West Virginia Structural Health Monitoring Project Implementation Report

FY 2022 Strengthening Mobility and Revolutionizing Transportation (SMART) Grant

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Part 1: Executive Summary

The West Virginia Structural Health Monitoring (SHM) Project, funded by the FY 2022 Strengthening Mobility and Revolutionizing Transportation (SMART) Grant, aims to address the state's critical infrastructure challenges, particularly its high percentage of structurally deficient bridges. The project focuses on implementing advanced SHM technology to enhance West Virginia's bridge network’s safety, reliability, and efficiency.

The primary goal of the SHM Project is to maintain the resiliency of West Virginia's bridge infrastructure by promptly identifying and addressing critical needs. The objective is to leverage real-time data collection to prioritize repairs and maintenance, ensuring the state's bridges remain safe and functional despite aging structures and unforeseen incidents.

The project is centered on the East Huntington/Gunner Gatski Bridge, a cable-stay bridge that spans the Ohio River, providing a vital link between Huntington, WV, and Proctorville, OH. This bridge supports over 14,000 vehicles daily and plays a significant role in the regional economy, particularly for marine ports and terminals that handle millions of tons of cargo annually.

The West Virginia Department of Transportation, Division of Highways (WVDOH), collaborated with HNTB and Marshall University to implement the SHM system. Marshall University's involvement provided valuable academic insights and worked to uphold regional economic development. The WVDOH owns and operates the bridge structure with HNTB serving as a technical consultant for the project’s complex SHM and asset management portions.

Stage 1 of the SHM Project involved installing a comprehensive SHM system on the bridge. The system included accelerometers, tiltmeters, crackmeters, displacement sensors, a weather station, and a vessel collision detection system. These sensors provided critical data on the bridge's structural performance, enabling the WVDOH to prioritize repairs and maintenance more effectively. The wireless system's design allowed for efficient installation, and the sensors are battery-powered and have a life expectancy of up to eight years.

The SHM system's real-time data collection proved a game-changer, offering continuous monitoring that surpasses traditional biannual inspections. The accelerometers detected subtle changes in vibration patterns, indicating potential structural deterioration and damage. The strong correlation between measured dynamic responses and those predicted by theoretical models validated the accuracy of the SHM system. The sensor triggering system was also proven effective when the bridge structure’s response to a 3.3 magnitude earthquake was captured in real time. The SHM system also provided valuable insights into the bridge's response to environmental factors, such as temperature fluctuations, further informing maintenance decisions.

For Stage 2, the WVDOH plans to expand the SHM technology to six additional Ohio River bridge structures in surrounding communities. The goal is to create a scalable and repeatable monitoring system that can be adapted to various types of bridges. This expansion will further enhance the state's ability to strategically manage its transportation assets, ensuring that the most critical bridge structures receive needed attention. Key learnings from Stage 1 include the value of continuous monitoring, the importance of long-term data for proactive maintenance, and the advantage of strategic partnerships to optimize project outcomes.

Part 2: Introduction and Project Overview

Real World Issues Being Addressed

West Virginia faces a significant challenge with a higher percentage of structurally deficient bridges (21%) than the national average (7%). Given the limited funds available for bridge rehabilitation and reconstruction, the Structural Health Monitoring (SHM) Project is crucial for maintaining the resiliency of West Virginia's bridge infrastructure. Identifying and addressing critical needs promptly ensures that the state's bridges remain safe and functional, even in the face of aging infrastructure and unexpected incidents.

The initial demonstration of the SHM system on the East Huntington Bridge provided valuable insights. This bridge, which spans a major waterway with significant economic activity, was an ideal candidate due to its inspection challenges and potential impacts from river traffic. The successful implementation of the SHM system on this bridge will set a precedent for future installations on other critical bridge structures.

The SHM system's real-time data collection is proving to be a game-changer. Traditional biannual inspections provide only a snapshot of a bridge's condition, whereas continuous monitoring offers a dynamic and ongoing assessment. This capability is crucial for cable-stay bridges, where internal cables are more challenging to inspect due to protective outer layers. With continuous data from the SHM system, the West Virginia Department of Transportation, Division of Highways (WVDOH), can now prioritize repairs and maintenance more effectively. This data-driven approach ensures that limited funds are allocated to the most critical needs, enhancing the overall efficiency of the state's transportation infrastructure management.

Geographic Area Served

The East Huntington/Gunner Gatski Bridge is a cable stay bridge that provides a vital link between Huntington, WV, and Proctorville, OH (Figure 1). This bridge supports over 14,000 vehicles daily and is crucial for local commuters and freight traffic. Given its location on the Ohio River, it also plays a significant role in the regional economy, particularly for marine ports and terminals that handle millions of tons of cargo annually.

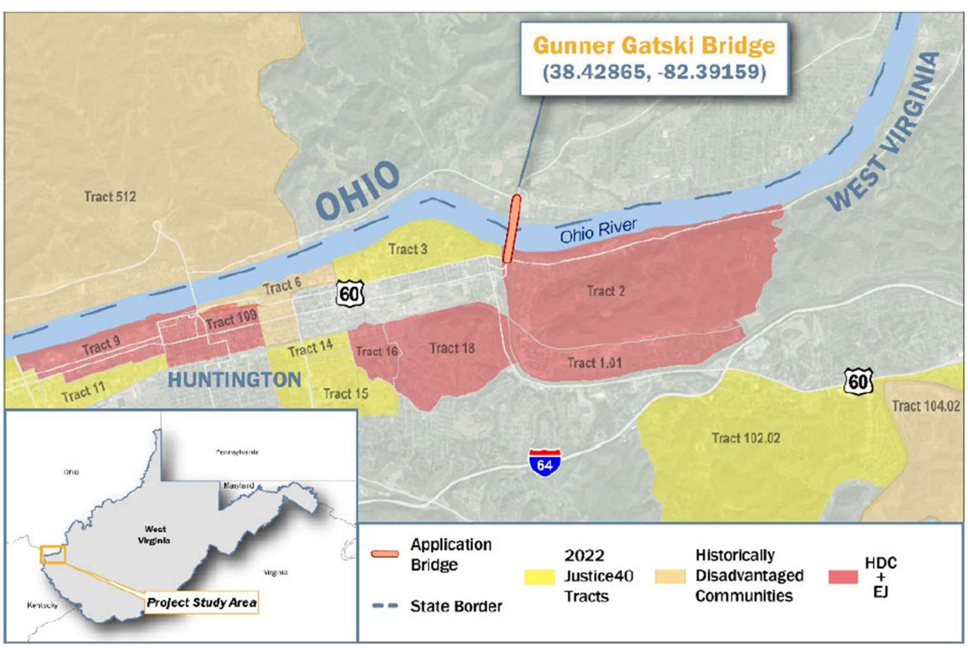

Figure 1 - Project Location

In Stage 2 of the SHM Project, the WVDOH will build on Stage 1 efforts by installing SHM equipment at six additional Ohio River bridge structures along the Ohio-West Virginia state line, located in disadvantaged communities as identified by the Climate and Economic Justice Screening Tool (CEJST) (Figure 2). These critical bridges play a vital role in interstate and local commerce, connecting ports along the Ohio River with major highways. Stage 2 will enable the investigation of six different bridges of various types, facilitating even more complex analysis and robust predictive analytics.

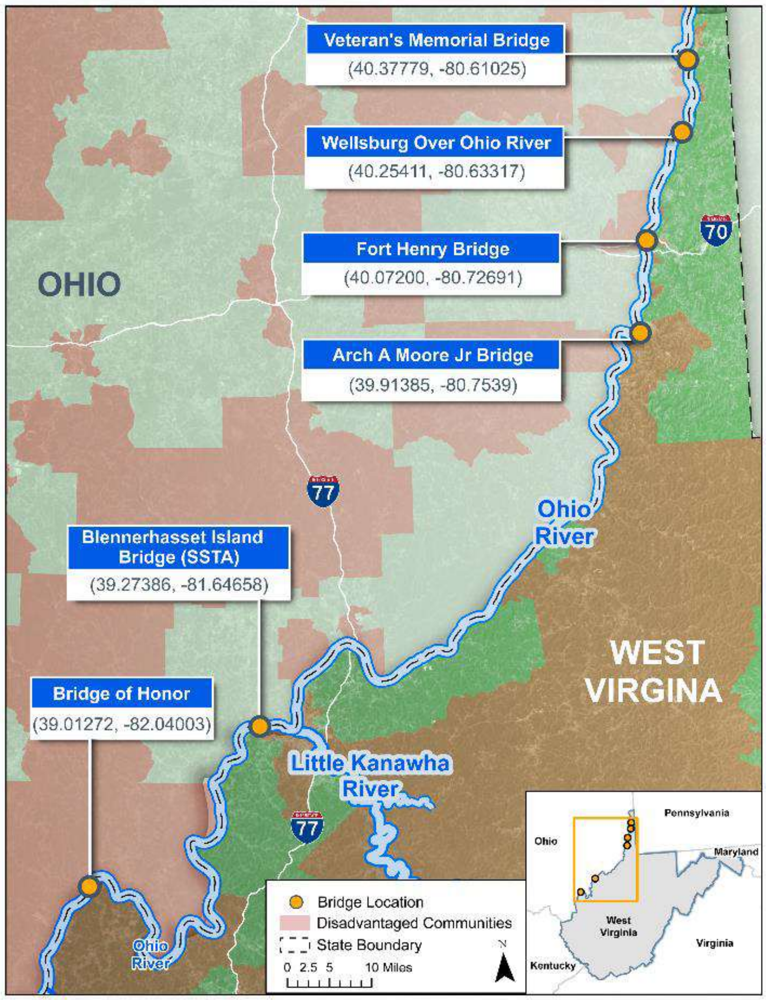

Figure 2 - Project Map with CEJST Disadvantaged Communities

Technology Deployed

This project utilized intelligent sensor-based infrastructure, which in this case is a structural health monitoring system. Throughout Stage 1, the WVDOH determined the specific technology that would best meet the project goals. The SHM technology was chosen based on the current and anticipated future system capabilities, flexibility for use in varied structural settings, installation opportunities, and ability to assist the WVDOH in making decisions regarding possible incident response and long-term asset management.

The SHM system included installing 20 accelerometers on the cables (Figure 3), 19 accelerometers on the deck and towers (Figure 4), six tiltmeters (Figure 5), a weather station (Figure 6), a vessel collision detection system (Figure 7), four crackmeters (Figure 8), and six displacement sensors (Figure 9).

The accelerometers installed on a cable-stayed bridge, such as the Gunner Gatski Bridge, offer critical insights into its structural performance, particularly its dynamic behavior under various loading conditions. These sensors measure vibrations and accelerations caused by external factors such as vehicular traffic, wind, seismic activity, or temperature fluctuations. The data captured helps engineers understand how the bridge responds to these dynamic loads over time. By analyzing the frequency domain characteristics of the accelerometer signals, subtle changes in the bridge's vibration patterns can be detected that potentially indicate structural deterioration, damage, or fatigue. In addition to monitoring general vibrations, accelerometers can also track specific movements of key bridge components, such as the deck and towers. This information is essential for evaluating the stability of the bridge structure and ensuring that deformations remain within safe operational thresholds.

Figure 3 – Accelerometer Installed on a Stay Cable

Figure 4 – Accelerometer Installed on Bridge Tower

The tiltmeters provide critical data on the tilt or rotation of the bridge structure. Tiltmeters can detect minor tilts or rotations that may indicate the onset of structural problems before visible signs appear. This allows for early intervention and preventive maintenance. They provide continuous, real-time data on structural movements, which can be used for immediate detection of anomalies and timely response. By monitoring the tilt over time, tiltmeters help manage a bridge structure's lifecycle, extending its operational life, reducing maintenance costs, and enhancing safety.

Figure 5 – Tiltmeter

The weather station features three types of sensors: air temperature, wind speed, and wind direction. All long-span bridges are susceptible to weather changes and having an on-site weather station enables comparison of responses of structural members due to local environmental changes. By correlating weather data with structural responses, the WVDOH can better understand how weather conditions affect the bridge structure. For example, high winds might cause increased vibrations or deflections in the bridge. In extreme weather events, such as storms or heavy snowfall, real-time weather data can assist in making informed decisions about the bridge's safety and operation, including closing the bridge during high winds or heavy rain.

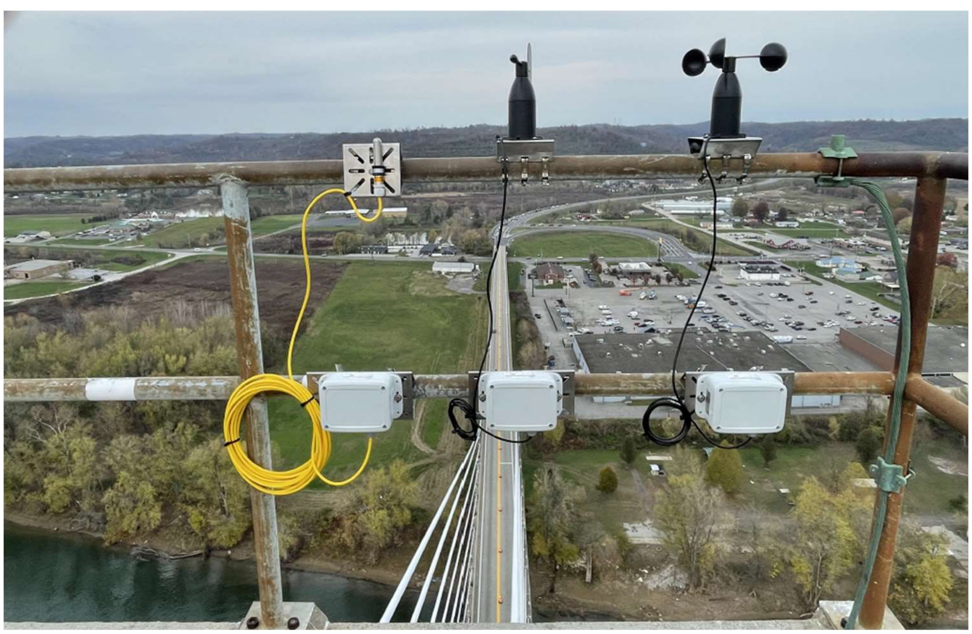

Figure 6 - Weather Station Installed at Top of the Bridge Tower

The vessel impact detection system provides substantial value across critical infrastructure safety and maintenance areas. Primarily, it enables real-time detection of collisions or impacts from marine vessels such as barges, ships, or tugboats on the bridge piers. This immediate awareness is vital for assessing the severity of an incident and determining whether any structural damage has occurred. Early detection allows the WVDOH to quickly evaluate the bridge condition, initiate safety protocols, and conduct inspections and necessary repairs before the situation worsens. By enabling rapid response and mitigation protocols, the inspected system can help prevent secondary damage, reduce the risk of structural failure, and ensure public safety. Additionally, the system can contribute to long-term infrastructure resilience, reduce costly downtime, and support more efficient asset management by providing valuable data for risk assessment.

