Development and Evaluation of a Dual Purpose Bridge Health Monitoring and Weigh-In-Motion System for a Steel Girder Bridge – Phase II

FINAL REPORT

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Standard Conversions

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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		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.
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16. Abstract

The primary objective of this second phase is the further development, demonstration and field evaluation of a permanent dual purpose bridge weigh-in-motion and health monitoring system over an extended period of time. Calibrated test truck results demonstrated that the proposed algorithm can accurately predict vehicle speeds, and that even if the speed is exact other factors can contribute to the inaccuracy of the algorithm. The research has also been applied to a large continuous traffic data-set consisting of 385 days, providing information including GVW, truck speeds, and ADTT for certain months. The GVW, speed, and time stamp of each identified truck has been saved and loaded to a website accessible by the Connecticut Department of Transportation.

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1. INTRODUCTION

1.1 Motivation and Background for Bridge Weigh-in-Motion

The goal of long-term bridge monitoring is to identify changes in a bridge's dynamic behavior over multi-year periods as an indicator of the structural health of the bridge. To achieve this goal, highway bridges are instrumented with sensors, and computers for data acquisition and processing power. Research is on-going in the area of long-term bridge monitoring, in particular long-term vibration-based monitoring, to detect damage, monitor deterioration and allocate resources (Farrar et. al, 1994; Chakrabarty and Okaya, 1995; Salawn and Williams, 1995; Doebling, et. al, 1996; Farrar and Doebling, 1997; Salawn, 1997; Farrar et. al, 1999; Caicedo et. al, 2000; Chang, 2000). Bridge monitoring systems were specifically identified in the Federal SAFETEA-LU Legislation [5202] (FHWA, 2005). A recently funded Federal Highway Administration (FHWA) program at Rutgers University will initiate a program to examine long-term bridge performance (http://www.tfhrc.gov/ltbp/index.htm). Another project, funded in large part through the Technology Innovation Program of the National Institute of Standards and Technology and being carried out at the University of Michigan, is developing new wireless sensor technology to provide structural health monitoring of highway bridges (http://www.ns.umich.edu/htdocs/releases/story.php?id=6928). The Connecticut Department of Transportation (ConnDOT) and University of Connecticut (UConn) have a long history of close partnership in bridge monitoring with over three decades of bridge health monitoring (BHM) experience and currently six permanently monitored bridges for a variety of bridge types (Oland et. al, 2006; and DeWolf, 2009).

Transportation agencies are faced with the need to design and improve transportation networks to meet the ever increasing demand for safe, efficient and cost effective transport of people and goods. To meet this need, whether for the design of infrastructure (bridges and pavements), application of air quality or freight models, or enforcement of the size and weight limits, information is needed to quantify the loads experienced on the network. Weight data and related traffic data are used for a variety of engineering designs and decisions. Weigh-in-motion (WIM) systems are one mechanism used to gather such weight data. ConnDOT's Bureau of Policy and Planning collects and submits weigh-in-motion (WIM) data as required by the Federal Government (23 CFR (Code of Federal Regulations) 500 Part B) to obtain Federal funding and to support ConnDOT's planning and engineering applications. Polymeric piezoelectric WIM sensor technology is used for this purpose. ConnDOT also collects WIM data as part of the FHWA Long Term Pavement Performance Study (http://www.fhwa.dot.gov/PAVEMENT/ltpp/), and has installed and evaluated quartz-piezoelectric WIM sensors in these efforts. ConnDOT in cooperation with FHWA conducted the first installation and evaluation of a Quartz Piezoelectric WIM sensor on a U.S. Highway (McDonnell, 2000). Employing WIM systems presents many challenges including cost, installation, calibration, maintenance and accuracy. Alternative means to collect weight data, in particular non-intrusive methods are desired.

Bridge Weigh-In-Motion (BWIM) uses the dynamic response of a bridge to determine gross vehicle weight, speed, and axle spacing. The advantage of BWIM is that it does not require installation of sensors in the pavement, nor use any axle locators in the roadway. Proposed over 30 years ago (Moses, 1979), BWIM has become more feasible with the advancement of sensor and data acquisition technologies and with the extensive research conducted in Europe during the

1990’s through the *Weighing in motion of Axles and Vehicles for Europe* (WAVE) project (Jacob, 2002). BWIM uses sensing, acquisition, and processing capabilities similar to those used in vibration-based BHM. Recent work on BWIM in France, Slovenia and Ireland has focused on fully portable temporary installations for enforcement and is typically limited to short single span bridges. To date BWIM has been used throughout Europe, in India and Canada. A project to test and evaluate BWIM in the United States was recently conducted at the University of Alabama using a commercial system developed in Europe (http://rip.trb.org/browse/dproject.asp?n=13137). In 2006 and 2008, ConnDOT and UConn completed two pilot studies on BWIM that focused on single span steel girder bridges (McDonnell, 2006; Cardini and DeWolf, 2009; and Wall and Christenson, 2009). These studies have all been short-term applications of BWIM. A recent study by the Connecticut Academy of Science and Engineering (CASE) recommends that BWIM, as a promising non-intrusive technology, should be considered for WIM in Connecticut (CASE, 2008).

Bridge WIM systems and bridge health monitoring systems have similar components. With a combined or leveraged BHM/BWIM application, more comprehensive data can be collected. The actual measured volume and speed of traffic combined with indicators of structural degradation can also benefit planners if implemented at a system level. Truck traffic attributes used for weight enforcement, structural health monitoring and traffic monitoring can be obtained and shared through the use of combined BHM/BWIM systems.

There is a current need to demonstrate a synergistic application in BHM and BWIM and conduct basic testing to identify the challenges and realize the benefits of a leveraged bridge monitoring system. The contribution from this project is basic testing through a controlled field installation of a BHM/BWIM system to: further develop BWIM and combined BHM/BWIM methods and techniques; examine the challenges associated with implementing a leveraged bridge monitoring system; demonstrate the feasibility of this technology; develop a system framework that can apply to collect traffic data from various bridge structures; and develop guidelines for future implementation.

In the first phase of this project, a permanent dual purpose BHM/BWIM system was designed and installed on a single-span multi-girder steel composite highway bridge in Connecticut (I-91 Northbound, Meriden) (Christenson et al., 2011). The primary objective of Phase 1 was the exploration and development of the dual purpose system. A literature review was conducted to identify current WIM technologies and specifications as well as current BHM techniques as they apply to bridges. A scan of current sensor technologies used to measure strain and acceleration to identify the most promising sensor technologies for BHM/BWIM was also conducted. Five types of sensors, including foil strain gages, piezoelectric strain sensors, piezoelectric accelerometers, capacitive accelerometers and remote temperature detector (RTD) transducers, were selected and installed on the bridge to examine the capabilities and benefits of the different sensor technologies. Selection included the novel use and placement of sensors for the purposes of the study. For example, while piezoelectric accelerometers and foil strain gages are commonly used in bridge monitoring applications, capacitive accelerometers and piezoelectric strain sensors are rarely used and considered novel applications. Further, placement of strain sensors above the neutral axis on the girders for use in determining truck weights is typically not done and considered a novel approach.

Also in the first phase of the project, a BWIM method that allows for all sensors to be off of the pavement was developed (Christenson et al., 2011.) Applicable BHM methods utilizing damage measures based on natural frequency, neutral axis, strain distribution, and peak strain and acceleration responses have been identified. Work was conducted to enable data to be automatically triggered, collected and saved to a server for statistical analyses.

Phase I of this project developed and implemented a system with various sensor technologies. In the first phase information on the methodologies being proposed and employed were examined, system and sensor design completed and installed in the field, and an initial field test conducted. The system deployed in the first phase of this project is used in this second phase to further examine the dual purpose bridge weigh-in-motion and health monitoring capabilities through a series of field tests and refinements. The primary objective of this second phase is the further development, demonstration and field evaluation of a permanent dual purpose bridge weigh-in-motion and health monitoring system over an extended period of time.

2. LITERATURE REVIEW

2.1 Bridge Weigh-in-Motion

Bridge Weigh-in-Motion was first proposed in the late 1970s by Moses (Moses, 1979). Moses combined traffic and strain sensors installed on the pavement and the highway bridge girder, respectively. In his study, the traffic sensors were used to determine the vehicle velocities and axle spacing, while the strain sensors were used to compare strain data to influence lines determined from a bridge model.

In 1999, O'Brien improved the testing process by requiring a theoretical influence line as opposed to an actual influence line. The theoretical influence line could be scaled up or down based on a calibration truck (O'Brien et al, 1999). A more recently created procedure by Ojio and Yamada (2002) was used to determine Gross Vehicle Weight (GVW) without the need for an influence or theoretical line. This method involves the integration of strain response data, combined with a speed adjustment and a calibration factor, to determine the GVW (Ojio and Yamada, 2002). The calibration factor is determined from a test truck passing over the bridge.

2.1.1 COST323 and WAVE Programs

In Europe, extensive research into WIM systems was performed in the late 1990s as part of the COST323 and WAVE programs. COST323 was the first European cooperation on WIM. This study produced reports concerning the needs for a specification of WIM systems, a glossary of terms, a European database, large scale common tests of various systems, and two conferences (Quilligan, 2003). The research study also developed criteria regarding the optimal bridge selection to use a BWIM system. The optimal length of the bridge section, which influences the instrumentation, should be between five and 15 meters (16.4 and 49.2 feet), while an acceptable length is between eight and 35 meters (26.2 and 114.9 feet) (COST 323, 2002). The study also suggested an optimal bridge skew of less than 10 degrees, and an acceptable bridge skew of less than 25 degrees (COST 323, 2002). A further benefit of this study was a classification system for WIM accuracy that is based on percentage of gross vehicle weight difference between estimated and actual GVW. The accuracy class letters of A, B+, B, C, D+, and D correspond to an GVW percent accuracy of ±5, ±7, ±10, ±15, ±20, and ±25 for a 95% confidence interval, respectively.

Due to considerable demand for more accurate WIM systems in Europe, a proposal for the large research project WAVE emerged. The WAVE project began in 1996 and lasted until 1999, involving a total of eleven researchers from ten different countries (WAVE, 2001). The general objectives of this study were to improve the accuracy of traditional WIM systems, extend WIM to different types of bridges, test WIM systems in cold regions, and improve calibration procedures. As a result of this extensive study, a new approach was developed for achieving good accuracy with a system that requires no axle detector on the road surface. Additionally, the study developed a Quality Assurance system for WIM and two new algorithms for Multi-Sensing WIM.

During the WAVE project, Slovenia's National Building and Civil Engineering Institute (ZAG) developed a BWIM system known as SiWIM. This nothing on the road (NOR) or free of axle detector (FAD) system uses a series of strain transducers instrumented below the bridge in order to determine a vehicle's axle weight, axle spacing, speed, class, and GVW (UTCA, 2012).

