge is ideal for BWIM testing. The selected highway bridge, illustrated in Fig. 7, closely matches these ideal characteristics while also being in close proximity to a truck weight station.

Figure 5: Aerial view of bridge in relation to weigh station on I-91N.

Figure 6: View of the bridge's road surface.

Figure 7: East elevation view of bridge over Baldwin Avenue.

The bridge is a 25.91 m (85 foot) single-span with multiple plates stringers supported by bearings. The out-to-out width is 16.76 m (55 feet), which is designed for three lanes of traffic 3.66 m (12 feet) each. In Connecticut trucks drive legally in two right lanes of the three-lane roadway. When two trucks travel closely, either bumper-to-bumper following in the same lane, or parallel in adjacent lanes post-processing difficulties are encountered. During this test, two closely traveling trucks were found to be uncommon, occurring less than 5% of the total passes.

Three important geometric aspects for BWIM are the slope of the roadway, the curve of the roadway, and the skew of the bridge itself. There is a +2.56% longitudinal slope on the bridge. The bridge is located on a straight portion of the highway, but the roadway below forced the bridge to have an 11.5° skew. Previous research has shown that a skew up to 26º has a minor impact on accuracy of BWIM (WAVE, 2001).

The bridge has appropriate access to the desired sensor locations on the steel girders beneath the bridge shown in Fig. 8.

Figure 8: View of the steel girders and underside of the bridge.

Weigh Station

The State of Connecticut, Department of Public Safety operates a weigh station located on Interstate-91 (I-91) Northbound in the town of Middletown, Connecticut. The weigh station is located 0.8 km (0.5 miles) north of the bridge instrumented for the test, as shown in Fig. 5. The trucks are required to report for static weight measurements when the station "OPEN" sign is lighted. Data collection was coordinated between the bridge and weigh station using synchronized video recordings that were manually reviewed to match vehicle to vehicle results. Still photos of each truck at the weigh station were used to measure the axle spacing. Calculated GVW from the BWIM system were compared with static weights and axle spacing of the trucks recorded at the weigh station in order to determine the level of accuracy of the system. The static scales at the weigh station were calibrated by the manufacturer one week prior to testing, shown in Fig 12. The static scale consists of three platforms, shown in Fig. 13. The first platform weighs the first axle, the second platform the second axle and the third platform weighs the remaining axles. With only three platforms, all trucks, no matter how many axles, generate three load values. The axle weights are summed together to get the gross vehicle weight.

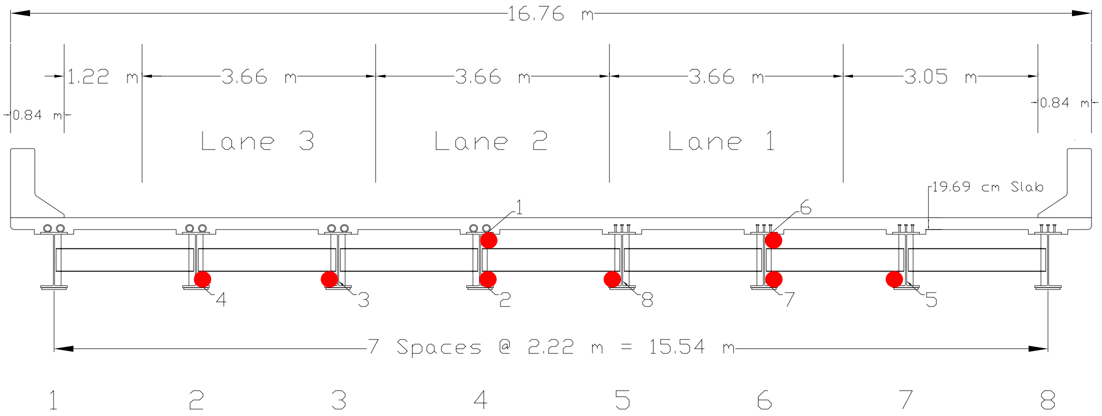

Figure 9: Cross-section view of the bridge and sensor layout (red dots).

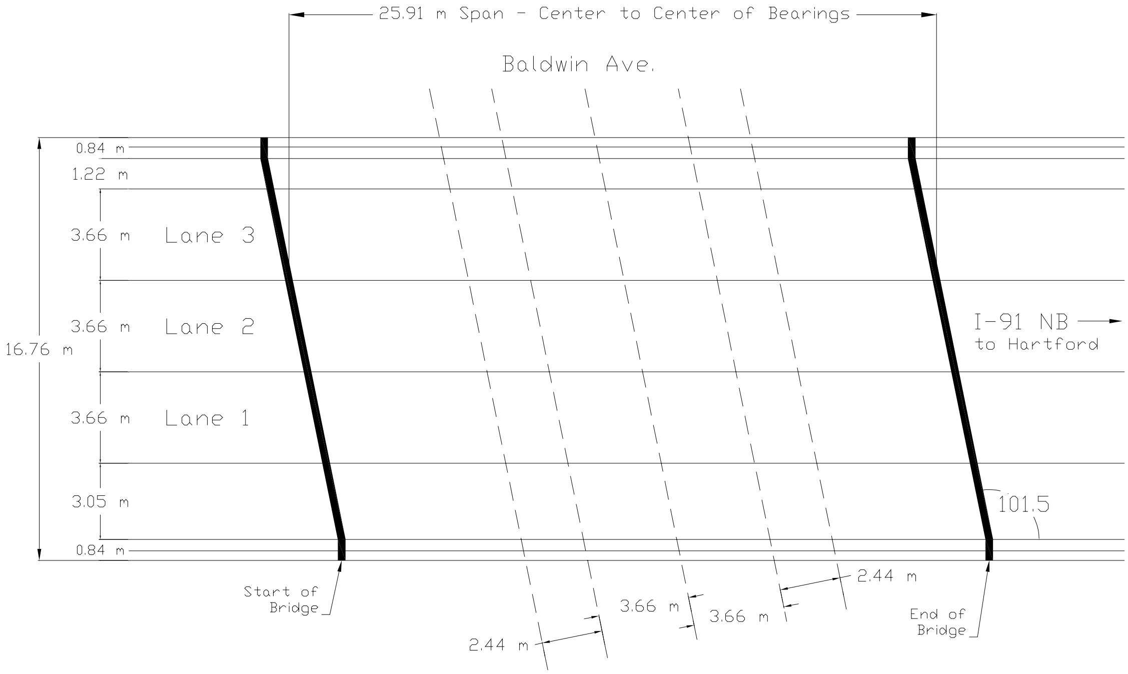

Figure 10: Plan view of the highway bridge.

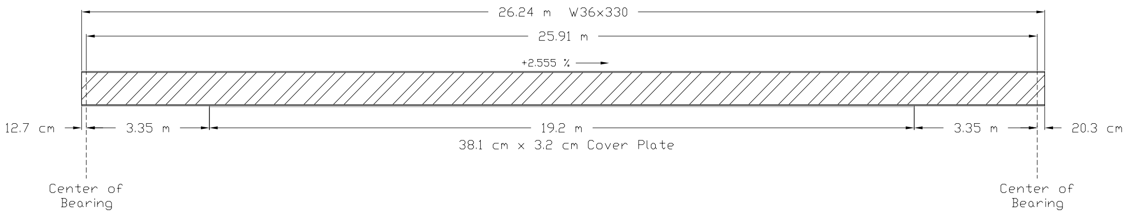

Figure 11: Elevation view of a typical steel girder.

Figure 12: Calibrating the scales at the static weight station.

Figure 13: View of the three platforms at the static weigh station.

Bridge Monitoring System

The monitoring system used for this testing is the Bridge Diagnostics Incorporated STS–WiFi System. The system shown in Fig. 14 consists of eight strain sensors which can be temporarily installed onto the bridge.

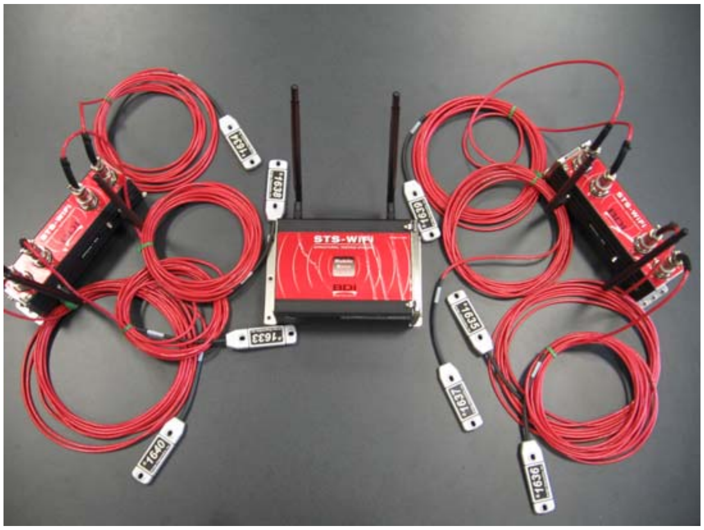

Figure 14: Bridge monitoring system used during testing.

The sensor and data acquisition system consists of eight strain sensors, two nodes, and one base station. Strain transducers are permanently attached to wires ranging from 4.57 to 7.62 m (15 to 25 feet) in length. These wires plug into one of two nodes holding up to four sensors. The two nodes then wirelessly transmit strain measurements to a small base station nearby. The base station collects data from both nodes and broadcasts all the data wirelessly to a laptop with the appropriate software.

