Advancing the State of Bridge Weigh-In-Motion for the Connecticut Transportation Network

Final Report

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Disclaimer

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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)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°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)		
°C	Celsius	1.8C+32	Fahrenheit	°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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Executive Summary

Bridge Weigh-In-Motion (BWIM) uses the dynamic response of a bridge to determine gross vehicle weight, speed, and axle spacing of truck traffic to quantify the loads in a transportation network. The advantage of BWIM is that it does not require installation of sensors in the pavement nor use any axle locators in the roadway. Research in BWIM methods has been conducted in Connecticut since 2004, with the goal of moving this technology closer to deployment in Connecticut. Benefits of BWIM can be realized for the design and management of pavements, and results in less risk and increased cost savings. Improved oversize/overweight truck permitting, bridge load rating, and truck re-routing all enable informed decisions and improved expectations of performance that translate into sound investment decisions for the Connecticut Department of Transportation (CTDOT). With this goal, this project has continued BWIM data collection at the Meriden (I-91) Bridge, making data collected since 2013 available to CTDOT in a queryable format, and providing a testbed for further improvement and understanding of BWIM data processing and bridge monitoring techniques in general. Further, the project has developed a portable monitoring system in two configurations that can be deployed for BWIM purposes in Connecticut, for single day or multiple month durations. As part of the project, these BWIM systems were deployed on various bridge types in Connecticut to identify best practices and to evaluate performance and potential for application by CTDOT. The project has moved the state of knowledge and practice of BWIM in Connecticut to enable deployment of this technology by CTDOT.

CHAPTER 1 Introduction

1.1. Motivation

A well-managed, healthy transportation network is vital to prosperity in the State of Connecticut. Critical to the healthy transportation network is the effective movement of people and goods on Connecticut's highways. To design, maintain and optimize the highway network, it is important to have accurate and reliable traffic data, and in particular, actual truck characteristics and weight data. Typically, truck weight data are collected at highway speeds using "weigh-in-motion (W-I-M)" technology. Current in-pavement methods to collect weight (WIM) data have limitations, including risk to workers in the work zone, dependence on pavement condition and pavement life, the influence of vehicle dynamics, as well as cost and accuracy. The category of WIM systems that use bridges to collect weight data is designated as bridge weigh-in-motion (BWIM). BWIM offers advantages to address some of the short-comings of traditional in-pavement WIM systems.

WIM data can be utilized for the design and management of pavements, oversize/overweight truck permitting, and determination of the need for bridge load rating and/or truck re-routing. The State of Connecticut uses WIM data to fulfill its responsibility to collect and submit truck weight data to the Federal Highway Administration (FHWA) for inclusion in the National Truck Weight Survey as part of the FHWA Traffic Monitoring Program (FHWA, 2013). Additionally, there is a direct need for WIM to sort vehicles for optimizing truck weigh station operations, as well as for the strategic deployment of enforcement operations. Engineers and planners at the Connecticut Department of Transportation (CTDOT) do not routinely use or seek actual truck weight data for a wide range of important applications, simply because of historic unavailability. As a result, many routine design methods are based on approximations and assumptions. Accurate and sufficient WIM data will enable improved design, more effective operations as well as greater efficiencies in numerous functional areas of the Department. Some of these functions include pavement design, highway and bridge maintenance, safety analyses, air quality, and noise analyses, freight planning, scheduling of construction activities, and operation of work zones. Quality WIM data can also assist in, characterization of supply-chain logistics, performance of economic analyses, allocation of funds, management of extreme weather events, as well as for asset management and performance measures. In recent years, the benefits of data-driven decision practices have been advocated by FHWA, AASHTO and TRB. The 'ground-truth' basis of accurate and reliable WIM data is instrumental to data-driven decision processes. For these reasons, the use of WIM data is encouraged and supported in Moving Ahead for Progress in the 21st Century Act (**MAP-21**) for many applications. (Tang, 2012; Strocko, 2013)

Many functional areas at CTDOT use guidelines that are built on 'presumed' or theoretical truck characteristics and truck loads. Truck vehicles' size and weight have changed considerably since the development of many of these models. For this reason, actual truck weights are important to verify the validity of models. This is true for infrastructure (bridges and pavements) as well as various other functions. The responsibility is on the CTDOT to determine the applicability of National guidelines for their purposes. For example, reliable truck weight data collected systematically through WIM systems could potentially be used to refine the load factors in the AASHTO Load and Resistance Factor Design (LRFD) bridge design and construction specifications. Nationally, bridge data has been organized in the National Bridge Inventory (NBI) from which a typical bridge configuration of a specific state can be statistically identified. Thus, the load factors in the AASHTO LRFD Specifications can be refined for each state based on state-specific truck weights, traffic volumes, and bridge configurations. The state-specific refinement of load factors for bridge design could result in uniform reliability and optimal design. Both the Michigan and Missouri DOT's have refined load factors and have proposed adjustment factors to increase the live load to account for heavy truck traffic in metropolitan areas (Van de Lindt et. al, 2006; Fu and Van de Lindt, 2006; Kwon et al, 2010).

The rise in fuel prices, concerns regarding economic competitiveness, as well as issues regarding dependence on oil have again prompted proposed changes to national vehicle size and weight limits. As required in the provisions of MAP-21 (P.L. 112- 141), the US DOT is conducting the 'Comprehensive Truck Size and Weight Limits Study' (MAP-21, §32801) (MAP-21, 2013) on alternative truck configurations to study and evaluate proposed national policies. In addition, significant changes to freight distributions were expected with the widening of the Panama Canal, completed June 2016, and the deepening of several Eastern U.S. Ports (Fountain, 2011). WIM data can enable CTDOT to prepare for and assess the impacts of these, which have been described (TRB, 2013) as 'game-changing' developments in U.S. freight.

1.2. Background

Bridge Weigh-In-Motion (BWIM) uses the dynamic response of a bridge to determine gross vehicle weight, speed, and axle spacing of truck traffic to quantify the loads in a transportation network.The advantage of BWIM is that it does not require the installation of sensors in the pavement nor use any axle locators in the roadway.A 2008 study by the Connecticut Academy of Science and Engineering (CASE) recommended that BWIM be considered to provide a more comprehensive WIM network in Connecticut (CASE, 2008).

The concept of using bridge response for calculating bridge weights has been around since the 1970s (Moses, 1979).Prototype systems were deployed in several states during the 1980's, which demonstrated their potential.Locations included the states of South Dakota, Washington and Kentucky. BWIM systems have been typically conducted under very limited circumstances: on bridges of short length, simply supported, with little skew, and with low traffic volumes.Advances in sensor technology, data acquisition, and computing systems provide excellent opportunities to address challenges that were faced during the early studies.

BWIM is used in Europe (Slovenia and France), under the current leading system called the SiWIM® System (SiWIM, 2013). SiWIM is a proprietary system developed in Europe for European bridges and trucks. After the 2007 International Scan Tour on "Commercial Motor Vehicle Size and Weight Enforcement in Europe" (Honefanger et. al, 2007) FHWA initiated the testing of the SiWIM system in collaboration with the Alabama DOT and University of Alabama to pursue applicability on a U.S. structure. Varying results from specific structures have been reported (Hitchcock et. al, 2009).

The State of Connecticut is well recognized for significant research on the testing of weigh-in-motion technologies and practices and the instrumentation and health monitoring of bridges. Collaboration between these cross-discipline areas of local expertise was initiated to address the need for truck weight data in Connecticut. National and international experience in WIM and bridge monitoring has enabled the principal investigators to receive input and cooperation from an extensive network of experts. These include Northwestern University, University of Alabama, University of Utah, as well as states (South Dakota, Kentucky, Washington) and countries (Slovenia, Ireland) that have generously shared first-hand experience and insight.

Exploratory work was initiated in 2004 to learn more about the feasibility and practicality of using bridges for WIM data collection in Connecticut. Early tests included the running of trucks of known weight at a location that was instrumented for bridge monitoring purposes (Cardini et. al, 2006). In November 2008, a field test was conducted using a portable bridge monitoring system (Wall et. al, 2009). The field test included identification of an ideal testing location: close to static weigh scales, simple bridge characteristics (flat, short, straight, single-span, steel-girder), high volume and diversity of trucks and truck weights, and access to utilities. The chosen location was I-91, northbound in Meriden. A test was conducted to investigate the feasibility of using a novel WIM method developed by the study principal investigators to calculate trucks weights using both trucks of known weight and samples from the traffic stream. Results from this test were extremely promising and were presented at the TRB 88th Annual Meeting in 2009 (Wall and Christenson, 2009).

Based on the promising feasibility results, a system was designed and deployed under Connecticut Research Project SPR-2265, "Development and Evaluation of a Dual-Purpose Bridge Health Monitoring and Weigh-In-Motion System for a Steel Girder Bridge," to test for both BWIM and bridge health monitoring (BHM). Due to the commonality of the sensors and system, it made logical sense to test the duality, and to leverage the mutual benefits. The test included five sensor types (two types of strain gages, two types of accelerometers and temperature sensors), strategically located, with a total of thirty-six sensors deployed (Christenson et. al, 2011). Acoustic and video capture devices were also added to the system. After the system was designed and preliminary tests were conducted, Phase II of the study was initiated, under Connecticut Research Project SPR-2271, to test the operations and conduct refinements to the system. A goal was to achieve ASTM E 1318-09, "Standard Specifications for Highway Weigh-In-Motion (WIM) Systems with User Requirements and Test Methods", (ASTM E 1318, 2009) results for an FHWA Class 9 test vehicle for Type III performance. Results from Connecticut's research were shared at the 6th International Conference on Weigh-In-Motion in 2012. The paper entitled "A Dual Purpose Health Monitoring and Weigh-In-Motion System for a Steel Girder Bridge" (Christenson et. al, 2012) received the Conference Best Paper Award.

This cutting-edge research utilized 'live' traffic on Interstate 91. As such, the sensors and system underwent the rigors and variability of actual field conditions. Tests were conducted in cooperation with the Connecticut State Police and the Connecticut Department of Motor Vehicles to gather matching data sets for comparison between the static weigh station data and the bridge response data. The data comparison against the range of trucks in the traffic stream was much more stringent than those of single test vehicles customarily conducted on WIM sites and offered the extraordinary opportunity to examine the bridge responses against the wide range of vehicles in the actual traffic stream.

Innovations of BWIM thus far in Connecticut include the use of two new sensors (one strain and one accelerometer) for a bridge application, a novel WIM calculation approach, a non-destructive magnetic sensor mount (later shared and used by Tufts University), recognition of the potential for the use of accelerometers for the calculation of speed, and the use of a microphone for bridge responses. Interestingly, outputs designed for the BWIM or the BHM have offered innovation to address the primary needs of the other purpose, as well. Such is the case in observations that suggest accelerometers may be used for the calculation of speed, subsequently improving weight calculation accuracy.

1.3. Research Objectives

In order to support and improve numerous CTDOT functions, accurate and reliable WIM data are needed to characterize trucks and loadings on the State's transportation network. It is preferable to collect these data non-intrusively and cost-effectively. BWIM provides the potential to meet these needs and to supplement traditional WIM sensors on the transportation network. The BWIM should, as identified at a March 10, 2014, CTDOT Bridge Weigh-In-Motion (BWIM) Stakeholders Meeting, provide accurate WIM data; be easy, safe, and quick to install and maintain; and be relatively inexpensive. Further, to get an understanding for the types of bridges that are well suited for BWIM and to offer options for deployment on the transportation network, a broad range of bridge types must be evaluated.

The CTDOT currently collects WIM data from piezoelectric and quartz piezoelectric sensor WIM systems at a limited number of locations. These in-pavement WIM systems present many challenges, including significant costs, installation complexity (logistics & safety), calibration requirements, maintenance needs and accuracy concerns. Many locations are not appropriate for the installation of in-pavement WIM sensors due to the high volume of traffic (safety of installation) or inadequate pavement and site conditions. The level of accuracy and uncertainty in the data produced from ceramic and polymer piezoelectric sensors may not be appropriate for many applications, such as, e.g., weight enforcement (Vaziri et. al, 2012). An inexpensive and easily installed BWIM system is desired that can provide accurate network data for periods of (at least) 1-2 years. This can benefit various technical areas within CTDOT including:

Pavements: Where data are needed for pavement management (network-level), as well as pavement design (project level). There is a strong need for classification data in addition to WIM data, with all data available in a format that can be easily queried.

Load Rating: Where it is useful to have information on loading for the network and has been suggested to instrument in-bound border locations (bridges) on each of the major (six) permit routes. There is also a need to validate LRF Code for certain structure types (specifically, concrete) using sensor data (strain data) from the BWIM system, and a direct need for reliable WIM data for load rating practices.

Bridge Design: Where verification of design loading assumptions and validation of designs can be achieved through the BWIM data.

Traffic Data Collection: Which would focus on producing the FHWA format for data submittals to FHWA, specifically to advocate for non-intrusive methods for worker safety and longevity of systems.

Enforcement: Where BWIM data would be useful as a scale sorter or for effective scheduling of weigh station operations.

Connecticut has 4,214 bridges, according to the 2013 National Bridge Inventory (NBI, 2016). Stringer/multi-beam or girder bridges make up 52% (2,173 of the 4,214 bridges) of the bridge inventory and steel bridges 53% (2,256 of the 4,214 bridges). However, for BWIM to be deployable throughout the State, a broad range of bridge types must be considered. This research considers BWIM application on different bridge types, including steel and concrete, and simple and continuous spans.

Three objectives are identified in this project to advance toward deployment of BWIM in CTDOT:

- To continue BWIM data collection at the Meriden (I-91) Bridge, making data available to CTDOT in a format that can be easily queried and allowing for improvement and further understanding of BWIM data processing.
- To develop a reliable, easy to deploy portable monitoring system for BWIM in Connecticut for 1-2 day deployments, as well as for 1-2 year deployments, as needed.
- To deploy a BWIM system on various bridge types in Connecticut and to identify best practices and evaluate performance and potential for application by CTDOT.

1.4. Benefits of Research on Bridge Weigh-In-Motion (BWIM)

Utilizing advancements in both sensor and data processing technologies, as well as innovative methodologies, the State of Connecticut has demonstrated it is feasible to collect actual truck weights by a "non-intrusive" system using an instrumented bridge. The CT BWIM system offers several advantages to traditional WIM systems, including:

*Safety:The s*afety of workers and the traveling public is paramount in any traffic data collection. The Connecticut BWIM system is completely "non-intrusive" (a.k.a. NOR "Nothing-On-The-Road" (Jacob, 2002), where all sensors and associated equipment can be located under the bridge and off the roadway. This increases the safety of the workers installing and maintaining the system by allowing them to remain out of the traffic and provides safety to the traveling public by minimizing the disruption to traffic flow.

Less Dependent on Pavement Condition/Life: Due to the longer sensing time while a truck is on the bridge platform, BWIM systems are less susceptible to both vehicle dynamics and pavement road profile and condition. Sensors do not need to be replaced when the pavement is rehabilitated and accuracy is not dependent upon the pavement condition.

Discrete: BWIM provides the added benefit of not being visible to the motoring public. Driver behavior can potentially be altered at WIM sites when there is awareness of the system, and this can skew the collected data. The discrete attribute lends itself well for employment as a virtual WIM.

The benefits of BWIM can only be realized when the system is applied to suitable bridges. It is not envisioned that the CT BWIM system will be applicable to all of the 4,218 bridges in Connecticut, however the study has allowed for a better understanding of which bridge types and what coverage BWIM might provide on the State-owned 7,700 bi-directional miles of roadway in Connecticut.

Benefits can also be realized for the design and management of pavements. Traffic data is a critical piece of information in design and analysis of pavements as deterioration and damage of pavements is most affected by heavy truck traffic (NCHRP 1-37A, 2004; Lu et. al, 2007). Due to an exponential relationship between load and pavement deterioration, (e.g., one heavy truck is equivalent to 10,000 passenger vehicles for accumulated road damage), characterization of traffic is particularly critical. Correct measurement and estimates of loading result in less risk to CTDOT, and cost savings from appropriately designed pavements that extend pavement life. Improved oversize/overweight truck permitting, bridge load rating and truck re-routing all enable informed decisions and improved expectations of performance that translate into sound investment decisions for CTDOT. Overall, improved network and project-level truck characteristics and weight data can enable improved practices throughout CTDOT for a healthy transportation network.

CHAPTER 2 Research Approach

This project demonstrated the ability to identify the speed and weight of truck traffic by monitoring strain measurements of various in-service highway bridges. The study also examined and demonstrated abilities for:

- collection and archiving of BWIM data on a three-lane single-span 85 ft. steel girder bridge monitored since March 2013.
- measurement of strain with a sensor attached directly to concrete on a two-lane single-span 95 ft. prestressed concrete girder bridge.
- calculation of shear strain from a (normal) strain rosette mounted on a five-lane 100 ft span of a multi-span continuous steel plate girder bridge: and
- deployment of a solar powered BWIM system intended for week or even month-long deployments on a five-lane 100 ft. single span steel girder bridge.

The monitoring done in this research successfully demonstrated the applicability of BWIM to a broader range of bridge types in Connecticut. This chapter details the bridges and monitoring systems examined for this project.

2.1. Meriden Bridge (CT Bridge No. 03051)

The Meriden Bridge, CT Bridge No. 03051, is a three-lane bridge, which carries Interstate 91 (I-91) Northbound over Baldwin Avenue in Meriden, Connecticut. The bridge has a total length of 85 ft., a width of 55 ft., and a bridge skew angle of 11.5˚. According to CTDOT, the bridge carries average daily traffic of 57,000 vehicles with 7% (3990) of those being trucks (Li, 2014). A photo of the east elevation of the bridge is provided in Figure 2.1. The bridge dimensions of interest for this study are provided in Figure 2.2.

Figure 2.1: East elevation of the Meriden Bridge, I-91 Northbound (Wall et al, 2009)

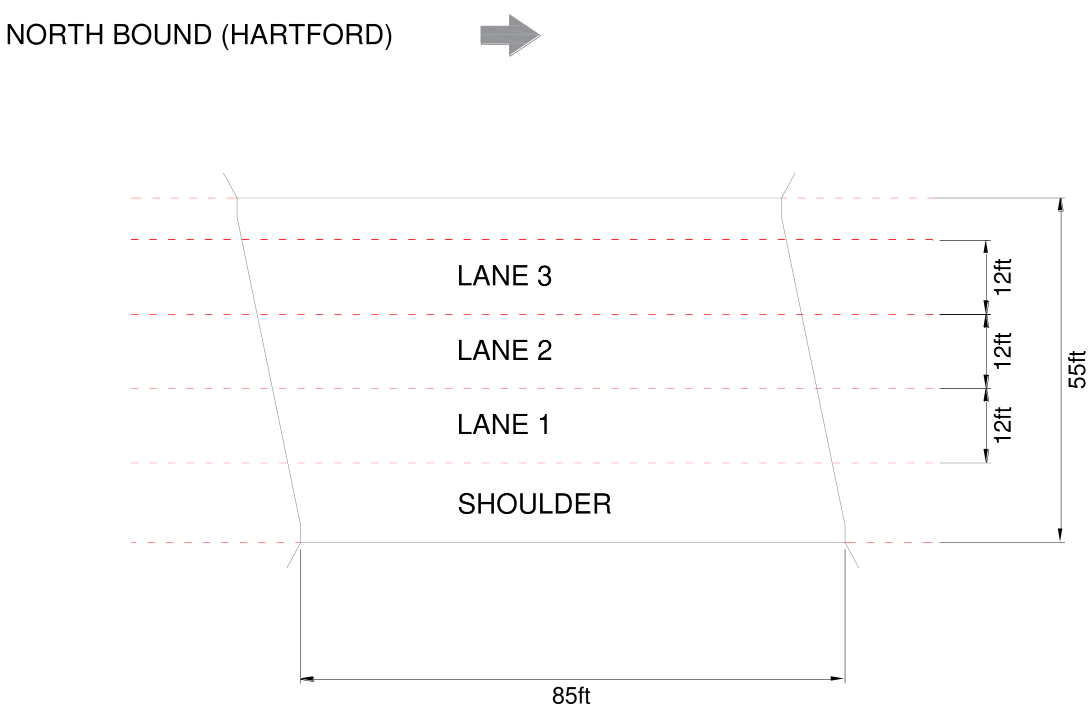

Figure 2.2: Meriden Bridge plan view

A monitoring system was instrumented on the Meriden Bridge in 2013 during a previous phase of this research (Christenson and Motaref, 2016). A total of 38 sensors and one microphone were installed on the bridge, including:

- 18 foil strain sensors,
- four high sensitivity quartz strain transducers,
- eight piezoelectric accelerometers,
- four capacitive accelerometers, and
- four resistance temperature detectors (RTDs)

Figure 2.3 shows the location of the strain sensors used for BWIM on the Meriden Bridge.

