Indefinite Preservation of Two Long-Span Movable Bridges Through the Use of Structural Monitoring

The Burlington County Bridge Commission's Perspective

Team Introductions

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Burlington County Bridge Commission

MISSION STATEMENT

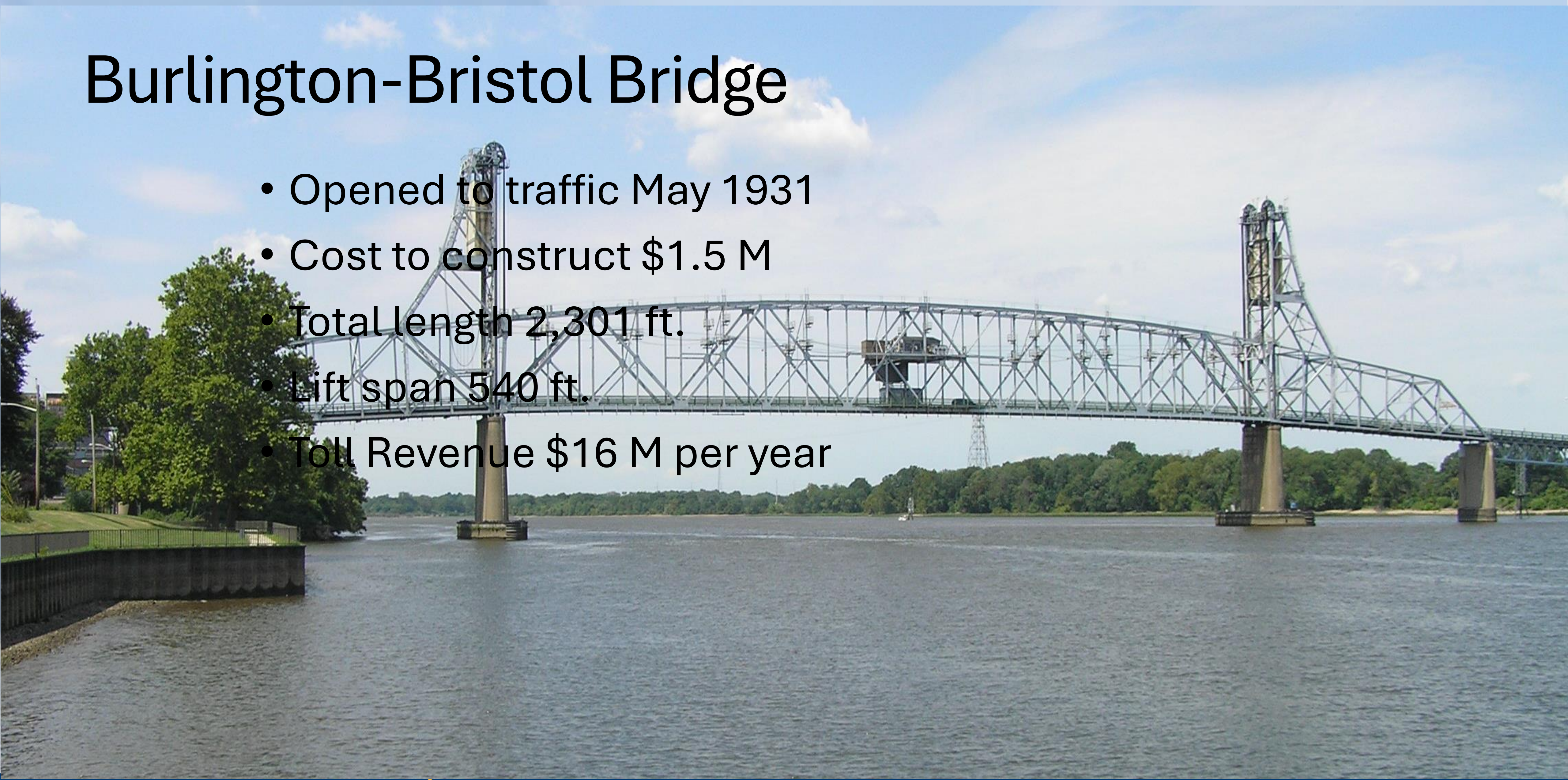
Provide Burlington County residents, commuters, and visitors with safe, accessible, and affordable bridges, roads and facilities. We are dedicated to serving our customers courteously, and to helping Burlington County prosper by saving taxpayers money through innovative financing programs and by fostering and assisting our neighbors in their economic development and community revitalization projects to ease the burden on local property taxpayers.

