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16. Abstract Digital twin technologies have the potential to reshape the management of civil infrastructure by providing an integrated platform for real-time monitoring, predictive maintenance, and data-driven decision-making. These new tools for asset management are enabled by advances in internet-of-things (IoT) sensors, 5G connectivity, and cloud computing, integrating high-resolution data from diverse sources, in real time, across accessible digital domains. This report details the design, deployment, and initial evaluation of a "proof-of-technology" digital twin for the Homer M. Hadley floating bridge, the only floating bridge in the world that supports light-rail transit. While this unique structure requires many more maintenance and operations decisions than a typical bridge, the lessons learned and the tools and technologies implemented are directly transferrable to other infrastructure assets. A system of IoT sensors was installed to monitor key structural and environmental parameters, including anchor cable tension, pontoon movement, pontoon freeboard, and temperature. Data was transmitted over the 5G cellular network and integrated into a cloud-based digital twin platform. Lake level, traffic, and weather data from outside sources were also federated into the system. The digital twin was used to assess bridge behavior in real-world conditions, focusing on anomaly detection capabilities, real-time monitoring, and the feasibility of integrating such a system into existing maintenance programs.			
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Evaluating Digital Twin Technology and Internet-Of-Things Sensors for Informed Asset Management

Final Report

October 2026

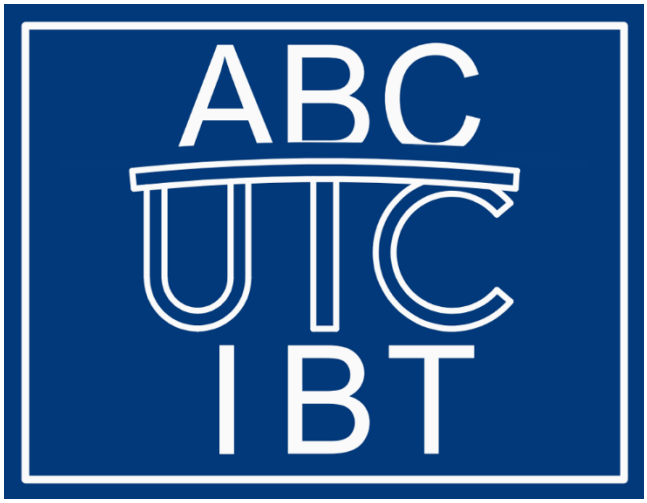
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ACKNOWLEDGMENTS

This report details a "proof-of-technology" project to develop a digital twin for the Homer M. Hadley (I-90) floating bridge, in collaboration with the Washington State Department of Transportation, the University of Washington's Mobility Innovation Center, and industry and technology partners.

This project was supported by the Innovative Bridge Technologies / Accelerated Bridge Construction - University Transportation Center (IBT/ABC-UTC at www.abc-utc.fiu.edu) at Florida International University (FIU), as lead institution, and the University of Nevada-Reno (UNR), University of Oklahoma (OU), University of Washington (UW), University of Georgia (UGA), Florida A&M University (FAMU), and Texas A&M University as partner institutions. The authors would like to acknowledge the IBT/ABC-UTC support.

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The authors would like to extend special appreciation to the IBT/ABC-UTC and the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology for funding this project.

CHAPTER 1. INTRODUCTION

1.1. Project Motivation

Agencies that own, operate, and maintain transportation infrastructure need validated, science-based tools to inform critical decisions regarding maintenance, repair, and operation of their assets. Typically, the current condition of assets (and the identification of any issues) is assessed through visual inspection and thus depends on the experience and judgment of the inspector. Maintenance and repair decisions follow these inspections and are based on the observed conditions. Given the large uncertainty and limits of the data available, this procedure has the potential either to be unduly conservative (and therefore to waste precious resources through premature maintenance actions) or to miss anomalous behavior, which might lead to emergency work when the issue becomes problematic.

Real-time embedded sensing technologies that feed a digital model, or "digital twins", have the potential to monitor conditions over time. This capability leads to an accumulated database of response, covering all seasons of the year, and thus a rich understanding of past and present operational conditions on which to base maintenance and repair decisions. This historical record gives background data against which present performance can be compared, for the purpose of identifying anomalies.

Digital twins are virtual representations of physical objects that enable real-time data flow between the physical asset and the virtual replica. This transformative technology is now feasible thanks to recent developments in Internet of Things (IoT) sensors that enable a new era of integrated sensing and real-time analytics. Digital Twins are already used in the manufacturing, automotive, and aerospace industries to improve product quality and process efficiency (e.g., Kritzinger et al. 2018, Tao et al. 2019). However, the construction industry has generally lagged in adopting this technology, despite evidence demonstrating the benefits of digital twins during each phase of the project's lifecycle (design, construction, operation, and demolition) (Opoku et al. 2021). In bridge applications, much of the research on digital twins has focused on advancing automated model construction of existing infrastructure (e.g., Hosamo & Hosamo 2022), digital inspection using unmanned vehicles (e.g., Opoku et al. 2021), and integrating non-destructive testing methods with existing finite element models to predict future structural degradation (e.g., Opoku et al. 2021). In practice, digital twins have been developed for several existing bridges, including the I-35W Saint Anthony Falls Bridge in Minnesota (Hedegaard et al. 2013), Henry Hudson I-89 Bridge in New York (Andersen & Rex, 2019), the Queensferry Crossing in Scotland (Saul 2017), and the Köhlbrand Bridge in Germany (Wenner et al. 2021), however they are not yet in widespread use, in part because there is a limited understanding of how to interpret the data from such systems, what that data means in terms of changes in the performance of the structure as a whole, the environmental context of the collected data, and the in-situ reliability of these systems over their intended service life.

Advanced, data-driven decision-making tools, such as IoT driven digital twins, are needed to enable state DOTs and stakeholders to effectively set priorities for repair, retrofit, or replacement of existing bridges (which includes the decision to select ABC and repair methods). The innovative bridge technology explored in this research will serve as a building block for other efforts undertaken by the IBT/ABC-UTC to develop technologies for the accelerated repair and upgrade of existing bridges, recognizing that that asset management (repair, rehabilitation,

and replacement of aging infrastructure) consumes most State DOTs' resources and is critical to meet current and future demands for the movement of people and goods in the 21st Century.

1.2. Research, Objectives, and Tasks

The objective of this proof-of-technology project was to evaluate the benefits, limitations, and tradeoffs that an agency or agencies could expect when using IoT digital twin technologies for asset management, maintenance, and operations. Given the limited budget of this pilot project, the number and position of sensors was optimized to demonstrate the potential of the technology to aid in decision-making, rather than provide a comprehensive monitoring program.

Figure 1 shows, schematically, the Interstate 90 Homer Hadley floating bridge across Lake Washington between Seattle and Mercer Island in Washington State. The four floating bridges owned by the Washington State Department of Transportation (WSDOT) are critical for the economic prosperity of the Puget Sound region and represent complex pieces of infrastructure with unique maintenance requirements and operational considerations. The constant attention that the floating bridge requires made it an ideal candidate for a short-term pilot project investigating the benefits of embedded sensor technologies. Additional attention is warranted for the Homer Hadley bridge because of the new demands imposed on it by light rail vehicles that now operate on the bridge. Performance of floating bridges is sensitive to many more inputs, and depends on many more response quantities, than a more conventional bridge. This makes them ideal candidates for applying IoT sensors and digital twin technology, particularly because the interplay between different measured quantities, such as anchor cable forces and lateral bridge movement, cannot be examined using present methods.

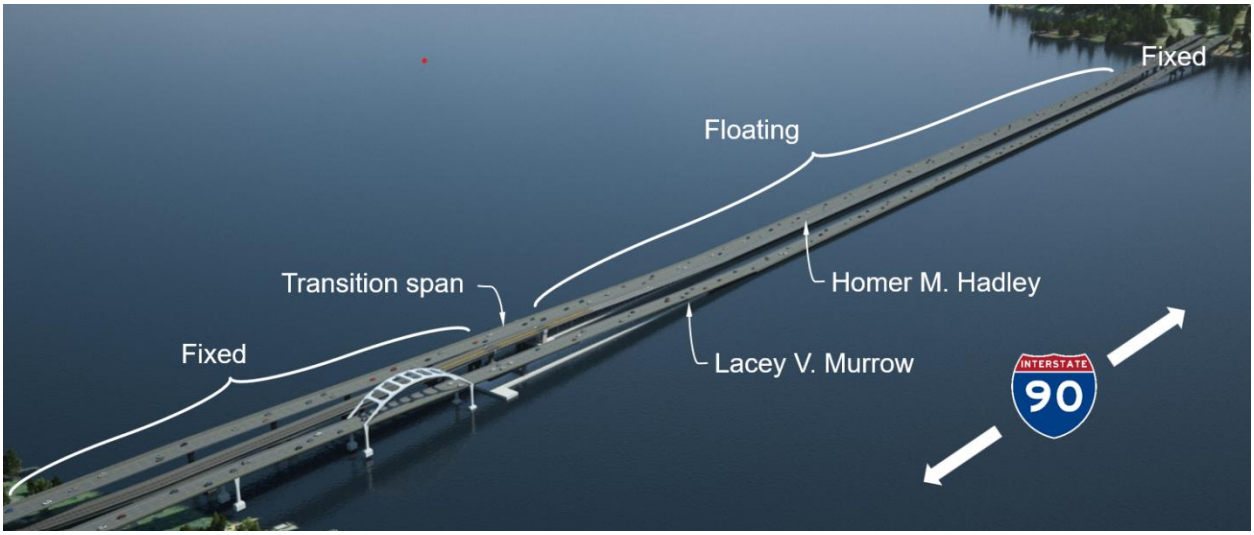


Figure 1. Schematic of I-90 Homer Hadley floating bridge (3D visualization model courtesy of WSP USA).

The research investigated the location and utility of different IoT sensor types, ease of data retrieval and interpretation, integration of disparate data streams, and the ability to draw inferences pertaining to maintenance and operation decisions. The research was separated into a series of five tasks.

Task 1 –Trial IoT Implementation: The objective of this task was to gain familiarity with the IoT sensors that were used in the project by deploying the IoT sensors in a controlled laboratory environment with known inputs and environmental conditions. A small number of IoT sensors were connected to Microsoft's Azure IoT Hub platform, in a trial implementation of that part of the technology. Several different sensor types were investigated, including: vibrating wire strain sensors for measuring anchor cable strains, GNSS -based positioning devices for determining the position of pontoons within the bridge, pressure sensors to determine the freeboard of the pontoons above lake level, and weather stations to monitor lake conditions and correlate with other measurements.

For informed asset management, both long-term and transient behaviors are potentially useful and were explored in this research task. While the first three instrument types (strain sensors, GNSS position sensors, and weather station) are intended for tracking long-term changes at specified time intervals (e.g., every 30 minutes), the freeboard of the pontoons under vehicle loading is a dynamic response that requires a much higher frequency of data collection, event detection, triggering for data storage and output. The technical hurdles in collecting and retrieving both types of instrument data was tackled in this first research task.

- *Task 2 – Develop Digital Twin:* The objective of this task was to develop a three-dimensional digital twin model of the floating bridge that was used to visualize IoT data, send alerts, and record long term maintenance activities. iTwin IoT (Bentley Systems, Exton, PA) already includes built in functionality for visualizing collected data in its structural context, which was leveraged here to provide a user-friendly interface for engineering and maintenance crews.

  The digital twin visualization was developed, in coordination with WSDOT and technology partners, and connected to the IoT sensors on the physical bridge. No single cloud infrastructure met all of the project requirements, requiring the use of multiple systems that communicated through API connections. Sensors from the long-term monitoring system were connected to the digital twin through an integrated IoT solution (Bentley Sensemetrics, Exton, PA) while sensors from the triggered monitoring system and external data streams were connected to the digital twin using Azure IoT hub (Microsoft's Azure, Redmond, WA).

- *Task 3- Deployment and Monitoring:* The objective of this task was to investigate the location and utility of different IoT sensor types, ease of data retrieval and interpretation, integration of disparate data streams, and the ability to draw inferences pertaining to maintenance and operation decisions. The instrumentation plan for the bridge was based on use cases identified during unstructured interviews with WSDOT engineers and maintenance crew and reflected the limited resources available. A detailed description of the interview process and findings is provided in Borjigin et al. (2025). The instruments were placed to demonstrate potential value, rather than to create a comprehensive monitoring program.

The IoT instruments were installed on the floating bridge and connected to the cloud through the 5G cellular network (T-Mobile 5G Enterprise, Bellevue, WA). Anchor cable instruments were installed, with the assistance of WSDOT's maintenance staff. Monitoring of the instruments has continued beyond the conclusion of the research project.

- *Task 4- Workshops:* The objective of this task was to deliver training and workforce development to engineers and maintenance crews who may be considering deploying digital twin technology for asset management. A workshop was held, in collaboration with the project's technology partners, for WSDOT staff on June 17, 2026, to showcase this new technology and outline the outcomes of the research program, focusing on the benefits, limitations, and tradeoffs that an agency or agencies could expect when using IoT digital twin technologies for asset management, maintenance, and operations.