For the purpose of this study, only two of the 22 strain sensors identified in Fig. 2.3 are used. These sensors are located at the center of Girders 3 and 5. Both sensors are installed on the web of the girder, just above the bottom flange, and measure horizontal strain in the girders. Girders 3 and 5 are located almost directly under the slow lane and middle lane of the highway, respectively. The Meriden Bridge has a total of three lanes; however, very few trucks travel in the far left (fast) lane, as they are generally prohibited from using this lane. As a result, data was only collected for the right and middle lanes. It was expected that the girders discussed would experience the greatest strain measurements from each corresponding lane at the mid-span of the bridge. Henceforth, the middle lane will be referred to as Lane 2 and the slow (right) lane as Lane 1.

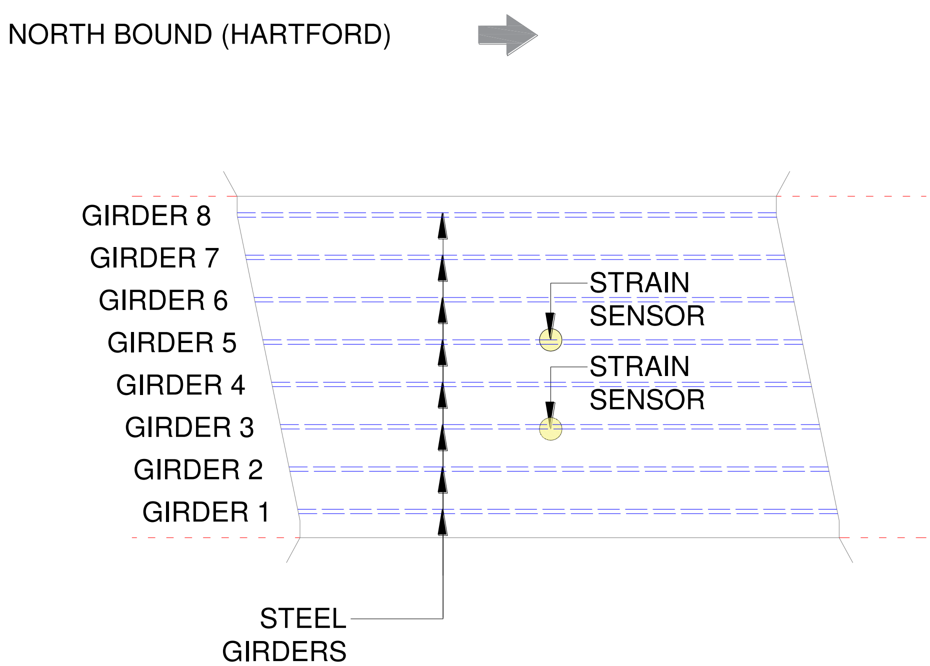

Figure 2.3: Schematic of sensor layout and types for the Meriden Bridge

The strain sensors are branded Vishay® Micro-Measurements, and the data acquisition unit is a National Instruments (NI) NI cDAQ-9178 (CompactDAQ) (Li, 2014). The CompactDAQ 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. Vibration responses of the Meriden Bridge are collected continuously, and an external 2 TB hard drive is used to store the data. A remote internet connection is established with the desktop using a Digi WAN 3G Wireless router from Sprint, which allows for remote access to the desktop.

The gross vehicle weight (GVW) is found by relating a known GVW from a calibration vehicle to the unknown GVW of a vehicle of interest, as adopted in previous BWIM studies in Connecticut (Wall et. al, 2009). This method was developed by Ojio and Yamada (2002). Based on the assumption that the bridge remains elastic, this method equates the quotient of the influence area to the GVW of a truck of known characteristics to the one correspondent to an unknown truck, as stated in Eq. [1].

$$\frac{A_k}{GVW_k} = \frac{A_u}{GVW_u} \qquad [1]$$

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

$$GVW_u = A_u\beta \qquad [2]$$

The influence area of a moving truck is a function of strain with respect to distance, $\varepsilon(x)$ as, expressed in Eq. [3].

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

Assuming that the truck travels at a constant speed, Eq. [3] is modified to obtain

[4]

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

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

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

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

The method to determine the vehicle's speed from the strain measurement uses the peak 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, assuming that the truck travels at a constant speed. Because the strain does not necessarily go to zero due to adjacent or following vehicles, or bridge dynamics, a sufficiently small strain is used that corresponds to the vehicle nearing the end of the bridge. The speed calculation is given as:

$$v = \frac{L}{2t} \quad [6]$$

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 the mid-span of the bridge to the end.

Data was collected over the duration of this project and are aggregated in a searchable database and displayed on a password-protected Web site. The underlying data aggregation and display technology were developed at the Northwestern University Infrastructure Technology Institute, where long-term remote performance monitoring at 27 different in-service transportation and related infrastructure projects was supported. The database and display technology is (1) scalable, able to support an arbitrary number of monitored structures/facilities, each with an arbitrary number of measurement and data collection devices; (2) extensible, able to accommodate new data streams without the need to rewrite storage and display logic, as well as able to support new display logic without the need to rewrite conversion or storage logic; and

(3) adaptable: able to accept plug-ins to read input data from a variety of source formats and export data into other formats for external analysis (Kosnik, 2012a).

Northwestern University developed a Web-enabled database and display technology have been used to compare dynamic responses of diverse structures to stimuli such as live loads crossing a bridge, ground-borne vibrations from blasting a nearby quarry, and everyday habitation activity in an occupied building (Kosnik and Dowding, 2014). In addition, the technology was employed as part of a combined weigh-in-motion and structural monitoring system deployed on a regionally important truck route in Wisconsin. At that site, the Web-enabled database/display technology aggregated data from a commercial in-pavement weigh-in-motion system and research-oriented bridge monitoring system to evaluate effects of beyond-design-basis truckloads on the performance of the subject bridge (Kosnik, 2012b).

The scalable nature of the Web-enabled database supports archiving and allows for the searching of tens of thousands of records obtained at the Meriden BWIM site. Data are stored for the raw strain time histories upon which the BWIM calculations are made and for the summarized data/calculations for each truck (e.g. lane, GVW, speed). This approach supports retrieval and display of individual records, as well as preparation of summaries by month, year, and/or for the project as a whole.

The Web-enabled database and display technology may be extended to accommodate data analysis and visualization schemes, to support specific project goals. Currently, the web site supports visualization of strain time histories and tabular output of other data. If desired, the site may be extended to visualize other data in support of research goals.

In terms of adaptability, the Web-enabled database supports the export of data in customized formats. In the case of the Meriden Bridge, the data is exported in the prescribed FHWA traffic monitoring format to enable comparison of the BWIM data to data from fixed weigh stations and in-pavement WIM, statewide. Previous applications of adaptable output include the export of data to support a statistical process control approach for the detection of changes in the response of instrumented structures (Kosnik et al., 2014).

2.2. Lebanon Bridge (CT Bridge No. 01865)

The Lebanon Bridge, CT Bridge No. 01865, is a two-lane bridge, which carries Connecticut State Highway Route 2 (CT-2) Westbound over Camp Mooween Road in Lebanon, Connecticut. The bridge has a total length of 94ft, a width of 46ft and a bridge skew of 11˚. It is a single-span bridge constructed with six prestressed concrete girders and a reinforced concrete deck. According to a CTDOT April 2016 inspection report, the bridge carries anaverage daily traffic of 11,900 with 6%

(714) of those being trucks. A photo of the south elevation of the bridge is provided in Figure 2.4. The bridge dimensions of interest are provided in Figure 2.5.

Figure 2.4: South elevation of the Lebanon Bridge, CT-2 Westbound (Google Maps, 2017)

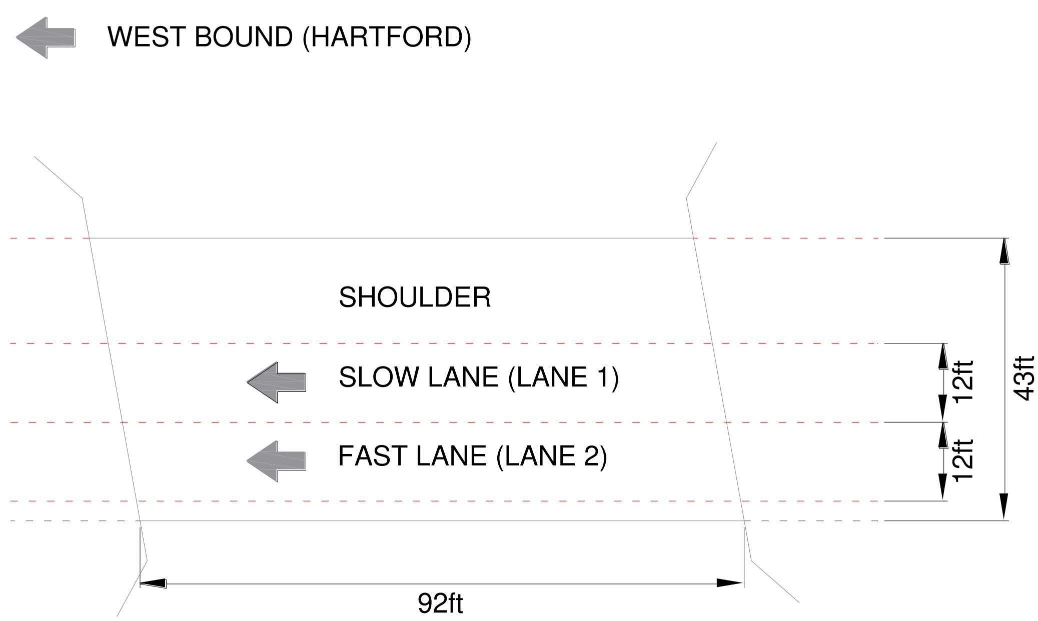

Figure 2.5: Lebanon Bridge plan view

A Bridge Diagnostics Inc. (BDI) STS4 portable monitoring system was used to measure the bridge data. Two BDI ST350 strain transducers were installed on the bridge. They were installed at the midspan of the bridge on the bottom flange of girders 2 and 3. Figure 2.6 shows the location of the two strain sensors relative to the lanes of travel on the bridge. It should be noted that, because of the wide shoulder (as shown in Figure 2.5), girder 2 lies beneath Lane 2 and girder 3 does in fact lie beneath Lane 1. Each sensor is wired to a sensor node that in turn provides a wireless hop to a base station and a second wireless hop to a laptop controlling the system and collecting data.

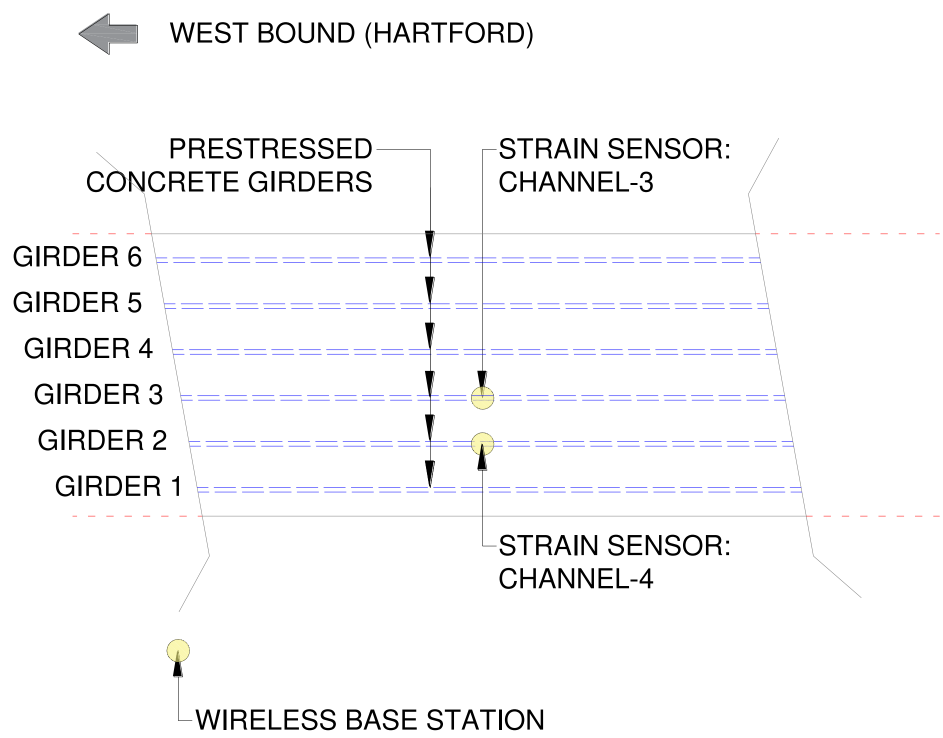

Figure 2.6: Schematic of sensor layout for the Lebanon Bridge

To account for nonhomogeneous concrete material properties the strain sensors are outfitted with extenders to provide for a measure of strain over a greater length, thus reducing the effect of aggregate materials as well as any cracking. A picture of the strain sensor with the extender is shown in Figure 2.7.

Figure 2.7: Strain sensor with extender to be used on concrete material

2.3. Stiles Street Bridge (CT Bridge No. 00174A)

The Stiles Street Bridge, CT Bridge No. 00174A, is a five-lane bridge, which carries Interstate 95 (I-95) Northbound over Stiles Street in New Haven, Connecticut. The bridge is on the downstream approach to the Pearl Harbor Memorial Bridge with no on or off-ramps between the Pearl Harbor Memorial Bridge and itself, such that all northbound traffic on the Pearl Harbor Memorial Bridge also passes over this bridge. The bridge has a total length of 104ft and a width of 86ft. It is a continuous span bridge constructed with seven steel girders and a reinforced concrete deck. According to CTDOT, the bridge carries average daily traffic of 65,950 vehicles, with 11% (7,255) of those being trucks. A photo of the south-facing elevation of the bridge is provided in Figure 2.8. The bridge dimensions of interest are provided in Figure 2.9. A challenge for using BWIM on continuous span bridges is the influence on the measured strains in the span being monitored from vehicles on adjacent spans. This influence can reduce the performance and accuracy of the BWIM system for this class of bridge (continuous span). As such, this study examines the ability to measure the shear strain using a rosette of standard strain sensors. The shear strain can then provide an alternative means to calculate GVW that is less sensitive to vehicles on adjacent spans.

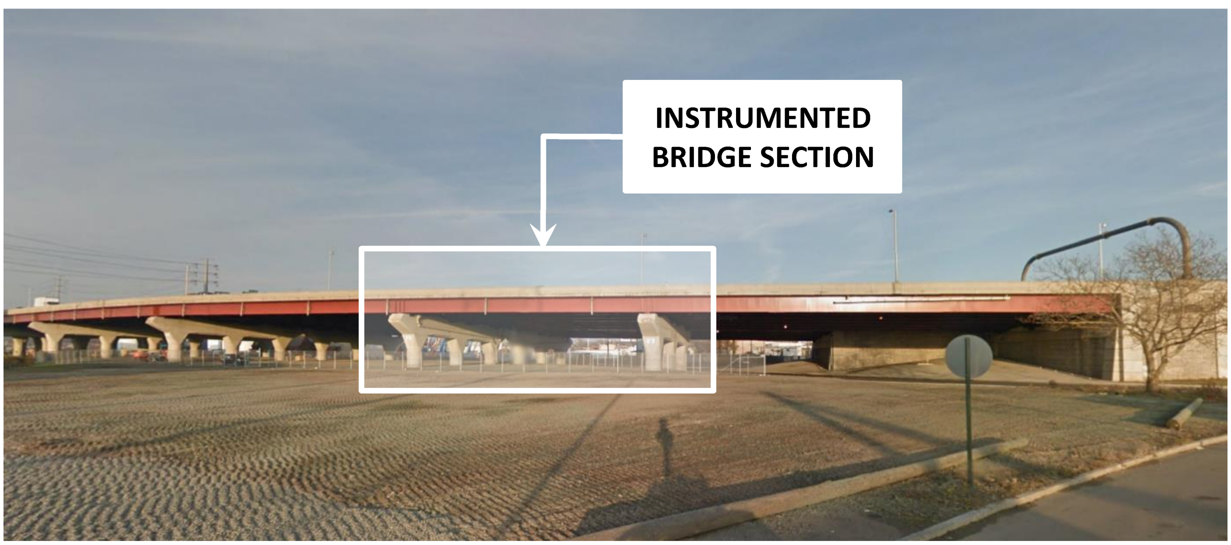

Figure 2.8: South elevation of the Stiles Street Bridge, I-95 Northbound (Google Maps, 2017)

Figure 2.9: Stiles Street Bridge plan view

A Bridge Diagnostics Inc. (BDI) STS4 portable monitoring system was used to measure the bridge data. Twelve BDI ST350 strain transducers were installed on the bridge. They were installed at the one-third span location on the second span from the right (Figure 2.8) of the bridge on the bottom flange of girders 2 and 4. For this bridge, two strain rosettes are applied on each side of the two girders being studied. This is done to measure any out-of-plane bending that may be occurring and compensate for it by averaging the results of the two strain sensor rosettes. Figure 2.10 shows the location of the two pairs of strain sensor rosettes relative to the lanes of travel on the bridge. Each rosette consists of three strain sensors oriented at 45 degrees from one another, as shown in Figure 2.12, and wired to a sensor node that in turn provides a wireless hop to a base station located under the bridge and a second wireless hop to a laptop controlling the system and collecting data.