Tacony-Palmyra Bridge

- Opened to traffic – August 14, 1929
- Total cost (1928 – 1929) $4 million
- Total length 3,659 ft.
- Bascule span is 282 ft.
- Powering the bascule span are two rolling lifts each with a diameter of 14 ft.
- Toll Revenue - $34 M per year

Tacony-Palmyra Bridge – Ship Passing – Planet Mirrorball https://youtu.be/Iw1faP6jjKM

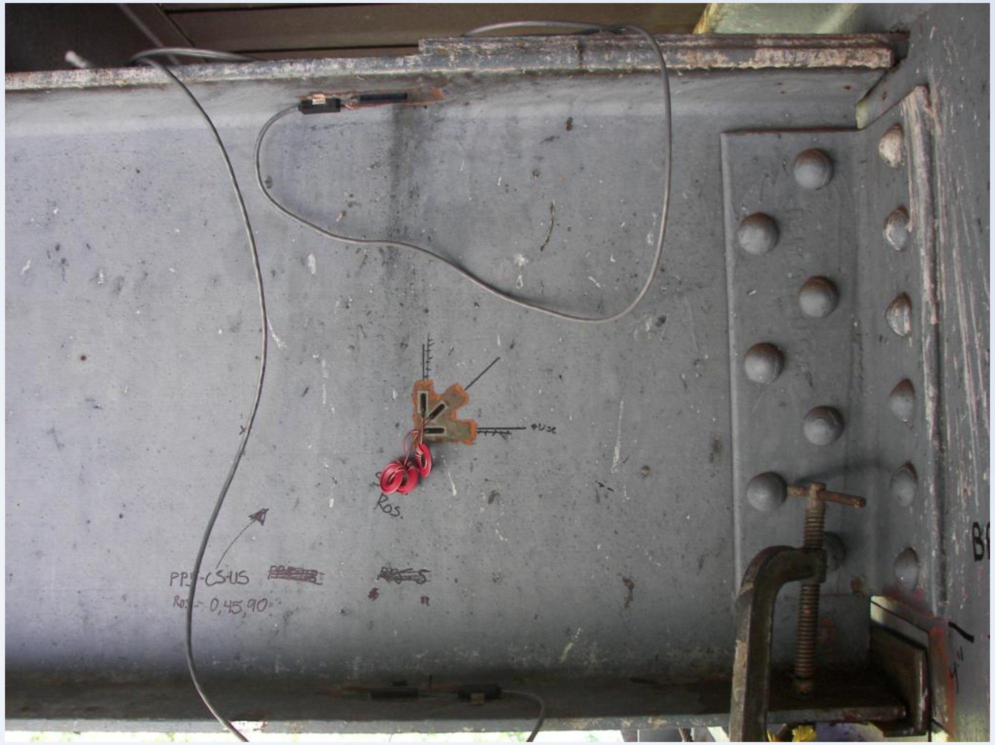
Burlington-Bristol Bridge



- Opened to traffic May 1931
- Cost to construct $1.5 M
- Total length 2,301 ft.
- Lift span 540 ft.
- Toll Revenue $16 M per year

Introduction to SHM - Drexel University

- Burlington Bristol Bridge
  - Fatigue monitoring and load testing in response to discovery of weld cracks
  - Strain results indicated root cause of cracks was not an urgent concern, and BCBC could retrofit the detail in a programmatic manner ($1M savings)
  - Seeing value in combining inspection, engineering, and instrumentation, BCBC was open to explore other beneficial investigations.



SHM Research and Ad Hoc Systems

- From 2008 through 2017, BCBC engaged Drexel to research and implement monitoring systems to address specific concerns of interest.
- Drexel / Rowan / Burlington County College were awarded an NSF grant to develop and implement a “Learning Bridge” program that used real structural responses from TPB in a classroom environment to teach engineering.