2.1.2 Recent Studies in BWIM

A recent application of the BWIM system was performed in Alabama using the commercially available SiWIM system. In 2007, the University Transportation Center for Alabama worked on the first CESTEL Ltd. SiWIM system in the United States (UTCA, 2012). The objective of the research study was to evaluate the potential use of the SiWIM BWIM system in Alabama. Over an 18 month period, two interstate bridges in the state of Alabama were instrumented with the system and calibrated using trucks of known weight. The conclusions of the study resulted in many field study recommendations, such as using bridges with two lanes or less, selecting a bridge with no skew, and to use fully loaded test vehicles (UTCA, 2012).

A comprehensive study by the Virtual Vehicle Competence Center in Austria has explored different methods for detecting vehicle data in BWIM systems. Data was used from structural health monitoring (SHM) systems installed on three different bridges in Austria (Pircher et al, 2008). Based on this research a method for detection of vehicle velocity, axle weights, axle spacing, and number of axles has been explored using wavelet analysis and optimization procedures (Lechner et al, 2013). The study further explored using statistical approaches and regular vehicle information to calibrate BWIM systems rather the use of trucks of known weight and configuration, which have been commonly used in these studies. Past research from this institution has velocities of trucks calculated by using wavelet decomposition and obtaining the difference between the first and last axle of a truck (Lechner et al, 2010).

In Europe, a research project led by four SMEs (Small and Medium Enterprises) from multiple European countries has been conducted with the goal of improving BWIM systems (Bridgemon, 2015). Partners of this project include ZAG and CESTEL as well as other institutions. This project involved testing of three bridges in Slovenia including a box culvert and two concrete girder bridges (O'Brien, 2014). The study focused on improving accuracy of BWIM systems by taking bridge vibrations into account, calibrating the system for temperature changes and dynamic effects from speeds, enhancing axle detection using wavelets signal processing methods and improving data quality assurance using statistical methods (O'Brien, 2014). This project was completed in 2015 and detailed results are yet to be released (Bridgemon, 2015).

2.1.3 BWIM Research in Connecticut

In 2004, work began on the application of BWIM systems in the state of Connecticut. A field test was performed in 2006 on an already monitored multi-span steel girder bridge in Connecticut, which demonstrated that a BWIM system can be created using an existing bridge monitoring system (Cardini and DeWolf, 2007). In November 2008, a field test was performed where strain sensors from a portable system were installed on a single-span, steel girder bridge located in Meriden, Connecticut (Wall et al, 2009). The bridge characteristics (short span, little skew, and a good structural condition) proved promising for instrumentation. Using a test truck of known weight and a known travelling speed the GVW accuracy of the system was found to be +6.31 / -6.31% for the slow lane, +15.20 / - 15.19% for the central lane, when comparing estimated and actual GVWs. Accuracy of the algorithm from free flowing traffic, by examining 117 trucks for a 95% confidence interval, was found to be +23.39 / -27.28% for the slow lane and +51.70 / -39.23% for the middle lane. As a result of these studies a research project SPR-2265 was developed and a dual purpose BWIM and Structural Health Monitoring (SHM) system was installed on the same bridge in Meriden. The study presented from this SPR-2271 project enhances the BWIM research performed in Connecticut.

3. FULL-SCALE EXPERIMENTAL VALIDATION

In this section, details are presented regarding the Meriden Bridge, which is the test bed for this research. The information presented includes dimensions and characteristics of the bridge, as well as sensor locations, types, and parameters. In addition, details of three separate data sets are included. The first set of data is composed of vibration responses from a test truck travelling over the bridge. Characteristics such as GVW, axle weights, axle spacing, and speeds are previously known for this vehicle. The second set of data is obtained from a sample of trucks from free flowing traffic, the vibration responses of which have been recorded and matched with vehicles that were weighed using a static scale. The third set of data includes 385 days of collected vibration data from continuous truck and other vehicle traffic. The methodology behind the algorithm is presented below, including the calculations used for GVW and speed estimations.

3.1 Test Bed Description: Meriden Bridge

The test bridge used in this study is a three-lane bridge, which carries Interstate 91 (I-91) Northbound over Baldwin Avenue. It is located in Meriden, Connecticut and has the Bridge No. 03051. As was discussed previously, the length and skew of the bridge can significantly contribute to the accuracy of a BWIM system. This bridge has a total length of 85 ft., a width of 55 ft., and a bridge skew of 11.5˚, which falls in the recommended COST323 category for length and acceptable COST 323 category for skew (COST, 2002). According to CTDOT, the bridge carries an average daily traffic of 57,000 vehicles with 7% of those being trucks (Li, 2014). This results in an approximate average daily truck traffic (ADTT) of 4,000. A photo of the east elevation of the bridge can be seen in Figure 3.1.

Figure 3.1: East elevation of the Meriden Bridge, I-91 Northbound (Wall *et al*, 2009)

An inspection of the bridge was performed on September 24, 2012 by HAKS Engineers (HAKS, 2012)**.** The bridge received a sufficiency rating of 95 out of 100, where a rating of 100 is entirely sufficient. According to Wall (2009), the Meriden Bridge received a rating of 96 out of 100 from an inspection performed on August 12, 2009 (Wall *et al*, 2009). Based on these reports there have been no significant changes to the structural integrity of the bridge in the past four years. Both ratings are satisfactory for the bridge to remain in service. Figure 3.2 shows the dimensions of the bridge.

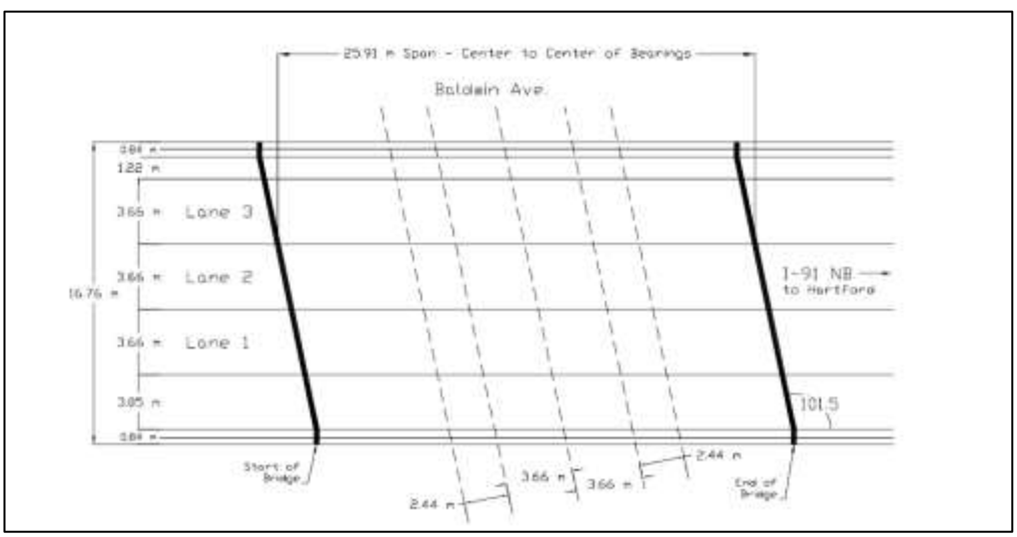

Figure 3.2: Meriden Bridge plan view (Wall *et al*, 2009)

3.2 SHM-BWIM System

A dual Structural Health Monitoring (SHM) and BWIM system was instrumented on the Meriden Bridge during Phase 1. A total of 38 sensors were installed on the bridge including 18 foil strain sensors, four high sensitivity quartz strain transducers, eight piezoelectric accelerometers, four capacitive accelerometers, four resistance temperature detectors (RTDs), and one microphone. Figure 3.3 shows the configuration of the various sensor technologies.

For the purpose of this phase 2 study only two strain sensors are used, located at the center of Girders 4 and 6. Both sensors are installed on the web of the girder, just above the bottom flange and measure vertical strain. Girders 4 and 6 are located almost directly under the slow and middle lane of the highway, respectively. The Meriden Bridge has a total of three lanes; however, very few trucks are known to travel in the far left (fast) lane. As a result, data was only collected for the right and middle lanes. It was expected that the girders discussed will experience the greatest strain measurements from each corresponding lane at the mid span of the bridge. Hence, the middle lane will be referred to as Lane 2 and the slow (right) lane as Lane 1.

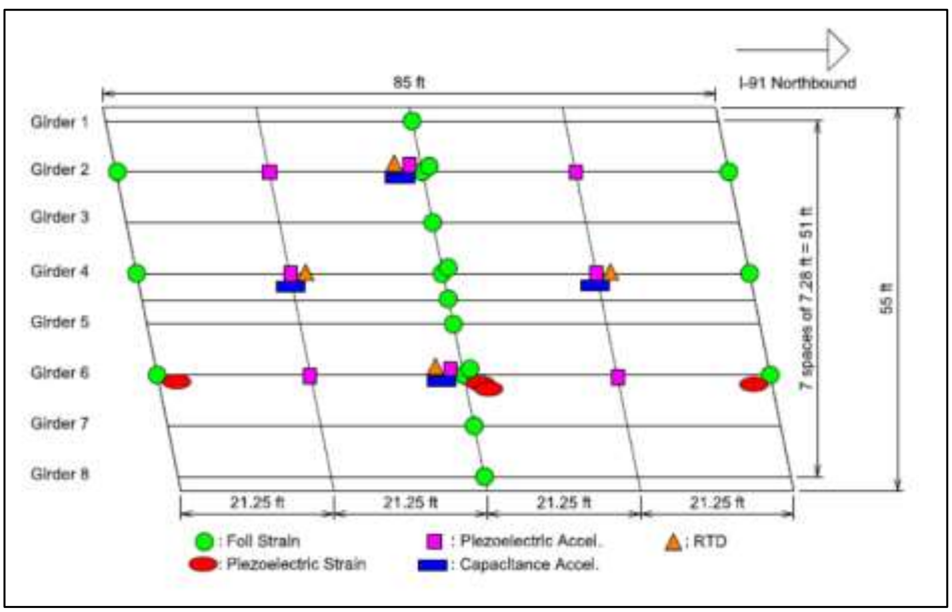

Figure 3.3: Schematic of sensor layout and types (Christenson *et al*, 2012)

Only the foil strain sensors are used in the research presented and will be discussed in more detail. These types of strain sensors are commonly used for the purpose of bridge monitoring. The specific sensors used in this study are manufactured by Vishay® Micro-Measurements and they have a measurement range of 1000s of microstrain, while the greatest peaks observed on the bridge have been less than 50 microstrain.

The data acquisitioning unit used is a National Instruments (NI) NI cDAQ-9178 (CompactDAQ) eight slot USB chassis with four different types of modules used for different sensor types (Li, 2014). The DAQ unit is connected to a small desktop using a USB 2.0 High-Speed Cable (Li, 2014). The configuration described is placed inside a traffic signal cabinet that is installed on the south abutment of the Meriden Bridge. Figure 3.4 shows an image of the cabinet. The desktop contains the programming language MATLAB, which is used to collect data. Vibration responses of the Meriden Bridge are collected continuously (24/7) and an external 2 TB hard-drive is used to store the data. A remote internet connection is established with the desktop using Digi WAN 3G Wireless router from Sprint, which allows for remote access to the desktop.

