# USE OF STRUCTURAL HEALTH MONITORING DATA TO EVALUATE THE EFFECTS OF PERMIT VEHICLES AND THE CREATION OF A SYNTHESIZED REPORT FORMAT

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Civil Engineering

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# ABSTRACT

Current methods for load rating bridges are based on simple girder analysis. This is not an ideal procedure for many complex bridges, and as more and more complex bridges are built, new methods are needed to aid bridge owners in generating accurate load ratings. When trying to accurately load rate a complex bridge, such as a cable-stayed bridge, the use of analysis results from detailed FEM models is required. This results in a very time consuming and costly process.

The research reported herein focuses on a specific class of vehicles for rating known as permit vehicles. Permit vehicles are very large loads that exceed the legal limit and need to be individually evaluated to see if they can be permitted to cross a specific bridge (sometimes with specific restrictions). In order to determine if a permit vehicle can cross a bridge, the bridge owner must first evaluate the vehicle's effect on the bridge, and if needed, determine the necessary restrictions for the vehicle.

This research aims to provide a simple method for rating permit vehicles for complex bridges through the utilization of structural health monitoring (SHM) data. By using a combination of influence lines generated based on SHM data and traditional load rating equations, a method for determining a rating factor for any vehicle that crosses a bridge is developed. This method is then applied to the Indian River Inlet Bridge.

A second, and separate, contribution of the research was to create a simple synthesized quarterly report format that would enable DelDOT to more easily understanding the data produced by the Indian River Inlet Bridge's SHM system. The

report provides a quick way of viewing and evaluating three-month's worth of data. This allows the owner to quickly see how the bridge is performing, and can help to identify any issues that may need attention.

# Chapter 1

# INTRODUCTION

## 1.1 Problem Description

Two distinct areas of research were conducted and are reported herein. The first deals with creating a simplified method for computing permit vehicle ratings using structural health monitoring (SHM) data. The second area deals with how to best synthesize large quantities of SHM data and report it in an easily understood format.

Due to the complexity of cable stayed bridges, load rating of permit vehicles is a complicated, time consuming, and costly process. The Delaware Department of Transportation (DelDOT) currently uses methods that break down the complexity of the structure into a simplified model, which may lead to inaccurate ratings. To address the limitations of the simplified model, a complex FEM model is currently created using STAAD. This model is used to predict the effects of the permit vehicle. The difficulty with this approach is that it is labor intensive with no guarantee that the model is accurate. The goal of the first area of research is to utilize SHM data collected from the Indian River Inlet Bridge (IRIB) to create a simpler and more accurate method of determining a rating factor for permit vehicles. This method involves the use of influence lines created from live load data and captured by the SHM system.

When dealing with complex bridges having comprehensive SHM systems, one will accumulate massive amounts of data. It can become overwhelming to look at all the data and assess what it means. With regards to the SHM system on the Indian River Inlet Bridge (IRIB), one can easily view the data in real time, and all of the data is stored. However, since there is so much data being recorded and stored, there needs to be an easy way to synthesize the data, view it, and evaluate it. Only by having a simple synthesized report on the collected data can the owner be able to quickly and efficiently understand the status of the bridge. Satisfying this need leads to the second area of research: to create quarterly reports that synthesize the data from all important sensors and report it in an easy to understand format. If done so properly, the quarterly reports will allow DelDOT to see what the current condition of the bridge is through a series of simple tables and graphs.

## 1.2 Background

The research presented in this thesis uses data acquired by the IRIB's SHM system. The particular data used was collected during a controlled load test conducted in May of 2016. This data is used to develop an influence line which in turn can be used to rate the bridge.

To help better understand the research explained herein, background information regarding several different aspects of the work are provided. In Section 1.2.1 information regarding the research conducted by Catbas et al. on the use of influence lines in combination with structural health monitoring can be found. This research is similar to the research found herein and provides some evidence as to the validity of the developed method used to determine the rating factors of permit vehicles. In Section 1.2.2, information regarding what permit vehicles are and the current methodology for calculating rating factors for them can be found. This method is useful for simple structures, but may not be appropriate for complex bridges. In

Section 1.2.3, a quick description of the general load rating procedure is presented, as is research that was conducted on how to use load test data to provide more accurate rating factors when using standard rating equation.

### 1.2.1 Influence Lines and Structural Health Monitoring

The use of influence lines in combination with structural health monitoring was investigated by (Catbas et al, 2012). Catbas et al. created influence lines using structural health monitoring and video recordings while studying the Sunrise Bridge in Fort Lauderdale, Florida (see in Figure 1).

Figure 1: Sunrise Bridge (Catbas et al, 2012)

They used video images and computer software along with influence lines from SHM data in order to determine load ratings of vehicles as they drove over the bridge. They used the video and software to categorize the vehicle that was driving over the bridge. Once categorized, the magnitude and position of the axle loads are known and influence lines can be extracted using the location of the vehicle on the bridge. This process produces a normalized influence line, as shown in Figure 3, which gives the response regardless of the weight or type of the vehicle.

The research by Catbas et al. demonstrated the accuracy and usefulness of determining rating factors using influence lines. However, their research produced rating factors only for a specific truck that had already crossed the bridge. The method developed herein uses the influence line concept to compute a rating factor for any vehicle that might cross a bridge in the future. By using an influence line created by a calibrated test truck, the method developed herein can be used to predict the truck's strain effect and compute a rating factor of any vehicle that might cross the IRIB.

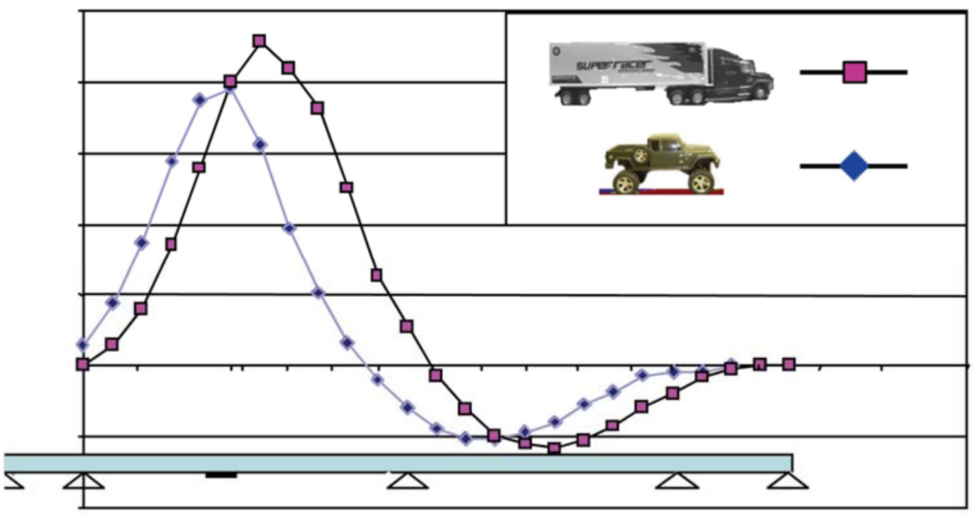

Figure 2: Strain vs Distance (Catbas et al, 2012)

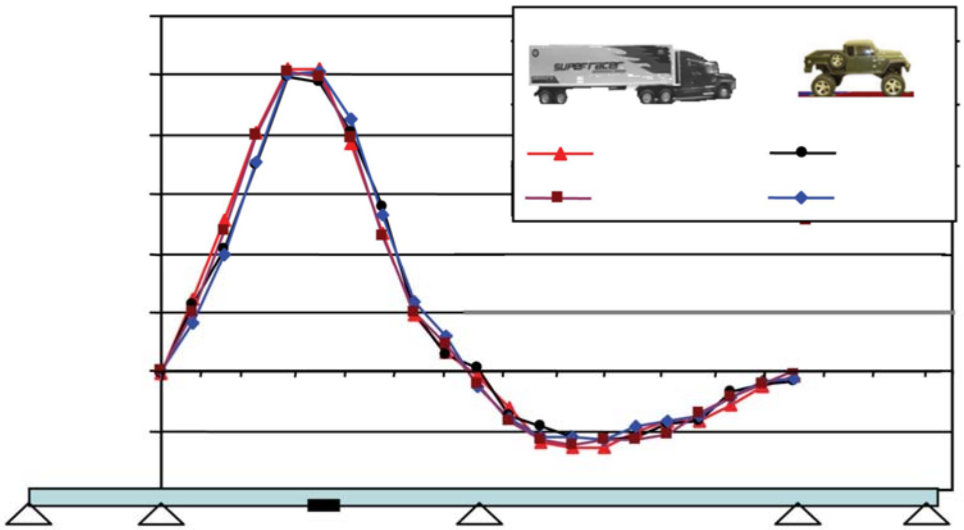

Figure 3: Unit Influence Lines (Catbas et al, 2012)

Another study that involved experimentally calculated influence lines was presented in Hirachan and Chajes's paper on "Experimental Influence Lines for Bridge Evaluation" (Hirachan, 2005). The work showed the value of experimentally determined influence lines, and how to create them from diagnostic load tests.

### 1.2.2 Permit Vehicle

A permit vehicle as defined by AASHTO is “Any vehicle whose right to travel is administratively restricted in any way due to its weight or size” (AASHTO, 2009). The restriction comes in the form of a written document. This document is called a permit which AASHTO defines as “The written agreement by which a transportation department approves the use and occupancy of highway rights-of-way by utility facilities or private lines” (AASHTO, 2009). Permit vehicles are typically designated using “Oversize Load” or “Wide Load” signs on the front and back of the truck (see Figure 4).


Figure 4: Oversize Load Truck Carrying a Bridge Beam (Wikipedia Image)

#### 1.2.2.1 DelDOT Permit Calculation Method

The current way that DelDOT determines if a permit vehicle will be safe to travel across the Indian River Inlet Bridge is by using a program called QPERMIT. An example of the QPERMIT screen can be seen in Figure 6. All of the information regarding the calculation method used by QPERMIT was taken from the Delaware Standard Specification (Transportation, 2015).

The first step of the process involves calculating the maximum allowable weight using a formula based on the Bridge Gross Weight Formula published by the Federal Highway Administration (Federal Highway Administration, 1994). The formula uses a combination of the distances between the axles and the number of consecutive axles that the vehicle has. The Bridge Gross Vehicle Weight formula yields possible maximum allowable weights (W) of the vehicle to the nearest 500 lb.

$$W = 500 \times \left[\frac{L \times N}{N-1} + 12 \times N + 36\right]. \qquad \text{Equation 1.1}$$

Where:

- L = the distance between the extreme of any group of two or more consecutive axles, feet
- N = the number of axles in the group under consideration.

The program runs this equation multiple times using different combinations of axle groups with their respective lengths. Figure 5 shows an example of a truck containing three axle groups. An axle group is the group of axles being considered, for example axles 1, 2, and 3 from Figure 5, would be called Axle Group 1, then axles 2, 3, 4, and 5 would be Axle Group 2, and lastly axles 1, 2, 3, 4, and 5 would be Axle Group 3.

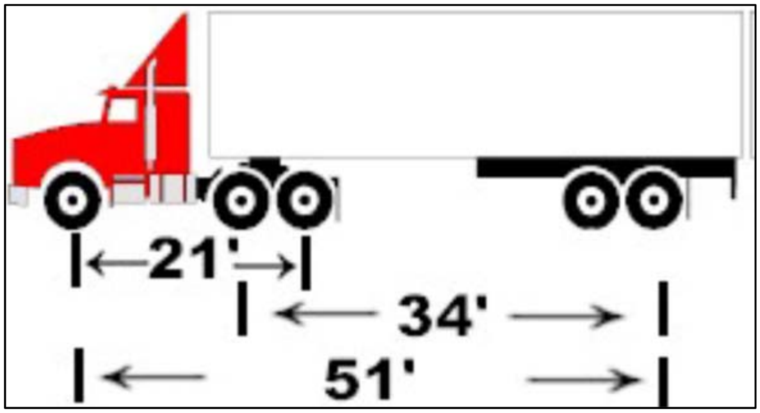


Figure 5: Axle Group Example (Transportation, 2015)

In this case the formula would be used three times to calculate the maximum allowable weight for the vehicle (which is the largest of any of the W values computed). Once the maximum allowable weight is calculated, the program calculates the equivalent factor (EF)

$$EF = \frac{Actual\ Weight}{Max\ Allowable\ Weight}. \quad \text{Equation 1.2}$$

Where:

- Actual Weight = the sum of all the axle weights being considered.

The next step for QPERMIT involves forking off into two different procedures depending on what information is available. If there are permit analysis results for the selected bridge on file, then the program performs a Permit Analysis Procedure. If analysis results are not available, the program performs the HS20 Operating RF Evaluation Procedure. For the IRIB there are no permit analysis results to use, so the

HS20 Operating RF Evaluation Procedure needs to be performed. The first step in this process is to calculate the comfort factor (CF) for each axle group.

- If the maximum span length of the bridge exceeds the length of the axle group spacing.
    - Then:
        - $CF = \frac{HS20\ Oper.Rating\ Factor}{HS20\ Equivalent\ Factor}$. Equation 1.3

Where:

- HS20 Operating Rating Factor = a value associated with the bridge.
- HS20 Equivalent Factor = the EF determined in Equation 1.2.

- If the maximum span length of the bridge is less than eight feet.
    - Then:
        - $CF = \left[32000 \times \left(\frac{HS20\ Oper\ RF}{Max\ Axle\ Weight}\right)\right]$. Equation 1.4

The span length of the IRIB is larger than any axle group will be, so the first equation is used. The final step is to see if the vehicle can cross the bridge. If the lowest comfort factor value is greater than or equal to one, then the permit vehicle can proceed without restrictions. If the lowest comfort factor value is less than one, the permit vehicle cannot be allowed to cross the bridge unless the bridge is evaluated using a more robust method that shows that it is safe to cross. This usually involves creating detailed computational models which can be very time consuming.

The following is an example of the QPERMIT method applied to the truck from Figure 5. Axle 1 weighs 12,000 lbs and Axles 2-5 weigh 17,000 lbs each. To reiterate, Axle Group 1 is axles 1-3, Axle Group 2 is axles 2-5, and Axle Group 3 is axles 1-5.

Step 1: Calculate the Equivalency Factor.

Axle Group 1,

$$W(actual) = 12{,}000 + 17{,}000 + 17{,}000 \rightarrow 46{,}000\ lbs$$

$$W = 500 * \left[\frac{21 \times 3}{3 - 1} + 12 \times 3 + 36\right] \rightarrow 51{,}750\ lbs$$

$$EF = \frac{46{,}000}{51{,}750} \rightarrow 0.889$$

Axle Group 2,

$$W(actual) = 17{,}000 + 17{,}000 + 17{,}000 + 17{,}000 \rightarrow 68{,}000\ lbs$$

$$W = 500 * \left[\frac{34 \times 4}{4 - 1} + 12 \times 4 + 36\right] \rightarrow 64{,}666\ lbs$$

$$EF = \frac{68{,}000}{64{,}666} \rightarrow 1.052$$

Axle Group 3,

$$W(actual) = 12{,}000 + 17{,}000 + 17{,}000 + 17{,}000 + 17{,}000 \rightarrow 80{,}000\ lbs$$

$$W = 500 * \left[\frac{51 \times 5}{5 - 1} + 12 \times 5 + 36\right] \rightarrow 79{,}875\ lbs$$

$$EF = \frac{80{,}000}{79{,}875} \rightarrow 1.002$$

Step 2: Calculate the Comfort Factor. The HS20 Operating Rating Factor is given as 2.66. For this example the bridge span length is 70 feet which is greater than the total length of the truck, so a Comfort Factor must be calculated. Since Axle Group 2 produced the largest Equivalency Factor, it is the governing Axle Group. Therefore, as shown, the Comfort Factor is 2.66 and since that is greater than 1.0, the vehicle can safely cross the bridge

$$CF = \frac{2.66}{1.052} \rightarrow 2.53$$

$$CF \; > 1.0 \rightarrow Vehicle\ is\ OK$$

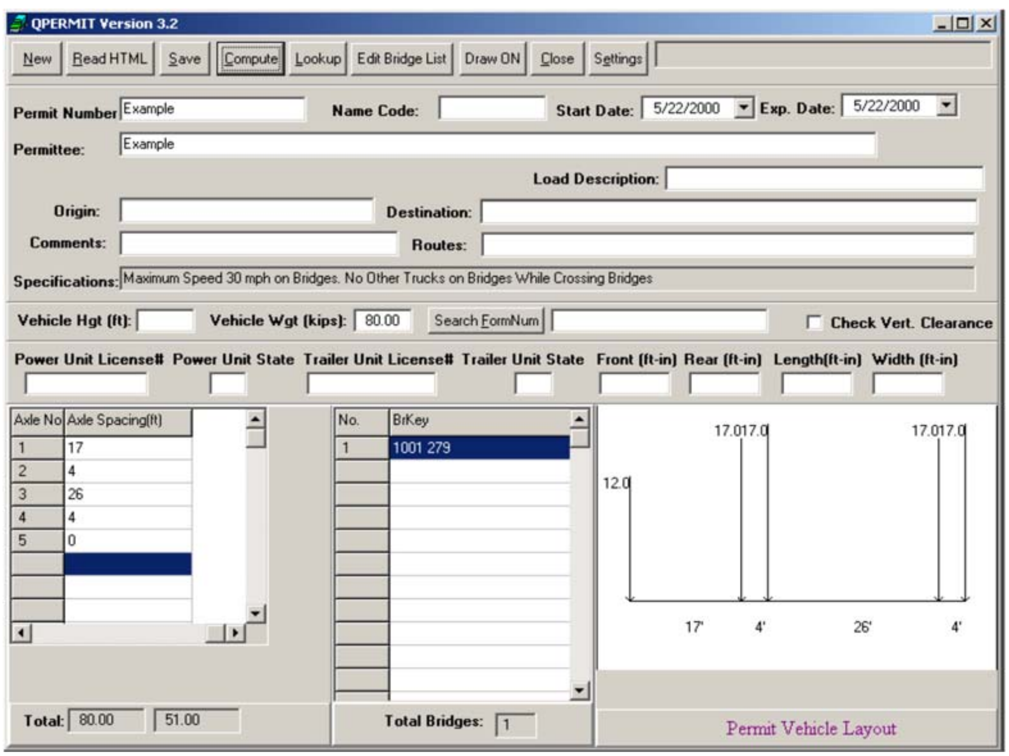


Figure 6: Example of QPERMIT Screen (Transportation, 2015)

Because the IRIB is a complexed structure, the QPERMIT method is not the most accurate for determining whether or not a permit vehicle can cross the bridge. If the vehicle's comfort factor is computed to be less than one, either the truck needs to be prevented from crossing the bridge, or an engineer will have to spend significant time conducting FEM analyses to see if the vehicle actually can safely cross. To address this limitation, a methodology that uses the data collected by the IRIB SHM system has been developed and a Matlab code was written to rapidly calculate accurate rating factors for any permit vehicle that requests to cross the IRIB.

### 1.2.3 General Load Rating

Load rating is comprised of two components: inspection and analysis. Inspection provides the necessary information for analysis regarding any major changes to the bridge, for example, cracking, loss of section, scour, or damage. The analysis takes the information from design and adjusts them based on inspection results to calculate the rating of the bridge. The general rating equation, as defined by AASHTO, is:

$$RF = \frac{Capacity - Dead\ Load}{Live\ Load} \qquad \text{Equation 1.5}$$

Research performed by Pablo Marquez (Marquez, 2013) demonstrates the benefits of using load test data for load rating. "Load rating using load testing can be conducted using the typical load rating equation, given in Equation 1.5, except that the live load effects are measured rather than obtained analytically" (Marquez, 2013). This measured field data can be used to calculate more accurate rating factors.

## 1.3 Contributions of this Research

Although calculating rating factors via influence lines and SHM has been done before in Catbas et al.’s research, the methodology developed here is different than theirs. As stated previously, the Catbas method uses a combination of video software, influence lines and SHM data to calculate the rating factors of vehicles as they pass the bridge. By using the data in real time, along with the video, they are able to categorize and calculate the rating factor without the need of knowing the actual weight of the vehicle. However, this method cannot be used to compute rating factors for trucks before they cross the bridge. As such, their method is useful for research purposes, but not for evaluating permit vehicles. The methodology developed and reported in this thesis allows rating factors to be computed for any vehicle prior to its crossing the bridge. By using this method, permit vehicles can be evaluated before they cross the bridge (and in fact, the method would be used to evaluate the permit vehicle and help decide if a permit should be granted). All the method requires is the axle spacings of the permit vehicle and the weight of the various axles. The method is only as accurate as the axle weights and spacings given by the company requesting the permit. Furthermore, the method uses unit increments of feet across the bridge so there are slight approximations in axle spacing due to rounding the axle spacing to the nearest foot. The reason this is done is to be able to automate the Matlab calculations. However, even with these approximations, the method provides a very accurate and reliable permit rating for the owner to use to make a decision regarding a permit. For instance, the Indian River Inlet Bridge has a governing rating factor of 1.17 for a HL93. If the proposed method produces a rating factor around that value, the DOT may feel inclined to perform another calculation just to be safe. But if the rating factor is around 3 to 5, then the DOT can confidently know that the vehicle is going to be fine traveling across the bridge.

# Chapter 2

# BRIDGE AND SYSTEM DESCRIPTION

## 2.1 Bridge Details

The Indian River Inlet Bridge (IRIB) is a 1,750 foot long cable-stayed bridge in southern Delaware that carries four lanes of traffic on Delaware Route 1 over the Indian River Inlet. The construction of this bridge was completed in 2012. The main span is 950 feet and the back spans are 400 feet each. The cables are connected to four pylons with each pylon having two separately connected symmetric sets of cables. Due to previous problems with scour, the design of the Indian River Inlet Bridge called for its pylons to be built on land to hopefully avoid the scour issue that caused past problems. The bridge is 106 feet wide with two lanes and a shoulder in both the northbound and southbound directions. The northbound direction, located on the east side of the bridge, also has a 12 foot walkway. This walkway causes the centerline of the bridge to be shifted towards the west side, causing the highest stresses to occur in the west girder. Figure 7 shows the elevation view of the bridge.

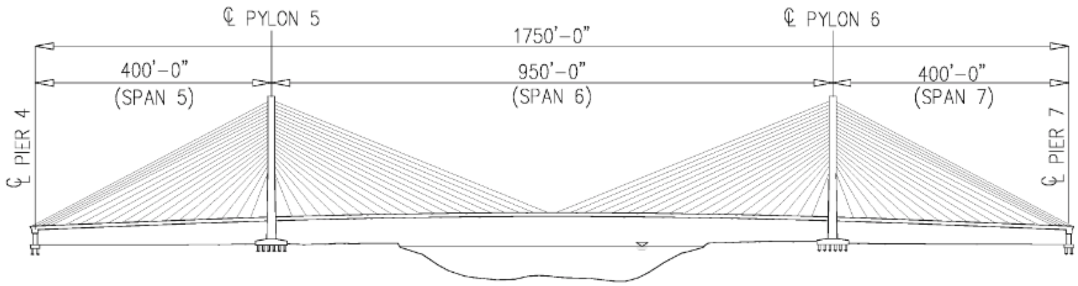


Figure 7: Elevation View of the Indian River Inlet Bridge (Marquez, 2013)

### 2.1.1 Edge and Transverse Girders

The edge and transverse girders, as shown in Figure 8, are comprised of pre-cast and cast-in-place beams. These beams are approximately six feet tall and five feet wide and are spaced about 12 feet apart. The beams are reinforced with rebar with a concrete strength of about 8,200 psi on average. The deck is supported by the beams and is about 8 ½ inches thick with a 1 ½ inch thick wearing surface. The edge and transverse girders are post-tensioned together to further increase the strength of the beams. The edge girders contain the cable-stay anchors, which are spaced at about 24 feet, which can be seen in Figure 9.