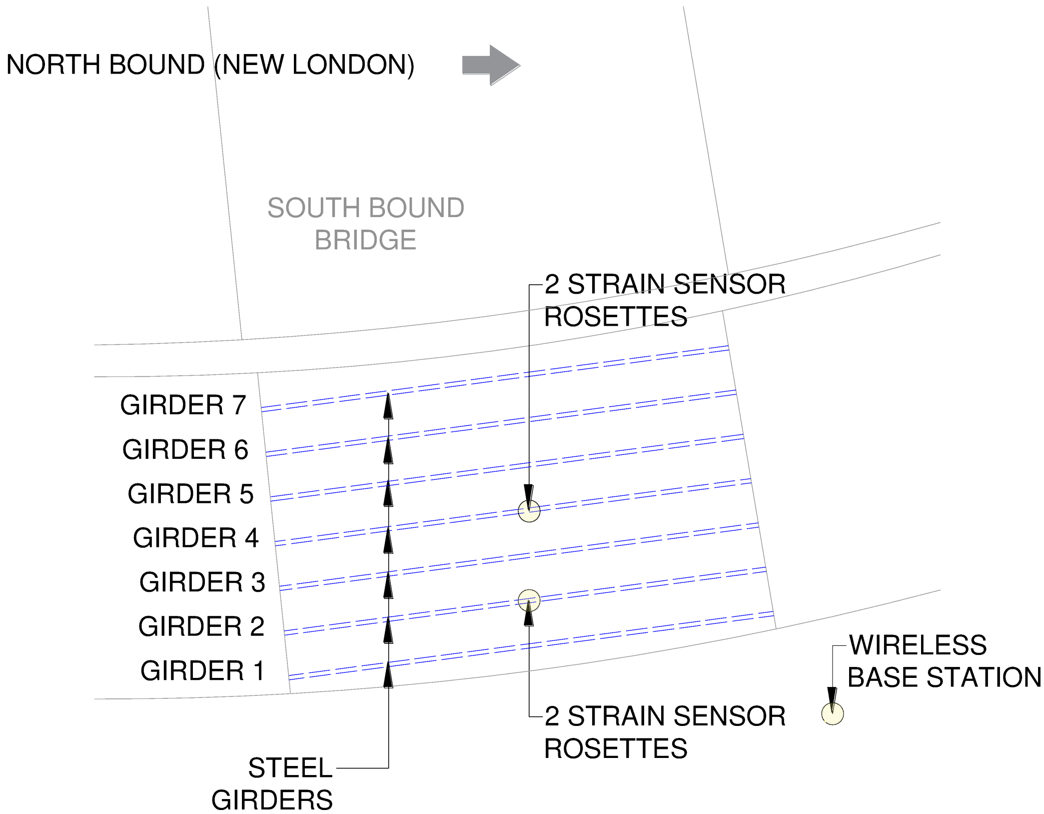

Figure 2.10: Schematic of sensor layout for the Stiles Street Bridge

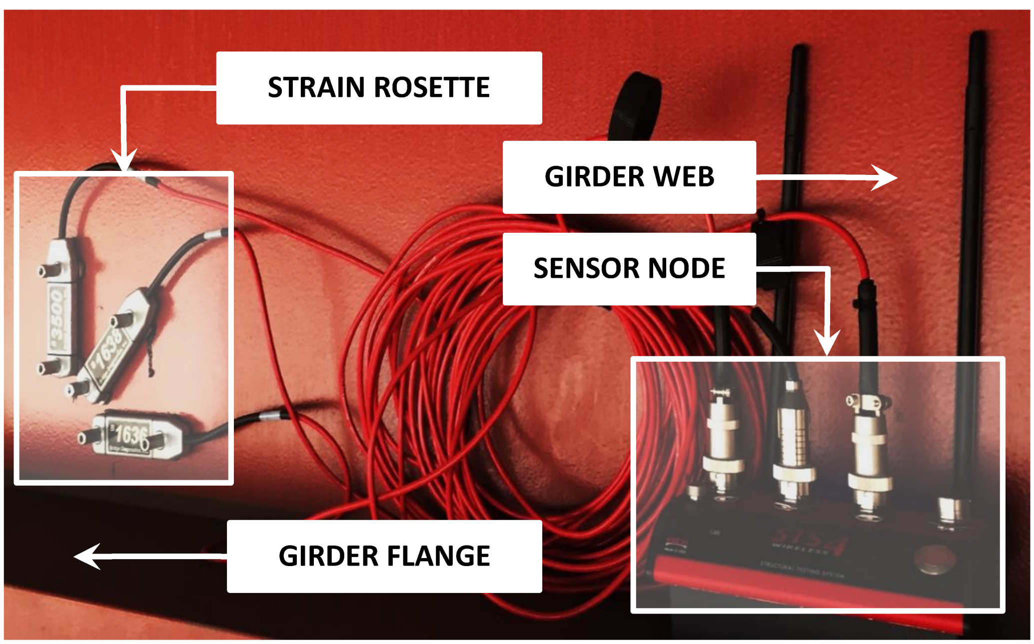

Figure 2.11: Photo of strain rosette used to calculate shear strain for Stiles Street Bridge

The identification of gross vehicle weights from shear strain measurements is based on mechanics of materials and Mohr's circle theory. Consider a simplified beam model of the bridge, where the individual axle load P is applied at a distance x from the left support of a simply supported beam of length L. The shear force diagram generated by this force is shown in Figure 2.12.

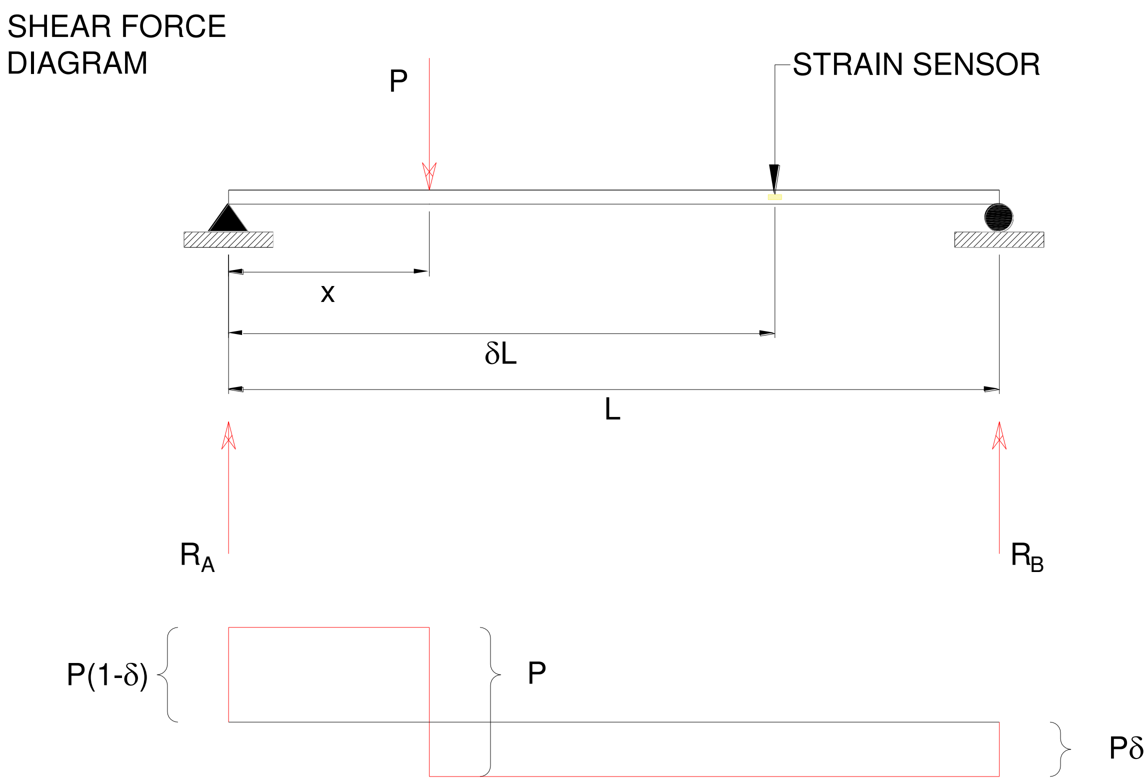

Figure 2.12: Shear diagram of a point load located a distance x from the left support.

If the individual axle moves along the beam (and dynamic effects are ignored), the theoretical influence line for the internal shear force V, measured by a sensor located at a distance δL from the right end can be obtained from the influence line for shear shown in Figure 2.13.

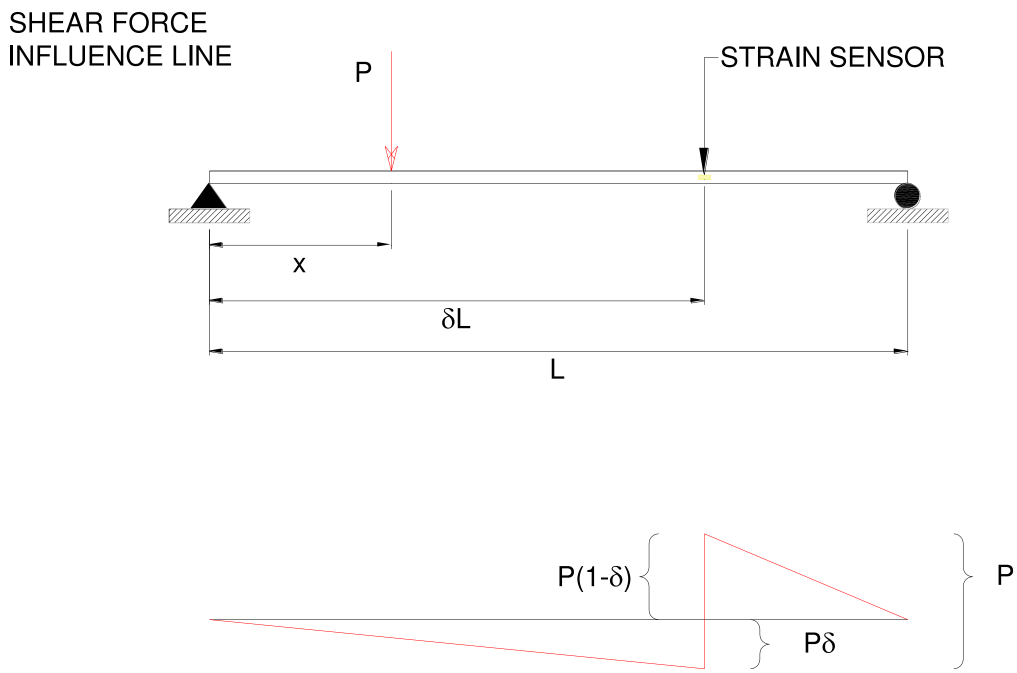

Figure 2.13: Shear influence line of the shear force, measured at a distance δL from the right support.

Mathematically, such theoretical influence line is expressed as

$$V(x) = \begin{cases} \frac{-P}{L}x & 0 < x < \delta L \\ \frac{-P}{L}x + P & \delta L < x < L \end{cases} \quad [7]$$

When the shear is evaluated at a distance $x = \delta L$, it is obtained

$$V^{-}(\delta L) = -P\delta$$
$$V^{+}(\delta L) = P(1 - \delta) \quad [8]$$

which means that

$$P = V^{+}(\delta L) - V^{-}(\delta L) \qquad [9]$$

which is consistent with the discontinuity showed in Figure 2.13. This change in shear stress corresponds with the load transmitted by the axle. The transition of the load from the position $V^{+}(\delta L)$ to the position $V^{-}(\delta L)$ can be also interpreted as a the movement of the load from a position x^{-} to another position x^{+}, or

$$P = V(x^{+}) - V(x^{-}) \qquad [10]$$

Now, the average shear strain generated by a shear load, $V(x)$, calculated at a certain location from the neutral axis of the beam is equal to that shown in equation [11].

$$\tau(x) = \frac{V(x)Q}{It_b} \qquad [11]$$

where Q is the first moment of area of the portion delimited by the fiber in consideration and the top fiber, I is the second moment of area of the cross section of the beam, and t_b is the thickness of the beam at the location where the shear stress is calculated. Then, combining equations [10] and [11], it is obtained

$$P = \frac{It_b}{Q}\tau(x^{+}) - \frac{It_b}{Q}\tau(x^{-}) \qquad [12]$$

For a given fixed sensor location, the geometric parameters are constant. Then,

$$P = \frac{It_b}{Q}[\tau(x^+) - \tau(x^-)] \qquad [13]$$

Furthermore, assuming that the load travels at a constant speed, v, and acknowledging that $x = vt$, Equation [13] is rewritten as

$$P = \frac{vIt_b}{Q}[\tau(t^+) - \tau(t^-)] \qquad [14]$$

Now, the behavior of a real life girder is complex, and therefore, it is not easy to properly define accurate values for Q, I and t_b from mathematical models. However, if the structure remains linear, it is possible to combine these parameters into a single calibration factor, which is called herein as α. This constant that can be found experimentally utilizing a truck with known axle loads passing over the bridge. This α constant is analogous to the factor β used for the normal strain measurement technique presented previously. Then, Equation [14] can be expressed as

$$P = \alpha[\tau(t^+) - \tau(t^-)] \qquad [15]$$

Equation [15] shows that it is possible to establish a proportional relationship between the shear stress measured from a strain rosette in the bridge girder and the loads that travel over the bridge. However, for the calculation of the gross vehicle weight it is necessary to use the superposition principle. For this, consider the theoretical influence line for the shear force generated by a train of loads, as shown in Figure 2.14.

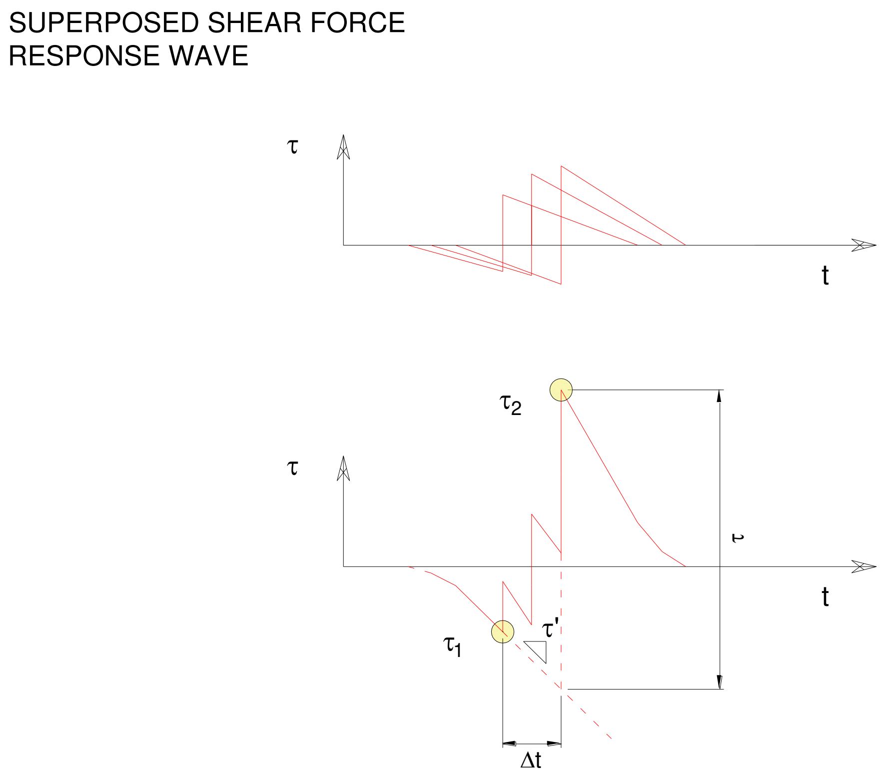

Figure 2.14: Superposed shear influence lines for a truck.

In this figure τ_1 and τ_2 are the extreme shear stresses captured on the record, Δt is the time between them and $\tau_1{}'$ is the slope at τ_1. Using these values it is possible to estimate the total change in the shear by assuming that total change in the shear stress would be obtained from the prolongation of the stress τ_1 over Δt as $\Delta t\, \tau_1{}'$. Then, the proposed GVW calculation is estimated as

$$GVW = \alpha[(\tau_2 - \tau_1) + \Delta t\, \tau_1{}'] \qquad [16]$$

where α is the calibration factor mentioned before.

Now, in order to use Equation [16] it is necessary to properly measure the shear strains. There are no existent ways to directly measure the shear strains and stresses. Therefore, it is common practice to approximate the shear strains and stresses by means the use of sensor rosettes. Figure 2.11 shows how the rosettes were placed on the bridge's girders. The measurements provided by the sensors produce the (normal) strains ε_A, ε_B and ε_C, according to the diagram shown in the Figure 2.15.

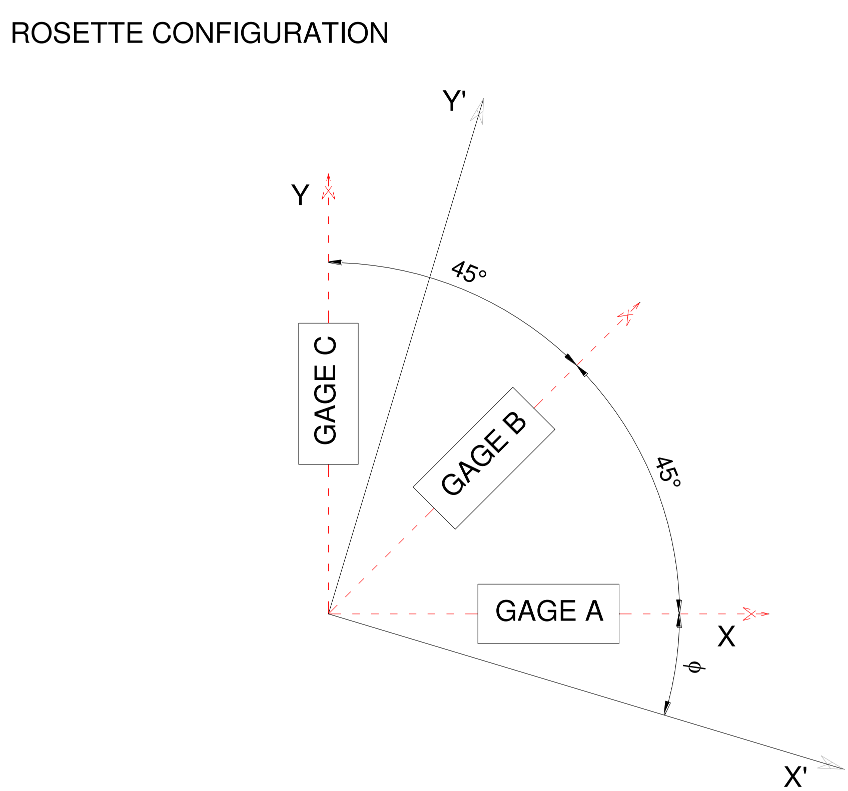

Figure 2.15: Orientation of strain sensors in the rosette configuration used on Stiles Street Bridge

In this configuration, ϕ is the angle between the axis of Gage A, which is parallel to the flange (horizontal), and the plane at which the principal strains (and correspondingly stresses) are located. Using these strain measurements, it is possible to apply the theory of Mohr's circle to obtain the principal (normal) strains and orientation of the principal strains with equations [17]

$$\varepsilon_1 = \frac{(\varepsilon_A + \varepsilon_C)}{2} + \sqrt{\frac{(\varepsilon_A - \varepsilon_B)^2 + (\varepsilon_B - \varepsilon_C)^2}{2}}$$

[17]

$$\varepsilon_2 = \frac{(\varepsilon_A + \varepsilon_C)}{2} - \sqrt{\frac{(\varepsilon_A - \varepsilon_B)^2 + (\varepsilon_B - \varepsilon_C)^2}{2}}$$

$$\phi = \arctan\left(\frac{2\varepsilon_B - \varepsilon_A - \varepsilon_C}{\varepsilon_A - \varepsilon_C}\right)$$

It is noteworthy to mention that this rosette configuration will give the principal stresses for any orientation of the rosette. This means that the Gage A does not necessarily have to be horizontal as long as the relative locations of the other gages are consistent with Figure 2.12, oriented at 45 degrees from one another. However, of interest is the shear strain in the vertical plane of the girder, so the desired orientation of Gage A is parallel to the flange, orthogonal to the vertical plane.

Assuming that the loading on the bridge does not produce inelastic behavior, it is possible to apply Hooke's law to obtain the principal stresses from the principal strains as in equations [18]

$$\sigma_1 = \frac{E}{(1-\upsilon^2)}(\varepsilon_1 + \upsilon\varepsilon_2)$$
$$\sigma_2 = \frac{E}{(1-\upsilon^2)}(\varepsilon_2 + \upsilon\varepsilon_1) \qquad [18]$$

In this case, it is assumed that the modulus of elasticity is $E = 29000\ ksi$ and that the Poisson's ratio is $\upsilon = 0.30$ for the steel girders. To account for possible out of plane bending that might be occurring in the bridge girder for any number of reasons, the principal stresses are measured on both sides of the web of the bridge girder and averaged. Using Mohr's circle theory again, the maximum shear stress τ_{max} can be found to be as shown in equation [19].

$$\tau_{max} = \frac{(\sigma_1 + \sigma_2)}{2} \qquad [19]$$

The shear stress given by Equation [19] shows that, by means of the rosette, it is possible to measure the maximum shear stress that is expected to occur at a specific location of the beam. However, in order to relate the shear measurement to the loads on the bridge, of interest is the shear stress produced by the axle loads of trucks crossing the bridge, which is the shear stress in the vertical plane. The shear strain in the vertical plane (assuming Gage A is oriented horizontally) is determined using equation [20].

$$\tau = \tau_{max} \sin \phi \quad [20]$$

This relationship can be formulated using Figure 2.13 below, and standard mechanics of materials theory.