- *Task 5- Final Report:* A final report was prepared meeting the RITA requirements for UTC funded projects. The content of the report contains a detailed summary of the results from the preceding tasks and a recommendation for future phases of the project, if necessary.

1.3. Research Advisory Panel (RAP)

The project work was done in collaboration with many industry and technology partners, who formed the project's Research Advisory Panel (RAP). While the composition of the RAP changed throughout the life of the project, the contributions of individuals from the following companies and organizations are gratefully acknowledged (listed alphabetically):

- Bentley Systems,
- Challenge Seattle,
- Compass IoT,
- eScience Institute,
- Microsoft,
- Semtech,
- T-Mobile,
- UW IT,
- WSDOT, and
- WSP USA.

1.4. Report Overview

This report comprises five chapters.

- Chapter 2 presents a literature review, which briefly covers the background of digital twin technology, specifically within the context of infrastructure applications.
- Chapter 3 introduces the I-90 Homer Hadley floating bridge, which was the subject for this project, as well as elaborating on the motivation for its selection.
- Chapter 4 describes the proof-of-technology digital twin framework and sensor systems that were installed on the bridge.

- Chapter 5 summarizes the research effort, offers several conclusions about the completed work, and describes lessons learned throughout the project.

CHAPTER 2. LITERATURE REVIEW

The implementation of digital twin technology for infrastructure monitoring represents the convergence of multiple technological domains that enable data-driven decision making and predictive maintenance. This literature review is comprised of three parts.

- Section 2.1 examines the fundamental components that comprise infrastructure digital twins: the physical asset, digital representation, and bi-directional data connections between them (Tao et al., 2017a).
- Section 2.2 highlights several case studies in which digital twin technology has been implemented in the infrastructure space.
- Section 2.3 deals with two major challenges associated with the convergence of digital twin technology and the infrastructure space: cybersecurity and integration with existing systems.

2.1. Digital Twin Fundamentals

The concept of a digital twin is a relatively recent development, initially conceived in 2003 as a tool for product lifecycle management (Grieves, 2015). The preliminary form of digital twin technology defines three distinct parts: physical asset, virtual representation, and connections between them. Since this initial concept, the technologies which digital twin is based on have undergone rapid development (Tao et al., 2019). As a result, digital twin has been expanded to include several definitions and focus on different aspects (Wang et al., 2022a). Many researchers continue to focus on the original three-part model as a simple basis for digital twin (e.g., Qi et al., 2018; Tao et al., 2017b; Grieves, 2015). Meanwhile, others think that digital twins should focus on simulations (e.g., Gabor et al., 2016; Maurer, 2017; Weyer et al., 2016). Figure 2 shows a diagram of an advancement on the original theory was put forward by Tao et al. which proposes that a complete digital twin consists of a five-part model: the physical entity (PE), virtual entity (VE), connections (CN), digital twin data (DD), and service (Ss) (Tao et al. 2017a). This more advanced model highlights the importance of data as the central focus of a digital twin. Data is the core of a modern digital twin, as it drives better decision making and optimization strategies.

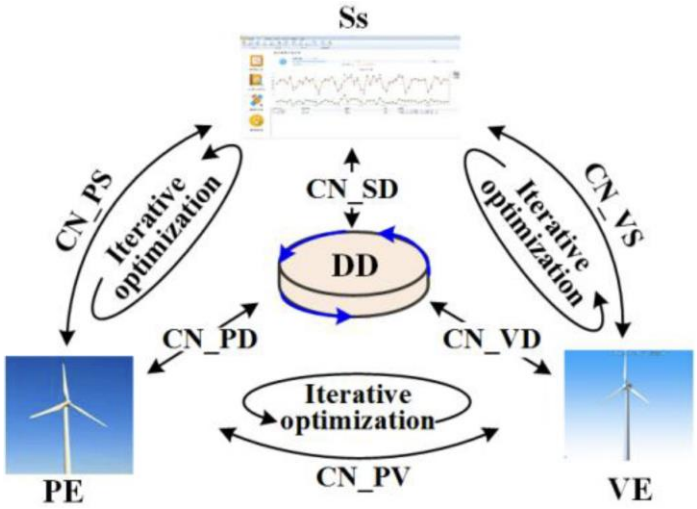


Figure 2. Five-part model of digital twin (Tao et al., 2019)

The IoT provides the sensor network foundation that enables comprehensive data collection for infrastructure digital twins. IoT sensors offer reduced installation costs, improved spatial coverage, and real-time data transmission capabilities on a greater scale than before. The data they collect can be integrated into digital twin models and used to perform advanced analytics. The proliferation of low-cost, high-precision sensors has made comprehensive infrastructure monitoring economically feasible for diverse applications. The combination of IoT sensor networks data collection capabilities, with digital twin's analytics capabilities enables data driven decision making, predictive maintenance strategies, and anomaly detection. These added capabilities stand to enhance the reliability and efficiency of many engineered systems, including infrastructure assets (e.g, Hu et al., 2024; Omrany et al., 2023; Pregnolato et al., 2022; Wang et al., 2024b; Yan et al., 2023; Zaheer et al., 2023; Qiu et al., 2024; Qiu et al., 2025).

Modern IoT sensor networks incorporate multiple communication protocols including cellular (4G/5G), WiFi, and specialized IoT protocols. 5G networks provide advantages for infrastructure monitoring through enhanced bandwidth, reduced latency, and improved reliability in dense urban environments. For infrastructure digital twins, 5G capabilities enable real-time transmission of high-frequency sensor data streams (e.g., Liu et al., 2022; Zhou et al., 2021). However, the addition of IoT sensor networks is not without challenges. In order for real-time and high quantity data transmission to exist, "robust communication protocols, data standardization, and interoperability must exist across diverse systems" (Tao et al., 2019). Additionally, the high volume of data captured using these systems requires advanced analytical and computational capabilities to fully utilize. It is critical for a modern digital twin to carefully address these challenges if it is to take full advantage of IoT sensors (e.g., Hossam & Youssef, 2024; Barricelli et al., 2019; Ham & Kim, 2020; Kshetri et al., 2021; Wang et al., 2022; Liu et al., 2022; Zhou et al., 2021).

Cloud computing platforms provide the computational infrastructure necessary for processing, analyzing, and visualizing large datasets generated by infrastructure monitoring systems. The integration of multiple data streams through cloud platforms enables comprehensive analysis of shared data between the multiple stakeholders in infrastructure projects (Qi et al., 2021). The scalability and accessibility of cloud platforms make them essential components of infrastructure digital twins. A multitude of modern cloud services offer data ingestion, analytics, visualization tools, and scalability (e.g., Bhatta et al., 2024; Jiang et al., 2014; Pushpa & Kalyani, 2020; Qi et al., 2018b). Cloud-based digital twin platforms can correlate sensor measurements with external data sources including weather conditions, traffic patterns, and operational parameters to provide contextual insights into asset behavior.

2.2. Case Studies

In recent years, the infrastructure sector has begun to recognize digital twin technology as a powerful tool for asset management. Digital twins enable data-driven decision making, predictive-maintenance, and anomaly detection, all of which can extend the service life and reduce operating costs of large infrastructure assets. This section outlines various case studies where digital twins were successfully implemented in the infrastructure sector.

The application of digital twins for railway bridges have demonstrated the value of integrating continuous monitoring with predictive analytics. Ye et al. (2019) developed a comprehensive digital twin for a railway bridge using dense fiber optic sensor arrays to capture high-resolution structural response data. The implementation combined physics-based finite

element modeling with statistical analysis techniques to create a hybrid approach that leveraged both theoretical understanding and empirical observations. This case study established important precedents for bridge digital twin development, particularly in demonstrating how continuous sensor monitoring could be effectively integrated with analytical models to provide insights beyond traditional inspection methods.

The integration of Weight-in-Motion technology with Building Information Modeling represents another significant advancement in bridge digital twin applications. Dan et al. (2022) investigated the feasibility of developing a digital twin of a mock-up bridge by integrating WIM data into a bridge information model. The implementation utilized Arduino-based sensor systems to replicate Weight-in-Motion technology, with data integration facilitated through Dynamo software to enable real-time interaction between the digital model and physical bridge measurements. This approach created a responsive system capable of detecting overweight vehicles and triggering preventive measures, demonstrating how digital twins can move beyond passive monitoring to active operational control.

A practical bridge maintenance application was developed by Dang and Shim (2020) for an existing cable-stayed bridge in Korea. The implementation focused on creating a comprehensive maintenance management system that regularly updated the digital twin model with real-time sensor data from the bridge structure. The system assessed inventory and information requirements for various maintenance tasks, demonstrating how digital twin technology could be integrated into existing maintenance workflows without requiring complete operational restructuring.

Recent implementations have emphasized cost-effectiveness and scalability. Armijo and Zamora-Sánchez (2024) presented a case study of a railway bridge where low-cost wireless MEMS accelerometers were combined with edge computing and cloud-based digital twin technologies. The system processed vibration data collected after train crossings in the frequency domain and applied machine learning techniques to detect anomalous spectral peaks indicative of potential structural issues. Validated over a two-year deployment on an in-service bridge, the study demonstrated how scalable, IoT-enabled digital twin frameworks can enable real-time anomaly detection and predictive maintenance without requiring prohibitively expensive instrumentation.

2.3. Potential Challenges

The implementation of digital twin technology faces numerous potential challenges (Borjigin et al. 2026). Integrating modern IoT sensor networks and cloud services with existing systems raises questions about interoperability, proprietary formats, and closed protocols. Digital twin systems must consider these factors in order to facilitate communication and data exchange with existing technologies that were installed over the course of the asset's lifetime (Zhang et al., 2023; Su et al., 2023; Song et al., 2023). Integrating new digital twin systems with legacy systems presents an additional barrier. Many were not designed to interface with modern systems. Integrating these older systems often requires costly retrofitting or middleware solutions, and in some cases, complete replacement may be necessary (Hussain et al., 2024; Jiao et al., 2024; Ramonell et al., 2023; Xie et al., 2022). Successful integration also requires collaboration across disciplines, involving engineers, IT professionals, and data scientists who together can align digital twin requirements with the operational realities of existing systems (Cheng et al., 2023). These technical and organizational challenges underscore the need for

strategic upgrades that can both preserve existing system investments and ensure future compatibility (Wang et al., 2024; Yonggang & Qamar, 2022).

Cybersecurity is a critical consideration in the implementation of infrastructure digital twins due to their reliance on pervasive connectivity, sensitive data exchange, and integration with operational technologies. As digital twins act as high-fidelity representations of physical assets, they can expose vulnerabilities that extend beyond the digital domain into real-world infrastructure operations (Suhail et al., 2023). A successful cyberattack on a digital twin platform could not only compromise data integrity but also manipulate the physical system itself, resulting in safety hazards or operational disruptions (Pärn et al., 2024).

The attack surface of digital twins is considerable, encompassing IoT devices, cloud computing platforms, edge nodes, and data visualization interfaces. Each layer introduces distinct risks, ranging from sensor spoofing and unauthorized data interception to denial-of-service attacks and malicious model manipulation (Alcaraz & López, 2022). The distributed nature of IoT-enabled monitoring further compounds these challenges, as hundreds or thousands of connected devices must be secured simultaneously, often with limited computational resources for advanced encryption or intrusion detection.

The construction and infrastructure sectors face unique risks because digital twins often involve multiple stakeholders, including contractors, owners, operators, and technology providers. This distributed governance structure complicates the implementation of unified security policies and increases the likelihood of misconfigurations or access control gaps (Alshammari et al., 2021). To mitigate these risks, multi-layered security strategies are recommended, including tamper-resistant hardware, secure communication protocols, network segmentation, and role-based access control. Proactive measures such as continuous monitoring, penetration testing, and anomaly detection algorithms are essential for identifying potential breaches before they impact critical infrastructure (Alcaraz et al., 2022).

As digital twins become more tightly integrated into decision-making and operational control, their cybersecurity must be treated as a foundational design requirement rather than a supplementary safeguard (Alshammari et al., 2021). Ongoing research emphasizes the importance of developing standardized security frameworks, cross-sector collaboration, and resilient architectures capable of adapting to evolving cyber threats. Without such measures, the promise of digital twins in enhancing infrastructure resilience could be undermined by their own vulnerabilities.

CHAPTER 3. HOMER M. HADLEY MEMORIAL FLOATING BRIDGE

Floating bridges represent a particularly compelling case study for digital twin implementation due to their unique operational characteristics and maintenance requirements. These structures experience complex dynamic responses to environmental conditions and require sophisticated monitoring approaches, in addition to more traditional inspection methods. The operational and maintenance demands of floating bridges create substantial costs and complexities that digital twin technology is uniquely positioned to address through continuous monitoring and predictive insights.

In particular, the Homer M. Hadley Memorial floating bridge (I-90), referred to here as the “Homer Hadley”, across Lake Washington presented an exceptional opportunity to demonstrate the potential of digital twin technology for complex infrastructure systems. As the designated route for Sound Transit's East Link Extension, it is the world's first floating bridge to carry light-rail transit, creating unprecedented operational and monitoring challenges. The bridge’s critical role in regional connectivity and the substantial investments required for its ongoing maintenance make it an ideal candidate for demonstrating how digital twin technology can optimize asset management decisions and extend infrastructure service life.