Figure 3.4: Cabinet containing Meriden Bridge system components

3.3 Dynamic Truck Loading Tests

A total of three different data sets have been collected and will be referred to throughout the study. All data was collected using a sampling rate of 2048 Hz. A test was performed using a 5-axle loaded test truck of known characteristics in December of 2010. The vehicle travelled over Lanes 1 and 2 a total of eleven and five times, respectively. For the separate trials the vehicles travelled at constant speeds from 47 to 63 mph. The strain response for each pass was matched with the corresponding run. The truck had a total static GVW of 68,360 lbs and a length of 68 ft. An image of the vehicle can be seen in Figure 3.5.

Figure 3.5: Test truck used in calibration

Data collection of trucks free flowing traffic was performed over three days in June of 2013. Each day contained a different number of vibration sets, with strain sensors running for a total of two minutes for each set. The trucks that passed over the instrumented bridge were later weighed using static scales at a near-by weigh station. Strain responses of the bridge were matched with the corresponding trucks. Figure 3.6 shows strain responses from Girder 6 during a period of two minutes. From this particular string of data seven trucks have been identified by the system and their GVWs and speeds have been estimated.

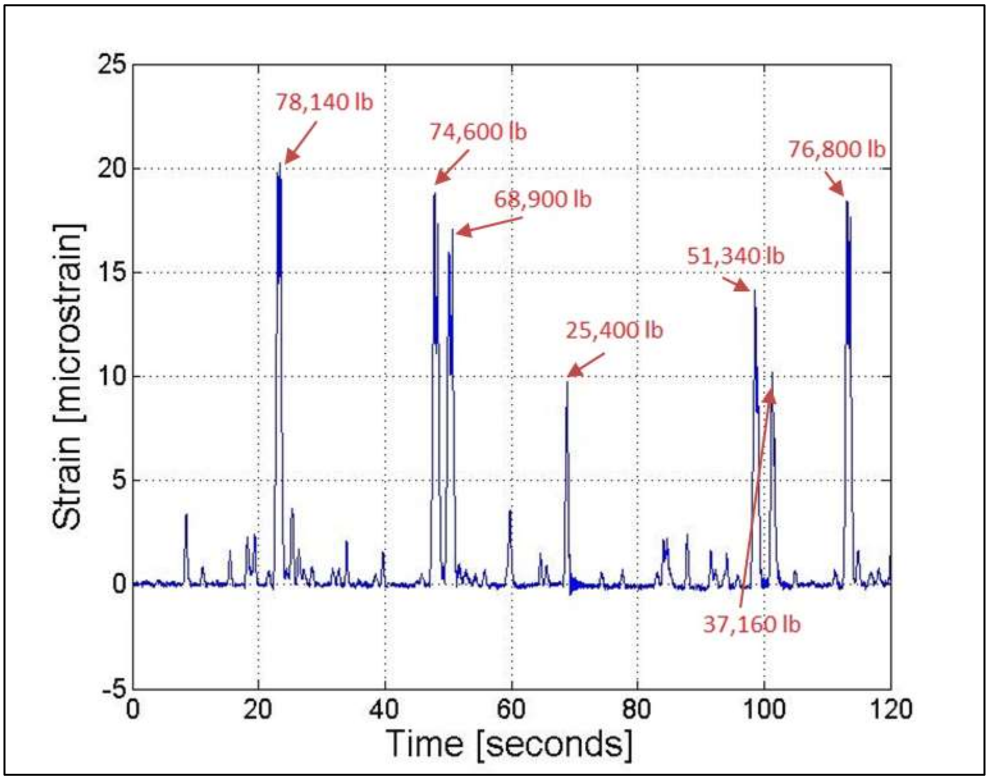

Figure 3.6: Girder 6 strain responses during two minutes

3.4 Long-term Data Collection

Meriden Bridge data was also collected continuously for a period of close to one year. Every hour, ten strings of five minute data have been collected. These data files contain information from fourteen out of the 48 available sensors, and include the sensors needed for this methodology. An additional five minute string of all 48 sensors were also collected in between every ten strings. In this manner, about 95% of all possible strain data is collected with some delays occurring while the files are being saved and the algorithm is being reinitiated. A truck event is identified when a set strain value is exceeded; prompting the algorithm to examine all strain data 0.75 seconds before and 1.75 seconds after the mentioned value. This setup has shown consistency in capturing strain data caused by a particular truck event.

Long-term traffic information has been collected since March of 2013. However, due to various issues with power, internet and sensor connections, and project continuation the records have been collected inconsistently. Table 3.1 shows the months during which data has been collected, the number of days of each month data was collected, percentage of data during the days it has been collected, and the percentage out of total data possible for the specific month. For example, for the month of March 2013 data was collected for sixteen out of a possible 31 days. For these sixteen days, 85% of possible strain data was collected, which results in 44% of data available for the entirety of this month.

Table 3.1: Percentages of data collected per month

Month	Number of Days Collected	Percentage of Data for Days Collected	Percentage out of Total Data Possible per Month
March 2013	16	85%	44%
April 2013	9	82%	25%
May 2013	17	64%	35%
June 2013	10	57%	19%
July 2013	10	89%	29%
August 2013	3	68%	7%
September 2013	21	80%	43%
October 2013	31	97%	97%
November 2013	30	98%	98%
December 2013	31	97%	97%
January 2014	26	93%	78%
February 2014	22	96%	76%
March 2014	31	95%	95%
April 2014	16	85%	45%
May 2014	30	91%	88%
June 2014	12	87%	35%
November 2014	20	61%	41%
December 2014	31	81%	81%
January 2015	30	87%	84%
February 2015	26	96%	89%

3.5 BWIM Methodology

One strain sensor per traffic lane is used in this study to determine the speed and GVW of trucks passing over the instrumented bridge. Both sensors are located on the steel girders of the bridge and measure the vibration excitations of a specific girder located under a travel lane. This method applies the theory initially developed by the works of Ojio and Yamada (2002), and builds on the findings of Cardini and DeWolf (2007) and Wall (2009).

The developed theory uses the assumption that each girder under a lane behaves as a simply supported beam when exposed to a load from that specific lane. By instrumenting a girder directly under a highway lane, each axle of a vehicle can be assumed to act as a point load moving along the girder at a fixed spacing and a constant speed. This will make the vibration response caused by each moving truck to act like a group of point loads moving along a simply supported beam.

3.5.1 Gross Vehicle Weight

The GVW is found by relating a known GVW from a calibration vehicle to the unknown GVW of a vehicle of interest. This method was developed by Ojio and Yamada (2002), and was used by Wall (2009). The GVW of an unknown truck can be determined by multiplying the influence area of an unknown truck times a calibration factor. This calibration factor is found by dividing the GVW of a known calibration truck over the influence area of that known truck, as shown in Eq. 1 (Wall, 2009).

$$\frac{A_k}{GVW_k} = \frac{A_u}{GVW_u} \tag{1}$$

where, GVW_k and GVW_u are GVW weights of known and unknown trucks, and A_k and A_u are influence areas for known and unknown trucks, respectively.

The ratio of the GVW of a known vehicle over the influence area can be defined as a calibration constant, β. By substituting this constant in Eq. 1 the relationship shown in Eq. 2 can be established.

$$GVW_u = A_u\beta \tag{2}$$

The influence area of a moving truck is a function of strain with respect to distance, ε(x). This value can be modified to be with respect to time, by multiplying it by speed. This is shown in Eq.'s 3 and 4.

$$A(x) = \int_{-\infty}^{\infty} \varepsilon(x)dx \tag{3}$$

$$A(x) = v\int_{-\infty}^{\infty} \varepsilon(t)dt \tag{4}$$

Finally, the strain can be represented over discrete time intervals, as shown in Eq. 5,

$$A(x) = \frac{v\Delta t}{N}\sum_{i=1}^{N} \varepsilon(i\Delta t) \tag{5}$$

where, Δt is the discrete time interval, and N is the total number of measurements obtained while the truck is crossing the bridge.

3.5.2 Vehicle Speed Estimation

A vital step in the proposed method to accurately determine the GVW of a moving vehicle is to first correctly predict the vehicle's speed. The methodology in this study captures the peak in strain caused by the last axle of the vehicle being directly over the strain sensor and calculates the point in time the axle leaves the bridge. By knowing the distance between the strain sensor and the end of the bridge, and the time it took for the vehicle to travel this distance, the speed can be estimated. An assumption is made that the truck travels at a constant velocity over this span. An approximate speed calculation can be made using the following equation:

$$v = \frac{L}{2t} \tag{6}$$

where, v (ft/s) is the average speed of the truck, L (ft) is the length of the bridge, and t (sec) is the time it takes for the truck to get from mid-span of the bridge to the end. Figure 3.7 shows a typical strain response from a five-axle vehicle. An image of the truck that caused this response can be seen in Figure 3.8. From the strain response two clear peaks can be seen corresponding to the influence from the 2nd-3rd axles at approximately 56.9 seconds and 4th-5th axles at approximately 57.4 seconds. It can be seen from the image that a peak from the first axle at approximately 56.6 seconds is difficult to capture, which is why the methodology for speed calculation uses the end peaks rather than the first peaks. The last axle of trucks tends to be heavier in most cases leading to more consistent results.

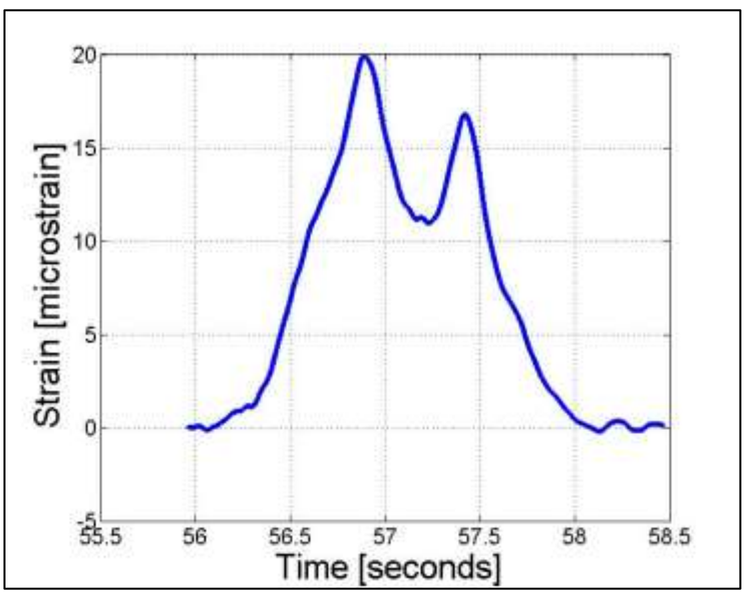

Figure 3.7: Typical strain response due to a five axle truck

Figure 3.8: Typical five axle truck

4. BRIDGE WEIGH-IN-MOTION RESULTS

In this section results are presented from the three data sets introduced previously. The GVW and speed calculations are examined for both lanes using the test trucks of known weight. The free flowing traffic sample truck data set is also analyzed, from which the beta calibration factors are computed, and accuracies of this algorithm are discussed. Analyses of various types of vehicles that result in speed miscalculations are discussed, and strain responses as well as truck images are shown for each case. Equations of statistical parameters for GVW accuracy are presented and the results from the methodology are shown for all trucks, five-axle trucks, as well as trucks travelling in Lane 1 or 2. Long-term data results include an evaluation of speeds computed for weekdays or weekends and holidays. The information is presented for all months, the month of February 2015, as well as one day: February 13th, 2015. Furthermore the ADTT of the bridge for months containing more than 70% of all possible traffic data is estimated. To close, results for various types of speed errors, which occur due to strain abnormalities from the long-term data set, are presented.