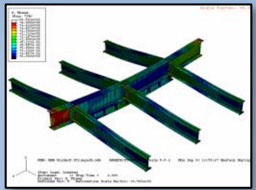
Burlington-Bristol Bridge

- Top chord strain investigation to identify overloaded trucks
- Ambient vibration study
- Laser height monitoring
- Operator house replacement

Tacony-Palmyra Bridge

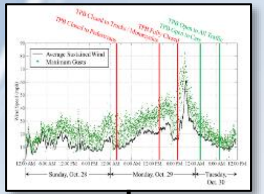
- Bascule span gusset replacement
- Ambient vibration study
- Site specific weather
- Expansion bearing performance of 540’ tied arch span

Unintentional benefits – SHM Use Cases

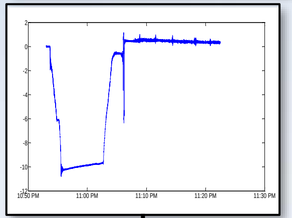


2008
Floor System Connection Issues
Load testing, Refined Modeling, Fatigue analysis

2010
Operating Rope Breakage
Rapid structural assessment, forensic monitoring



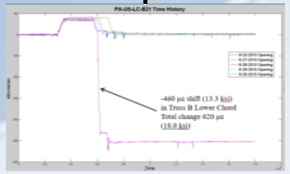
2012
Hurricane Sandy
Real-time monitoring, real-time wind speed



2014
Mechanical Issue
Forensic monitoring

2021
Tornado
Forensic monitoring

2017
Turnpike Bridge Closure
Live Load Assessment



2010
TPB Rivet Replacement
Forensic & Real-time monitoring

2011
Hurricane Irene
Virginia Earthquake
Real-time monitoring & assessment of bridges

2013
Grid Deck Replacement, Counterweight Constr.
Real-time monitoring of the bridge

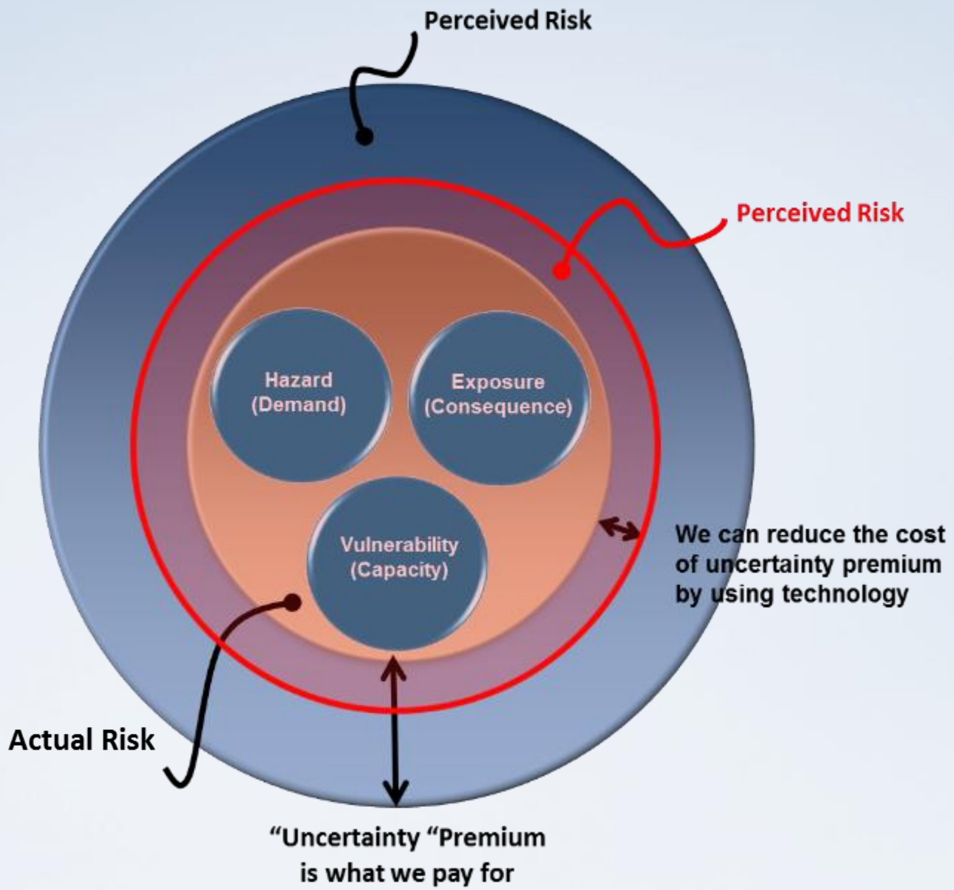
2016
BBB Operator House Replacement
Real-time monitoring & Assessment