3.1. Bridge Overview

The Homer Hadley is one of four floating bridges owned by the Washington State Department of Transportation (WSDOT). These bridges are critical for the economic prosperity of the Puget Sound region and represent complex pieces of infrastructure with unique maintenance requirements and operational considerations. The idea of using concrete pontoon bridges to cross Lake Washington was first proposed in 1921 by engineer Homer M. Hadley, for whom the bridge was later renamed. Lake Washington is sufficiently deep and the underlying soil is sufficiently poor that a fixed span bridge, such as a suspension bridge, was cost prohibitive.

Of the four floating bridges that WSDOT operates, the Homer Hadley bridge is of particular interest for this project due to Sound Transit’s construction of the East Link light rail extension, which began revenue service in 2026. This represents the world’s first light rail line over a floating bridge and subjects the structure to new, uncertain demands. Because of the unprecedented nature of this project, the collected real-time data was of significant value, allowing engineers to verify assumptions used in their computer simulations and assess the accuracy and conservatism of those models.

Figure 3 shows the location of the Homer Hadley across Lake Washington between Seattle and Mercer Island in Washington State. It currently carries westbound traffic from Mercer Island to Seattle and Sound Transit’s 2-Line. The 2-Line connects the Central Link and East Link lines which are currently in service, unifying the Sound Transit light rail system. To prepare for the use of light rail vehicles (LRVs) over the existing bridge, ballast has been adjusted in the pontoons and the existing structure has been strengthened with a longitudinal post-tensioning system that spans the length of the bridge. This added prestress is intended to stiffen the floating portion, which will reduce its deflection in response to the off-center LRV loads on the bridge, and reduce cracking, which could cause water intrusion into the pontoons.

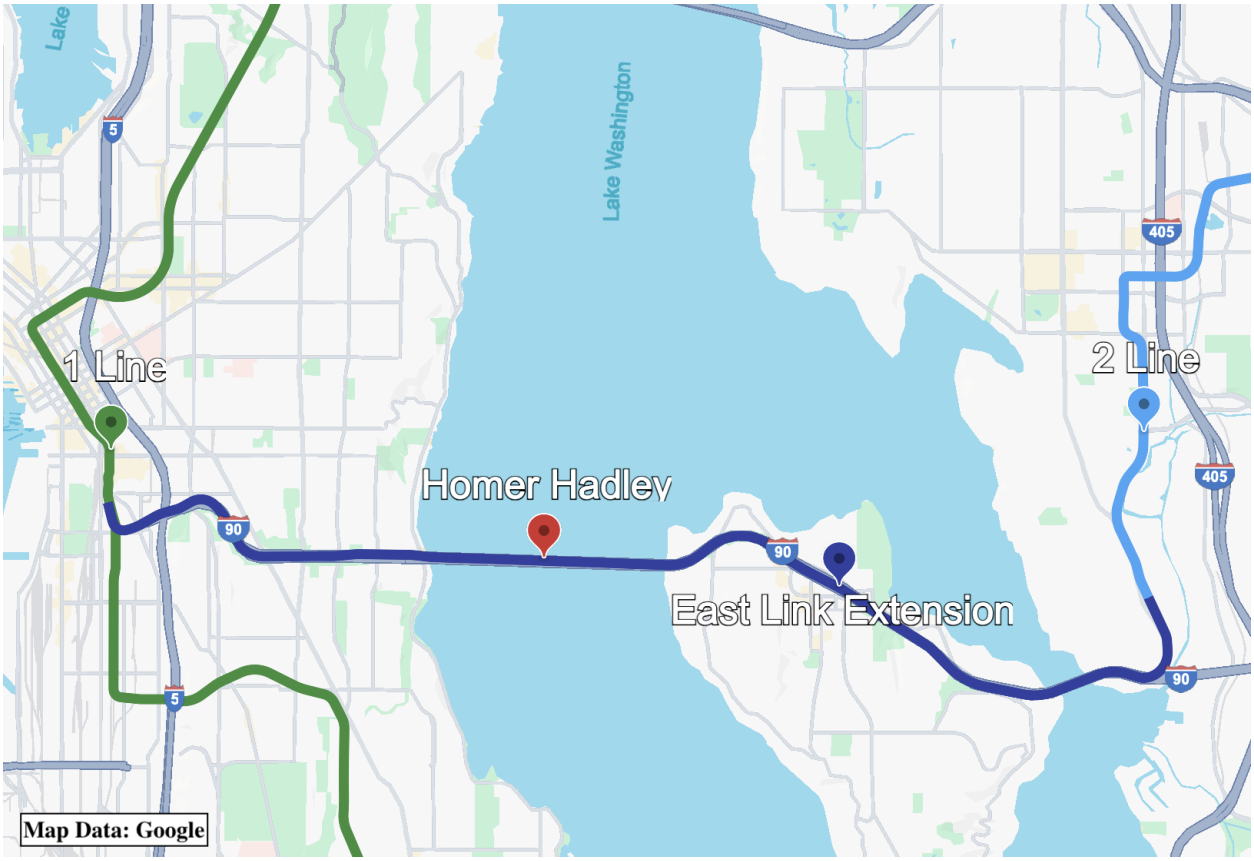


Figure 3. Bridge location and 2-Line route

3.2. Floating Span Structural System

The Homer Hadley Bridge comprises five separate spans; two fixed end-spans, a central floating span, and two transition spans that act as simply supported connections between the fixed and floating spans. The focus of this study was the central floating portion, consisting of 18 floating concrete pontoons held in alignment by 52 anchor cables as shown schematically in Figure 4. An additional longitudinal post-tensioning system, that prestresses the pontoons together, was added in 2018 in preparation for light rail vehicle loading. The floating span is restrained from axial, lateral, vertical, and torsional movement by the anchor cables, However, much like a boat at harbor, the bridge experiences minor movements under loading and environmental conditions. Specialized expansion joints at the end of the fixed and floating spans, separate systems for road and rail traffic, allow for smooth transitions in roadway and track geometry (Foan et al. 2018).

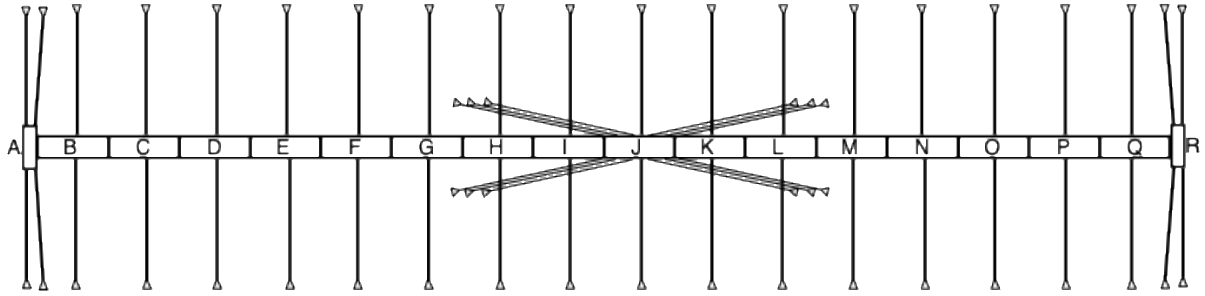


Figure 4. Floating span pontoon and anchor cable layout

Each of the 18 pontoons are a hollow reinforced concrete box, fastened to its adjacent pontoons by steel post-tensioned rods at each end. These bolted connections enforce displacement compatibility of the structure, which acts similarly to a slender beam, supported vertically by buoyancy and held in horizontal alignment by anchor cables. Each pontoon is sectioned into approximately 60 smaller watertight cells by reinforced concrete bulkheads that provide stiffness as well as reduce the risk of water incursion. The central 16 pontoons were approximately 350 ft long, 75 ft wide, and 20 ft deep. End pontoons A and R were 75 ft long, 200 ft wide, and 30 ft deep, and oriented perpendicular to the other pontoons for stability. For the initial 1981 design, gravel ballast was placed in each pontoon to align their top surfaces and to position their center of gravity close to lake level, allowing the bridge to remain stable in elevated weather conditions and under heavy loads. To accommodate the additional eccentric loading from light rail vehicles, this ballast was adjusted, to counterbalance the additional fixed weight of the rail and crossties.

Each of the 52 steel anchor cables entered the pontoon through a hawse tube at an angle, passing through a waterproofing seal and over a steel saddle, before anchoring horizontally in the pontoon at walkway level, to allow for maintenance and adjustment. The other ends of the anchor cables were fixed in the lakebed below with a variety of anchor designs. Cables inside the pontoon were coated in grease to reduce friction over the saddle and provide additional corrosion resistance. In plan, cables were primarily oriented at 90 degrees from the roadway (transverse) to hold the structure in alignment, with 12 (longitudinal) cables in the center pontoon that orient closer to the longitudinal axis of the bridge, reducing movement in that direction. Each cable was tensioned to a set value, designated during the original design, to minimize movement and prevent overstressing during high-weather events.

3.3. Project Motivation

The Homer Hadley is a complex structural system that is subject to changing lake, weather, and traffic conditions. For example, the elevation of Lake Washington fluctuates with the seasons and is controlled by outflow through the Hiram M. Chittenden Locks, carrying freshwater from the lake out to the Puget Sound. As the lake elevation changes, the tension in the anchor cables, which are required to maintain the bridge's alignment in the lake, must be adjusted. This creates a unique maintenance consideration for the floating structure: the re-tensioning, annual inspection, and periodic replacement of these anchor cables. In 2022, WSDOT replaced 38 anchor cables at the cost of approximately $9 million (Bellevue, 2010; WSDOT, 2023b). If better data on anchor cable demands and performance could extend the

service life of the cables by just five years, the annualized cost of anchor replacement would be reduced by 25%. These structural and operational considerations present an ideal subject for a proof-of-technology digital twin project.

Digital twin technology has the potential to reduce maintenance costs and extend the lifetime of infrastructure by allowing maintenance crews to make better, faster, and more informed decisions. By providing continuous monitoring and real-time insights into structural behavior, digital twins enable the transition from reactive maintenance schedules to predictive maintenance strategies based on actual asset condition rather than predetermined intervals. In the case of the Homer Hadley, this approach can significantly extend service life by identifying optimal maintenance timing, preventing premature anchor cable replacement, and detecting potential issues before they develop.

Planned data collection included traffic and weather metrics, global navigation satellite system (GNSS) position of the pontoons, anchor cable strains, and the vertical displacement of the pontoons in the lake during train passage. The goal of this data collection and digital twin visualization was to allow maintenance teams to make more informed decisions regarding the short- and long-term health of the bridge.

The data that the digital twin provided will likely be more valuable given the complicated nature of the Homer Hadley. Current monitoring systems were not currently installed to capture the nuances of structural response and health of this complicated structure. Given the short project lifetime, it was important to select a bridge with a complex structural system where data collected would be useful while the project was ongoing. For these reasons and those stated above, the Homer Hadley was chosen for a proof-of-technology digital twin project.

CHAPTER 4. DIGITAL TWIN

This chapter describes the proof-of-technology digital twin which was installed on the Homer Hadley for this project.

- Section 4.1 provides a short overview of the framework of the digital twin.
- Section 4.2 addresses cybersecurity considerations for protecting critical infrastructure data.
- Sections 4.3 and 4.4 detail the physical monitoring systems which were installed on the bridge and provides examples of representative data collected so far.
- Section 4.5 identifies additional sources of publicly available data that were federated into the digital twin.

Certain commercial equipment, computing infrastructure, and instruments are identified in this chapter in order to specify the digital twin system adequately. Such identification does not necessarily imply recommendation or endorsement of any product or service, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

4.1. Digital Twin Framework

The I-90 digital twin employed the simple three-part architecture for data collection, federation, and visualization described by Tao et al. (2017). Modern cloud-based solutions enable data aggregation from multiple sources with relative ease. Figure 5 shows the digital twin framework that was developed and deployed as a part of this project.

