Lessons Learned from Data Fusion of Structural Health Monitoring (SHM), Digital Twin Simulation, and Weigh-In-Motion (WIM) Sensors for Evaluation Concrete Bridges

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Rutgers Infrastructure Monitoring and Evaluation (RIME) Group

Tuesday, April 4, 2-23

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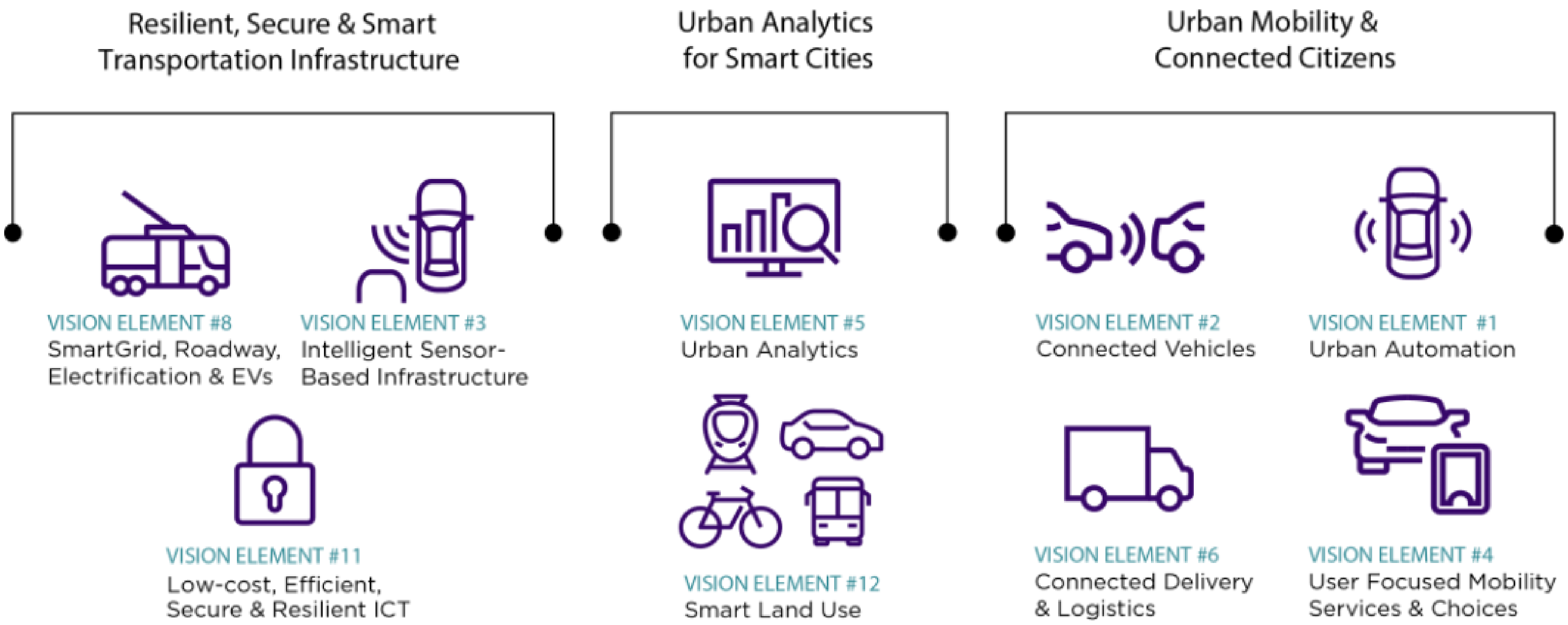


Outline

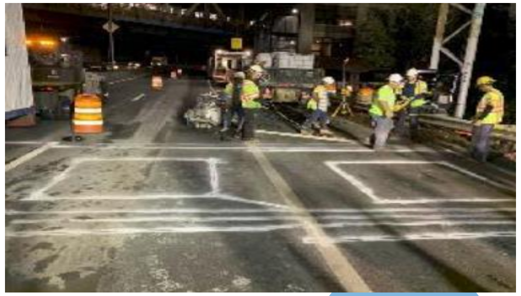
- Target Bridge Overview
- Wired vs Wireless Sensor
- Structural Health Monitoring (SHM)
- Digital Twins / Finite Element Modeling (FEM)
- Weigh-in-Motion (WIM)
- Lessons Learned