2017
Delaware Earthquake
Assessment of bridges

2022
BBB & TPB Painting

Transitioning Research to Practice

- Systems installed by grad students began to show their age after 10 years of service
- BCBC was already planning IT infrastructure upgrades and wanted to include a permanent / robust SHM approach
- 2022 painting project was going to destroy most of the legacy instrumentation
- BCBC staff were interviewed to understand top concerns and to initiate a risk-based prioritization design



Risk Assessment – High Level Summary

Limit State	Hazard	Vulnerability	Failure Mode
Operations	Span Imbalance	Motor Wear	Mechanical Failure
	Inaccurate Position Indicators	Overcautious Operator	Long Openings
Safety	Ice on Roadway	Unaware Motorist	Traffic Accident
	High Winds	Large Trucks	Traffic Accident / Structural Impact
	Speeding Motorist	Vehicle Breakdown	Traffic Accident
Performance	Overloaded Vehicle	Overstressing of Component	Structural Failure
	Construction	Overstressing / Connection Slip	Structural Failure
	Unforeseen Event	Overstressing / Connection Slip / Bearing Unseating	Serviceability / Structural Failure
	Frozen Bearing	Cracking of Support Structure	Serviceability Failure
Maintenance	Low Power Supply	Motor Wear	Mechanical Failure
	Unlubricated Machinery	Motor Wear	Mechanical Failure

System Goals & Objectives (Functional Requirements)

Goal	Objective
Structural	• Establish and track the **performance of movement systems**
	• Provide stable, **long-term structural response baselines** for post-event comparison for fracture critical and primary load path elements
	• Establish and monitor **opening and seating signatures of lift & bascule spans**
Operations (Movable)	• Record metrics documenting operator **adherence to opening protocols** through recording of opening control panel button press durations and time stamps
	• Monitor **performance of electrical and mechanical components** during bridge moves
	• Provide operator with **situational awareness** via data
Maintenance	• Provide **measures of motor health** during openings
	• Monitor **expansion bearing performance** for total movement and friction values

System Goals & Objectives (Functional Requirements)

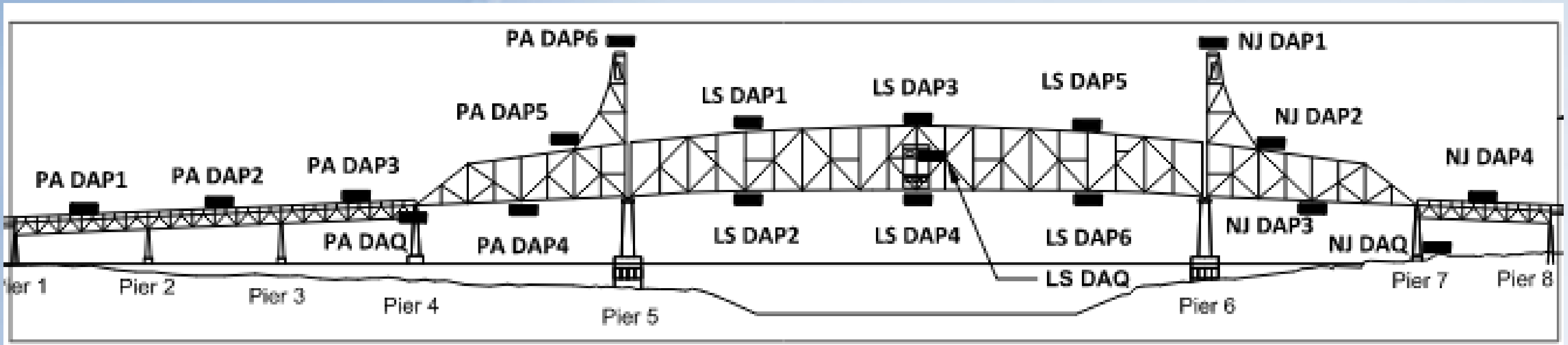
Goal	Objective
Safety	• Provide bridge operators and managers with **bridge under-clearance**
	• Provide alarms when **wind speed** has surpassed thresholds ▪ Unsafe for pedestrians and motorists ▪ Unsafe for bridge openings
	• Monitor roadway conditions and provide **notifications of hazardous conditions** such as snow, ice, or water and the need for deicing or other maintenance actions
	• Detect the **occurrence of vehicle-bridge and vessel-bridge impact** events
System Status / Watchdog	• Provide real time **status indicators** for all sensors, data acquisition systems, and SHM services
	• Provide **notification of sensor and communication outages** to engineering & BCBC IT Department