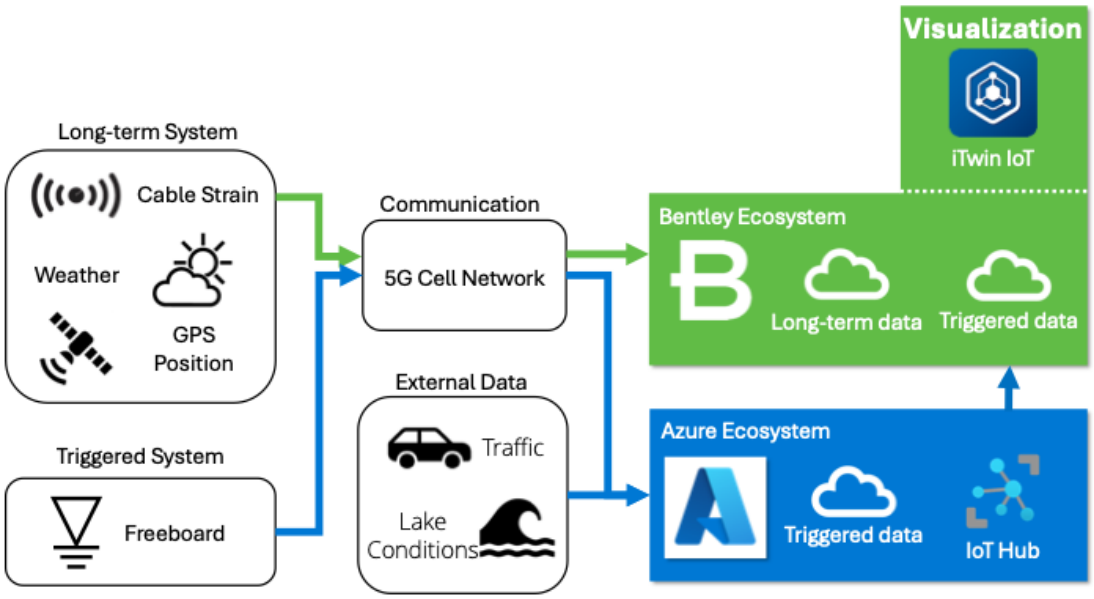


Figure 5. Digital twin framework

Two separate monitoring systems were deployed in combination with publicly available external data:

- A “long-term” system that captured daily, weekly, and seasonal trends with data with collection rates ranging from once per minute to once per hour.
- A “triggered” system that collected bursts of data at 100 Hz during LRV passage

Data collected onsite was transmitted to two separate cloud ecosystems using the 5G cellular network. The cellular approach eliminates the need for dedicated fiber optic installations or wireless point-to-point links, reducing infrastructure costs and installation complexity while providing flexibility for sensor placement anywhere on the bridge structure. The 5G network provided advantages over previous generations of cellular technologies, including increased bandwidth (up to 1 Gbps theoretical), reduced latency (sub-20ms), and improved reliability in dense urban environments like the I-90 corridor. For this project, 5G capabilities enabled real-time transmission of triggered data streams. The data collected from the triggered system was collected at 100 Hz and transmitted every 30 seconds, generating substantial data volumes that benefited from 5G's enhanced throughput.

The long-term system, which had “plug and play” functionality, sent data directly to the iTwin IoT platform (Bentley Systems Exton, PA), which acted as both backend storage and visualization platform for the digital twin. Device configuration used the built-in GUI, with automatic communication via REST HTTP API. iTwin IoT served as the primary data visualization and analysis platform for the digital twin, providing time-series plotting, data export capabilities, and alarm/notification systems capabilities for threshold-based monitoring. The platform's strength lied in its ability to handle multiple data types from different sources within a unified interface. Each individual users could create custom dashboards combining GNSS coordinates, strain measurements, weather data, and pressure readings, and public data on synchronized time axes. Built-in data retention policies and backup systems ensured long-term data availability for trend analysis and historical comparison. Integration with Bentley's broader infrastructure software ecosystem provided potential for future expansion into 3D visualization and digital twin modeling capabilities.

The triggered system sent data to a separate cloud computing platform (Microsoft Azure, Redmond, WA) where it was parsed, stored for later analysis, and sent to iTwin IoT for collective storage. External data from public sources was also collected using this separate cloud computing platform, which offered more functionality for external API calls. The use of a separate cloud platform was needed in this case to parse the triggered system and external data streams, which had varying and sometimes complex output, to a format suitable for federation into the iTwin IoT visualization. Azure IoT Hub provided enterprise-grade device management and bidirectional communication capabilities, though only unidirectional data flow was utilized for this project. The platform handled device authentication, message routing, and provided monitoring dashboards for connection status and message throughput. IoT Hub's ability to scale to millions of devices and messages made it suitable for future expansion to additional bridge monitoring locations. Triggered monitoring system data was sent to Azure IoT hub using Azure's REST HTTPS API. The datalogger sent TOA5 formatted, base 64 encoded sensor data every 30 seconds to minimize file size and transmission requirements.

Figure 6 shows the Azure system architecture that ingested data and sent it to iTwin IoT. An Azure Stream Analytics job converts incoming data from TOA5 to JSON format using a custom JavaScript function. Formatted JSON files were then sent to a blob storage container for long term storage as well as transmission to iTwin IoT. Stream Analytics provided the ability for real-time data processing capabilities including filtering, aggregation, and anomaly detection. The service's ability to process streaming data in near real-time positioned the system for future implementation of automated alerting based on sensor thresholds or pattern recognition. An

Azure Logic App then uses iTwin IoT API to send converted data to iTwin, where all system data was stored collectively.

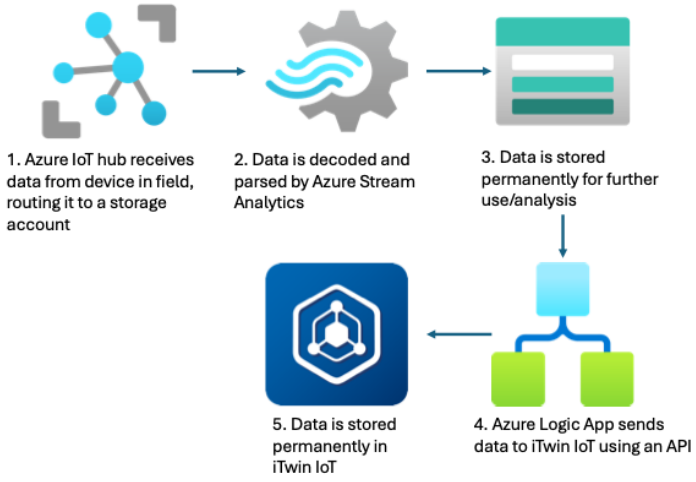


Figure 6. Azure system architecture

4.2. Cybersecurity

The Homer Hadley represents critical infrastructure vital to the greater Seattle area economy and transportation network. Great care was taken to ensure the physical and digital security of digital twin elements. Three different layers of cybersecurity were implemented, as recommended by Parn et al. (2024);

- physical,
- organizational, and
- digital.

Physical security included restricted access areas and sensor placement away from public walkways. Pontoon access required boat transportation or crossing light rail right-of-way and protective fencing, with locking doors and key-access hatches, provided additional protection. Bridge maintenance personnel provided an additional layer of security due to their near constant presence and visual monitoring of bridge access.

Organizational security consisted of both a cultural and access management aspect. While not a “hard” security method, previous work has emphasized the importance of cultivating a culture of cybersecurity (Borjigin et al., 2024). In order to promote this culture, the project team has stressed the importance of cybersecurity when interfacing with project stakeholders and interested parties. Access management was provided by authorization portals within digital twin cloud applications. Authorization portals allow organizations, in this case WSDOT, to manage exactly what information each individual user has access to. This provides a greater degree of granularity in the control of potential sensitive data.

Digital security utilizes platform-specific APIs with encryption and time-sensitive authorization tokens. The datalogger uses SAS tokens (symmetric keys) valid for hours, chosen for programming language compatibility and project scale appropriateness. Azure-iTwin

connections use Bentley's OAuth system with tokens expiring within an hour, providing enhanced security through more modern authentication methods.

4.3. Long-term Monitoring System

The long-term monitoring system captured trends associated with daily and/or weekly cycles, cable tension adjustments, and seasonal change. The intent of the long-term system was to identify and observe systematic patterns that impact the floating structure, allowing WSDOT bridge maintenance teams to utilize predictive maintenance strategies based on actual bridge conditions. It was comprised of three separate IoT gateway devices with several sensor configurations that collected minutely, hourly, and daily data.

The IoT gateways used in this project (Worldsensing Thread X3, Barcelona, Spain), shown in Figure 7, provided power, sensor connectivity, and communications gateway functionality within a single weatherproof enclosure. Features that were considered in the selection of the particular IoT gateway used included:

- **Power -** on the floating bridge, power was supplied to the IoT gateway via standard 120V/20A outlets, which were available inside the pontoons throughout the bridge for hydraulic prestressing pumps and lights. An internal battery in the IoT gateway allowed for limited interruption in power. Optionally, solar panels could have been installed to maintain uninterrupted power.
- **Networking -** although the IoT gateways had built-in 4G cellular communication, the wireless carrier and network settings had to be configured by the manufacturer at the point of sale. For additional flexibility, and to take advantage of higher throughput offered by a 5G connection, the IoT gateways were connected to external modems (Semtech AirLink XR60, Camarillo, CA), shown in Figure 8. These cellular modems had additional features such as built-in GNSS and edge computing capabilities that were not used in this project. The IoT gateways also supported mesh wireless networking which was not used in this project but provided potential cost saving capabilities for a larger deployment.
- **Compatibility -** built-in plug-and-play sensor integration to the iTwin IoT platform greatly simplified sensor integration and deployment. Preloaded settings for compatible instruments streamlined communications setup.
- **Ruggedness –** The IoT gateways, connectors, and power adapters were all outdoor rated (IP66) and were installed on the exterior of the bridge without additional protection. The modems were contained within an NEMA-4X enclosure, since the devices were only IP64 rated, cable glands and cabling needed to meet the same ratings to prevent water and dust ingress.



Figure 7. IoT gateway



Figure 8. Telecommunication enclosure

Figure 9 shows schematically the locations of the three IoT gateways that were installed on site. Two gateway devices were located on the bridge, one at midspan (Pontoon J), shown in Figure 11, and one at the eastern end (Pontoon R), shown in Figure 10. Both gateways were connected to GNSS receivers to track geospatial movement of the pontoons. The gateway at the midspan of the bridge was equipped with a weather station, while the gateway on the eastern end included a vibrating wire interface to monitor anchor cable strains. The third gateway was located off the floating bridge, elevated by a light pole adjacent to the permanent WSDOT maintenance office at the east end of the bridge, shown in Figure 12. It was equipped with a GNSS receiver configured as a base station to provide differential corrections to the bridge-mounted units. All three long-term setups were equipped with a wireless modem connected to the 5G cellular network.

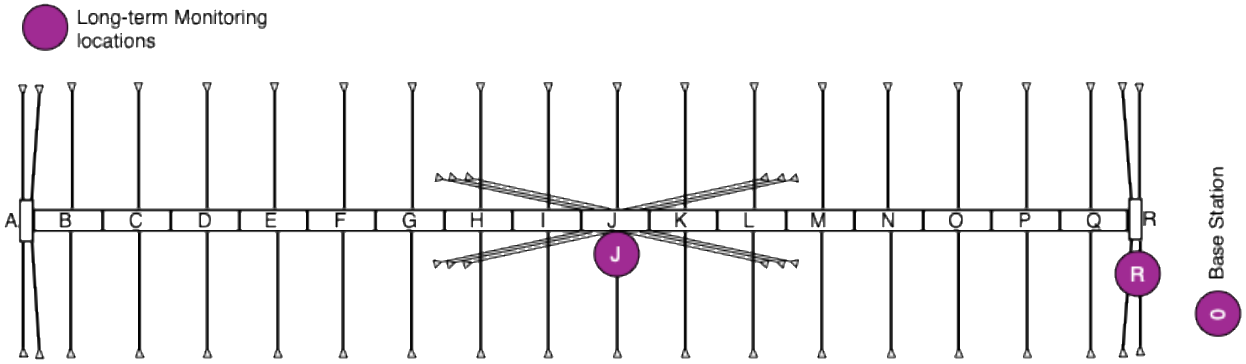


Figure 9. IoT gateway locations on the bridge



Figure 10. Long-term monitoring setup on eastern end pontoon (Pontoon R)



Figure 11. Long-term monitoring setup at bridge midspan (Pontoon J)



Figure 12. Long-term monitoring base station

Figure 13 shows the weather station (Vaisala WXT536, Vantaa, Finland) that was installed at the midspan of the bridge. The weather station provided localized weather data for contextualizing strain gauge and GNSS readings and captured atmospheric pressure, temperature, humidity, rainfall, wind speed, and wind direction every 15 minutes. This localized

weather data proved essential for separating environmental effects from structural behavior, enabling more accurate assessment of bridge response to loading conditions.



Figure 13. Weather station installed at the midspan of the bridge

Figure 14 and Figure 15 shows collected temperature (°F) and windspeed (mph) data plotted against publicly available weather data from a King County owned lake buoy near the bridge. Figure 14 shows that the temperature variation wis minimal between the two. One concern with installing the weather station at grade was interference from road and train traffic and turbulence caused by the bridge. Figure 15 shows a clear difference in windspeed between the weather station (yellow line) and lake buoy (purple line) which can be attributed to a combination of this effect and the differing topography surrounding the two. Weather data follows expected patterns but provides bridge-specific conditions that differ from regional weather stations.