Fig. 15 presents the eight strain sensor locations, as well as the locations of the two nodes on the steel girders. The base station was located at ground level below the bridge. There was also a data collecting station as part of the bridge monitoring system on the side of the highway just north of the bridge which is where the laptop was located. This configuration was devised as a result of trial and error to determine the optimum range of the broadcast, as well as the ability to view traffic. The data acquisition system was manually triggered at the data collecting station located by the bridge. Typical testing intervals lasted five minutes with a frequency of 100 Hertz.

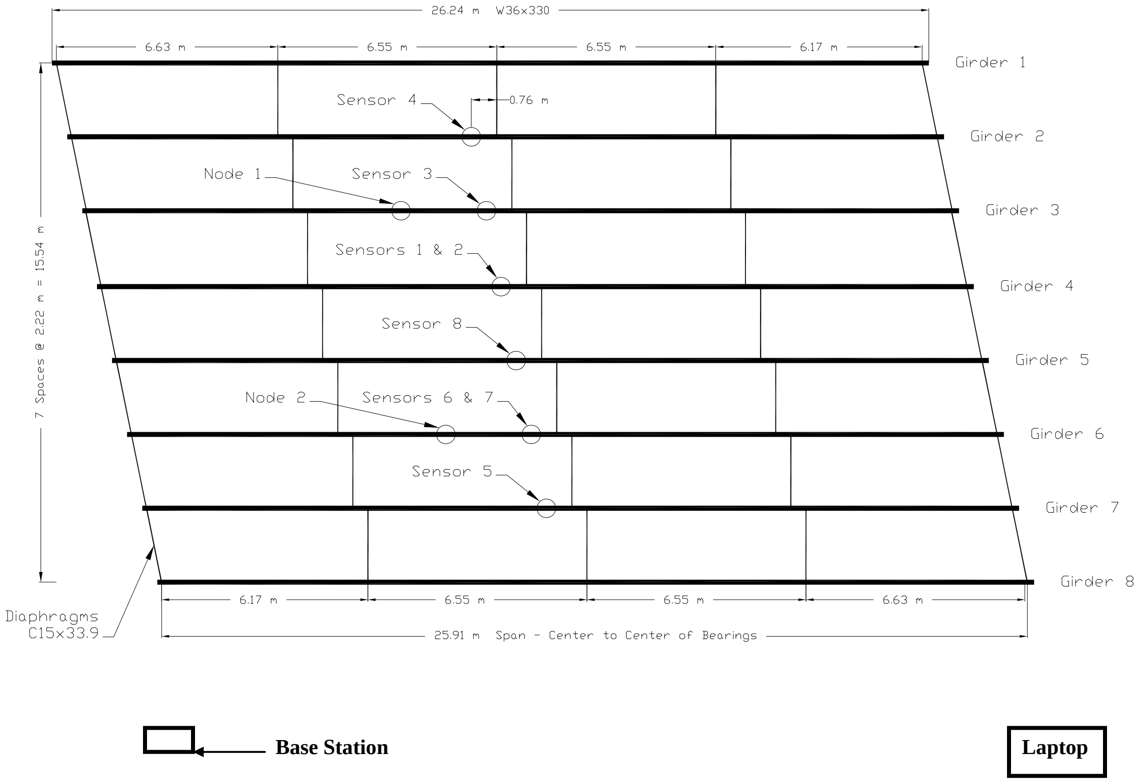

Figure 15: Plan view of the girder and sensor layout.

Truck Traffic

The truck traffic for this field study included a five-axle test truck in addition to trucks from the traffic stream. Details of these trucks are presented in this section.

The fully loaded five-axle truck was used during testing as a test truck to calibrate the BWIM system. The truck was loaded with a stable load. The test truck was statically measured, as shown in Fig. 16, at the weigh station both before and after passes at the test site. The test truck's corresponding lengths and weights are presented in Table 1. The test truck made a total of 10 passes over the bridge, five passes each in lane 1 and lane 2, at various speeds ranging from 23.7 m/sec to 28.2 m/sec (55 to 65 mph). The test truck passes are used for calibration.

Figure 16: Five-Axle Test Truck

Table 1: Length and Weight Characteristics of the five-axle test truck.

Gross Vehicle Weight	300.00 kN	67,420 lbs
Wheelbase length (first (1) to last (5) axle	13.58 m	44.57 feet
Length (bumper to bumper)	16.46 m	54 feet
Number of Axles	5	5
Axle Spacing (1-2)	3.59 m	11.77 feet
Axle Spacing (2-3)	1.34 m	4.40 feet
Axle Spacing (3-4)	7.42 m	24.35 feet
Axle Spacing (4-5)	1.23 m	4.05 feet
Axle Weight (1)	44.59 kN	10,020 lbs
Axle Group Weight (2 & 3)	120.32 kN	27,040 lbs
Axle Group Weight (4 & 5)	135.09 kN	30,360 lbs

The sample of 117 trucks from the traffic stream analyzed in this study consisted of a variety of vehicles. Details on each vehicle are provided in the Appendix. Trucks ranged from a two-axle 51.6 kN (11.6 kips) flatbed to a six-axle 445 kN (100 kips) truck transporting an excavator. Figure 17 shows the gross vehicle weight distribution of the trucks from the traffic stream as determined from the weigh station static measurements.

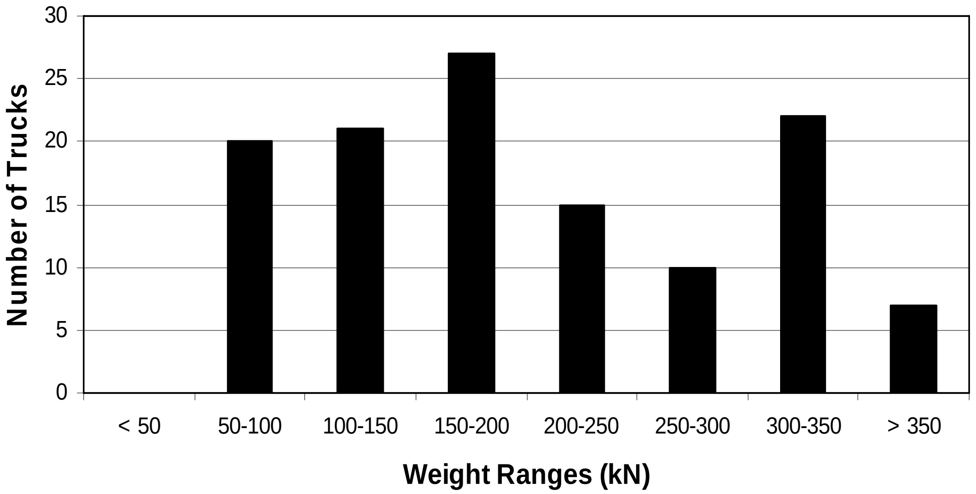

Figure 17: Histogram of truck weights from the traffic stream.

PROCESSING AND CALIBRATION

A program was developed in MATLAB (ref) for the post-processing and calibration of the field test data. In the MATLAB program the strain time histories are loaded, data filtered, and truck crossing events identified automatically. Each truck event is processed using the proposed BWIM methodology, as identified in the Proposed BWIM Methodology section. The level of accuracy for the BWIM is quantified by comparing the difference between the BWIM calculated and weigh station measured GVW, axle spacing, and axle weights.

The fully automated program developed in MATLAB is used to determine the speed, gross vehicle weight, axle spacing, and axle weight for trucks from the traffic stream. The program obtains the raw strain data from each sensor. A typical fiveminute time history plot of strain at sensor 7 is shown in Fig. 18. An eight-pole low-pass filter with a 15 Hertz cutoff frequency is used to reduce the effect of noise on the derivatives of strain. Minimizing noise is especially important for calculating vehicle speed. Speed is determined from the second derivative of strain versus time and results are sensitive to high frequency components of the signal present from the measurement noise.

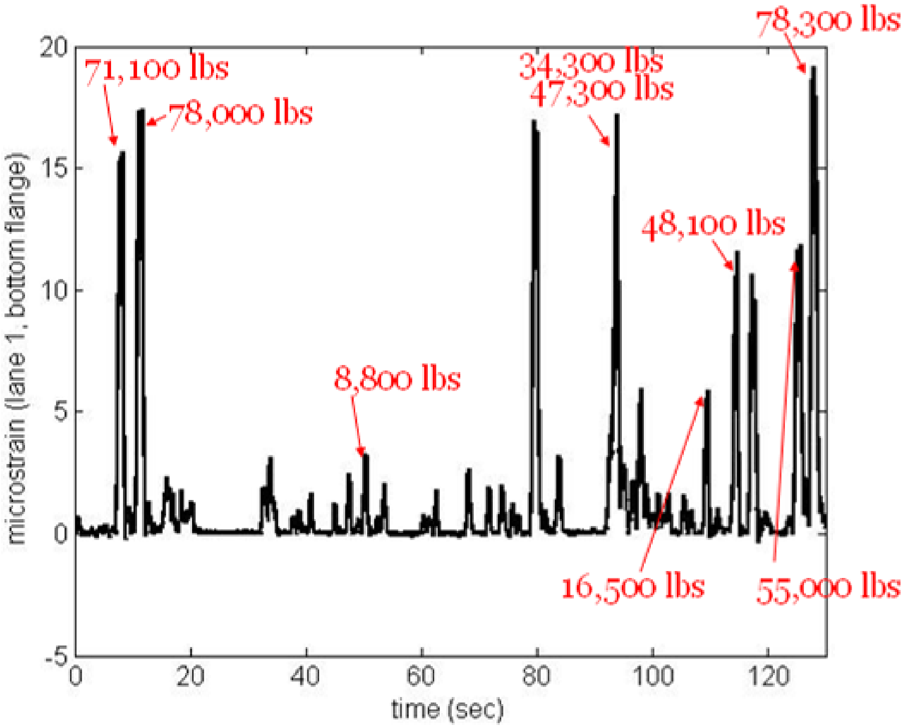

Figure 18: Typical time history plot of strain with truck GVW indicated.