Goals & Objectives led to Performance Requirements

Example – Structural Performance

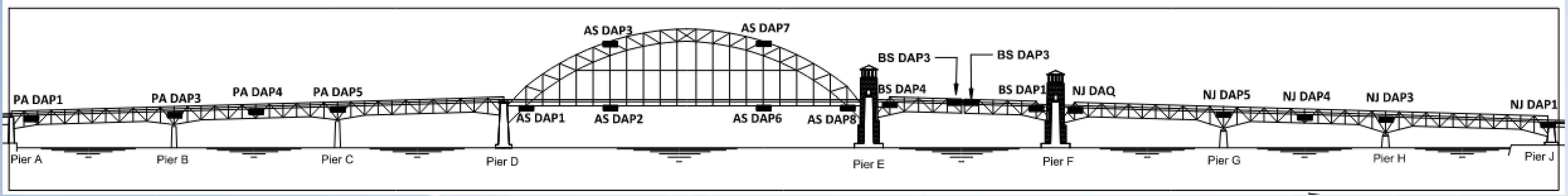
Objective	Performance Requirement
• Establish and track the **performance of movement systems**	• Provide status indicator and alerting when bearings do not allow free expansion/contraction of the bridge
	• Identify the impact of the expansion/contraction of the bridge on pier movements/motions
	• Identify ramifications of a frozen bearing on adjacent members
• Provide **long-term structural response baselines**	• Identify significant changes in primary load path force distribution
	• Track the distribution of live load
	• Develop statistical bridge signatures for anomaly detection