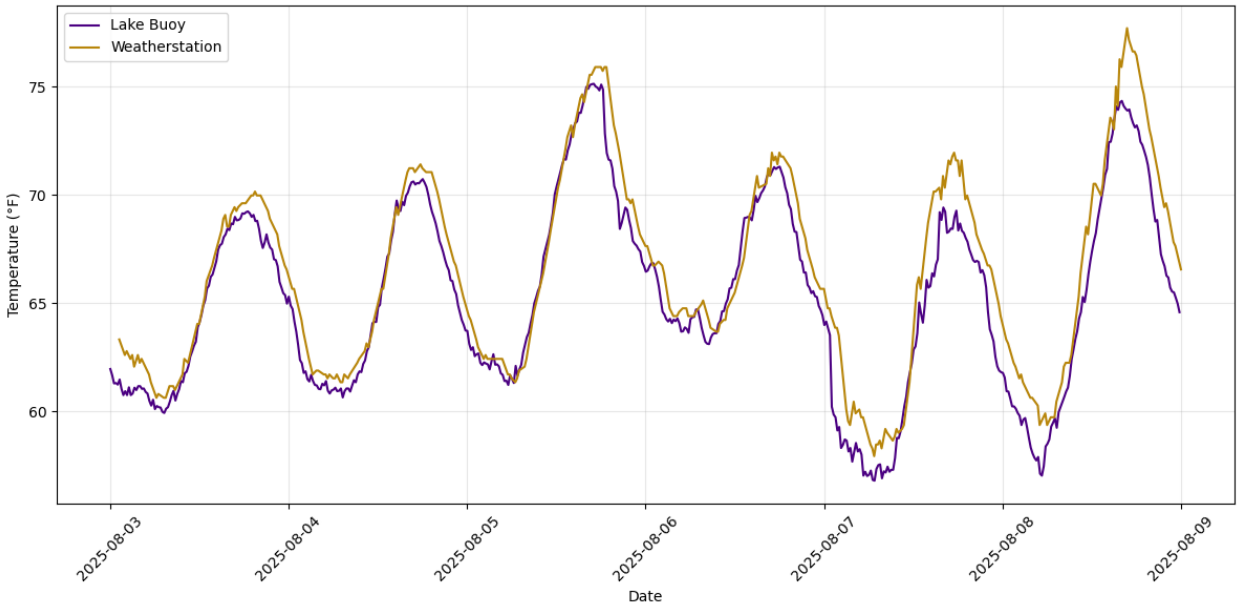


Figure 14. Weather station temperature data

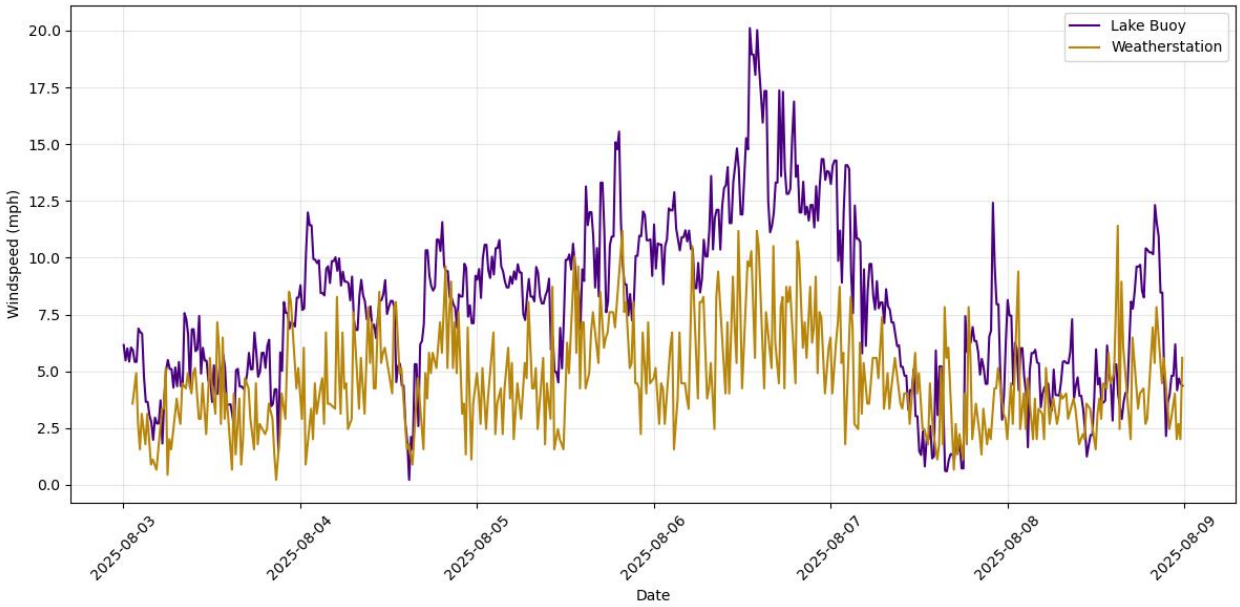


Figure 15. Weather station wind speed data

Long-term geospatial movement of the pontoons was captured using GNSS receivers (Topcon AGM-1, Chico, CA). Three receivers were installed: one at the center of the bridge (Pontoon J), one at the east end of the bridge (Pontoon R), and one at the maintenance facility as a base station, which provided differential correction data to improve the accuracy of the measurements. Features that were considered in the selection of the particular GNSS devices used included:

- **Accuracy** – with advertised accuracy of 0.12 in (3 mm) horizontally and 0.28 in (7 mm)

vertically, the GNSS devices (with a base station) provided the necessary accuracy. For the design of the East link light rail project, the anticipated horizontal movement of the end pontoons relative to the fixed span during wind and weather events was assumed to be on the order of 1-2 inches.

- **Collection frequency** – by averaging collected data over an hour, higher accuracy was achieved at the cost of a longer time between data point collection for calibration of differential correction data. This was ideal for tracking the movements of the floating bridge pontoons on a long-term scale but would not be suitable for capturing dynamic bridge movements. If GNSS devices were used to capture dynamic movements, real-time kinematic (RTK) units would be required in order to reduce the time between measurements.
- **Compatibility** – plug-and-play compatibility, on list of supported devices for the IoT gateway. This allowed for automatic integration without additional setup. The built-in software handled differential corrections and data averaging automatically, which otherwise would have required a significant effort to implement.
- **Ruggedness** – the chosen GNSS devices were IP69K rated, allowing them to be installed without an additional enclosure.



Figure 16. GNSS receiver installed at East end of bridge (Pontoon R)

Figure 17 shows the change in the pontoon positions in the longitudinal direction of the bridge (Δ Easting) over a period of one week, with the air temperature at the midpoint of the bridge also shown for reference. It is worth noting is that longitudinal movement is being equated to easting here, while the bridge itself was oriented a few degrees from the east-west direction. The change in longitudinal position of the midspan of the bridge (Pontoon J) during this period was small, less than 0.5 inches (yellow line). In contrast, the longitudinal (easting) position of the end of the bridge (Pontoon R) showed consistent movement of an inch or more

and this movement largely correlated with the fluctuation in air temperature. This movement was attributed to thermal expansion and contraction of the bridge, with the structure expanding during daytime heating and contracting at night. Because the midspan of the bridge is restrained by longitudinal anchor cables, it remained stationary, while the end of the bridge moved longitudinally in response to thermal strains. Assuming a coefficient of thermal expansion of 5.5×10^{-6} (in/in)/°F and a 10°F fluctuation in temperature, the simple thermal expansion calculation in Equation 1 shows that the magnitude of the expected thermal movement to be.

$$\Delta L_{end} = \frac{\alpha L \Delta T}{2} = \frac{5.5\times10^{-6}\times5811ft\times12in/ft\times10°\text{F}}{2} = 1.9\ in \quad (1)$$

where α is the coefficient of thermal expansion of concrete, L is the length of the floating span, ΔT is change in temperature, and the result is divided by two to account for the longitudinal restraint at the center of the bridge. Taking an example day near the middle of the plot, a change of around 10 °F in ambient temperature is observed in congruence with a movement of approximately 1.3 inches. Comparing this to the expected movement of 1.9 inches, we can see that the structure is expanding and contracting as expected. The lower actual expansion can be attributed to other factors, such as the structure not reaching ambient temperature, and additional resistance provided by the transition spans.

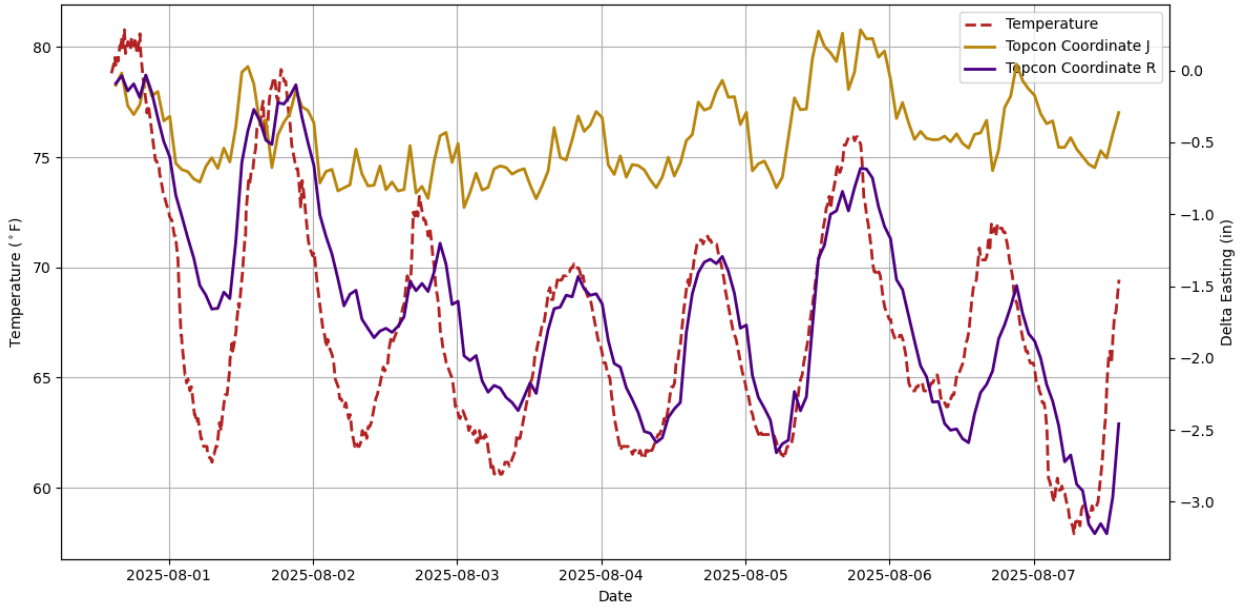


Figure 17. Axial movement vs. ambient temperature

Figure 18 shows the change in the pontoon positions in the transverse direction of the bridge (Δ northing) over a period of five days. It is worth noting is that transverse movement is being equated to northing here, while the bridge itself was oriented a few degrees from the east-west direction. Transverse data shows both pontoons shifting northward each night and returning during the day, indicating temperature-driven lateral movement patterns previously unobserved. These small movements may be partially attributable to the alignment of the bridge in the geospatial reference frame, however the consistency of the measurements between the pontoons may indicate another source. Also shown in the figure is the lateral shift that was observed in both pontoons coinciding with the adjustment of the anchor cable tensions. The cables on the

east end of the bridge (Pontoon R) were adjusted on August 4th (purple line), and the cables at the midspan of the bridge (Pontoon J) were adjusted the following day (yellow line). A shift in the range of 1.5 inches can be seen in both pontoons, in opposite directions. This information could be useful for determining the alignment of the bridge in the lake and if any corrective actions need to be taken. Over the length of the bridge, the measured differential movement would represent a bending deflection of L/12,000 and is therefore likely acceptably small.

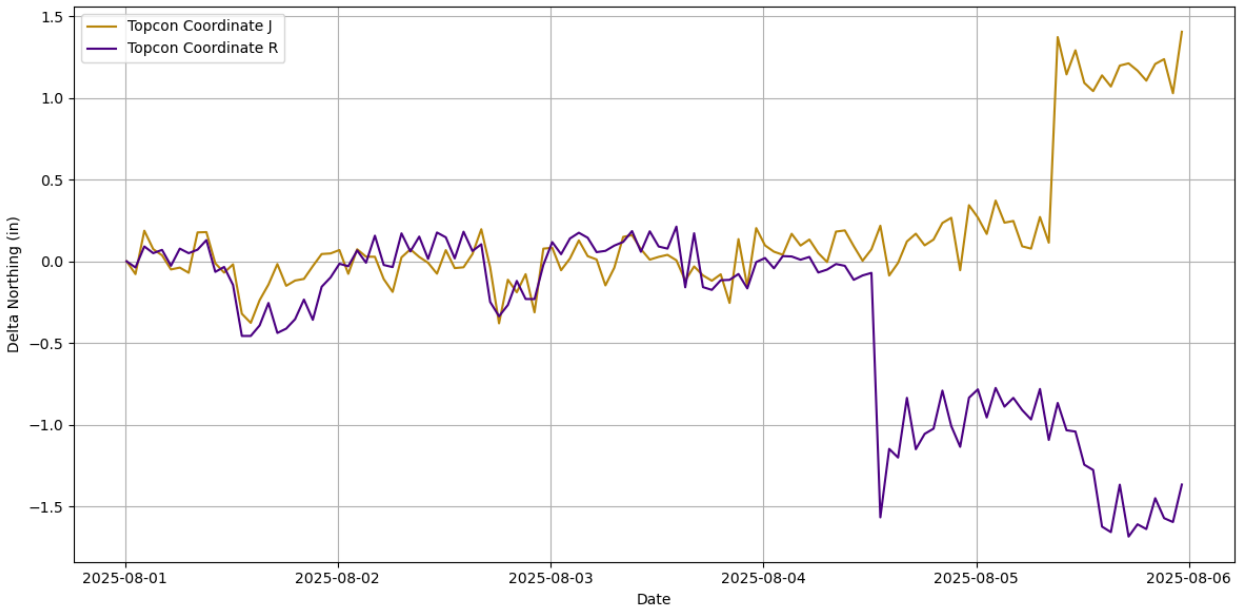


Figure 18. Transverse movement during cable adjustment

Figure 19 shows the change in the pontoon elevation (Δ Elevation) over a period of one month, with lake level data from the US Army Corps of Engineers overlaid for comparison. Elevation data clearly shows a seasonal drop in the level of Lake Washington between July 1 and August 1, 2025. Both pontoons showed a steady drop of nearly ten inches in elevation corresponding to lake level data, validating both the data accuracy and the system's ability to track long-term structural movements with high precision.