Time history plots of the strain and second time derivative of the strain are shown in Figs. 19 and 20 for the three passes of the test truck traveling in Lane 1 at the same speed.

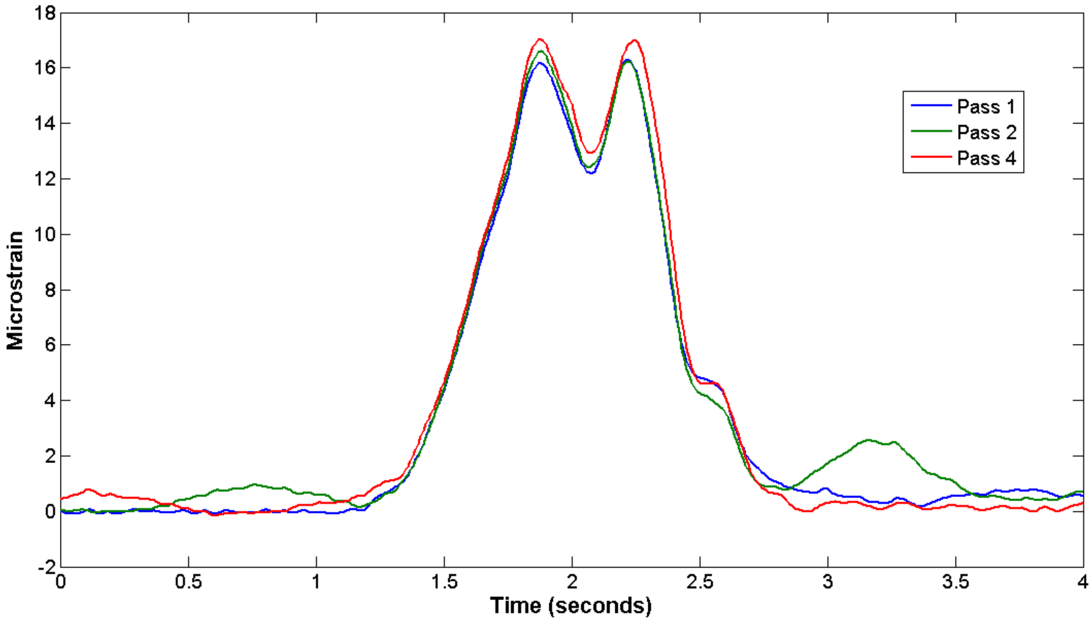

Figure 19: Time history plot of the strain for three passes in Lane 1.

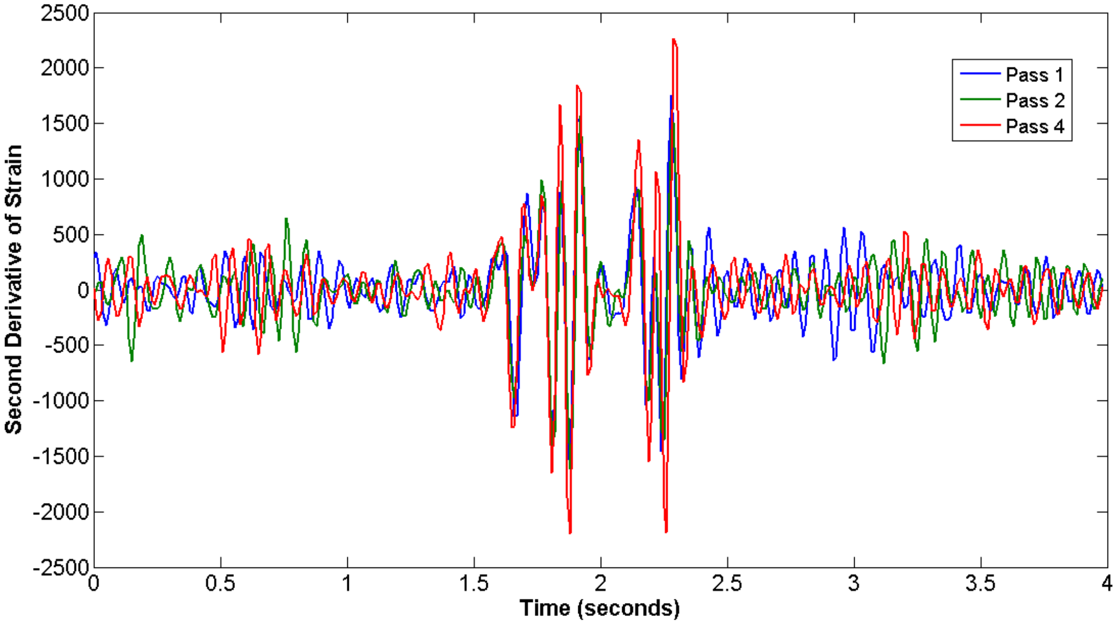

Figure 20: Time history plot for the second derivative of strain for the three passes.

The calibration constant, β, from Eqs. 22 and 23 is determined by trial and error from the experimental results for the test truck to minimize mean difference between the BWIM calculated GVW and the static scale measured GVW. Five passes of the test truck, at various speeds, for each of the two lanes were used to establish the calibration factor for each lane for trial and error. The calibration constants for this bridge using strain sensor 7 for Lane 1 and strain sensor 2 for Lane 2 are: β_1=0.6291 $\frac{kN}{\mu\varepsilon \cdot m}$ and β_2=0.6906 $\frac{kN}{\mu\varepsilon \cdot m}$. Table 2 reports the measured values for all of the examined characteristics of the test truck and compares them to the BWIM results for the five passes in Lane 1. Table 3 provides the same comparison for the five passes in Lane 2. The values of β calculated for the test truck are applied for BWIM for the trucks from the traffic stream as reported in the following section of this report.

Table 2: Comparison of calculated truck characteristics for passes in Lane 1.

Pass Number	***Measured***	**1**	**2**	**3**	**4**	**5**
GVW (kN)	*300.00*	300.64	293.10	305.25	292.13	308.91
Reported Speed (m/s)	-	24.59	24.59	26.82	24.59	23.69
BWIM Speed (m/s)	-	25.10	26.12	28.45	23.27	23.70
Wheelbase – sum of d_i (m)	*13.58*	14.81	15.15	13.09	13.97	14.70
Number of Axles	*5*	5	5	4	5	5
Axle Spacing – d_1 (m)	*3.59*	3.77	3.92	3.70	3.03	3.79
Axle Spacing – d_2 (m)	*1.34*	1.76	1.83	1.42	2.09	1.66
Axle Spacing – d_3 (m)	*7.42*	7.53	7.84	7.97	6.98	7.59
Axle Spacing – d_4 (m)	*1.23*	1.76	1.57	-	1.86	1.66
Axle Weight – P_1 (kN)	*44.59*	43.19	47.84	93.50	56.11	53.39
Axle Group Weight – P_2+P_3 (kN)	*120.32*	140.56	149.38	138.67	103.18	149.41
Axle Group Weight – P_4+P_5 (kN)	*135.09*	123.01	101.84	79.29	138.79	112.39

Table 3: Comparison of calculated truck characteristics for passes in Lane 2.

Pass Number	***Measured***	**1**	**2**	**3**	**4**	**5**
GVW (kN)	*300.00*	299.21	316.14	273.09	315.94	295.71
Reported Speed (m/s)	-	27.71	25.93	26.82	26.37	28.16
BWIM Speed (m/s)	-	27.83	28.45	26.12	30.48	26.12
Wheelbase – sum of d_i (m)	*13.58*	16.42	15.08	15.68	14.02	15.68
Number of Axles	*5*	6	5	6	6	6
Axle Spacing – d_1 (m)	*3.59*	3.90	3.98	3.40	3.35	3.66
Axle Spacing – d_2 (m)	*1.34*	1.67	1.71	1.83	2.44	1.83
Axle Spacing – d_3 (m)	*7.42*	7.79	7.97	7.32	1.83	6.53
Axle Spacing – d_4 (m)	*1.23*	1.11	1.42	1.05	2.44	1.57
Axle Weight – P_1 (kN)	*44.59*	38.01	50.78	52.10	95.11	8.77
Axle Group Weight – P_2+P_3 (kN)	*120.32*	27.69	189.47	31.32	150.96	138.26
Axle Group Weight – P_4+P_5 (kN)	*135.09*	237.57	80.20	193.39	74.18	152.71

The test truck passes provided an opportunity to examine the accuracy of the speed calculation. The BWIM calculated speed is compared to the speed identified by the operator of the test truck reading of the speedometer when crossing the test site. For Lane 1, the speed calculation is between 0.01 m/sec and 1.63 m/sec magnitude difference from the reported speed. For Lane 2, the speed calculation is between 0.12 m/sec and 4.11 m/sec magnitude difference from the reported speed. The calculated speeds are plotted in Fig. 22 against the reported truck speeds identified by the operator of the test truck reading of the speedometer when crossing the test site. The pass numbers are numbered sequentially, so the first five passes are for Lane 1 and next five passes, reported 6-10, are for Lane 2.