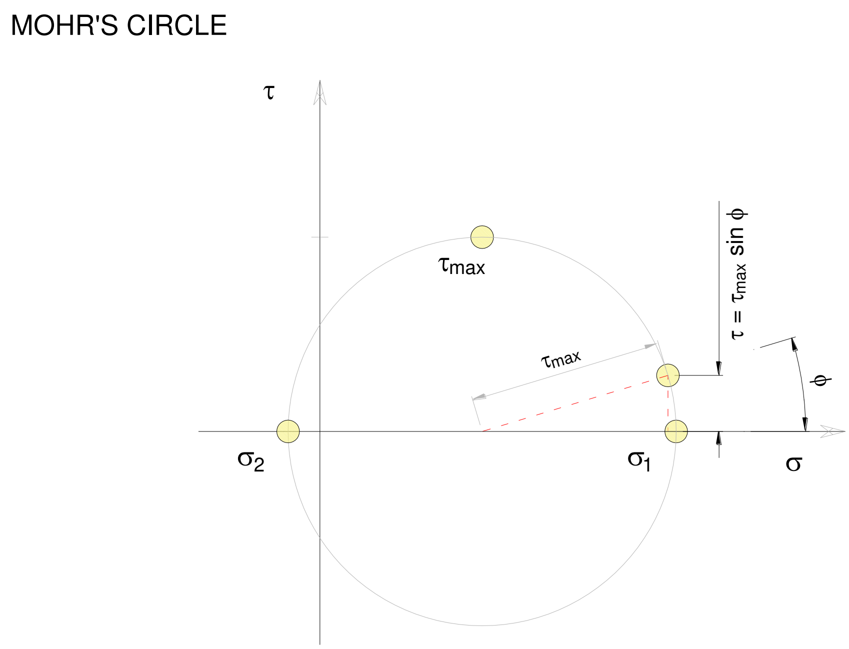

Figure 2.16: Use of the Mohr's circle to obtain the shear stress due to point loads

In summary, the GVW can be obtained as follows:

- Measure the strains at both faces of the web girder using the rosette configuration shown in Figure 2.11
- Calculate the principal strains and stresses using Equations [17] and [18]
- Calculate the shear stress due to the vertical loads using Equations [19] and [20]
- Calculate the gross vehicle using Equation [16]

To calibrate the α factor, a truck with known GVW can be used, just as in the case of the β factor that is applied in the BWIM method that uses bending strain measurements only.

2.4. Fulton Terrace Bridge (CT Bridge No. 06611A)

The Fulton Terrace Bridge, CT Bridge No. 06611A, is a five-lane bridge, which carries Interstate 95 (I-95) Northbound over Fulton Terrace in New Haven, Connecticut. The bridge is downstream of the Stiles Street Bridge with no on or off-ramps between the Pearl Harbor Memorial Bridge, the Stiles Street Bridge, and itself, such that all northbound traffic on the Pearl Harbor Memorial Bridge passes over this bridge, as well. The bridge has a total length of 98ft, a maximum width of 96ft and a bridge skew of 7.83˚. It is a single span bridge constructed with ten steel girders and a reinforced concrete deck. According to CTDOT, the bridge carries an average daily traffic of 65,950 vehicles, with 11% of those being trucks. A photo of the south-facing elevation of the bridge is provided in Figure 2.17. The dimensions of interest for the bridge are provided in Figure 2.18.

Figure 2.17: South elevation of the Fulton Terrace Bridge, I-95 Northbound (Google Maps, 2017)

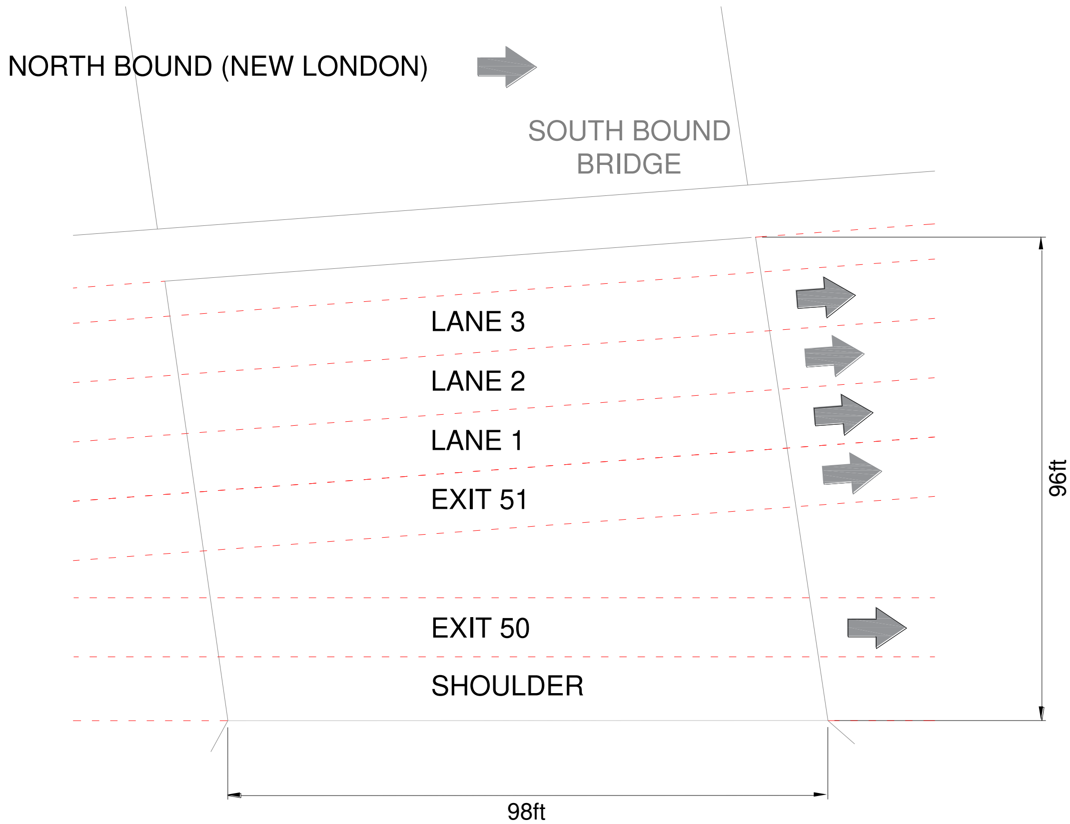

Figure 2.18: Fulton Terrace Bridge plan view

A Bridge Diagnostics Inc. (BDI) data acquisition system specifically designed for BWIM purposes was installed on this bridge. Three BDI ST350 strain transducers were installed. They were installed at the one-third span location from the right (Figure 2.19) of the bridge on the bottom flange of girders 2, 5, and 8. For this bridge, two strain rosettes are applied on each side of the two girders being studied. Figure 2.19 shows the location of the three strain sensors relative to the lanes of travel on the bridge. Each strain sensor is wired to a sensor node that in turn provides a wireless hop to a base station located under the bridge and a second wireless hop to a laptop controlling the system and collecting data.

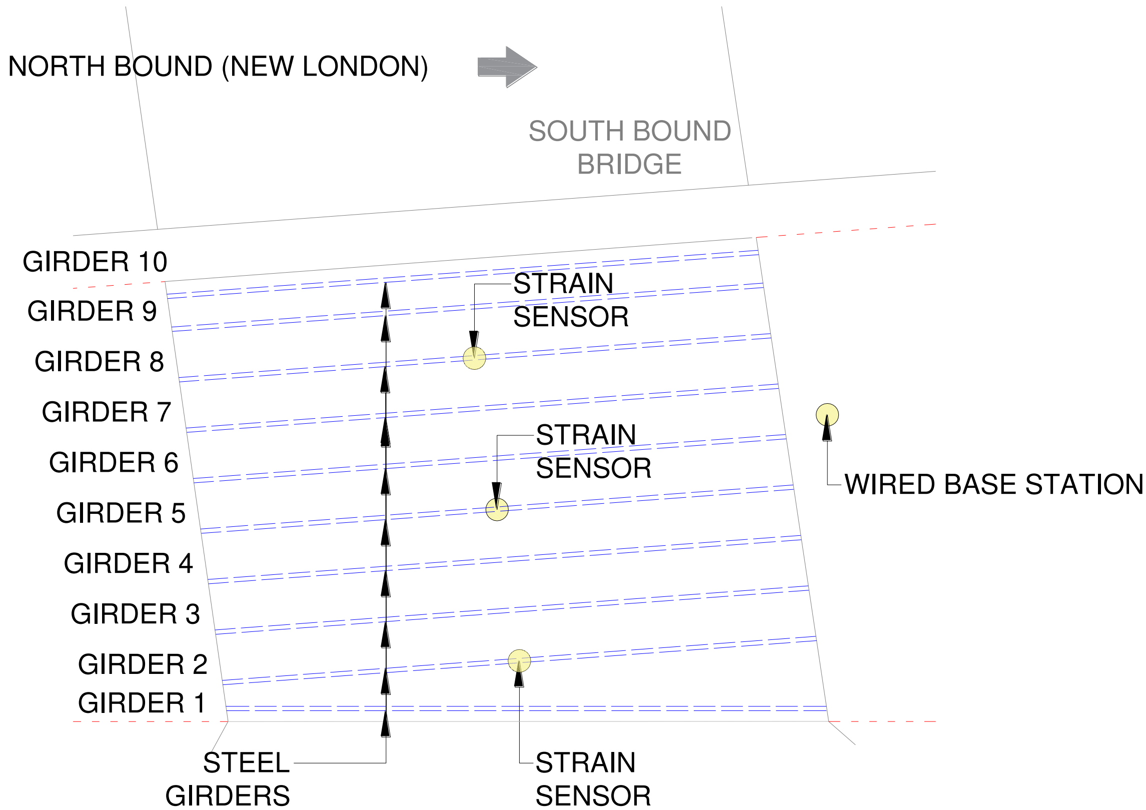

Figure 2.19: Schematic of sensor layout for the Fulton Terrace Bridge

For this simple single-span steel girder bridge, the GVW and vehicle speed are calculated using Eqs. [2] and [6] described previously. A truck of known weight is used to calibrate the system for this particular bridge.

CHAPTER 3 Findings and Applications

3.1. Meriden Bridge (Bridge No. 03051) Results

Data has been collected on the Meriden Bridge since March 15, 2013. This data has been processed using the methodology presented in Section 2.1 to determine GVW and speed. The data has been stored in a database in a queryable format. Screenshots of the user interface of the database are shown in Figure 3.1.

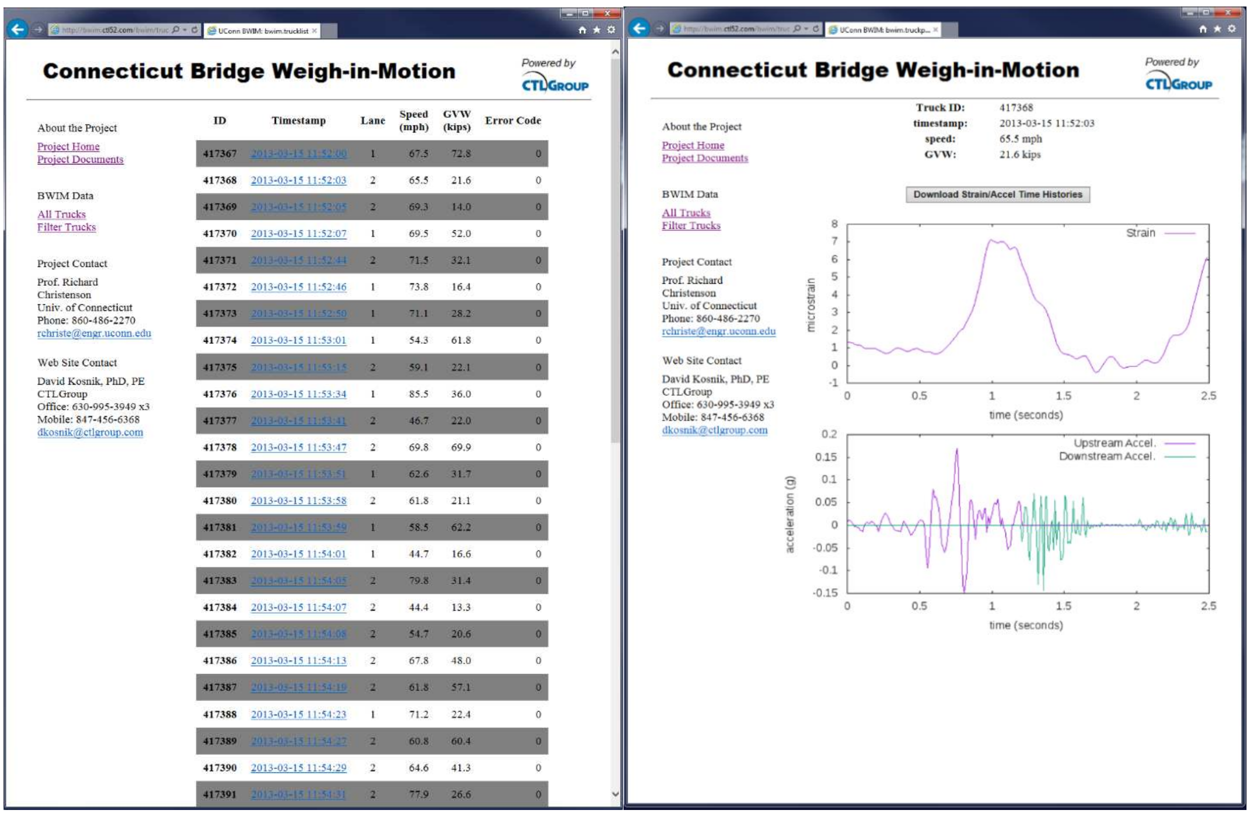

Figure 3.1: Connecticut Bridge Weigh-in-Motion Database User Interface

Over 3,637,465 records of truck crossings are saved in the database. This includes 395,904 trucks measured in the second through fourth quarters of 2013, 531,179 trucks in 2014, 1,139,181 trucks in 2015, 1,171,932 trucks in 2016 and, 399,269 trucks in the first quarter of 2017. Due to system maintenance, upgrades, and outage, various days and even some months have no data collected. Therefore, average daily truck traffic (ADTT) is reported moving forward where the monthly data is normalized by the number of full days data was collected. The ADTT per month is shown in Figure 3.2 for each of the five years data was collected. The average ADDT is approximately 3500 trucks crossing the bridge each day. The lower volumes of truck traffic in 2013 are likely due to a larger threshold of strain used to trigger a truck crossing in the prior research project. The current project was able to collect data over the period of March 2015 through May 2017. Only a few days at the beginning of December 2017 were collected due to a power outage at the bridge.

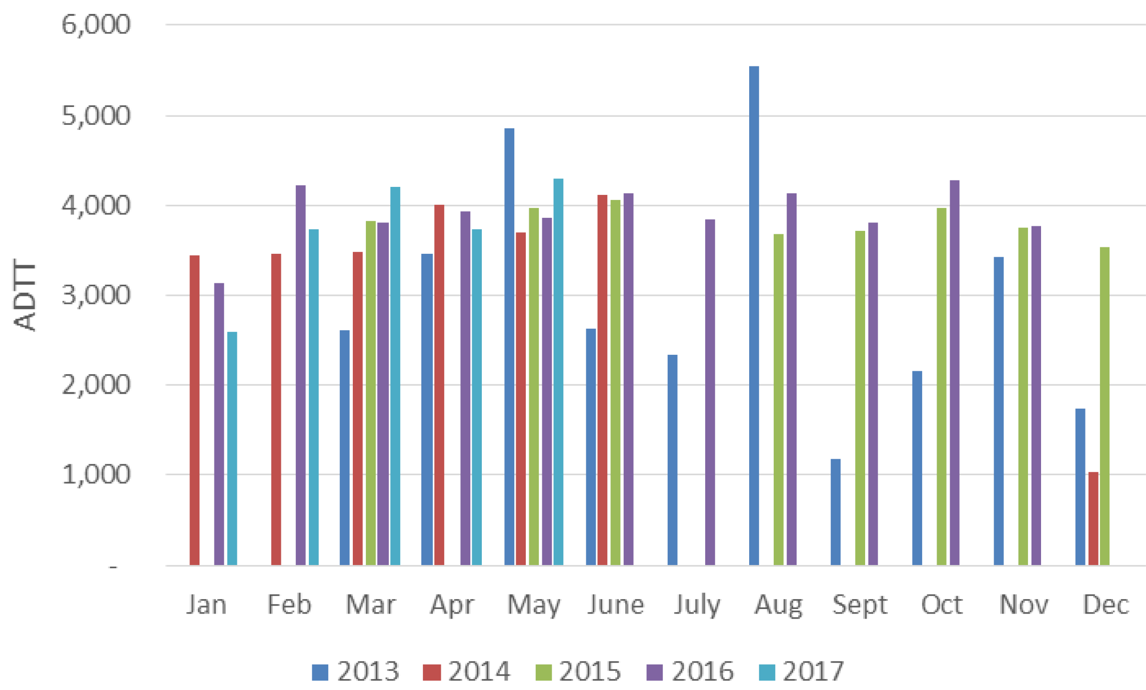

Figure 3.2: Average Daily Truck Traffic Per Month calculated from BWIM system on the I-91 Meriden Bridge.

3.1.1 Gross Vehicle Weight

Distribution of the truck GVWs for 2013-2017, where no error codes are identified, is shown in Figure 3.3. The error codes reflect difficulty calculating truck and therefore GVW. This occurs often for lighter trucks, below 15 kips, as the method is developed to calculate the speed for heavier 5-axle trucks. The GVW distribution shows a bi-modal distribution with both loaded and unloaded truck traffic crossing over the bridge.

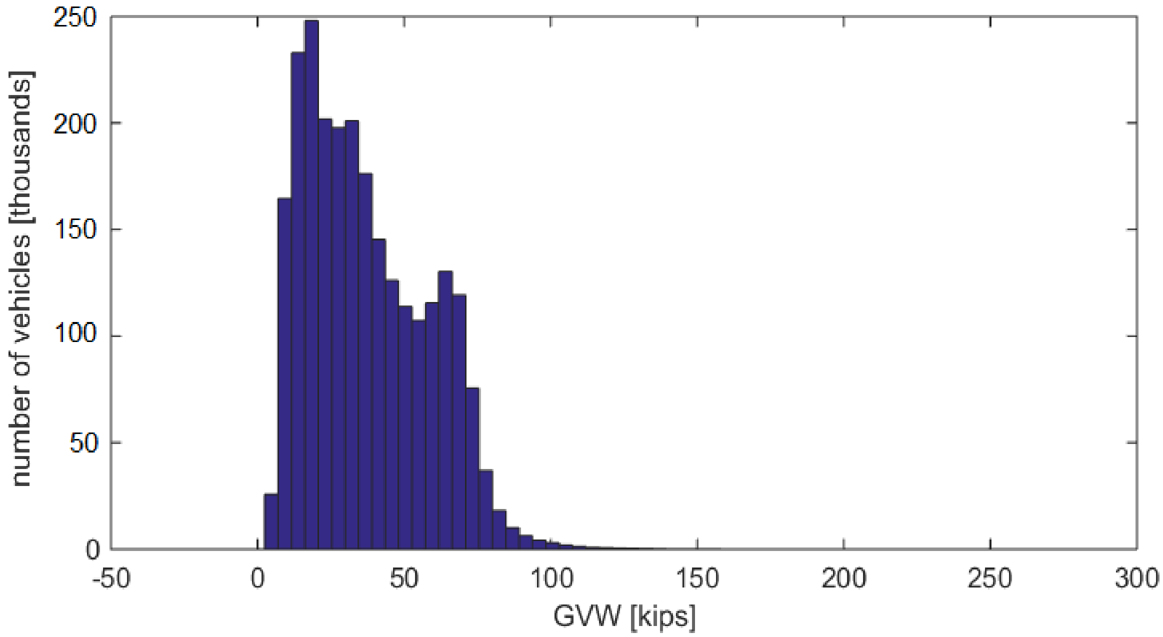

Figure 3.3: Distribution of Gross Vehicle Weight Calculated from BWIM System on the I-91 Meriden Bridge.