Burlington-Bristol Bridge – SMS Design



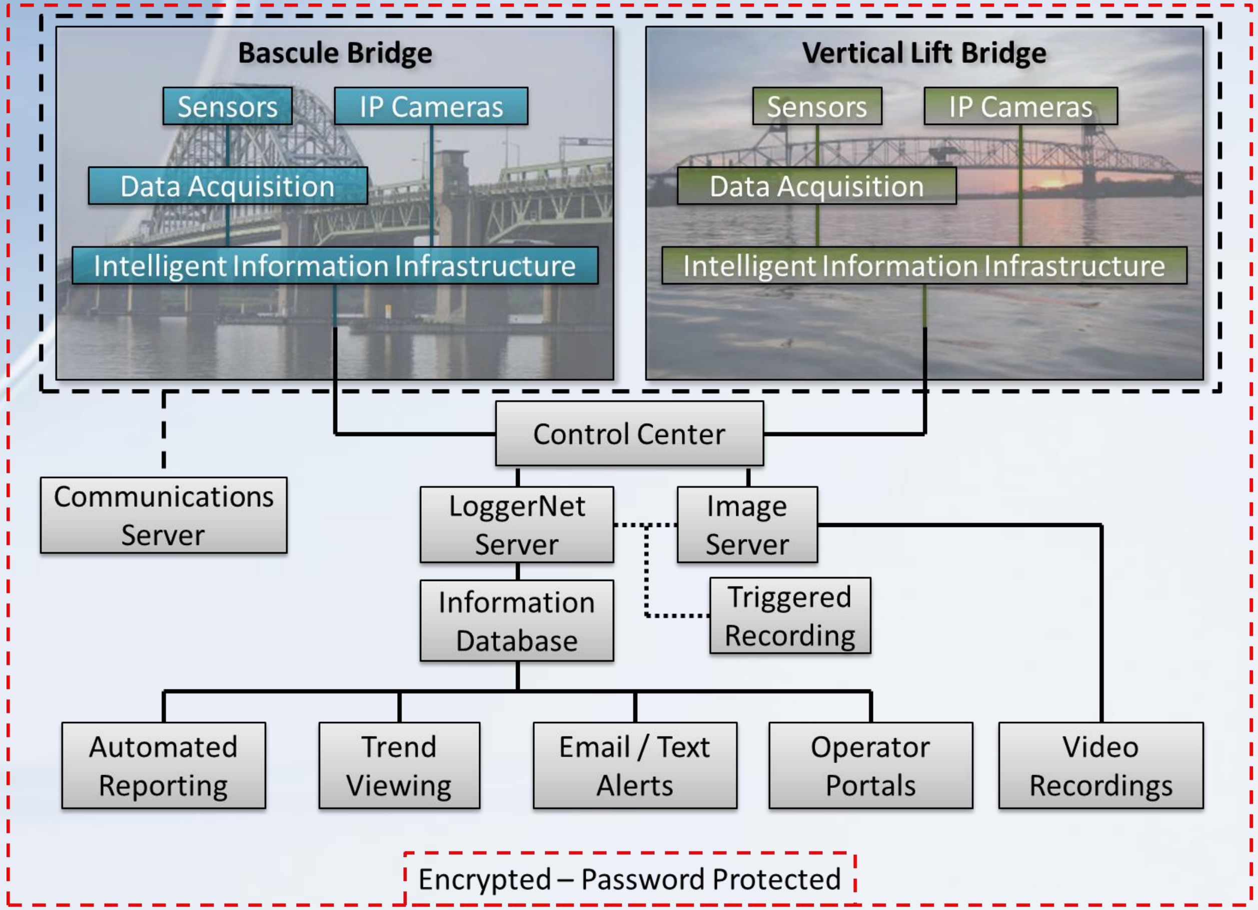
Structural Performance	No.	Operations	No.	Safety	No.	Maintenance
Strain Gauge	180	Incremental Encoder	1	Weather Station	1	Supported by all sensors
Displacement	12	3-Phase Monitor	2	Visibility	1	
Tilt Meter	8	Current Switch	13	Surface State	2	
Accelerometer	6	Current Transformer	6	Air Gap	2	
Strand Meter	8			Laser	1	

Tacony-Palmyra Bridge – SMS Design



Structural Performance	No.	Operations	No.	Safety	No.	Maintenance
Strain Gauge	168	Incremental Encoder	2	Weather Station	1	Supported by all sensors
Displacement	14	3-Phase Monitor	4	Visibility	1	
Tilt Meter	11	Current Switch	15	Surface State	2	
Accelerometer	4	Current Transformer	12	Air Gap	1	