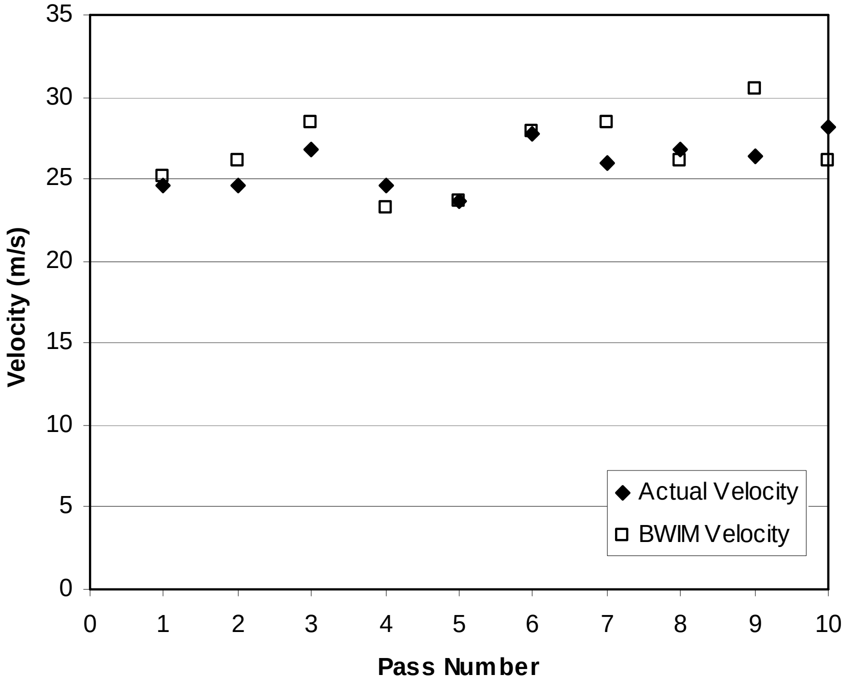

Figure 22: Plot of calculated speeds for the test truck (1-5 lane 1; 6-10 lane 2).

Noting that the influence area, A_u, is directly proportional to the speed, and thus the gross vehicle weight is directly proportional to the predicted speed, reveals the importance of accurately predicting speed. Adjacent or leading/following vehicles, including non-truck traffic, are observed to add error to the identification of the time when the vehicle enters the bridge and/or the first axle crosses the mid-span of the bridge span.

ACCURACY OF BWIM FIELD STUDY

The accuracy of the BWIM methodology proposed here is evaluated for the trucks from the traffic stream. Accuracy for WIM systems is defined by the closeness or degree of agreement of an estimated value to an accepted reference value, measured as the 95% confidence intervals (95% compliance) of the difference in the estimated and reference values as a percent of the reference value (ASTM, 2009). The BWIM accuracy is defined as the difference in the BWIM measurement compared to the measurement taken at the static scale as a percent of the static scale measurement and is calculated as

$$E^{GVW} = \frac{\left(GVW_{BWIM} - GVW_{static}\right)}{GVW_{static}} \times 100 \tag{30}$$

where GVW_{BWIM} is the gross vehicle weight as determined by the BWIM, GVW_{static} is the gross vehicle weight as determined by the static scale. Note that while E^{GVW} is defined in Eq. (30) for the GVW, it is similarly defined for the wheelbase, axle spacing, and axle weights.

The sample mean, μ, of the value of interest is calculated as

$$\mu = \frac{1}{n}\sum_{i=1}^{n} E_i \tag{30}$$

where E_i is the i^{th} vehicle characteristic difference as defined in Eq. (30), and n is the number of samples. The sample variance, s^2, is then calculated as

$$s^2 = \frac{1}{(n-1)}\sum_{i=1}^{n} (E_i - \mu)^2 \tag{31}$$

When $n \geq 20$ the sample variance is a good estimator of the population variance.

The BWIM measurement should contain no bias and, therefore, a mean of the difference that is close to zero. To ensure that the mean value of the difference is *sufficiently* close to zero, the 95% confidence interval of the mean, with unknown variance, is determined assuming the underlying population is Gaussian using the t-distribution as

$$\langle \mu \rangle_{1-\alpha} = \left[\mu - t_{\alpha/2,n-1}\frac{s}{\sqrt{n}};\ \ \mu + t_{\alpha/2,n-1}\frac{s}{\sqrt{n}} \right] \tag{32}$$

where $t_{\alpha/2,n-1}$ are p-percentile values of the t-distribution. For 95% confidence intervals, $\alpha = 0.05$, $n = 117$, and $t_{0.025,117} = 1.98$. The interval around the mean indicates an accurate scale if the interval includes the value zero (Strathman, 1998).

The accuracy of the BWIM measurements can be defined by the 95% confidence interval of the difference. The confidence interval indicates that 95 out of 100 of the BWIM calculated truck characteristics will have a measurement difference within this range (Ang and Tang, 1975). The 95% confidence interval of the BWIM characteristic is

$$\langle E\rangle_{1-\alpha} = \left[\mu - t_{\alpha/2,n-1}s; \quad \mu + t_{\alpha/2,n-1}s\right] \tag{33}$$

Applying this probabilistic analysis of the BWIM data, the data from the test truck is first evaluated. The results from the 10 test truck runs, five passes in Lane 1 and five passes in Lane 2, are presented in Tables 4 and 5, respectively. It should be noted that when the number of samples is less than 10, as is the case here, the confidence intervals obtained will be very approximate. However, the analysis for the test truck runs do provide a basis for comparison of both lane accuracy and ultimately accuracy of the method when applied to similar and varying truck configurations.

Table 4: BWIM percent difference statistics for the test truck in Lane 1.

Difference	μ	s	$<\mu>_{0.95}$	$<E>_{0.95}$
GVW [%]	0.00	2.45	[-3.05 3.05]	[-6.31; 6.31]
Axle Weight (P_1) [%]	31.88	44.91	[-23.89; 87.65]	[-83.59; 147.36]
Axle Group Weight (P_2+ P_3) [%]	13.23	15.90	[-6.51; 32.97]	[-27.64; 54.11]
Axle Group Weight (P_4+ P_5) [%]	-17.79	16.58	[-38.38; 2.81]	[-60.43; 24.85]
Wheelbase (sum of d_i) [m]	0.76	0.82	[-0.26; 1.79]	[-1.35; 2.88]
Axle Spacing (d_1) [m]	0.05	0.35	[-0.38; 0.49]	[-0.85; 0.95]
Axle Spacing (d_2) [m]	0.41	0.24	[0.11; 0.72]	[-0.22; 1.04]
Axle Spacing (d_3) [m]	0.16	0.38	[-0.31; 0.64]	[-0.82; 1.14]
Axle Spacing (d_4) [m]	0.14	0.77	[-0.82;1.10]	[-1.85; 2.13]

Table 5: BWIM percent difference statistics for the test truck in Lane 2.

Percent Difference	μ	**s**	$<\mu>_{0.95}$	$<E>_{0.95}$
GVW [%]	0.01	5.91	[-7.33; 7.34]	[-15.19; 15.20]
Axle Weight (P_1) [%]	9.79	69.83	[-76.92; 96.49]	[–169.75; 189.32]
Axle Group Weight (P_2+ P_3) [%]	-10.62	61.25	[-86.68; 65.43]	[–168.11; 146.86]
Axle Group Weight (P_4+ P_5) [%]	9.27	52.54	[-55.97; 74.51]	[-125.81; 144.35]
Wheelbase (sum of d_i) [m]	1.80	0.89	[0.68; 2.91]	[-0.50; 4.10]
Axle Spacing (d_1) [m]	0.07	0.28	[-0.29; 0.42]	[-0.66; 0.80]
Axle Spacing (d_2) [m]	0.56	0.31	[0.17; 0.94]	[-0.25; 1.36]
Axle Spacing (d_3) [m]	-1.13	2.55	[-4.30; 2.04]	[-7.70; 5.43]
Axle Spacing (d_4) [m]	0.29	0.56	[-0.41; 0.98]	[-1.15; 1.72]

For Lane 1, the mean of the GVW difference is 0 (as calibrated) and the 95% confidence interval of the mean includes the value zero. In fact, the 95% confidence interval of the means for all of the truck characteristics calculated include the value zero, except for the percent difference of the axle spacing between the second and third axle, which is a relatively short distance of 1.34 m. The 95% confidence interval for the percent difference of BWIM GVW is +-6.31%. This is to say that 95 times out of 100 the reference (static measured) GVW will be within 6.31% of the GVW calculated from the bridge. The wheelbase estimate for Lane 1 has a 95% confidence interval of [-1.35 m; 2.88 m], which is to say that 95 out of 100 times the reference wheelbase will not be less than 1.35 m (4.43 ft) of the calculated value nor more than 2.88m (9.45 ft) larger than the calculated value. The axle weight estimates for Lane 1 have much less accuracy, with 95% confidence intervals of the difference on the order of 25%-150%.

For Lane 2, the mean of the GVW difference is 0.01% and the 95% confidence interval of the mean includes the value zero. For Lane 2 the 95% confidence interval of the means for all of the truck characteristics calculated include the value zero, except for the percent difference of the axle spacing between the second and third axle, as for Lane

1, and for the Wheelbase. The 95% confidence interval for the percent difference of the BWIM GVW for Lane 2 is +-15.2%. This is to say that 95 times out of 100 the reference (static measured) GVW will be within 15.2% of the GVW calculated from this truck traveling over Lane 2 of the bridge. The 95% confidence interval for GVW in Lane 2 is over two times larger than the GVW calculated for the test truck traveling over Lane 1. The other confidence intervals for Lane 2 are similarly larger than for Lane 1. This increase in the 95% confidence interval for the test truck passes is an indication that the measurements obtained for trucks traveling over the bridge in Lane 2 may not be as accurate as for the trucks traveling in Lane 1. Additionally, further analysis in this report will focus on the accuracy of the GVW estimates of the proposed BWIM method.