Figure 7 – Vessel Collision Detection Sensor Attached to Concrete

Crackmeters help detect the initiation and progression of concrete cracks. Crackmeters were placed at existing cracks to measure crack propagation over time. Early monitoring of such cracks allows the WVDOH to identify potential structural concerns before they become serious, reducing the risk of sudden failures. The data collected helps determine whether cracks are stable or worsening. This insight supports more informed decisions about when, where, and what maintenance or repairs are needed, improving resource allocation, and reducing unnecessary interventions. Over time, crackmeters contribute to a comprehensive understanding of how the bridge structure behaves under various conditions. The continuous data collection of the crack measurements is invaluable for lifecycle assessment and risk management.

Figure 8 – Crackmeter Placed at Existing Crack

Displacement sensors have been strategically installed at various joints and bearings of the bridge structure. The sensors monitor the bridge's behavior as it expands and contracts due to temperature fluctuations. The displacement readings are used to assess the functionality of both the bridge bearings and the joints. Consequently, data from the displacement sensors assist in guiding maintenance and replacement practices. Regular monitoring of the displacement allows the WVDOH engineers to detect signs of wear and tear, enabling timely interventions to prevent more significant issues. This proactive approach not only enhances the safety and longevity of the bridge but also optimizes maintenance efforts, ensuring that resources are used efficiently.

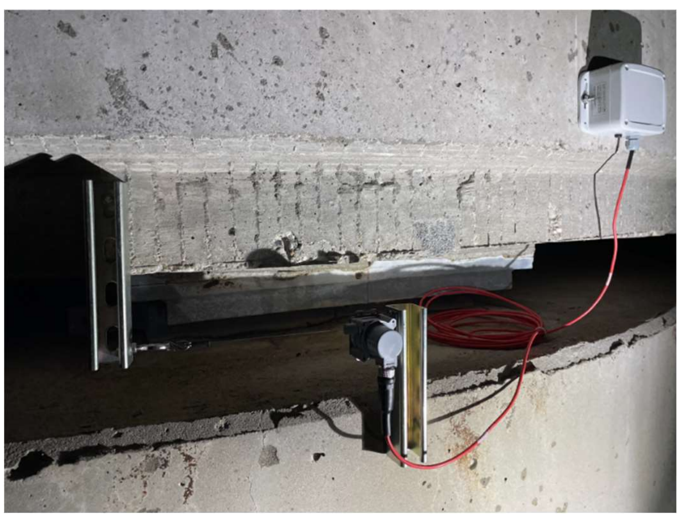

Figure 9 - Bearing Displacement Sensor

The entire system is wireless, which allowed for a quick and efficient installation. The sensors are battery powered with a life expectancy of up to eight years, depending on data collection rates. The SHM system uses the Internet of Things (IoT) technology. IoT refers to the network of physical objects ("things") embedded with sensors, software, and other technologies that enable them to connect and exchange data with other devices and systems over the internet. IoT transforms everyday objects into "smart" devices capable of communicating, analyzing, and acting on the data they gather. A schematic of the SHM system is shown in Figure 10, and an example of a wireless gateway is shown in Figure 11.

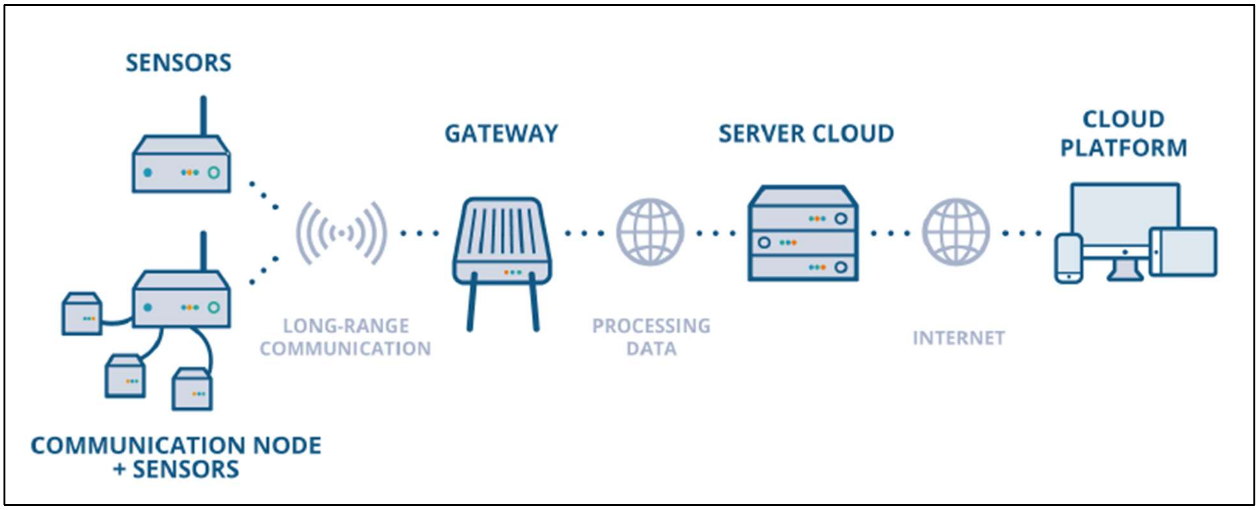

Figure 10 - Schematic of the SHM System

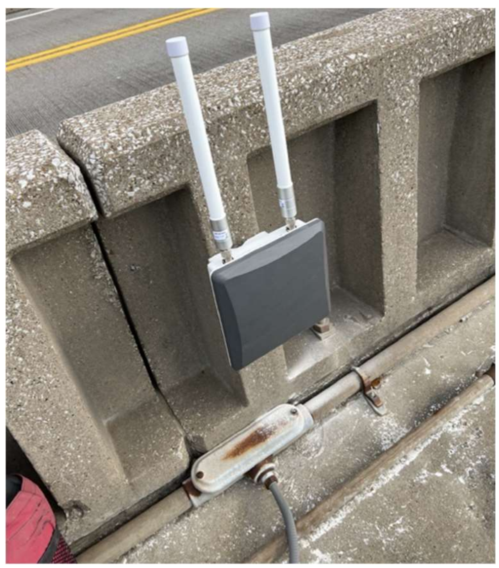

Figure 11 – Gateway Attached to the Bridge

The barge impact system requires additional power to support continuous data collection, which is necessary for providing videos showing the vessel as it approaches and impacts the bridge. The primary data acquisition unit is shown in Figure 12, and the solar panels that power it are shown in Figure 13.

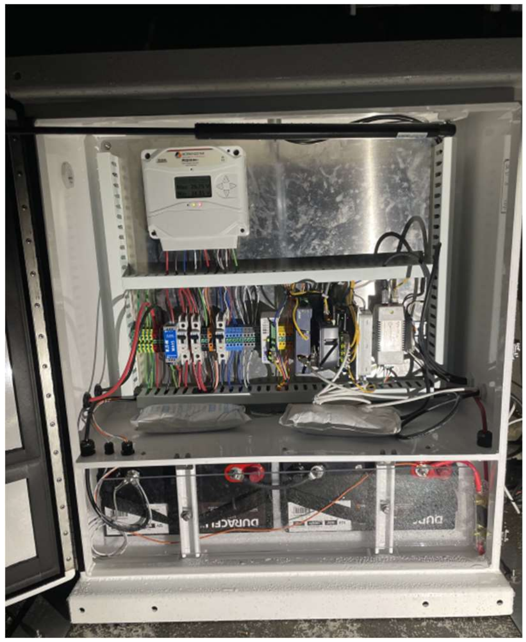

Figure 12 – Barge Impact Data Acquisition System

Figure 13 - Solar Panels Attached to the Bridge

Goals and Desired Outcomes for At-Scale Implementation

Looking ahead, the WVDOH plans to expand SHM technology to additional cable-stay bridge structures at priority locations. The goal is to create a scalable and repeatable monitoring system that can be adapted to various types of bridges. This expansion will further enhance the state's ability to strategically manage its transportation assets, ensuring that the most critical bridge structures receive the needed attention. Additional information on the Stage 2 implementation plan is provided in Part 4 of this report.

The SHM Project aligns with the SMART Program goals by improving the reliability of the existing transportation network, reducing congestion and delays for commerce and traveling public, improving access for underserved or disadvantaged populations, and improving emergency response, thereby improving safety and resiliency. The project aims to improve access to jobs, education, and essential services, including health care, thus contributing to the region's medium and long-term economic competitiveness. Using real-time monitoring data helps maintain the structural integrity of bridges, supports efficient traffic flow, and enables the employment of better asset management protocols. These improvements contribute to the overall safety and efficiency of the national highway system, benefiting both local communities and the broader economy.

The WVDOH planned for the SHM Project's Stage 1 success and the sustainability of the technology going into Stage 2. We provided comprehensive training for employees and partner academic institutions. This initiative has empowered the WVDOH workforce to employ SHM for Stage 1 on the East Huntington Bridge, laying the foundation for Stage 2 implementation to support continuous monitoring across other West Virginia bridges. By leveraging advanced technology and data-driven decision-making, the WVDOH is taking significant steps to modernize its infrastructure management practices and ensure its bridge network's long-term safety and reliability.

Communities that Would be Impacted by At-Scale Implementation

As discussed above, in Stage 2 of the West Virginia SHM Project, the WVDOH will expand upon the foundational work completed in Stage 1 by deploying SHM equipment on six additional bridges spanning the Ohio River, situated along the Ohio–West Virginia state line. These selected bridge structures are located within disadvantaged communities, as identified by the Climate and Economic Justice Screening Tool (CEJST) (Figure 2). These bridges are critical components of the region's transportation infrastructure, serving as key connectors between ports along the Ohio River and major highway networks.

The West Virginia SHM Project aims to enhance the reliability and safety of these bridges, which are crucial for supporting local commerce and transportation. This improvement is vital for economic growth in disadvantaged areas, where robust infrastructure can significantly impact the community's prosperity. The project facilitates the smooth flow of goods and services by ensuring that bridges are well-maintained and structurally sound. Reliable transportation networks enable businesses to operate more efficiently, attract investment, and create job opportunities, stimulating local economies.

Moreover, improved infrastructure directly contributes to the overall well-being of the community. Safe and reliable bridges provide essential access to healthcare facilities, educational institutions, and employment centers. This accessibility is fundamental for residents to receive medical care, pursue educational opportunities, and secure jobs, which collectively enhance the quality of life.

In addition to economic benefits, the SHM Project fosters a sense of security and stability within the community. Knowing that the infrastructure is regularly monitored and maintained reassures residents and encourages further development and growth. Key local stakeholders, including the engineering community at Marshall University, which is less than 2 miles from the bridge structure, had essential roles in the technical and holistic development of the project. Their influence was critical to ensuring the initiative herein served, and will continue to serve, the community as comprehensively as possible.

Overall, the SHM Project not only supports economic development but also plays a pivotal role in improving the social and environmental resilience of disadvantaged areas, ensuring that these communities thrive and prosper.

Deployment Scale in Stage 1 and Projections for Stage 2

During Stage 1 of the SHM Project, a comprehensive SHM system was successfully implemented on the East Huntington/Gunner Gatski Bridge. This system included 57 meticulously placed sensors to monitor various aspects of the bridge. These sensors provided valuable data on vibrations, displacements, and other critical structural parameters, ensuring the bridge's safety and performance.

Building on the success of Stage 1, the WVDOH is set to expand the SHM Project in Stage 2. This phase will involve deploying advanced SHM equipment on six additional bridges of varying types spanning the Ohio River, strategically located along the Ohio–West Virginia state line. These bridges are vital for connecting communities and facilitating interstate commerce, making their monitoring and maintenance crucial.

The expansion will include a diverse array of sensors, similar to those used in Stage 1, to monitor the health of these bridge structures. By collecting real-time data on the structural behavior of these six bridges, the SHM system will enable early detection of defects or potential issues, allowing for timely maintenance and repairs. This proactive approach not only enhances the safety and reliability of the bridges but also supports the region's economic growth by ensuring uninterrupted transportation and commerce.

Overall, Stage 2 of the SHM Project represents a significant step forward in safeguarding the infrastructure and improving the quality of life for residents in the Ohio–West Virginia area.

Summary of Stage 1 Activities

During the SHM Project planning, the WVDOH identified the critical features of the East Huntington/Gunner Gatski Bridge's monitoring system and determined associated improvements to the asset bridge's management strategy utilizing the system's data. The aim was to create a scalable SHM system applicable to various bridge structures throughout the state, enabling a better understanding of needs and prioritizing repairs for the state's critical highway bridge structures.

To better understand the expected SHM needs, the WVDOH gathered previous inspection reports and existing plans. Within these documents, the team reviewed the existing condition of the bridge elements. The bridge was noted to be in fair condition based on distortion in the stay cables and cracking greater than hairline width throughout the prestressed concrete girders, segmental box girder unit, and tower legs/head.

The bulging or distortion of cables could indicate broken wires and had previously been investigated using ultrasonic and magnetic flux testing performed in 2018 and 2019. Furthermore, a bridge staged construction analysis was performed in 2019, followed by a 3D load rating analysis of the cable-stay bridge and segmental bridge structure units in 2020. As a result of the load rating, the bridge was posted for a 20-ton load limit.

The SHM system's design focused on reducing the risk of unforeseen issues and service interruptions. As monitoring every bridge member of the East Huntington Bridge was impractical, the WVDOH used a risk-based approach to determine which members carried the most risk to provide a cost-effective solution.

The 80/20 risk principle is a concept that suggests 80% of the effects or outcomes are caused by 20% of the causes or inputs. When applied to risk management, the 80/20 risk principle implies that most risks or problems arise from a small portion of the potential causes. In other words, a minority of risk factors or sources are responsible for most negative outcomes or incidents. By identifying and focusing the SHM efforts on these 20% of causes, the WVDOH could prioritize risk management efforts and allocate resources more efficiently.

A risk-based approach has been adopted in many industries as a tool for inspection planning, to focus attention on the component or machine that represents the greatest "risk." Risk is defined as the product of the probability of an event and the associated consequences:

Risk = Probability x Consequence

Probability in this equation is the likelihood of an adverse event or failure occurring during a given time. This is sometimes expressed quantitatively as a probability of failure (POF) estimate for a given time interval, or as a qualitative assessment of the likelihood of an adverse event based on experience and engineering judgment. Consequence is a measure of the impact of the event occurring, which may be measured in terms of economic, social, safety, or environmental impacts.