The database can provide insight into trucks with excessive GVW. A total of 26,205 trucks with weights over 80 kips were calculated, from 2015-2017, consisting of 1% of the truck traffic (2,710,382 trucks from 2015-2017). Figure 3.4 shows the percentage of trucks over 80 kips for each month. On average, as calculated by the BWIM system from 2015-2017, there are 39 trucks each day weighing over 80 kips that cross over the Meriden Bridge.

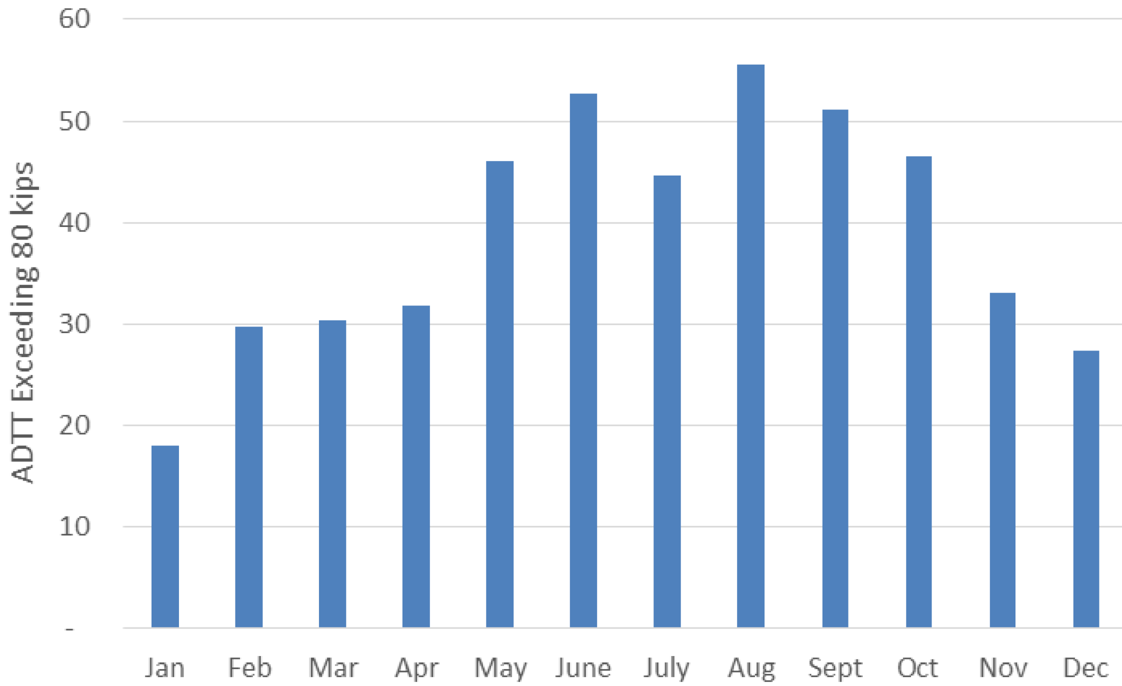

Figure 3.4: Average Daily Truck Traffic Exceeding 80 kips GVW by Month from 2015-2017.

3.1.2 Truck Speed

A distribution of the truck speeds for 2013 – 2017, are shown in Figure 3.6. The average truck speed is 65.9 miles per hour (mph). The average truck speeds per month are shown in Figure 3.7 for the five years data was collected. The months of July and August 2013 have the highest average truck speeds crossing the bridge, while the months of February and December 2014 have the lowest speeds, with a difference of less than 5 mph.

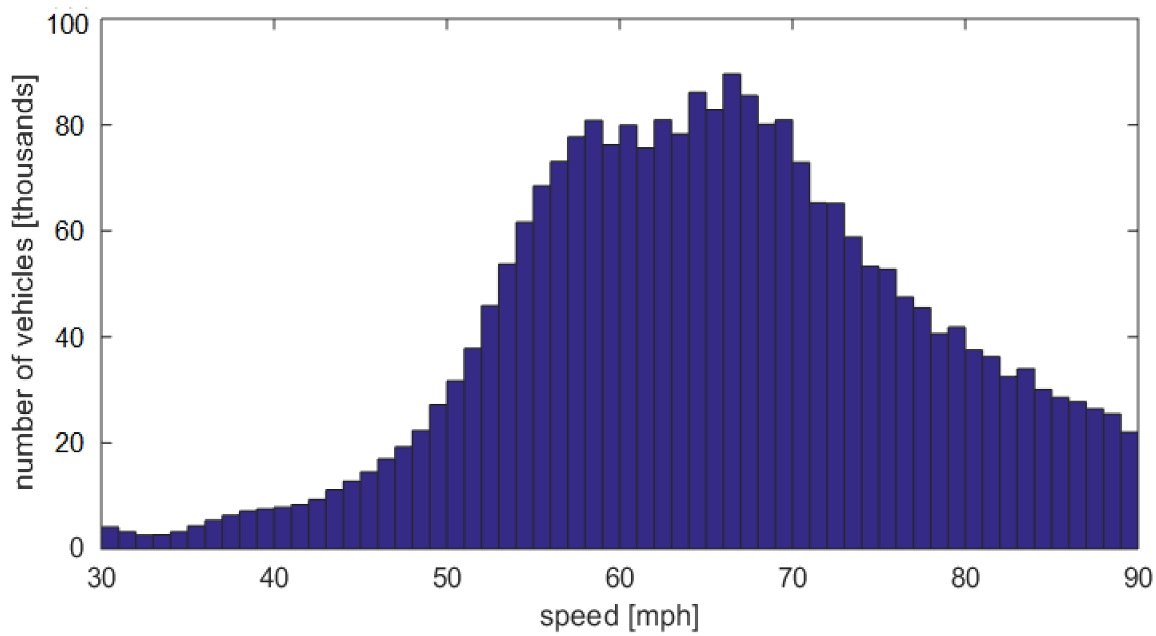

Figure 3.6: Distribution of Truck Speeds Calculated from BWIM System on the I-91 Meriden Bridge.

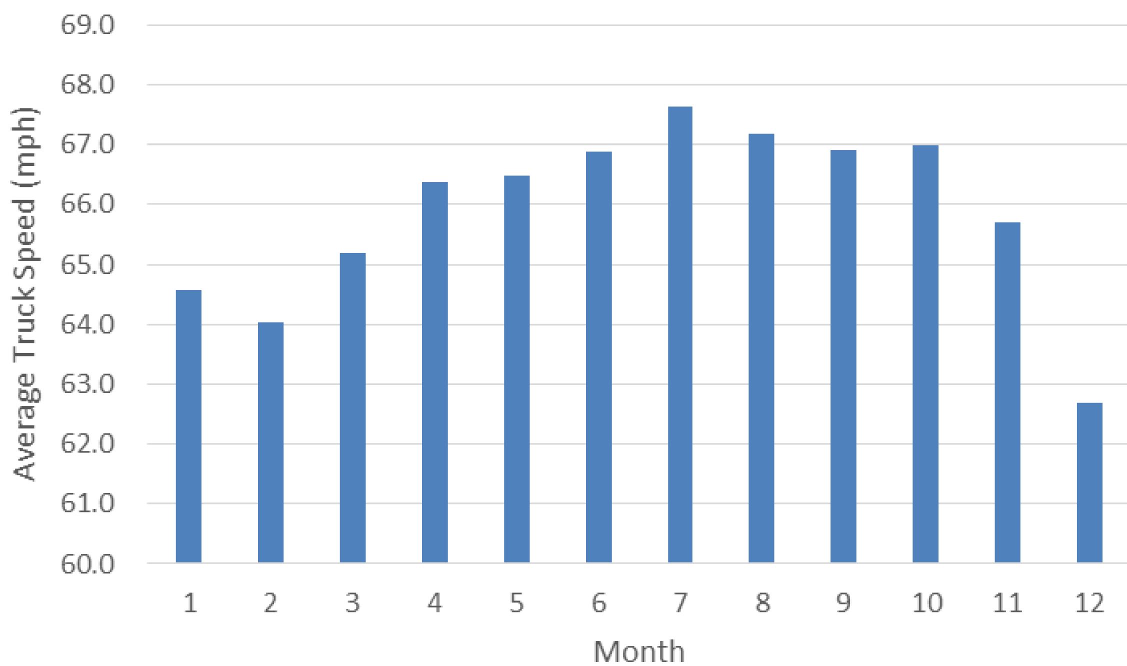

Figure 3.7: Average Truck Speed per Month Calculated from BWIM System on the I-91 Meriden Bridge.

3.2. Lebanon Bridge (Bridge No. 01865) Results

A field test was conducted on May 16th, 2016, in order to evaluate the performance of a portable monitoring system for Bridge Weigh-In-Motion (BWIM) purposes as applied to a concrete girder bridge. The GVW and vehicle speed are calculated using Eqs. [2] and [6] described previously.

3.2.1 Truck of known weight

The truck of known weight, as shown in Figure 3.10, is used to calibrate the system for this bridge. The truck was measured on the day of testing to have a GVW of 55 kips.

Figure 3.10: Distribution of loads on the calibration test truck.

The test truck traveled at a constant speed over the bridge, completing four passes over the slow lane (Lane 1) and four passes over the fast lane (Lane 2), Data collected from these eight passes were used for calibration of the BWIM factors. Images of selected passages of the test truck over Lanes 1 and 2 are shown in Figures 3.11 and 3.12, respectively. The images were extracted from the camera and radar unit that was installed on the day of the test.

Test A	Test C

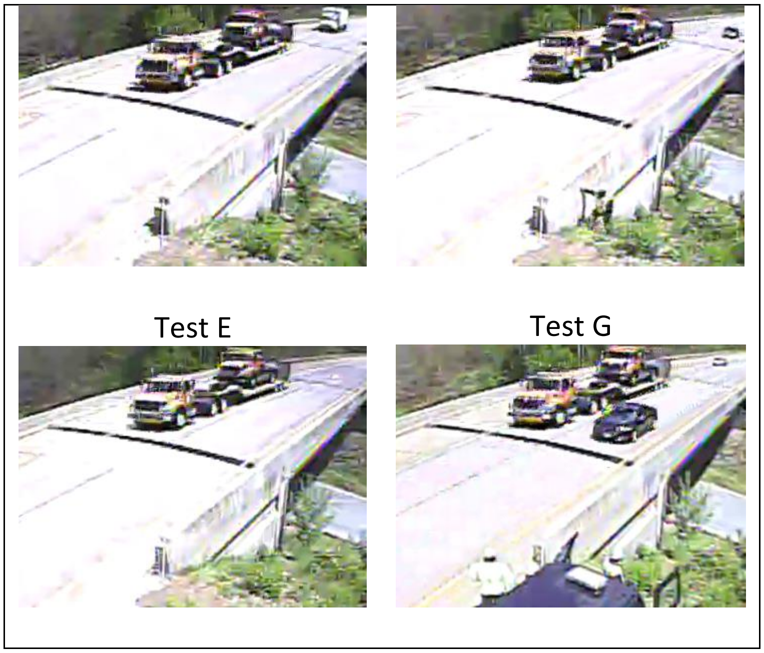

Figure 3.11: Passages of test truck over the slow lane.

Figure 3.12: Passages of test truck over fast lane.

For this bridge, a speed calibration factor was introduced in order to account for the differences of the calculated and the measured velocities at which the calibration truck travels over the bridge. This speed calibration factor is denoted as k and it simply modifies the calculated velocity of Equation [6] as

$$v = k\frac{L}{2t} \qquad [21]$$

Table 3.1 shows the reported speeds for each test truck passage.

Table 3.1. Speed data recorded for the test truck on lanes 1 and 2.

Truck Test Pass	Speed (mph)	Lane
A	64.0	1
B	64.0	2
C	65.0	1
D	65.0	2
E	65.0	1
F	62.6	2
G	60.0	1
H	63.0	2

3.2.2 Measured Strain Time Histories

The measured time histories of the strain gage on girder # 3 for the test truck traveling over Lane 1 are shown in Figure 3.13. The corresponding measured time histories of the strain gage on girder # 2 for the test truck traveling over Lane 2 are shown are shown in Figure 3.14.

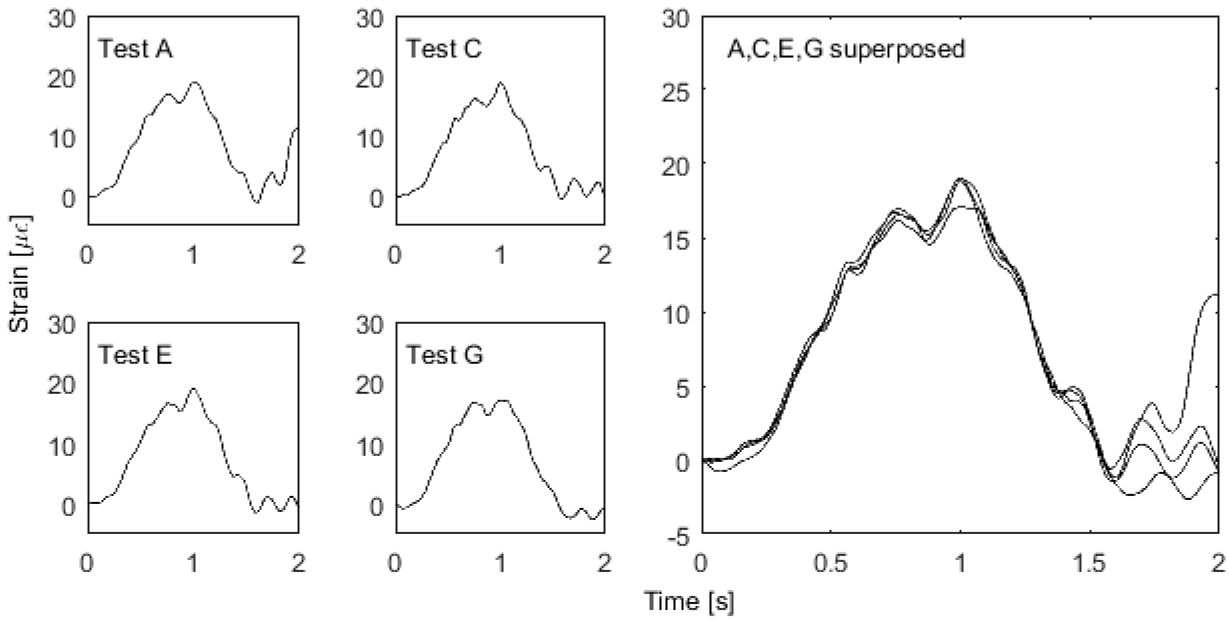

Figure 3.13: Response waves of the test truck passing over Lane 1.

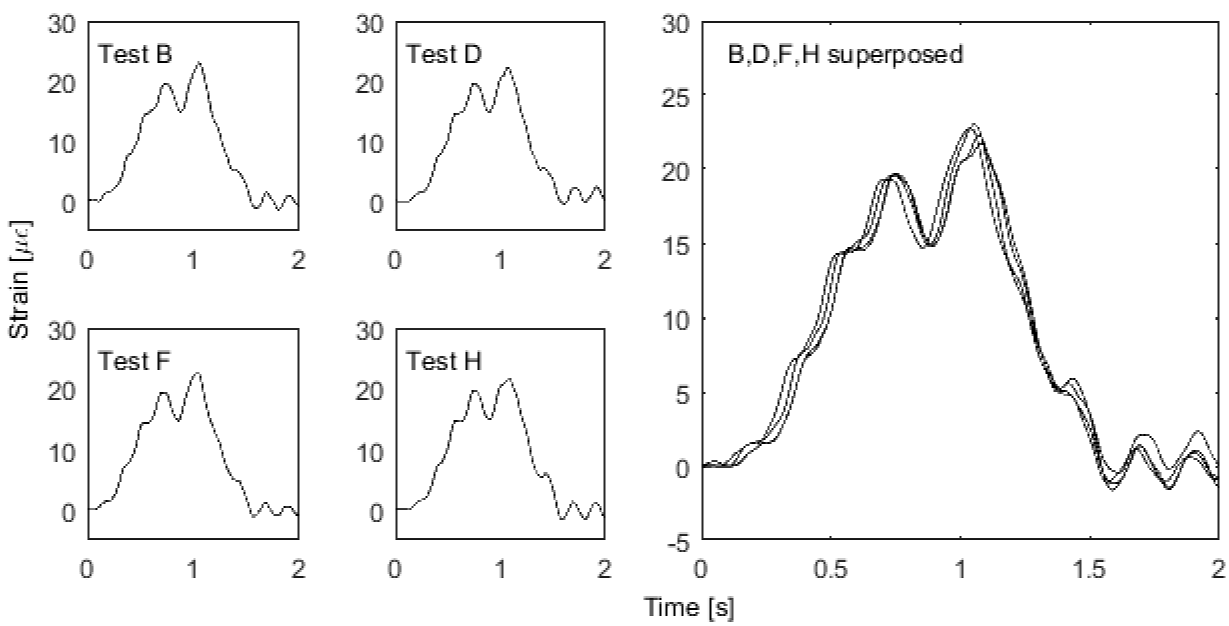

Figure 3.14: Response waves of the test truck passing over Lane 2.

The strain measurements are observed to be repeatable. The variations shown at the end of the time record (after 1.5 seconds) for Lane 1 can be attributed to adjacent and/or following traffic. The temporal variation observed for Lane 2 can be attributed to the different truck speeds.

The theoretical influence line for the truck of known weight passing over the Lebanon Bridge can be constructed assuming a simple beam proportionality between the strain amplitude and axle weight. The theoretical strain response and the response compared to the measured strains for Lanes 1 and 2 are all shown in Figure 3.15.

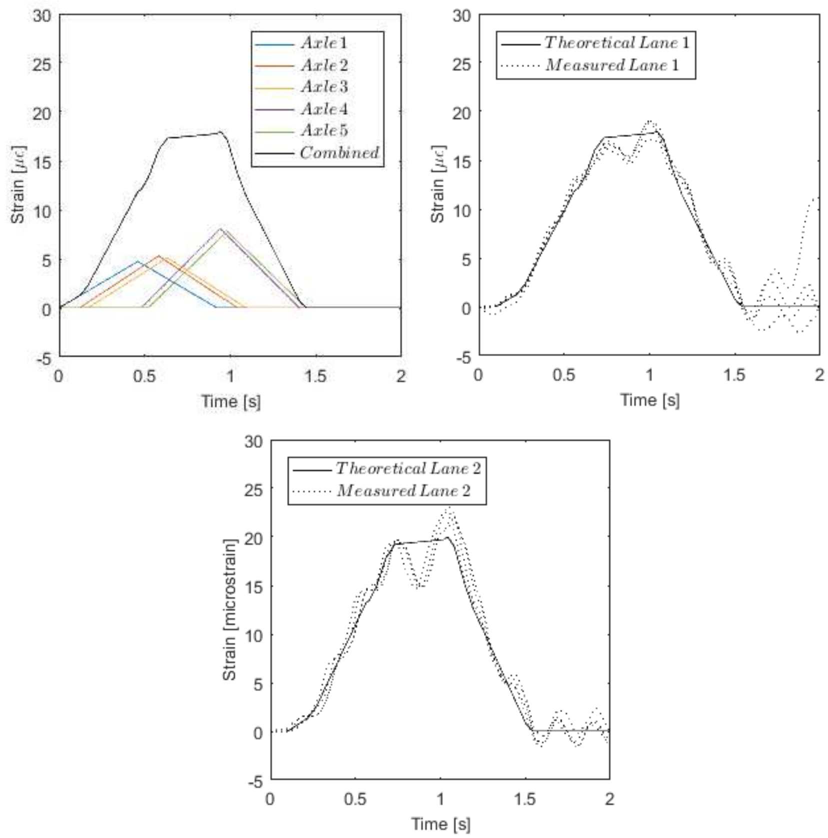

Figure 3.15: Passages of test truck over Lanes 1 and 2 superposed with a theoretical response wave.

Using the measured strain time histories from the crossings of the truck of known weight, the calibration factors shown in Tables 3.2 and 3.3 were obtained for lanes 1 and 2.

Table 3.2. Calibration factors for test truck passing over Lane 1.