Target Bridge Overview

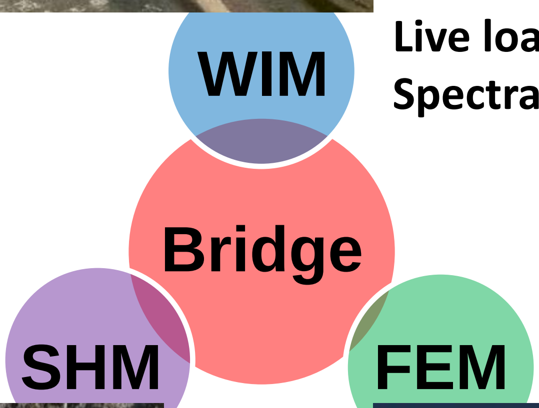
- Robert Moses built the bridge beginning in 1944.
- The Triple Cantilever: A unique structure with two levels of traffic and Promenade.
- Based on A.A.S.H.O. 1941 Specifications
- H20-S16 Vehicular Loading
- One of the most heavily traveled roadways in New York City
- ADT = 153,000 vehicles
- ADTT = 25,000 trucks

Project Overview

- Evaluation of the concrete bridge from data fusion.

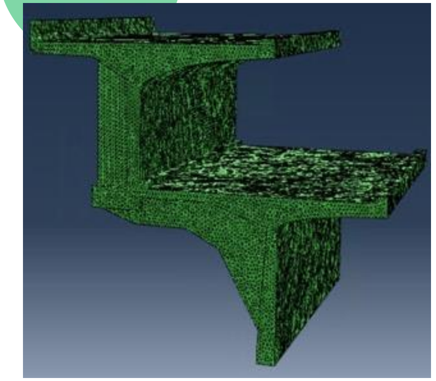


Live load Spectra



Structure Response

Predict Service Life



SHM Data Collection (acceleration, strain, tilt angle) → **Data Processing & Analysis** (frequency & strain) → **FEM Calibration** (using strain & frequency)

Live loads from WIM Sensors and System (current and future live loads) → **FEM Calibration** (using strain & frequency); → **Reliability-Based Analysis**

Reliability-Based Analysis → **Reliability index over time** (service life prediction)

Wired vs Wireless Sensors

Wired sensor

- ***Pros:*** *Reliable data collection. No battery replacement effort is required.*
- ***Cons:*** *Hassle to lead all the cables. Cable might obstruct.*

Cable?

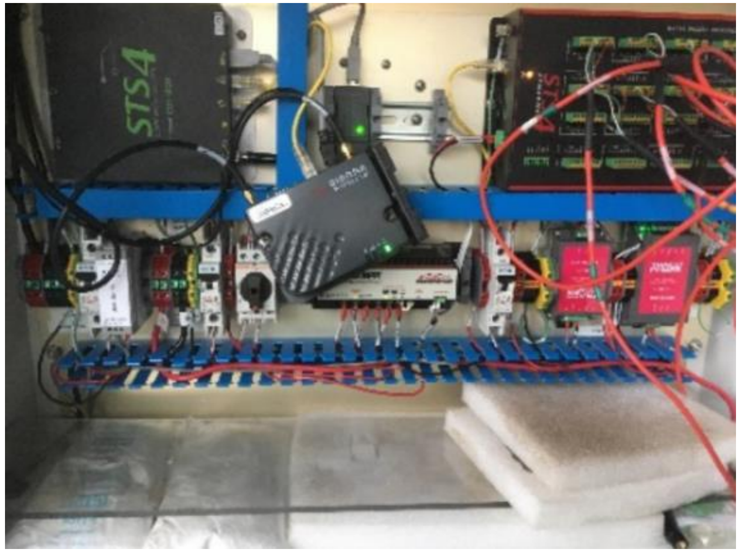
Closure?

Power?

Battery?

Wireless sensor

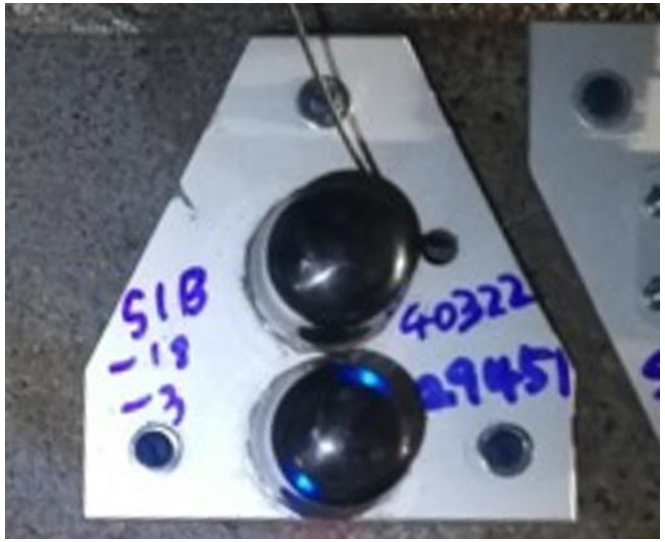
- ***Pros****: Easy to install and maintain. No obstruction to the traffic due to the cable.*
- ***Cons****: Periodic battery replacement is required.*