Presenting risk qualitatively is a common and effective method for evaluating risk and assessing relative risk efficiently. Figure 14 shows a qualitative risk matrix. This matrix illustrates the overall concept and basic principles of risk. A high occurrence factor (probability) combined with a high consequence factor results in a high risk, located in the upper right corner of the figure. Low likelihood combined with a low consequence will result in a low risk, located in the lower left-hand corner of the figure.

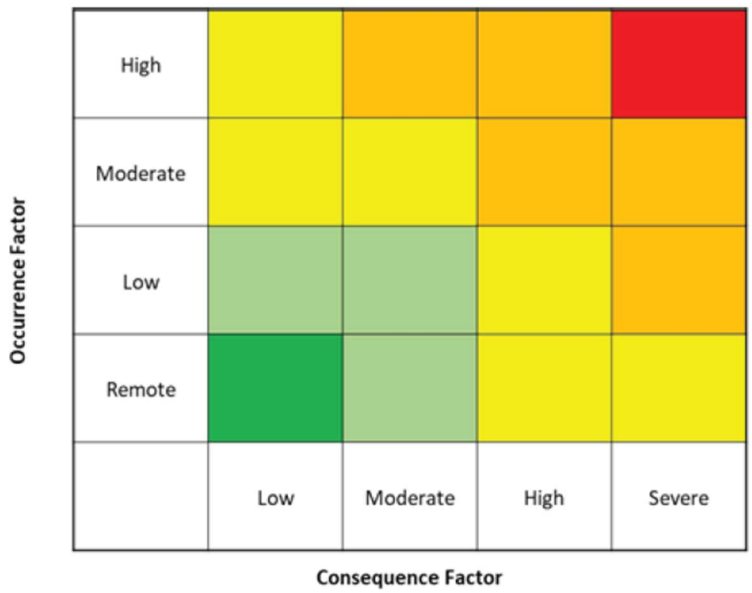

Figure 14 – Risk Matrix Employed

The other consideration was serviceability, the effect the bridge's operation (or lack thereof) had on the community. Closing a high-volume bridge in a large urban area would have had a more significant consequence on serviceability than closing a low-volume bridge in a rural area.

Assessing the above risks, the SHM system's design, described in the previous section, was completed. The SHM system was successfully installed on the East Huntington Bridge starting on November 18, 2024, and was substantially complete on November 22, 2024.

Additionally, the WVDOH planned to engage Marshall University as a project partner. The SHM project can offer a platform for faculty in structural engineering, data science, and related fields to conduct cutting-edge research on infrastructure monitoring, materials behavior, and data analytics. This will allow them to attract additional federal and state research grants (e.g., from NSF, DOT, or DOE) to develop new monitoring technologies or methodologies.

Going forward, the SHM project can serve as a base for student internships, senior design projects, or graduate theses, enhancing experiential learning. Since the SHM project targets bridges in disadvantaged communities near Marshall University, the institution's involvement directly supports regional resilience, safety, and economic development. Marshall University can host workshops, public talks, or STEM outreach events that showcase how engineering and technology help protect local communities and infrastructure. Engaging in the SHM project allows Marshall University to strengthen its ties with the WVDOH, engineering firms, and tech companies, paving the way for collaborative projects, funding, and student career pipelines.

Attention the WV SHM Project has Gained

The results of this project will be disseminated through a variety of papers and presentations throughout the transportation community. To date, a paper has been accepted for presentation at the 2025 New York City Bridge Conference entitled "Revolutionizing Bridge Maintenance in West Virginia: A Risk-Based Approach to Structural Health Monitoring on the East Huntington/Gunner Gatski Bridge." Additional presentations are planned to be made at the International Bridge Conference, and the Transportation Research Board Annual Meeting, amongst others.

The installation of the SHM system was closely coordinated with ongoing maintenance work on the bridge. Collaboration among the WVDOH, the contractor, the consultant, and the SHM vendor optimized maintenance funds and minimized time and traffic disruption on this busy bridge. The SHM equipment was installed at night to further reduce traffic impacts, ensuring smooth traffic flow and maintaining the bridge's integrity between West Virginia and Ohio. Thus, the project did not draw any negative attention due to traffic impacts. The operation of the system has also had no impact on traffic. The benefits of the abovementioned project will be realized over the coming years. Therefore, the project has not garnered negative perception or attention from the public.

Major Deviations from Original Proposal

No significant deviations from the Stage 1 proposal were required.

Part 3: Proof-of-Concept or Prototype Evaluation Findings

Performance Evaluation of the SHM System Proof-of-Concept

The following evaluation questions were posed in the Evaluation Plan with the objective of quantitatively evaluating the proof-of-concept in Stage 1. We used the measurement of these questions to shape the goal-setting process for at-scale implementation during Stage 2 to improve targeted performance of the SHM networks.

1. **Question: Can the SHM system identify the cause of deterioration and use this to recommend maintenance practices that improve the long-term health of the structure?**
    a. **Measure:** Identification of advanced deterioration through a comprehensive data-driven asset management program that facilitates informed resource distribution.
    b. **Target:** Identify the root cause of at least one anomalous behavior detected by the SHM system and how that identification led to better resource distribution.
    c. **Implementation:** Damaging vortex-induced vibrations (VIV) were identified in multiple stay cables on the bridge structure. As elaborated on later in Part 3, this phenomenon only occurs during a specific window of conditions and thus could only be detected by a long-term monitoring solution. Despite VIV being relatively uncommon, this phenomenon probably led to the premature fatigue-induced failure of the viscous dampers due to their high amplitude and high frequency vibrations. With this phenomenon now identified, continual replacement of broken dampers years before the end of their standard service life can be reevaluated in favor of a solution more suited to VIV, such as Stockbridge dampers. Due to limitations in the sensors' ability to capture long duration events due to the battery life, full confirmation and understanding of the extent of VIV throughout the bridge structure will require additional effort. This represents a successful completion of evaluation goal number one.
2. **Question: Can the SHM system identify extreme events such as barge impacts or earthquakes?**
    a. **Measure:** Identification of an extreme event through the SHM system alerts.
    b. **Target:** 99 percent detection rate of significant extreme events relevant to reported seismic, meteorological, and vessel impact in the performance window.
    c. **Implementation:** During the performance period, only one known extreme event occurred. As described later in Part 3 of this report, a 3.3-magnitude earthquake was registered only a few miles from the East Huntington Bridge site on December 16th, 2024. The bridge tower accelerometers captured data from this event, which enabled detailed analysis to assess the structure's post-earthquake health. Utilizing the SHM system, it was determined that it was unlikely the bridge structure suffered any damage because of the event. This demonstrates a successful completion of evaluation goal number two.
3. **Question: How quickly can an alert message be sent out if a threshold level is exceeded?**
    a. **Measure:** Time between event and receipt of notification for threshold exceedance.
    b. **Target:** Relevant project personnel notified by email within 10 minutes of event occurrence.
    c. **Implementation:** Utilizing the MyMove platform, sensor thresholds were established, and project personnel were added to the alarm list. To test the system's response time, one sensor had its notification threshold manually reduced to obtain a sample set of times between event occurrence and email receipt. The average time to notification was five minutes, with a maximum of seven minutes. It is critical for the system to deliver timely notifications to ensure the speed of response in an emergency scenario. This demonstrates a successful completion of evaluation goal number three.

4. **Question: Can the SHM system reduce the need for special inspections and help reduce inspection costs?**
    a. **Measure:** Demonstration of the system's ability to remotely detect changes to the bridge structure's performance.
    b. **Target:** Identify one observation from the SHM system that can be used to influence special inspection practices.
    c. **Implementation:** As described further in Part 3 of this report, the SHM system was used to identify potential damage to the West Cable number 18 by measuring a reduction in the frequency of the first mode of vibration. This deterioration was confirmed by observing advanced distortion throughout the full length of the cable. Given that this study's performance period was relatively short compared to the deterioration rate of a typical bridge element, evaluating how this observation can change resource distribution is yet to be thoroughly vetted. However, knowing which cables are likely to have advanced deterioration can inform future inspections to target resources for those cables. Since the latest Magnetic Flux Testing of the stay cables was performed in 2019 and did not include the West Cable number 18, the potential for this year's 2025 biannual inspection to include such testing on this cable presents an incredible added value. Not only would performing this directed inspection improve the understanding of the health of the East Huntington Bridge structure, but also provides important feedback data for validating the SHM system. As the SHM network grows at-scale, the asset management system will mature, and an increasingly sophisticated distribution of resources will emerge. This demonstrates a successful completion of evaluation goal number four.
5. **Question: How did this SHM initiative foster and strengthen strategic relationships for relevant stakeholders?**
    a. **Measure:** Provable cooperation above and beyond typical standards between agencies, consultants, academia, and contractors.
    b. **Target:** Demonstrate how strategic relationships extend the WVDOH's resource capabilities and prepare for at-scale implementation in Stage 2.
    c. **Implementation:** The East Huntington Bridge SHM initiative generated academic collaboration with Marshall University and its flagship SHM program under Dr. Wael Zatar, a well-respected expert in the SHM field. This strategic partnership strengthens the local research presence of this federally funded grant, as the university is less than two miles away from the East Huntington Bridge. Dr. Zatar was also part of the implementation team and provided critical input on the system design and the evaluation of the results.
       In Dr. Zatar's Letter of Commitment, he establishes his dedication to t developing the SHM system through the collaborative use of Marshall University's extensive resources. SHM is a uniquely multi-disciplinary, academic collaboration that leverages research expertise from fields such as signal processing in electrical engineering and data analytics in computer science. The data produced by the SHM system is being analyzed by these cutting-edge professionals using the latest and most innovative techniques available in an array of fields. Additionally, this data will be used to rapidly train students and emerging professionals on key SHM principles that act to secure the future of the field. As the at-scale implementation of Stage 2 of this grant would remain regional to West Virginia, we understood that it is critical to start this knowledge transfer process early and develop the local expertise to manage, maintain, and operate the broader SHM system in the future. This demonstrates a successful completion of goal number five.

Data Limitations

When working with SHM systems, several data limitations may arise that can impact the collected information's accuracy, completeness, and usefulness. Given the available budget for this project, sensors were only installed at specific points on the structure as discussed above, leaving other areas unmonitored. This can lead to blind spots where damage or stress changes may go undetected. Also, the data may not fully reflect in-service behavior if the sensors were not positioned where structural responses are most significant.

There are also challenges and limitations related to the monitoring period. Currently, there is limited baseline or pre-damage data, making it difficult to detect changes in the bridge's performance. Structural anomalies identified in the data do not always equate to actual damage, and vice versa. Signal anomalies may arise from benign sources or environmental factors, while some damage may not produce clear signals. This introduces the risk of false positives or false negatives without corroborating evidence.

To address these limitations, it is critical to implement routine sensor maintenance, ensure robust data management protocols, and complement sensor data with periodic visual inspections or other nondestructive evaluation methods. Leveraging advanced analytics, machine learning, and cross-sensor data integration can improve judgement reliability and enhance decision-making.

How the SHM System Proof-of-Concept Met Grant Proposal Expectations

The Stage 1 Grant Proposal aimed to address the challenge of implementing SHM equipment on the WVDOH cable-stay bridge structures, particularly at major crossings like the East Huntington Bridge over the Ohio River. The objective was to gather critical data on bridge components that are difficult to inspect or are more vulnerable due to river traffic serving ports along the Ohio River Basin. By utilizing real-time data, the project sought to detect changes in structural integrity and deviations from baseline performance, ultimately reducing the need for bridge closures while addressing maintenance issues or extreme events, thereby minimizing user disruptions. While biannual inspections only offer a periodic assessment of this aging bridge infrastructure, the proposal emphasized the value of continuous SHM data collection to enable ongoing evaluation and prioritization of maintenance efforts across the transportation network. Finally, the ability to provide real-time incident response following an extreme event was a stated goal. The following sections of this report assess how the SHM system's performance aligned with the expectations outlined in the Stage 1 Grant Proposal.

Evaluation of Components that are Difficult to Inspect

Inspecting cable-stay bridge structures is a challenging endeavor. Each cable is covered by an outside layer that prevents visual inspection. Bridge defects are complex to identify without employing additional equipment to determine areas of concern. The ability to determine the stay cable tension force was concluded to assist in assessing the cable's condition. Among the different methods for assessing stay cable tension forces, vibration-based techniques are the most used as they provide a practical and efficient evaluation by analyzing the cable's dynamic response. Utilizing the cable-mounted accelerometers installed as part of this study, the reported time-acceleration data can be processed to calculate the natural frequencies of each cable. This conversion process from time domain to frequency domain utilizes the Fast Fourier Transform to isolate the dominant frequencies of the cable. Once the first fundamental frequency of the cable is determined, Taut String Theory is applied to calculate the cable force as a function of the fundamental frequency, chorded cable length, and mass per unit length of the cable.

$$T_{TAUT} = 4f_n^2L^2/m$$

Note that additional empirical equations for cable tension incorporate effects due to bending stiffness and sag extensibility that were not evaluated herein. Table 1 reports the natural frequency and corresponding taut string force for all instrumented cables. Additional data from CTL Group Cable Force Estimation 2018, CTL Group Cable Damping Evaluation 2022, and the original Design Dead Loads are also presented. Chorded cable length and mass per unit length are derived from the available plans to remain consistent with CTL Group 2018 and 2022 reports. Note that the 2018 and 2022 frequencies were calculated by manually exciting the stay cable, whereas this study relies on ambient excitations from wind, traffic, etc., to derive frequencies.