4.1 Test Trucks Speed Calculation

Data collection was performed on the bridge using a test truck. The vehicle performed a total of sixteen runs over the bridge at a constant speed, five runs over Lane 2 and eleven runs over Lane 1. Greater details regarding this test can be found in Section 3.3.

The algorithm presented in this study has been applied to the strain responses of the test truck to examine the speed accuracy. Tables 4.1 and 4.2 show the actual speeds verses the calculated speeds for Lanes 1 and 2, respectively. Additionally a percent difference between the two calculations is presented. Two test runs were excluded from the validation of speed calculations. During test run 2 in Lane 1, the strain response did not appear to match the type of response observed in previous trials. For test run 1 performed on Lane 2, the system was unable to calculate the vehicle speed because the strain response was not entirely captured.

It can be seen from the two tables that the percent difference between the actual and calculated speed is relatively small. The average percent differences for Lanes 1 and 2 were 0.55% and 3.38%, respectively.

Table 4.1: Lane 1 test truck speed calculations

Test Run Number	Actual Speed [mph]	Calculated Speed [mph]	Percent Difference
1	62	62.80	1.30
3	61	62.58	2.59
4	62	64.02	3.26
5	62	59.41	-4.17
6	62	62.73	1.18
7	63	64.89	2.99
8	55	52.40	-4.73
9	55	51.58	-6.22
10	49	45.65	-6.84
11	55	57.85	5.18
		Average Percent Difference:	-0.55

Table 4.2: Lane 2 test truck speed calculations

Test Run Number	Actual Speed [mph]	Calculated Speed [mph]	Percent Difference
2	62	63.87	3.01
3	62	63.10	1.78
4	63	64.89	2.99
5	63	66.60	5.72
		Average Percent Difference:	3.38

The GVW for the truck was determined from which a calibration β factor was computed. An optimal β value for each lane was determined using a trial and error, and the methodology presented in Section 4. The two factors were found to be $\beta_1 = 0.0416 \ \frac{lb}{\mu\varepsilon \times ft}$ for Lane 1 and $\beta_2 = 0.0397 \ \frac{lb}{\mu\varepsilon \times ft}$ for Lane 2. Tables 4.3 and 4.4 present the results for the test truck using the factors mentioned. The calculated GVW using the speed calculated from the methodology developed is found in the second column of both tables. The percent difference is based on the comparison with the weight of the test truck, which is 68.4 kips, and results of this are shown in column 3. Column 4 shows the percent difference using the correct (actual) speed, and the calibration factors are based on these values. These larger errors from the actual speed indicate using the calculated speed can provide less variance in the GVW difference.

Table 4.3: Lane 1 test truck GVW calculations

Test Run Number	Calculated GVW [kips]	Percent Difference	Percent Difference using Correct Speed
1	66.81	-2.27	-3.52
3	66.24	-3.11	-5.55
4	65.82	-3.71	-6.75
5	63.93	-6.49	-2.41
6	64.46	-5.71	-6.81
7	65.35	-4.41	-7.19
8	71.66	4.83	10.04
9	71.55	4.66	11.60
10	67.81	-0.80	6.48
11	64.85	-5.14	-9.81
	Average Percent Difference	-2.22	-1.39

Table 4.4: Lane 2 test truck GVW calculations

Test Run Number	Calculated GVW [kips]	Percent Difference	Percent Difference with Exact Speed
2	80.24	17.38	13.95
3	59.06	-13.60	-15.11
4	63.42	-7.23	-9.93
5	80.30	17.46	11.11
	Average Percent Difference	2.80	0.01

4.2 Free Flowing Traffic

The methodology discussed was further validated using strain responses of trucks from free flowing traffic. This test was used to establish accuracy for the algorithm. A total of 190 trucks were weighed right after passing the Meriden Bridge, and a time stamp for each vehicle was matched based on images from a camera.

Not all trucks were used to determine the accuracy of the algorithm. Certain truck events did not allow the system to correctly estimate the vehicle speeds or GVW. Such cases included trucks travelling over the bridge too slowly due to a traffic jam, trucks changing lanes, multiple trucks on the bridge at the same time, trucks decelerating or accelerating excessively, and trucks that are very light. Out of the 190 vehicles mentioned, 25 trucks travelled too slowly, three changed lanes while crossing the bridge, two were affected by a multiple presence of vehicles, and five trucks were considered to be too light weight. The algorithm registered another sixteen cases as errors, due to either: vehicles changing speeds (due to acceleration/deceleration); unusual vehicle configurations; or vehicle not captured by the algorithm scheme. Each of the mentioned types of errors is discussed in this section. An example using an image of a vehicle and strain response is presented.

4.2.1 Trucks Travelling during Traffic Jams

The algorithm scheme captures strain responses of each truck for 2.5 seconds. This time frame was established to optimize the capture of single vehicles. The length of the Meriden Bridge is 85 ft and a point load can cross the entirety of the bridge in 0.89 seconds travelling at 65 mph. A long truck with the length of 68 ft., such as the test truck mentioned in previous sections, would be able to cross the bridge in 1.60 seconds. However, were the 68 ft. long truck travelling at a speed of 40 mph, the entire truck would take 2.61 seconds to cross the bridge. This would mean the entire strain response would not be captured and as a result the GVW would be miscalculated.

Figure 4.1 shows the strain response of a truck during slow moving traffic. As can be seen from the image the entirety of the strain response is not captured. In such cases, the algorithm presented registers such vehicles as having a speed error, because the tail portion of the strain has not reached a value low enough for the truck to be considered entirely off the bridge. Figure 4.2 shows the image of the registered truck during traffic. Cars located close to each other in the distance can be seen, thus confirming the congestion.

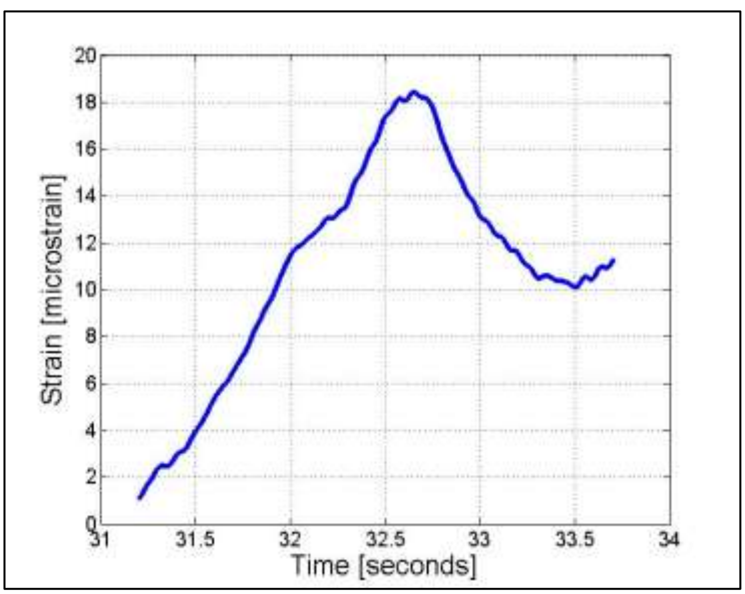

Figure 4.1: Lane 1 strain response of a slow-moving truck during heavy traffic

Figure 4.2: Five axle truck during heavy traffic

4.2.2 Lane Changes

Trucks changing lanes or travelling in between two lanes or on the shoulder occur infrequently. However, such cases do cause an underestimation of the GVW of the truck, since the strain of either Girder 4 or 6 will be lower than if the vehicle is travelling in one lane. This type of scenario is particularly difficult to identify, because the strain response appears similar to a normal strain response, with the exception of large strains in the adjacent lane. Therefore, these types of cases cannot be identified by the algorithm. For the purpose of identifying the accuracy of the methodology the three cases during which lane changes occurred have been removed manually.

Figure 4.3 shows the strain response while a truck is travelling in two adjacent lanes at the same time. It can be seen in the image that the strain response from Girders 4 and 6 is very similar with Girder 6 having higher values. Figure 4.4 shows the five axle truck travelling over the bridge. In this figure it can observed that the truck is travelling in between Lanes 1 and 2.

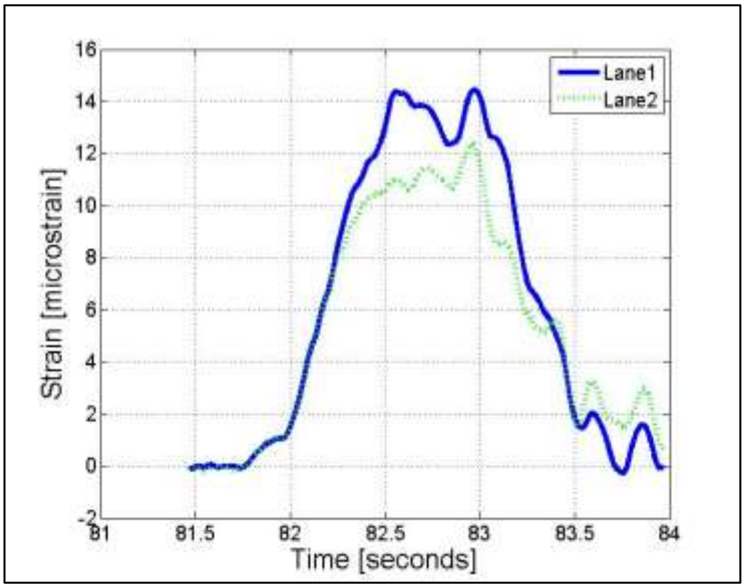

Figure 4.3: Lanes 1 and 2 strain response of a truck changing lanes

Figure 4.4: Five axle truck changing lanes

4.2.3 Multiple Presences

Multiple presences of trucks can affect the accuracy of the algorithm. If two trucks are side by side in two different lanes, the methodology will register only one truck, which has a larger strain response. If two trucks are close together in the same lane it is possible for the strain response of both trucks to be combined. The algorithm usually is able to detect the latter case and identify an error, since it is possible for the last peak to be located at the end of the time frame. For the case of trucks being in parallel lanes, the algorithm is not able to distinguish that there is such an issue since the response is similar to a normal strain response.