Test	k	β
A	1.075	0.052
C	1.078	0.058
E	1.057	0.059
G	0.865	0.070

Average	1.019	0.060

Table 3.3. Calibration factors for test truck passing over Lane 2.

Test	k	β
B	0.914	0.053
D	0.928	0.052
F	0.898	0.054
H	0.878	0.055
Average	0.905	0.054

As indicated in Tables 3.2 and 3.3, the k and β parameters were averaged to obtain the calibration factors for the velocity and GVW, yielding values of $k_1 = 1.019$ and $\beta_1 = 0.060$, and $k_2 = 0.905$ and $\beta_2 = 0.054$. These factors were then used to calculate the speeds and GVW's for data collected from other selected vehicles crossing the bridge, as discussed in the next section.

3.2.3 BWIM Results

Using the values presented earlier, the speeds and weight of the known truck were calculated. The results are shown in Tables 3.4 and 3.5. It is noteworthy to mention that the BWIM algorithm was constructed in such a way that it detects the lane in which the truck is traveling, by comparing the magnitude of the two measured strain records, and therefore uses the appropriate calibration factor in an automated fashion.

Table 3.4. Calculated test truck speed and weight while passing over Lane 1 (with error given in parentheses).

Test	Speed [mph]	Weight [Kips]
A	60.6 (5.3%)	60.2 (9.5%)
C	61.5 (3.9%)	53.7 (2.4%)
E	62.7 (3.5%)	54.2(1.5%)
G	70.7 (8.8%)	55.7(1.3%)

Table 3.5. Calculated test truck speed and weight while passing over Lane 2 (with error given in parentheses).

Test	Speed [mph]	Weight [Kips]

B	63.4 (2.5%)	55.5 (0.9%)
D	63.4 (1.3%)	56.2 (2.2%)
F	63.1 (5.2%)	55.4 (0.7%)
H	65.0 (3.2%)	56.0 (1.8%)

The remainder of the trucks measured by the BWIM system are processed using the previously described method and calibration factors. A total of 58 truck crossings were recorded over a 150 minute period between 10:45am and 1:15pm on May 16, 2016. A distribution of the truck speeds is shown in Figure 3.16. The average truck speed is 68 miles per hour (mph) with speeds ranging from 40 mph to 88 mph. A distribution of the truck GVWs is shown in Figure 3.16. The distribution shows a clear bi-modal distribution centered on 55 kips and 85 kips. The maximum truck weight calculated is 121 kips. A total of 22 trucks with weights over 80 kips were calculated, consisting of 38% of the truck traffic.

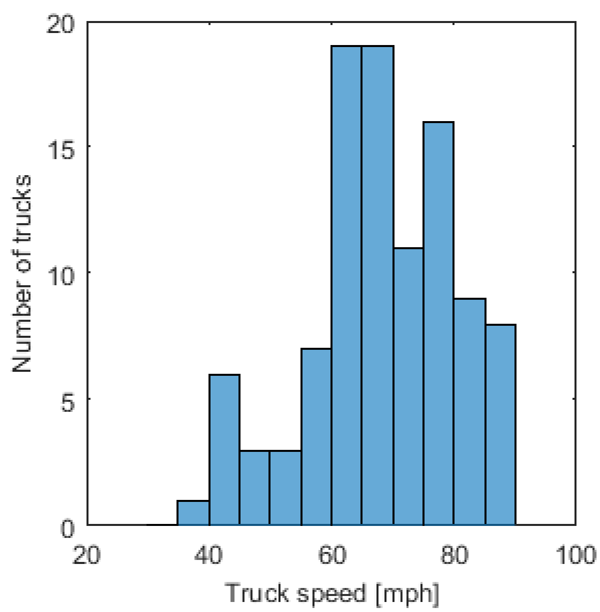

Figure 3.16: Speed histogram for 58 selected trucks crossing the Lebanon Bridge.

Trucks traveling at speeds slower than 30mph or faster than 90mph were discarded by the algorithm, as they are considered as processing errors due to factors such as multiple presence of the trucks at the bridge, trucks changing lanes and trucks traveling very close to each other.

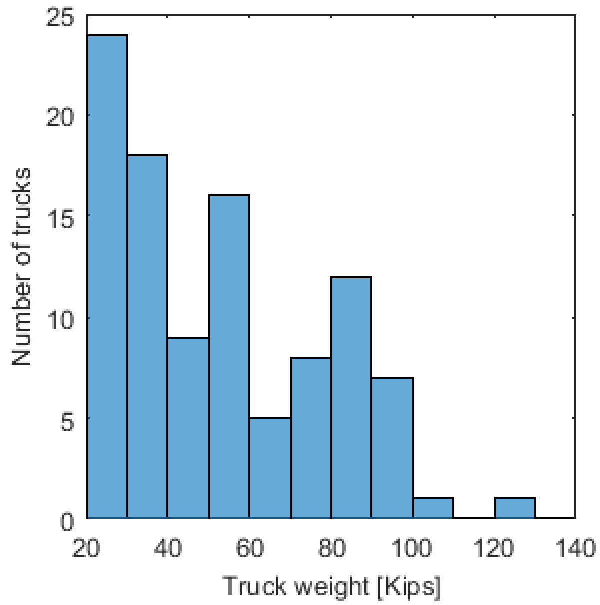

Figure 3.17: Gross Vehicle Weight histogram for 58 selected trucks crossing the Lebanon Bridge.

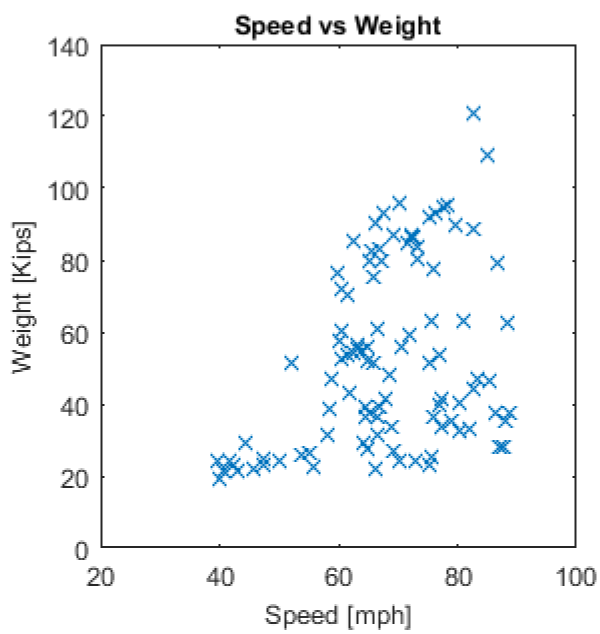

Figure 3.18: Speed versus weight for 58 selected trucks crossing the Lebanon Bridge.

Figure 3.18 shows the distribution of the weight of the truck versus their speed, as calculated by the BWIM algorithm. The correlation coefficient for these two variables is 0.37, showing that there is little relationship between them.

3.3. Stiles Street Bridge (Bridge No. 00174A) Results

A field test was conducted on May 11, 2017, to evaluate the ability of the BWIM system to determine GVW and speed for a continuous span bridge. BWIM can be more challenging for continuous span bridges due to the influence of vehicles on other spans on the (normal) strain measured on the span of interest. The shear strain is shown previously to provide discrete jumps when the axle passes over the location of measurement. As the authors are not aware of any sensor that can measure shear strain on a structural member directly, this work utilizes normal strains measurements arranged in a rosette to calculate the shear strain. As mentioned before, the shear stress is then determined and used to calculate the GVW for the test truck.

3.3.1 Truck of known weight

The truck of known weight, as shown in Figure 3.19, was used to calibrate the BWIM system for both the Stiles Street and Fulton Terrace Bridges.

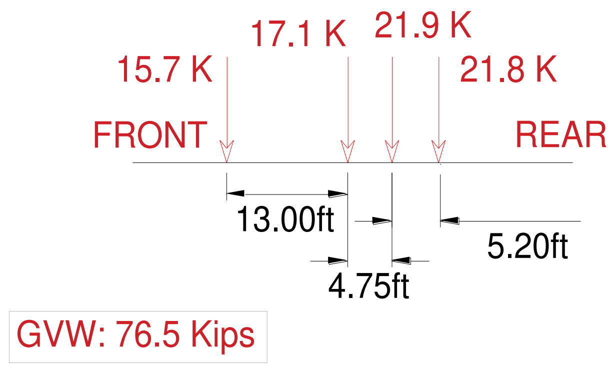

Figure 3.19: Distribution of the loads on the test truck used on the Stiles St. and Fulton Terrace bridges.

The test truck traveled at a constant speed over the bridge completing 2 passes at 50 mph and 1 pass at 40 mph over Exit 50 and Lane 1 on the Stiles Street Bridge on I-95 northbound.

3.3.2 Shear Strain Time Histories

Using the measurements from the strain sensors, the shear stresses were calculated according to the procedure explained on Chapter 2. The horizontal, vertical and inclined strains were recorded for each one of the locations. Horizontal, vertical and inclined strains for the passages of the test truck over the lane corresponding to Exit 50 and over Lane 1 are shown in Figures 3.20, 3.21 and 3.22, respectively. For each instrumented girder, the principal strain was calculated as the average of the principal strains of each rosette on opposite sides of the girder. This averaging is done to compensate for any out of plane behavior that might be observed in the web of the girder.

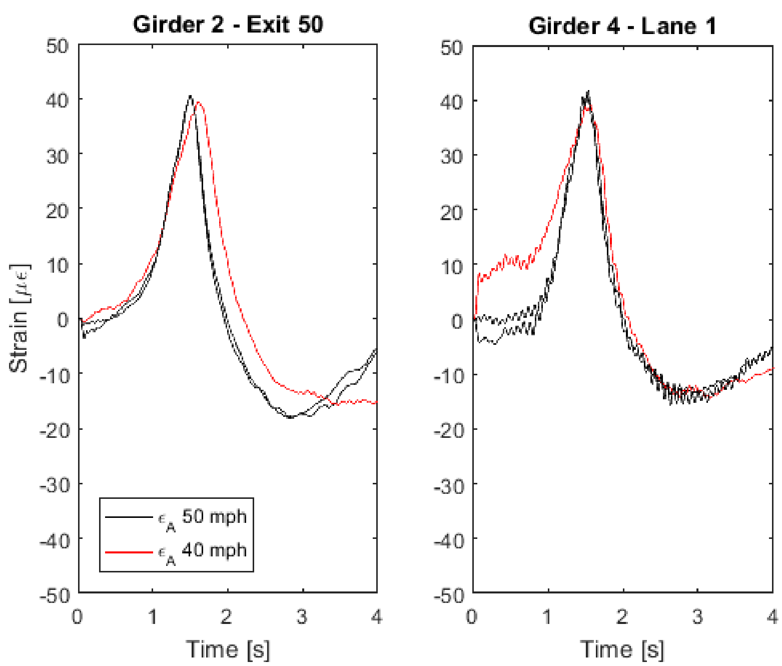

Figure 3.20: Horizontal strains caused by the test truck.

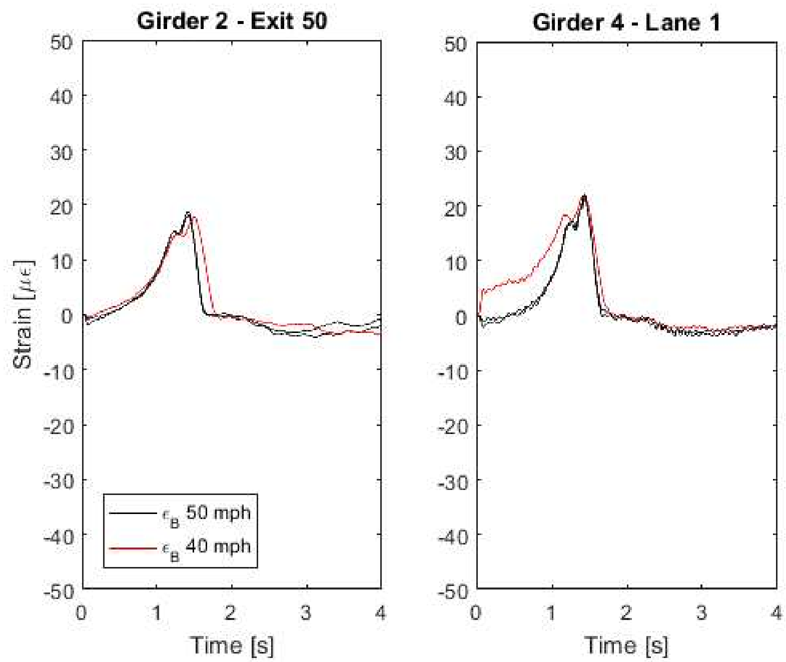

Figure 3.21: Inclined strains caused by the test truck.

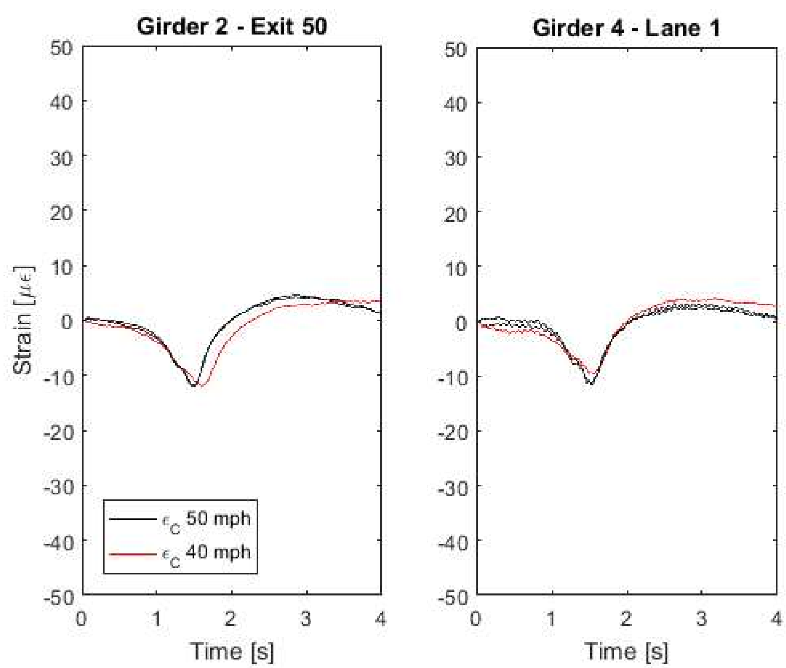

Figure 3.22: Vertical strains caused by the test truck.

Combining these strains together on Equations [17] and [18], the principal strains were calculated for the test truck passages over Exit 50 and Lane 1. The results for the test truck traveling over Exit 50 and Lane 1 are shown in Figure 3.23.

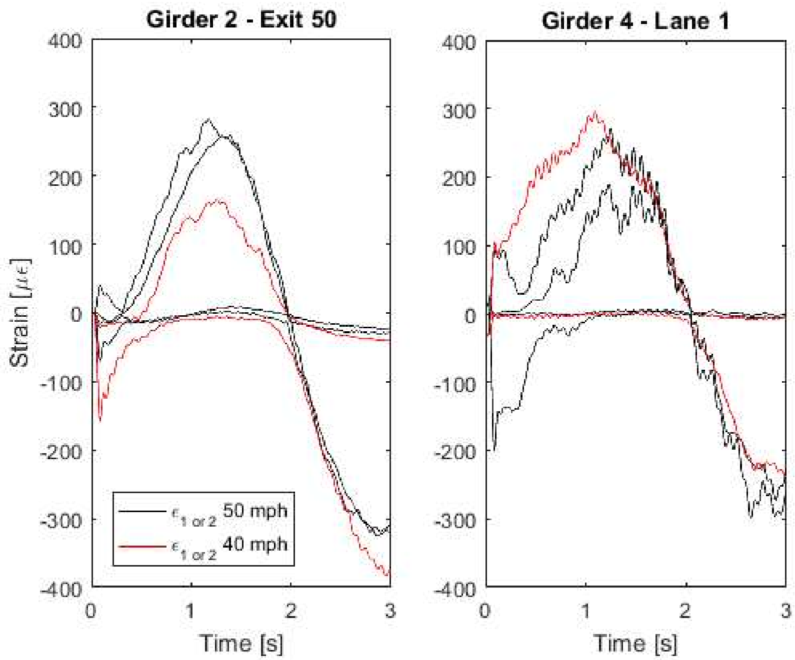

Figure 3.23: Principal strains.

In the previous figure, positive values correspond to ε_1 and negative values to ε_2. It is clear that when one of these principal strains is non-zero, the other one vanishes. In addition, it is observed a pivot point around 2 seconds at which they change from non-zero to zero or vice-versa. This is a clear indication that the truck exits the span, because the reversion means that there has been a change in the sign of the shear. The principal strain for the Lane 1 shows a significant alteration. This is an indication of not only of a noisier signal (as seen on Figure 3.20) but also possible lateral distribution effects or the lateral-torsional buckling that might cause out-of-plane behavior. As mentioned before, these principal strains were used to calculate the shear stresses, according to Equations [19] and [20]. The resulting shear time histories for runs over Exit 50 and Lane 1 are shown in Figure 3.24.

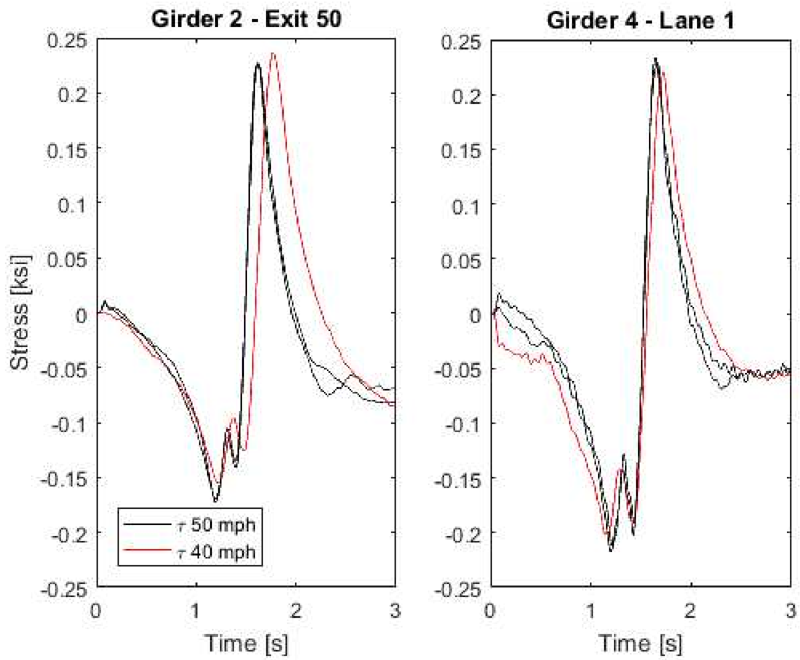

Figure 3.24: Direct shear stresses.

In the previous Figure, it is remarkable the repeatability of the test, since there is a good agreement on the magnitude and shape of the strains recorded for multiple runs of the test trucks. For this particular test truck, the theoretical influence line for the shear stress was constructed using the superposition principle and the result for an individual axle described in Eq. [7]. For the test truck used in this case, the results are shown in Figures 3.25 and 3.26.