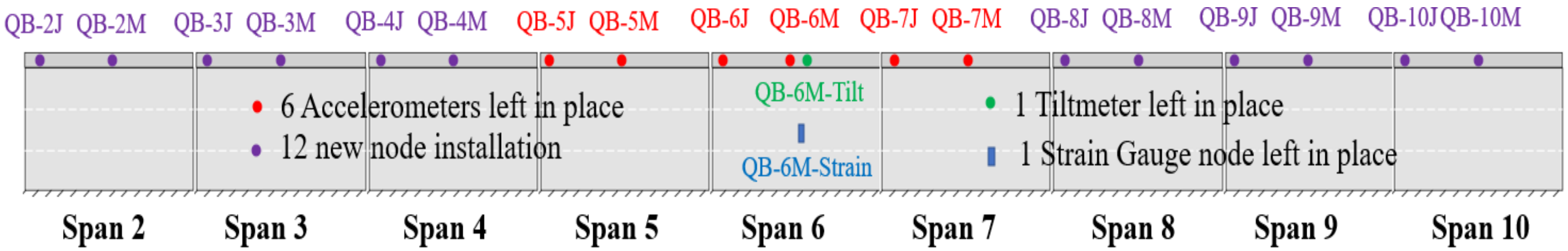


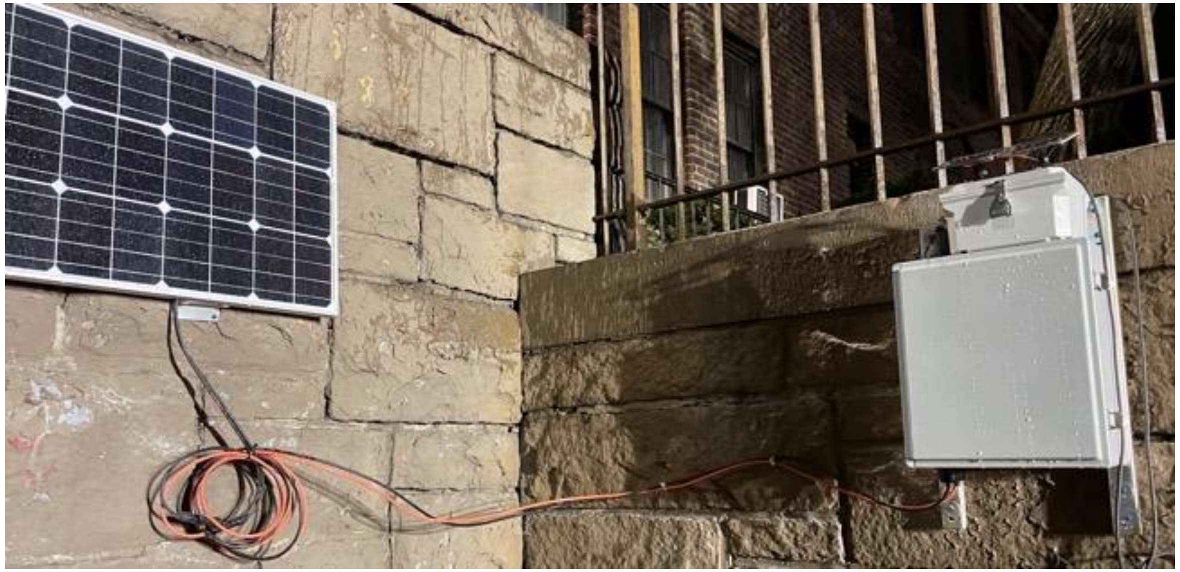
Wireless Sensor Network

- Accelerometer
- Tiltmeter
- Strain Transducer

- **Battery**: 2wk(3 Ch) ~ 1m (1 Ch) @ 128 Hz
- **Range**: up to 1.25 mile (typical 150 ft)
- **Data Collection Frequency**: 1 hr ~ 4096 Hz
- **Collection Mode**: periodic, burst, thresholds