For the trucks from the traffic stream, 137 random trucks were measured crossing over the bridge and successfully matched with static measurements at the weigh station. All of these vehicles were traveling in Lanes 1 and 2. Of the 137 trucks, 6 trucks (4.4% of 137) were identified as changing lanes while crossing over the bridge. Additionally, there were six occurrences where multiple trucks were on the bridge at the same time. This resulted in 12 occurrences (8.8% of 137) where two trucks in adjacent lanes were on the bridge at the same time. Multiple presences of automobiles with trucks are not separated out, as this is a regular occurrence. Vehicles switching lanes on the bridge and cases of multiple trucks on the bridge at the same time were not considered in determining accuracy. Since the proposed BWIM method is not able to accommodate lane changes and multiple vehicles without further modifications, these 18 identified trucks are not considered. Two of the remaining trucks (1.7% of 119) were found to have erroneous calculated speeds; that are speeds greater than 40.23 m/sec (90 mph). These two trucks are also not considered in determining accuracy of the BWIM method. The remaining 117 trucks are evaluated for accuracy.

A table of the BWIM calculated and static scale measured results for the 117 trucks from the traffic stream is located in the Appendix of this report. The truck speeds are calculated to be traveling an average speed of 26.36 m/sec (59 mph). The accuracy for trucks traveling over the bridge are summarized in Table 5 and shown in Figure 23.

Table 6: BWIM percent difference statistics for trucks from the traffic stream, by lane.

Lane	# Trucks	μ	s	$<\mu>_{0.95}$	$<E>_{0.95}$
1	109	-1.94	12.78	[-4.37; 0.48]	[-27.28; 23.39]
2	8	6.23	19.72	[-10.25; 22.72]	[-39.23; 51.70]

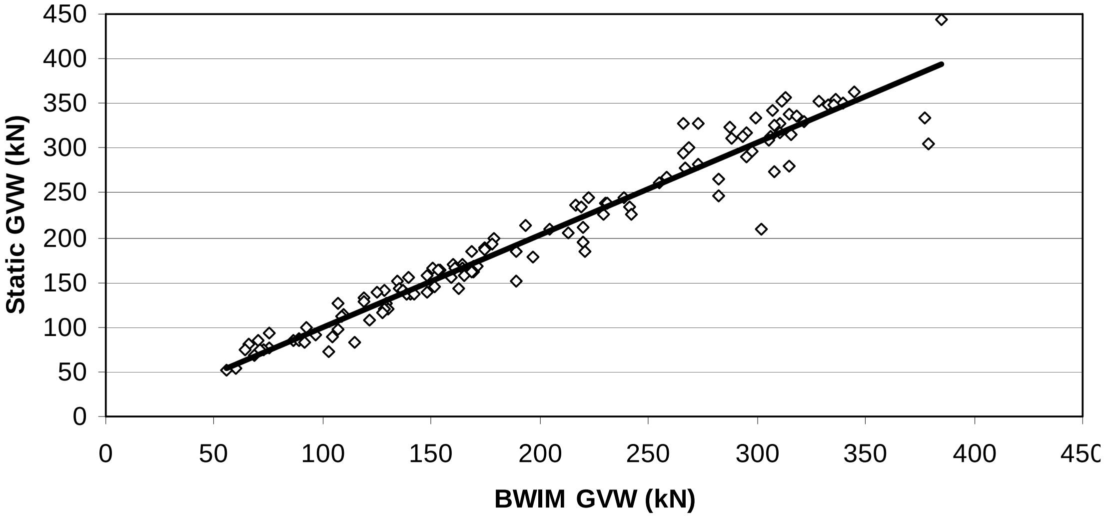

Figure 23: Plot of static measured GVW versus BWIM calculated GVW for the 117 trucks from both lanes of the traffic stream.

The mean of the GVW difference is -1.09% and 6.23% for Lanes 1 and 2, respectively. The 95% confidence interval of the two mean estimates both includes the value zero. The 95% confidence interval for the BWIM difference of the GVW of the 109 trucks traveling over Lane 1 is [-27.28%; 23.39%]. The 95% confidence interval for the

BWIM difference of the GVW of the eight trucks traveling over Lane 2 is [-39.23%; 51.7%]. As observed previously the confidence interval for Lane 2 GVW measurement difference is larger than for Lane 1. This is likely due to the location of the steel girders instrumented below Lanes 1 and 2. This increased interval range may also be attributed to the low number of trucks traveling (i.e. small sample size) over Lane 2.

The BWIM GVW estimate is based on the assumption that the vehicles traveling over the bridge are five-axle trucks with similar axle spacing and weights as the test truck. Table 7 examines the accuracy of the BWIM method as a function of the number of truck axles (considering both Lane 1 and Lane 2 together). The six-axle and seven-axle trucks, one of each, are not considered in this analysis. It is observed, as expected, that the 69 five-axle trucks have the smallest 95% confidence interval of [-20.24%; 20.20%]. The five-axle truck sample was not further delineated by subsets of the 5-axle vehicle type. In contrast, the 18 two-axle trucks have a confidence interval over twice as large, [-48.52%; 43.81%]. To compensate for this increase in difference multiple test trucks can be employed in future work to calibrate the GVW estimate based on vehicle type.

Table 7: Percent difference statistics for random sample of trucks by number of axles (does not include one six-axle and one seven-axle truck).

Axles	# Trucks	μ	s	$<\mu>_{0.95}$	$<E>_{0.95}$
5	69	-0.02	10.14	[-2.46; 2.41]	[-20.24; 20.20]
4	16	-5.84	14.99	[2.15 -37.63]	[-37.63; 25.95]
3	12	-2.97	12.39	[-10.84; 4.91]	[-29.97; 24.04]
2	18	-2.35	21.97	[-13.28; 8.58]	[-48.52; 43.81]

The BWIM GVW estimate is now examined for only five-axle trucks considering the lane traveled. Table 8 examines the accuracy of the BWIM method for five-axle trucks as a function of the lane. It is observed that the 64 five-axle trucks in Lane 1 have the smallest 95% confidence interval of [-17.52%; 15.26%]. The five five-axle trucks in Lane 2 have a 95% confidence interval calculated to be [-38.03%; 66.39%]. The ASTM Standard Specifications for Highway Weigh-In-Motion Systems (2009) requires the tolerance for 95% conformance for the percent difference of gross vehicle weight to be ±15% for a Type II system. For Lane 1 limited to five-axle trucks, the proposed BWIM system nearly meets this requirement with a 95% confidence interval of [-17.52%; 15.26%].

Table 8: Differences from static GVW statistics for random sample of five-axle trucks by lane.

Lane	# Trucks	μ	s	$\langle\mu\rangle_{0.95}$	$\langle E\rangle_{0.95}$
1	64	-1.13	8.22	[-3.18; 0.92]	[-17.52; 15.26]
2	5	14.18	20.31	[-11.04; 39.39]	[-38.03; 66.39]

CONCLUSION

This study demonstrates that a non-intrusive bridge weigh-in-motion system using only strain measurements applied to a single span steel girder bridge can be used to produce WIM data including gross vehicle weights, axle spacing, axle weights, and speed. This was achieved by development of a new bridge WIM methodology that applied existing approaches together with a novel approach to calculate vehicle speed and axle displacements and weights. The bridge WIM methodology was automated to identify truck events and calculate estimates from the strain response.

A field test was conducted on an in-service highway bridge. The field test included calibration of the system using a five-axle test truck and application of these BWIM methodology and calibration results on a random sample of 117 trucks from the traffic stream to calculate BWIM estimates and to verify the methodology in comparison to static measurements obtained for the same vehicles.

For the test truck, the 95% confidence interval for GVW is +-6.31% for Lane 1 and +-15.20% for Lane 2. It is observed that the BWIM estimates are more precise for Lane 1 than Lane 2. This is likely due to the configuration of the instrumented girders beneath the lanes of travel, as well as the location of Lane 2 on the cross section of the bridge, with adjacent lanes on both sides.

The accuracy of the BWIM system is also evaluated for 117 trucks from the traffic stream. From the random truck traffic set, it was observed that for five-axle trucks travelling in Lane 1, which compose 55% of the 117 trucks, the 95% confidence interval for the GVW difference is [-17.52%; 15.26%]. The accuracy of the system may be dependent on the vehicle type used to calibrate the system. Employing a calibration methodology that accounts for the various vehicle types (multiple trucks with varying number of axles and spacing, suspensions, etc.) for calibration might reduce this difference. Collecting more data for both the test truck(s) and for trucks in Lane 2 may help to provide more confidence in the parameter estimates and ultimately the resulting confidence intervals. Furthermore, as the BWIM GVW estimate is directly dependent on speed, there is a need in future studies to more closely examine and consider the accuracy of the speed estimate.

The initial field results reported in this study indicate that a non-intrusive BWIM methodology shows great promise to achieve the tolerance of 95% probability of conformity for Type II ASTM Standard Specifications for Highway Weigh-In-Motion Systems.