Figure 4.5 shows the strain response in Lane 1 due to two vehicles travelling closely together in the same lane. It can be seen from this image that the last peak in this response is at the very end of the time frame. Due to this the algorithm registers a speed error, since a speed cannot be estimated. Figure 4.6 shows the two vehicles that caused the strain response in Figure 4.5. A five axle truck can be seen being closely followed by a bus. Because the bus is close to the truck the 2.50 second time frame set for each vehicle is not sufficient to capture the strain from only one vehicle. The vehicle whose strain is between 85.3 seconds and 86.7 seconds is the five-axle truck, while the rise in strain after 87 seconds is caused by the bus.

A case where two trucks are travelling in parallel lanes at the same time has not been observed in this set of data and thus no figure for this case is provided.

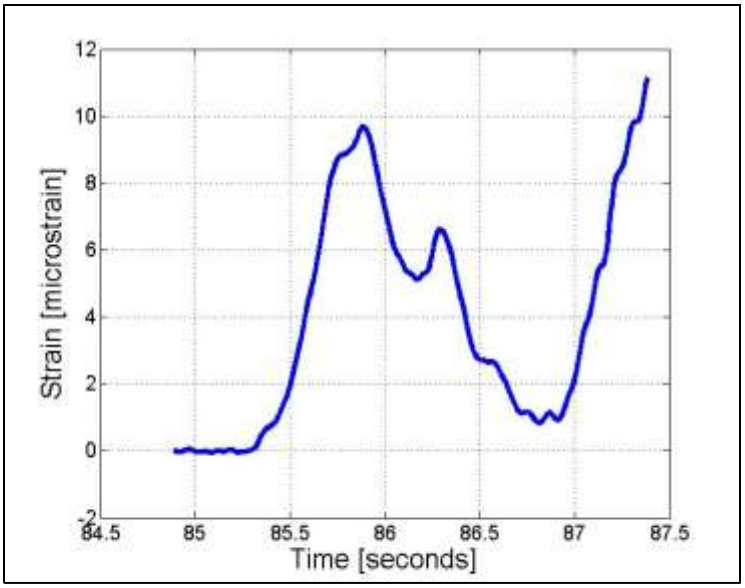

Figure 4.5: Lane 1 strain response of a multiple presence event

Figure 4.6: Multiple presence event

4.2.4 Extensive Accelerations or Unusual Vehicle Configurations

The final category for truck miscalculations is the broadest one. Extensive acceleration/deceleration, trucks slowing down or speeding up while crossing the bridge, can cause unusual vibrations on the bridge and do not agree with the original assumption that trucks are travelling at a constant speed. Due to these factors gross miscalculation of the truck speeds is possible. In order to avoid such cases, two upper limits have been set on the maximum speeds for both Lanes 1 and 2.

In addition, the algorithm accuracy can be compromised with vehicle configurations that are not five axle, since the methodology was established for five axle trucks with consistent characteristics. This can lead to identifying a false strain peak as the last axle of the vehicle, or not correctly identifying when a vehicle is on the bridge. Regardless, a speed threshold is used to identify such cases.

Figure 4.7 shows the strain response of an unusual vehicle. In this particular case the correct peak corresponding to the last axle of the vehicle is difficult to identify, and the algorithm registered this vehicle travelling unreasonably fast. Figure 4.8 shows a picture of the discussed vehicle.

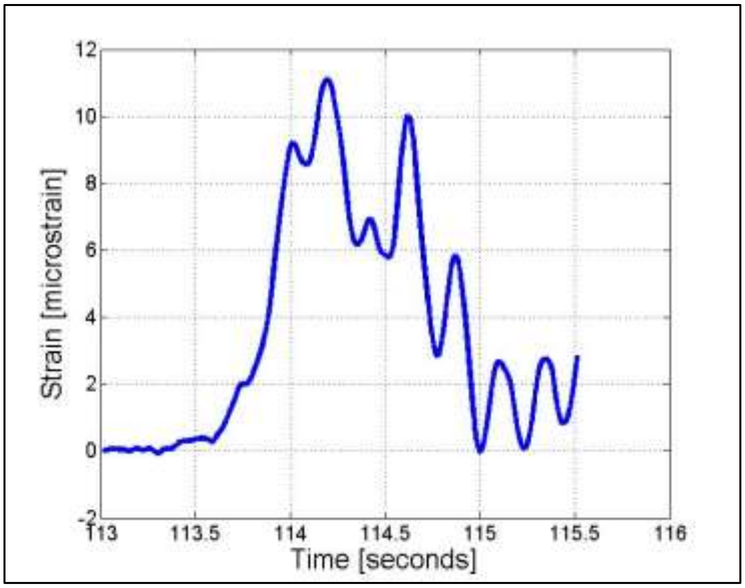

Figure 4.7: Lane 1 strain response of a unusual vehicle

Figure 4.8: Irregular vehicle configuration

4.2.5 Light Vehicles

The algorithm did not perform well in determining the GVW of vehicles under the weight of 21 kips. A total of five examples of such vehicles were recorded and all five samples had two axles. Three trucks were travelling in Lane 1 and two in Lane 2.

Out of the five identified light trucks, four of them were overestimated or underestimated by more than 20 percent. Due to this, it was established that the method presented does not support such light vehicles. The maximum legal GVW of a two axle truck in the state of Connecticut is 36 kips. It is extremely unlikely that two axle vehicles under 21 kips are to be overestimated by more than 60%, therefore if this system was used to assist with identification of overweight vehicles, it might not be of concern that it performs poorly for light vehicles.

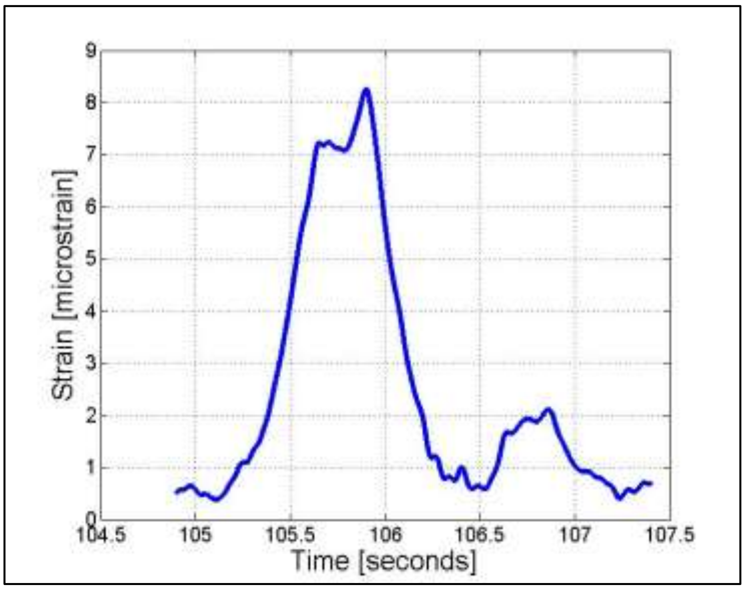

Figure 4.9: Strain response of a light weight truck

Figure 4.10: Two-axle commercial truck

4.3 Free Flowing Traffic Evaluation

Out of the 190 weighed trucks, only 139 (73%) were used to validate the methodology. The mentioned cases due to slow moving traffic, multiple presence, and unusual vibrations have been automatically identified by the algorithm as errors. Eight cases of trucks changing lanes and/or extremely light trucks have been removed manually. Out of these vehicles 133 travelled in Lane 1, while six travelled in Lane 2. In addition, 115 were five-axle trucks and 24 had more or less axles.

A minimum speed threshold has been set as 40 mph for both Lanes 1 and 2. As discussed previously, longer trucks would not be able to cross the bridge in the 2.5 second time frame, and the strain would not be captured entirely. The thresholds for high speed were chosen as 90 mph for Lane 2 and 80 mph for Lane 1. Since the speed limit on the bridge is 65 mph, it was concluded unreasonable that a truck travelling in the middle lane would be going more than 25 mph over the speed limit, although possible. Similarly, it was deemed unreasonable that trucks would be travelling 15 mph over the speed limit in the slow(right) lane. For cases where the speed was estimated as an unreasonably low or high value, the truck event being analyzed was removed from the algorithm. This scheme works well for the majority of truck events.

4.4 Statistical evaluation of the algorithm

The accuracy of this algorithm is evaluated using both; the sample of trucks from test truck trials and 139 trucks from free flowing traffic. The GVW determined by the BWIM system is compared with the static weight. The calculation of GVW percent difference is shown in Eq. 7 such that,

$$E = \frac{(GVW_{BWIM} - GVW_{static})}{GVW_{static}} \times 100 \tag{7}$$

Where, GVW_{BWIM} is defined as the gross vehicle weight determined by the BWIM methodology, GVW_{static} is the gross vehicle weight determined by a static scale, and E is the calculated percent difference between BWIM and static measurements. Eq. 7 and E can be manipulated to calculate GVW difference in kips rather than percentage. Further, both the GVW differences in kips and percent can be taken as an absolute value. These sets can be applied to the rest of the equations in this section.

The mean GVW difference in percent was determined as,

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} E_i \tag{8}$$

where E_i is the i^{th} vehicle GVW percent difference, n is the number of samples, and $\bar{x}$ is the mean value for GVW percent difference. The mean GVW value was initially computed for all trucks using the calibration factor found from the test trucks. However, the mean from free-flowing traffic samples was not close to zero and so both β factors were adjusted for this data set to be $\beta_1 = 0.0389 \frac{lb}{\mu\varepsilon * ft}$ for Lane 1 and $\beta_2 = 0.0386 \frac{lb}{\mu\varepsilon * ft}$ for Lane 2.

The GVW percent difference is assumed to act as a Gaussian (normal) distribution. In order to verify this, a Chi-square test was performed for the free-flowing traffic dataset. This test found that it is acceptable to assume these results behave as a normal distribution to a confidence of 90%. In addition to determining the mean value for GVW difference, it is also important to analyze the standard deviation of the sample. The standard deviation is defined as,

$$s = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} (E_i - \bar{x})} \tag{9}$$

Where, s is the standard devation, and n, $\bar{x}$, and E_i are defined previously.

The GVW percent difference is defined in terms of 95% confidence interval of difference, meaning that there is 95% confidence that the values fall within this range. Since the global mean is unknown and the amount of trucks used to evaluate the algorithm is limited, a t-distribution was used to evaluate the accuracy. The 95% confidence internal range for E can be seen in Eq. 10 using t-distribution:

$$\langle E \rangle_{t-\alpha} = \left[\mu - t_{\frac{\alpha}{2},n-1} \bar{x};\ \mu + t_{\frac{\alpha}{2},n-1} \bar{x} \right] \tag{10}$$

Where $t_{\frac{\alpha}{2},n-1}$ is the critical values of t distribution, n is the number of samples, and α is the probability of Type 1 error. For example, by examining all trucks available, the number of samples would be n = 139, for a 95% confidence interval α = 0.05, and $t_{\frac{\alpha}{2},n-1}$ = 1.978.