Figure 8: Edge and Transverse Girders for the IRIB (Courtesy of M. Haddad)

Figure 9: Cable Stay Anchors on West Edge Girder for the IRIB (Courtesy of M. Haddad)

### 2.1.2 Cable-Stays and Pylons

As stated previously, each cable is anchored into the pylon and is non-continuous. Since the cables are non-continuous they can be removed and replaced easier and have less of an impact on the strength of the bridge. Also if a cable were to break, the other side doesn't break with it or lose strength. Each of the four pylons contain 38 stay anchors per pylon, breaking down into 19 anchors per north and south side. A pylon cable stay anchor can be seen in Figure 10 and an exterior cable stay anchor can be seen in Figure 9.

Figure 10: Cable Stay Anchor inside Pylon for the IRIB (Curtesy of M. Haddad)

Each cable contains 270 ksi seven wire strands, which are approximatly 0.62 inches in diameter. The strands are coated in grease and plastic and are contained inside a helical high density polyethylene pipe (HDPE) to protect the strands against outside elements and prevent corrosion. Each cable contains a varrying amount of strands ranging from 19 strands towards the bottom of the pylon to 61 strands towards the top.

## 2.2 Structural Health Monitoring System

### 2.2.1 Overview of System

The SHM system used is fiber-optic and most of the sensors are embedded along the entire length bridge, with some of the sensors being surface mounted and accessible from the outside. The fiber optic sensors work by measuring the change in the wavelength of a light beam, which is then converted to its appropriate unit of measure (i.e. strain, rotation, movement, etc.). The sensors used in the system include 27 accelerometers, 72 strain sensors, 2 anemometers, 16 corrosion sensors, 9 tilt meters, and 3 displacement sensors, which can be seen in Figure 11. The strain gages and corrosion sensors are embedded in the concrete edge girders, deck, and pylons, while the remaining sensors are surface mounted. The data from the sensors is relayed to the data acquisition system that is located in a communications hut under the bridge. The data recording speed can be altered at any time by adjusting the frequency. If high speed data is desired, then the recording frequency is increased. If low speed data is desired, then the recording frequency is decreased. Both of these speeds provide us with important information about the bridge.


Figure 11: Sensor Locations on the Bridge (Marquez, 2013)

#### 2.2.1.1 Important Sensors

The sensors of most importance to this research are SW7 and 8 and SW21 and 22, and they are located in the west edge girder. These are deemed the critical sensors as they are located at the location that controls the load rating, SW 21 and 22, and at midspan where it has been shown that the rating is very similar to the controlling location, SW7 and 8. As such, these sensors are expected to record the largest strains on the edge girder. Figure 12 shows where the sensors are located longitudinally on the bridge. SW7 and SW21 are located about five inches from top face of the girder and measure compression (negative strain) when the location is experiencing positive bending, while SW8 and SW22 are located about five inches from the bottom face of the girder and measure tension (positive strain) when the location is experiencing positive bending. Because these two locations control the bridges load rating, they will be the primary focus of my research when trying to calculate the rating factor of permit vehicles.

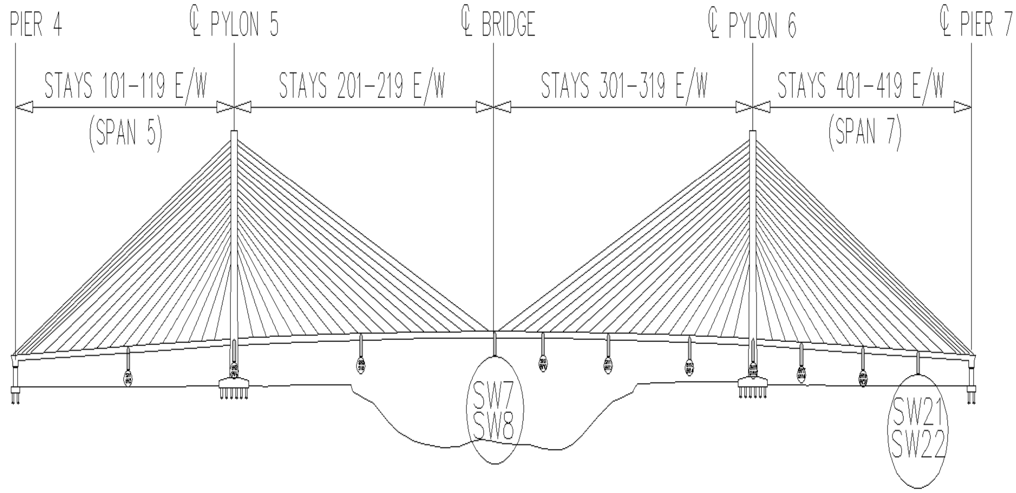


Figure 12: Key Sensor Locations (Marquez, 2013)

# Chapter 3

# LOAD TEST

## 3.1 Load Test Description

One reason controlled bridge load tests are performed is to enable researchers and bridge owners to compare actual recorded values to those predicted using computational models. It also allows one to see how the bridge system responds to a variety of loadings. To date, five controlled load tests have been performed on the IRIB. The most recent of these was called Load Test #5 and was conducted on May 18, 2016. During that test, 28 separate truck load passes were conducted, including several passes of truck trains conducted specifically for this effort. The trucks used during the test were three-axle dump trucks (see Figure 13), which were provided by DelDOT. The trucks were weighed, using portable scales, prior to arriving at the bridge. The trucks were positioned on the south side of the bridge and driven northbound in specified lanes depending on the pass. Passes 1 through 22 varied based on the number of trucks used and what lane they travelled in. A pass 0 was also conducted for the purpose of monitoring tilts and conducting a survey of the bridge to measure the deflection of the edge girder. Passes 23 through 26 involved various truck trains (multiple trucks in a train) and all truck trains travelled in the southbound slow lane. A more detailed discussion of the truck trains and their use is presented in the next section.

Figure 13: Typical Truck Used During Load Tests (Courtesy of G. Wenczel)

### 3.1.1 Truck Train/Permit Vehicle Simulation

Truck trains are two or more trucks driven very close together in the same lane. Truck trains are used to simulate a multi-axle permit vehicle and the resulting strains from these passes can be used to validate the methodology being developed herein for permit vehicle evaluation. During this load test the trucks were spaced about 7 feet apart (distance from rear bumper of the forward truck to front bumper of the rear truck). Passes 23 and 25 were two-truck trains, Pass 24 was a three-truck train, and Pass 26 was a four-truck train. All truck train layouts can be seen in Figure 15. Figure 16, Figure 17, and Figure 18 give the axle spacings and axle weights for the 6 trucks used during the load test. Truck #2771 was the truck that was in the single truck pass in the southbound slow lane and was the lead truck in both of the two-truck trains. Truck # 2904 followed Truck #2771 in both of the two-truck trains. For the three-truck train, Truck #2677 was the first truck, Truck #2829 was the second truck, and Truck #2943 was the third truck. For the four-truck train, the three-truck train order was used with Truck #2783 as the fourth truck. Figure 19 is a picture that was taken while the three-truck train was crossing the bridge.

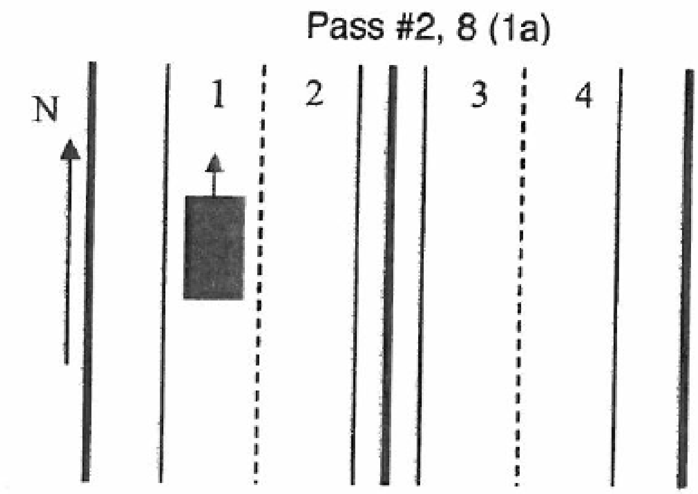


Figure 14: Load Test 5 Pass #2 Single Truck in Southbound Slow Lane

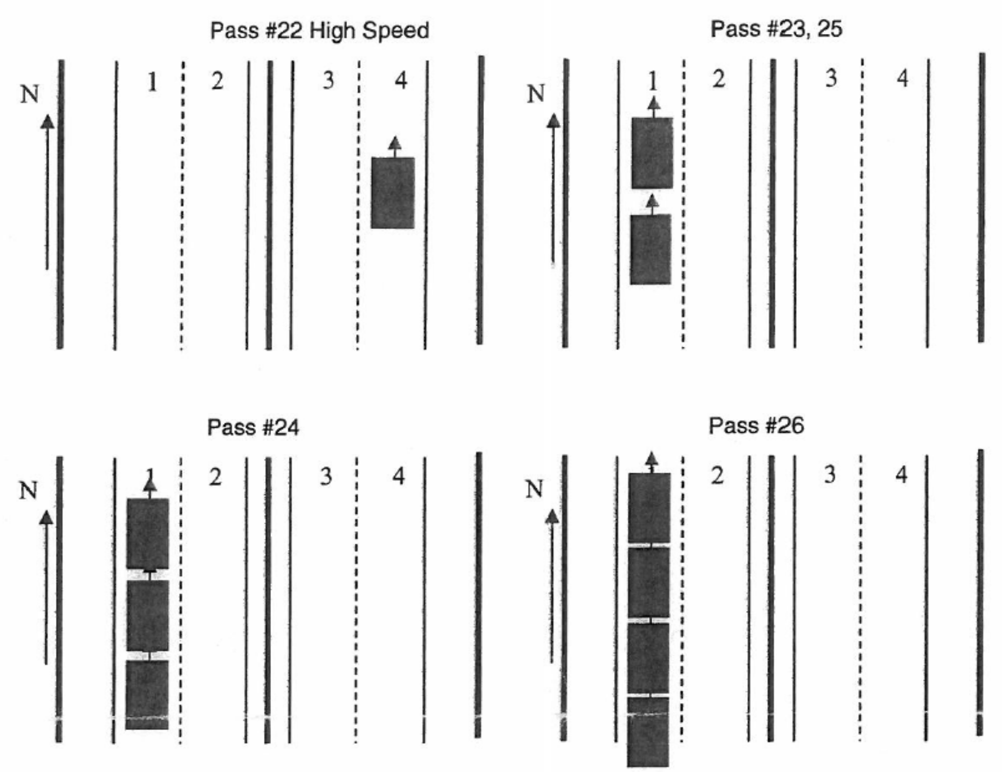


Figure 15: Load Test 5 Passes 23-26 Truck Trains in Southbound Slow Lane

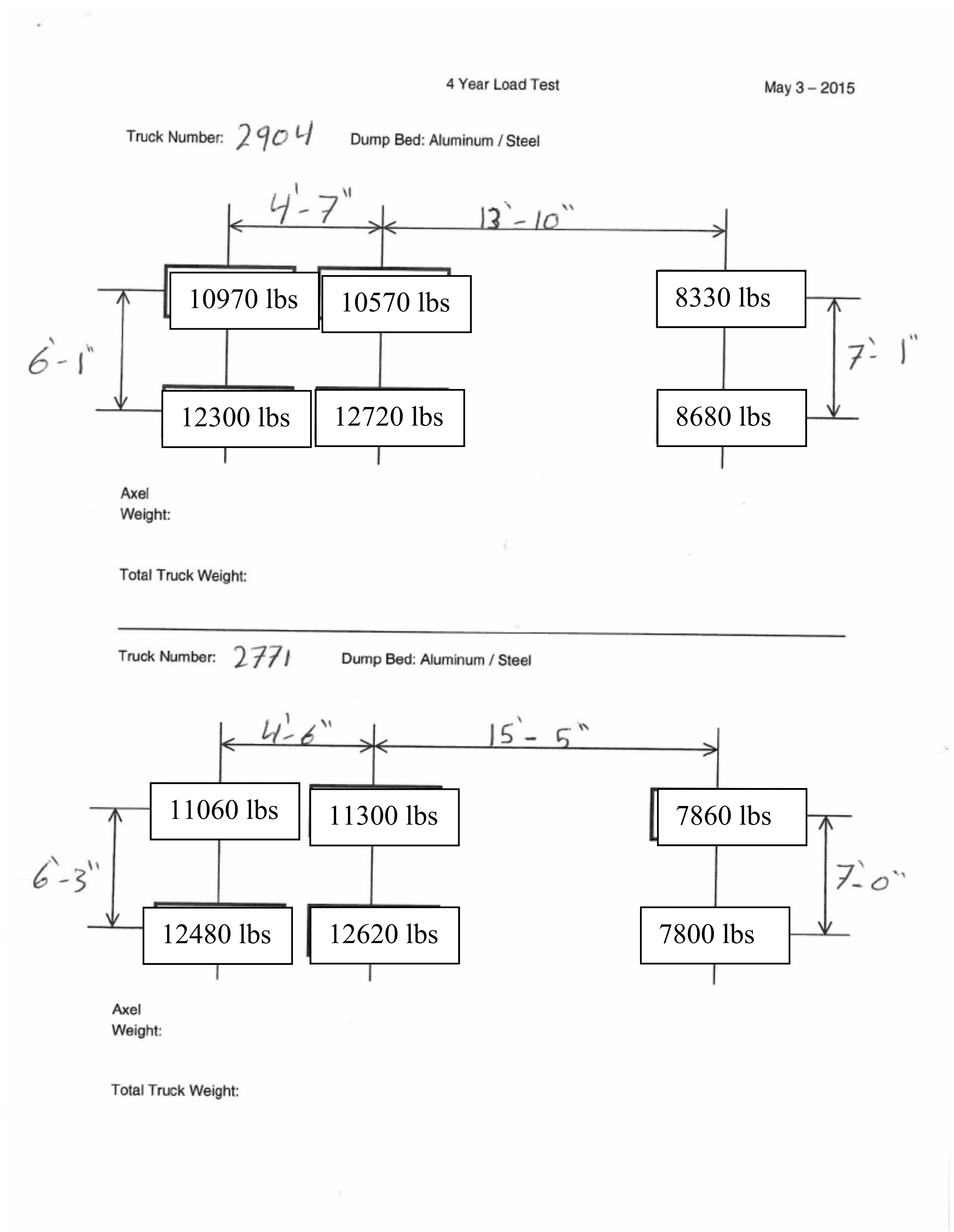


Figure 16: Load Test 5 Trucks 1 and 2

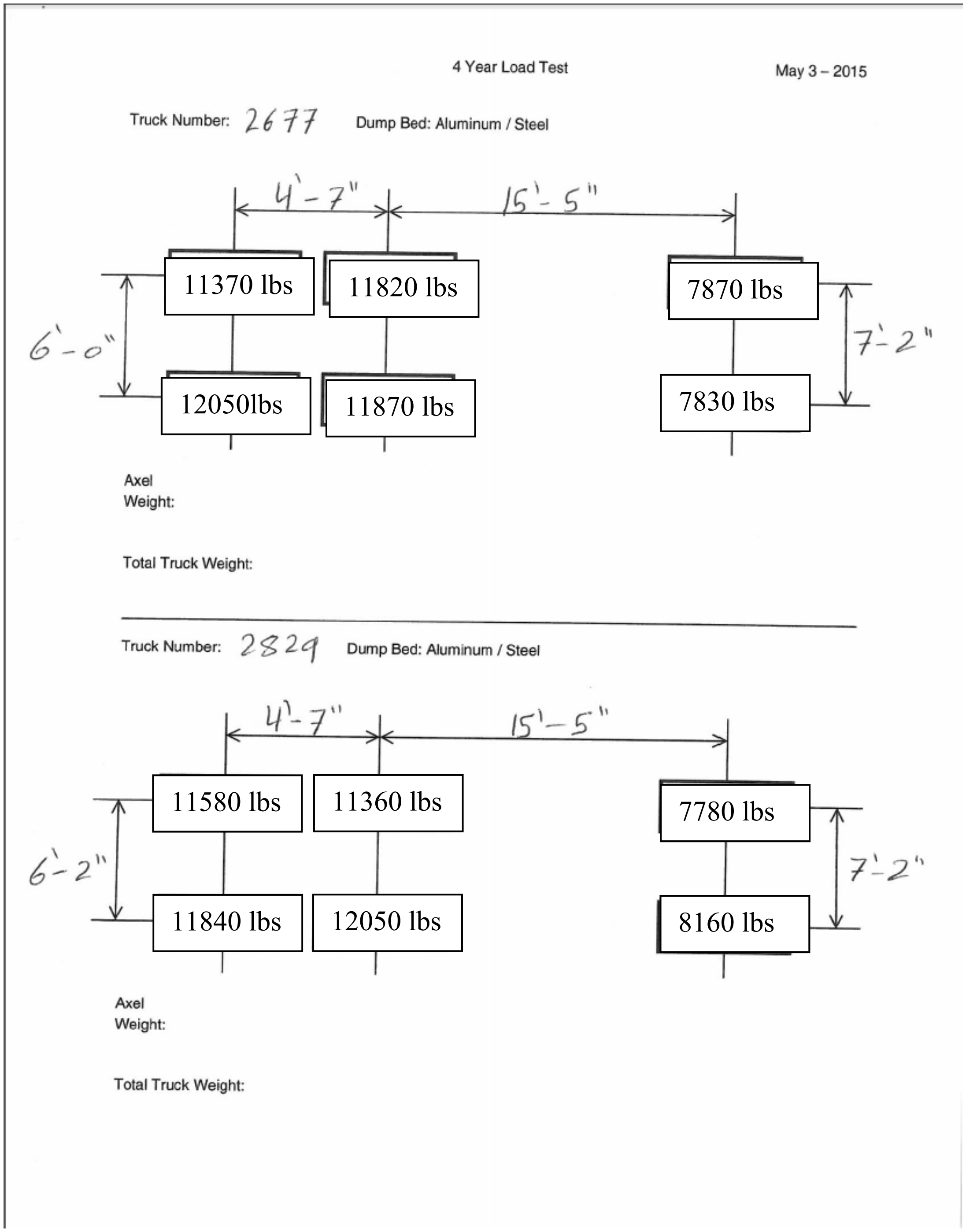


Figure 17: Load Test 5 Trucks 3 and 4

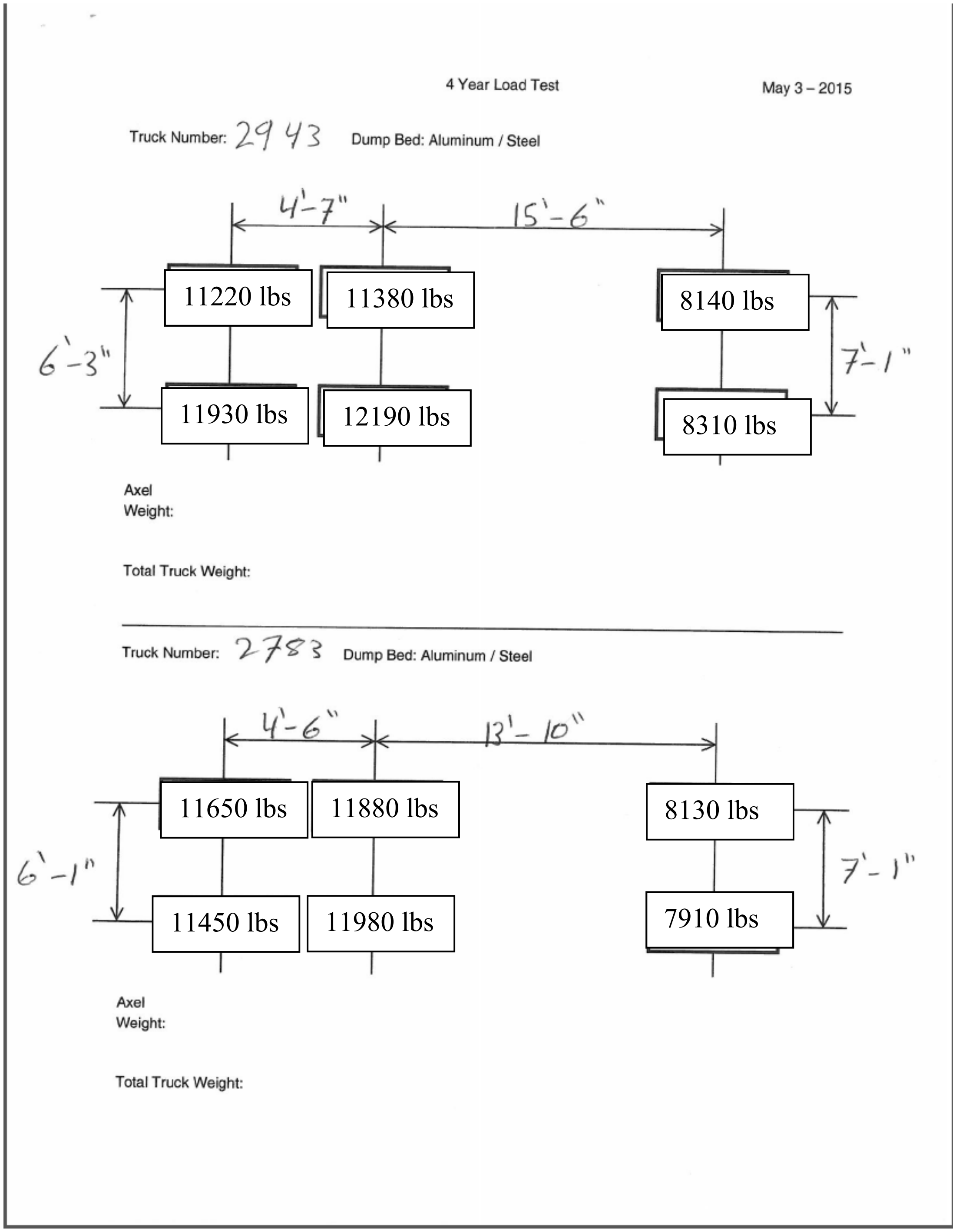


Figure 18: Load Test 5 Trucks 5 and 6

Figure 19: Three Truck Train, Pass 24 (Curtesy of M. Haddad)

## 3.2 Data Analysis

In analyzing the load test data, the first step was to create a time history plot of the strain data from sensors SW8 and SW22 for all truck train passes including the single truck pass in the southbound slow lane. The strain data contained noise, some of which is it due to bridge vibration. To create a smoother influence line, as would be expected theoretically, the noise was removed using a smoothing function within Matlab. A smoothed time history for Pass 23 (a two-truck train) is shown in Figure 20.