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APPENDIX – Experimental Data of Trucks from Traffic Stream (Note: italics and [.] indicate static measured or visually determined values)

Truck #	GVW (kN)	Speed (m/s)	Travel Lane	Number of Axles	Wheel-base (m)	Axle Spacing (1-2) (m)	Axle Spacing (2-3) (m)	Axle Spacing (3-4) (m)	Axle Spacing (4-5) (m)	Axle Weight Group 1 (kN)	Axle Weight Group 2 (kN)	Axle Weight Group 3 (kN)
1	92.11	28.78	1	-	-	-	-	-	-	-	-	-
	[99.11]		[1]	[3]	*6.46*	*5.10*	*1.37*	-	-	-	-	-
2	160.27	28.16	1	5	18.02	4.50	1.69	10.14	1.69	-	-	-
	[169.48]		[1]	[5]	*16.02*	*4.98*	*1.36*	*8.48*	*1.19*	*44.66*	*46.26*	*78.56*
3	265.69	30.84	2	5	16.96	2.47	2.78	2.78	8.95	63.39	93.95	108.36
	[328.01]		[2]	[4]	*7.46*	*4.79*	*1.35*	*1.33*	-	*62.10*	*88.34*	*177.57*
4	88.65	26.43	1	3	6.08	4.23	1.85	-	-	-	-	-
	[86.12]		[1]	[2]	*5.86*	*5.86*	-	-	-	*35.23*	*18.06*	*32.83*
5	127.88	24.44	1	-	-	-	-	-	-	-	-	-
	[140.47]		[1]	[5]	*16.74*	*4.77*	*1.34*	*9.42*	*1.20*	*45.28*	*54.54*	*40.66*
6	174.79	25.91	2	-	-	-	-	-	-	-	-	-
	[185.76]		[2]	[5]	*18.02*	*5.23*	*1.33*	*10.30*	*1.16*	*48.93*	*70.55*	*66.28*
7	109.36	25.40	1	-	-	-	-	-	-	-	-	-
	[112.98]		[1]	[2]	*6.60*	*6.60*	-	-	-	*41.28*	*71.71*	-
8	164.23	27.56	2	4	6.06	0.55	1.66	3.86	-	65.39	69.08	29.76
	[170.54]		[2]	[3]	*7.79*	*6.40*	*1.39*	-	-	*71.71*	*98.84*	-
9	287.68	24.44	1	5	10.51	3.67	1.71	1.71	3.42	-	-	-
	[324.28]		[1]	[5]	*12.87*	*5.11*	*1.37*	*5.20*	*1.19*	*48.66*	*152.48*	*123.13*
10	321.87	23.13	1	-	13.19	1.85	1.39	1.62	1.85	48.04	60.58	213.25
	[329.35]		[1]	[5]	*12.09*	*5.16*	*1.37*	*4.36*	*1.21*	*44.39*	*140.56*	*144.39*
11	281.83	24.59	1	-	-	-	-	-	-	-	-	-
	[246.97]		[1]	[5]	*13.25*	*3.42*	*1.36*	*7.30*	*1.17*	*48.31*	*90.57*	*108.09*
12	138.54	24.59	1	-	-	-	-	-	-	-	-	-
	[136.47]		[1]	[3]	*7.30*	*5.97*	*1.33*	-	-	*39.14*	*49.20*	*48.13*
13	189.19	29.44	1	-	-	-	-	-	-	-	-	-
	[151.15]		[1]	[4]	*14.95*	*3.98*	*9.81*	*1.16*	-	*42.61*	*42.88*	*65.66*
14	174.87	24.44	1	3	5.62	3.91	1.71	-	-	-	-	-
	[188.16]		[1]	[5]	*16.71*	*5.44*	*1.37*	*8.69*	*1.21*	*49.38*	*91.54*	*47.24*
15	108.40	24.91	1	3	5.48	2.24	3.24	-	-	35.10	53.42	19.88
	[112.10]		[1]	[3]	*7.48*	*6.13*	*1.35*	-	-	*45.91*	*37.10*	*29.09*
16	295.30	27.56	1	-	-	-	-	-	-	-	-	-
	[316.45]		[1]	[5]	*18.56*	*5.89*	*1.36*	*10.16*	*1.15*	*54.09*	*120.28*	*142.08*
17	335.47	26.99	1	-	18.35	4.86	1.62	2.16	2.97	59.29	134.43	141.76
	[347.49]		[1]	[5]	*17.87*	*5.17*	*1.40*	*10.09*	*1.22*	*51.69*	*146.61*	*149.19*
18	268.95	23.13	1	-	14.34	2.78	1.39	1.62	5.32	-	-	-
	[299.90]		[1]	[5]	*13.58*	*3.59*	*1.34*	*7.42*	*1.23*	*44.57*	*120.28*	*135.05*
19	64.41	24.59	1	-	-	-	-	-	-	-	-	-
	[73.84]		[1]	[2]	*6.44*	*6.44*	-	-	-	*29.89*	*43.95*	-
20	193.34	24.59	1	5	-	-	-	-	-	-	-	-
	[213.87]		[1]	[5]	*17.99*	*5.62*	*1.38*	*9.78*	*1.21*	*51.24*	*82.03*	*80.60*
21	222.21	24.59	1	4	-	-	-	-	-	-	-	-
	[244.74]		[1]	[5]	*18.01*	*5.35*	*1.39*	*10.04*	*1.22*	*50.35*	*88.43*	*105.96*
22	332.29	23.55	1	-	17.19	4.24	1.65	1.65	8.48	42.93	112.36	177.04
	[348.30]		[1]	[5]	*16.17*	*4.30*	*1.38*	*9.26*	*1.23*	*56.76*	*148.04*	*143.50*

23	265.79	28.16	1	5	16.90	5.35	1.69	1.97	7.89	-	-	-
	[293.58]		[1]	[5]	*19.40*	*6.47*	*1.39*	*10.33*	*1.21*	*49.02*	*75.35*	*169.21*
24	135.47	28.16	1	3	3.66	1.97	1.69	-	-	-	-	-
	[143.23]		[1]	[5]	*16.62*	*3.68*	*1.38*	*10.35*	*1.22*	*41.10*	*52.76*	*49.38*
25	178.01	27.56	1	-	-	-	-	-	-	-	-	-
	[193.14]		[1]	[5]	*19.48*	*6.09*	*1.41*	*10.79*	*1.19*	*45.99*	*82.83*	*64.32*
26	178.71	24.59	1	4	-	-	-	-	-	-	-	-
	[198.84]		[1]	[5]	*18.82*	*5.61*	*1.37*	*10.59*	*1.26*	*45.82*	*42.70*	*110.32*
27	312.86	24.91	1	-	15.20	0.75	2.24	1.49	1.74	-	-	-
	[357.01]		[1]	[5]	*16.68*	*4.43*	*1.41*	*9.64*	*1.21*	*52.49*	*151.51*	*153.02*
28	71.37	28.16	1	-	-	-	-	-	-	-	-	-
	[73.84]		[1]	[2]	*6.84*	*6.84*	-	-	-	*34.43*	*39.41*	-
29	70.36	24.91	1	2	6.23	6.23	-	-	-	28.74	41.64	-
	[84.96]		[1]	[2]	*7.76*	*7.76*	-	-	-	*38.52*	*46.44*	-
30	124.45	25.91	1	3	5.18	2.85	2.33	-	-	-	-	-
	[138.61]		[1]	[4]	*16.18*	*4.17*	*10.79*	*1.22*	-	*37.10*	*55.16*	*46.35*
31	75.09	24.91	1	-	-	-	-	-	-	-	-	-
	[93.50]		[1]	[3]	*6.94*	*5.54*	*1.39*	-	-	*52.49*	*41.01*	-
32	114.84	24.59	1	-	-	-	-	-	-	-	-	-
	[83.27]		[1]	[2]	*6.57*	*6.57*	-	-	-	*34.43*	*48.84*	-
33	134.67	24.59	1	-	-	-	-	-	-	-	-	-
	[150.35]		[1]	[4]	*11.74*	*4.12*	*6.34*	*1.29*	-	*40.21*	*58.27*	*51.87*
34	310.59	25.40	1	-	16.00	4.82	1.01	2.29	7.87	66.06	95.15	149.37
	[328.28]		[1]	[5]	*18.03*	*4.48*	*1.38*	*9.23*	*2.94*	*49.82*	*131.04*	*147.41*
35	151.61	26.43	1	4	8.46	2.12	4.23	2.12	-	43.90	60.18	47.55
	[144.75]		[1]	[5]	*13.07*	*6.45*	*1.35*	*4.04*	*1.22*	*49.55*	*29.71*	*65.48*
36	164.47	24.59	1	-	-	-	-	-	-	-	-	-
	[166.81]		[1]	[5]	*14.66*	*3.84*	*1.32*	*8.28*	*1.22*	*40.21*	*69.75*	*56.85*
37	336.28	25.91	1	-	-	-	-	-	-	-	-	-
	[353.99]		[1]	[5]	*15.96*	*4.08*	*1.33*	*9.36*	*1.19*	*45.99*	*163.78*	*144.21*
38	129.55	24.59	1	2	-	-	-	-	-	-	-	-
	[127.31]		[1]	[3]	*7.12*	*5.77*	*1.34*	-	-	*50.00*	*77.31*	-
39	139.30	24.91	1	5	16.44	1.74	3.49	1.74	9.47	38.21	53.29	47.82
	[154.71]		[1]	[5]	*18.59*	*4.97*	*1.37*	*9.29*	*2.97*	*49.64*	*60.41*	*44.66*
40	96.36	24.59	1	-	-	-	-	-	-	-	-	-
	[90.57]		[1]	[2]	*7.02*	*7.02*	-	-	-	*37.54*	*53.02*	-
41	169.52	25.91	1	-	17.10	3.63	1.81	2.07	7.77	39.37	56.94	73.22
	[168.85]		[1]	[5]	*15.60*	*3.78*	*1.30*	*9.32*	*1.19*	*38.88*	*59.96*	*70.01*
42	377.57	24.59	1	-	-	-	-	-	-	-	-	-
	[334.51]		[1]	[4]	*6.93*	*4.22*	*1.39*	*1.33*	-	*86.74*	*96.08*	*151.68*
43	219.30	24.59	1	-	-	-	-	-	-	-	-	-
	[235.22]		[1]	[5]	*13.09*	*5.37*	*1.34*	*5.17*	*1.22*	*45.64*	*98.22*	*91.37*
44	160.54	30.12	1	5	7.53	0.60	1.81	3.61	1.51	68.41	49.51	42.66
	[166.27]		[1]	[5]	*17.85*	*5.62*	*1.35*	*9.68*	*1.20*	*50.98*	*68.41*	*46.88*
45	168.38	25.91	1	5	13.47	2.07	1.81	8.03	1.55	-	-	-
	[183.89]		[1]	[5]	*14.85*	*3.58*	*1.34*	*8.73*	*1.20*	*41.19*	*83.89*	*58.81*
46	104.41	30.12	1	2	6.63	6.63	-	-	-	37.05	67.35	-
	[89.68]		[1]	[2]	*6.78*	*6.78*	-	-	-	*37.54*	*52.13*	-
47	153.48	28.16	1	5	7.60	0.56	1.69	3.38	1.97	49.60	30.20	73.71
	[163.69]		[1]	[4]	*16.98*	*5.29*	*10.49*	*1.20*	-	*49.11*	*56.94*	*57.65*