Bringing it all Together

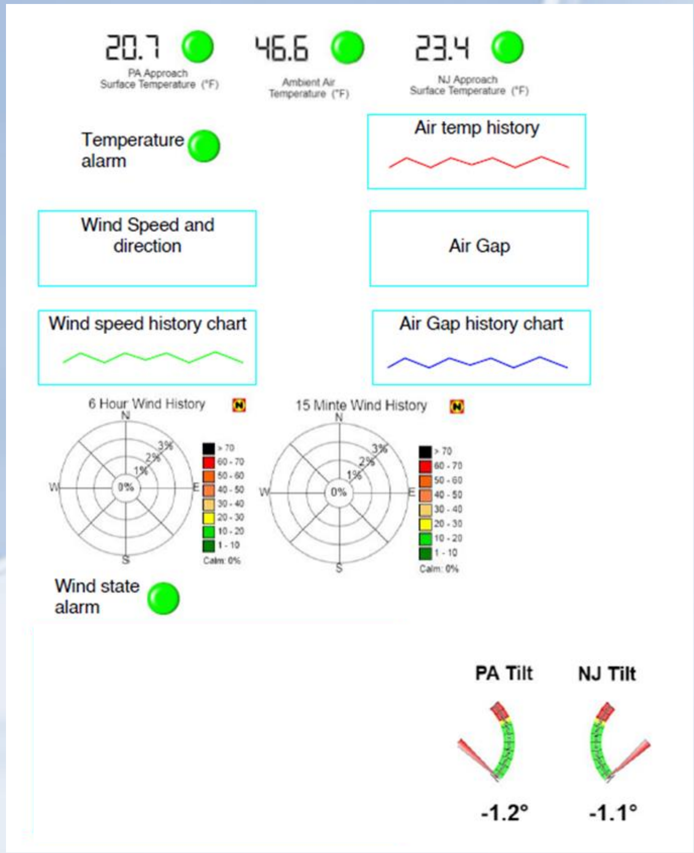


Project Execution

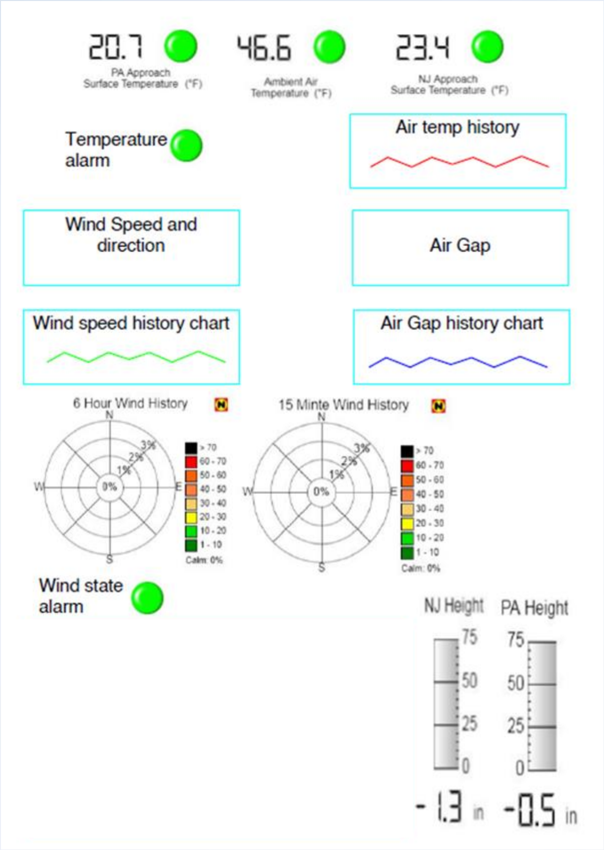
- Design Considerations
  - Integrate with the existing fiber optic network on each bridge
  - 10-year life of the system
    - Recognizing that there will be firmware and software upgrades along the way
  - Sensor sampling rates
    - 5-minute recording interval
    - 100 Hz data collection for openings & triggered events
- Procurement
  - Design-Bid-Build
    - Electrical Contractor (Carr and Duff) with SMS Specialty Engineer (BDI)
  - Construction Award: June 2022
  - Final System Acceptance: February 2024
  - Construction Cost at Completion: $3,357,500

System Delivery – Operator Dashboard

TPB Dashboard

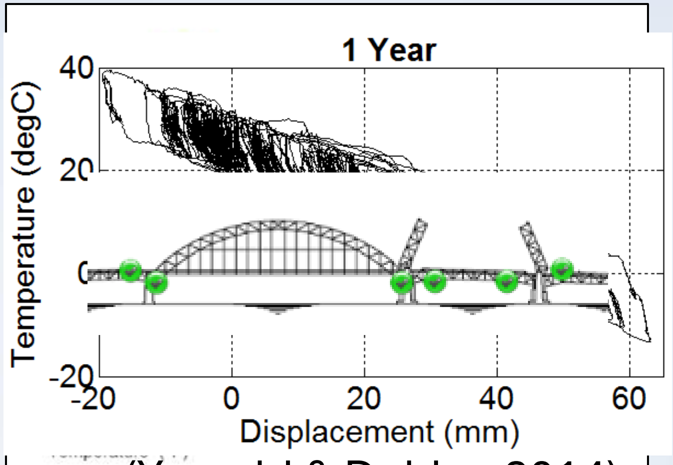


BBB Dashboard



Engineering Analysis - Alerting

- Three main types of alerts:
  1. Threshold exceedance
     a. Direct (based on clear acceptable criteria – speed, etc.)
     b. Indirect (based on engineering calculations)
  2. Anomalous response
     a. Statistical analysis (non-physics based)
  3. Sensor / communication failure
     a. “Watchdog”