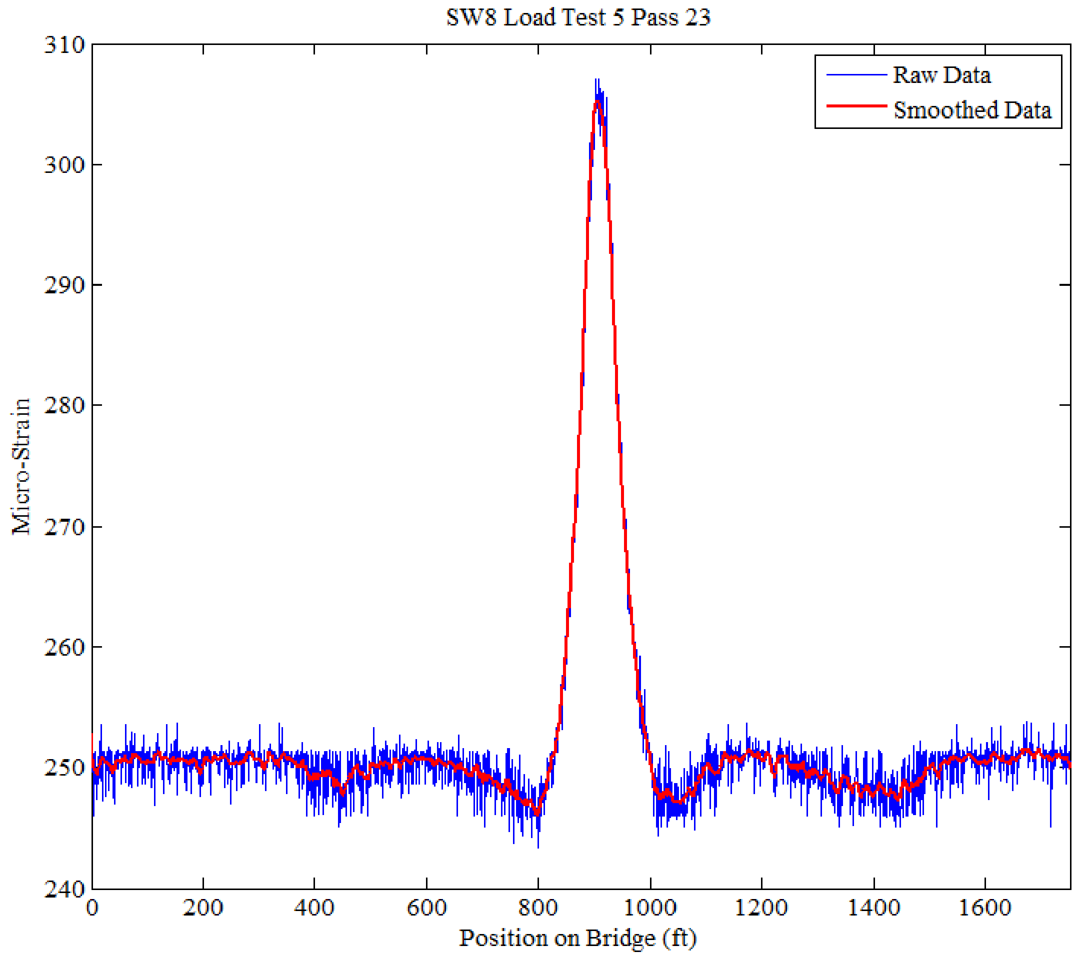


Figure 20: Load Test 5 Pass 23 at Midspan

The next step is to shift the curve such that the initial and final values are zero. These initial and final values represent the strain at midspan when the truck train first comes onto the bridge and then when it finally leaves the bridge. In both of these instances, we would like to zero this strain as we are interested in the strain relative to these two instances (i.e. how much strain is induced by the truck train). This will then show the change in strain caused by the truck. The zeroed plot is shown in Figure 21.

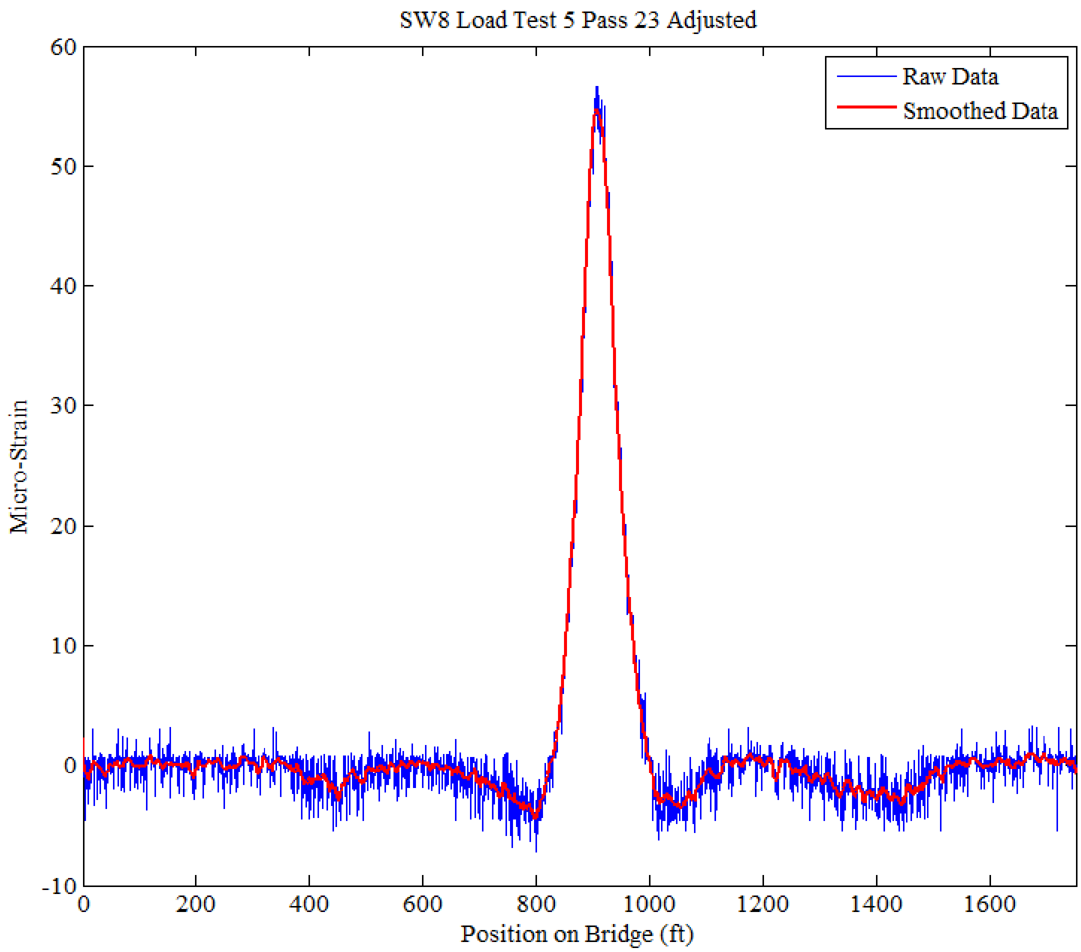


Figure 21: Load Test 5 Pass 23 Adjusted at Midspan

The plots created for all the truck train passes, for SW8 and SW22, after the smoothing function and shifting, served as a means to compare maximum strain values that were recorded by the system to the maximum strain values that will be calculated using the developed influence line methodology. The full code for the smoothing and zeroing can be found in Appendix (A).

# Chapter 4

# PERMIT VEHICLE LOAD RATING

## 4.1 Methodology

AASHTO provides a method for load rating bridges in their LRFD Specifications (American Association of State Highway and Transporation Officials, 2014). The AASHTO rating formula is a function of the live load effects on the bridge. The live load effects can either be computed analytically using design parameters to model the bridge, or collected from the bridge through field testing or structural health monitoring. Live load effects collected through field tests or structural health monitoring can provide a very accurate rating since they reflect the actual bridge response due to a given truck load including environmental effects.

If one wants to compute the load rating of a specific permit vehicle, one can either estimate the live load effects using an analytical model, or estimate the effects using information from prior load tests. In the case of the IRIB, standard rating methods that use simple line-girder analysis are not possible due to the complexity of the cable-stayed structure. If live load effects are to be estimated analytically for the IRIB, detailed FEM analyses must be performed. To overcome the many challenges of implementing FEM analyses for each and every permit vehicle, a method for utilizing load test data to predict the live load effects of any permit vehicle was developed.

The basis for predicting live load effects on the IRIB for any permit vehicle involves utilizing an experimentally derived influence line for the IRIB that comes directly from load test data. An influence line gives the force, moment, strain, etc., at a given point on a structure due to a unit load that moves across the entire structure. Once an influence line is created, superposition can be used to find the live load effect of any permit vehicle (assuming the axle configuration and axle weights are known). That live load effect can then be used within any load rating methodology.

#### 4.1.1 Using Data from an Analytical Model to Evaluate Various Influence Lines

Since a load test will yield an influence line due to a truck and not due to a point load, an analytical model was used to show that for the IRIB, a very long span bridge, the influence line for a truck is very similar to the influence line of a point load. The model data used to make this comparison was from a 3D beam element model of the IRIB that was created by Hadi Al-Khateeb using the program CSI Bridge (Computers and Structures, Inc (CSI), 2017).

Figure 22 provides a comparison of influence lines generated using the analytical model for both a 1-kip point load and a 1-kip truck load (the truck is the same single truck used in the load tests). As one can see, the influence line for the truck is nearly identical to the influence line for the point load. This indicates that one can use an influence line created by a test truck crossing the bridge to represent an influence line for a point load crossing the bridge.

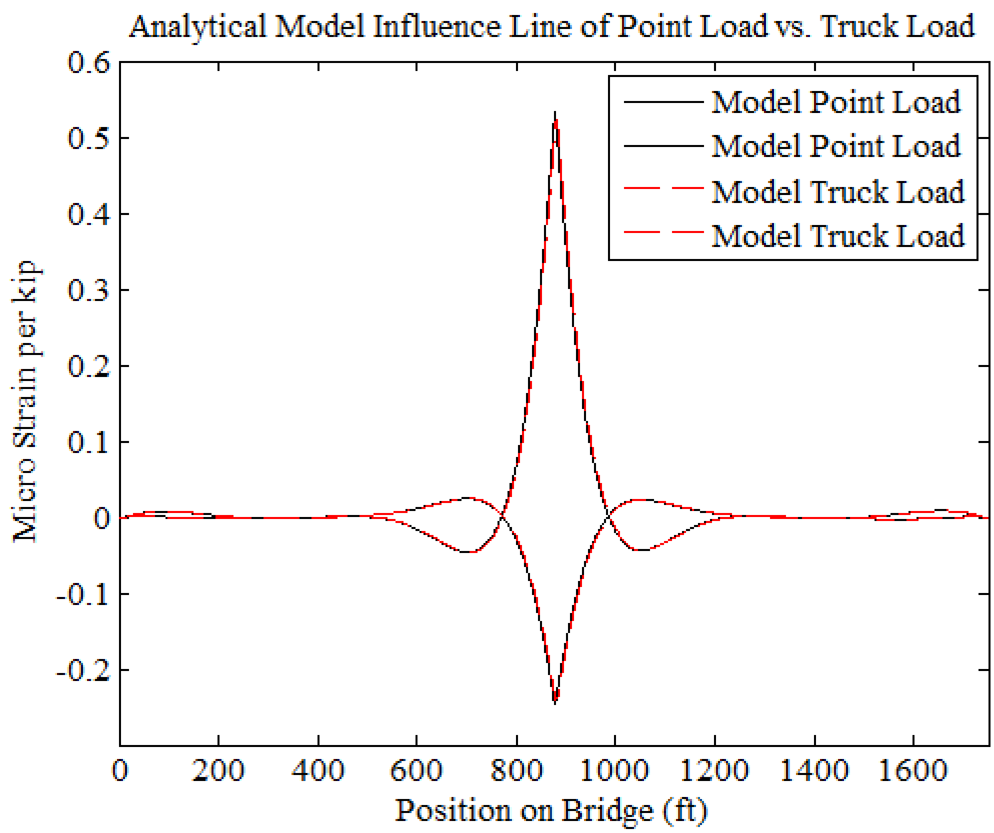


Figure 22: Comparison between Analytical Model Point Load and Truck Load Based Influence Lines at Midspan

### 4.1.2 Using Field Test Data

As it has just been shown, one does not have to rely on an analytical model and the inherent assumptions in that model to get an influence line for strain at critical locations on a long span bridge if field test data is available. In fact, perhaps the most accurate way to generate such an influence line is to utilize data from a controlled diagnostic load test. The influence line to be used in the rating method that will be developed herein was created using measured strain data from a single truck crossing the IRIB in the western slow lane (pass 2) during load test 5. This pass was selected because it represents a truck traveling in the lane that will cause the largest strains in either the east or west edge girder.

In terms of the mechanics of creating an influence line from load test data, one first needs to convert the strain vs. time data to strain vs. distance data. In order to do this, one needs to determine the average velocity of the test truck based on the length of the bridge and the time it takes for the truck to cross the bridge. One can then convert the time of each data point to a corresponding location along the span. This is an approximation as the truck is not actually travelling at a constant velocity. To make the influence line more easily useable when stepping a unit loads across the bridge, it is helpful to find values for the influence line at unit increments (one foot in this case). This requires approximating the influence line values through interpolation at each unit increment from the strain vs. distance values.

After converting the time data to distance, a normalized experimental influence line for strain in the west edge girder at midspan is found (see Figure 23). To get the normalized influence line, the measured strain values are divided by the total weight of the test truck.

Figure 23 also provides a comparison of the experimentally derived influence line due to an actual test truck (after normalizing it) to that of the response produced using an analytical model subjected to a 1-kip truck. The comparison shows how the experimentally derived influence line is very similar to the one computed using an analytical model. In fact, the magnitudes of the experimentally derived influence line are more accurate than the approximations given by the analytical model. Both of these comparisons show that the experimentally derived influence line can be used to predict the strain effects for any truck crossing the IRIB. The difference in the location of the peak along the x-axis is due to the use of the average truck speed when converting time to distance.

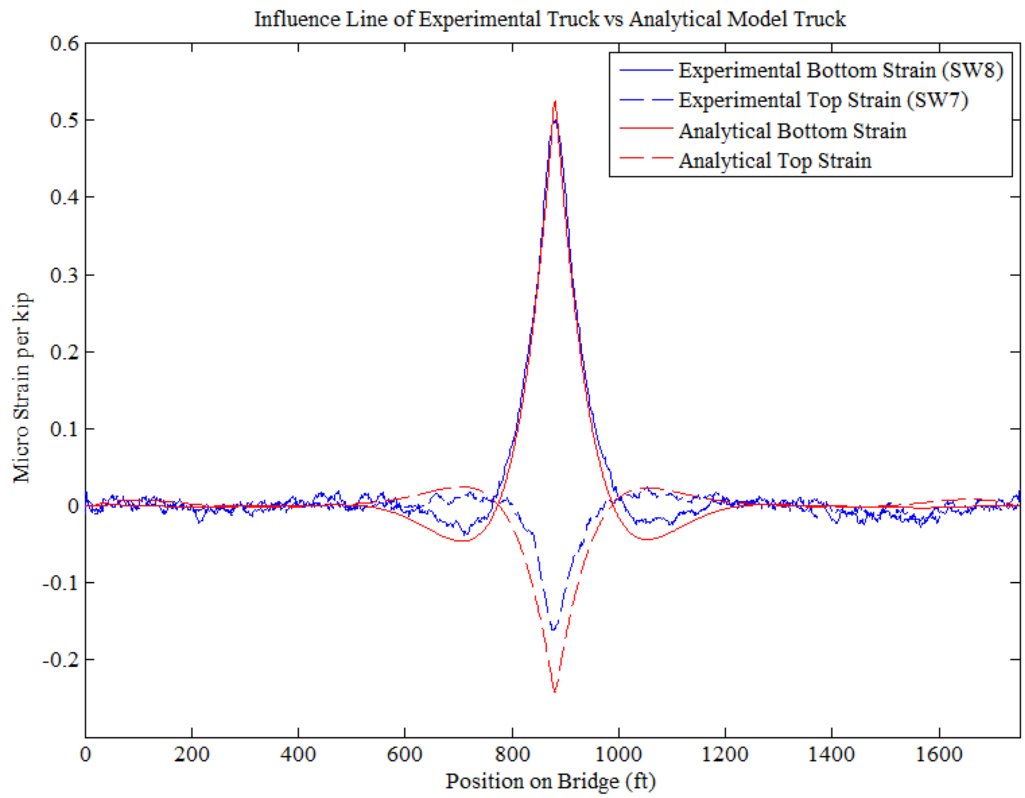


Figure 23: Measured Data Influence Line at Midspan

Figure 24 shows the experimental influence line for strain at the controlling location. The controlling location is the location along the edge girder that controls the load rating of the IRIB.

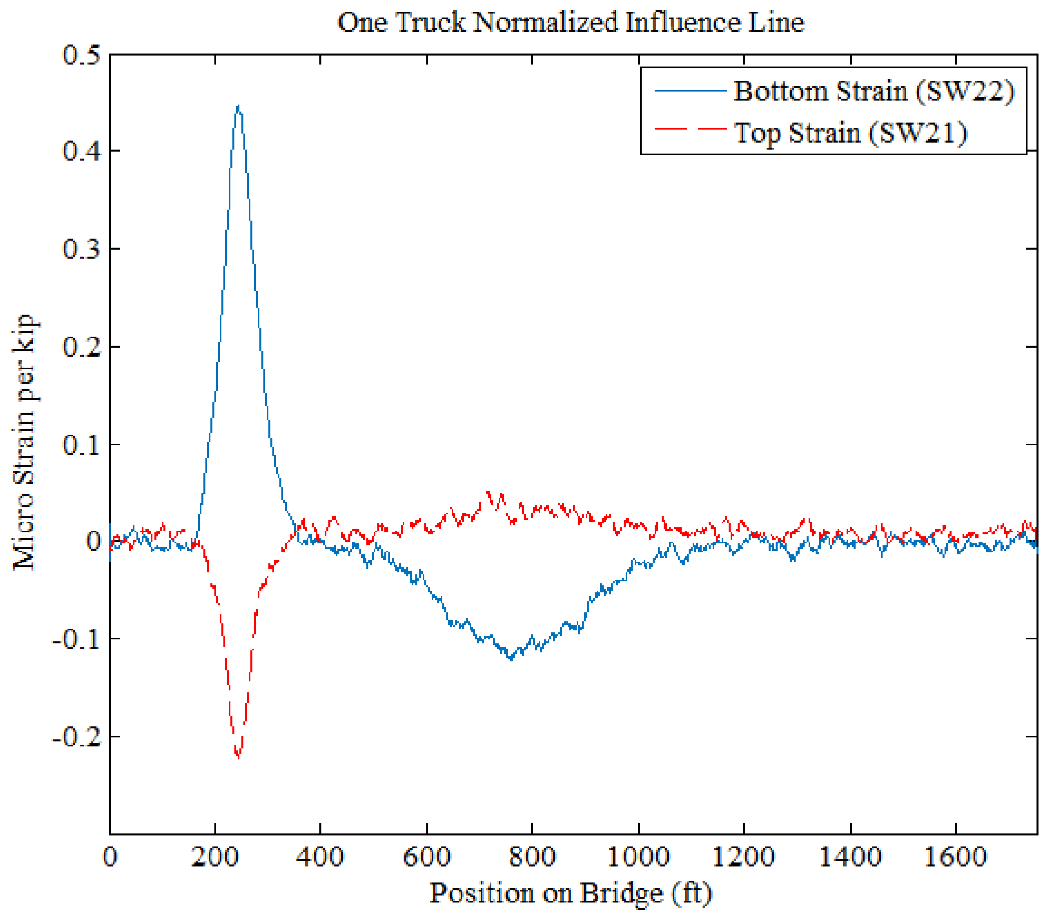


Figure 24: Measured Data Influence Line at the Controlling Location

Having the experimental strain influence lines for the midspan and controlling locations, the next step is to move the axles of the truck being evaluated along the bridge (i.e. along the influence line) to determine the strain caused by each axle. The axle spacings are rounded to the nearest foot so they will line up with the longitudinal ordinates of the influence line (which is also one foot). By incrementally moving the axle train across the bridge one foot at a time, the maximum strain caused by the truck can be determined. The effect of the truck at any location is found by summing strains caused by each axle multiplied by their respective axle weights. The largest value found after incrementally moving the truck, one foot at a time, across the influence line is the largest possible strain caused by the truck. This is the live load effect that will be used in the rating process.

In addition to needing the live load effect of the truck being evaluated, it is also useful to have the effect of an HS20 vehicle. Since the axle spacing and axle weights for an HS20 are known, the same procedure utilizing the experimental influence line can be followed. Doing so leads to the strains given in Table 1 where tension is positive.

Table 1: Predicted Peak Strains at Midspan and Controlling Location due to an HS20

| Girder | Midspan | Controlling location | Units |
|---|---|---|---|
| Top | -11.1 | -15.5 | (με) |
| Bottom | 33.4 | 29.8 | (με) |

In the next section, it will be shown that the peak strain values obtained using the experimental influence line accurately predict the peak strain values at midspan and at the controlling location due to an individual truck and due to closely spaced truck trains comprised of two, three, and four trucks (these trains are meant to resemble permit vehicles).

### 4.1.3 Comparing Measured Peak Strains to Ones Computed Using Influence Lines

Tables 2 and 3 compare the peak strains, recorded during load test 5 for passes involving a single truck and truck trains of two, three, and four trucks (all traveling in the western most slow lane), to strains computed using the experimental influence lines. As one can see, the computed peak strains are very close to the measured values for all cases. For the midspan location, the computed values differ between 2.0 and 8.1 percent. At the controlling location, the computed values differ between 3.1 and 9.6 percent. These differences are relatively small, and likely smaller than the accuracy to which the bridge owner will know the exact weight of the permit load vehicle. This means that the use of the experimental influence lines to predict peak strains can safely be done. It should be noted that using an influence line based on a truck in the western most travel lane will lead to the largest (i.e. most conservative) strain, and therefore will provide a conservative value for the rating factor.