48	106.58	29.44	1	4	7.65	0.30	2.36	5.00	-	26.69	28.96	50.93
	[97.77]		[1]	[2]	*7.00*	*7.00*	-	-	-	*38.17*	*59.61*	-
49	150.73	24.44	1	4	14.42	3.91	2.20	8.31	-	18.02	93.95	38.74
	[166.19]		[1]	[5]	*16.07*	*3.64*	*1.26*	*9.98*	*1.19*	*35.41*	*71.26*	*59.52*
50	66.17	24.59	1	-	-	-	-	-	-	-	-	-
	[79.98]		[1]	[2]	*7.03*	*7.03*	-	-	-	*35.41*	*44.57*	-
51	91.37	25.40	1	-	-	-	-	-	-	-	-	-
	[83.63]		[1]	[2]	*7.94*	*7.94*	-	-	-	*39.50*	*44.13*	-
52	68.61	25.40	1	-	-	-	-	-	-	-	-	-
	[69.13]		[1]	[2]	*6.47*	*6.47*	-	-	-	*29.80*	*39.32*	-
53	106.97	32.38	1	3	5.50	1.94	3.56	-	-	20.15	86.83	-
	[126.60]		[1]	[5]	*15.37*	*3.82*	*1.33*	*8.99*	*1.23*	*42.35*	*50.44*	*33.81*
54	311.18	24.91	1	-	-	-	-	-	-	-	-	-
	[352.39]		[1]	[5]	*16.00*	*4.32*	*1.34*	*9.16*	*1.18*	*47.06*	*82.03*	*223.30*
55	302.27	33.21	2	-	28.23	8.30	2.33	2.33	12.95	54.98	91.06	156.27
	[208.98]		[2]	[5]	*17.80*	*5.55*	*1.32*	*9.78*	*1.15*	*46.44*	*162.54*	-
56	307.12	23.55	1	-	18.37	0.47	5.18	1.18	9.89	61.25	116.59	129.27
	[342.51]		[1]	[5]	*17.11*	*5.35*	*1.32*	*9.28*	*1.17*	*52.84*	*67.79*	*221.88*
57	220.12	24.59	1	3	-	-	-	-	-	-	-	-
	[195.10]		[1]	[4]	*13.97*	*4.08*	*8.71*	*1.18*	-	*40.92*	*154.18*	-
58	130.04	28.16	1	-	-	-	-	-	-	-	-	-
	[120.10]		[1]	[3]	*7.08*	*5.74*	*1.35*	-	-	*54.89*	*65.21*	*65.21*
59	258.12	25.40	1	5	5.59	0.51	2.29	1.52	1.27	87.59	81.98	88.61
	[267.78]		[1]	[4]	*5.51*	*2.84*	*1.28*	*1.40*	-	*70.19*	*105.69*	*91.90*
60	138.92	26.43	1	-	12.95	0.27	3.44	1.58	2.12	36.74	44.66	57.56
	[137.27]		[1]	[5]	*13.40*	*3.65*	*1.33*	*7.22*	*1.20*	*42.26*	*53.91*	*41.10*
61	169.25	26.99	1	-	-	-	-	-	-	-	-	-
	[162.18]		[1]	[5]	*14.48*	*3.76*	*1.32*	*8.23*	*1.16*	*41.81*	*120.37*	-
62	306.48	24.59	1	-	-	-	-	-	-	-	-	-
	[312.71]		[1]	[5]	*15.44*	*3.69*	*1.38*	*9.19*	*1.19*	*41.46*	*139.32*	*131.93*
63	254.80	25.40	1	-	16.51	2.03	2.80	1.78	1.78	50.80	64.68	139.32
	[261.73]		[1]	[5]	*17.05*	*4.99*	*1.33*	*9.56*	*1.17*	*49.20*	*125.17*	*87.36*
64	128.38	29.06	2	2	-	-	-	-	-	-	-	-
	[119.57]		[2]	[3]	*5.58*	*4.19*	*1.39*	-	-	*56.58*	*32.03*	*30.96*
65	287.87	25.91	1	-	18.14	0.26	2.07	3.37	1.04	61.74	60.45	165.65
	[311.11]		[1]	[5]	*17.15*	*5.37*	*1.34*	*9.29*	*1.16*	*57.65*	*64.59*	*188.87*
66	229.04	30.12	2	-	-	-	-	-	-	-	-	-
	[225.26]		[2]	[3]	*6.58*	*5.27*	*1.32*	-	-	*59.61*	*165.65*	-
67	118.45	24.59	1	-	-	-	-	-	-	-	-	-
	[128.82]		[1]	[4]	*15.66*	*3.96*	*10.51*	*1.19*	-	*40.39*	*40.03*	*48.40*
68	314.49	24.91	1	-	16.19	1.25	3.24	1.74	1.49	-	-	-
	[337.80]		[1]	[5]	*17.47*	*4.82*	*1.32*	*10.18*	*1.15*	*53.38*	*145.72*	*138.70*
69	272.39	24.91	1	4	4.98	1.25	1.74	1.99	-	-	-	-
	[328.28]		[1]	[4]	*7.35*	*4.72*	*1.32*	*1.32*	-	*64.77*	*87.63*	*175.88*
70	295.10	28.78	1	-	19.57	0.29	1.44	1.73	2.01	59.25	39.90	195.94
	[290.38]		[1]	[5]	*15.65*	*3.64*	*1.34*	*9.49*	*1.17*	*44.75*	*94.57*	*151.06*
71	328.41	24.44	1	-	18.82	1.71	2.69	1.47	1.71	52.67	69.66	206.09
	[352.39]		[1]	[5]	*15.70*	*3.99*	*1.32*	*9.21*	*1.17*	*49.38*	*155.24*	*147.77*
72	307.82	24.91	1	-	-	-	-	-	-	-	-	-
	[325.43]		[1]	[4]	*5.39*	*2.77*	*1.24*	*1.37*	-	*136.83*	*188.60*	-