Table 1 – Comparison of Measured Cable Tension Forces

Cable ID	1st Mode Frequency f1 (Hz)			Taut String Force (k)			Design Dead Load (k)
	2018	2022	2025	2018	2022	2025	
E01	0.53	0.54	0.53	1141	1171	1128	1202
E02	0.61	0.61	0.60	1405	1428	1381	1202
E05	0.61	0.61	0.61	600	601	601	672
E12	1.36	1.36	1.35	375	378	372	331
E15	1.74	*	1.73	315	*	313	267
E20	1.09	1.10	1.09	311	316	310	373
E23	0.90	0.90	0.89	490	493	482	438
E24	0.84	0.83	0.82	498	490	479	392
E25	0.77	0.77	0.76	525	528	514	451
E26	0.66	0.66	0.65	756	761	738	783
E28	0.56	0.57	0.56	712	732	706	750
E31	0.58	0.58	0.57	1273	1299	1254	1189
W01	0.54	0.54	0.53	1147	1171	1128	1202
W05	0.60	0.60	0.60	578	581	581	672
W10	1.12	1.12	1.11	425	424	416	394
W12	1.31	1.31	1.30	351	351	345	331
W18	1.54	1.54	1.47	382	385	351	307
W24	0.83	0.83	0.82	490	490	479	392
W25	0.77	0.77	0.76	531	528	514	451
W29	0.52	0.52	0.51	673	673	648	688

*** Cable frequency not measured in 2022 study**

The data above indicates a strong correlation between measured first mode frequencies from the previous 2018 and 2022 reports to this 2025 study's instrumentation, as 19 of the 20 measured cable frequencies were within 2% of the 2018 and 2022 average. This high degree of precision suggests that ambient monitoring of stay cables over an extended period provides sufficient dynamic excitation to predict modal frequencies. The calculated error is small enough to be attributed to rounding from the reported 2018 and 2022 data. As the cable force depends on modal frequency and these frequencies are highly correlated over time, new conclusions on the force and other cable parameters are limited. However, cable number W18 had a stark reduction in frequency from 1.54 Hz in 2022 to 1.47 Hz in 2025, which indicates a change in one of the cable parameters. The 2018 and 2022 inspection reports observed advanced distortion throughout the cable's length, indicating possible wire breaks. Damage to the cable's cross-section caused by distortion could appreciably reduce the cable's stiffness. As frequency is related to the square root of stiffness, the distortion and frequency reduction are likely correlated, indicating the potential for advanced cable deterioration since 2022. These observations demonstrate the potential value of cable-mounted accelerometers in remotely monitoring the performance of critical structural members in real time.

Detecting Changes in Structural Integrity and Deviations from Baseline Performance

To validate the measured dynamic response of the bridge structure from the SHM system and create a baseline for future changes in behavior to be measured against, a Finite Element Analysis (FEA) model was created, and a modal analysis was performed. This exercise aimed to compare the frequencies of the mode shapes calculated from the analytical model to the frequencies of the response from the accelerometers on the deck. A complex bridge structure may have hundreds or thousands of theoretical modes, but the modes with the lowest natural frequency are typically observed in sensor data, as they are the easiest to excite.

With a baseline FEA model calibrated to the real-time structural response, it is possible to update the model based on any changes in the SHM system's output. This process is known as Model Updating and is used to approximate where damage exists on the bridge structure and how that damage influences global and local stiffness. Model Updating is not an exact science and can involve iterative or statistical methods to attempt to match a highly complex, damaged dynamic response. Prior identification of damage using the FEA model prioritizes inspection efforts and can be used to perform various levels of repairs that work to increase the bridge structure's longevity.

Our results showed strong agreement between the analytical model's dominant modes and the deck accelerometer data measured modes. Figure 15 depicts the first analytical mode of the bridge structure in blue/green vibrating at 0.306 Hz, overlapped with the location of the deck accelerometers in red circles. This overlay illustrates how the bridge structure dynamically vibrates in the first mode from its static position. As shown on the bridge structure's North (right) side, the accelerometer at node number four should oscillate with significant amplitude and show a strong response to this first mode. With this knowledge in hand, the modal frequency data derived from the deck accelerometer number four can be reviewed to validate the result from the analytical model. A strong correlation occurs when the frequency calculated by the theoretical model appears in the modal analysis of the accelerometer measurements.

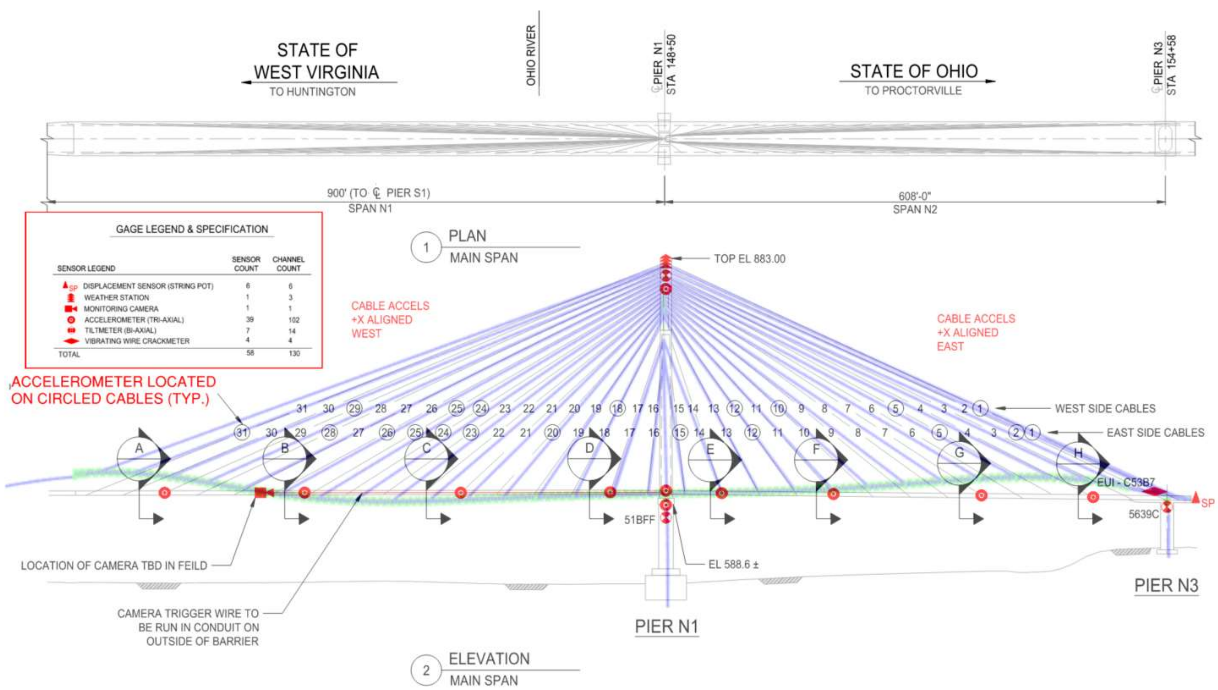

Figure 15 – FEA Model's First Mode Shape Overlapped with Accelerometer Locations in Red

Figure 16 depicts the vertical direction (Z axis) modal analysis of the East Deck number four accelerometer for the data acquisition on 2/22/2025 at 2:00 P.M. EST. The steep peak furthest left on the graph is the first measured mode, with a frequency of 0.302 Hz. Comparing this frequency to the first theoretical mode, which has a frequency of 0.306 Hz, yields high confidence in the accuracy of the FEA model for this mode. Repeating this process for modes one through six in the theoretical model is shown on the modal analysis graph below and in Table 2.

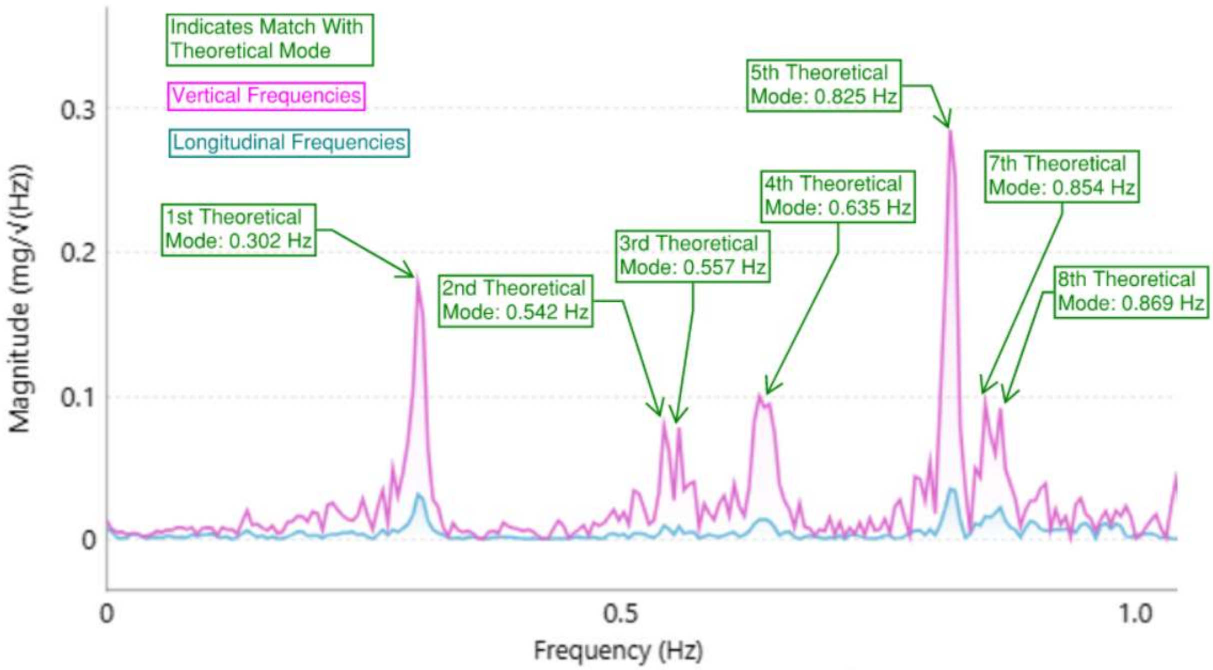

Figure 16 - MyMove FFT Output for East Deck Number Four Accelerometer with Theoretical Modal Frequencies Identified

Table 2 – Modal Frequency Comparison

Number	Type	Frequency [Hz]		Instrument	Acquisition
		Model	SHM Sys.		
1	Vertical	0.306	0.302	Deck East 4	2/22/2025 15:00
2	Vertical	0.55	0.542	Deck East 4	2/22/2025 15:00
3	Torsional	0.568	0.557	Deck East 4	2/22/2025 15:00
4	Vertical	0.641	0.635	Deck East 4	2/22/2025 15:00
5	Longitudinal	0.805	0.825	Deck East 4	2/22/2025 15:00
6	Pier	0.829	NO INSTRUMENT		
7	Vertical	0.864	0.854	Deck East 4	2/22/2025 15:00
8	Torsional	0.908	0.869	Deck East 4	2/22/2025 15:00

As observed, correlation was robust for each of the first eight modes except for the sixth theoretical mode. This sixth theoretical mode involved longitudinal flexing of pier N3, which is not instrumented with a high-resolution accelerometer and thus will not appear in the modal analysis. There are many additional reasons why a theoretical mode may not be visualized in the measured data, but these do not imply that the FEA model is inaccurate. This could be explained from an excitation or a model updating perspective.

The excitation perspective suggests that there is not enough significant ambient excitation in a given direction to force the bridge structure to move in a specific fashion. Sufficient excitation may occur during a high wind event or under a seismic event. As these events may not occur often, they are likely not to be strongly expressed in the measured modes of the SHM system.

The model updating perspective centers around updating targeted model parameters that are knowingly difficult to quantify to match the SHM system output. For example, the first run of the theoretical model assumed that the pier supporting the main tower was cracked, which reduced the stiffness by 30%. After not identifying some of the longitudinal modes that involved flexing of the pier, the stiffness was raised to its uncracked value, which yielded results with a stronger measured correlation in all directions. While concrete is designed to crack and maintain its strength during overload conditions, this result may imply that the existing concrete has remained within its realm of serviceability and has not cracked significantly. This conclusion can have additional positive implications on the current state of the structural health of the pier.

Although replicating a bridge structure's measured dynamic response in a theoretical model may be a complex endeavor, this study's data indicate the successful creation of an independent analytical model that has potential for expansive value throughout the bridge structure's remaining service life. This study also demonstrates the accuracy of the SHM system in replicating many of the core principles of the theory of structural dynamics.

Evaluation and Prioritization of Maintenance Efforts

Informs bridge life cycle cost analyses and preventative maintenance

The SHM system for the East Huntington Bridge included the following types of instruments for collecting data on the bridge structure: accelerometers on the cables, accelerometers on the deck and towers, tiltmeters on the piers, a weather station, a vessel collision detection system, crackmeters, and displacement sensors as detailed in Part 1 of this report. While significant benefits can be drawn from these sensors individually, perhaps the greatest value lies in utilizing the instrumentation as a system for informed asset management strategies. For example, displacement sensors alone provide reliable on-demand insight into the integrity of the joints and expansion bearings. Pairing joint data with the temperature data from the weather station, as shown in Figure 17, can indicate how sensitive a damaged expansion bearing is to a given range of temperatures that may cause it to lock or freeze. With prior knowledge of upcoming weather conditions and seasonal temperature trends, the WVDOH will use this information to make informed decisions on prioritizing repairs. The SHM system and online analysis platform make multi-sensor analyses readily accessible so that the value of the network is widely expressible in the WVDOH's asset management decision-making.

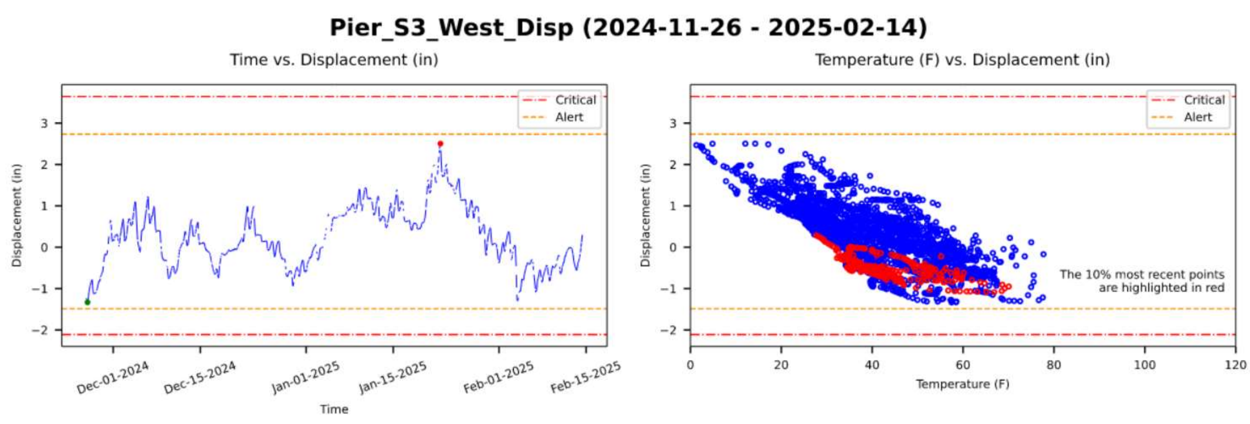

Figure 17- Sample Graphs for Joint Displacement vs Time and Joint Displacement vs Temperature

Information from the SHM system informs bridge life cycle cost analyses and preventative maintenance planning by confirming assumptions on service life and performance degradation of components over time. As these strategies are refined from the lessons learned in the execution of the SHM system at East Huntington, additional critical bridge structures can be instrumented such that each bridge feeds into a larger network. This comprehensive network introduces the ability to quantify the health of the most important bridges in the WVDOH inventory. As maintenance, repair, retrofit, and replacement resources are finite, the network would be used to distribute valuable resources where they are needed most. At-scale benefits from the SHM system take time to develop and may be challenging to realize in the short term. The informed distribution of resources creates the long-term potential advantage of the SHM network as part of a comprehensive asset management strategy. Additional advantages may materialize by preventing excessive damage due to early detection of poor component performance, which can be addressed faster to extend the bridge structure's service life.