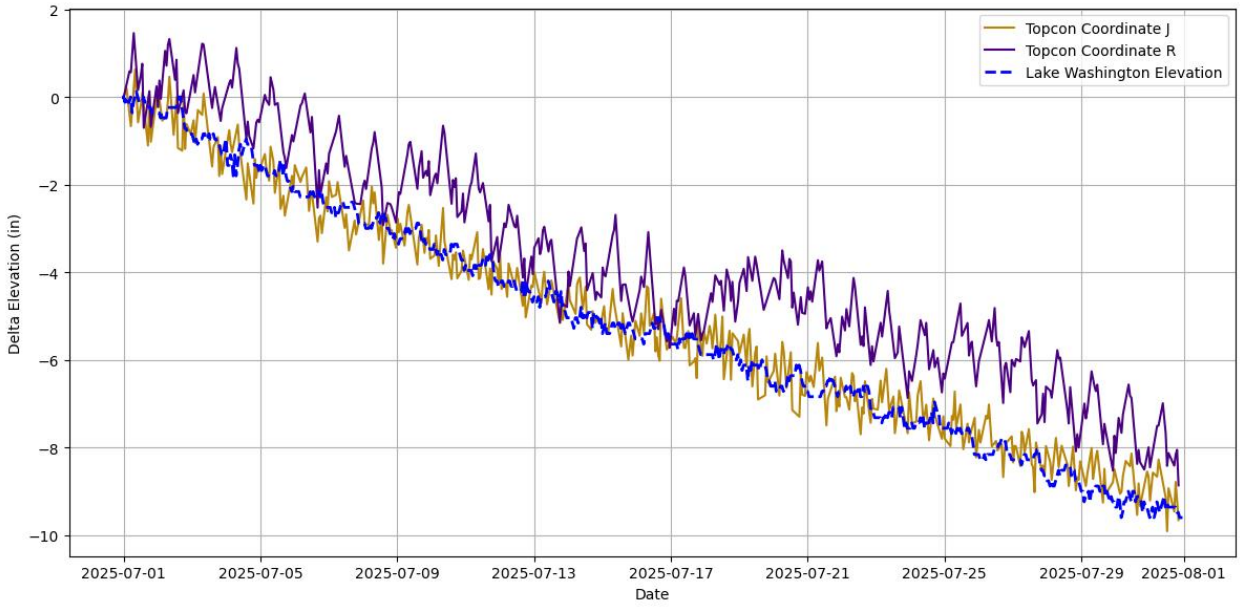


Figure 19. Vertical movement vs. lake elevation

Additional trends can be seen in the elevation of pontoon R, which appears to see both daily fluctuations and a significant bump on the 18th of July which remains. Potential reasons for the daily fluctuations include unequal vertical temperature distribution and eccentric longitudinal restraint from post-tensioning in the floating span cross-section, causing negative internal curvatures which forces the ends downwards during the warmest point in the day. Another consideration is the thermal expansion of the transition spans which connect the floating and fixed portions of the bridge, which could push down on the end pontoons and cause a similar bending effect. Figure 20 below shows that peak ambient temperature coincides with the minimum elevation of pontoon R.

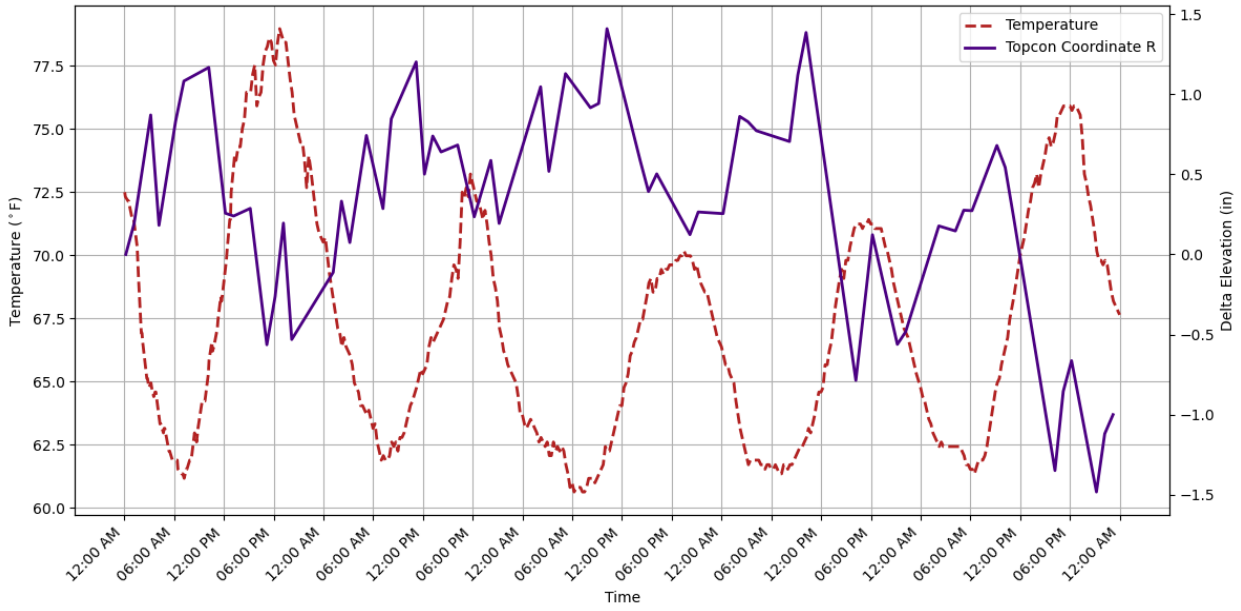


Figure 20. Elevation vs ambient temperature

Figure 21 shows the position of the anchor cable vibrating wire strain gages (Geokon Model 4000, Lebanon, NH) at the east end of the bridge (Pontoon R) that were used to measure the force in each of the anchor cables. The vibrating wire strain gages were installed on three of the four anchor cables inside the pontoon. Features that were considered in the selection of the vibrating wire strain gage devices used included:

- **Drift** – because the instruments were intended to be left in place for long periods of time, instrument drift was an important consideration in instrument selection. Vibrating wire strain gauges monitor strain through harmonic frequency change of a wire of known length, making them inherently more stable than electrical resistance or voltage over long measurement periods.
- **Electrical isolation** – the anchor cables were actively protected from corrosion using impressed current cathodic protection. During the project development phases, there were concerns from project engineers that the installation of strain gages could impact the effectiveness of the cathodic protection system or the DC potential from the cathodic protection system could impact the instrument readings. Because the electrical components of the vibrating wire gages were isolated from the body of the instrument, there was no electrical path added to the system. Also, because the vibrating wire gages measured resonant frequency, rather than electrical resistance, the DC potential of the anchor cables did not impact the measurement.
- **Installation** - Since the anchor cables were already in service, the use of through-hole load cells or load sensing devices was not possible, opting instead for an instrument that could be externally affixed onto the cables. Welded or epoxied connections were avoided to prevent damage to anchor cables. Instead strain gauges were mechanically fastened to clamps that were installed on the anchor cables, as a less intrusive and cost-effective solution. Other installation challenges arose due to the grease coating on the cables as well as the presence of the steel saddles that adjusted the trajectory of the anchor cables in the pontoon.

- **Cable length** – sensors installed required cable runs in excess of 200 ft which can be difficult for electrical resistance gages. Long cable runs can introduce significant noise and voltage drop in resistance-based measurement systems, compromising data accuracy. The use of vibrating wire gauges overcame this limitation by transmitting frequency information, ensuring reliable measurements despite the substantial cable lengths required for installation within the pontoons.

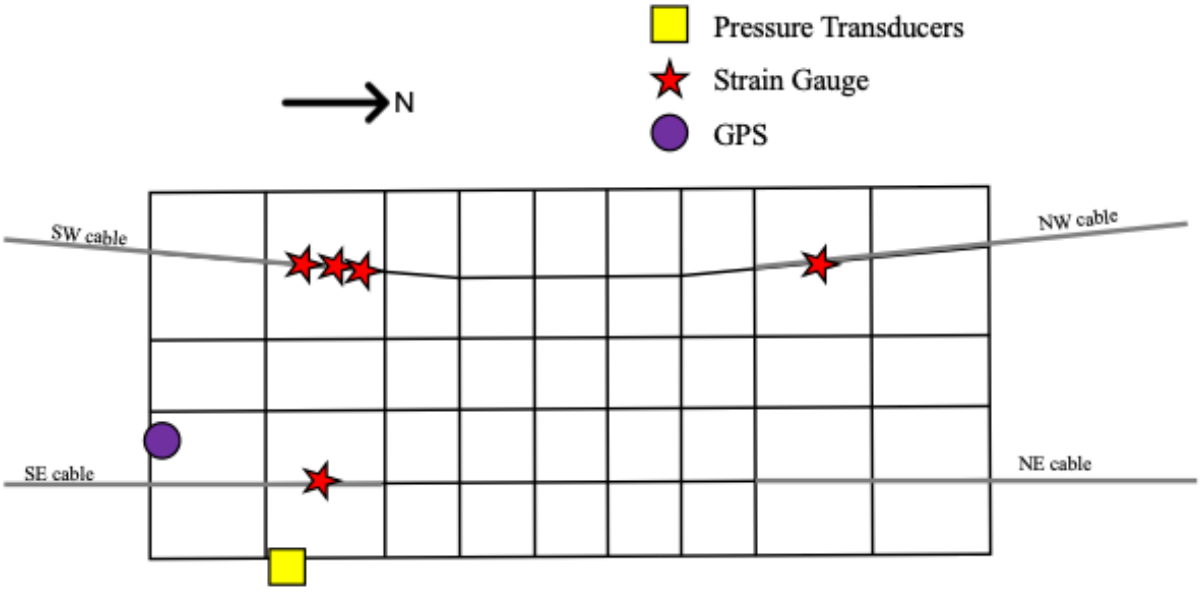


Figure 21. Pontoon R sensor layout

Figure 22 shows the final clamping method devised to minimize slipping. It utilized a cast steel galvanized clamp body for a greater clamping force. Belleville washers allowed pre-tensioning of the clamps to accommodate changes in cable diameter due to changes in tension in the cables. A small steel screw provided a mechanical connection between the vibrating wire housing and the clamps, while epoxy prevented rotation and loosening of the threaded connection over time. Isopropyl alcohol and a cotton cloth was used to remove the grease coating prior to clamp installation. A total of five strain gauges were installed on pontoon R in this way. Three on the southwest cable in the same locations as the test installations, one before the saddle on the northwestern cable, and one after the saddle on the southeastern cable. A variety of locations, both before and after the saddle, were investigated to study the effect of the saddles on the instrument readings.