Table 2: Results using the Experimental Influence Line Compared to Actual Data from Load Test 5 at Midspan

| | Bottom Strain (με) (Tension) | | | Top Strain (με) (Compression) | | |
|---|---|---|---|---|---|---|
| # of Trucks | Actual Data | Field Test Data Influence Line | % Difference | Actual Data | Field Test Data Influence Line | % Difference |
| 1 | 33.24 | 30.56 | -8.1% | -10.17 | -9.37 | -7.9% |
| 2 | 54.72 | 53.49 | -2.2% | -15.24 | -15.82 | 3.8% |
| 3 | 70.96 | 73.22 | 3.2% | -18.43 | -18.80 | 2.0% |
| 4 | 81.43 | 86.38 | 6.1% | -19.61 | -20.96 | 6.9% |

Table 3: Results using the Experimental Influence Line Compared to Actual Data from Load Test 5 at the Controlling location.

| | Bottom Strain (με) (Tension) | | | Top Strain (με) (Compression) | | |
|---|---|---|---|---|---|---|
| # of Trucks | Actual Data | Field Test Data Influence Line | % Difference | Actual Data | Field Test Data Influence Line | % Difference |
| 1 | 28.24 | 26.48 | -6.2% | -14.33 | -12.96 | -9.6% |
| 2 | 48.58 | 46.98 | -3.3% | -22.70 | -21.53 | -5.2% |
| 3 | 60.57 | 58.00 | -4.2% | -27.27 | -25.31 | -7.2% |
| 4 | 69.29 | 65.41 | -5.6% | -28.47 | -27.58 | -3.1% |

Figure 25 further demonstrates the accuracy of the influence line. One can see that the influence line for the three truck train closely matches the actual recorded data. The x-axis offset of the influence line result is due to being based on the front axle location and not the location of the centroid of the truck.

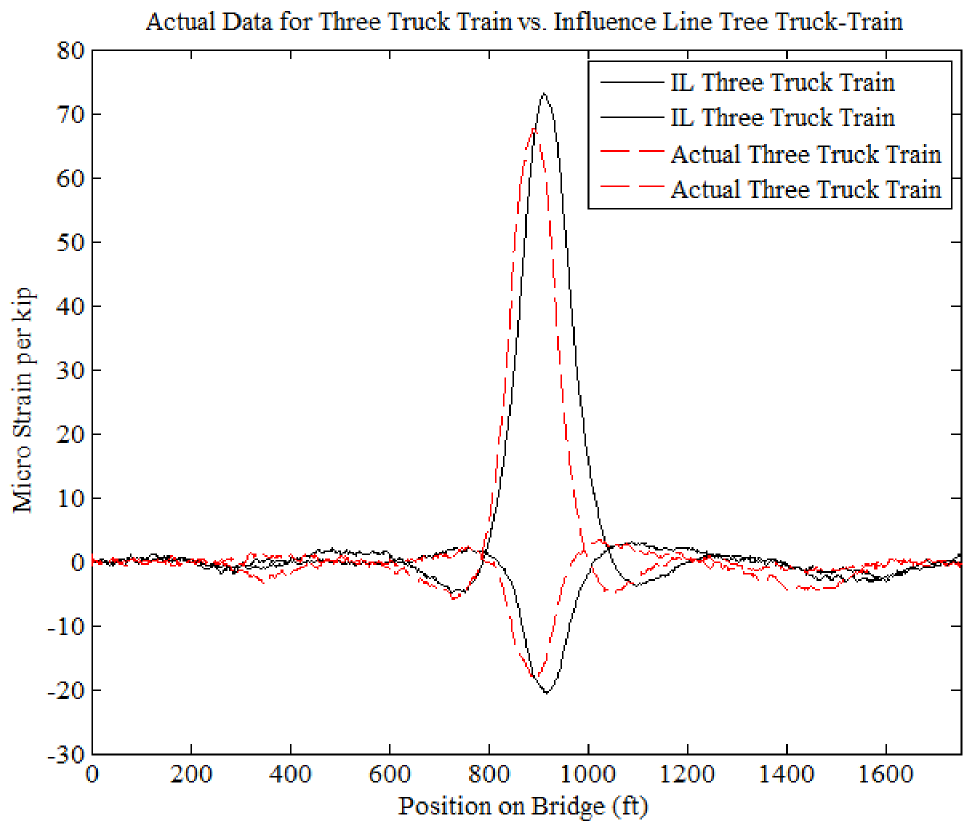


Figure 25: Comparison between Actual Data vs. Influence Line Predicted Data for the Three Truck Train from Load Test 5

## 4.2 General Load Rating Equation

Now that it has been established that accurate live load effects can be predicted using experimental influence lines and without the need for a complex analytical model, it is possible to simply and efficiently generate load ratings utilizing the standard rating methodology. The basic rating factor (RF) equation from AASHTO is as follows:

$$RF = \frac{Capacity - Dead\ Load}{Live\ Load}. \qquad \text{Equation 4.1}$$

When computing a rating factor during the design process, design live loads are used. These are assumed loads and the most common loading to apply is due to a hypothetical HL-93 loading. The HL-93 loading is composed of an HS-20 truck with an added lane load which has been found to yield the appropriate moment for design. It should be noted that for long span bridges, because the HL-93 loading includes a lane load, it results in a very large loading that yields quite conservative (i.e. low) rating values. The rating based on design was found to be 1.17 by AECOM (Al-Khateeb, 2016). The purpose of the large design load is to ensure a safe (conservative) design. The design rating factor is not meant to be used for making operational decisions regarding the bridge (i.e. what vehicles can safely cross it).

When performing a load rating for an existing bridge, in order to evaluate whether or not specific vehicles can safely cross it, bridge management engineers use specific trucks (like the HS-20 truck or a permit vehicle) for the loading without the lane load (since a distributed lane load will not likely be on the bridge when the truck is on the bridge). This will yield an appropriate rating factor for that vehicle, and a value that can be used in determining whether or not a specific vehicle can cross the bridge (or if a bridge needs to be posted for a certain class of vehicles). For an HS20 truck, this will result in a rating that is larger than the HL-93 design rating. In the case of the IRIB, since the span is so long and the resulting distributed lane load associated with the HL-93 loading will be very significant, the load rating for any individual truck is expected to be significantly larger than the design value of 1.17.

When applying Eq. 5.1, both service and strength limit states need to be evaluated. The units for the capacity, dead load, and live load are based on the limit state being reviewed. If it is a service limit state, the units are stress (ksf). If it is a strength limit state, the units are moment (kip-ft).

The three load rating limit states that are checked for this bridge are Service 1, Service 3, and Strength 1 – Flexural. Service 1 checks for the service compression stresses and Service 3 checks for the service tensile stresses. The service limit state is not checking for structural strength but rather for serviceability issues such as deflections or cracking of the concrete in tension. For the IRIB, the service limit states are aimed at making sure the concrete does not crack (i.e. the strains in the concrete should not exceed the tensile cracking strain). The Strength 1 – Flexure limit state takes into account both the compression and tensile stresses. The strength limit state accounts for the structural strength of a component. That strength could be in terms of axial, shear, or moment capacity. In the case of the IRIB, the Strength 1 – Flexure limit state takes into account the moment capacity of the edge girder. In terms of service limit states, Service 3, which checks for concrete cracking, controls for the IRIB. Service 1, which checks for concrete in compression will not control and can be ignored when checking for the governing rating factors.

### 4.2.1 Load Rating Procedure for Permit Vehicles

To conduct a rating of permit vehicles using the experimentally determined influence line, the design capacity values determined by AECOM for the capacity and for the dead load effects are used, and the HS20 live load effects are scaled so that they represent the effects of the permit vehicle (Al-Khateeb, 2016). The design values that are used can be found in Table 4.

.

Table 4: Capacities and Dead Loads for Service 1, Service 3, and Strength 1

| Limit State | Location | Capacity | Dead Load | Units |
|---|---|---|---|---|
| Service 1 | Midspan | -604.8 | -161 | ksf |
| | Controlling location | -561.6 | -253 | ksf |
| Service 3 | Midspan | 36.14 | -147 | ksf |
| | Controlling location | 34.83 | -173 | ksf |
| Strength 1 | Midspan | 52146 | 13861 | kip-ft |
| | Controlling location | 32500 | 3340 | kip-ft |

The live load effects are determined from the strain values produced from the experimentally determined influence lines. The strain values of interest are the maximum absolute strains at the top and bottom of the edge girder both at midspan and at the controlling location. The same experimentally determined influence lines used to determine the maximum strain caused by the permit vehicle are also used to determine the maximum strain caused by an HS20 vehicle, (these values are shown in Table 1). The resulting values can be used to compute the ratio X of permit vehicle strain over HS20 strain. This ratio X allows the HS20 live load effect in the rating factor equation to be scaled to represent the live load effect of the permit vehicle. The resulting rating factor equation becomes:

$$RF = \frac{Capacity - Dead\ Load}{X \times HS20\ Live\ Load\ Effect} \qquad \text{Equation 5.2}$$

Where:

$$X = \frac{Permit\ Vehicle\ Strain}{HS20\ Strain}. \qquad \text{Equation 5.3}$$

For the IRIB, the rating factor is evaluated at midspan and the controlling location. To calculate the live load values for the Service 1 and Service 3 limit states, one multiplies the corresponding strain value by the modulus of elasticity ($E$) to get the live load stress in units of ksf (see Eq. 5.4).

$$Service\ 3\ Live\ Load = E \times HS20_{Bot\ Max\ Strain} \qquad \text{Equation 5.4}$$

To calculate the live load moment needed to evaluate the Strength 1 - Flexure limit state, one multiplies $E$ by the moment of inertia ($I$) of the corresponding location then by the difference of the top and bottom strains and finally divides the resulting value by the height of the cross section ($h$) to get a moment in units of kip-ft (see Eq. 5.5).

$$Strength\ 1\ Live\ Load = \frac{E \times I_{Location}}{h} \times \left(HS20_{Bot\ Max\ Strain} - HS20_{Top\ Max\ Strain}\right) \times 10^{-6}$$

Equation 5.5

Once this is done, the capacity, dead load effect, scaling factor, and live load effect for the desired limit state can be substituted into the rating factor equation (shown again below) to get a rating factor for the permit vehicle at either midspan or the controlling location. The values for all material properties can be found in Table 5.

$$Rating\ Factor = \frac{Capacity - Dead\ Load}{X \times Live\ Load}$$

Table 5: Material Properties of West Exterior Girder

| Material Properties | | Units |
|---|---|---|
| Compressive Strength (*f'c*) | 6500 | psi |
| Modulus of Elasticity (*E*) | 661750 | ksf |
| Moment of inertia (*I*) @ Midspan | 260.9 | $ft^4$ |
| Moment of inertia (I) @ Controlling location | 192.8 | $ft^4$ |
| Height of Cross Section (*h*) | 6 | ft |

### 4.2.2 Permit Vehicles Load Rating Example

The following calculations illustrate the load rating procedure described in Section 1.2.1 that utilizes experimentally determined influence lines. In this example, an actual permit vehicle, a Grove 3050 Crane, is used to illustrate the process.

Assumptions:

- Spacing between axles are rounded to the nearest foot.
- Capacity and Dead Load can be found in Table 4.
- HS20 Strains can be found in Table 1.
- Material Properties can be found in Table 5.

Permit Vehicle Used: Grove 3050 Crane

- Axle Spacing: [5.25 ft, 8.667 ft] → [5 ft, 9 ft]
- Axle Weight: [26.6 kips, 26.7 kips, 26.7 kips]

Calculate Maximum Strain due to Permit Vehicle:

Using the Matlab program (The Mathworks, Inc, 2017), the governing location of the normalized truck created strain values for the three axles of 0.4930 με, 0.4989 με, and 0.4758 με respectively. Scaling these to represent the actual permit truck yield a strain of 39.14 με.

$$Permit_{Max\ Strain} = 26.6 \times 0.4930 + 26.7 \times 0.4989 + 26.7 \times 0.4758 \ \rightarrow 39.14$$

<u>Live Load Conversion Factor</u>:

Using Eq. 5.3, the conversion factor becomes 1.17.

$$X = \frac{39.14}{33.57} \rightarrow 1.17$$

<u>Calculate Rating Factor Service 3</u>:

Using Eq. 5.4 and 5.2, the Service 3 rating factor becomes 7.048.

$$Service\ 3\ Live\ Load = 6.6175 \times 10^5 \times 33.58 \times 10^{-6} \rightarrow 22.21\ ksf$$

$$Rating\ Factor = \frac{36.14 + 147}{1.17 \times 22.21} \rightarrow \mathbf{7.048}$$

<u>Calculate Rating Factor Strength 1</u>:

Using Eq. 5.5 and 5.2, the Strength 1 rating factor becomes 25.439.

$$Strength\ 1\ Live\ Load = \frac{6.6175 \times 10^5 \times 260.9}{6} \times (33.58 + 11.13) * 10^{-6}$$

$$\rightarrow 1286.28\ kip\ ft$$

$$Rating\ Factor = \frac{52146 - 13861}{1.17 \times 1286.28} \rightarrow \mathbf{25.439}$$

Therefore, the rating factor for this permit vehicle would be 7.048. This is significantly greater than the design rating factor of 1.17 and indicates that the permit vehicle is safe to cross the bridge. Rating results for several example permit vehicle configurations, as well as the HS20 truck, are shown in Table 6. One can see that as the permit vehicle weights increase, the rating factors decrease. This range of vehicles and truck weights can allow the owner to make ballpark predictions based on the weight and length of a vehicle to get an estimate of what the permit vehicle rating might be. However, just because a vehicle has a large weight, it does not mean it will necessarily have a low rating factor, as the rating factor also depends on length of the truck.

Table 6: Permit Vehicle Configurations

| Truck Name | Truck Configuration [Axle Spacing and Weight] | | Total Length (ft) | Total Weight (Kips) | Service 3 Rating | Strength 1 Rating |
|---|---|---|---|---|---|---|
| HS20 | [14 ft, 14 ft] | [8 k, 32 k, 32 k] | 28 | 72 | 8.245 | 29.732 |
| Grove 3050 Crane | [5 ft, 9 ft] | [26.6 k, 26.7 k, 26.7 k] | 14 | 80 | 7.071 | 25.529 |
| Linkbelt Crane | [4 ft, 15 ft, 5 ft] | [23 k, 23 k, 27.45 k, 27.45 k] | 24 | 100.9 | 5.800 | 20.937 |
| Two Truck Train | [15 ft, 5 ft, 7 ft, 14 ft, 5 ft] | [15.66 k, 23.92 k, 23.54 k, 17.01 k, 23.29 k, 23.27 k] | 46 | 126.69 | 5.174 | 18.660 |
| Rotomill | [13 ft, 5 ft, 5 ft, 35 ft, 5 ft, 5 ft] | [13 k, 24.5 k, 24.5 k, 24.5 k, 24.5 k, 24.5 k, 24.5 k] | 68 | 160 | 4.685 | 16.913 |
| Three Truck Train | [15 ft, 5 ft, 7 ft, 15 ft, 5 ft, 7 ft, 16 ft, 5 ft] | [15.7 k, 23.69 k, 23.42 k, 15.94 k, 23.41 k, 23.42 k, 16.45 k, 23.57 k, 23.15 k] | 75 | 188.75 | 3.780 | 13.646 |
| Four Truck Train | [15 ft, 5 ft, 7 ft, 15 ft, 5 ft, 7 ft, 16 ft, 5 ft, 7 ft, 14 ft, 5 ft] | [15.7 k, 23.69 k, 23.42 k, 15.94 k, 23.41 k, 23.42 k, 16.45 k, 23.57 k, 23.15 k, 16.04 k, 23.86 k, 23.1 k] | 101 | 251.75 | 3.204 | 11.566 |

If the rating factor were to be below the established threshold (which might be 1.17, or might be 1.0, or perhaps some other value as determined by the owner), other actions may still permit the vehicle to cross the bridge. For example, the truck could be asked to drive in the fast lane which is closer to the centerline of the entire cross-section. This would reduce the strains on the edge girder (recall that the experimentally derived influence line is for a truck in the slow lane). Load tests show that this could reduce the live load effect by approximately 14 percent. If the truck were to drive on the shoulder, which would not be desirable since it is closer to the edge girder, the live load effect would increase by approximately 6 percent. These values have come from analyzing the single truck passes of load test 5. Other common methods of decreasing the load effect of the permit vehicle, such as reducing the speed of the vehicle, which will reduce dynamic effects, or having the vehicle drive alone, to reduce the strain, will not work since the influence line was generated with those two effects already being considered (since the experimentally derived influence line was created from a load test in which the truck was on the bridge without other traffic and was moving at a crawl speed thereby minimizing dynamic effects).

## 4.3 Matlab Code for Computing Rating Factors Based on Influence Lines

A computer program has been written in Matlab which utilizes the experimental influence lines at the midspan and the controlling location to calculate a rating factor for any permit vehicle using the methodology just described. The code also reports the maximum live load strain produced by the permit vehicle, as well as the location of the strain along the bridge. The Matlab program requires the input of only two sets of parameters. The first is the spacing between each of the permit vehicle's axles (rounded to the nearest foot). The second is the weights of each of the axles in kips. The reason the axle spacing is rounded to the nearest foot is because the influence lines are not continuous as previously discussed, but rather have magnitudes at every foot. The Matlab program essentially moves the set of axles of the permit vehicle along the experimental influence line to create a matrix of the strains. For example, if you had a permit vehicle with five axles (an axle train of five loads), you would get a [5x1751] matrix (the bridge is 1,750 feet long). Each row represents the effect of a particular axle of the axle train as determined by the corresponding magnitude of the influence line. As the vehicle first gets put on the bridge, only the first row/column will have a calculated value with the trailing axles being set to zero, since they are not yet on the bridge (i.e. are not on the influence line). Each respective trailing axle will stop being set to zero once they have begun to be placed on the bridge. Once the front axle has reached the end of the bridge the [5x1751] matrix in this case will be filled out. The program then sums the values in each column, thereby creating a [1x1751] matrix. This summation is essentially the application of superposition of the effects of each axle. The resulting value in any given column represents the total live load predicted strain effect caused by the permit vehicle when the front axle is located at the position corresponding to the column. For example, the value associated with column 1000 would be the total live load strain when the permit vehicle's front axle is located 1,000 feet from the start of the bridge. And most importantly, the maximum value in the resulting [1x1751] matrix represents the largest possible live load strain effect of the permit vehicle, and that value is used to calculate the rating factor.

Once the maximum strain is determined, the next step is to find the ratio X (Eq. 5.3), which represent the ratio of the maximum permit vehicle strain to the maximum strain produced by an HS20 (values for the HS20 strains are given in Table 1). The program then calculates the rating factor for the Service 3 limit state and the strength 1 limit state. Finally, the code produces a table with the Service 3 rating factor and the Strength 1 rating factor at both midspan and the controlling location. It also reports the maximum strain corresponding to the lower of the two rating values, as well as the governing location (see Figure 26). The complete code can be found in Appendix (B).

```
>> [ RF, Max_Strain, Location] = Rating_Factor( [7 8 10 10], [15.66 23.92 23.54 17.01 23.29 23.27] )

RF =

                           Service_3     Strength_1
                           _________     __________

    RF Midspan             [6.0305]      [21.7711]
    RF Critical Location   [7.7686]      [22.2926]


Max_Strain =

   45.8917


Location =

Midspan
```

Figure 26: Output from Rating Factor Function in Matlab

# Chapter 5

# QUARTERLY REPORT GENERATION

## 5.1 Quarterly Report

In order to easily understand and evaluate the vast amount of data collected during a three-month period, a format for a synthesized quarterly report was developed. The remainder of this chapter describes what is contained within the quarterly report.

The quarterly report is broken up into five sections: Alerts, Key Comparisons at Critical Locations, Plots, Sensor Table, and Observations. The Alerts section includes all notifications that were sent out because they were deemed critical by either the person generating the report or because a reading exceeded a set threshold value. The Key Comparisons section shows, in a simple and easy to understand set of tables, peak recorded values at midspan and at the controlling location (1,654 ft from the south end of the bridge). The Plots section provides graphs of data recorded by key sensors during that quarter as well as computed in-service rating factors at midspan and at the controlling location. The Sensor Table section includes a large table that provides the maximum and minimum value recorded during the quarter by every active sensor. Finally, the Observations section includes any important observations or supplemental information that has not already been captured in the prior sections. This section would document unusual events such as large permit vehicle crossings or extreme weather events. There is also a subsection under Observations where the person generating the report can summarize the quarterly performance of the bridge and note any significant changes. Explanations for anomalies that may have occurred in the data would also be addressed here. An example of a full report can be found in Appendix (C).

It should be noted that as much of the quarterly report as possible is generated automatically, and only a few entries, primarily observations, need to be entered by the person generating the report. The recorded data is processed through a Matlab code, which was written by Hadi Al-Khateeb. The code generates graphs and calculates the values for the in-service strain, the rating factors, and the expansion joint movement for each applicable sensor location. More information regarding this process can be found in Hadi Al-Khateeb's dissertation titled *Bridge Evaluation Utilizing Structural Health Monitoring Data* (Al-Khateeb, 2016). The maximum and minimum values and their difference (referred to as Δ) for the strains, expansion joint movement, and temperature is acquired by exporting the recorded data from intellioptics to an Excel file. That Excel file is then used in conjunction with another pre-generated Excel file which calculates the maximums, minimums and the difference between the maximum and minimum values (referred to as Δ) for each corresponding active sensor. The strain and temperature vs. time graph and the low frequency ambient air temperature graph are generated using a different Matlab code written as part of this research.

### 5.1.1 Alerts

The alerts section documents any alerts that were triggered by a sensor during the quarter. This occurs when a pre-set threshold value for the sensor is exceeded. The summary of trigger subsection lists the sensors that were triggered and whether the sensor was triggered by exceeding the upper or lower limit. For example, if a sensor exceeded the upper limit, the sensor will be listed as: Sensor Name (High). If the sensor went below the lower limit, then the sensor will be listed as: Sensor Name (Low). The cause of trigger subsection will describe the possible cause of the trigger for each sensor listed in the above subsection. If a cause cannot be determined, then it will be displayed that: Sensor Name (Unidentified Cause). This section must be entered manually by the person generating the report.

#### 5.1.2 Key Comparisons at the Critical Locations

The key comparisons at the critical locations section displays key data from the sensors at the two critical locations, midspan and the controlling location (1,654 ft from the South End of the bridge). As explained earlier, these are critical locations because they are where the lowest rating factors for the bridge occur. The sensors for these two locations are SW7 and 8 and SW21 and 22 which are located at the midspan and controlling location respectively. This section is broken up into four subsections: Strains, Expansion Joint Movement, Rating Factors, and Ambient Air Temperature.

##### 5.1.2.1 Strains

This section provides the current and historic maximum and minimum strains for SW7 and 8 and SW21 and 22. The table, shown in Figure 27, also displays the difference between the maximum and minimum strain values for each sensor (referred to as Δ). The Δ values give a better idea of the change in strain over time as it is not affected by baseline values. The Δ simply displays the difference between the maximums and minimums which can reveal either a drift in the strain, or change in strain affecting the temperature.