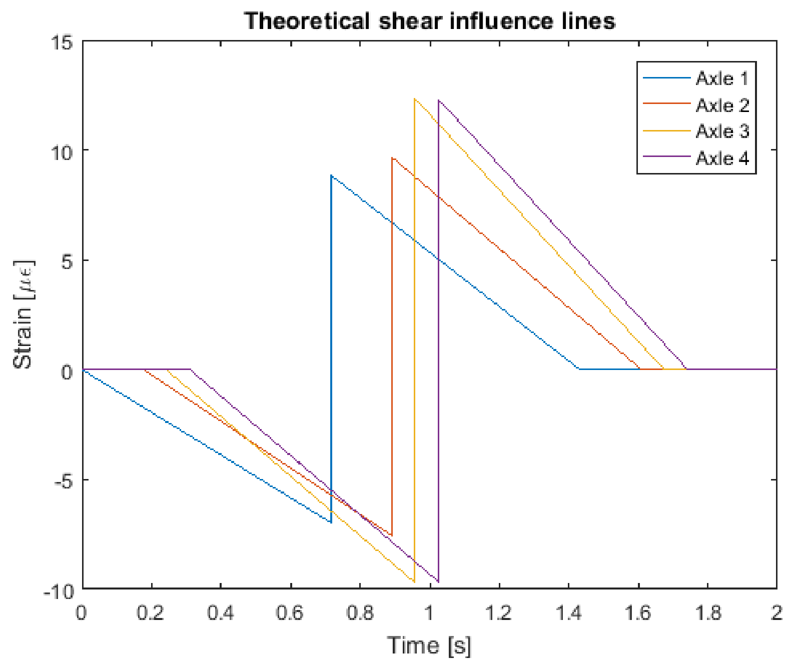

Figure 3.25: Theoretical influence lines of each one of the axles of the test truck.

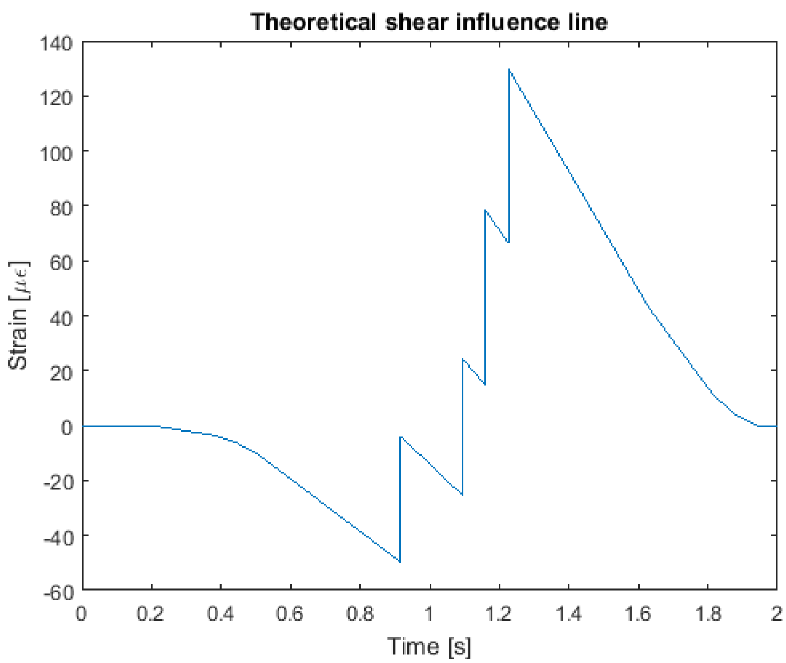

Figure 3.26: Theoretical influence lines of total response of the test truck.

The theoretical shear influence lines are compared to the measured strain responses when the truck passes over Exit 50 and Lane 1 in Figure 3.27.

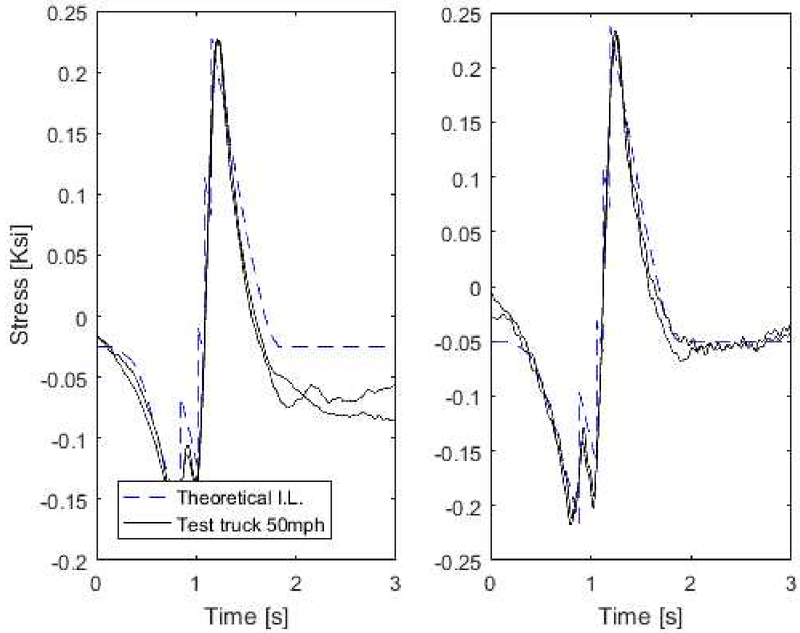

Figure 3.27: Theoretical influence line superposed with passages over Exit 50.

The superposed influence lines shown in these figures were adjusted to match the measured values by changing the magnitude of the strains (which would correspond to the theoretical factor α). It is possible to observe that there is a good agreement between the expected and the measured shape of the shear stress records. Since this is a continuous multi-span bridge, the presence of other loads in adjacent sections introduces offsets from zero on the shear stress records, which can be noted for the test truck over Exit 50. In addition, it is observed a lump on the last portion of the records, which corresponds to the moment at which the truck exits the span. This is caused by the test truck passing over the next span of the continuous bridge, and it is different from the theoretical influence line because it was constructed for a simple span. Finally, the sudden jumps in the initial portion of the records shown in Figure 3.30 are attributed to numeric rounding on angle ϕ on Equation [17], which might cause a sudden 180 degrees change on the angle.

3.3.3 BWIM Results

From the plots on Figures 3.29 and 3.30, the values for τ_1, τ_2, Δt and $\tau_1{}'$ were determined. Knowing that the GVW for this particular truck is 76.5 Kips, the values for α were calibrated for each one of the passages. The results are shown in Table 3.6.

Table 3.6. Calculation of calibration factors for each passage.

Test	Lane	Speed [mph]	τ_1 [Ksi]	τ_2 [Ksi]	Δt [s]	τ_1 [Ksi / s]	α [in^2]
A	Exit 50	50	-1.72	2.27	0.42	-4.31	34.9
B	Exit 50	50	-1.70	2.25	0.44	-3.34	31.0
C	Exit 50	40	-1.55	2.37	0.54	-2.36	29.1
D	Lane 1	50	-2.11	2.33	0.44	-5.66	39.3
E	Lane 1	50	-2.18	2.29	0.47	-5.63	42.2
F	Lane 1	40	-2.02	2.20	0.58	-3.94	39.2

From the previous table, the average values are $\alpha_{E50} = 31.67\ in^2$ (Exit 50) and $\alpha_{L1} = 40.24\ in^2$ (Lane 1). Using this averages and Equation [16], the calculated GVWs for the passages of the trucks are shown in Table 3.7.

Table 3.7. Test truck (76.5 Kips) passing over Exit 50 and Lane 1 (with error given in parentheses).

Test	Lane	Weight [Kips]
A	Exit 50	69.4 (9.3%)
B	Exit 50	78.1 (2.1%)
C	Exit 50	83.4 (9.0%)
D	Lane 1	78.3 (2.4%)
E	Lane 1	72.9 (4.7%)
F	Lane 1	78.5 (2.7%)

3.4. Fulton Terrace Bridge (Bridge No. 0611A) Results

A field test was conducted on May 11, 2017 (the same day as Stiles Street bridge), to demonstrate the feasibility of a longer period BWIM system powered by a solar panel, as shown in Figure 3.29. Using such a system allows for an easy installation of the system, which is able to collect BWIM data for longer periods than the portable system mentioned before. The bridge used in this case is also located on route I-95 Northbound at a short distance from the Stiles Street Bridge, which means that the same traffic goes over both bridges. The 76.5 Kips test truck shown in Figure 3.19 was also used for this bridge.

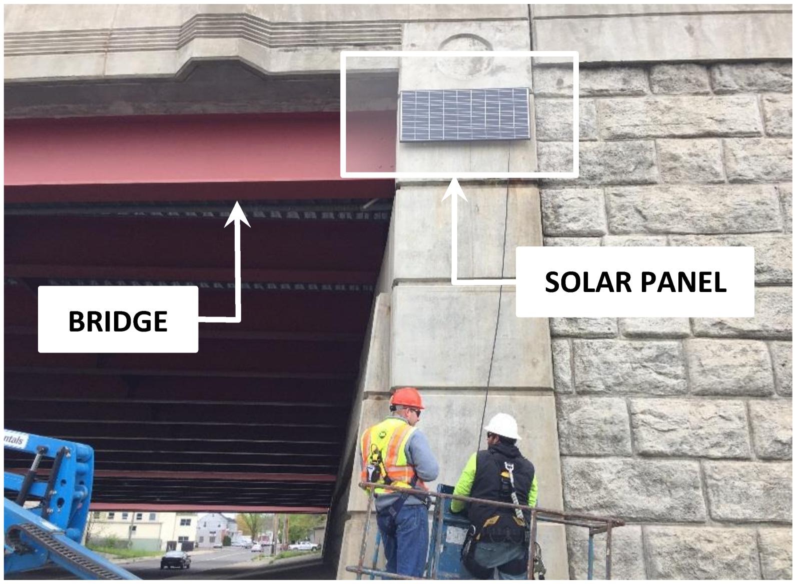

Figure 3.28: Solar panel used for powering BWIM system.

To verify the calculation of speed and identify a speed calibration factor, k, the travel speeds for each truck passage were recorded two ways: from a GPS unit in the vehicle itself and by using radar. Table 3.6 shows the reported speeds for each test truck passage.

Table 3.8. Speed data recorded for the test truck over five travel lanes of Stiles Street bridge on I-95 NB.

Truck Test	Speed (mph) GPS	Speed (mph) Radar	Lane
1	50	N.D.	Exit 50
2	49	N.D.	Exit 50
3	50	49	Lane 1
4	48	47	Lane 1
5	48	49	Exit 51
6	53	50	Exit 51
7	50	47	Lane 2
8	52	51	Lane 2
9	53	50	Lane 3
10	49	52	Lane 3
11	38	N.D.	Exit 50
12	42	38	Exit 51
13	40	43	Lane 1

14	40	42	Lane 2
15	38	40	Lane 3

N.D. indicates the speed was Not Determined by the radar.

In the previous table, the velocity values for Exit 50 were not detected by the radar since the instrument provides measurements for four lanes only. These velocity values were used to calibrate the k calibration factors in Equation [21].

3.4.1 Bending normal stress time histories

The passage of the test truck over each one of the lanes of the bridge is shown in Figure 3.29. Three strain sensors were placed on the bottom of the web of Girders 2, 5 and 8, as shown in Figure 2.19.

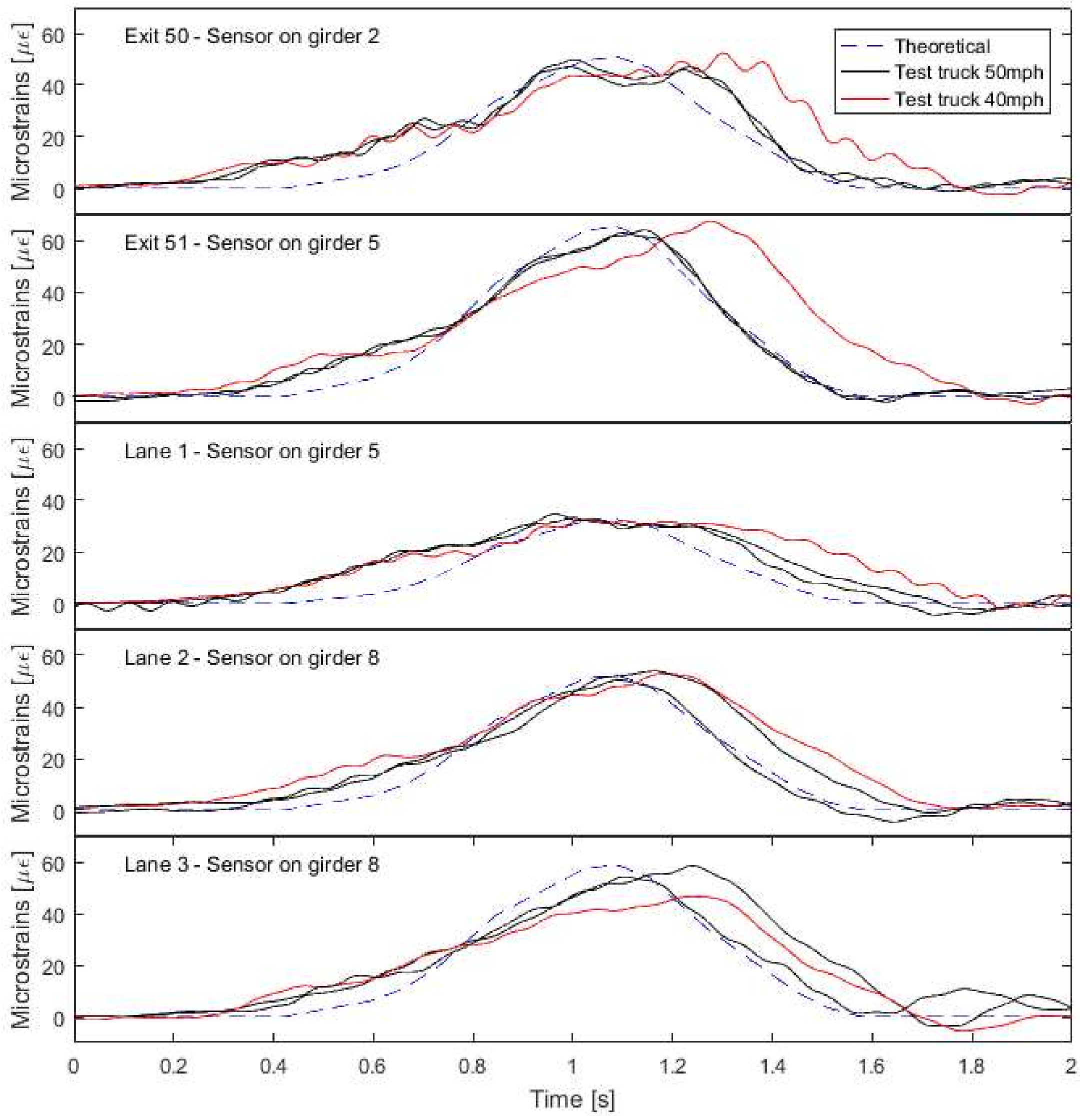

Figure 3.29: Passages of test truck each lane.

From the previous Figure, it can be seen that there is not an appreciable difference in the strain record measured on girder 8 when the test truck goes over Lane 2 and Lane 3, which means that the results of trucks traveling on such lanes might be confounded. As such, it was assumed that no trucks were traveling on Lane 3.

3.4.2 BWIM results

Using the strain time histories shown, the calibration factors k and β were calculated for travels over each lane. The results are shown in Tables 3.9 through 3.13. For this particular case, it is of interest to acknowledge that the plan geometry of the bridge over Fulton Terrace is atypical and therefore influences the calculation of such factors. Also, for this particular section of route I-95 NB, the speed limit is stated as 50mph. Therefore, the BWIM algorithm was adjusted to consider a velocity higher than 75mph as slower than 35mph as errors (as opposed to 90mph and 30mph for the previous cases).

Table 3.9. Calibration factors for test truck passing over Exit 50 Lane.

Test	k	β
1	0.554	0.458
2	0.631	0.470
11	0.421	0.541
Average	0.535	0.489

Table 3.10. Calibration factors for test truck passing over Exit 51 Lane.

Test	k	β
5	0.595	0.386
6	0.663	0.405
12	0.646	0.394
Average	0.635	0.395

Table 3.11. Calibration factors for test truck passing over Lane 1.

Test	k	β
3	0.682	0.595
4	0.583	0.565
13	0.621	0.639
Average	0.629	0.600

Table 3.12. Calibration factors for test truck passing over Lane 2.

Test	k	β
7	0.653	0.510
8	0.678	0.362
14	0.601	0.536
Average	0.644	0.469

Table 3.13. Calibration factors for test truck passing over Lane 3.

Test	k	β
9	0.678	0.362
10	0.695	0.421
15	0.525	0.534
Average	0.633	0.439

Using the averaged values, the speeds and weight are re-calculated for the truck of known weight. The values are shown in Table 3.15.

Table 3.14. Calculated test truck speed and weight while passing over each lane (with error given in parentheses).

Test	Lane	Speed [mph]	Weight [Kips]
1	Exit 50	48.3 (3.4%)	79.0 (9.5%)
2	Exit 50	41.0 (16.3%)	67.6 (2.4%)
3	Lane 1	45.7 (7.7%)	62.9 (17.8%)
4	Lane 1	51.3 (7.9%)	77.5 (1.3%)
5	Exit 51	51.1 (5.3%)	83.6 (9.2%)
6	Exit 51	48.7 (5.4%)	71.5 (6.6%)
7	Lane 2	49.2 (1.4%)	65.1 (14.8%)
8	Lane 2	47.0 (8.7%)	63.8 (16.6%)
9	Lane 3	48.1 (6.7%)	86.7 (13.3%)
10	Lane 3	46.0 (9.0%)	72.7 (5.0%)
11	Exit 50	48.3 (27.1%)	87.9 (14.9%)
12	Exit 51	40.3 (0.7%)	75.4 (1.5%)
13	Lane 1	42.0 (1.3%)	64.2 (16.1%)
14	Lane 2	43.2 (5.3%)	66.0 (13.7%)
15	Lane 3	47.0 (20.5%)	75.7 (1.0%)

A total of 186 trucks were identified for the test day over a 150min period from 11:15 a.m. until 1:15p.m., approximately. The distribution of the speeds and weights of the vehicles are shown in the histograms of Figures 3.30 and 3.31, respectively.

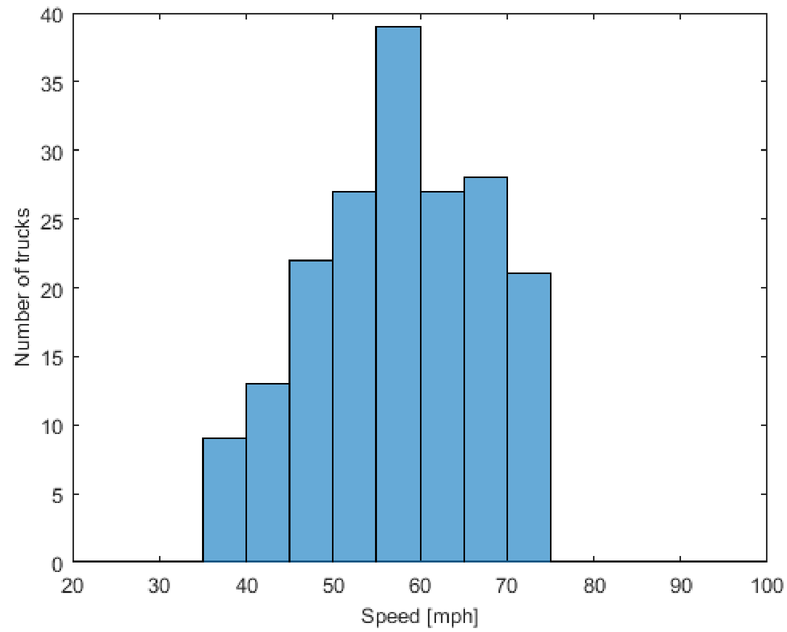

Figure 3.30: Speed histogram for Fulton Terrace Bridge.