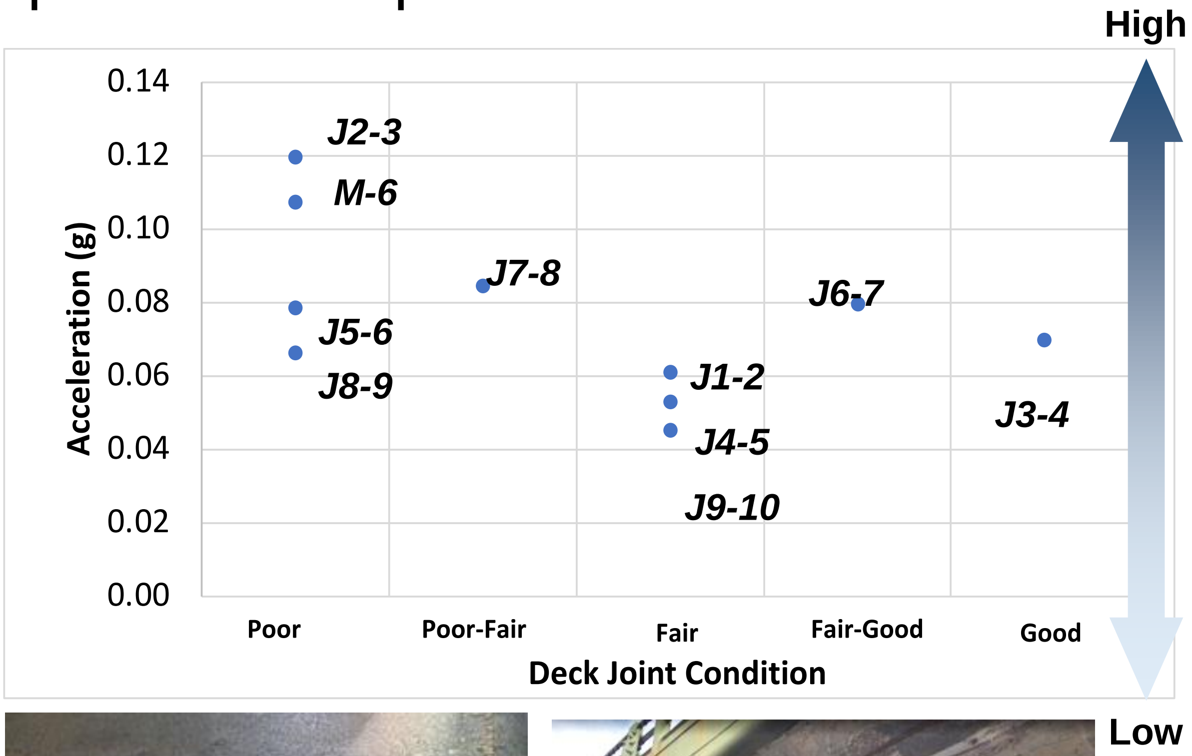




Evaluation of Deck Condition using Acceleration

- Mean of maximums acceleration vs. qualitative inspection

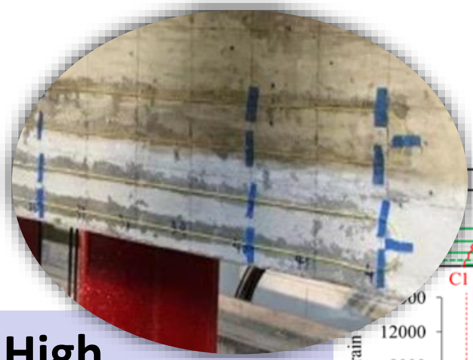
Joint	Inspection	SHM acceleration (mean of maximums)
Joint 1-2	Fair	0.0610
Joint 2-3	Poor	0.1197
Joint 3-4	Good	0.0697
Joint 4-5	Fair	0.0530
Joint 5-6	Poor	0.0787
Midspan 6	Patches	0.1073
Joint 6-7	Fair to Good	0.0797
Joint 7-8	Poor to Fair	0.0847
Joint 8-9	Poor	0.0661
Joint 9-10	Fair	0.0452
Joint 10-11	Fair	N/A



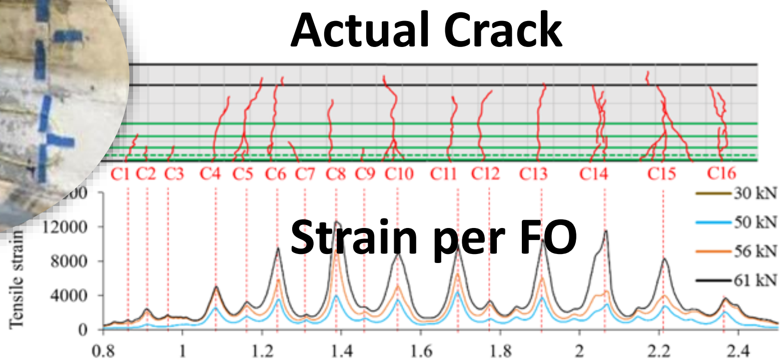
- *This result indicates that the structure may have further deterioration in regions that cannot be visually inspected.*

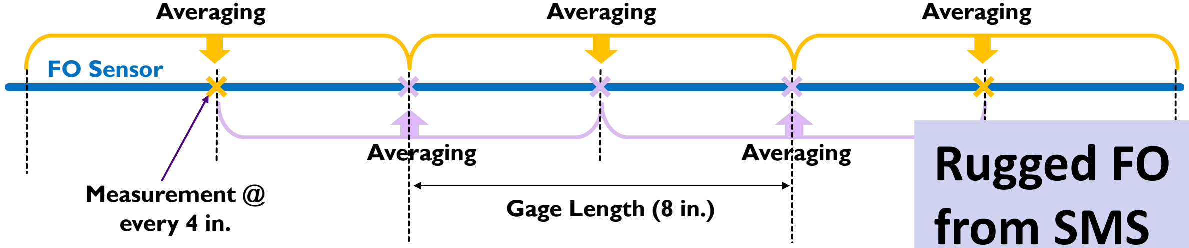
Distributed FO Sensor

- Rugged FO Sensor vs.
  High Resolution FO Sensor
  - Long measurement range
  - Rugged jacket for harsh environment
  - Spatial resolution at every 4-in.