4.5 Free Flowing Traffic Final Results

The GVW difference for the free flowing traffic can be seen in Table 4.5. The table presents the mean percent difference of GVW being calculated for both overestimated and underestimated values. An absolute mean and a standard deviation value are also presented. All three values are shown for all 139 trucks, for five axle trucks, as well as for trucks travelling in Lanes 1 and 2. In column 1 the number of samples for each category is written in brackets.

Table 4.5: Percentage GVW difference for free flowing traffic

Percentage GVW Difference	mean [%]	absolute mean [%]	standard deviation [%]
All Truck [139]	-0.21	7.19	10.18
Five Axle Trucks [118]	-0.16	7.66	10.51
Trucks in Lane 1 [133]	-0.19	7.10	9.75
Trucks in Lane 2 [6]	-0.17	8.62	14.74

Apart from examining the GVW percent difference, the data can be further examined by the difference in weight. Table 4.6 presents this information in terms of GVW difference in kips rather than percent.

Table 4.6: GVW difference for free flowing traffic in kips

GVW Difference in kips	mean [kips]	absolute mean [kips]	standard deviation [kips]
All Truck [139]	-0.35	3.68	5.00
Five Axle Trucks [118]	-0.30	4.10	4.93
Trucks in Lane 1 [133]	-0.39	3.63	4.79
Trucks in Lane 2 [6]	0.45	4.44	7.57

Furthermore, the 95% confidence intervals for all types of trucks are presented in Table 4.7 in both percentage of GVW difference and kips.

Table 4.7: 95% confidence interval accuracy

95% confidence interval ranges	Percentage GVW difference	GVW difference [kips]
All Truck [139]	< -20.34 ; 19.92 >	< -10.26 ; 9.57>
Five Axle Trucks [118]	< -20.98 ; 20.65 >	< -10.06 ; 9.46 >
Trucks in Lane 1 [133]	< -19.48 ; 19.09 >	< -9.87 ; 9.08 >
Trucks in Lane 2 [6]	< -36.25 ; 35.90 >	< -18.08 ; 18.99 >

The standard deviation for this methodology was found to be 10.18%. With this data it can be stated with a 95% confidence that trucks without unusual vibration characteristics will fall between -20.34% and 19.92%. These results are an improvement from previous studies (Wall et al., 2009) done in 2009 with 117 trucks, which gave a standard deviation of 12.78% for Lane 1 and 19.72% for Lane 2. If these accuracies were to be classified using COST 323 specifications, the GVW for all truck and five-axle trucks would fall just short of a D+ (20) category and will be classified under D (25). The vehicles in Lane 1 will fall in the D+ (20) category. The number in parenthesis indicates the accuracy percentage for a 95% confidence. The vehicles in Lane 2 are unable to meet the lowest D (25) criteria. Since only six trucks are found in this lane results might be improved with more vehicle cases in this lane.

4.6 Long-term Traffic Results

The BWIM methodology for determining GVW and speed of trucks passing over the Meriden Bridge has been applied to continuous data, which has been collected since March 2013. Details regarding these data are presented in Section 3.4.

When examining all truck events, which were identified from the long-term data collection, the mean speed is found to be 63.1 mph with a standard deviation of 9.9 mph. It can be stated with a 95% confidence that all truck speeds during periods of normal free flowing traffic will fall in the range of 43.7 mph and 82.5 mph. In addition, the mean speed for measured trucks in Lane 1 is 60.4 mph with a standard deviation of 8.5 mph, and the mean speed for measured trucks in Lane 2 is 65.9 mph with a standard deviation of 10.5 mph. These statistics result in 95% confidence ranges between 43.7 mph and 77.1 mph for vehicle speeds in Lane 1, and 45.5 mph and 86.4 mph for vehicles in Lane 2. Given the speed thresholds discussed in section 4.3, the ranges found for truck events in both lanes are reasonable, because the majority of registered truck events are close to the mean values, which are similar to the speed limit on the bridge, 65 mph.

4.6.1 Type of Data Collected

From each individual day certain information has been stored and uploaded to a website accessible by CTDOT representatives and researchers at the University of Connecticut. The information collected after processing the larger data sets consists of details regarding a time stamp, lane, speed, GVW, error, as well as strain responses for each truck event. Additionally, two accelerometer responses for each truck event are saved, but are not used in the current methodology.

For each truck event an exact time stamp is registered. This includes a matrix of six numbers saving a year, month, day, hour, minute, and second. The lane matrix involves a number of 1 or 2, depending on the lane in which the truck was travelling. This distinction is determined based on the strain values, meaning that out of the two girders under Lanes 1 and 2 the higher strain will indicate which lane the truck is in. The GVW and speed are based on the higher strain response under the identified lane.

4.6.2 Monthly Speed

The average speeds calculated for both Lanes 1 and 2 are presented Table 4.8 for weekends and holidays, as well as weekdays. The average speeds are calculated per day and the average speed of all the days are then computed for each month, considering each day equally regardless how much data is collected in any given month.

Table 4.8: Monthly speed data

	Lane 1		Lane 2	
Month	**Weekdays Average Speed**	**Weekends | Holidays Average Speed**	**Weekdays Average Speed**	**Weekends | Holidays Average Speed**
March 2013	59.10	59.82	64.39	64.91
April 2013	60.43	61.54	66.14	67.53
May 2013	60.85	62.12	66.66	67.13
June 2013	59.82	59.60	65.36	65.11
July 2013	61.72	60.42	68.33	66.67
August 2013	61.25	67.44	N/A	N/A
September 2013	60.05	59.99	66.12	66.36
October 2013	59.69	59.70	65.92	65.43
November 2013	59.48	60.53	65.21	65.97
December 2013	59.77	59.57	65.08	64.50
January 2014	61.79	61.17	67.65	66.76
February 2014	60.72	61.34	65.21	66.62
March 2014	60.44	60.62	66.00	65.99
April 2014	59.56	59.77	64.97	64.83
May 2014	60.04	61.22	65.68	66.73
June 2014	60.57	61.43	66.08	66.73
November 2014	59.32	60.18	64.59	65.79
December 2014	59.22	59.77	64.48	64.84
January 2015	61.80	61.27	66.95	66.68
February 2015	61.69	62.34	66.44	67.41

From this information it can be observed that the average monthly speeds for Lane 1 are between 59 and 63 mph for the two categories; weekdays, and weekends and holidays. For Lane 2 the speeds are between 64 and 68 mph for both category days. The information presented does not account for the amount of data collected each month, nor the percentage of data collected for each day. Therefore, Table 3.4.1, which presents the amount of data collected for each month, should be consulted before making conclusions regarding the overall traffic speeds. . Months that contain more than 75% of all possible data collected are considered in this study to have a sufficiently large enough data set to be examined more closely. Those months include: October, November, and December of 2013, January, February, March, May, December of 2014, and January and February of 2015.

4.6.3 Speed Calculation: February 2015

The month of February 2015 is examined individually to present the data in a different form. This month contained 96% of all possible data for 26 days, resulting in an overall 89% of total data possible. Table 4.9 presents the average speeds for each day in February 2015. It can be observed in this table that the average speed in Lane 1 is between 52 and 64 mph and the average speed in Lane 2 is between 52 and 70 mph. For all days the speed in Lane 2 is greater than that in Lane 1.

To validate the speed estimations the weather during this period is examined. The historical data in Meriden, CT was reviewed using the website “weather underground.” (Weather Underground, 2015). According to the website it snowed on multiple days during this month. The days during which there was precipitation were February 2, 8, 9, and 26. The amount of melted precipitation from the four days was 0.28, 0.08, 0.10, and 0.01 inches, respectively. It can be observed that the average speeds were much lower than the monthly average on the days mentioned. Particularly on February 2, 8, and 9 the speeds were the three lowest for this month, likely due to the snow, which accumulated during this time.

Table 4.9: Average speeds per day for February 2015

Day	Average Speed Lane 1 [mph]	Average Speed Lane 2 [mph]
1-Feb	63.38	69.55
2-Feb	52.27	52.77
3-Feb	61.09	65.58
4-Feb	62.93	68.59
5-Feb	61.65	65.60
6-Feb	62.64	68.69
7-Feb	64.12	69.80
8-Feb	59.27	61.76
9-Feb	56.11	56.64
10-Feb	60.69	64.97
11-Feb	62.43	67.36
12-Feb	63.30	68.24
13-Feb	62.71	68.06
14-Feb	63.07	67.49
15-Feb	60.80	66.24
16-Feb	63.51	69.75
17-Feb	63.25	68.31
18-Feb	63.62	69.26
19-Feb	62.50	68.31
20-Feb	63.61	69.08
21-Feb	63.16	68.42
22-Feb	61.39	66.26
23-Feb	62.69	67.39
24-Feb	63.46	69.95
25-Feb	63.56	69.86
26-Feb	61.98	67.21
27-Feb	N/A	N/A
28-Feb	N/A	N/A

This method of examining the data does not account for factors such as vehicle crashes or traffic delays not caused by weather. The speeds for February 2nd are unusually slow, which could have been caused by factors other than weather, yet the largest snowfall occurred during this day.

4.6.4 Speed and GVW Calculation for February 13th, 2015

The speed for a 'typical' single day is further examined. The thresholds for Lane 1 are set between 40 and 80 mph, while the thresholds for Lane 2 are set between 40 and 90 mph, and it is possible that the averages are significantly affected by the thresholds. The average speed for Lanes 1 and 2 of 60 and 65 mph, respectively, are close to the averages determined by the methodology presented.

February 13th was chosen to be examined individually, a day during which no unusual weather conditions were observed. The amount of truck events detected for this day is 4,813, including vehicles with speed errors. Figures 4.11 and 4.12 show histograms of truck speeds detected for individual truck events for Lanes 1 and 2, respectively. It can be seen from the two graphs that the most common speed is close to 65 mph for both Lanes 1 and 2. However, Lane 1 has almost as many trucks travelling in the 60 mph range and similarly Lane 2 has the second most trucks travelling in the 70 mph range.

The GVWs for February 13, 2015 are also presented in a histogram form. Figures 4.13 and 4.14 show truck GVWs for Lanes 1 and 2, respectively. In Figure 4.13 two distinct truck event peaks can be observed at the 25 and 55 kip marks on the x-axis. These two peaks represent lighter and heavier vehicles, due to vehicle type and/or loaded and unloaded. The same two peaks can be observed in Figure 4.14, with the 25 kips mark being significantly higher than any other observed vehicle weight category. This seems to indicate that both lighter (e.g. 2-axle) and larger (e.g. 5-axle) unloaded trucks travel in the middle lane, which is a reasonable conclusion. Similarly, from these graphs an overall observation can be made that heavier trucks tend to travel in the slow lane, which is an expected traffic pattern.