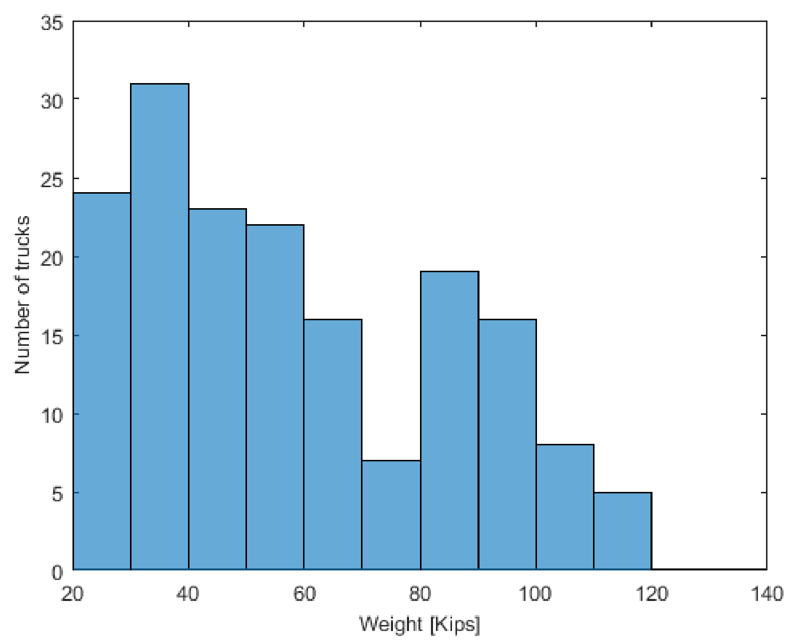

Figure 3.31: Weight histogram for Fulton Terrace Bridge.

The mean speed of the trucks was identified to be 57.7mph, with speeds ranging from 35 mph to 73 mph. The mean weight was 55.2Kips, with weights ranging from 6 Kips to 117 Kips. The weight distribution tends to be bimodal around 35 kips and 90 Kips, which is similar to the case of Lebanon Bridge described before. A total of 48 trucks were identified to have a weight over 80 Kips, corresponding to a 26% of the total. Figure 3.32 shows the distribution of the trucks traveling on each one of the lanes, according to the algorithm. The majority of the trucks tend to travel on Lane 2, corresponding to 97 (52%) out of the 186 trucks identified.

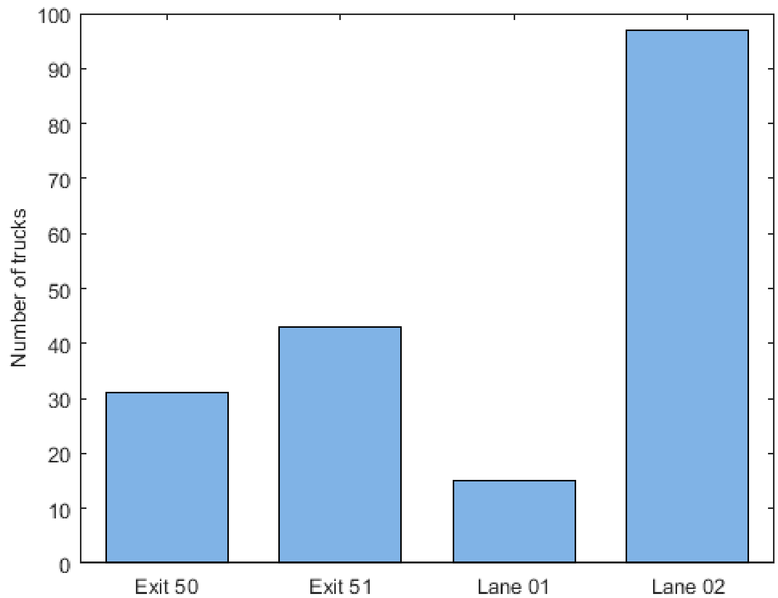

Figure 3.32: Lane count for Fulton Terrace Bridge.

Figure 3.33 shows the distribution of the weigh versus the speed of the trucks. The correlation factor for these variables is 0.46, which means that there is little relation between them. This is shown by the dispersion of the points on the figure.

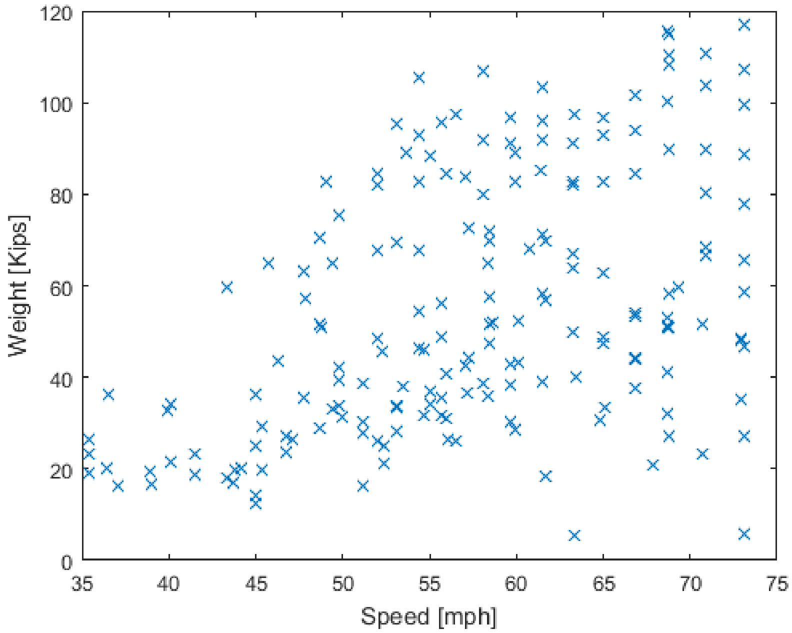

Figure 3.33: Speed vs. weight for Fulton Terrace Bridge.

CHAPTER 4 Conclusions, Recommendations and Suggested Research

The performance of the BWIM system applied to four different bridges in Connecticut is documented in this report. The performance is based on running a truck of known weight over the bridge being studied. The study of four BWIM deployment applications has been successfully completed within the course of this project. This project demonstrated the ability to identify the speed and weight of truck traffic by monitoring strain measurements of various in-service highway bridges. On the I-91 Meriden Bridge, collection and archiving of BWIM data was demonstrated on a three-lane single-span 85-ft. steel girder bridge. This bridge has been monitored since March 2013, and a database that can be readily queried has been established within the scope of the project., Measurement of strain with a sensor attached directly to concrete on a two-lane single-span 95-ft. prestressed concrete girder bridge was demonstrated on the CT state route 2 Lebanon Bridge. It was shown that with sensor extenders made specifically for collecting strain on concrete elements, the BWIM speed and GVW could be calculated from strain measurements located under each lane of travel. On the I-95 Stiles Street Bridge, calculating shear strain from a (normal) strain rosette mounted on a five-lane 100-ft span of a multi-span continuous steel plate girder bridge was demonstrated. This approach can be applied to single-span bridges as well but is useful for continuous span bridges as it allows for localized weight response of the passing truck to be measured on the bridge where truck traffic on adjacent spans can influence traditional BWIM methods. Lastly, on the I-95 Fulton Terrace Bridge, the deployment of a solar-powered BWIM system, intended for weeks or months of deployment, was installed on a five-lane 100-ft. single span steel girder bridge. This system monitors data continuously and collects truck traffic information for processing.

The CT BWIM system offers several advantages to traditional WIM systems, including:

Safety: The safety of workers and the traveling public is paramount in any traffic data collection. The Connecticut BWIM system is completely “non-intrusive” (a.k.a. NOR “Nothing-On-The-Road” (24)), where all sensors and associated equipment can be located under the bridge and off the roadway. This increases the safety of the workers installing and maintaining the system by allowing them to remain out of the traffic and provides safety to the traveling public by minimizing the disruption to traffic flow.

Less Dependent on Pavement Condition/Life: Due to the longer sensing time, while the truck is on the bridge platform, BWIM systems are less susceptible to both vehicle dynamics and pavement road profile and condition. Sensors do not need to be replaced when the pavement is rehabilitated and are less sensitive to the pavement condition.

Discrete: It provides the added benefit that it is not visible to the motoring public. Driver behavior can potentially be altered at WIM sites when there is awareness of the system, and this can skew the collected data. The discrete attribute lends itself well for employment as a virtual WIM.

The benefits of BWIM can only be realized when the system is applied to suitable bridges. It is not envisioned that the CT BWIM system will be applicable to all of the 4,218 bridges in Connecticut. The study allowed for a better understanding of which bridge types and what coverage BWIM can provide on the State-owned 7,700 bi-directional miles of roadway in Connecticut. Deployment of the BWIM equipment on multiple bridges in Connecticut is the next phase to transition this research into CTDOT. Both equipment refinement for deployment and personnel training of the equipment and methods should be a focus of any further research.

Beyond the conditions specific to the BWIM project, it has been observed that the microphone on the bridge can measure (literally hear) the bridge vibration. This has allowed measurement of the natural frequencies of the bridge without the need to install any sensors onto the bridge itself. This work is being extended to explore the possibility of measuring vibration shapes that can provide structural health monitoring information and direct information on bridge condition in an easily implementable manner.

The need for and benefits from accurate and reliable truck weight data are interchangeable. Immediate benefits can be realized for the design and management of pavements. Traffic data is a critical piece of information in design and analysis of pavements as deterioration and damage of pavements is most affected by heavy truck traffic. Due to the exponential relationship between load and pavement deterioration, characterization of traffic can be particularly critical. Correct measurement and estimates of loading result in less risk to CTDOT and cost savings translated from extended pavement life. Improved oversize/overweight truck permitting, bridge load rating and truck re-routing all enable informed decisions and improved expectations of performance that translate into sound investment decisions for CTDOT. Overall, improved network and project-level truck characteristic and weight data can enable the generation of improved practices throughout CTDOT for a healthy transportation network.

In summary, the monitoring accomplished in this research has successfully demonstrated the applicability of BWIM to a broad range of bridge types in Connecticut. The evaluation of enhancements and new approaches to BWIM data processing was accomplished through field tests conducted at each of the in-service highway bridges monitored in this study.

Collaboration with national and international partners was achieved through the delivery of a workshop on BWIM held in Connecticut during October 26-27, 2015. The activities of this workshop are documented in a workshop report provided to CTDOT.

This study also proved that commercially available hardware for collecting BWIM data could be specified and purchased for testing. The equipment was tested on an in-service highway bridge to verify reliability and ease of installation. The system was deployed on the final bridge at the end of the project to evaluate the long-term capabilities of the developed BWIM system. This project has been able to continue to demonstrate it is feasible to collect actual truck weights by a "non-intrusive" system using an instrumented bridge.

4.1. Recommendations

The following recommendations are provided to enhance BWIM in Connecticut.

- Use a strain sensor for each one of the lanes that are of interest. Both the normal bending strain and the shear stress methodologies require the calibration factors that represent the mechanic and geometric properties of the bridge that are difficult to capture with a mathematical model. Therefore, it is very important that the BWIM system is able to identify on which depend on which lane the trucks travel so the proper calibration factor is applied during the calculation of the speed and the GVW. For this purpose, it is needed a comparison of the records obtained from sensors that are installed as close as possible to each one of the travel lanes of the bridge. This arrangement might also be useful to properly investigate spurious cases such as multiple trucks traveling at the same time, trucks traveling back-to-back, and trucks changing lanes on the bridge.

- Use a calibration truck that has five axles. The normal bending strain BWIM method uses the backside of the strain response curve to calculate the speed at which the truck travels over the bridge. This technique is very sensitive to the calculation of the velocity because it is based on finding the peak corresponding to the last axle. For this reason, when the algorithm used in this research is used, it recommended the test truck to be five-axle, because typically they have longer distances between axles, and the identification of them is easier on the strain records. This has the potential to increase the accuracy of the calculation of the calibration factors for the speed and the GVW. Further, explore the possibility of escorting the calibration truck to avoid other nearby vehicles.

- Use a video camera that captures the passages of the test truck. During the test day, many vehicles and trucks travel over the bridge of interest. The use of a video camera is very efficient for the identification of the passage of the truck on the strain records, avoiding the use of other trucks that might have similar properties.

- Avoid the use of non-rhomboid bridges. Trapezoidal bridges introduce more variables and uncertainty in the BWIM calculations.

4.2. Suggested research

To ensure a sustainable deployment of BWIM technologies, it is important to have straightforward deployable systems, easily retrievable results, a clear understanding of the limitations of the equipment, and sufficient training materials available to ensure people can use the system. Further research efforts should continue to strive to meet these goals.

Furthermore, BWIM data can be used to estimate the remaining fatigue life of existing bridges. With the installed sensors, strain data and stress time history for the critical locations of the bridges can be obtained. Coupled with numerical simulations of vehicle-bridge interactions, the fatigue damage accumulations might be evaluated based on the fatigue damage model and cycle counting techniques for the stress time history and stress-range bin histogram. The effects of stress levels and environmental corrosions on structural members will be useful for the Department to make maintenance and repair strategies.

Research is suggested to continue BWIM data collection at the Meriden (I-91) Bridge for improvement and further understanding of BWIM data processing, including vehicle classification and traffic volume. Research is also suggested to purchase and deploy reliable, easy to deploy portable monitoring systems for BWIM in Connecticut, provide training materials for CTDOT employees to provide sufficient knowledgebase to properly deploy and produce data from BWIM systems.

Research is also suggested to explore new sensors methods applied for monitoring bridges including infrasound (low-frequency acoustics) and vision-based processing of video in particular for eventual BWIM applications.

CHAPTER 5 Implementation of Research Results

Findings from this research study were documented and disseminated in the form of reports and presentations. The project has resulted in two BWIM systems operating in the State. These systems can continue to be operated to collect BWIM data for the State.

A follow-on implementation project can serve to bring BWIM into use in the Department.

References

Federal Highway Administration's Traffic Monitoring Guide. FHWA, April 2013. Available (10/31/13) at: http://www.fhwa.dot.gov/policyinformation/tmguide/tmg_fhwa_pl_13_015.pdf

FHWA Truck Weight Survey Data (VTRIS). Available (10/31/13) at: https://fhwaapps.fhwa.dot.gov/vtris-wp/

Tang, Tianja (FHWA) presenting "MAP-21 Traffic Monitoring". FHWA Talking Traffic Webinar, July 2012.

Strocko, Ed (FHWA) presenting "Data Opportunities and Challenges in Meeting MAP-21 Performance Measure Requirements". TRB Plenary Session2, June 11, 2013. Available (10/31/13) at: http://onlinepubs.trb.org/onlinepubs/conferences/2013/MPO/Strocko.pdf.

Van de Lindt, J.W., Fu, G., Zhou, Y., and Pablo Jr., R. (2006). "Locality of Truck Loads and Adequacy of Bridge Design Load". Journal of bridge engineering, ASCE, Vol.10, No.5, pp. 622-629.

Fu, G. and Van de Lindt, J.W. (2006). "LRFD Load Calibration for State of Michigan Trunkline Bridges". Report RC-1466, Michigan Department of Transportation, MI.

Kwon, O., E. Kim, S. Orton, H. Salim, and T. Hazlett (2010). "Calibration of the Live Load Factor in LRFD Design Guidelines," Project 2a. Report, Missouri Department of Transportation, MO

MAP-21, USDOT Comprehensive Truck Size and Weight Limits Study, October, 2013. Available at: http://www.ops.fhwa.dot.gov/freight/sw/map21tswstudy/index.htm.

Fountain, Henry, "Panama Adding a Wider Shortcut for Shipping". New York Times, originally published on August 16, 2011. Link available at (10/31/13): http://www.nytimes.com/2011/08/17/science/17canal.html?pagewanted=all&_r=0

Transportation Research Board Annual Meeting, Session on Freight Systems, January 2013.

Connecticut Academy of Science and Engineering (2008). "A Study of Weigh Station Technologies and Practices", a report by the Connecticut Academy of Science and Engineering for the Connecticut Department of Transportation, November 2008.

Moses, Fred. "Weigh-In-Motion System Using Instrumented Bridges". American Society of Civil Engineers, Transportation Engineering Journal, v 105 n3, May 1979.

SiWIM Information Available (10/31/13) at: http://www.siwim.com/

Honefanger, J., Stawhorn J., Athey, R., Carson, J., et. al. “Commercial Motor Vehicle Size and Weight Enforcement in Europe”. FHWA, FHWA-PL-07-002, July 2007.

Hitchcock, W. Uddin, N., Sisiopiku, V., et al. “Bridge Weigh-In-Motion (B- WIM) System Testing and Evaluation”. University of Alabama, FHWA/CA/OR, UTCA Report Number 07212, April 2009.

Cardini, A., Olund, J. DeWolf, J. D’Attilio, P., Feldblum, E., McDonnell, A. presenting (CTDOT) “Use of A Bridge Monitoring System for Weigh-In-Motion (WIM) Evaluation”. National Traffic Monitoring Conference (NATMEC), Minneapolis, MN, 2006.

Wall, C., Christenson, R., McDonnell, A., Jamalipour, A. “A Non-Intrusive Bridge Weigh-In-Motion System for a Signal Span Steel Girder Bridge Using Only Strain Measurements”. Connecticut Department of Transportation, CT-2251-3-09-5, August 2009.

Wall, C., Christenson, R. “A Bridge Weigh-In-Motion Case Study in Connecticut”. Proceedings of the Transportation Research Board Annual Meeting, Washington DC, January 2009.

Christenson, R., Bakulski, S., McDonnell, A. “Establishment of a Dual-Purpose Bridge Health Monitoring and Weigh-In-Motion System for a Steel Girder Bridge”. Proceedings of the Transportation Research Board Annual Meeting, Washington DC, January 2011.

ASTM E 1318, Road and Paving Standards. “Standard Specifications for Highway Weigh-In-Motion (WIM) Systems With User Requirements and Test Methods”, 2009.

Christenson, R., McDonnell, A., Motaref, S. “A Dual Purpose Bridge Health Monitoring and Weigh-In-Motion System for a Steel Girder Bridge”. Paper 46, Proceedings of the 6th International Conference on Weigh-In-Motion, (Jacob B., et. al. Editors), June 2012.

Vaziri, S., Haas, C., and Rothenburg, L. “Investigation of Piezoelectric Weigh-in-Motion Sensors’ Performance in Asphalt Concrete Pavements in Cold Temperatures of Southern Ontario”. 91th Annual Meeting of Transportation Research Board, Washington D.C., January 2012.

National Bridge Inventory (NBI) Information. Available at (): https://www.fhwa.dot.gov/bridge/nbi.cfm

Jacob, B. “Weighing in Motion of Axles and Vehicles for Europe (WAVE) Project”, 2002.

NCHRP 1-37A. “Guide for Mechanistic- Empirical Design of New and Rehabilitated Pavement Structures – Final Report,” Part 2, Design Inputs, Chapter 4, Traffic”, March 2004.

Lu, Q., Zhang, Y., and Harvey, J. “Analysis of Truck Traffic Growth for the Mechanistic-Empirical Pavement Design Guide”. Transportation Research Board, Washington D.C., January 2007.

Christenson, R.E. and Motaref, S. (2016). “Dual purpose Bridge Health Monitoring and Weigh-in-Motion (BWIM) -- Phase I”. Report Number CT-2265-F-15-7.

Li, J. (2014). “Structural Health Monitoring of an in-service highway bridge with uncertainties”. PhD thesis, Department of Civil and Environmental Engineering, University of Connecticut, 2014, pp. 52.

Wall, C.J., Christenson, R.E., McDonnell, A.M. and Jamalipour, A. (2009). “A Non-Intrusive Bridge Weigh-in-Motion System for a Single Span Steel Girder Bridge Using Only Strain Measurements”. Report Number CT-2251-3-09-5. pp. 20

Ojio, T. & Yamada, K. (2002). “Bridge Weigh-in-Motion System Using Stringer of Plate Girder Bridges”. Pre-Proceedings of the Third International Conference on Weigh-In-Motion, Orlando, pp. 209-218.

Kosnik, D. (2012). “A Web-enabled data management system for structural health monitoring of civil infrastructure”. PhD dissertation. Northwestern University, Evanston, Illinois.

Kosnik, D. and Dowding, C. (2014). “Autonomous monitoring of dynamic response of in-service structures for decision support.” Journal of Structural Engineering, 10.1061/(ASCE)ST.1943-541X.0001044 , D4014003.

Kosnik, D. (2012). “A combined weigh-in-motion and structural health monitoring system on a Wisconsin-Michigan border bridge.” In Proceedings of the 6th International Conference on Weigh-in-Motion. Wiley-ISTE.

Kosnik, D., Zhang, W., and Durango-Cohen, P. (2014). ” Application of statistical process control for structural health monitoring of a historic building.” Journal of Infrastructure Systems, 20(1), 05013002.