(Yarnold & Dubbs, 2014)

Challenges - Operational

- General
  - Bridge openings constrained efficiency of installation
  - Commission was not able to support traffic control
  - Peregrin Falcons nesting with fledglings
- Burlington-Bristol Bridge
  - Work schedule at night due to traffic control
- Tacony-Palmyra Bridge
  - Rope access on arch span

Challenges - Contractual

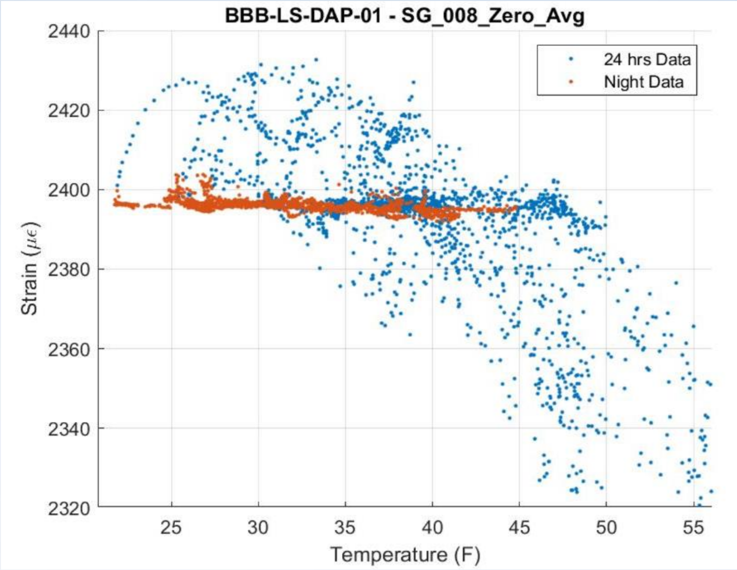
- Prevailing Wage for Specialty Engineer
  - NJ Department of Labor finding was unclear
  - Burlington County Bridge Commission Solicitor was conservative
  - Prevailing wage required
    - Impact schedule
    - Impacted the division of work between the GC and Specialty Contractor
    - Increased costs
- Required construction inspection of all work performed
  - Daily notification of when and where work was planned and executed
  - Resulted in some work NOT being inspected

Challenges – IT Hosting

- Alerts
    - Threshold Exceedance
- Data Storage
    - Dynamic data access
        - 5-days of bridge opening data to support forensic analysis
    - Data archive
        - Analysis of long-term environmental response
        - Analysis of structural performance
        - Legal retention policy
    - 80 GB per bridge per year
- Remote Access
    - Commission security system makes remote access difficult

Maintaining the System

- Early identification of maintenance issues
  - Watchdog Alerts
    - Power outage
    - Sensor Data Loss
  - Sensor Thresholds
    - Single sensor threshold alert
    - Sensor group alert
- Power interruptions (scheduled and unscheduled)
  - Monthly testing of generators (scheduled)
- Planned network upgrades
- Bridge painting & capital projects
  - Analysis of containment generated strains
  - Finite element analysis construction staging



Lessons Learned

- You are forging a long-term relationship with the engineer and possibly the IT support firm.
  - Forensic Investigations
  - Alert Threshold revision / refinement
  - Development of new functionality
  - Recurring annual costs for both.
- You will need a robust data network on bridge
  - Fiber optic network provides the needed bandwidth
  - Data retention policy – massive amount of data to store, query, and transmit to consultants.
  - Wireless can reduce some costs but comes with other challenges (operation and maintenance of radio-based battery powered hardware)

Thank you!