2.1 STRAINS (MICROSTRAIN, + TENSION)

| System Gauge | Location | Max (Current) | Max (Historic) | Min (Current) | Min (Historic) | Max Δ (Current) | Max Δ (Historic) |
|---|---|---|---|---|---|---|---|
| S-W7 | Mid-Span (Top) | 228.9 | 389.3 | -66.4 | 47.2 | 295.4 | 342.1 |
| S-W8 | Mid-Span (Bottom) | 288.4 | 416.8 | -36.0 | 63.0 | 324.4 | 353.8 |
| S-W21 | 1654 ft from South End (Top) | 246.3 | 396.5 | -62.3 | 27.8 | 308.6 | 368.7 |
| S-W22 | 1654 ft from South End (Bottom) | 198.8 | 340.8 | -40.4 | 56.1 | 239.2 | 284.7 |

Figure 27: Example of Strains from Report

#### 5.1.2.2 Expansion Joint Movement

This section is broken up into two tables as shown in Figure 28. The first table displays the current and historic maximum and minimum bearing displacements as measured from their initial position. It also displays the Δ's (difference between maximum and minimum readings) for the three bearings. Basically, this section shows the largest excursion of the bearings during the quarter. The second table displays the slopes taken from the expansion joint movement vs. change in temperature plots that are given in Section 5.1.3.3 of the report. The slopes indicate the effect of temperature on the bearing movement due to thermal expansion and contraction of the bridge. They provide the best possible indicator of whether the bearings are moving freely or whether they have started to seize up. While the magnitude of movement will change depending on the changes in temperature, the slopes should not change. If the average slope changes from the prior quarters, this would be a sign that inspectors should look more closely at the condition of the bearings during their next inspection.

2.2 Expansion Joint Movement (Inches)

| System Gauge | Location | Max (Current) | Max (Historic) | Min (Current) | Min (Historic) | Max Δ (Current) | Max Δ (Historic) |
|---|---|---|---|---|---|---|---|
| DE1 | Pier 4 | 2.5 | 4.8 | -1.6 | 0 | 4.1 | 4.8 |
| DE2 | Pylon 5 | 0.4 | -0.6 | -2.9 | -4.5 | 3.3 | 3.9 |
| DE3 | Pier 7 | 0.7 | 1.4 | -0.6 | 0.1 | 1.3 | 1.3 |

| System Gauge | Location | Slope (Current) | Slope (Historic) |
|---|---|---|---|
| DE1 | Pier 4 | -4.235 | -4.634 |
| DE2 | Pylon 5 | -3.241 | -3.716 |
| DE3 | Pier 7 | 1.347 | 1.419 |

Figure 28: Example of Expansion Joint Movement from Report

#### 5.1.2.3 Rating Factors

This section displays the current and historic rating factors determined from both high and low frequency data at midspan and the controlling location. As mentioned before, these rating factors are computed by a Matlab code written by Hadi Al-Khateeb (Al-Khateeb, 2016). In the event of erroneous values, such as large negative values, the rating factor will be replaced with *See Observations Section*. If this happened, in the observations section, an explanation of what the possible causes of the erroneous rating values would be included. For example, a drift in the strain could cause a large negative rating factor. An example of such a drift is shown in Figure 29.

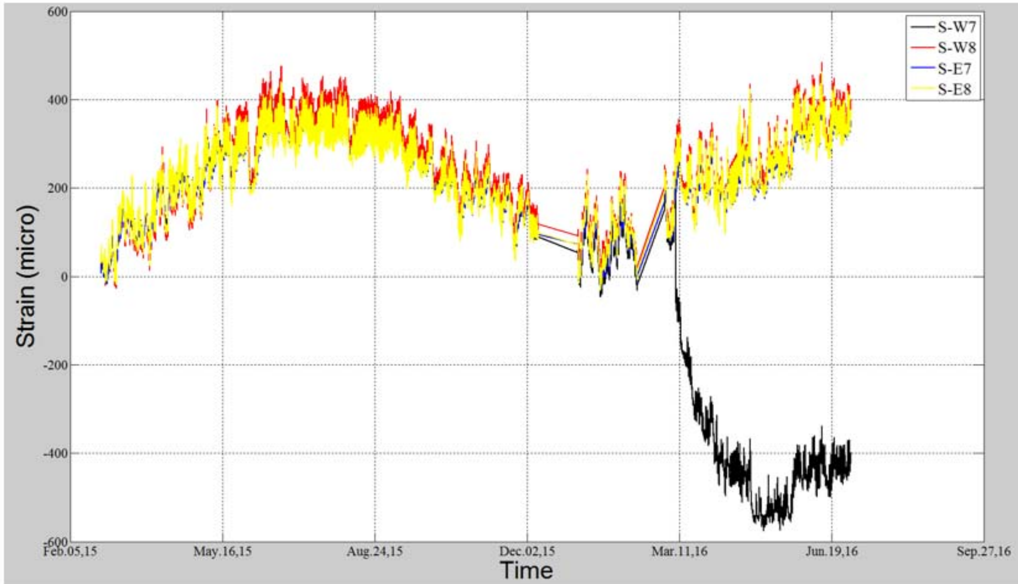


Figure 29: Drift in Strain from Feb 2015 to Sep 2016

#### 5.1.2.4 Ambient Air Temperature

This section displays the current and historic maximum and minimum temperatures during the quarter.

### 5.1.3 Plots

The plots section displays graphs of data recorded by key sensors over the entire quarter. This section enables one to see trends over the entire quarter by showing all the data for that quarter for key sensors. Like the previous section, this section is broken up into four subsections, Strain, Rating Factors, Expansion Joint Movement, and Low Frequency Ambient Air Temperature.

#### 5.1.3.1 Strain

There are two plots in the strain section as shown in Figure 30 and Figure 31. The first plot is titled In-Service Strain and is generated from high-frequency data.

This plot contains two graphs, the first showing peak in-service strain vs. time and the second graph showing a histogram of the recorded peaks vs. frequency. The first graph is useful to see the magnitude of the peak strains while the second graph is useful to see the frequency of the peak values. These values will not match the strain values from the strain table due to in-service strain being high frequency data and the strain table being low frequency data. This means that the in-service strain data captures short term events (traffic) as well as long term behavior (temperature change, wind, creep and shrinkage, etc.). The low frequency strain data in the table only represents intermittent readings (average values over a 10 minute window) meant to capture long term effects.

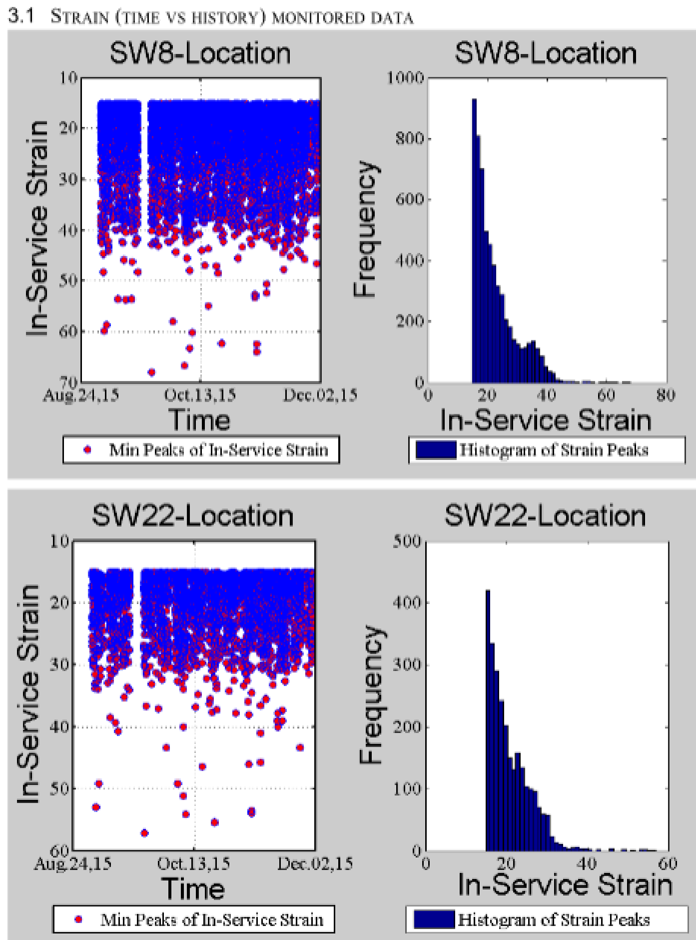


Figure 30: Example of In-Service Strain Plot from Report

The second set of plots show strain and temperature vs. time and are taken from the low frequency data. These plots show the clear correlation between the changes in temperature and changes in strain. In design, temperature effects are often ignored, but as the SHM data shows, they can be quite significant.

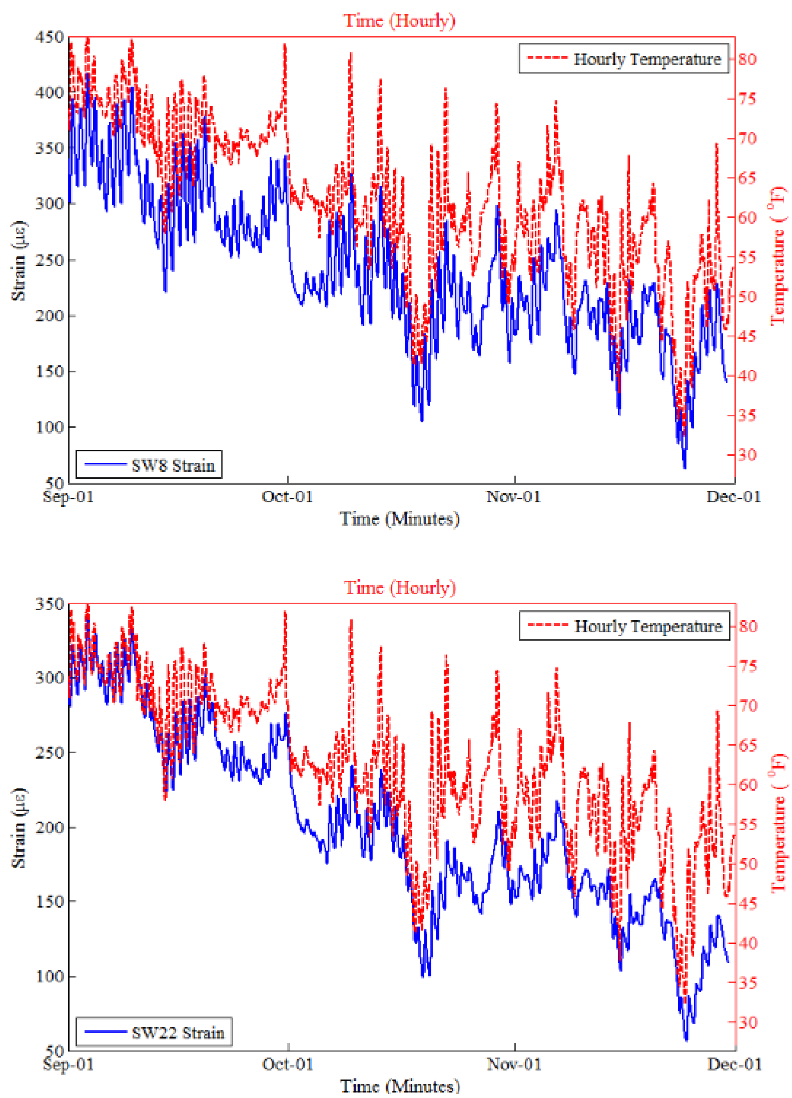


Figure 31: Example of Strain and Temperature vs Time Plot from Report

#### 5.1.3.1.1 Temperature Sensors

In order to compare strain to temperature over time, it was necessary to identify which of four non-embedded temperature sensors on the bridge gives the most accurate ambient temperature readings. The four temperature sensors are located at (1) the communications hut under the bridge, (2) at midspan, (3) at the center of the bridge in the pedestrian barrier junction box, and (4) at segment 412's pedestrian junction box. To make the decision of which bridge sensor is best to use, it is valuable to have a reliable ambient temperature sensor to compare their readings to. One reliable source of ambient temperature in the region of the bridge are readings from the Delaware Environmental Observing System (DEOS) station located at the Indian River Inlet. Therefore, it was decided that the non-embedded temperature sensor on the bridge that most closely matched the DEOS data would be the one used for ambient temperature.

Kevin Brinson, the Associate State Climatologist and Director of DEOS, provided hourly change in temperature data over a nine-month period from the Indian River Inlet station. This temperature data was compared to the data from the four non-embedded SHM temperature sensors on the bridge by plotted both sets of data on four separate graphs; one for each sensor. The resulting comparisons can be seen in Figure 32, Figure 33, Figure 34, and Figure 35, with the red dashed lines being DEOS data and the blue solid lines being SHM data. The plots indicate that sensor P4_T is the most similar sensor with P7_T being the next closest. The decision was made to use sensor P4_T to create the strain to temperature vs. time plots. The code used to do this can be found in Appendix (D).

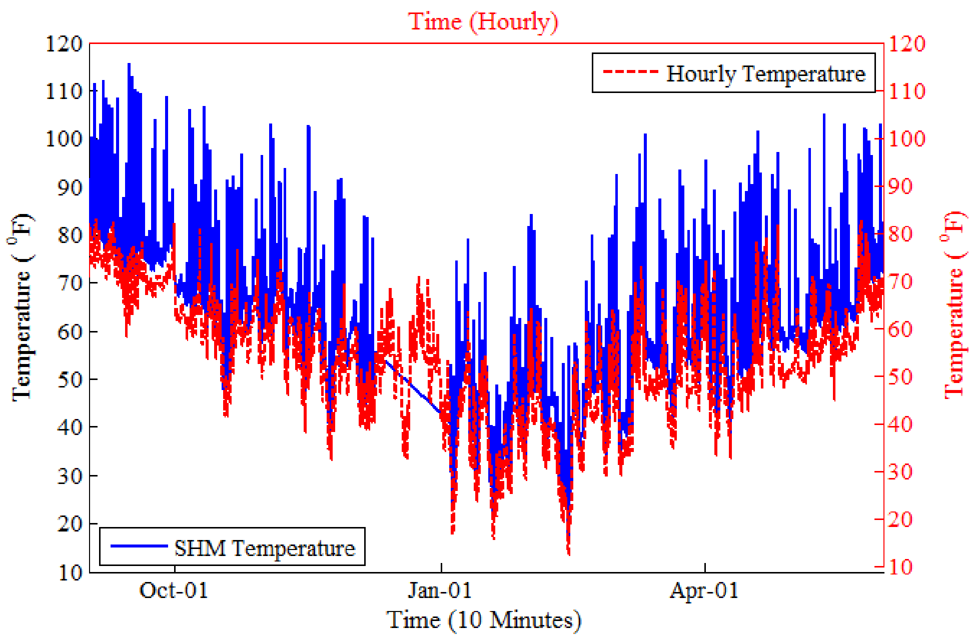


Figure 32: Sensor CH_T located at the Com Hut under the Bridge

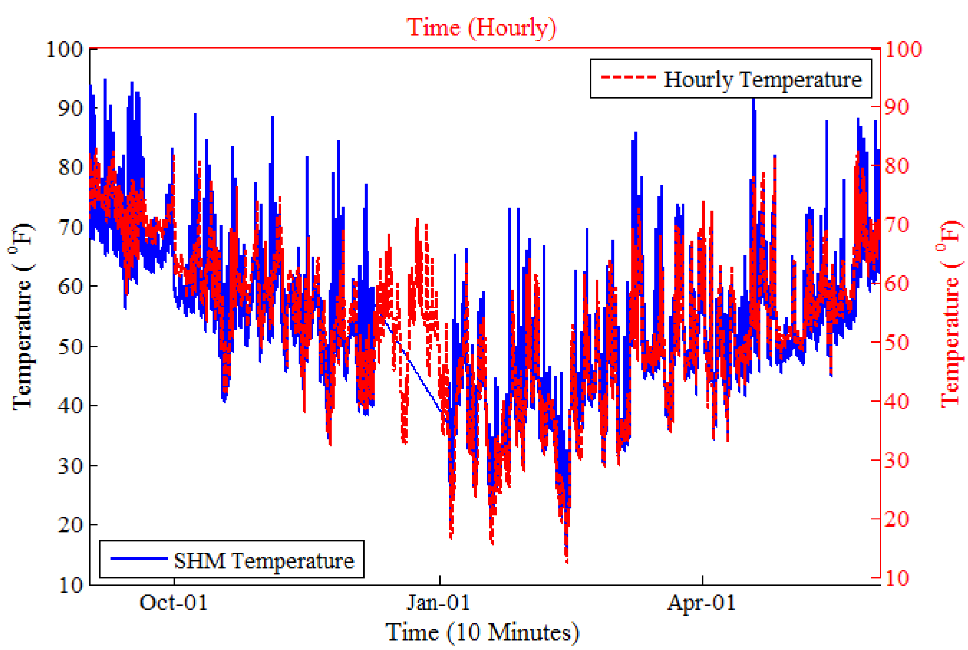


Figure 33: Sensor CJ_T located at Midspan

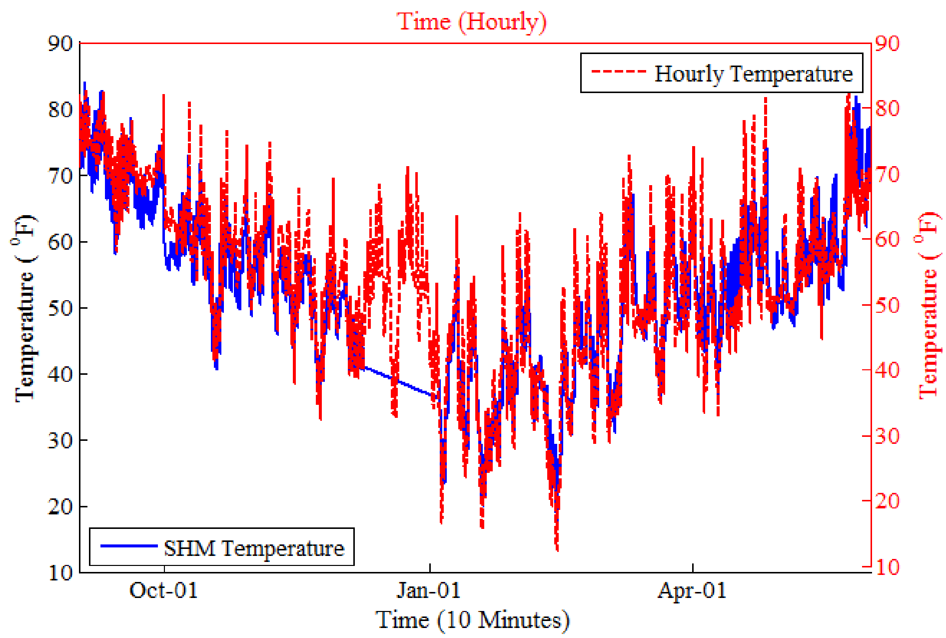


Figure 34: Sensor P4_T located at the center of the bridge in the pedestrian barrier junction box

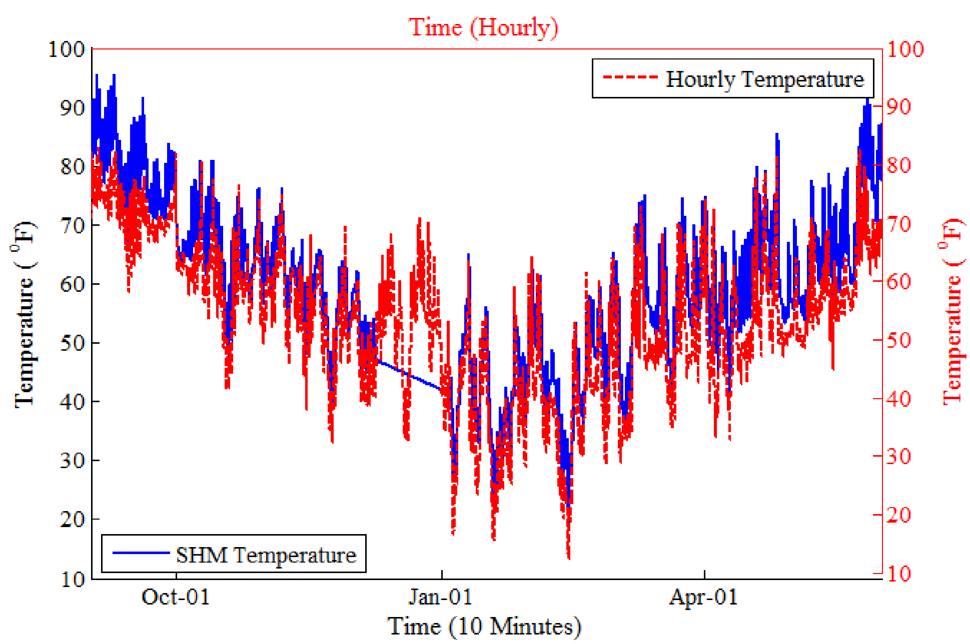


Figure 35: Sensor P7_T located at segment 412's pedestrian junction box

#### 5.1.3.2 Rating Factors

This section displays the continuous rating factor plots for the midspan location (SW7 and SW8) and the controlling location (SW21 and SW22) (see Figure 36).

The high-frequency rating factors are based completely on SHM data (in particular high-frequency live-load strain data) and therefore the ratings represent continuous ratings due to actual truck loads.

The low-frequency rating factors are based on low-frequency SHM data and as a result capture thermal effects and other long-term changes over time. The ratings are compared to the LRFR rating factor. These rating factors use design live loads (which are typically very conservative) and the initial values were never zeroed relative to the temperature at the time of bridge completion (when thermal stresses are expected to be zero). As a result, the importance of these plots is to see how they behave over many years of service, and not their absolute value.