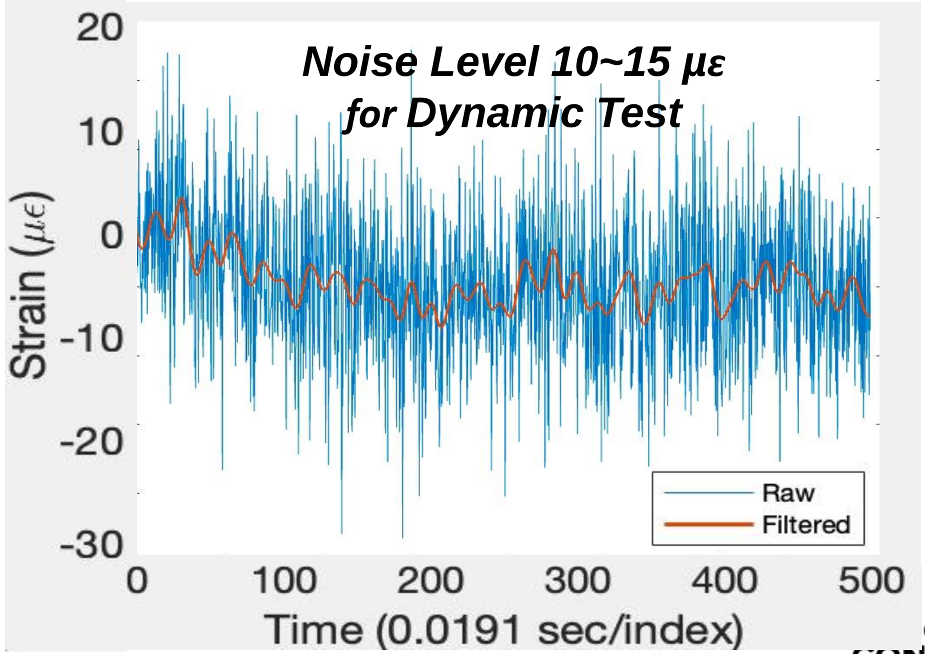


High resolution FO



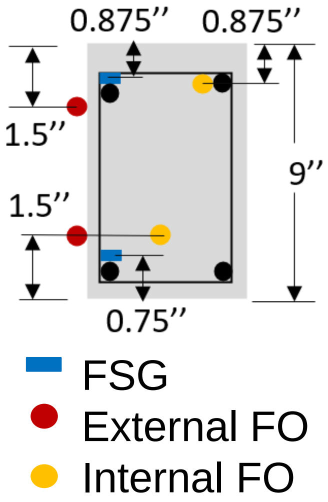


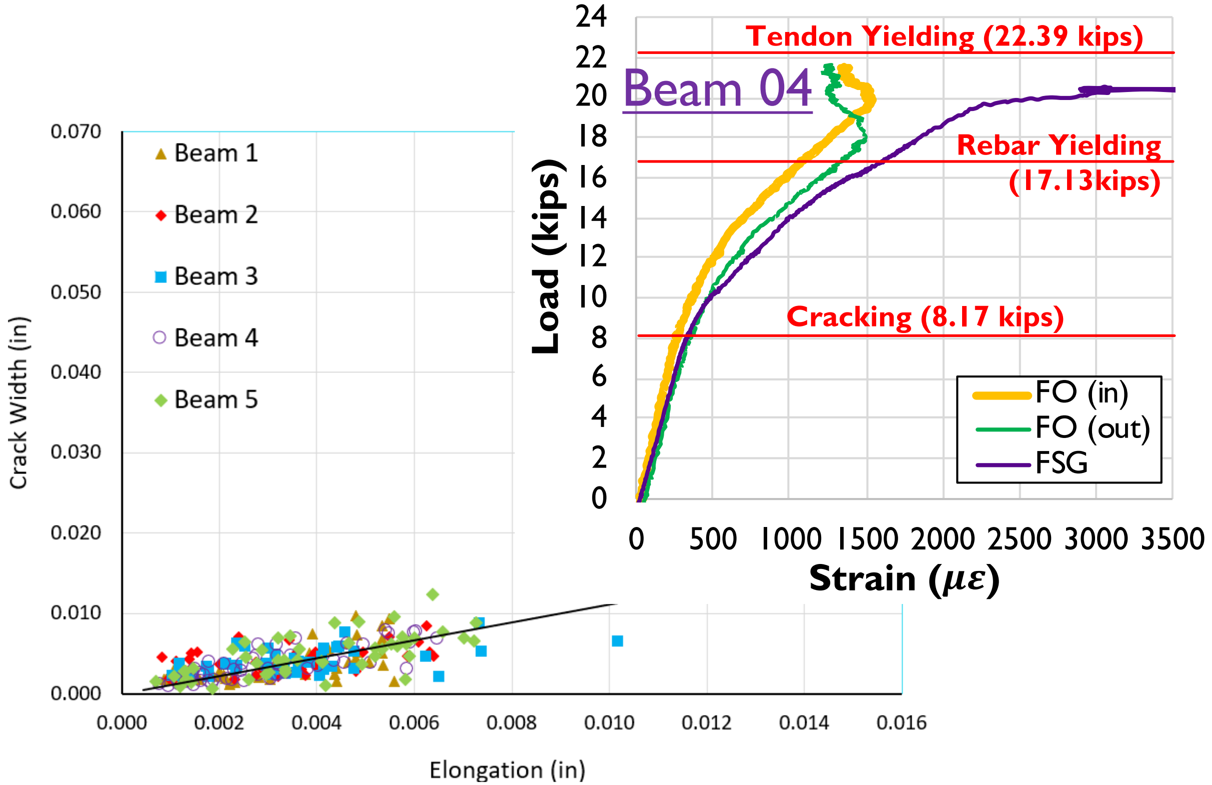
Rugged FO from SMS



DFO Validation

- DFO and FSG were compared.

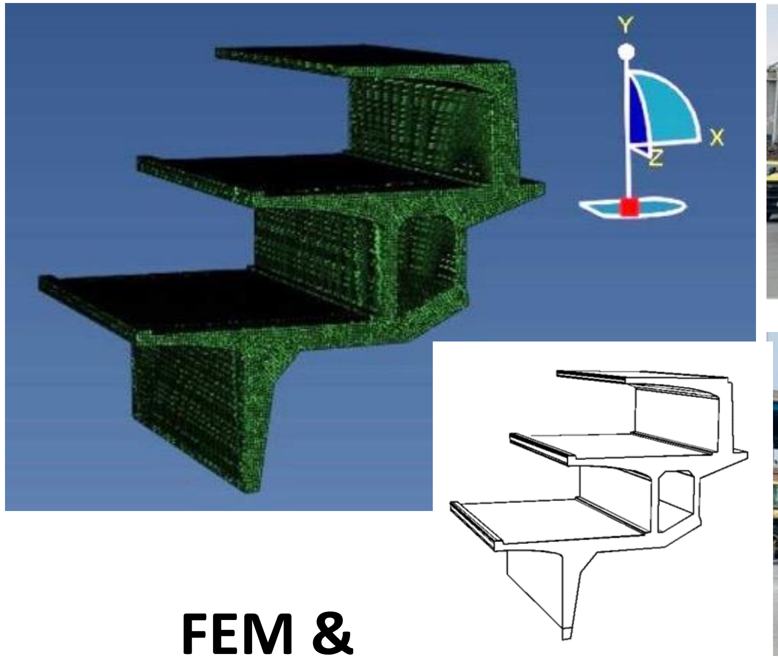




- **Before cracking**, the strains recorded from both sensors match well.
- **After cracking**, most of the FSG strains are higher than the FO strains at the same load level. This phenomenon is attributed to bonding issues.
- Therefore, DFO has a potential use for long-term monitoring in detecting alarming strain levels.