73	308.16	29.06	2	-	-	-	-	-	-	-	-	-
	[273.12]		[2]	[5]	*15.80*	*3.61*	*1.33*	*9.72*	*1.15*	*43.95*	*102.31*	*126.86*
74	212.77	25.40	1	5	17.02	4.57	1.78	2.03	8.63	-	-	-
	[205.69]		[1]	[5]	*17.54*	*5.48*	*1.34*	*9.60*	*1.14*	*52.76*	*100.44*	*52.49*
75	153.73	23.99	1	2	5.04	5.04	-	-	-	58.27	95.46	
	[163.87]		[1]	[5]	*18.37*	*5.29*	*1.34*	*10.59*	*1.16*	*49.38*	*68.15*	*46.35*
76	188.90	26.99	1	4	8.91	3.51	1.62	3.78	-	34.92	115.79	38.21
	[183.98]		[1]	[5]	*10.27*	*3.69*	*1.32*	*4.06*	*1.21*	*44.13*	*63.25*	*76.60*
77	171.39	23.99	1	-	-	-	-	-	-	-	-	-
	[167.52]		[1]	[4]	*16.08*	*4.00*	*10.90*	*1.18*	-	*40.39*	*53.91*	*73.22*
78	86.14	24.59	1	-	-	-	-	-	-	-	-	-
	[85.58]		[1]	[2]	*6.03*	*6.03*	-	-	-	*38.08*	*47.51*	-
79	140.68	26.43	1	3	5.55	4.23	1.32	-	-	41.99	62.99	35.72
	[137.09]		[1]	[5]	*16.43*	*3.98*	*1.35*	*9.94*	*1.16*	*40.57*	*50.80*	*45.73*
80	147.83	29.06	2	3	-	-	-	-	-	-	-	-
	[157.64]		[2]	[5]	*16.10*	*3.71*	*1.33*	*9.90*	*1.17*	*42.26*	*67.97*	*47.42*
81	88.97	26.99	1	-	-	-	-	-	-	-	-	-
	[84.78]		[1]	[2]	*6.06*	*6.06*	-	-	-	*37.81*	*46.97*	-
82	102.56	30.84	1	-	-	-	-	-	-	-	-	-
	[71.53]		[1]	[2]	*6.67*	*6.67*	-	-	-	*33.54*	*37.99*	-
83	196.44	30.12	2	-	-	-	-	-	-	-	-	-
	[177.48]		[2]	[5]	*18.22*	*5.77*	*1.34*	*9.96*	*1.15*	*43.50*	*37.63*	*96.35*
84	59.86	29.06	1	2	-	-	-	-	-	-	-	-
	[53.38]		[1]	[2]	*4.44*	*4.44*	-	-	-	*23.84*	*29.54*	-
85	75.31	28.78	1	-	-	-	-	-	-	-	-	-
	[77.04]		[1]	[3]	*6.19*	*4.78*	*1.41*	-	-	*39.68*	*37.37*	-
86	204.65	30.12	2	2	2.11	2.11	-	-	-	48.09	156.58	-
	[209.87]		[2]	[5]	*15.12*	*3.68*	*1.35*	*8.90*	*1.19*	*45.55*	*98.13*	*66.19*
87	168.73	26.43	1	5	10.31	2.12	4.76	1.32	2.12	44.75	61.83	62.14
	[161.56]		[1]	[3]	*7.67*	*6.32*	*1.35*	-	-	*68.95*	*92.61*	-
88	219.68	25.91	1	4	17.10	5.44	1.55	10.10	-	62.45	94.70	62.54
	[211.74]		[1]	[5]	*18.10*	*5.35*	*1.32*	*10.25*	*1.17*	*44.93*	*80.51*	*86.30*
89	266.96	26.99	1	-	19.43	5.67	1.62	1.89	3.78	50.49	83.98	132.47
	[278.81]		[1]	[5]	*17.95*	*5.43*	*1.30*	*10.08*	*1.14*	*49.64*	*229.17*	-
90	314.36	30.12	1	-	18.98	0.60	1.81	3.61	1.81	103.87	46.08	164.41
	[279.17]		[1]	[5]	*17.25*	*4.86*	*1.35*	*9.87*	*1.18*	*50.53*	*147.50*	*81.14*
91	384.68	23.99	1	-	18.95	5.04	1.68	1.68	1.68	-	-	-
	[444.64]		[1]	[6]	*20.04*	*5.38*	*1.33*	*10.81*	*1.26*	*48.04*	*183.71*	*212.89*
92	230.03	27.56	1	-	16.81	3.58	1.66	1.93	6.06	40.97	72.82	116.23
	[238.16]		[1]	[5]	*13.95*	*3.71*	*1.35*	*7.68*	*1.22*	*46.17*	*112.45*	*79.53*
93	230.63	23.55	1	-	19.08	4.95	1.65	2.12	8.95	41.87	72.51	116.28
	[238.16]		[1]	[5]	*16.89*	*4.84*	*1.30*	*9.57*	*1.18*	*49.20*	*86.83*	*102.13*
94	216.46	25.40	1	-	16.00	1.27	3.30	1.52	1.78	-	-	-
	[236.73]		[1]	[5]	*18.17*	*5.33*	*1.31*	*10.36*	*1.16*	*48.13*	*92.61*	*95.99*
95	318.08	26.99	1	-	18.35	1.89	3.24	1.62	1.89	22.06	77.35	218.63
	[335.66]		[1]	[5]	*17.81*	*5.29*	*1.31*	*10.07*	*1.14*	*50.09*	*132.20*	*153.37*
96	121.33	26.99	1	5	7.02	0.54	2.16	2.43	1.89	45.82	39.01	36.48
	[106.94]		[1]	[3]	*6.24*	*4.88*	*1.37*	-	-	*49.55*	*57.38*	-
97	119.05	24.44	1	3	5.13	3.18	1.96	-	-	8.18	110.85	-
	[131.85]		[1]	[4]	*15.05*	*3.96*	*9.89*	*1.20*	-	*29.80*	*51.87*	*50.18*

98	310.73	24.91	1	-	13.20	0.25	4.48	1.74	1.99	68.41	99.95	142.39
	[317.25]		[1]	[5]	*12.79*	*5.01*	*1.36*	*5.22*	*1.20*	*48.75*	*133.80*	*134.69*
99	148.35	24.59	1	3	-	-	-	-	-	-	-	-
	[139.50]		[1]	[4]	*16.07*	*4.22*	*10.63*	*1.22*	-	*40.03*	*40.83*	*58.63*
100	293.61	25.40	1	4	5.59	3.05	1.52	1.01	-	-	-	-
	[312.98]		[1]	[4]	*6.63*	*3.87*	*1.33*	*1.42*	-	*69.39*	*55.60*	*187.98*
101	55.29	24.59	1	-	-	-	-	-	-	-	-	-
	[51.60]		[1]	[2]	*3.02*	*3.02*	-	-	-	*19.84*	*31.76*	-
102	315.55	29.44	1	-	-	-	-	-	-	-	-	-
	[315.20]		[1]	[5]	*18.16*	*5.09*	*1.34*	*10.59*	*1.14*	*50.98*	*131.13*	*133.09*
103	127.57	29.44	1	-	-	-	-	-	-	-	-	-
	[115.48]		[1]	[3]	*6.86*	*5.51*	*1.35*	-	-	*40.92*	*74.55*	-
104	339.10	25.40	1	-	17.78	1.78	3.30	2.03	1.78	47.55	67.48	224.10
	[350.34]		[1]	[5]	*17.36*	*5.48*	*1.40*	*9.31*	*1.18*	*46.08*	*169.21*	*135.05*
105	219.55	24.59	1	-	-	-	-	-	-	-	-	-
	[193.85]		[1]	[5]	*17.92*	*5.33*	*1.37*	*8.28*	*2.95*	*50.98*	*62.28*	*80.60*
106	136.83	23.99	1	-	-	-	-	-	-	-	-	-
	[141.36]		[1]	[5]	*18.01*	*4.80*	*1.26*	*10.80*	*1.16*	*47.60*	*26.24*	*67.52*
107	297.71	26.99	1	-	18.90	2.16	2.97	2.16	1.89	46.84	63.61	187.23
	[297.41]		[1]	[5]	*18.13*	*5.34*	*1.34*	*10.28*	*1.17*	*43.59*	*145.46*	*108.36*
108	240.78	30.84	2	-	11.72	4.01	1.23	2.16	4.32	67.92	99.06	73.80
	[234.51]		[2]	[5]	*15.25*	*3.86*	*1.35*	*8.84*	*1.19*	*42.79*	*103.02*	*88.70*
109	162.53	29.06	2	2	-	-	-	-	-	-	-	-
	[142.88]		[2]	[5]	*17.61*	*5.41*	*1.35*	*9.61*	*1.24*	*46.26*	*96.62*	-
110	379.04	30.84	1	-	-	-	-	-	-	-	-	-
	[305.59]		[1]	[4]	*6.63*	*3.91*	*1.31*	*1.42*	-	*44.84*	*91.37*	*169.39*
111	220.50	24.59	1	-	-	-	-	-	-	-	-	-
	[185.05]		[1]	[5]	*16.89*	*5.14*	*1.33*	*9.24*	*1.19*	*44.48*	*80.51*	*60.05*
112	238.97	26.99	1	-	18.89	1.62	3.51	1.62	2.16	-	-	-
	[245.45]		[1]	[5]	*19.28*	*6.25*	*1.31*	*10.55*	*1.17*	*49.38*	*52.84*	*143.23*
113	142.28	24.44	1	4	12.71	2.69	1.71	8.31	-	-	-	-
	[136.29]		[1]	[5]	*14.97*	*3.83*	*1.35*	*8.54*	*1.24*	*41.46*	*49.64*	*45.19*
114	344.67	26.43	1	-	-	-	-	-	-	-	-	-
	[362.53]		[1]	[5]	*16.06*	*4.00*	*1.31*	*9.56*	*1.19*	*47.86*	*156.40*	*158.27*
115	273.12	24.59	1	-	-	-	-	-	-	-	-	-
	[282.28]		[1]	[5]	*19.74*	*6.53*	*1.31*	*9.03*	*2.86*	*50.98*	*20.64*	*210.67*
116	299.24	24.91	1	-	18.93	2.24	3.74	1.74	1.49	55.07	75.66	168.54
	[333.62]		[1]	[5]	*18.22*	*5.84*	*1.31*	*9.91*	*1.16*	*52.76*	*280.86*	-
117	72.73	26.43	1	2	2.91	2.91	-	-	-	-	-	-
	[74.82]		[1]	[2]	*6.62*	*6.62*	-	-	-	*32.21*	*42.61*	-
118	158.96	26.99	1	4	6.48	2.16	2.70	1.62	-	49.60	66.06	43.33
	[155.24]		[1]	[5]	*18.31*	*4.72*	*1.32*	*11.13*	*1.13*	*45.82*	*33.45*	*75.98*
119	305.34	27.56	1	-	-	-	-	-	-	-	-	-
	[307.99]		[1]	[5]	*17.84*	*4.73*	*1.35*	*10.58*	*1.19*	*51.15*	*106.85*	*149.99*
120	242.43	24.59	1	-	-	-	-	-	-	-	-	-
	[224.99]		[1]	[7]	*17.30*	*3.69*	*10.33*	*0.82*	*0.84*	*30.51*	*78.56*	*115.92*
121	281.80	24.91	1	-	16.94	1.74	2.49	1.74	1.74	42.30	56.89	182.60
	[264.94]		[1]	[5]	*14.78*	*3.91*	*1.32*	*8.36*	*1.19*	*44.30*	*98.84*	*121.79*
122	165.00	26.43	1	2	4.76	4.76	-	-	-	-	-	-
	[156.67]		[1]	[5]	*17.64*	*5.29*	*1.30*	*9.85*	*1.20*	*43.86*	*28.56*	*84.25*