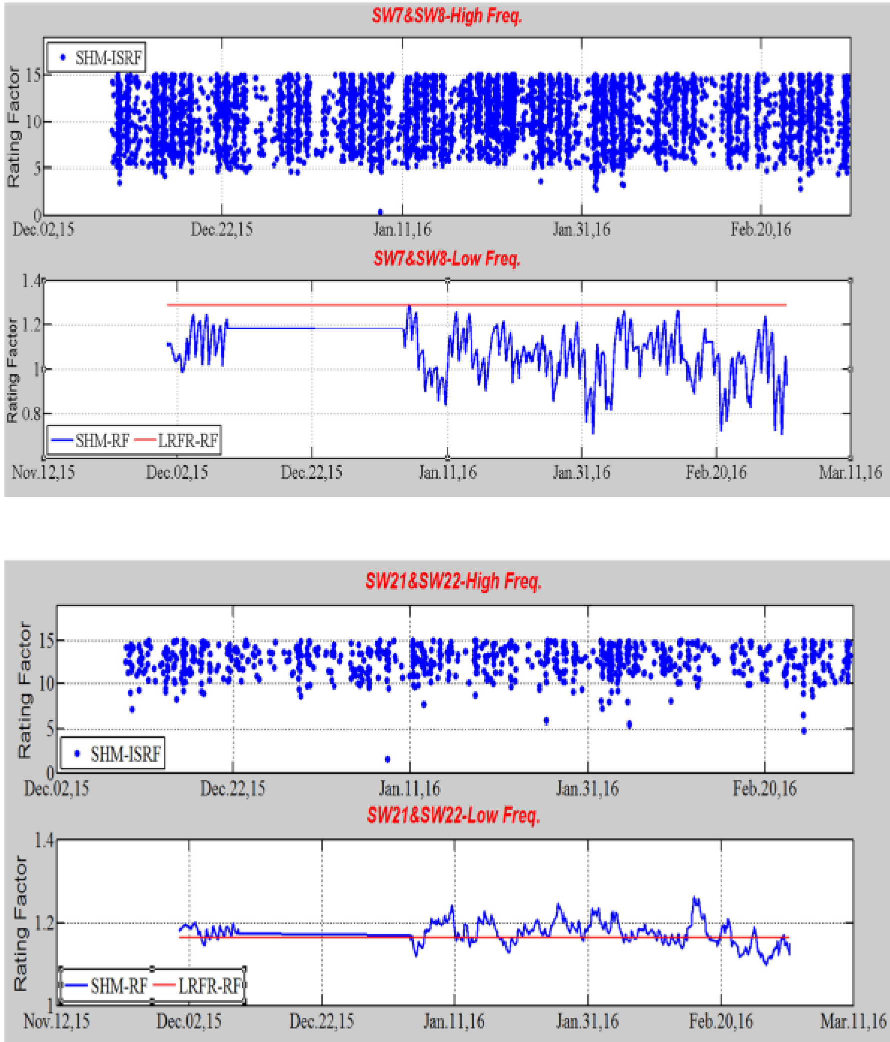


Figure 36: Example of Rating Factor Plot from Report

#### 5.1.3.3 Expansion Joint Movement

This section displays bearing movement vs. temperature change over the quarter (see Figure 37). The slope of the plot, found through regression analysis, provides a useful indicator of how the bearings are functioning.

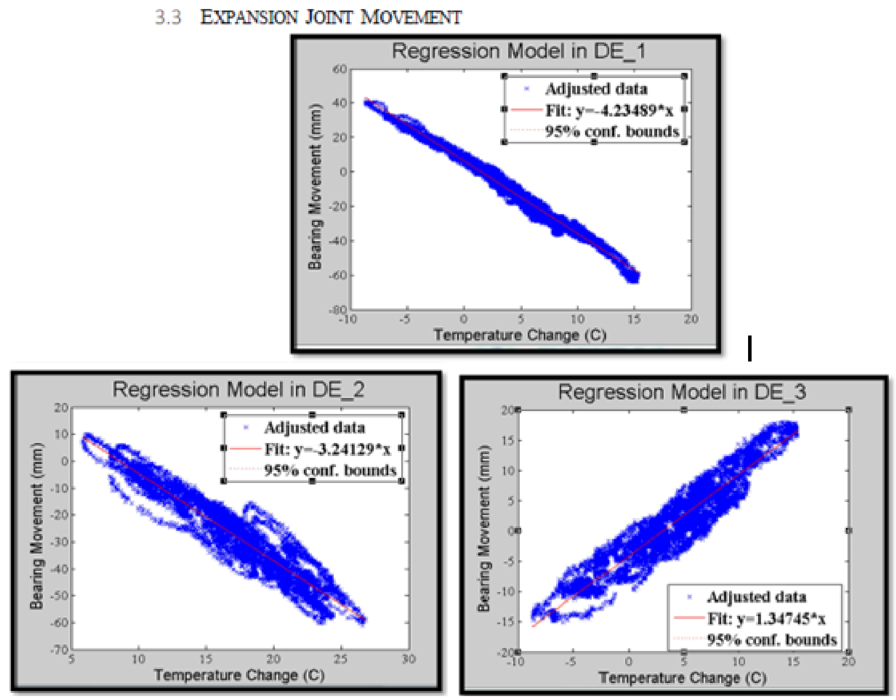


Figure 37: Example of Expansion Joint Movement Slopes from Report

#### 5.1.3.4 Low Frequency Ambient Air Temperature

This section shows the maximum and minimum temperature values for every day of the quarter, as well as the total change in temperature during each day of the quarter. An example of these plots, shown in Figure 38, may be useful to the reader if they are interested in the daily fluctuation in temperature, or their effects.

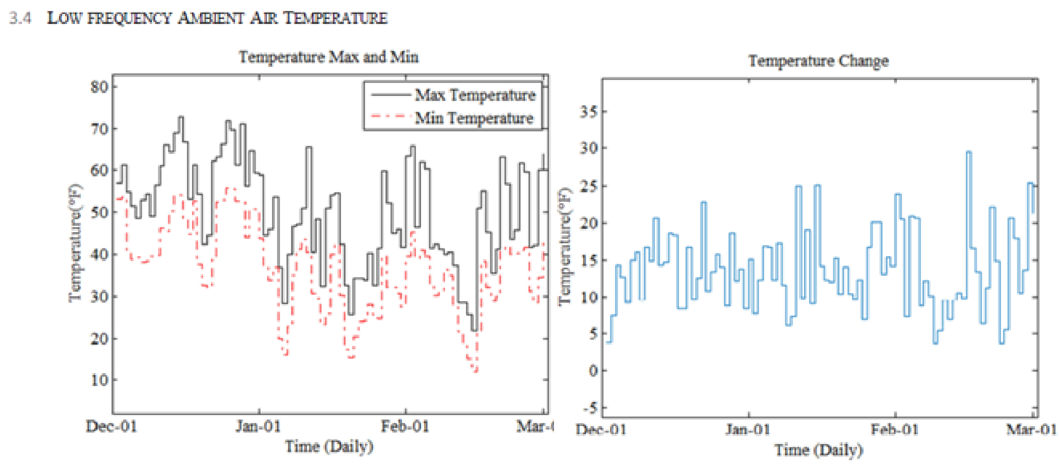


Figure 38: Example of Ambient Air Temperature from Report

### 5.1.4 Sensor Table

The sensor table section displays all of the current and historic maximum and minimum values for every active sensor on the bridge. This table provides a convenient way of keeping track of every sensor, and not just the critical ones.

### 5.1.5 Observations

This section provides the reader with observations that have been made through a review of the data. This section is broken up into five subsections: Sensor Status Comments, Reason for Anomalies in Data, Permit Vehicles, Event Comments, and Notable Changes.

#### 5.1.5.1 Sensor Status Comments

This section discusses any sensors that have stopped recording data or that have been fixed during the quarter.

#### 5.1.5.2 Reason for Anomalies in Data

This section discusses potential causes for anomalies in the data. For instance, a drift in strain, as shown in Figure 29, would be mentioned here and used to explain why a rating factor was negative.

#### 5.1.5.3 Permit Vehicles

This section mentions how many permit vehicles crossed the bridge during the quarter. This provides a useful method to track the number and weight of permits vehicles that have crossed the bridge. This information may help to explain the occurrence of sudden strain peaks or of sudden rating factor drops.

#### 5.1.5.4 Event Comments (Wind, Earthquake, Accidents, or Fire)

This section notes any drastic events that occurred during the quarter. These events could be associated with strong winds (hurricanes or northeasters), or could be related to accidents or any other type of significant loading event.

#### 5.1.5.5 Notable Changes

This section notes changes of any significant parameters in the report, such as increases in strain, decreases in rating factors, or large bearing movements.

## 5.2 Methodology

The quarterly report’s sections were ordered in terms of what was believed to be the most important for the owner to see first. By presenting alerts first, the owner immediately sees the status of the sensors and whether or not any thresholds were exceeded. The alerts draw attention to particular sensors so the owner can look at them in the sensor report or, if additional information is needed, go to the more complete intellioptics report. The key comparisons section is second because the data for the two sets of sensors presented (key sensors) represent the most important data being tracked. The plots in this section give a way to see not only peak values, but also behavior over the entire quarter. The sensor report comes before observations because the observations give supplementary information. On its own, the observations are not very useful. But, when trying to figure out anomalous data, one can look at the observations section to see if it corresponds with a weather event or perhaps a permit vehicle crossing.

# Chapter 6

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Conclusions

The research reported herein was focused in two areas. The first area involved utilizing data collected by a SHM system during controlled load tests to calculate the rating factor of permit vehicles. The second area led to the creation of a quarterly report format that enables the vast quantity of data collected by the IRIB SHM system to be simply displayed and readily comprehended.

With regard to the first area of research, data from a controlled diagnostic load test of the IRIB conducted in May of 2016 was used. From this data, an experimentally derived influence line representing a single truck crossing the bridge was created. That influence line was compared to an analytical model which showed that a single truck had a very similar effect to a point load. This ensured that directly using an influence line from a truck loading would be acceptable (since it is not feasible to have a concentrated point load cross the bridge). To further confirm this, strains predicted utilizing the experimentally derived influence line were compared to strains measured for a single truck, and three truck trains. The comparison confirmed that the use of the experimental influence line is effective in predicting the actual strain caused by multi-axle trucks and showed that the developed influence line could be used to accurately predict the strain caused by any permit vehicle crossing the bridge. Using the predicted strain due to a particular permit vehicle, a methodology for calculating a rating factor was developed.

To compute the rating factor for a permit vehicle, one must first calculate the strain caused by an HS20 truck by using the experimentally derived influence line. Since load ratings are typically calculated based on an HS20, in calculating the rating factor for a permit vehicle, it is useful to compute and use an equivalency factor. An equivalency factor represents the effect that the permit vehicle has on a bridge relative to an HS20 (which will not change). This ensures that we have a common factor in the equation and the only variable is the amount of HS20s we have. For instance, if the permit vehicle has twice the strain of an HS20, then the bridge is essentially feeling the effects of two HS20s.

The methodology was demonstrated using seven trucks and truck trains with total weights ranging from a 72-kip HS20 truck to a 251-kip four truck train. For these trucks, the rating factors ranged from 8.245 to 3.204 (with Service 3 governing in all cases). The values produced by this method seem appropriate as one would expect to see a lower rating factor for a heavy vehicle and a high rating factor for a lighter one. In light of the 1.17 design rating factor for the Service 3 limit state, which is based a combined HS20 loading and a full lane loading, the computed values also seem reasonable.

Having developed the methodology for getting a load rating value, a Matlab code was developed that automates the rating calculations. The developed code requires the user to input the axle spacings (rounded to the nearest foot) and the axle weights of the permit vehicle. With this input, the code uses the experimentally derived influence lines (one for midspan and one for the controlling location) and the methodology developed to compute the maximum strain due to the permit vehicle, the location where the maximum strain occurs, and the rating factor. The entire process takes only a matter of seconds for the bridge management engineer to conduct, and the resulting rating has a high degree of accuracy since it is based on actual bridge response.

With regard to the second area of research, a quarterly report which provides the reader with important information in a quick and easy to read format was created. The report includes alerts, information regarding the controlling locations, plots of information for those locations, a full chart of the current and historic maximum and minimum data values for the quarter for all active sensors, and finally supplementary information to help answer questions that the reader may have regarding outlier readings.

## 6.2 Assumptions Made in Developing the Method and Advantages of Using the Method

When computing the rating factor with the new methodology, a few assumptions were made. First, it was assumed that an influence line for a truck is similar to an influence line for a single point load. This assumption was validated using an analytical model. Second, the rating process does not incorporate potential dynamic effects of the permit vehicles (since the load test data used to derive the influence line resulted from a slow-moving truck). Neglecting dynamic effects may be reasonable for several reasons. One reason is that permit vehicles typically travel slowly. Another reason is that data taken during full speed truck passes showed minimal dynamic effects. Should one want to include dynamic effects, one can simply divide the rating factor by the AASHTO impact factor. The third assumption was that the permit vehicle will travel southbound in the slow lane (this is where the test truck traveled during the pass that was used to derive the influence line). This is conservative unless the permit vehicle travels in the shoulder. The rating for the permit vehicle can be increased if the truck travels in the fast lane since that lane is closer to the midspan of the cross section (and therefore will result in a decrease in strain on the closest edge girder). If one were to evaluate a permit vehicle traveling northbound (i.e. closer to the east girder as opposed to the west girder), the influence line used for the west girder can still be used and is considered to be conservative (since the pedestrian side walk on the east side pushes vehicles away from the easy girder). If a vehicle were to be driven in the fast lane on the east side there is an approximately 19 percent reduction in strain, while a truck traveling in the northbound shoulder would cause an approximately 11 percent increase in strain compared to the slow lane. The fourth assumption was to neglect the effect of ambient traffic on the rating. The likelihood of a second heavy truck being at the same longitudinal location, either at midspan or the controlling location, at the same time as the permit vehicle is very small.

There are several advantages of using this new methodology. First, this methodology is quick to perform and avoids the need for using time consuming complex models. Second, this methodology avoids using a simplified method that has a higher chance for inaccuracy. Third, and most importantly, this methodology uses actual field response and therefore results in highly accurate ratings that reflect actual live load effects.

## 6.3 Recommendation/Future Work

As with all research, there is always more that can be done. The following are recommended areas to be pursued.

### 6.3.1 Permit Vehicle Influence Lines

One thing that needs to be done is to transfer the Matlab code to DelDOT and for DelDOT's bridge management engineers to be trained to use it. In terms of upgrades to the code, it would be useful to re-evaluate the experimentally derived influence lines after every new controlled diagnostic load test (which are scheduled to be conducted every two years). In the future, it would be useful to know when permit trucks cross the bridge so resulting strain values can be captured and the method can be further validated. Two factors to consider when doing this are that the permit vehicle will not be traveling alone on the bridge, and the exact weight of the permit vehicle and its axles will not be known (only the provided loads on the permit is known). Finally, if it is deemed useful, the methodology developed by Catbas et al. could be used to check the accuracy of the rating factors predicted using the influence line methodology.

### 6.3.2 Report Generation

There isn't much more to be done when it comes to improving the format of the report. It is possible that future evaluation of results will lead to additional information that should be added, or information that is deemed unnecessary and can be removed. The most significant recommendation is to automate the generation of the report. By coding a function to quickly grab and print out plots and data from the system, one can create a functioning report in minutes as opposed to the current method of placing everything into the report by hand. The automation will also remove any need to teach others how to properly create the report.

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# Appendix A

## CODE FOR SMOOTHING AND ZEROING LOAD TEST DATA

```
load Load_Test_5_Pass_2_Flipped.mat  % One Truck
load Load_Test_5_Pass_23_Flipped.mat % Two Truck Train
load Load_Test_5_Pass_25_Flipped.mat % Two Truck Train
load Load_Test_5_Pass_24_Flipped.mat % Three Truck Train
load Load_Test_5_Pass_26_Flipped.mat % Four Truck Train
```

Pass 23 Two Truck Train West Girder

```
S_W7_L5_P2_smooth = smooth(S_W7_L5_P2,20); % One Truck

S_W8_L5_P2_smooth = smooth(S_W8_L5_P2,20); % One Truck

S_W7_L5_P23_smooth = smooth(S_W7_L5_P23,15); % Load Test 5 Data
% figure(1)
% plot(S_W7_L5_P23,'b');
% hold on
% plot(S_W7_L5_P23_smooth,'r');
% hold off

S_W8_L5_P23_smooth = smooth(S_W8_L5_P23,15); %Load Test 5 Data
% figure(2)
% plot(S_W8_L5_P23,'b');
% hold on
% plot(S_W8_L5_P23_smooth,'r');
% title('SW8 Load Test 5 Pass 23')
% ylabel('Microstrain')
% hold off

S_W21_L5_P23_smooth = smooth(S_W21_L5_P23,15); %Load Test 5 Data
% figure(3)
% plot(S_W21_L5_P23,'b');
% hold on
% plot(S_W21_L5_P23_smooth,'r');
% hold off
```

```
S_W22_L5_P23_smooth = smooth(S_W22_L5_P23,15); %Load Test 5 Data
% figure(4)
% plot(S_W22_L5_P23,'b');
% hold on
% plot(S_W22_L5_P23_smooth,'r');
% hold off
```

Pass 25 Two Truck Train West Girder

```
S_W7_L5_P25_smooth = smooth(S_W7_L5_P25,15); % Load Test 5 Data
% figure(1)
% plot(S_W7_L5_P25,'b');
% hold on
% plot(S_W7_L5_P25_smooth,'r');
% hold off

S_W8_L5_P25_smooth = smooth(S_W8_L5_P25,15); %Load Test 5 Data
% figure(2)
% plot(S_W8_L5_P25,'b');
% hold on
% plot(S_W8_L5_P25_smooth,'r');
% hold off

S_W21_L5_P25_smooth = smooth(S_W21_L5_P25,15); %Load Test 5 Data
% figure(3)
% plot(S_W21_L5_P25,'b');
% hold on
% plot(S_W21_L5_P25_smooth,'r');
% hold off

S_W22_L5_P25_smooth = smooth(S_W22_L5_P25,15); %Load Test 5 Data
% figure(4)
% plot(S_W22_L5_P25,'b');
% hold on
% plot(S_W22_L5_P25_smooth,'r');
% hold off
```

Pass 24 Three Truck Train West Girder

```
S_W7_L5_P24_smooth = smooth(S_W7_L5_P24,15); % Load Test 5 Data
% figure(1)
% plot(S_W7_L5_P24,'b');
% hold on
% plot(S_W7_L5_P24_smooth,'r');
% hold off
```

```
S_W8_L5_P24_smooth = smooth(S_W8_L5_P24,15); %Load Test 5 Data
% figure(2)
% plot(S_W8_L5_P24,'b');
% hold on
% plot(S_W8_L5_P24_smooth,'r');
% hold off

S_W21_L5_P24_smooth = smooth(S_W21_L5_P24,15); %Load Test 5 Data
% figure(3)
% plot(S_W21_L5_P24,'b');
% hold on
% plot(S_W21_L5_P24_smooth,'r');
% hold off

S_W22_L5_P24_smooth = smooth(S_W22_L5_P24,15); %Load Test 5 Data
% figure(4)
% plot(S_W22_L5_P24,'b');
% hold on
% plot(S_W22_L5_P24_smooth,'r');
% hold off
```

Pass 26 Four Truck Train

```
S_W7_L5_P26_smooth = smooth(S_W7_L5_P26,15); % Load Test 5 Data
% figure(1)
% plot(S_W7_L5_P26,'b');
% hold on
% plot(S_W7_L5_P26_smooth,'r');
% hold off

S_W8_L5_P26_smooth = smooth(S_W8_L5_P26,15); %Load Test 5 Data
% figure(2)
% plot(S_W8_L5_P24,'b');
% hold on
% plot(S_W8_L5_P24_smooth,'r');
% hold off

S_W21_L5_P26_smooth = smooth(S_W21_L5_P26,15); %Load Test 5 Data
% figure(3)
% plot(S_W21_L5_P26,'b');
% hold on
% plot(S_W21_L5_P26_smooth,'r');
% hold off
```

```
S_W22_L5_P26_smooth = smooth(S_W22_L5_P26,15); %Load Test 5 Data
% figure(4)
% plot(S_W22_L5_P26,'b');
% hold on
% plot(S_W22_L5_P26_smooth,'r');
% hold off
```

Max Strains

```
Max_S_W7_L5_P2 = min(S_W7_L5_P2_smooth);
Max_S_W8_L5_P2 = max(S_W8_L5_P2_smooth);

Max_S_W7_L5_P23 = min(S_W7_L5_P23_smooth);
Max_S_W8_L5_P23 = max(S_W8_L5_P23_smooth);

Max_S_W7_L5_P25 = min(S_W7_L5_P25_smooth);
Max_S_W8_L5_P25 = max(S_W8_L5_P25_smooth);

Max_S_W7_L5_P24 = min(S_W7_L5_P24_smooth);
Max_S_W8_L5_P24 = max(S_W8_L5_P24_smooth);

Max_S_W7_L5_P26 = min(S_W7_L5_P26_smooth);
Max_S_W8_L5_P26 = max(S_W8_L5_P26_smooth);

Max_S_W21_L5_P23 = min(S_W21_L5_P23_smooth);
Max_S_W22_L5_P23 = max(S_W22_L5_P23_smooth);

Max_S_W21_L5_P25 = min(S_W21_L5_P25_smooth);
Max_S_W22_L5_P25 = max(S_W22_L5_P25_smooth);

Max_S_W21_L5_P24 = min(S_W21_L5_P24_smooth);
Max_S_W22_L5_P24 = max(S_W22_L5_P24_smooth);

Max_S_W21_L5_P26 = min(S_W21_L5_P26_smooth);
Max_S_W22_L5_P26 = max(S_W22_L5_P26_smooth);

% Max_Strains = [Max_S_W7_L5_P23 Max_S_W8_L5_P23; Max_S_W7_L5_P25 Max_S_W8_L5_P25; Max_S_W7_L5_P24
Max_S_W8_L5_P24; Max_S_W7_L5_P26 Max_S_W8_L5_P26];

% figure('name','Max Strains S_W7&8 L5','numbertitle','off')
% bar(Max_Strains, 'LineWidth' ,1.5)
% axis([0.5 5.5 -600 400])
% legend({'S_W7','S_W8'},'FontWeight','bold')
```

Subplot SW7 and SW8

```
figure('name','Strains S_W7&8 L5','numbertitle','off')

subplot(4,2,1) % Two Truck Train
plot(S_W7_L5_P23,'b');
hold on
plot(S_W7_L5_P23_smooth,'r');
hold off
title('S_W7 Pass 23')
axis([0 length(S_W7_L5_P23_smooth) -560 -530])
hline(Max_S_W7_L5_P23,'-.r', ['Max Strain = ' num2str(Max_S_W7_L5_P23)])

subplot(4,2,2) % Two Truck Train
plot(S_W8_L5_P23,'b');
hold on
plot(S_W8_L5_P23_smooth,'r');
hold off
title('S_W8 Pass 23')
axis([0 length(S_W8_L5_P23_smooth) 240 320])
hline(Max_S_W8_L5_P23,'-.r', ['Max Strain = ' num2str(Max_S_W8_L5_P23)])

subplot(4,2,3) % Two Truck Train
plot(S_W7_L5_P25,'b');
hold on
plot(S_W7_L5_P25_smooth,'r');
hold off
title('S_W7 Pass 25')
axis([0 length(S_W7_L5_P25_smooth) -560 -530])
hline(Max_S_W7_L5_P25,'-.r', ['Max Strain = ' num2str(Max_S_W7_L5_P25)])

subplot(4,2,4) % Two Truck Train
plot(S_W8_L5_P25,'b');
hold on
plot(S_W8_L5_P25_smooth,'r');
hold off
title('S_W8 Pass 25')
axis([0 length(S_W8_L5_P25_smooth) 240 320])
hline(Max_S_W8_L5_P25,'-.r', ['Max Strain = ' num2str(Max_S_W8_L5_P25)])

subplot(4,2,5) % Three Truck Train
plot(S_W7_L5_P24,'b');
hold on
```

```
plot(S_W7_L5_P24_smooth,'r');
hold off
title('S_W7 Pass 24')
axis([0 length(S_W7_L5_P24_smooth) -560 -530])
hline(Max_S_W7_L5_P24,'-.r', ['Max Strain = ' num2str(Max_S_W7_L5_P24)])

subplot(4,2,6) % Three Truck Train
plot(S_W8_L5_P24,'b');
hold on
plot(S_W8_L5_P24_smooth,'r');
hold off
title('S_W8 Pass 24')
axis([0 length(S_W8_L5_P24_smooth) 240 350])
hline(Max_S_W8_L5_P24,'-.r', ['Max Strain = ' num2str(Max_S_W8_L5_P24)])

subplot(4,2,7) % Four Truck Train
plot(S_W7_L5_P26,'b');
hold on
plot(S_W7_L5_P26_smooth,'r');
hold off
title('S_W7 Pass 26')
axis([0 length(S_W7_L5_P26_smooth) -560 -530])
hline(Max_S_W7_L5_P26,'-.r', ['Max Strain = ' num2str(Max_S_W7_L5_P26)])

subplot(4,2,8) % Four Truck Train
plot(S_W8_L5_P26,'b');
hold on
plot(S_W8_L5_P26_smooth,'r');
hold off
title('S_W8 Pass 26')
axis([0 length(S_W8_L5_P26_smooth) 240 350])
hline(Max_S_W8_L5_P26,'-.r', ['Max Strain = ' num2str(Max_S_W8_L5_P26)])
```