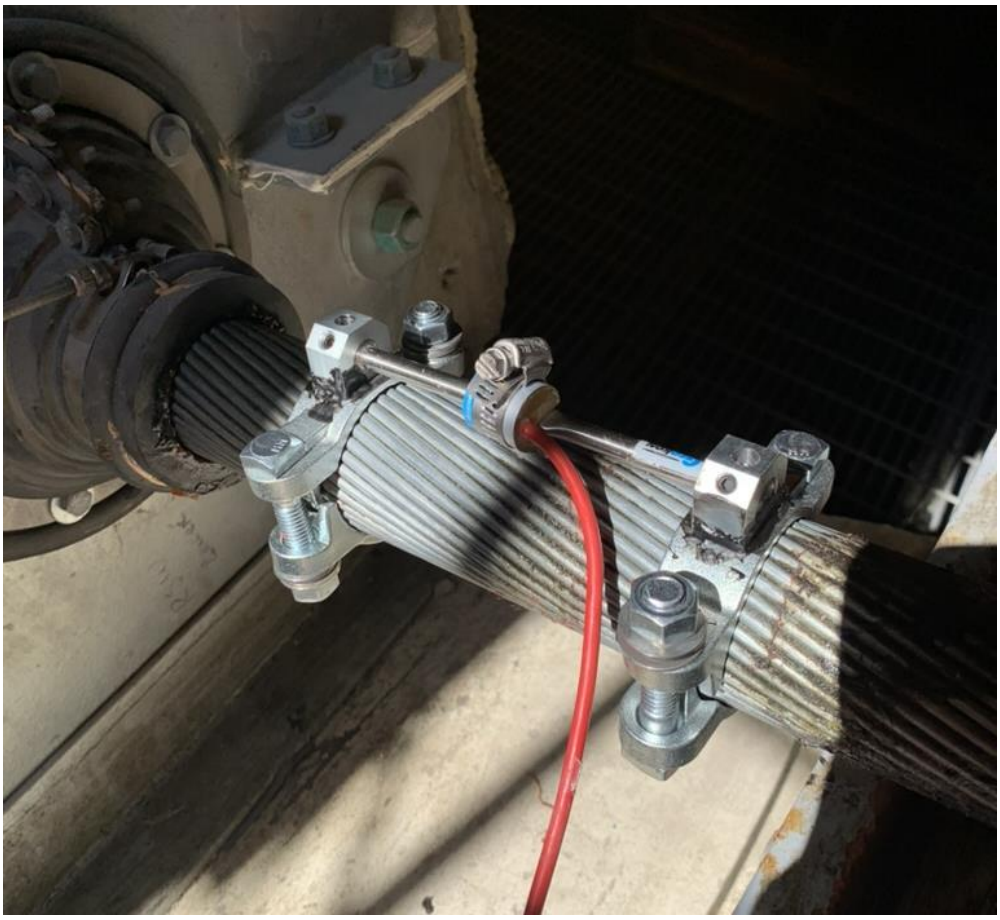


Figure 22. Vibrating wire strain gauge attachment method

Cables entered the pontoons at angles, transitioning to horizontal after passing over steel saddles, as shown in Figure 23. The friction across the steel saddles was assumed to filter some of the dynamic response of the cables to sudden loads. Therefore, strain gauges would ideally have been installed before the saddles, however that would have also put the instruments in a precarious position, requiring periodic relocation due to anchor cable adjustments to accommodate seasonal lake level changes. To assess the impact of the saddles on the measured strains, three test installations were deployed on the same cable at the start of the project to determine the magnitude of this effect, as well as the influence of the grease coating on the anchor cables. These instruments were installed onto the cables using worm gear hose clamps, since no storms or train passage was anticipated during the installation period. Installation 1 was located before the saddle structure, without the grease removed from the anchor cable; Installation 2 was located after the saddle, without grease removed from the anchor cable; and installation 3 was located after the saddle structure, but with grease removed with a cotton cloth and alcohol wipes.

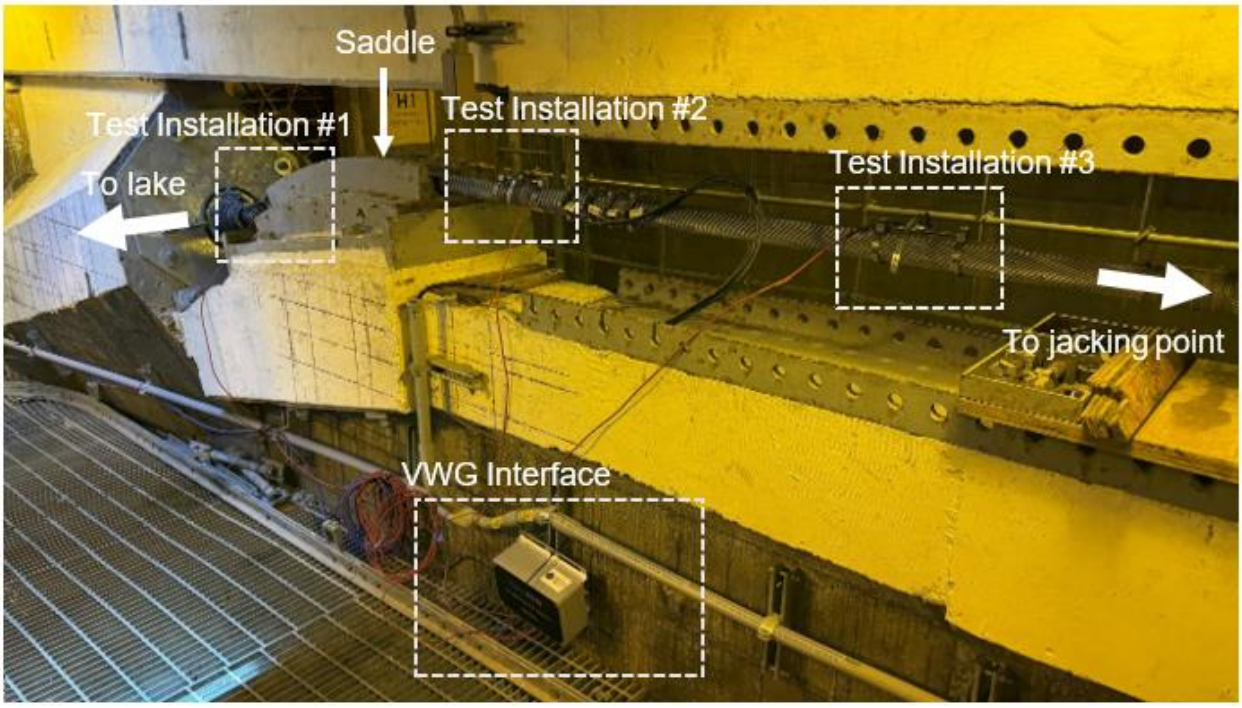


Figure 23. Vibrating wire test installations

Figure 24 shows the change in microstrain (in/in $\times 10^{-6}$) recorded by the three instruments over time for the month of June. Instrument readings were taken every minute. Installation 1 (purple line) and Installation 2 (yellow line), those installed without first removing the grease, slowly slipped out of agreement with Installation 3 (green line). During the month of June, the bridge slowly lowered as the lake elevation dropped; the observed negative change in strain was therefore expected. The dynamic dampening effect of friction from the saddle can also be seen in the figure, as greater short-term fluctuations were seen in Installation 1, in comparison to Installation 2. Assuming a nominal cross-sectional area of the tendon of 3 in^2 and an elastic modulus of 28,500 ksi, the change in tension measured in the anchor cables was roughly estimated to be 9 tons, which was within expectations of the bridge maintenance crew within this time period. Calibration of the instruments in-place, on the anchor cable, against the pressure gauge on the hydraulic prestressing system would improve the accuracy of these estimates.

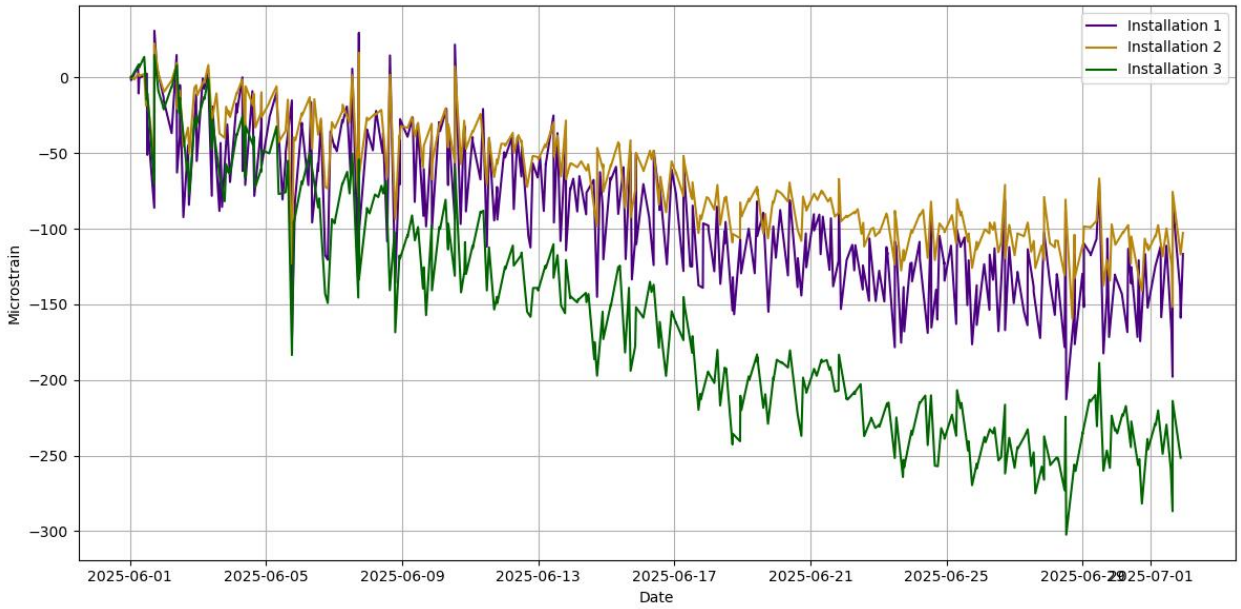


Figure 24. Anchor cable strain with slip

Figure 25 shows the change in micro strain at Installation 3 over time, plotted alongside the change in elevation of the east end of the bridge as measured by the GNSS device on Pontoon R. The strain gage data from installation 3 (purple) was compared to pontoon elevation (yellow) to confirm its accuracy. There was a clear and consistent correlation between the two, as expected. As the bridge level dropped with the lake, the anchor cables slowly lost tension. The strong correlation seen here confirmed that installation 3 was slipping minimally and that the anchor cable grease, which is needed around the cable saddle could lead to erroneous readings if it was not removed prior to installation.

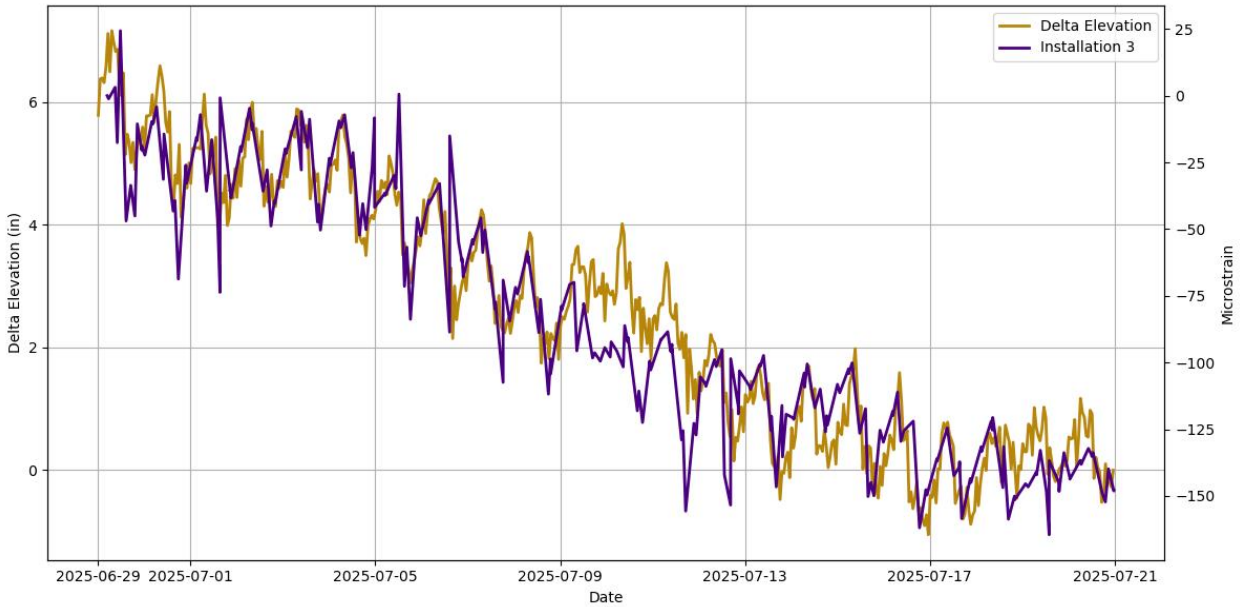


Figure 25. Installation 3 strain vs Pontoon R elevation

Figure 26 shows all anchor cable strains during the period in which maintenance teams adjusted anchor cable tensions. Jumps in strain can be seen which correlate with the tightening of cables to match lower lake levels. Note that the SW cable 1 and NW cable strain gauges exhibited downwards jumps (loss in anchor cable tension). This was because these instruments were located before the saddle and had to be temporarily uninstalled by the maintenance team to prevent any damage to instruments during cable tensioning. They were later reinstalled on the anchor cables the following day, explaining their jump to positive values, however it should be noted that the new values do not correspond to any physical change in anchor cable tension, rather a new set point for the instrument. The noisy signals seen for several of the anchor cables were the result of the strain gauges being near or exceeding their operating range, failing to properly bin frequency data, and not real physical phenomena. These instruments were later swapped out for new instruments.