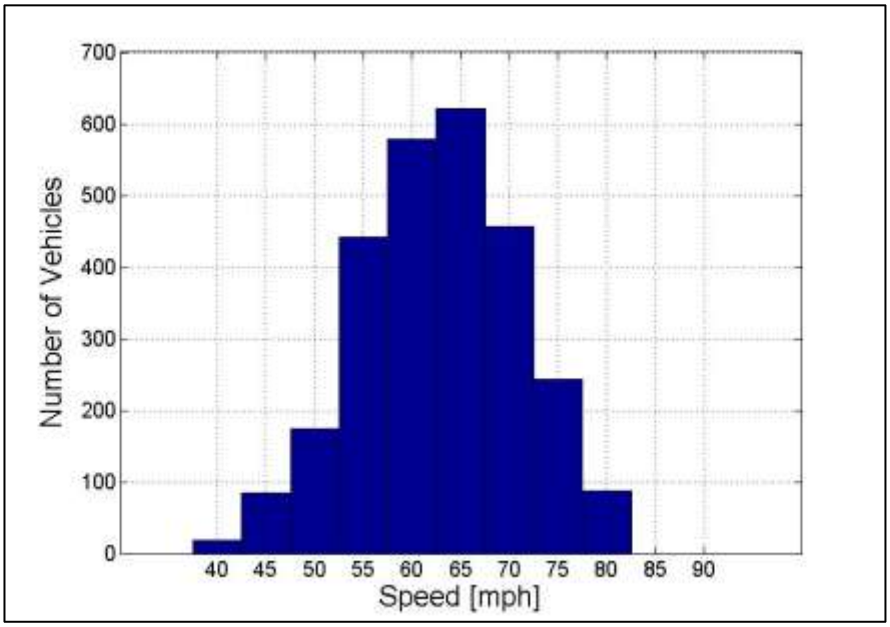

Figure 4.11: Lane 1 traffic speeds

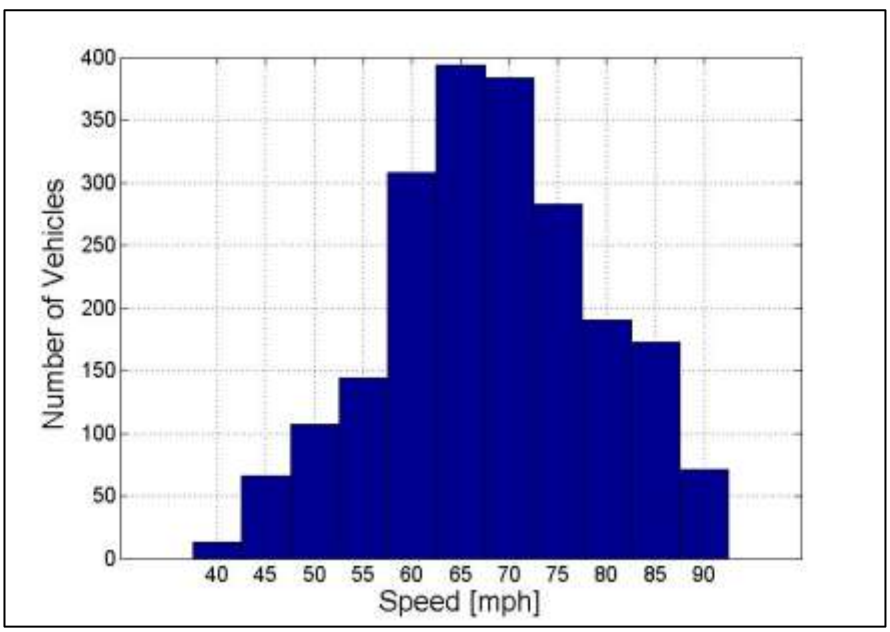

Figure 4.12: Lane 2 traffic speeds

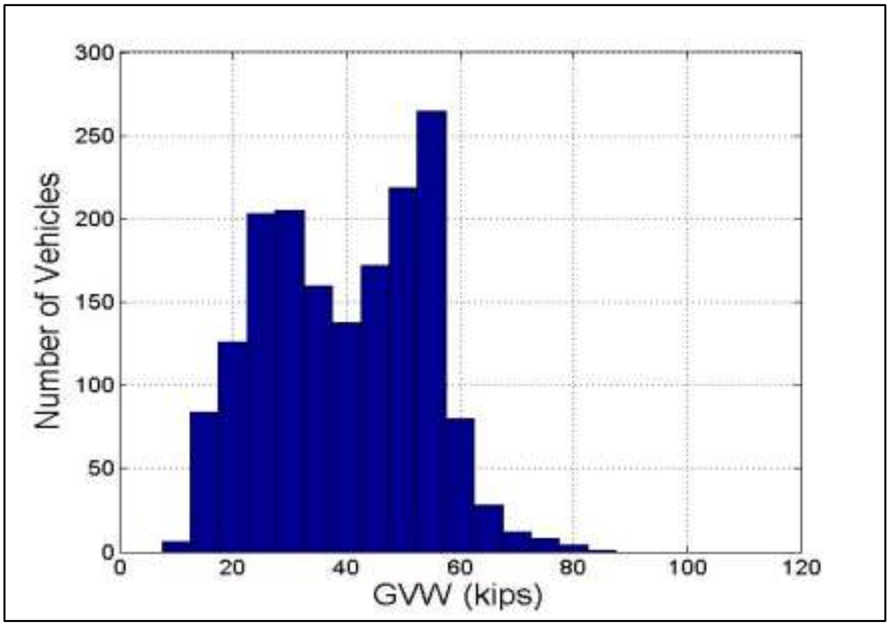

Figure 4.13: Lane 1 GVWs

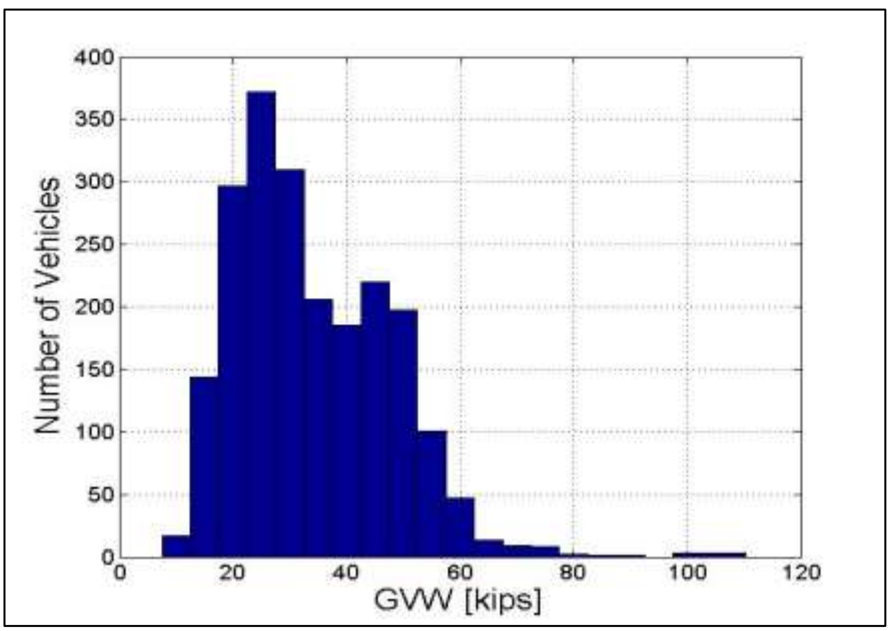

Figure 4.14: Lane 2 GVWs

4.6.5 Average Daily Truck events

The number of truck events registered by the BWIM system is presented. The events are computed for each day, after which all the days are averaged. If for a given day the entirety of data is not represented, additional data is added based on a percentage of the missing data. For example, on January 3, 2014, the total truck events registered by the BWIM system was 1,718. However, since only 80 percent of possible data was collected for this particular day an extra 20% of the registered truck events were added, resulting in a total estimate of 2,067 trucks. Out of this final amount an additional 10.95% is added to account for the capabilities of the BWIM system, which as discussed in previous chapters cannot collectthe data for 24 hours. It takes about seven seconds to save each five minute file of fourteen sensors and 306 seconds to save five minute files consisting of all sensors. Therefore for every 50 minutes of data there is about a six minute gap. The final amount of truck events for this day is 2,293.

This method of evaluating truck results can be misleading if an insufficient amount of data is collected. To address this the average daily truck events are only presented for months that contain more than 70% of data for the entirety of the month. A total of ten months contain this amount of data and are presented in Table 4.10. It can be seen that the Average Daily Truck Traffic (ADTT) is between 4,500 and 6,000 for all days. It should be noted that certain months are not represented in this table due to lack of data, including: April, June, July, August, and September. The two months that contain the largest amount of trucks are May and October, and it is likely that during the summer months larger amounts of freight are transported, since the construction industry is more active during this period. Consequently, months such as December, January, and February, are more likely to have a lower ADTT and these are most represented by the following data sets.

Table 4.10: Average Daily Truck Traffic

Month	Average Weekdays ADTT	Average Weekend | Holidays ADTT
October 2013	6002	2707
December 2013	5295	2345
January 2014	4581	2452
February 2014	5077	2727
March 2014	5480	2387
May 2014	6066	2510
December 2014	5405	2718
January 2015	4862	2425
February 2015	5257	2457

4.6.6 Speed Errors

Multiple types of speed errors can occur with variation of the strain response. In section 4.2 some cases are discussed. Applying the error variation to a data set this large is more difficult, and from the long-term data five different types of errors are identified and labelled. An error identifier type of 1, 2, 40, 80, or 90 is associated with each truck event.

Type 1 errors occurred very rarely when the peak strain occurred at the end of the 2.5 second time frame and a car or small vehicle was in front of this peak. Such a case can be seen in Figure 4.15. Type 2 errors occurred when the last peak of a strain was detected, but the strain after it did not reach a value low enough for the truck to be considered off the bridge. Such a case could exist, either because the vehicle was in a traffic delay or due to unusual vibrations. Figure 4.16 shows the strain response for such a case.