Long-term Monitoring to Detect Critical Structural Responses

One of the key benefits of a comprehensive long-term structural health monitoring (SHM) system is its capability to track structural responses under a wide range of environmental conditions, including temperature fluctuations, weather patterns, wind speed, and wind direction. Long-span, cable-supported bridge structures are inherently flexible, making their dynamic responses particularly sensitive to specific combinations of external influences. These influences can occasionally trigger uncommon, yet highly damaging, vibration behaviors that contribute disproportionately to the degradation of critical components. Capturing such rare events is beyond the scope of short-term monitoring systems and requires advanced understanding at the intersection of structural dynamics and aeroelastic instability to interpret the SHM data effectively.

Vortex-Induced Vibration (VIV) is a rare but impactful phenomenon. It occurs when moderate wind speeds generate alternating vortices around a stay cable, causing it to oscillate rhythmically. If the vortex shedding frequency aligns with the cable's natural frequency, resonance can develop, leading to high-amplitude, high-frequency vibrations. This VIV presents a serious threat to fatigue-sensitive components like viscous dampers. Evidence suggests that VIV is present on multiple stay cables of the East Huntington Bridge, contributing to the premature failure of dampers installed to suppress such vibrations.

Figure 18 and Figure 19 compare the acceleration responses and corresponding frequency spectra (FFT) of Cable W12 under normal and high wind conditions, respectively. Under strong wind events, peak accelerations were nearly 100 times greater than under calm conditions. Notably, these vibrations were concentrated in the 20–30 Hz range rather than the broader frequency band typically initiated around 1.30 Hz. Similar abnormal responses were observed in at least two other cables on the bridge—an issue more commonly seen in older cable-stayed bridge structures constructed prior to fully understanding this behavior. Figure 19 shows approximately 200 cycles of high-amplitude oscillation occurring within just 15 seconds, a clear VIV signature.

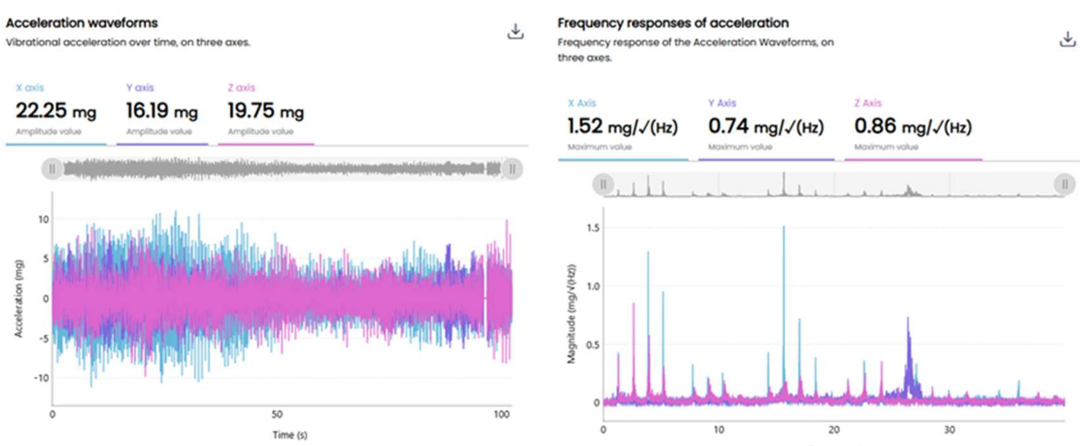

Figure 18 – Cable W12 Acceleration Response and FFT Under Normal Conditions

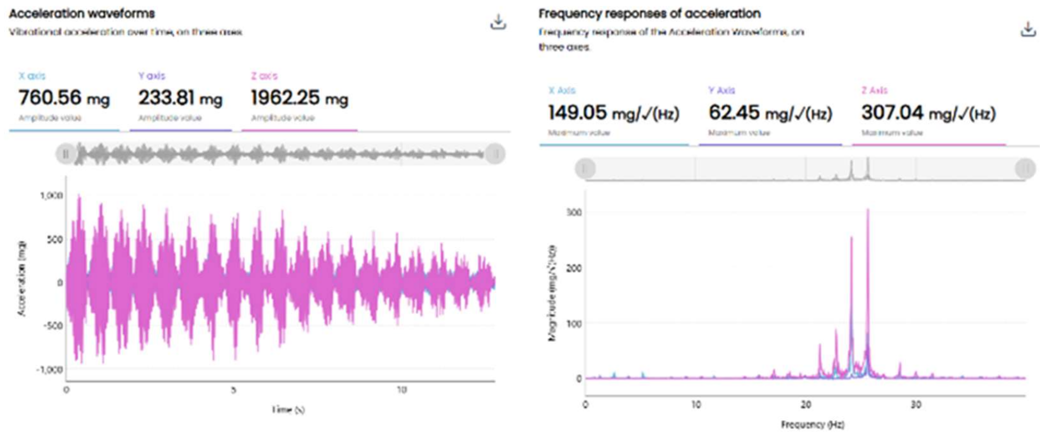

Figure 19 – Cable W12 Acceleration Response and FFT Under 20+ mph Wind Conditions Indicating VIV

According to the bridge's inspection and maintenance records, several dampers, including the one at W12, were repaired in 2021 but were found to be damaged or non-functional during the 2023 inspection. Figure 20 shows a photo of a failed damper at Cable E29, depicting the significant damage these components sustain throughout the bridge structure's life.

Figure 20 – Photo of Broken Damper at Cable E29

With each damper costing nearly $20,000 (including brackets and installation), 32 of 54 dampers replaced in 2021 are already showing issues by 2023, and the cost implications of repeated damper failure are significant. Moreover, viscous dampers are known to be less effective at mitigating VIV than alternatives like Stockbridge dampers. Rather than continuing with "in-kind" replacements with a very short service life, the SHM system has successfully identified a rare but critical behavior, enabling a targeted and cost-effective response that can reduce future maintenance needs and extend the life of this vital bridge structure.

Real Time Incident Response

Determining the thresholds for the structural health monitoring (SHM) system was critical to increasing safety and maximizing the usefulness of the data to the asset management system. These thresholds aid in identifying signs of structural distress to influence maintenance practices and potentially demonstrate the need for emergency intervention. The SHM system has two threshold applications: sensor thresholds and notification thresholds.

Sensor thresholds were set to trigger high-resolution data recording to ensure a complete picture of the structural response is captured during an extreme event. The sensor threshold value for each device varies and was calibrated based on the initial behavior of the bridge structure to ensure it is not constantly being triggered. These high-resolution data captures are stored indefinitely, permitting in-depth review of structural response following an event. After an extreme event, peak displacements, accelerations, and other responses are reviewed against design criteria and predicted performance levels to identify potential overstress or other adverse conditions.

Notification thresholds were set to alert relevant project personnel of potential structural distress that may require attention in real-time. This is communicated via an email containing high-level data from the event, as shown in Figure 21. Two notification threshold levels were established for the East Huntington Bridge sensors: “Alert” and “Critical”. These values represent a 10% and 50% increase from the maximum/minimum sensor readings obtained during the baseline period. The baseline data was established during this grant’s performance period to capture the innate behavioral characteristics of the bridge structure. Typically, sensor thresholds were set higher to conserve power while still providing the ability to capture as much relevant data as possible during events of interest that generate a response in between standard operations and extreme events.

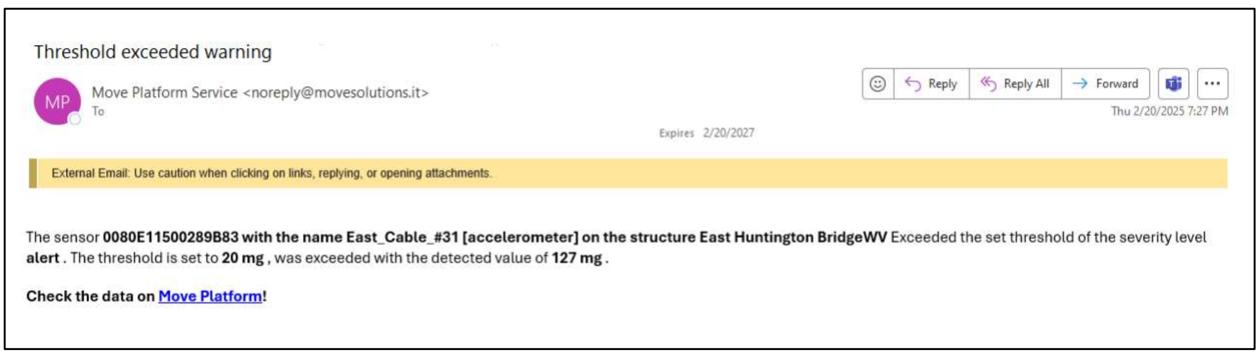

Figure 21 - Sample Move Solutions Notification Email

Setting the right thresholds can be a challenge, however. If the threshold ranges are too narrow, alerts will constantly be set off, generating a large queue of actions for the reviewer. The reviewer may fall behind in this scenario, and time-sensitive or critical trend alerts could be missed. The other end of the spectrum would be thresholds that are so wide that the bridge structure may change its behavior without setting off an alert. Thresholds for the East Huntington Bridge were set with a sensitivity to the WVDOH’s risk management strategy, including considering the consequences of changes in structural behavior. Consideration was also given to setting multiple thresholds with different notification lists to ensure critical and time-sensitive alerts are addressed promptly. It is typical for the threshold levels to require adjustment after the initial values are put in place.

On December 16th, 2024, at 4:39 P.M., the U.S. Geological Survey reported that a 3.3-magnitude earthquake struck less than two miles northwest of Chesapeake, Ohio. Chesapeake is a village of around 730 people in Lawrence County, across the Ohio River from Huntington, WV. As shown in Figure 22, the peak acceleration of the earthquake was effectively detected by the accelerometer mounted on the pylon. Post-processing of the subsequent acceleration samples in the immediate aftermath of the seismic event aided in assessing the state of the bridge structure. The constant modal trend line in Figure 23 indicated no change in the dynamic attributes of the pylon following the earthquake. Given that the dynamic response of any bridge structure is highly correlated to its stiffness and other critical structural health parameters, it was determined from the data that the pylon likely did not incur any significant damage due to the event. This demonstrated the instrument's sensitivity and reliability of the system in its ability to accurately capture short-duration extreme events with enough fidelity to enable detailed post-processing. High-risk events highlight the strength of SHM systems in rapidly and remotely assessing the bridge asset's safety, which empowers stakeholders to make informed decisions for at-scale bridge infrastructure management.

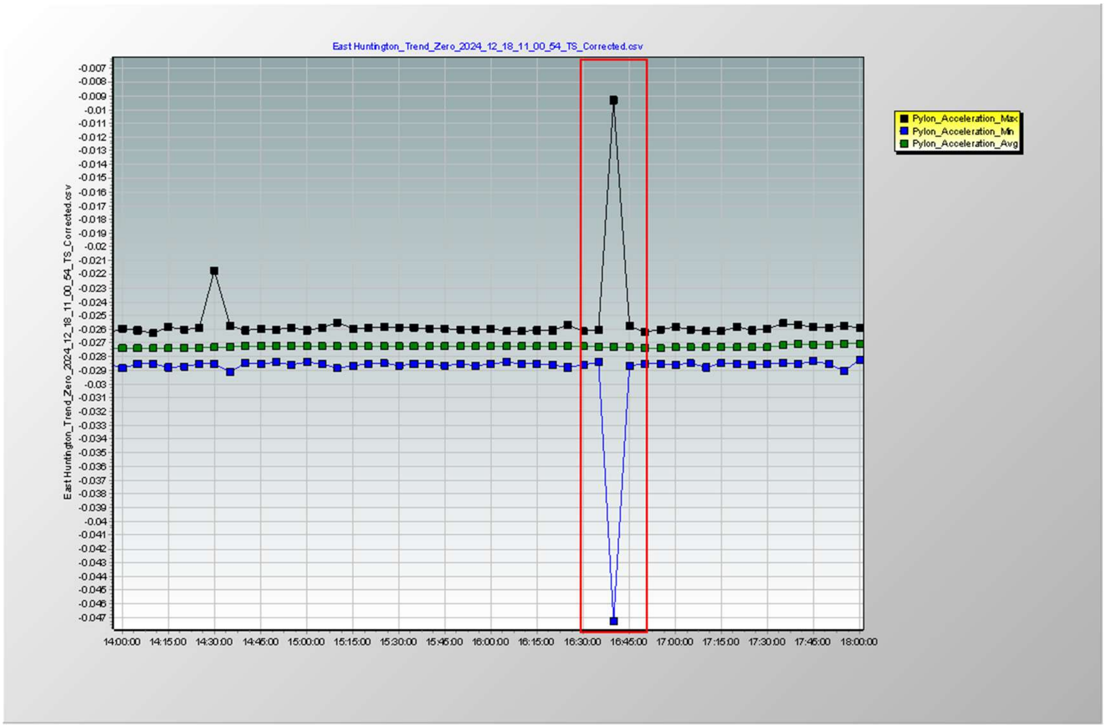

Figure 22 – Earthquake detected by pier accelerometer

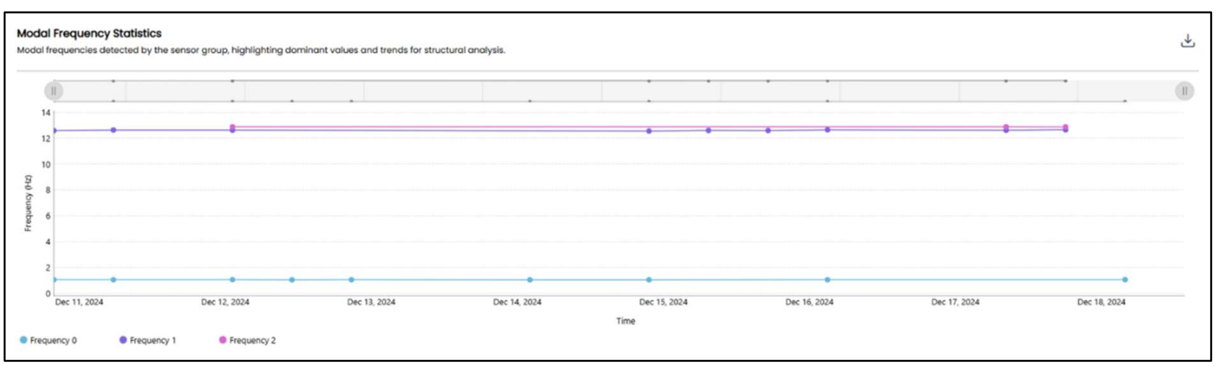

Figure 23 - Modal Analysis Before and After Earthquake

With the tragic collapse of the Francis Scott Key bridge in March 2024 due to a container ship striking a bridge pier, it became clear that many critical long-span bridge structures may lack adequate protection for significant vessel impacts. Stakeholders around the country are actively seeking measures to protect their infrastructure against future vessel collisions. The East Huntington bridge spans the Ohio River, which carries significant barge traffic, making collision with a pier an appreciable concern. SHM provides a way to collect data that can be used to quickly assess the bridge structure's safety in the immediate aftermath of the event. The vessel impact detection system consists of an accelerometer mounted on the pier that can trigger a camera (Figure 24) to collect a video of the event and send out alerts if an event is detected. Like the seismic event described above, the behavior of the bridge structure pre-impact and post-impact can be quickly assessed to determine the appropriate next steps.