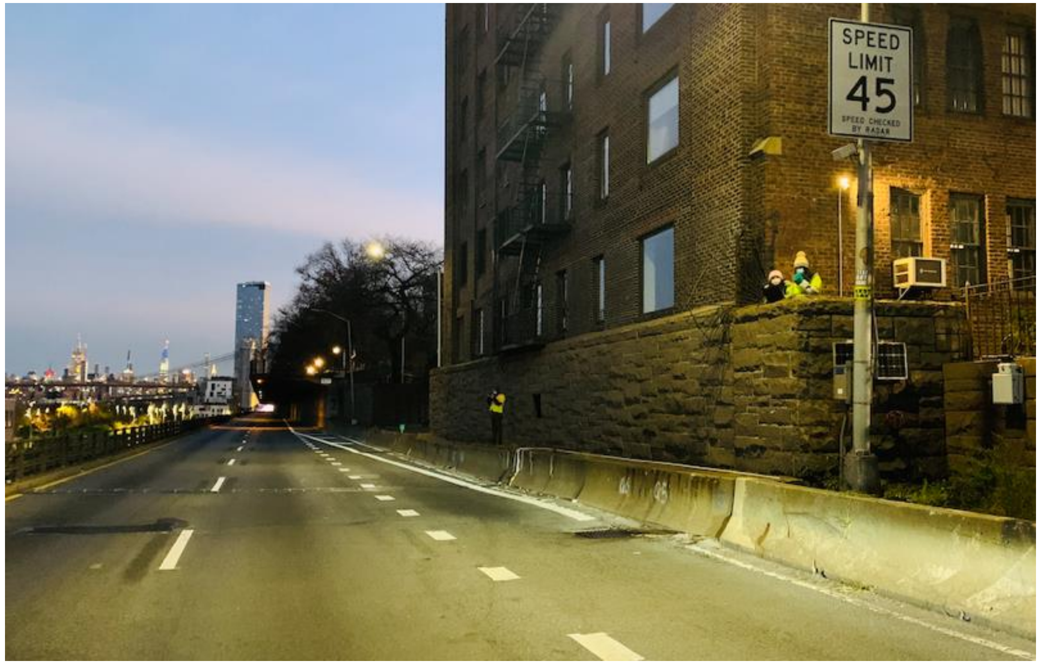
Digital Twins and Finite Element Modeling

- Target spans were modeled using 3D FEA Tool, ABAQUS
  - Material properties = existing inspection load rating reports and as-design values.
  - Static and dynamic tests were performed after closing entire bridge.



FEM & BrIM

Calibration Trucks



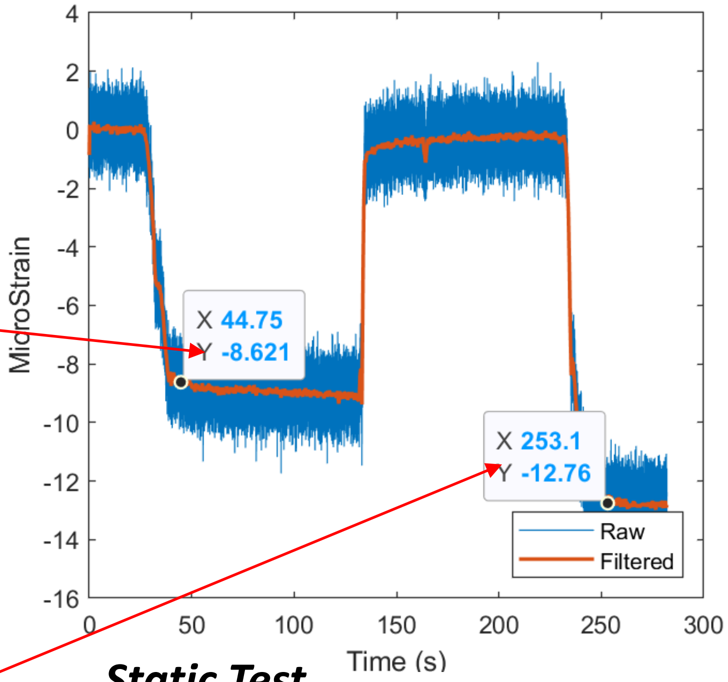
Calibration / No Traffic

FEM Calibration: Fusion of SHM and FEM

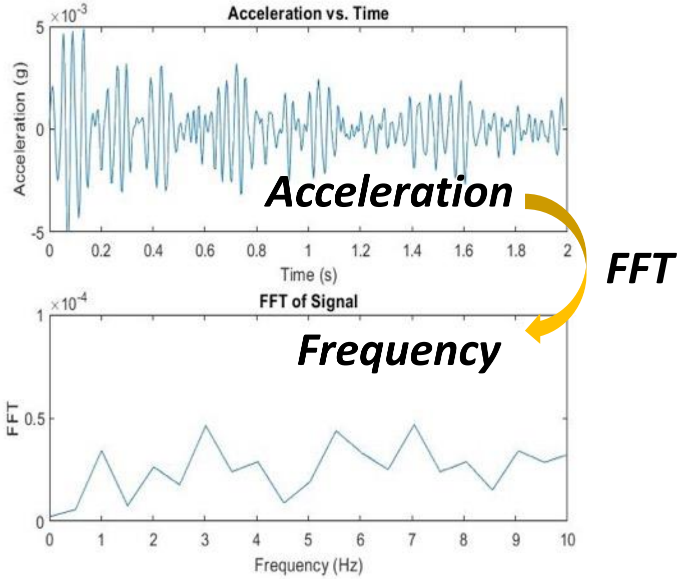
- FEM was calibrated using two trucks (Class 9 and Class 7)
- Free vibration was used to determine the natural frequency.
- Natural frequency and strain data were also used for calibration.