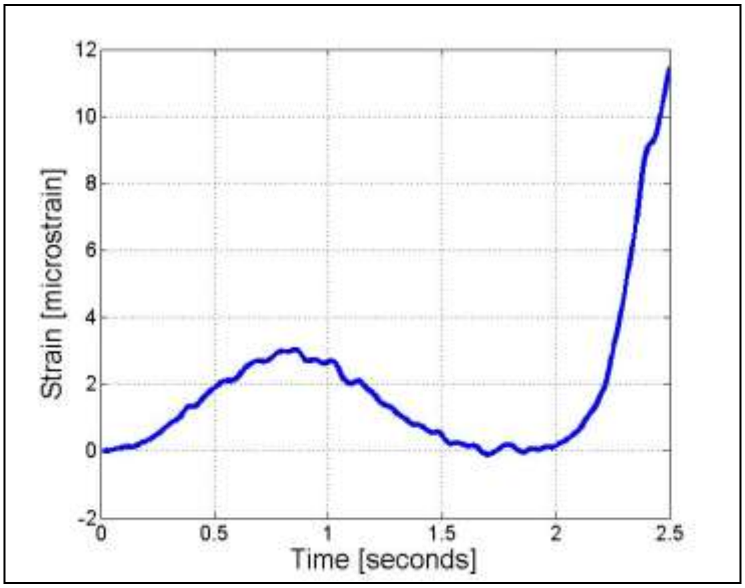

Figure 4.15: Truck followed closely by light vehicle, Error Type I

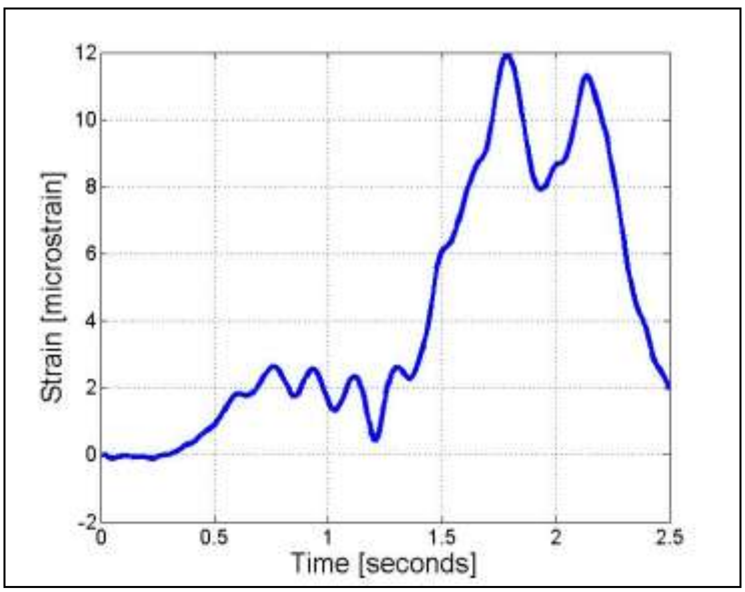

Figure 4.16: Truck record not captured by algorithm, Error Type II

Further types of errors include 40, 80, and 90. A Type 40 error corresponds to vehicles travelling slower than 40 mph. Unlike Type 2 errors, an actual speed is calculated for Type 40 errors. This can result from a false peak being identified as the last axle of the truck event. Type

80 and 90 errors correspond to the speed in Lane 1 exceeding 80 mph and Lane 2 exceeding 90 mph. These types of errors can occur from unusual vibrations caused by large accelerations, resulting in a false peak being identified as the last axle of a truck. The five categories of error presented do not account for two other possible errors discussed previously in Section 4.2, those being trucks changing lanes while crossing the bridge or errors due to low weight trucks.

The errors for each day are discussed below. Table 4.11 presents the average percent errors for each month for both weekdays, and weekends and holidays. The errors are presented as a percentage of total trucks.

Table 4.11: Average percent errors

Month	Average Percent Error for Weekdays [%]	Average Percent Error for Weekends | Holidays [%]
March 2013	18.60	9.74
April 2013	17.09	14.20
May 2013	17.96	12.92
June 2013	18.84	10.84
July 2013	18.44	13.05
August 2013	18.98	N/A
September 2013	20.13	12.71
October 2013	19.16	12.14
November 2013	20.99	11.73
December 2013	21.53	11.91
January 2014	19.06	11.53
February 2014	19.79	12.44
March 2014	18.09	10.48
April 2014	17.32	11.22
May 2014	18.51	11.58
June 2014	17.43	10.49
November 2014	18.26	12.96
December 2014	19.09	19.22
January 2015	18.58	14.70
February 2015	21.96	17.64

Table 4.12 presents the percentage of errors for each day in February, and type of errors observed. It can be noted in this table that error types 40, 80, and 90 are the most common. By examining February 2, 8, and 9, during which snow accumulated in the area, it can be noted that error types 80 and 90 are significantly lower than error types 40 and 2. This suggests that traffic delays occurred during these days, a reasonable suggestion given the accumulation of snow.

Table 4.12: Number of errors by type for days during the month of February 2015

Day	Percentage of Errors	Error 1	Error 2	Error 40	Error 80	Error 90
1-Feb	11.76	4	6	53	91	73
2-Feb	31.99	1	182	297	127	67
3-Feb	18.79	11	86	278	232	213
4-Feb	17.61	11	57	287	271	267
5-Feb	21.43	22	106	423	254	277
6-Feb	21.24	10	50	318	350	309
7-Feb	17.46	8	25	116	186	127
8-Feb	13.07	1	37	93	50	41
9-Feb	19.62	2	159	420	118	125
10-Feb	16.37	11	33	316	169	196
11-Feb	19.83	17	65	344	278	323
12-Feb	19.18	24	61	307	317	299
13-Feb	21.32	13	57	332	278	346
14-Feb	20.46	3	40	146	118	126
15-Feb	15.01	6	37	37	61	31
16-Feb	20.06	8	32	189	253	266
17-Feb	20.65	12	41	261	279	293
18-Feb	22.15	14	68	290	347	377
19-Feb	21.77	21	58	351	346	357
20-Feb	22.95	7	46	283	430	314
21-Feb	23.65	3	34	171	163	159
22-Feb	19.65	0	26	148	98	74
23-Feb	34.09	15	88	519	466	459
24-Feb	21.94	13	44	280	390	355
25-Feb	20.29	22	37	282	357	317
26-Feb	24.13	7	45	226	236	222

4.6.7 Effects on Algorithm Accuracy

To determine if changes in temperature have a significant effect on the algorithm accuracy, the effects of temperature on the calculated GVWs of truck events are examined, . The instrumented girders are made of steel, which deform less at lower temperatures; therefore, some reduction in the algorithm accuracy is likely.

In order to study the temperature effects, data for the month of March 2015 is analyzed. As can be seen from Table 3.1 March contains 95% of all possible truck data. Since temperature measurements are collected during five minutes of every hour using the RTD sensors presented in section 3.2, only a portion of the total trucks measured during this month can be evaluated for temperature. Figure 4.15 shows a scatter plot between temperature and GVW of individual trucks, represented by blue circles on the graph, for the month of March 2014. A line of best fit is plotted in red on the figure, which shows only a slight positive correlation between temperature and GVW. Only GVW data in the range of 10 to 80 kips is plotted in the graph, since a small amount of trucks measured heavier than 80 kips. This only slight positive correlation between temperature and GVW is an indicator that the BWIM system is nearly invariant to temperature.

To estimate the temperature during a truck event the average of three of the four RTD sensors instrumented on the bridge are taken, the fourth sensor having shown illogical results. A review of the website “weather underground” has shown that the temperature during March of 2014 was in the range of 13 to 56 degrees Fahrenheit for the city of Middletown (Weather Underground, 2015). This range matches the recorded temperature range shown in Figure 4.15, which confirms that the temperature estimation from the sensors is reasonable.

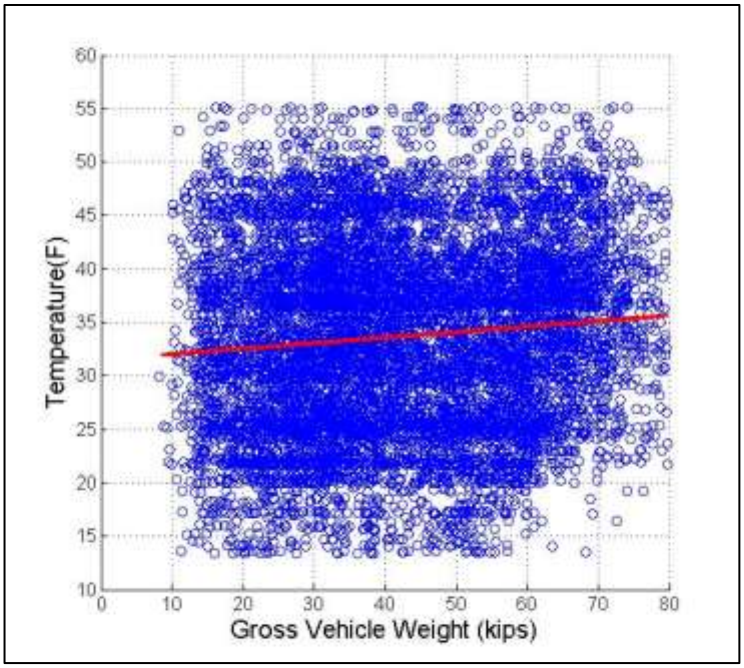

Figure 4.15: Temperature and GVW correlation

A slight positive correlation is seen between GVW and temperature for March of 2014. The positive line of best fit goes from 32 degrees Fahrenheit at 10 kips to 36 degrees Fahrenheit at 80 kips. The correlation shown between temperature and GVW is not significant and may very well be explained by a slight tendency for heavy trucks to travel during warmer temperatures for various reasons, perhaps related to delivery schedules, safety, or fuel efficiency.

5. CONCLUSIONS AND FUTURE WORK

A methodology for an existing BWIM system is presented and applied to three separate data sets including test trucks, free flowing traffic, and long-term traffic data. This methodology builds on findings from previous research and a new method is developed for calculating vehicle speeds.

A calibrated test truck trials experiment demonstrated that the proposed algorithm can accurately predict vehicle speeds, and that even if the speed is exact other factors can contribute to the inaccuracy of the algorithm. Applying this data to sampled trucks from free flowing traffic has shown that the system can identify vehicle GVWs within a certain confidence interval. Various types of cases are identified for which the methodology cannot function accurately, and a list of error types is developed and described.

A unique contribution of this research has been the application of this algorithm to a large continuous traffic data-set consisting of 385 days. Applying the methodology to long-term traffic data has provided much useful information about the type of traffic on the bridge, such as: the average speeds on the bridge; the ADTT for certain months; as well as percentages of errors that occur each month.

The type of data collected from long-term BWIM systems can be of extreme value to owners, operators and managers of infrastructure. Information on average speeds as well as the ADTT travelling on the bridge for certain months can be used to improve decisions regarding pavement and bridge design, and load rating analysis of bridges, as the ADTT is directly tied into those fields.

The GVW, speed, and time stamp of each identified truck has been saved and loaded to a website that can be accessed by representatives of the Connecticut Department of Transportation. Those reviewing the website are allowed to manipulate the data and draw general conclusions about the traffic pattern on the bridge. This can include identifying times with the heaviest traffic loads or similarly when the overweight vehicles are travelling over the bridge. Through this information improvement in weigh station operational efficiency might be improved.

Future work in BWIM research should continue seeking to identify the limitations of current sensing, acquisition, and algorithm technologies as applied to an increasingly broader type of bridges as well as truck behavior such as multiple vehicles and lane changes occurring on the bridge and offer corresponding solutions to move forward BWIM applications in Connecticut. Specifically, future BWIM research should include the development of a series of interconnected BWIM installations on major routes to monitor truck weights entering and leaving the State.

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