Figure 24- Screenshot of Under-bridge Camera Pointed at Pier

A protocol for action after an extreme event was also developed. These events include seismic activity, ship impact, or other rare occurrences. This protocol includes downloading/saving any high-resolution data available from the event, and maximum and minimum values observed during the event, reviewing the baseline of critical sensors, and comparing structural behavior before and after the event. The protocol also includes actions to be taken if irregularities are found, including dispatching appropriate personnel to the bridge to evaluate potential damage.

Improvement in the Statutory Areas Relevant to this Project

The West Virginia SHM Project has demonstrated the ability of this technology to improve the safety, reliability, and resiliency of key bridges that are vital to local transportation and commerce, as demonstrated above. Preserving this infrastructure is especially important in economically disadvantaged areas, where well-maintained bridges can play a pivotal role in driving community growth and prosperity. By ensuring the structural integrity of these bridges, the project supports the efficient movement of goods and services, helping businesses operate more effectively, attracting investment, and creating job opportunities to boost local economies. The ability to detect an extreme event and quickly assess any impacts to the bridge has been demonstrated, which improves emergency response time.

Beyond economic impact, reliable infrastructure also enhances the overall well-being of residents. Safe, dependable bridges are essential for maintaining access to healthcare, education, and employment. This connectivity is crucial for enabling individuals to receive medical treatment, attend school, and find work, ultimately improving the quality of life across the region. Making more effective maintenance decisions minimizes the need for lane closures that cause congestion and delays.

Part 4: Anticipated Costs and Benefits of At-Scale Implementation

As mentioned in Part 2 of this report, this project sought to implement SHM on a WVDOH cable-stay bridge structure to demonstrate the technology's value and practicality. The goal was to collect real-time data on hard-to-inspect or high-risk components, improving detection of structural changes and supporting proactive maintenance and real-time incident response. The following sections describe how the findings of Stage 1 have influenced the anticipated impacts of at-scale implementation of SHM on other WVDOH bridge structures.

Anticipated Impacts of At-Scale Implementation

The WVDOH expects Stage 2 of the West Virginia Structural Health Monitoring Project to expand the scalable technology from Stage 1 to additional bridges at high-priority locations. This expansion is key to prioritizing asset management and directing resources to critical bridge structures.

Continuous at-scale data reviews will help identify structural changes, refine inspection priorities, and enable timely maintenance adjustments. Real-time monitoring supports a proactive approach, optimizing resource allocation, reducing costs, and extending bridge lifespan. These efforts enhance West Virginia's transportation network's safety, reliability, and efficiency, as demonstrated in Part 2 of this report. The WVDOH will continue to review SHM technology to ensure adaptability and evolution over time.

Additionally, the SHM Project aligns with the USDOT departmental priorities, strategic goals, and innovative principles, as shown in Table 3.

Table 3 - SMART Goals Addressed by the Project

SMART Goal	Improvement
Reducing Congestion and Delays	The SHM Project is helping the WVDOH optimize its bridge maintenance efforts. Optimizing bridge maintenance reduces congestion and delays by preventing unplanned closures through early issue detection, allowing for efficient scheduling during off-peak hours, and shortening repair times with targeted interventions. It extends the lifespan of infrastructure, avoiding major disruptions from large-scale replacements. Additionally, advanced monitoring supports better traffic management and maintains public confidence by ensuring more reliable and predictable travel, ultimately contributing to smoother and more efficient transportation networks.
Connecting or Expanding Access for Underserved or Disadvantaged Populations	The SHM Project will leverage Stage 2 funding to expand its scope to six bridges, all located in fully or partially CEJST-designated disadvantaged areas. These bridges serve as vital links for underserved communities, where disruptions due to maintenance or closures can severely limit access to employment, education, and essential services. By introducing real-time data monitoring, the SHM Project enhances the reliability of these critical bridge structures, particularly those identified as priority or at-risk, supporting more informed asset management and ensuring continuity of access for the communities that depend on them.

SMART Goal	Improvement
Improve Reliability	The SHM Project increases the reliability of the bridge structures by utilizing SHM equipment to identify areas of structural concern within minutes, instead of waiting for an incident or biennial/special inspections. The Project also improves the reliability of vehicular traffic and commerce on national highway assets by using monitoring data to assist with maintaining these assets strategically. Employing effective SHM technologies will result in reopening bridges to continue highway operations more quickly after an incident, which decreases the possibility of a major roadway detour due to a bridge closure and, in turn, provides travel time, safety, and emissions benefits.
Increased Resiliency	West Virginia has limited funds available for bridge rehabilitation and reconstruction, making effective asset allocation challenging. The SHM Project enhances the ability to identify urgent repair needs and supports resilience not only for bridge structures equipped with monitoring devices, but also for the broader statewide bridge system through data-driven asset management.
Improved Emergency Response	If an unanticipated incident occurs, the WVDOH may need to close the bridge structure to verify its structural integrity, potentially delay traffic for an extended timeframe. Time lost to closures can be shortened with an SHM system, as post-incident field conditions can be compared to previously collected baseline data to make fast decisions regarding the need to potentially close the bridge structure.

Anticipated Costs

Proof-of-Concept Costs

The budget summary for Stage 1 implementation is shown in Table 4 below. The project was completed within the estimated budget. The costs consisted of the following elements for the SHM Project:

- Direct Labor—This included WVDOH direct costs to oversee the planning and installation of SHM equipment, as well as monitoring of the system over the period of performance. It also included costs for the administration of the contracts.
- Travel—Transportation costs for tasks associated with the SHM system.
- Equipment—The cost for SHM equipment.
- Supplies—The cost for supplies associated with the SHM system.
- Contractual—The costs for a consultant that assisted in planning the SHM system, provided installation services, and data monitoring for the Stage 1 performance period. This contract also included the Maintenance of Traffic (MOT) for access equipment to install the SHM system.
- Reporting—This included WVDOH direct costs for fulfilling grant reporting requirements.

Table 4 Stage 1 Costs

Item	Budget	Percent of Total
Direct Labor	$80,000	9.9%
Fringe Benefits	$0	0%
Travel	$4,000	0.5%
Equipment	$110,000	13.5%
Supplies	$208,000	25.6%
Contractual	$400,000	49.3%
Construction	-	-
Reporting	$10,000	1.2%
TOTAL	**$812,000**	**100.0%**

At-Scale Costs

The key to a successful Stage 2 implementation will be deploying the right amount and type of technology. Finding the sweet spot for an SHM system requires a strategic balance of performance, cost, scalability, and maintainability. It begins with a clear needs assessment to define the most critical structural risks and monitoring goals. For example, if cable fatigue or excessive deflection is a concern, technologies that directly address those issues should be prioritized, avoiding unnecessary or redundant components. This is done through a risk assessment as discussed in Stage 1 of this report. A phased approach can help evaluate technologies on a small scale before committing to full-scale implementation, allowing teams to test system integration, data quality, and maintenance demands. Choosing scalable and modular technologies ensures the system can adapt to future needs or funding opportunities without requiring extensive technology replacement.

To maintain a practical balance, the WVDOH will combine proven, reliable tools like accelerometers and strain gauges with selective integration of innovative technologies, such as AI-based analytics or wireless systems, where they offer measurable benefits. Lifecycle costs will be factored in alongside initial capital investment, ensuring the long-term cost-effectiveness and functionality of the system.

Technologies that integrate well with existing infrastructure and workflows will be used to minimize disruptions and training needs. Early engagement with engineers, IT personnel, maintenance teams, and vendors will be prioritized to ensure the chosen system is functional, user-friendly, and sustainable. Finally, regular evaluation and refinement based on key indicators will help optimize future deployments. State DOTs can ensure an efficient and impactful SHM strategy of their critical infrastructure inventories by aligning technology choices with specific needs and organizational capacity.

This Stage 1 project employs SHM equipment to monitor a critical cable-stay bridge. In Stage 2, similar SHM systems will be deployed on various bridge superstructure types. This expansion will allow the program to begin monitoring additional bridge structures in the WVDOH inventory that warrant more frequent inspections or have a higher risk of an incident. As more bridge structures are fitted with SHM equipment, the WVDOH will be able to more fluidly adjust its asset management strategy to focus on the bridge structures with the greatest need and to facilitate agile connectivity of its infrastructure. Deploying effective SHM systems to assist in managing the WVDOH assets will improve the agency's current processes. Constant feedback on structural conditions allows the agency to make smarter budget allocation decisions.

In Stage 2 of the West Virginia Structural Health Monitoring System Project, the WVDOH will build on Stage 1 planning and initial installation efforts at six additional Ohio River bridge structures. These assets are along the Ohio-West Virginia state line and are located entirely or partially in Disadvantaged Communities, as identified in the Climate and Economic Justice Screening Tool (CEJST).

These six multi-state critical bridge structure bridges play a vital role in interstate and local commerce, connecting ports along the Ohio River with major highways that facilitate the movement of freight and commuters between the states and beyond. Stage 2 of the project will enable investigation of five different bridge types, facilitating even more complex analysis and robust predictive analytics as shown in Table 5.

Table 5 – Proposed Stage 2 Bridges

Bridge Name	NBI Bridge Type	County	CEJST Disadvantaged	ADT
Bridge of Honor/Pomeroy Mason-Bridge	Concrete Continuous Stayed Girder	Mason	Partially	9,577
Blennerhasset Island Bridge	Steel Arch - Through	Wood	Partially	11,602
Veteran's Memorial Bridge	Steel Cont Stayed Girder	Brooke	Partially	33,960
Wellsburg Over Ohio River	Steel Arch - Through	Brooke	Partially	9,900
Arch A Moore JR Bridge	Steel Arch - Through	Marshall	Partially	12,629
Fort Henry Bridge	Steel Arch - Through	Ohio	Yes	29,400

These bridges were selected because they have some or all of the following attributes:

- Not inspectable due to the protective outer layer surrounding the cables.
- Critical to the passage of freight and commuters between West Virginia and Ohio, and beyond.
- Located in fully or partially disadvantaged communities.
- Aging bridge structures in need of more frequent monitoring than the current biannual cycle and budget allow.
- Represent five bridge types, enabling robust analysis relevant to statewide scaleup post-grant period of performance.

Taking advantage of the experience gained during Stage 1, we have developed a preliminary cost estimate for the Stage 2 implementation shown in Table 6. As Stage 2 will have a period of performance of up to 36 months, operational costs for maintaining the systems and evaluating the data collected were included in addition to the initial costs for this extended duration.

Table 6 - Estimated Stage 2 Costs

Item	Budget	Percent of Total
Direct Labor	$4,110,185	34.25%
Travel	$8,000	0.07%
Equipment	$628,271	5.24%
Supplies	$1,960,494	16.34%
Contractual	$5,283,0503	44.03%
Construction	-	-
Other	$10,000	.08%
TOTAL	**$12,000,000**	**100.0%**

Cost Analysis of At-Scale Implementation

Cost Effectiveness

As detailed in Part 3 of this report, the SHM system uncovered that several stay cables were experiencing vortex-induced vibrations (VIV), which significantly contributed to the premature failure of many of the dampers. Each damper replacement costs around $20,000, factoring in mobilization, traffic control, brackets, and installation. In 2021, 54 of the bridge's 62 dampers were replaced, yet by 2023, many had already shown signs of failure. This cycle of frequent replacements represents a recurring financial burden of at least $640,000 every few years, which is an unsustainable cost for the WVDOH. With the SHM system costing a comparable amount to a single damper replacement cycle, its value is evident.

Beyond identifying VIV as a root cause, the system supports targeted, data-driven interventions to prevent repeat failures. Rather than continuing with short-lived, "in-kind" replacements, the SHM system enables a more thoughtful, strategic response. Diagnosing a rare but damaging vibration behavior opens the door to cost-effective, long-term solutions. This proactive approach not only improves the longevity of bridge components but also reduces unnecessary expenditures and minimizes traffic disruptions. In this way, the SHM system is a fiscally responsible investment that enhances structural resilience and maintenance efficiency.

By enabling early detection of stress, fatigue, and damage, SHM allows for timely interventions that extend the service life of critical components and reduce the frequency of costly emergency repairs. It also supports condition-based maintenance strategies, ensuring that resources are allocated where needed and lowering labor, material, and traffic control costs, as described in Part 3 of this report.

With accurate, real-time data, the WVDOH can make better-informed decisions for retrofits and upgrades, minimizing the risk of under- or over-design. Furthermore, SHM helps justify future funding by providing objective evidence of structural needs, supports safer operations that reduce liability exposure, and minimizes traffic disruptions by reducing the need for frequent lane closures. Ultimately, SHM enables a proactive, data-driven approach to infrastructure management that delivers significant financial, operational, and public safety advantages over traditional maintenance models.

Risk Reduction

Effective SHM systems reduce risk by continuously tracking the structural performance of bridges and other infrastructure, allowing for the early detection of potential issues before they develop into critical failures. This proactive approach significantly lowers the risk of sudden structural problems that could compromise public safety, cause costly emergency repairs, or require unplanned closures. By identifying abnormal behaviors such as excessive vibrations, stress accumulations, or material fatigue, the WVDOH can take corrective actions early, preventing component failures like damper breakdowns or cable deterioration. SHM supports better-informed decision-making through accurate, real-time data, reducing maintenance planning and retrofit design uncertainty. Additionally, it enhances risk mitigation by improving compliance with safety standards, supporting inspection efforts, and reducing liability exposure through documented performance records. An effective SHM system is a continuous safeguard, improving resilience, safety, and reliability while reducing financial and operational risk.