Subplot Adjusted SW7 and SW8

```
figure('name','Strains S_W7&8 L5','numbertitle','off')

subplot(5,2,1) % One Truck
plot(S_W7_L5_P2-mean(S_W7_L5_P2(1:400)),'b');
hold on
plot(S_W7_L5_P2_smooth-mean(S_W7_L5_P2_smooth(1:400)),'r');
hold off
title('S_W7 Pass 2 Adj')
axis([0 length(S_W7_L5_P2_smooth) -20 10])
hline(Max_S_W7_L5_P2-mean(S_W7_L5_P2_smooth(1:400)),'-.r', ['Max Strain = ' num2str(Max_S_W7_L5_P2-
mean(S_W7_L5_P2_smooth(1:400)))])

subplot(5,2,2)
plot(S_W8_L5_P2-mean(S_W8_L5_P2(1:400)),'b');
hold on
plot(S_W8_L5_P2_smooth-mean(S_W8_L5_P2_smooth(1:400)),'r');
hold off
title('S_W8 Pass 2 Adj')
axis([0 length(S_W8_L5_P2_smooth) -10 40])
hline(Max_S_W8_L5_P2-mean(S_W8_L5_P2_smooth(1:400)),'-.r', ['Max Strain = ' num2str(Max_S_W8_L5_P2-
mean(S_W8_L5_P2_smooth(1:400)))])

subplot(5,2,3) % Two Truck Train
plot(S_W7_L5_P23-mean(S_W7_L5_P23(1:400)),'b');
hold on
plot(S_W7_L5_P23_smooth-mean(S_W7_L5_P23_smooth(1:400)),'r');
hold off
title('S_W7 Pass 23 Adj')
axis([0 length(S_W7_L5_P23_smooth) -30 10])
hline(Max_S_W7_L5_P23-mean(S_W7_L5_P23_smooth(1:400)),'-.r', ['Max Strain = ' num2str(Max_S_W7_L5_P23-
mean(S_W7_L5_P23_smooth(1:400)))])

subplot(5,2,4) % Two Truck Train
plot(S_W8_L5_P23-mean(S_W8_L5_P23(1:400)),'b');
hold on
plot(S_W8_L5_P23_smooth-mean(S_W8_L5_P23_smooth(1:400)),'r');
hold off
title('S_W8 Pass 23 Adj')
axis([0 length(S_W8_L5_P23_smooth) -20 60])
% ylabel('Microstrain')
hline(Max_S_W8_L5_P23-mean(S_W8_L5_P23_smooth(1:400)),'-.r', ['Max Strain = ' num2str(Max_S_W8_L5_P23-
```

```
mean(S_W8_L5_P23_smooth(1:400)))])

subplot(5,2,5) % Two Truck Train
plot(S_W7_L5_P25-mean(S_W7_L5_P25(1:400)),'b');
hold on
plot(S_W7_L5_P25_smooth -mean(S_W7_L5_P25_smooth(1:400)),'r');
hold off
title('S_W7 Pass 25 Adj')
axis([0 length(S_W7_L5_P25_smooth) -30 10])
hline(Max_S_W7_L5_P25-mean(S_W7_L5_P25_smooth(1:400)),'-.r', ['Max Strain = ' num2str(Max_S_W7_L5_P25-
mean(S_W7_L5_P25_smooth(1:400)))])

subplot(5,2,6) % Two Truck Train
plot(S_W8_L5_P25-mean(S_W8_L5_P25(1:400)),'b');
hold on
plot(S_W8_L5_P25_smooth-mean(S_W8_L5_P25_smooth(1:400)),'r');
hold off
title('S_W8 Pass 25 Adj')
axis([0 length(S_W8_L5_P25_smooth) -20 60])
hline(Max_S_W8_L5_P25-mean(S_W8_L5_P25_smooth(1:400)),'-.r', ['Max Strain = ' num2str(Max_S_W8_L5_P25-
mean(S_W8_L5_P25_smooth(1:400)))])

subplot(5,2,7) % Three Truck Train
plot(S_W7_L5_P24-mean(S_W7_L5_P24(1:400)),'b');
hold on
plot(S_W7_L5_P24_smooth-mean(S_W7_L5_P24_smooth(1:400)),'r');
hold off
title('S_W7 Pass 24 Adj')
axis([0 length(S_W7_L5_P24_smooth) -30 10])
hline(Max_S_W7_L5_P24-mean(S_W7_L5_P24_smooth(1:400)),'-.r', ['Max Strain = ' num2str(Max_S_W7_L5_P24-
mean(S_W7_L5_P24_smooth(1:400)))])

subplot(5,2,8) % Three Truck Train
plot(S_W8_L5_P24-mean(S_W8_L5_P24(1:400)),'b');
hold on
plot(S_W8_L5_P24_smooth-mean(S_W8_L5_P24_smooth(1:400)),'r');
hold off
title('S_W8 Pass 24 Adj')
axis([0 length(S_W8_L5_P24_smooth) -20 80])
hline(Max_S_W8_L5_P24-mean(S_W8_L5_P24_smooth(1:400)),'-.r', ['Max Strain = ' num2str(Max_S_W8_L5_P24-
mean(S_W8_L5_P24_smooth(1:400)))])

subplot(5,2,9) % Four Truck Train
```

```
plot(S_W7_L5_P26-mean(S_W7_L5_P26(1:400)),'b');
hold on
plot(S_W7_L5_P26_smooth-mean(S_W7_L5_P26_smooth(1:400)),'r');
hold off
title('S_W7 Pass 26 Adj')
axis([0 length(S_W7_L5_P26_smooth) -30 10])
hline(Max_S_W7_L5_P26-mean(S_W7_L5_P26_smooth(1:400)),'-.r', ['Max Strain = ' num2str(Max_S_W7_L5_P26-
mean(S_W7_L5_P26_smooth(1:400)))])

subplot(5,2,10) % Four Truck Train
plot(S_W8_L5_P26-mean(S_W8_L5_P26(1:400)),'b');
hold on
plot(S_W8_L5_P26_smooth-mean(S_W8_L5_P26_smooth(1:400)),'r');
hold off
title('S_W8 Pass 26 Adj')
axis([0 length(S_W8_L5_P26_smooth) -20 80])
hline(Max_S_W8_L5_P26-mean(S_W8_L5_P26_smooth(1:400)),'-.r', ['Max Strain = ' num2str(Max_S_W8_L5_P26-
mean(S_W8_L5_P26_smooth(1:400)))])
```

Subplot SW21 and SW22

```
figure('name','Strains S_W21&22 L5','numbertitle','off')

subplot(4,2,1) % Two Truck Train
plot(S_W21_L5_P23,'b');
hold on
plot(S_W21_L5_P23_smooth,'r');
hold off
title('S_W21 Pass 23')
axis([0 length(S_W21_L5_P23_smooth) 190 230])
hline(Max_S_W21_L5_P23,'-.r', ['Max Strain = ' num2str(Max_S_W21_L5_P23)])

subplot(4,2,2) % Two Truck Train
plot(S_W22_L5_P23,'b');
hold on
plot(S_W22_L5_P23_smooth,'r');
hold off
title('S_W22 Pass 23')
```

```
axis([0 length(S_W22_L5_P23_smooth) 180 260])
hline(Max_S_W22_L5_P23,'-.r', ['Max Strain = ' num2str(Max_S_W22_L5_P23)])

subplot(4,2,3) % Two Truck Train
plot(S_W21_L5_P25,'b');
hold on
plot(S_W21_L5_P25_smooth,'r');
hold off
title('S_W21 Pass 25')
axis([0 length(S_W21_L5_P25_smooth) 180 240])
hline(Max_S_W21_L5_P25,'-.r', ['Max Strain = ' num2str(Max_S_W21_L5_P25)])

subplot(4,2,4) % Two Truck Train
plot(S_W22_L5_P25,'b');
hold on
plot(S_W22_L5_P25_smooth,'r');
hold off
title('S_W22 Pass 25')
axis([0 length(S_W22_L5_P25_smooth) 180 300])
hline(Max_S_W22_L5_P25,'-.r', ['Max Strain = ' num2str(Max_S_W22_L5_P25)])

subplot(4,2,5) % Three Truck Train
plot(S_W21_L5_P24,'b');
hold on
plot(S_W21_L5_P24_smooth,'r');
hold off
title('S_W21 Pass 24')
axis([0 length(S_W21_L5_P24_smooth) 180 240])
hline(Max_S_W21_L5_P24,'-.r', ['Max Strain = ' num2str(Max_S_W21_L5_P24)])

subplot(4,2,6) % Three Truck Train
plot(S_W22_L5_P24,'b');
hold on
plot(S_W22_L5_P24_smooth,'r');
hold off
title('S_W22 Pass 24')
axis([0 length(S_W22_L5_P24_smooth) 180 300])
hline(Max_S_W22_L5_P24,'-.r', ['Max Strain = ' num2str(Max_S_W22_L5_P24)])

subplot(4,2,7) % Four Truck Train
plot(S_W21_L5_P26,'b');
hold on
```

```
plot(S_W21_L5_P26_smooth,'r');
hold off
title('S_W21 Pass 26')
axis([0 length(S_W21_L5_P26_smooth) 180 240])
hline(Max_S_W21_L5_P26,'-.r', ['Max Strain = ' num2str(Max_S_W21_L5_P26)])

subplot(4,2,8) % Four Truck Train
plot(S_W22_L5_P26,'b');
hold on
plot(S_W22_L5_P26_smooth,'r');
hold off
title('S_W22 Pass 26')
axis([0 length(S_W22_L5_P26_smooth) 150 300])
hline(Max_S_W22_L5_P26,'-.r', ['Max Strain = ' num2str(Max_S_W22_L5_P26)])
```

Subplot Adjusted SW21 and SW22

```
figure('name','Strains S_W21&22 L5','numbertitle','off')

subplot(4,2,1) % Two Truck Train
plot(S_W21_L5_P23-S_W21_L5_P23(1),'b');
hold on
plot(S_W21_L5_P23_smooth-S_W21_L5_P23_smooth(4),'r');
hold off
title('S_W21 Pass 23 Adj')
axis([0 length(S_W21_L5_P23_smooth) -30 10])
hline(Max_S_W21_L5_P23-S_W21_L5_P23_smooth(4),'-.r', ['Max Strain = ' num2str(Max_S_W21_L5_P23-
S_W21_L5_P23_smooth(4))])

subplot(4,2,2) % Two Truck Train
plot(S_W22_L5_P23-S_W22_L5_P23(2),'b');
hold on
plot(S_W22_L5_P23_smooth-S_W22_L5_P23_smooth(4),'r');
hold off
title('S_W22 Pass 23 Adj')
axis([0 length(S_W22_L5_P23_smooth) -20 60])
hline(Max_S_W22_L5_P23-S_W22_L5_P23_smooth(4),'-.r', ['Max Strain = ' num2str(Max_S_W22_L5_P23-
S_W22_L5_P23_smooth(4))])

subplot(4,2,3) % Two Truck Train
```

```
plot(S_W21_L5_P25-S_W21_L5_P25(2),'b');
hold on
plot(S_W21_L5_P25_smooth -S_W21_L5_P25_smooth(4),'r');
hold off
title('S_W21 Pass 25 Adj')
axis([0 length(S_W21_L5_P25_smooth) -30 10])
hline(Max_S_W21_L5_P25-S_W21_L5_P25_smooth(4),'-.r', ['Max Strain = ' num2str(Max_S_W21_L5_P25-
S_W21_L5_P25_smooth(4))])

subplot(4,2,4) % Two Truck Train
plot(S_W22_L5_P25-S_W22_L5_P25(2),'b');
hold on
plot(S_W22_L5_P25_smooth-S_W22_L5_P25_smooth(4),'r');
hold off
title('S_W22 Pass 25 Adj')
axis([0 length(S_W22_L5_P25_smooth) -20 60])
hline(Max_S_W22_L5_P25-S_W22_L5_P25_smooth(4),'-.r', ['Max Strain = ' num2str(Max_S_W22_L5_P25-
S_W22_L5_P25_smooth(4))])

subplot(4,2,5) % Three Truck Train
plot(S_W21_L5_P24-S_W21_L5_P24(3),'b');
hold on
plot(S_W21_L5_P24_smooth-S_W21_L5_P24_smooth(4),'r');
hold off
title('S_W21 Pass 24 Adj')
axis([0 length(S_W21_L5_P24_smooth) -30 10])
hline(Max_S_W21_L5_P24-S_W21_L5_P24_smooth(4),'-.r', ['Max Strain = ' num2str(Max_S_W21_L5_P24-
S_W21_L5_P24_smooth(4))])

subplot(4,2,6) % Three Truck Train
plot(S_W22_L5_P24-S_W22_L5_P24(3),'b');
hold on
plot(S_W22_L5_P24_smooth-S_W22_L5_P24_smooth(4),'r');
hold off
title('S_W22 Pass 24 Adj')
axis([0 length(S_W22_L5_P24_smooth) -20 80])
hline(Max_S_W22_L5_P24-S_W22_L5_P24_smooth(4),'-.r', ['Max Strain = ' num2str(Max_S_W22_L5_P24-
S_W22_L5_P24_smooth(4))])

subplot(4,2,7) % Four Truck Train
plot(S_W21_L5_P26-S_W21_L5_P26(2),'b');
hold on
```

```
plot(S_W21_L5_P26_smooth-S_W21_L5_P26_smooth(4),'r');
hold off
title('S_W21 Pass 26 Adj')
axis([0 length(S_W21_L5_P26_smooth) -40 20])
hline(Max_S_W21_L5_P26-S_W21_L5_P26_smooth(4),'-.r', ['Max Strain = ' num2str(Max_S_W21_L5_P26-
S_W21_L5_P26_smooth(4))])

subplot(4,2,8) % Four Truck Train
plot(S_W22_L5_P26-S_W22_L5_P26(2),'b');
hold on
plot(S_W22_L5_P26_smooth-S_W22_L5_P26_smooth(4),'r');
hold off
title('S_W22 Pass 26 Adj')
axis([0 length(S_W22_L5_P26_smooth) -40 80])
hline(Max_S_W22_L5_P26-S_W22_L5_P26_smooth(4),'-.r', ['Max Strain = ' num2str(Max_S_W22_L5_P26-
S_W22_L5_P26_smooth(4))])
```

## Appendix B

## CODE FOR PERMIT VEHICLE RATING FACTOR CALCULATION FUNCTION

```
function [ RF, Max_Strain, Location] = Rating_Factor( Axle_Spacing, Axle_Weights )

%Rating_Factor Calculates the Rating Factor, Max Strain, and Location of
%the Max Strain caused by a permit vehicle.
%   By inputing Axle Spacing and Axle Weights of a permit vehicle, the code
%   will calculate the Rating Factor, Max Strain, and Location of the Max Strain caused by the vehicle
%   at the two important locations of mid-span and the controlling location.
%   **This code is meant for vehicles traveling on the southbound slow lane of IRIB.**
%
%   INPUTS:
%   Axle_Spacing: A [1xn] matrix of axle spacings starting from first
%   axle. Must round up to the nearest whole number.
%   Ex: Axle_Spacing = [16 5 7 14 5];
%   Ex: Axle_Spacing = [6.3 7.6 9.3 10]; ~~ [7 8 10 10];
%   Axle_Weights: A [1xm] matrix of axle weights starting with first axle.
%   EX: Axle_Weights = [15.66 23.92 23.54 17.01 23.29 23.27];
%
%   OUTPUTS:
%   RF: A Table of Rating Factors of inputed vehicle.
%   Max_Strain: The Max Strain produced by inputed vehicle.
%   Location: The Location where the strain is max.
%
%
%   INSTRUCTIONS:
%   To use this function, you input into the command window the following:
%   [ RF, Max_Strain, Location] = Rating_Factor( [Axle_Spacing], [Axle_Weights] )
%   It is up to the user to insert the correct Axle Spacings and Axle Weights
%   into the input.
%   ***Make sure you are in the folder that contains (Influence_Line_Permit_Vehicles.mat).***
%   When the function is ran, it is loaded and provides the influence lines to determine the strain of the
%   truck.
%
%   EXAMPLE: HS_20
```

```
%   [RF, Max_Strain, Location] = Rating_Factor([14 14],[8 32 32])
%
%   Answer:                 Serivce_3   Strength_1
%                           ---------   ----------
%   RF Midspan              [8.2593]    [29.8172]
%   RF Controlling location    [10.5191]   [30.1857]
%
%   Max_Strain = 33.5080
%
%   Location = Midspan

load Influence_Line_Permit_Vehicles.mat % loads the influence lines of midspan and the controlling location

Total_Axle_Spacing = length(Axle_Spacing);
Total_Axle_Weights = length(Axle_Weights);



ct = 0;
while ct < Total_Axle_Weights;
    ct = ct+1;
    for i = 1:1751
        strain_save_SW8(ct,i) = Axle_Weights(ct)*Inf_Line_Permit_Vehicle_SW8(i);
        strain_save_SW22(ct,i) = Axle_Weights(ct)*Inf_Line_Permit_Vehicle_SW22(i);
    end
end

as = 1;
r = 2;
strain_save_SW8_hold(1,:) = strain_save_SW8(1,:);
strain_save_SW22_hold(1,:) = strain_save_SW22(1,:);

while as < Total_Axle_Spacing+1
    AS_sum = sum(Axle_Spacing(1:as));
    ins = zeros(1,AS_sum);
    strain_save_SW8_edit = [ins strain_save_SW8(r,:)];
    strain_save_SW22_edit = [ins strain_save_SW22(r,:)];

    strain_range_SW8 = length(strain_save_SW8_edit)-AS_sum;
    strain_range_SW22 = length(strain_save_SW22_edit)-AS_sum;

    strain_save_SW8_edit(strain_range_SW8+1:end) = '';
    strain_save_SW22_edit(strain_range_SW22+1:end) = '';
```

```
    strain_save_SW8_hold(r,:) = strain_save_SW8_edit;
    strain_save_SW22_hold(r,:) = strain_save_SW22_edit;
    r = r + 1;
    as = as + 1;
    clear ins
end

Strain_SW8 = sum(strain_save_SW8_hold);
Strain_SW22 = sum(strain_save_SW22_hold);

Max_Strain_SW8 = max(Strain_SW8);
Max_Strain_SW22 = max(Strain_SW22);

Max_Strain = max(Max_Strain_SW8,Max_Strain_SW22);
```

Mid Step

```
% X_SW7 = Max_Strain_SW7/-11.1334;
X_SW8 = Max_Strain_SW8/HS_20_Max_Strain; % HS_20_Max_Strain

% X_SW21 = Max_Strain_SW21/-15.5297;
X_SW22 = Max_Strain_SW22/29.7727; % HS_20_Max_Strain

f_prime = 6500; %psi
E = 57000 * sqrt(f_prime)/1000*144; %ksf
h = 6; %ft
c_prime = 1.9;
c = 4.1;

A_midspan = 65.6; %ft^2
I_midspan = 260.9; %ft^4

A_critical_location = 65.6; %ft^2
I_critical_location = 192.8; %ft^4
```

Service 3

```
S3_Midspan_Capacity = 36.14; % ksf
S3_Midspan_DL = -147; % ksf
% S3_Midspan_LL = 180.5; % ksf
S3_Midspan_LL_Live = E * HS_20_Max_Strain * 10^-6; % ksf  HS20 Strain = HS_20_Max_Strain
```

```
S3_RF_Midspan = (S3_Midspan_Capacity - S3_Midspan_DL)/(X_SW8*S3_Midspan_LL_Live);


S3_Critical_Location_Capacity = 34.83; % ksf
S3_Critical_Location_DL = -173; % ksf
% S3_Critical_Location_LL = 221.5; % ksf
S3_Critical_Location_LL_Live = E * 29.7727 * 10^-6; % ksf  HS20 Strain = 29.7727


S3_RF_Critical = (S3_Critical_Location_Capacity - S3_Critical_Location_DL)/(X_SW22*S3_Critical_Location_LL_Live);
```

Strength 1 – Flexure

```
Strength_Midspan_Moment_Capacity = 52146; % kip-ft
Strength_Midspan_Moment_DL = 13861; % kip-ft
% Strength_Midspan_Moment_LL = 22405;
Strength_Midspan_Moment_LL_Live = E*I_midspan/h*(HS_20_Max_Strain - -11.1334)*10^-6; % kip-ft

Strength_Midspan_Moment_RF = (Strength_Midspan_Moment_Capacity -
Strength_Midspan_Moment_DL)/(X_SW8*Strength_Midspan_Moment_LL_Live);


Strength_Critical_Location_Moment_Capacity = 32500;
Strength_Critical_Location_Moment_DL = 3340;
% Strength_Critical_Location_Moment_LL = 24760;
Strength_Critical_Location_Moment_LL_Live = E*I_critical_location/h*(29.7727 - -15.5297)*10^-6;

Strength_Critical_Location_Moment_RF = (Strength_Critical_Location_Moment_Capacity -
Strength_Critical_Location_Moment_DL)/(X_SW22*Strength_Critical_Location_Moment_LL_Live);
```

Results

```
% RF = (Capacity - Design_Dead_Load)/(HS_20_Strain_Factor * HS_20_Live_Load);

Rating_Factors = {'RF Midspan';'RF Controlling location'};
% Service_1 = {S1_RF_Midspan;S1_RF_Critical};
Service_3 = {S3_RF_Midspan;S3_RF_Critical};
Strength_1 = {Strength_Midspan_Moment_RF;Strength_Critical_Location_Moment_RF};

% RF = table(Service_1,Service_3,Strength_1,'VariableNames',{'Service_1' 'Service_3'
'Strength_1'},'RowNames',Rating_Factors);
RF = table(Service_3,Strength_1,'VariableNames',{'Service_3' 'Strength_1'},'RowNames',Rating_Factors);
```

```
if Max_Strain_SW8 > Max_Strain_SW22
%     plot(Strain_SW8)
   Location = 'Midspan';
else
%     plot(Strain_SW22)
   Location = 'Controlling location';
end

end
```