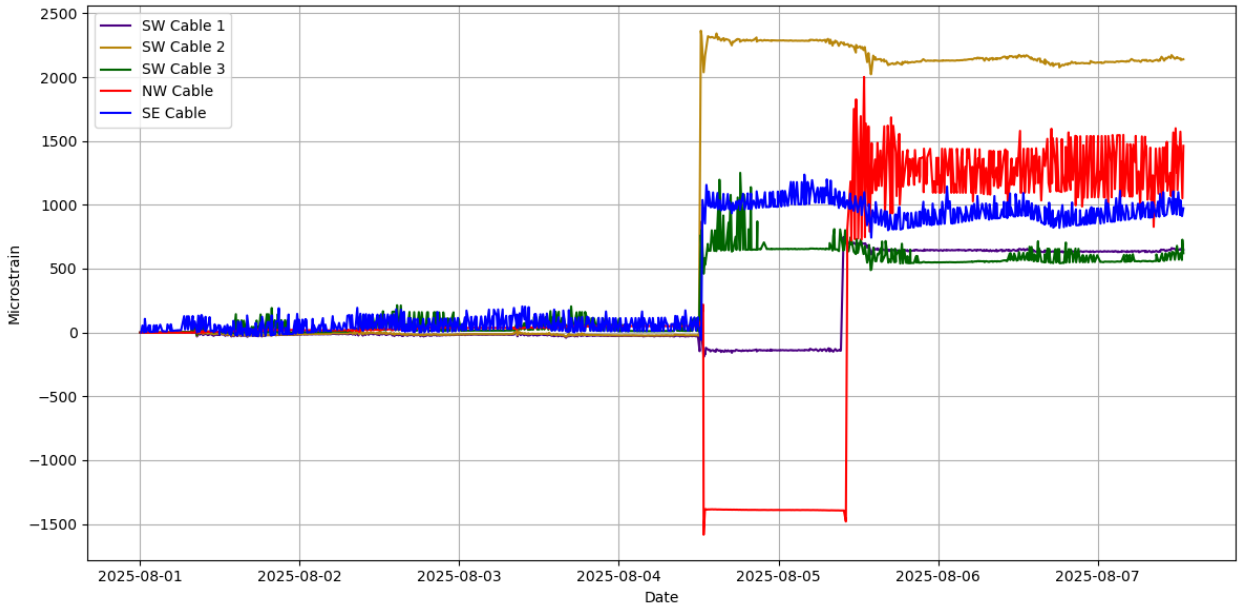


Figure 26. Strain gauge data during anchor cable adjustment

Following these initial vibrating wire gage installations, several conclusions were reached:

- Dynamic changes in anchor cable tension were filtered out from the signals that were installed “after” the steel saddle, on the horizontal portion of the anchor cables between the steel saddle and the jacking point.
- The perceived value of the data for the long-term monitoring system was the gradual change in anchor cable tension
- This gradual change was observed in instruments that were installed on either side of the steel saddle and was consistent with lake level changes and historical expectations
- Instruments installed “before” the steel saddle, i.e. on the inclined portion of the cable between the waterproof membrane and the saddle, would need to be removed each time adjustment took place
- This added maintenance step, removing and reinstalling the instrument several times a year, increases the risk of damaging the instruments and should be avoided.

4.4. Triggered Monitoring

The east approach sees vehicles descend onto the flat floating span at high speeds, expected to be the most critical location for monitoring bridge response to LRVs. In order to capture dynamic response to these events, a triggered system was developed to monitor movement of the east end of the bridge (Pontoon R). The triggered monitoring system contained equipment reused from a previous research project, shown in Figure 27, and consisted of three major components.

- A datalogger (Campbell Scientific CR6, Logan, UT), which had the ability to run user-written code and provided multiple analog and digital input channels with 24-bit resolution and programmable measurement intervals. The system's flexibility allowed for future expansion to accommodate additional sensor types or additional vibrating wire gauges as monitoring needs evolve.
- A dynamic vibrating wire analyzer (Campbell Scientific CDM-VW305,407
- Logan, UT), capable of interpreting changes to in vibrating wire sensors at 100 Hz.
- Vibrating wire pressure transducers (Geokon 4580-2-35kPa, Lebanon, NH) that were attached rigidly to the pontoons and submerged several inches into the lake to measure changes to the vertical position of the pontoon relative to lake level, or "freeboard", which was a critical design quantity under train passage.



Figure 27. Datalogger and dynamic VW analyzer in enclosure

The datalogger was connected to the same wireless modem as the long-term monitoring system present on the pontoon. Data from the triggered system had to be first transmitted to a separate cloud environment (Microsoft Azure, Redmond, WA), different from the iTwin IoT platform, to be parsed into the proper format before being transferred to iTwin IoT through an API.

A custom script was developed to collect data from up to eight pressure transducers and/or strain gauges at 100 Hz. CRBasic, based on the BASIC programming language, provided sufficient functionality for sensor interfacing and data formatting while remaining accessible for field modifications. The systems onboard memory stored data locally during communication interruptions, ensuring no data loss during network connectivity issues.

Communications with Azure IoT hub use HTTP API authenticated with SAS tokens. The datalogger's ethernet port connected to the modem, enabling reliable cellular data transmission. Built-in network protocols support various communication methods, though HTTP was selected for its simplicity and compatibility with Azure services.

Figure 28 shows the two pressure transducers which were mounted near the southeastern corner of pontoon R, as shown in Figure 21, and measured pontoon freeboard with theoretical accuracy of 0.2mm. Combined with 100 Hz data acquisition, this allowed detailed recording of the east end of the bridge's dynamic response. Pressure transducers were installed on the same mounting pipe, shown in Figure 28, but facing in opposite vertical directions. The intent of this duplication was to explore the best attachment strategy for the instruments. The instrument position influenced the ease of installation, since entrapped air needed to be removed from the instrument during installation, and this was easier to do if the end of the instrument was pointed upwards. The instrument position also had the potential to influence the data, given that the instruments experienced dynamic pressure changes due to both changes in freeboard and the velocity of the instruments through the water.



Figure 28. Pressure sensors

Figure 29 shows the change in depth (Δ Depth) readings of both sensors over a 30 second time period. Sensor 1 (purple line) faces downwards into the lake, and sensor 2 (yellow line) faces upwards. The captured data demonstrated exceptional resolution, displaying individual wave patterns of less than an inch passing over the sensors. While some dynamic variation was visible between the two transducers, the magnitude of this was minimal. The high resolution of these measurements indicated that pontoon response to future LRV passes would be detectable and quantifiable. Unfortunately, the trains were not operational during the first deployment of these sensors. However, this baseline data provided crucial context for distinguishing between environmental effects and train-induced response, i.e. what "trigger" should be used, in the future.

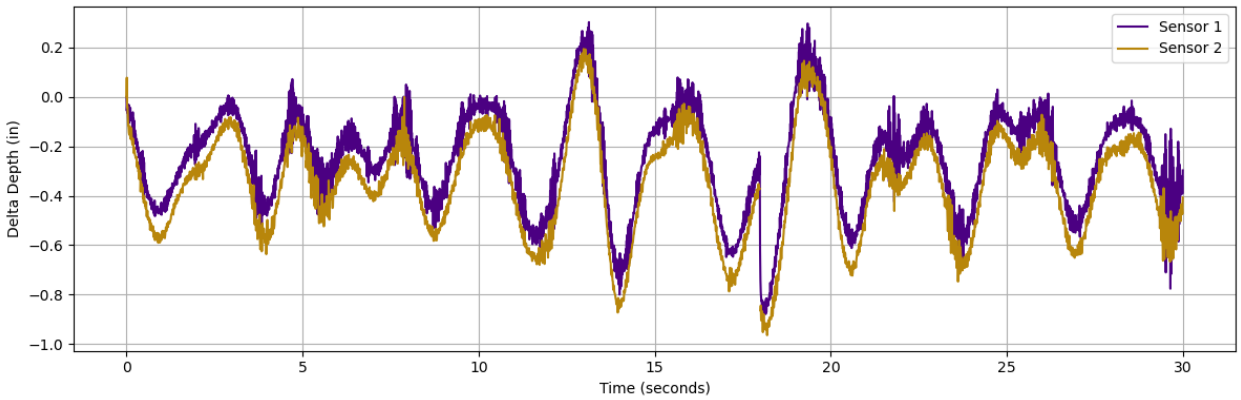


Figure 29. Pressure sensor readings

4.5. Publicly Available Data

Modern infrastructure operates within a data-rich environment where numerous public agencies and organizations collect and share information relevant to infrastructure monitoring and analysis. The I-90 digital twin leverages this ecosystem of publicly available data sources to provide additional context and enhance the understanding of bridge behavior beyond what onsite sensors alone can capture.

Several external data sources were integrated into the digital twin through their respective APIs, with data automatically pulled at regular intervals and federated through Azure before integration into iTwin IoT. This approach ensured all data sources were synchronized within the same platform and available for comparative analysis with onsite sensor measurements.

- Traffic data from WSDOT provided broader transportation network context, including traffic volumes, incident reports, and construction activities that may influence bridge loading patterns. This regional traffic information helped identify unusual loading conditions or events that might affect bridge response measurements.
- Lake Washington environmental data obtained from the King County Lake Washington buoy monitoring system provided context for pontoon behavior. The King County buoy provides real-time measurements of water temperature, dissolved oxygen level, and other water quality parameters at multiple depths throughout the lake. These measurements complement the onsite weather station data and provide broader context for understanding environmental conditions.
- Lake Washington elevation data from the US Army Corps of Engineers (USACE) which

provided official water level measurements that were essential for interpreting GPS elevation data and strain gauge readings. Seasonal lake level management by USACE directly affects pontoon buoyancy and anchor cable tensions, making this data critical for separating operational bridge movements from environmental factors.

The integration of these publicly available data sources demonstrated the value of federated data systems for infrastructure monitoring. By combining onsite sensor measurements with contextual environmental and operational data, the digital twin provided a more complete picture of bridge behavior than either data source could provide independently. This comprehensive approach enables more accurate condition assessment and supports better-informed maintenance decisions.

CHAPTER 5. SUMMARY, CONCLUSIONS, AND LESSONS LEARNED

A “proof-of-technology” digital twin for the Homer M. Hadley (I-90) floating bridge was developed. Two systems of IoT sensors were installed to monitor key structural and environmental parameters, a long-term system designed to monitor daily, weekly, and yearly cycles, and a triggered system to capture dynamic events. Data collected included anchor cable tension, pontoon movement, pontoon freeboard, and temperature. Data was transmitted over a 5G cellular network and integrated into a cloud-based digital twin platform. Additional data, for example, lake level, lake water quality, traffic, and weather data from outside sources were also federated into the system. The digital twin was used to assess bridge behavior in real-world conditions, focusing on anomaly detection capabilities, usefulness of real-time monitoring, and the feasibility of integrating such a system into existing maintenance programs. The project aimed to evaluate the usefulness of the technology for bridge operation and asset management.

5.1. Conclusions

The deployed monitoring systems demonstrated value in characterizing bridge behavior. The long-term monitoring system successfully captured long-term trends including thermal expansion cycles, seasonal movements, and cable tension variations that were previously unquantified. GNSS data revealed daily movement patterns with millimeter precision, providing insights into structural behavior that periodic inspections could not previously capture.

The correlation between temperature data and structural movements validated assumptions about thermal expansion and contraction on the pontoons while quantifying their magnitude. The observed elevation change tracking lake level adjustments demonstrates the system's accuracy and ability to separate environmental factors from structural changes, critical for accurate condition assessment.

The triggered systems provided unprecedented detail of dynamic bridge response, detecting centimeter surface waves, suggesting excellent sensitivity for detecting future train-induced movements. Collected data also implied that the dynamic effect of sensor direction could be of minimal magnitude, reducing future work to interpret freeboard data, although additional measurements under train-passage are needed for final interpretation. The baseline data collected establishes environmental response patterns essential for distinguishing operational loads from environmental effects.

The integration of multiple data streams through cloud platforms enabled comprehensive analysis impossible with traditional monitoring approaches. Trends such as the daily elevation change at the east end of the bridge which were previously unknown can be studied in context. Real-time data availability allows for immediate response to anomalies, while historical trends support predictive maintenance strategies. The system's ability to correlate weather conditions and external data with structural response provides maintenance crews with contextual information for better decision-making.

These initial results demonstrate that digital twin technology can provide quantitative insights into floating bridge behavior that traditional inspection methods cannot achieve, supporting a transition to data-driven, real-time operation and predictive maintenance strategies.

5.2. Lessons Learned

The implementation of the Homer Hadley digital twin brought several challenges to light. While the state of the technology is advanced enough to support the building of large-scale

infrastructure digital twins, no single platform was able to handle all of the data collection, federation, analysis, and visualization methods that were desired for the project. The digital twin framework required the use of two separate cloud environments, the 5G cellular network, and the integration of legacy systems not initially designed with modern cloud integration in mind. Many of these challenges would also be present if agencies and owners would want to implement digital twin systems for other existing infrastructure assets.

Specifically, challenges relating to interoperability of equipment, installation compatibility with existing systems, and cybersecurity were novel to the organizations involved and ad-hoc solutions were developed, both technical and organizational. Future digital twins would benefit from a detailed framework, which considers the many intraplatform connections and their requirements regarding cybersecurity, interoperability, and communication. Considering and engaging the many project stakeholders that tend to arise on projects with this level of complexity became key to a successful deployment.

Implementing a digital twin for the Homer Hadley floating bridge was more complex than a traditional structural health monitoring system. The integration of monitoring systems into cloud environments represented a significant challenge, even before considering cybersecurity and interoperability challenges. At an organization level, this development process required a combination of technical and information technology skills that may be not exist presently and would require workforce development. While infrastructure owners such as WSDOT do have significant technical capabilities, these are often in different areas (or these skills are separated by organizational structure) than those required for cloud integration and visualization of instrumentation data.

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