Extending Service Life

Quantifying the financial benefits of large-scale implementation is challenging, but based on the results of Stage 1, the expected advantages will significantly outweigh the costs, given the high expense of maintaining these complex bridge structures. Properly identifying optimal maintenance strategies and early identification of potential problems can extend the service lives of these bridges, delaying the need for replacement. Considering that replacing just one of these bridge structures would cost hundreds of millions of dollars, deferring that expense into the future provides substantial present-day cost savings, easily justifying the investment in Stage 2 implementation.

For example, the financial benefit of delaying the replacement of a $500 million bridge for 10 years effectively reduces its present-day cost, since money today holds more value than money in the future due to inflation and investment potential. Assuming an annual discount rate of 3% (aligned with government bond yields or standard infrastructure inflation rates), the present value of the bridge replacement in 10 years is approximately $372 million, resulting in a present-day savings of $128 million.

However, maintenance costs must be considered. If annual maintenance expenses are conservatively assumed to be $5 million, these costs accumulate over the 10 years. Applying a discount factor sum of 8.53, the present value of these maintenance costs is approximately $42.65 million. By subtracting the

$42.65 million in maintenance costs from the $128 million savings achieved through deferring replacement, the net present-day cost-benefit of postponing the project is approximately $85 million, far exceeding the anticipated costs for Stage 2 SHM monitoring on all six bridges.

Part 5: Challenges & Lessons Learned

Legal, Policy, and Regulatory Requirements

The WVDOH did not encounter any legal, policy, or regulatory requirements for the SHM system installation or any relevant exemptions, waivers, permits, or special permissions for those installations and data monitoring.

Procurement and Budget

The selection of vendors followed a best-value approach, evaluated against several criteria: vendor experience, adherence to the schedule, compliance with system requirements, introduction of innovative solutions, and total cost. Offerors were instructed to submit a 5-page summary detailing how they meet or exceed the stipulated minimum requirements, along with the completed bid summary as part of the Request for Proposals (RFP). Additionally, bidders were asked to include cut sheets for all proposed hardware as an appendix to their submissions. To qualify, all proposers must have installed at least five SHM systems of comparable complexity in the United States within the past five years, with a preference for experience related to cable-stayed bridges.

Bidders were required to outline their use of wired and wireless sensor technologies explicitly. The system's durability, encompassing sensors, hardware, and wiring, was required to provide a minimum service life of 25 years. Furthermore, bidders needed to offer a 5-year warranty for all hardware components.

Innovative solutions for the structural monitoring system were highly encouraged, which could encompass unique sensor configurations, advanced data analysis techniques, or inventive integration methods with the existing bridge infrastructure. Bids were required to provide unit costs for each listed item, including all installed costs such as labor, materials, mobilization, and travel expenses.

A key lesson learned during this process was the importance of preparing for unforeseen circumstances, including the potential for malfunctioning equipment arriving damaged during shipping to the bridge site. This lesson highlighted the need to make necessary traffic control adjustments to facilitate the reinstallation and rewiring of the replacement pieces and sensors ordered after the initial equipment failed to integrate with the system.

Lessons Learned:

1. **Best-Value Procurement Enhances Quality and Innovation**
   Utilizing a best-value selection process that considered vendor experience, technical compliance, innovation, and cost ensured the selection of qualified contractors capable of delivering reliable and advanced SHM systems tailored to the project's needs.

2. **Clear and Detailed RFP Requirements Drive Accountability**
   Requiring vendors to submit a comprehensive proposal with specific qualifications, technical details, and cost breakdowns fostered transparency and enabled a thorough evaluation. Including criteria such as previous installations and experience with cable-stayed bridges ensured vendor capability.

3. **Encouraging Innovation Leads to Improved System Design**
   By explicitly encouraging innovative sensor configurations and data analysis techniques, the RFP process fostered creative, forward-thinking solutions that improved integration with existing infrastructure and enhanced long-term monitoring capabilities.

4. **System Durability and Warranty Requirements Promote Longevity**
   Setting clear expectations for system lifespan (25 years) and warranty coverage (5 years) encouraged using high-quality materials and robust designs, aligning with the project's long-term sustainability goals.

5. **Detailed Cost Structuring Improves Budget Accuracy**
   Requiring unit pricing with all associated installation costs, including labor, materials, mobilization, and travel, allowed for better cost control and forecasting, helping to avoid unexpected expenses during implementation.

6. **Planning for Contingencies is Essential**
   The arrival of malfunctioning equipment underscored the need for contingency planning, including flexible traffic control strategies and backup installation procedures. Anticipating potential delays or issues with hardware delivery and integration is crucial for maintaining project schedules and minimizing traffic disruption.

Partnerships

The WVDOH partnered with Marshall University's Dr. Wael Zatar for the SHM Project, who assisted with the program as part of the curriculum for its engineering students. Real-time bridge condition data will be incorporated into the undergraduate and graduate curriculum, applying classroom learning to real-world use cases. With ongoing data collection and scaleup beyond the grant period, there will be sustainable advanced research opportunities that advance the state of practice on structural integrity through predictive analytics and artificial intelligence.

The WVDOH engaged another contractor to retrofit several of the bridge stay cables that were identified as damaged in a recent inspection report. Effective communication with the contractor allowed for the extension of mobilization equipment usage, facilitating the SHM equipment installation during Stage 1. The collaboration among the agency, the retrofitting contractor, the consultant, and the SHM vendor exemplifies how strategic partnerships can optimize allocated funds for bridge maintenance while minimizing time and traffic disruption on this busy two-lane bridge. The consultant and vendor installed the SHM equipment at night after the retrofitting work was completed to reduce traffic impact further. Traffic lanes were managed carefully to ensure smooth flow, maintaining the integrity of this crucial connector between West Virginia and Ohio.

Lessons Learned:

1. **Academic Partnerships Enhance Practical Learning and Innovation**
   Collaborating with Marshall University and incorporating real-time SHM data into engineering curricula created a valuable hands-on learning experience for students while supporting ongoing research in predictive analytics and AI for structural health. This partnership highlights the mutual benefits of integrating academia with real-world infrastructure projects.

2. **Sustainable Research Through Ongoing Data Collection**
   By designing the SHM system for long-term use beyond the grant period, the project ensures continued data collection and research potential. The project deliverables support the development of advanced tools and methods for monitoring structural integrity, promoting innovation in bridge maintenance.

3. **Strategic Coordination Maximizes Efficiency**
   Effective communication and coordination among the WVDOH, the retrofitting contractor, the consultant, and the SHM vendor enabled multiple activities to be completed using shared mobilization and equipment. The optimized resource use reduced overall project time and costs.

4. **Nighttime Work and Traffic Management Minimize Disruption**
   Performing SHM equipment installation at night after retrofitting activities helped reduce the impact on traffic. Careful traffic lane management ensured smooth vehicle flow, critical for maintaining accessibility on a heavily traveled, two-lane bridge.

5. **Collaborative Approaches Yield Operational and Financial Benefits**
   The multi-party collaboration demonstrated how well-coordinated partnerships can enhance

project outcomes, optimize funding, and minimize disruptions to the public, providing a model for future infrastructure initiatives.

Technology Suitability

To establish an effective SHM plan that aligns with the Phase 1 budget and supports scalability, the WVDOH undertook an extensive review of the East Huntington Bridge's historical inspection records, load ratings, measured cable forces, maintenance history, and the availability of finite element models. The planning process was designed to reassure the agency about the project's strategic direction and ability to adapt to evolving needs.

The bidding document outlined the requirements for various components, including accelerometers, tilt meters, crack gauges, linear displacement sensors, vessel collision information, dashboards, and data acquisition and management systems. Vendors were also asked to provide lead times for each hardware component, including sensors, wiring, and data acquisition units (DAUs).

While extensive planning works to mitigate potential unforeseen circumstances, technological challenges remain that could only be experienced during implementation and could not have been alleviated with thorough pre-planning. As the system was improved during the commissioning period, many of these challenges were realized, and system parameters were adjusted. For example, some sensors recorded maximum reading values close to what they could report. As such, those sensors' settings were adjusted to ensure the full scale of the system output was captured. It is very challenging to fully predict which sensors require modifications to their settings prior to deploying the whole system.

Lessons Learned:

1. **Thorough Preliminary Analysis Builds a Strong Foundation**
   Conducting a detailed review of historical inspection data, load ratings, cable force measurements, maintenance records, and available finite element models helped the WVDOH develop a well-informed SHM plan. This upfront effort ensured the project aligned with budget constraints and supported future scalability.
2. **Clear Technical Specifications Guide Vendor Alignment**
   Providing detailed component requirements, including sensor types, data acquisition systems, and lead times in the bidding documents, ensured vendors understood expectations and could plan accordingly. This clarity helped streamline the procurement process and reduce ambiguity.
3. **Lead Time Transparency Supports Realistic Scheduling**
   Requesting lead times for all hardware components helped anticipate delivery challenges and manage project timelines more effectively, minimizing delays during installation and commissioning.
4. **Flexibility is Key to Handling On-Site Challenges**
   Despite extensive pre-planning, some technical challenges only emerged during system commissioning. These challenges highlighted the importance of building flexibility into the plan to allow for adjustments and system tuning based on real-world conditions.
5. **Commissioning Period is Critical for System Optimization**
   The commissioning phase provided valuable insight into sensor performance and system limitations. It served as a crucial period for identifying and correcting issues, reinforcing the need for adaptive management and iterative refinement when deploying complex SHM systems.

Data Governance

Data governance is a critical component of the SHM project, ensuring that the collection, management, storage, and use of structural health monitoring data are handled responsibly, securely, and effectively. A robust data governance framework established clear protocols for data ownership, access rights, quality control, and cybersecurity. By defining roles and responsibilities for data stewards, engineers, and stakeholders, the WVDOH can ensure consistent data integrity and accountability across all implementation phases. This framework also supports compliance with applicable regulations, protects sensitive infrastructure information, and promotes transparency in data sharing between agencies and partners. As the SHM system scales, strong data governance will be essential for enabling reliable decision-making, supporting advanced analytics, and maintaining trust among stakeholders.

The system vendor on Azure securely maintains the data. This arrangement supports robust data governance by offering a secure, scalable, and compliant environment for managing critical infrastructure data. Azure provides built-in tools for access control, data encryption, and user authentication, which help ensure that only authorized personnel can view or modify system data. The platform also supports role-based access and audit logging, making it easier to track data usage and maintain accountability.

Moreover, Azure complies with various industry standards and government regulations, including ISO 27001, FedRAMP, and NIST frameworks, which align closely with data governance best practices. These certifications help ensure that hosted data is protected according to the highest cybersecurity and regulatory compliance standards. Azure also offers data backup, redundancy, and disaster recovery tools, crucial for maintaining data availability and integrity over time. By leveraging a platform like Azure, the SHM project can enforce strong data governance policies while benefiting from the flexibility and reliability of a modern cloud-based infrastructure.

Lessons Learned:

- **Early Planning Is Crucial**: Establishing a clear data governance framework at the outset helped define expectations, responsibilities, and protocols for data handling, ensuring smoother implementation and long-term management.
- **Partnership with a Trusted Cloud Provider Adds Value**: Hosting the system on Microsoft Azure enhanced data security, compliance, and operational efficiency, demonstrating the importance of selecting a platform with proven capabilities and certifications.
- **Role Clarity Prevents Data Mismanagement**: Clearly assigning data ownership and responsibilities for access and quality control reduced confusion and helped maintain data integrity throughout the project.
- **Compliance and Security Must Be Built-In, Not Bolted On**: Embedding cybersecurity and regulatory compliance into the system from the beginning ensured ongoing protection of sensitive data and adherence to federal standards.
- **Auditability Supports Accountability**: Leveraging Azure's audit logging features allowed the project team to monitor system access and activity, promoting transparency and accountability.
- **Scalable Solutions Are Essential**: Selecting scalable technologies and governance policies ensured that the data management approach can evolve alongside future SHM system expansions.
- **Training and Communication Are Key**: Ongoing education for staff and partners about data protocols helped reinforce best practices and build a culture of responsibility around data governance.

Workforce Capacity

In collaboration with its consultant, the WVDOH has strategically planned for the success and sustainability of the SHM Phase 1 project. Acknowledging the crucial role of workforce capacity, we have committed to providing comprehensive training for several employees within the agency and partner academic institutions.

In a strong demonstration of the project's dedication to cultivating and maintaining a skilled workforce, the consultant designated a portion of the budget to ensure that the vendor delivers training for all selected data users and engineers involved in the project. This initiative empowered the workforce to utilize the SHM Stage 1 implementation on the East Huntington Bridge and facilitate the scalability of continuous monitoring and assessment across other WVDOH-maintained bridges.

Lessons Learned:

1. **Investing in Workforce Development Ensures Long-Term Project Success**
   Recognizing the importance of internal capacity, the WVDOH prioritized comprehensive training for agency staff and academic partners, reinforcing that a knowledgeable workforce is essential for sustaining SHM efforts beyond initial implementation.
2. **Collaborative Training Enhances Knowledge Transfer**
   Partnering with the consultant to allocate budget for vendor-led training ensured that all key personnel, including data users and engineers, were equipped with the skills needed to interpret and act on SHM data effectively.
3. **Training Empowers Scalability and System Expansion**
   Providing hands-on experience with the East Huntington Bridge SHM system prepared staff to support the future expansion of monitoring programs across additional bridge structures, promoting long-term scalability and consistency.
4. **Cross-Organizational Involvement Builds Broader Expertise**
   Including academic institutions in the training initiative not only supports student development but also creates a broader network of SHM-literate professionals who can contribute to research on innovative bridge safety initiatives.
5. **Early Training Investment Reduces Future Reliance on Vendors**
   By ensuring knowledge is transferred during initial deployment, the WVDOH reduces long-term dependence on external vendors for system management and troubleshooting, increasing self-sufficiency and cost-efficiency.

Internal Project Coordination

Internal project coordination is essential to the successful deployment of a Structural Health Monitoring system. It ensures that all WVDOH divisions, including engineering, maintenance, IT, procurement, and leadership, are aligned on project goals, timelines, and responsibilities. This alignment streamlines decision-making, facilitates efficient resource allocation, and helps prevent delays caused by miscommunication or uncoordinated efforts. Coordinated planning also ensures that technical specifications, budget constraints, and scheduling considerations are addressed effectively.