**Appendix C**

**QUARTERLY REPORT EXAMPLE**

# Quarterly Report

March 2016 – May 2016

## 1 Alerts

### 1.1 Summary of trigger

- N/A

### 1.2 Cause of trigger

- N/A

# 2 KEY COMPARISONS AT CRITICAL LOCATIONS

## 2.1 STRAINS (MICROSTRAIN, + TENSION)

| System Gauge | Location | Max (Current) | Max (Historic) | Min (Current) | Min (Historic) | Max Δ (Current) | Max Δ (Historic) |
|---|---|---|---|---|---|---|---|
| S-W7 | Mid-Span (Top) | 227.0 | 389.3 | -572.7 | -66.4 | 799.7 | 342.1 |
| S-W8 | Mid-Span (Bottom) | 439.8 | 416.8 | 93.0 | -36.0 | 346.8 | 353.8 |
| S-W21 | 1654 ft from South End (Top) | 385.5 | 396.5 | 55.9 | -62.3 | 329.6 | 368.7 |
| S-W22 | 1654 ft from South End (Bottom) | 331.1 | 340.8 | 74.8 | -40.4 | 256.3 | 284.7 |

## 2.2 EXPANSION JOINT MOVEMENT (INCHES)

| System Gauge | Location | Max (Current) | Max (Historic) | Min (Current) | Min (Historic) | Max Δ (Current) | Max Δ (Historic) |
|---|---|---|---|---|---|---|---|
| DE1 | Pier 4 | 4.0 | 4.8 | -0.2 | -1.6 | 4.2 | 4.8 |
| DE2 | Pylon 5 | -0.6 | 0.4 | -4.4 | -4.5 | 3.8 | 3.9 |
| DE3 | Pier 7 | 1.1 | 1.4 | -0.1 | -0.6 | 1.2 | 1.3 |

| System Gauge | Location | Slope (Current) | Slope (Historic) |
|---|---|---|---|
| DE1 | Pier 4 | -4.131 | -4.634 |
| DE2 | Pylon 5 | -3.754 | -3.716 |
| DE3 | Pier 7 | 1.346 | 1.419 |

## 2.3 RATING FACTORS

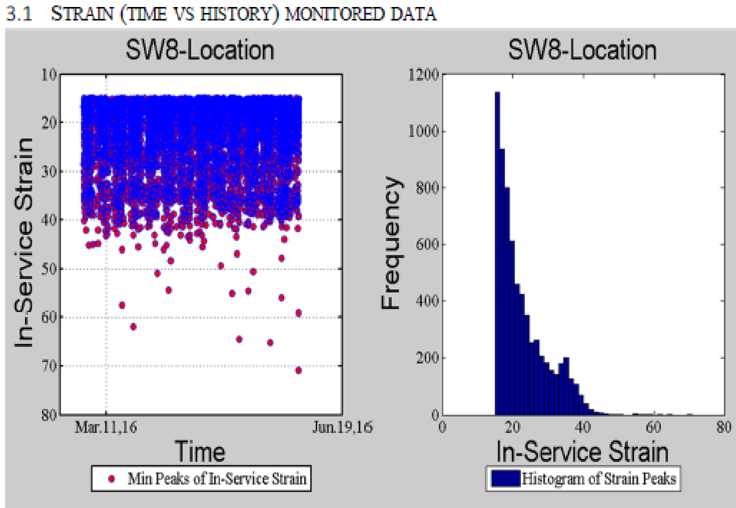
| System Gauge | Location | High Frequency (Current) | High Frequency (Historic) | Low Frequency (Current) | Low Frequency (Historic) |
|---|---|---|---|---|---|
| SW7 & SW8 | Midspan | * See Observations | 2.5 | * See Observations | 0.59 |
| SW21 & SW22 | 1654 ft from South End | 5.33 | 1.58 | 0.95 | 1.06 |

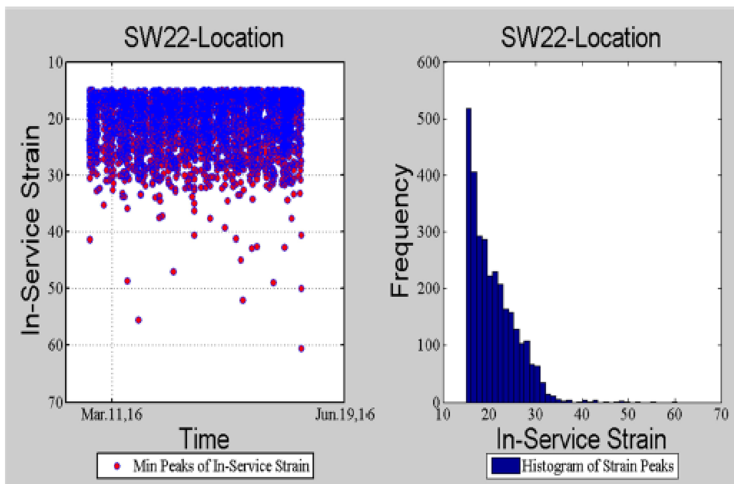
## 2.4 AMBIENT AIR TEMPERATURE (FAHRENHEIT)

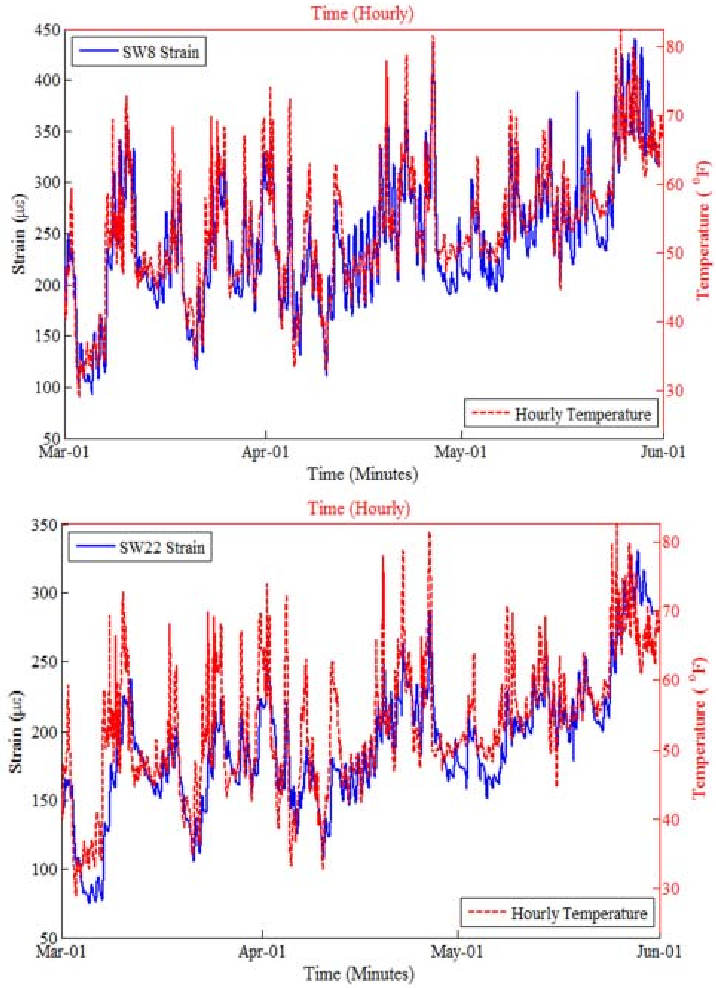
| Month | System Gauge | Location | Max (Current) | Max (Historic) | Min (Current) | Min (Historic) |
|---|---|---|---|---|---|---|
| March-May | DEOS | SR1 IRIB North | 84.1 | 84.4 | 28.6 | 12.1 |

# 3 Plots

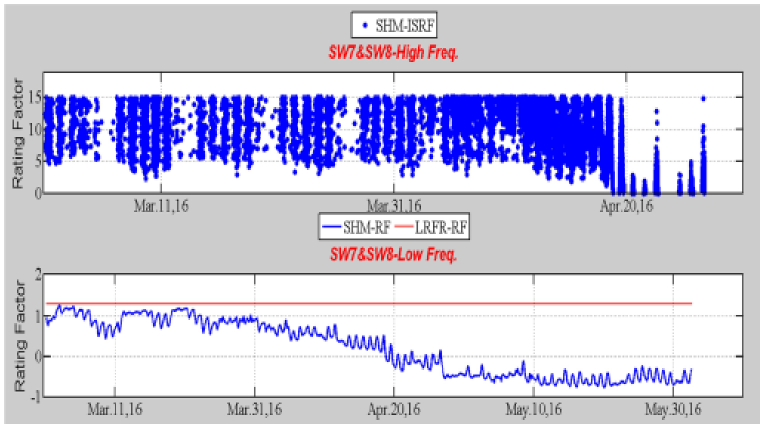
## 3.1 Strain (Time vs History) Monitored Data

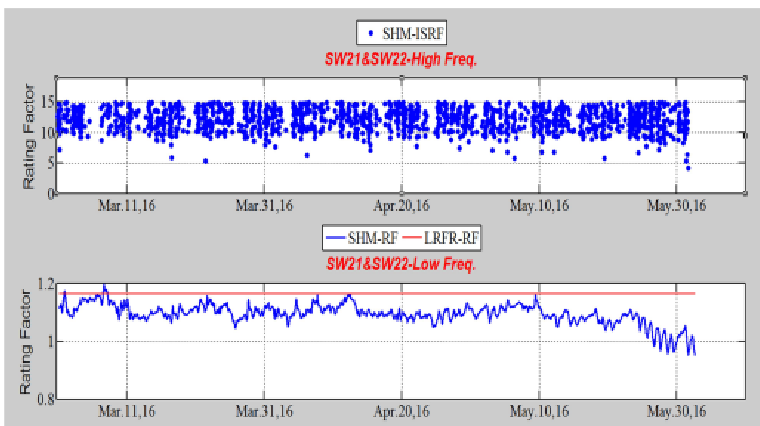


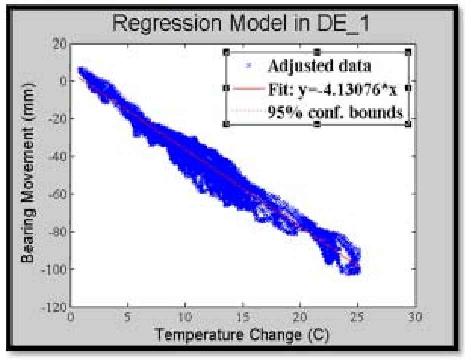

Time (Hourly)
SW8 Strain
Strain (με)
Temperature (°F)
Hourly Temperature
Mar-01
Apr-01
May-01
Jun-01
Time (Minutes)
Time (Hourly)
SW22 Strain
Strain (με)
Temperature (°F)
Hourly Temperature
Time (Minutes)

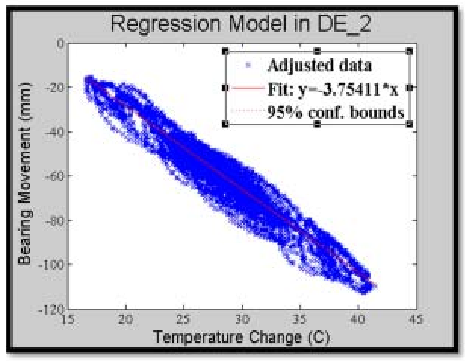
## 3.2 RATING FACTORS

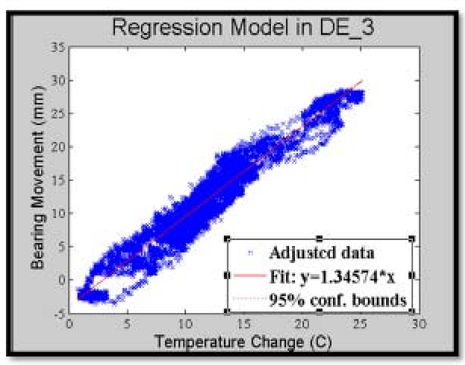


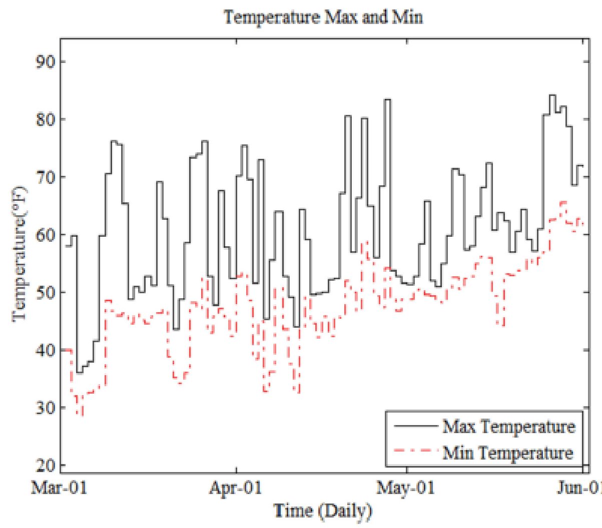
### 3.3 Expansion Joint Movement

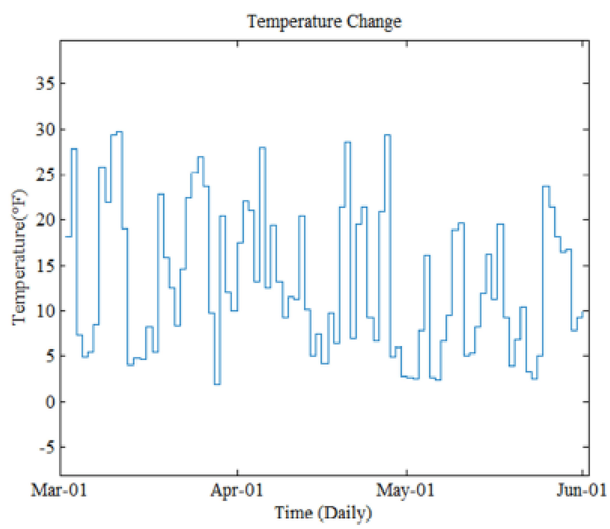


## 3.4 Low frequency Ambient Air Temperature



# 4 SENSOR TABLE

(SHALL BE EMAILED DUE TO SIZE OF SHEET)

## 4.1 CONTAINS:

### 4.1.1 Historical min/max

### 4.1.2 Quarterly min/max

### 4.1.3 Sensor status

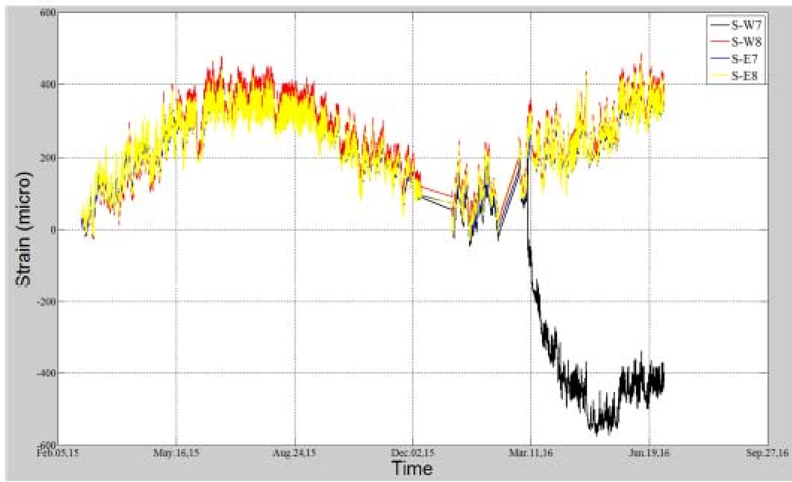
# 5 Observations

## 5.1 SENSOR STATUS COMMENTS

- N/A

## 5.2 REASON FOR ANOMALIES IN DATA

- Our rating factors for midspan were containing erroneous values due to a drift in the strain at SW7. The rating factors being produced were in the negatives. Here is a plot of the strain curve showing the drift in SW7.




## 5.3 PERMIT VEHICLES (DATE, TIME, AND NUMBER)

- Permit Vehicle #: **009O6150325001** (03/30/2015 – 04/03/2015)
- Permit Vehicle #: **0002N160418001** (05/04/2016 – 05/08/2016)

## 5.4 EVENT COMMENTS (WEATHER, ACCIDENT, ETC.)

- N/A

## 5.5 NOTABLE CHANGES

- No notable changes

## Appendix D

## CODE TO FIND SHM TEMPERATURE SENSOR THAT BEST MATCHES DEOS DATA

```
load DEOS_Temps_Time.mat
load SHM_Temps_Time.mat
```

### CH_T Com Hut----------- Bad Comparison

```
figure('name','CH_T Temperature Comparison','numbertitle','off')
x1 = date_time_matlab_SHM; % 10 minutes
y1 = temperature_SHM_CH_T; % SHM Temp
x2 = date_time_matlab; % hourly time
y2 = temperature_excel; % DEOS Temp;

hl1 = line(x1,y1,'Color','b','linewidth',1.5);
ax1 = gca;
set(ax1,'XColor','k','YColor','k')
datetick('x','mmm-dd');
ylabel('Temperature ( ^oF)','Fontsize',13)
xlabel('Time (10 Minutes)','Fontsize',13)
legend(ax1,'SHM Temperature','Location','Southwest')
axis([date_time_matlab_SHM(1) date_time_matlab_SHM(end) 10 120])

ax2 = axes('Position',get(ax1,'Position'),...
'XAxisLocation','top',...
'YAxisLocation','right',...
'Color','none',...
'XColor','r','YColor','r','XTick',[]);
hold on
hl2 = plot(ax2,x2,y2,'r--','linewidth',2);
% axis([Sept15_Nov15_timestamp(1) Sept15_Nov15_timestamp(end)...
%min(temp_Sept15_Nov15_DEOS)-5 max(temp_Sept15_Nov15_DEOS)])
axis([date_time_matlab(1) date_time_matlab(end) 10 120])
ylabel('Temperature ( ^oF)','Fontsize',13)
xlabel('Time (Hourly)','Fontsize',13)
legend(ax2,'Hourly Temperature','Location','NorthEast')

title('CH_T and Temperature Vs Time')
hold off
```

### CJ_T Midspan----------- Good Comparison

```
figure('name','CJ_T Temperature Comparison','numbertitle','off')
x1 = date_time_matlab_SHM; % 10 minutes
y1 = temperature_SHM_CJ_T; % SHM Temp
x2 = date_time_matlab; % hourly time
y2 = temperature_excel; % DEOS Temp;

hl1 = line(x1,y1,'Color','b','linewidth',1.5);
ax1 = gca;
set(ax1,'XColor','k','YColor','k')
datetick('x','mmm-dd');
ylabel('Temperature ( ^oF)','Fontsize',13)
xlabel('Time (10 Minutes)','Fontsize',13)
legend(ax1,'SHM Temperature','Location','Southwest')
axis([date_time_matlab_SHM(1) date_time_matlab_SHM(end) 10 100])

ax2 = axes('Position',get(ax1,'Position'),...
'XAxisLocation','top',...
'YAxisLocation','right',...
'Color','none',...
'XColor','r','YColor','r','XTick',[]);
hold on
hl2 = plot(ax2,x2,y2,'r--','linewidth',2);
% axis([Sept15_Nov15_timestamp(1) Sept15_Nov15_timestamp(end)...
%min(temp_Sept15_Nov15_DEOS)-5 max(temp_Sept15_Nov15_DEOS)])
axis([date_time_matlab(1) date_time_matlab(end) 10 100])
ylabel('Temperature ( ^oF)','Fontsize',13)
xlabel('Time (Hourly)','Fontsize',13)
legend(ax2,'Hourly Temperature','Location','NorthEast')

title('CJ_T and Temperature Vs Time')
hold off
```

## P4_T Center of Bridge in Pedestrian Barrier Junction Box

## Good Comparison

```
figure('name','P4_T Temperature Comparison','numbertitle','off')
x1 = date_time_matlab_SHM; % 10 minutes
y1 = temperature_SHM_P4_T; % SHM Temp
x2 = date_time_matlab; % hourly time
y2 = temperature_excel; % DEOS Temp;

hl1 = line(x1,y1,'Color','b','linewidth',1.5);
ax1 = gca;
set(ax1,'XColor','k','YColor','k')
datetick('x','mmm-dd');
ylabel('Temperature ( ^oF)','Fontsize',13)
xlabel('Time (10 Minutes)','Fontsize',13)
legend(ax1,'SHM Temperature','Location','Southwest')
axis([date_time_matlab_SHM(1) date_time_matlab_SHM(end) 10 90])

ax2 = axes('Position',get(ax1,'Position'),...
'XAxisLocation','top',...
'YAxisLocation','right',...
'Color','none',...
'XColor','r','YColor','r','XTick',[]);
hold on
hl2 = plot(ax2,x2,y2,'r--','linewidth',2);
% axis([Sept15_Nov15_timestamp(1) Sept15_Nov15_timestamp(end)...
%min(temp_Sept15_Nov15_DEOS)-5 max(temp_Sept15_Nov15_DEOS)])
axis([date_time_matlab(1) date_time_matlab(end) 10 90])
ylabel('Temperature ( ^oF)','Fontsize',13)
xlabel('Time (Hourly)','Fontsize',13)
legend(ax2,'Hourly Temperature','Location','NorthEast')

title('P4_T and Temperature Vs Time')
hold off
```

### P7_T Segment 412's Pedestrian Junction Box

### Semi-Good Comparison

```
figure('name','P7_T Temperature Comparison','numbertitle','off')
x1 = date_time_matlab_SHM; % 10 minutes
y1 = temperature_SHM_P7_T; % SHM Temp
x2 = date_time_matlab; % hourly time
y2 = temperature_excel; % DEOS Temp;

hl1 = line(x1,y1,'Color','b','linewidth',1.5);
ax1 = gca;
set(ax1,'XColor','k','YColor','k')
datetick('x','mmm-dd');
ylabel('Temperature ( ^oF)','Fontsize',13)
xlabel('Time (10 Minutes)','Fontsize',13)
legend(ax1,'SHM Temperature','Location','Southwest')
axis([date_time_matlab_SHM(1) date_time_matlab_SHM(end) 10 100])

ax2 = axes('Position',get(ax1,'Position'),...
'XAxisLocation','top',...
'YAxisLocation','right',...
'Color','none',...
'XColor','r','YColor','r','XTick',[]);
hold on
hl2 = plot(ax2,x2,y2,'r--','linewidth',2);
% axis([Sept15_Nov15_timestamp(1) Sept15_Nov15_timestamp(end)...
%%min(temp_Sept15_Nov15_DEOS)-5 max(temp_Sept15_Nov15_DEOS)])
axis([date_time_matlab(1) date_time_matlab(end) 10 100])
ylabel('Temperature ( ^oF)','Fontsize',13)
xlabel('Time (Hourly)','Fontsize',13)
legend(ax2,'Hourly Temperature','Location','NorthEast')

title('P7_T and Temperature Vs Time')
hold off
```