Additionally, internal coordination supports seamless data management, long-term system maintenance, and clear communication with external vendors and contractors. It enables IT and engineering teams to collaborate on data storage, analysis, and system integration, ensuring that SHM data is accurate, secure, and actionable. Well-defined internal roles and training plans promote sustainability and reduce reliance on external support, while organized oversight improves accountability, tracks project milestones, and builds institutional knowledge within the WVDOH for future deployments.

Lessons Learned:

1. **Cross-Department Coordination is Essential for Success**
   Involving all relevant internal departments early, such as engineering, IT, procurement, and maintenance, ensures alignment on project objectives, roles, and timelines, reducing delays and improving overall efficiency.

2. **Clear Communication Streamlines Decision-Making**
   Establishing structured communication channels among internal stakeholders enables faster, more informed decisions during system planning, installation, and troubleshooting.
3. **Resource Planning Must Be Coordinated Internally**
   Effective coordination helps ensure that necessary personnel, equipment, and funding are allocated and available when needed, avoiding scheduling conflicts and project bottlenecks.
4. **Integrated Data Management Requires Collaboration**
   Deploying an SHM system involves large-scale data collection and analysis, which requires close cooperation between technical and IT teams to ensure proper data integration, security, and usability.
5. **Defined Roles and Responsibilities Promote Accountability**
   Assigning clear roles within the internal team helps maintain momentum, track progress, and ensure accountability throughout the deployment and long-term operation of the SHM system.
6. **Internal Readiness Reduces Dependence on Vendors**
   By building internal capacity and ensuring staff are trained to operate and maintain the system, the WVDOH can reduce long-term reliance on external vendors and improve sustainability.
7. **Internal Coordination Improves Vendor and Contractor Oversight**
   A unified internal approach enables more effective communication with external partners, ensuring contract requirements are met and installation activities are executed smoothly.

Part 6: Deployment Readiness

Deployment readiness for the WVDOH's SHM project refers to being fully prepared technically and organizationally for the successful installation, operation, and long-term use of the structural health monitoring system. To reach this stage, we undertook several key preparations. First, we conducted a thorough review of the bridge's historical inspection records, load ratings, maintenance history, and available finite element models to inform system design and ensure alignment with structural needs. We also developed clear and detailed technical specifications in our bidding documents, which helped us select a vendor through a best-value approach based on experience, innovation, and system reliability.

Preparing our internal workforce was another critical component; we provided comprehensive training for agency staff, consultants, and academic partners to build the system operation and data interpretation capacity. To minimize public impact and optimize resources, SHM installation was coordinated with ongoing retrofit activities, and work was scheduled during nighttime hours. Finally, we built in a commissioning period to test and calibrate sensors under real-world conditions, allowing for adjustments that ensured system performance met expectations. These collective efforts positioned the project for a smooth and effective deployment while laying a strong foundation for future scalability and integration across the state's bridge network.

WVDOH's work plan for the planning and implementation of the SHM system was proven feasible and reflects a proven concept of operations development and implementation.

Requirements for Successful Implementation

Scaling the SHM project across a broader network of bridges presents several key obstacles that must be strategically addressed to ensure long-term success. One of the most significant challenges is securing sustained funding. While initial grants may cover pilot phases, expanding the system statewide requires ongoing equipment, installation, data infrastructure, and maintenance investment. Another critical barrier is workforce capacity; a larger deployment demands a skilled labor force to install, manage, and analyze system data. Without continuous training and workforce development, there is a risk of technical knowledge gaps that could hinder system effectiveness. Additionally, managing and integrating large volumes of real-time data across multiple bridge structures is technically complex, requiring robust, scalable, and secure platforms.

Procurement and vendor coordination also become more complicated as the project scales. Ensuring system quality and interoperability consistency across various sites means procurement processes must be standardized and tightly managed. Site-specific differences add further complexity, as each bridge has unique structural and environmental conditions that may require customized SHM configurations. Finally, successful large-scale implementation relies heavily on interagency coordination. Aligning goals, timelines, and resources across various departments and jurisdictions can be difficult without clear communication channels and strong leadership. Overcoming these challenges will require thoughtful planning, cross-sector collaboration, and a commitment to adaptability and innovation.

Legal, Policy, and Regulatory Requirements

The WVDOH is not aware of any legal, policy, or regulatory requirements that concern SHM system installation or of any relevant exemptions, waivers, permits, or special permissions for those installations and data monitoring for at-scale implementation.

Procurement and Budget

There are no anticipated procurement issues with obtaining the physical hardware or software licensing to outfit six additional bridge structures with a similar SHM system. Hardware and software suppliers are prepared to provide this technology competitively and eager to participate in this flagship at-scale initiative. The procurement standards described in Part 4 are expected to be met or exceeded during Stage 2.

Uncertainty exists about future funding and the ability to maintain or expand the system. To reduce this risk, the project was designed with scalability in mind, using modular components and emphasizing long-term cost efficiency. By building internal capacity and demonstrating early value through pilot results, the project also positions itself favorably for future funding opportunities. Collectively, these mitigation strategies help ensure the system remains resilient, functional, and valuable over time.

Partnerships

Partnerships will play a critical role in preparing for the SHM project's at-scale implementation by combining expertise, resources, and strategic alignment across sectors. Collaborating with the SHM experts from Marshall University helps build a sustainable pipeline of trained professionals equipped to manage and interpret SHM data. Integrating real-time monitoring into engineering curricula ensures a future-ready workforce and promotes ongoing research that can drive innovation and improve system performance over time.

Engagement with other public agencies and local governments ensures that the SHM program aligns with infrastructure priorities and funding mechanisms, enabling smoother scaling across multiple jurisdictions. These partnerships foster shared ownership and accountability, essential for long-term sustainability. Overall, strong, well-coordinated partnerships create the foundation for efficient, scalable SHM implementation by pooling resources, reducing redundancy, and promoting continuous learning and adaptation.

Technology Suitability

The existing hardware and software SHM technology utilized is at the forefront of the industry and remains as adaptable as possible, not to preclude future technological advancements. While much can be done to "future proof" these systems, designing the system for every possible expansion scenario is not feasible or economical. As the system is deployed at-scale, the technology implemented will be continuously reevaluated to find the most suitable products. Additionally, many of the instruments in the system rely on battery power for their operations. The settings for these devices were methodically set to conserve battery and thus limit the maintenance required. Deploying an array of sensitive electronics into potentially harsh weather environments can also lead to durability issues. As such, the system was designed with various redundancy levels to detect the bridge structure's global behavior.

Data Governance

All raw data from the sampling window is now publicly accessible as part of the SMART grant reporting requirements. Data covering two months from the system's commissioning to the end of the reporting period has been uploaded to ROSA P for public consumption. ROSA P is an online repository hosted by USDOT commonly used for long-term data storage of federally funded transportation initiatives. This project's upload includes data from January 1, 2025, to February 28, 2025, for all sensors in the SHM system and a series of ReadMes alongside a Data Management Plan outlining the documentation for each type of technology used.

Subsequent at-scale implementations will likely require similar practices that can be readily accommodated. Publicly uploading the raw data does not pose any additional uncertainties regarding the safety or security of the bridge structure.

Workforce Capacity

At-scale implementation of SHM technologies presents a valuable opportunity to create good-paying, skilled jobs while promoting workforce upskilling and empowerment. As the program expands, it will require many engineers, technicians, data analysts, and maintenance professionals to install, operate, and interpret the data of the SHM systems. These roles typically offer competitive wages and long-term career paths, particularly in infrastructure-focused public sector and consulting positions. By embedding SHM expertise into the WVDOH and the partner academic institutions, we can create new employment opportunities and build a pipeline of qualified workers through meaningful training and education initiatives.

Internal Project Coordination

The field of damage detection in SHM is a maturing area of research that will require ongoing coordination between existing project personnel and those onboarded at the conclusion of Stage 1. To maximize the holistic value generated by the system, it is critical that this onboarding process relays highly technical information in an accessible and implementable manner. As the asset management system expands to multiple bridge structures in the region, establishing reliable internal coordination between various technical and management personnel is crucial to at-scale implementation.

Maintenance and Operations Requirements

Building on lessons learned from Stage 1, the WVDOH will identify additional SHM equipment with available manufacturers and understand advantages/challenges with each option and the best technology for each bridge type. The process includes identifying trends in sensor reliability, data communication stability, and software functionality across different environmental and structural conditions. We have identified how to use information from the SHM system, the staffing that will be required, and other data-related details. We have confirmed the anticipated cost for the SHM Project bridge, including initial installation, monitoring by the WVDOH staff, maintenance, and future upgrades, and have set up overarching practices related to the SHM system for large-scale implementation.

The SHM project has been designed with flexibility and future growth in mind. By using modular, open-architecture systems and hosting data on a scalable cloud platform like Microsoft Azure, we have the capacity to integrate new technologies and tools without overhauling the existing infrastructure. We have also invested in workforce training and academic partnerships to build internal capacity, which ensures that technical expertise is available to adapt and evolve the system over time.

To prevent technical debt and continue to make improvements during at-scale implementation, we intend for new bridge structures to be instrumented gradually with different types of SHM technology. An intentional and diversified rollout of SHM systems will ensure that the lessons learned from one structure can be applied to the next. Repeatedly evaluating which sensors and instruments have the highest performance is necessary for ensuring this project remains at the forefront of the industry. This combination of planning, platform selection, and staff development helps reduce the risk of technical debt and supports a sustainable path forward for continuous innovation and improvement.

How at-scale Implementation Will Harness Beneficial Impacts

At-scale implementation of the SHM project presents a strong opportunity to generate good-paying jobs while supporting fair labor practices. Expanding SHM systems across multiple bridges will require a larger, skilled workforce to support installation, maintenance, data analysis, and ongoing system upgrades, creating demand for engineers, technicians, IT specialists, and data scientists. These roles often come with competitive wages and the potential for long-term career growth.

The installation of equipment on the Stage 1 SHM Project bridge structure for prototyping has demonstrated the readiness of the technology for a larger deployment. Tests performed with the system manufacturer and the WVDOH staff have validated that the system provides necessary and accurate information based on plan needs. The tests were verified by identifying structural parameters using the SHM system data and comparison of these measured parameters against prior physical measurements.

For example, the calculated first mode frequency of the stay cables using the SHM data matched exceptionally well with the 2018 and 2022 frequencies obtained by manual excitation of the cables. As elaborated on further in Part 3, this serves as a strong example that the techniques used to implement the Stage 1 system are consistent with other labor-intensive methods. Thereby demonstrating the value of remote monitoring via SHM and proving the concept is prepared for further deployment at-scale in Stage 2. Continued data monitoring will determine/verify best practices for the larger-scale implementation. Documented findings and lessons learned on initial SHM implementation will be incorporated into the Stage 2 SHM system design.

The SHM project offers substantial economic benefits for the WVDOH by enabling smarter, data-driven infrastructure management. With real-time monitoring, the WVDOH can transition from reactive to predictive maintenance strategies, identifying and addressing potential issues before they become costly problems. This proactive approach reduces emergency repair expenses and helps extend the service life of critical bridge components, delaying the need for expensive replacements. Additionally, by optimizing how maintenance resources are allocated, the agency can ensure its budget is used more efficiently, focusing on high-priority areas.

The ability to conduct targeted repairs and plan interventions more effectively also minimizes traffic disruptions, which helps maintain economic productivity and lowers the financial burden associated with detours and delays. Improved safety and reduced liability from avoiding catastrophic failures further protect the state’s financial interests. Moreover, WVDOH’s investment in innovative infrastructure solutions positions the agency to attract additional funding from federal and private sources. Reliable transportation infrastructure also supports local economies by enabling the smooth flow of goods and services, enhancing business operations, and supporting job creation. Overall, the SHM system contributes to the state's cost savings and economic resilience.

Part 7: Wrap-Up

The West Virginia Structural Health Monitoring (SHM) Project aims to enhance the state's bridge management and safety by deploying effective SHM systems. Initiated under the FY 2022 SMART Grant, the project focused on installing SHM technology on a critical cable-stay bridge over the Ohio River, addressing the challenges of inspecting aging and complex bridge structures.

The SHM system provides real-time data on structural integrity, enabling quick responses to incidents and optimizing asset management. West Virginia faces a significant challenge, with 21% of its bridges classified as structurally deficient, three times the national average. Traditional biannual inspections are insufficient for proactive maintenance, especially given the aging infrastructure. By providing continuous monitoring, effective SHM systems can result in reducing lane closures, mitigating economic impacts, and helping prioritize repairs.

The prototype system installed on the East Huntington Bridge utilizes IoT-enabled wireless sensors, including accelerometers, tiltmeters, crackmeters, and displacement sensors. This configuration ensures data collection from critical structural members, providing insights into the bridge's condition and informing strategic maintenance decisions. The wireless system's design allows efficient installation and long-term reliability, with battery-powered sensors lasting up to eight years.

Key challenges included budget limitations, technology selection, and unforeseen installation issues. The project adopted a risk-based approach, prioritizing high-risk components and leveraging partnerships with consultants, vendors, and academic institutions. Lessons learned from the prototype phase emphasized the importance of scalability, workforce training, and innovative data governance to maximize benefits.

The SHM project aligns with SMART Program goals by improving safety, resiliency, and economic efficiency. The technology has shown potential for scaling to additional bridge types and locations across the state, supporting a comprehensive asset management strategy. Anticipated outcomes include reduced maintenance costs, extended infrastructure lifespan, and enhanced public safety through data-driven decision-making.

The executed SHM system fulfilled project expectations with only marginal changes to the protocol surrounding equipment installation and calibration. The overall concept and value of the SHM system were thoroughly demonstrated and should require minimal modification for successful at-scale implementation. This grant's documentation of technical successes and challenges will serve as a framework for other communities embarking on similar endeavors. Project personnel from this grant remained committed to documenting the lessons learned so that substantial progress can be made rapidly throughout the SHM field.

The proposed solution met our expectations in several key areas, including system functionality, data quality, and the ability to support long-term monitoring goals. Integrating real-time data collection, scalable architecture, and workforce training proved effective for immediate implementation and future expansion. The solution's adaptability and the collaborative approach between the agency, consultant, vendor, and academic partners created a strong foundation for success.

Advice to other communities: Start with a clear understanding of your infrastructure priorities and invest in internal capacity early through staff training and stakeholder coordination. Engage experienced partners, establish clear technical requirements, and allow room for innovation in your procurement process. Most importantly, plan for adaptability and expect some adjustment during implementation. Build in time and flexibility to refine the system as it goes live. A strong foundation in planning, communication, and training will significantly increase the success and sustainability of your SHM program.