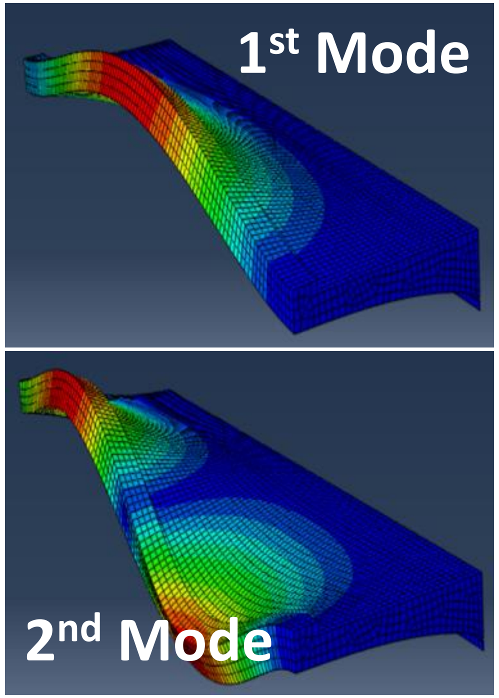
Class 9 = 8.62 με

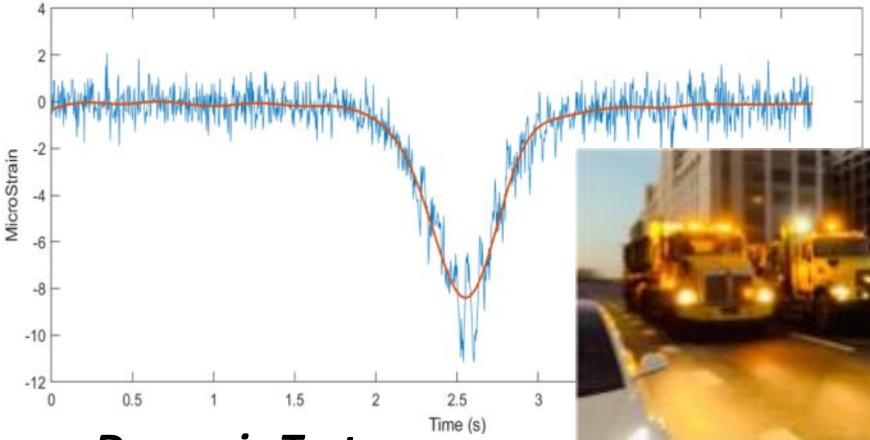
Class 7 = 12.76 με



Static Test







Dynamic Test (side-by-side)

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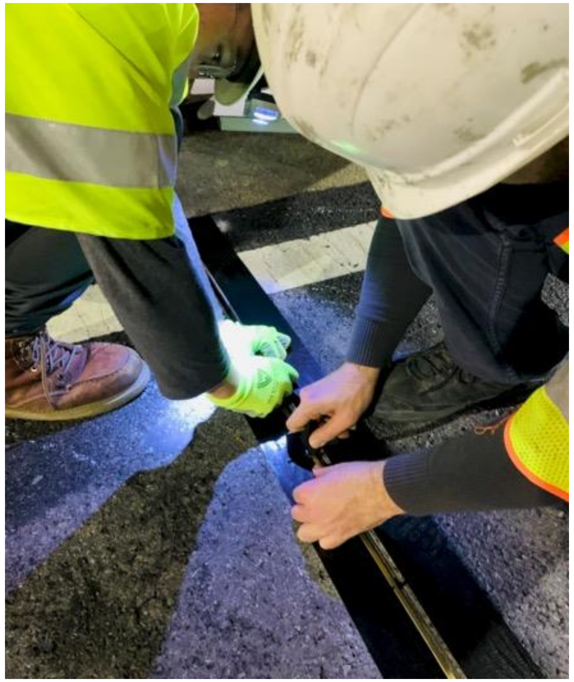
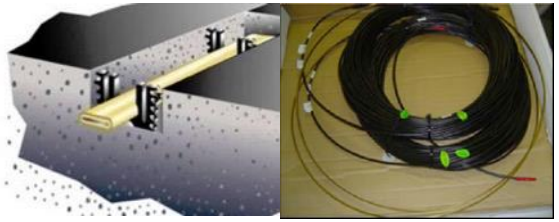
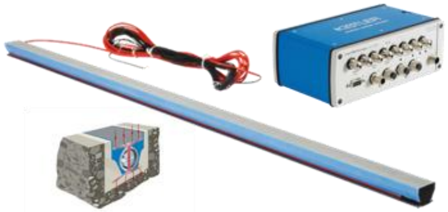
Weigh-In-Motion (WIM) Installation

- **Two types** of WIM sensors
  - Live load spectra using PVDF & Quartz

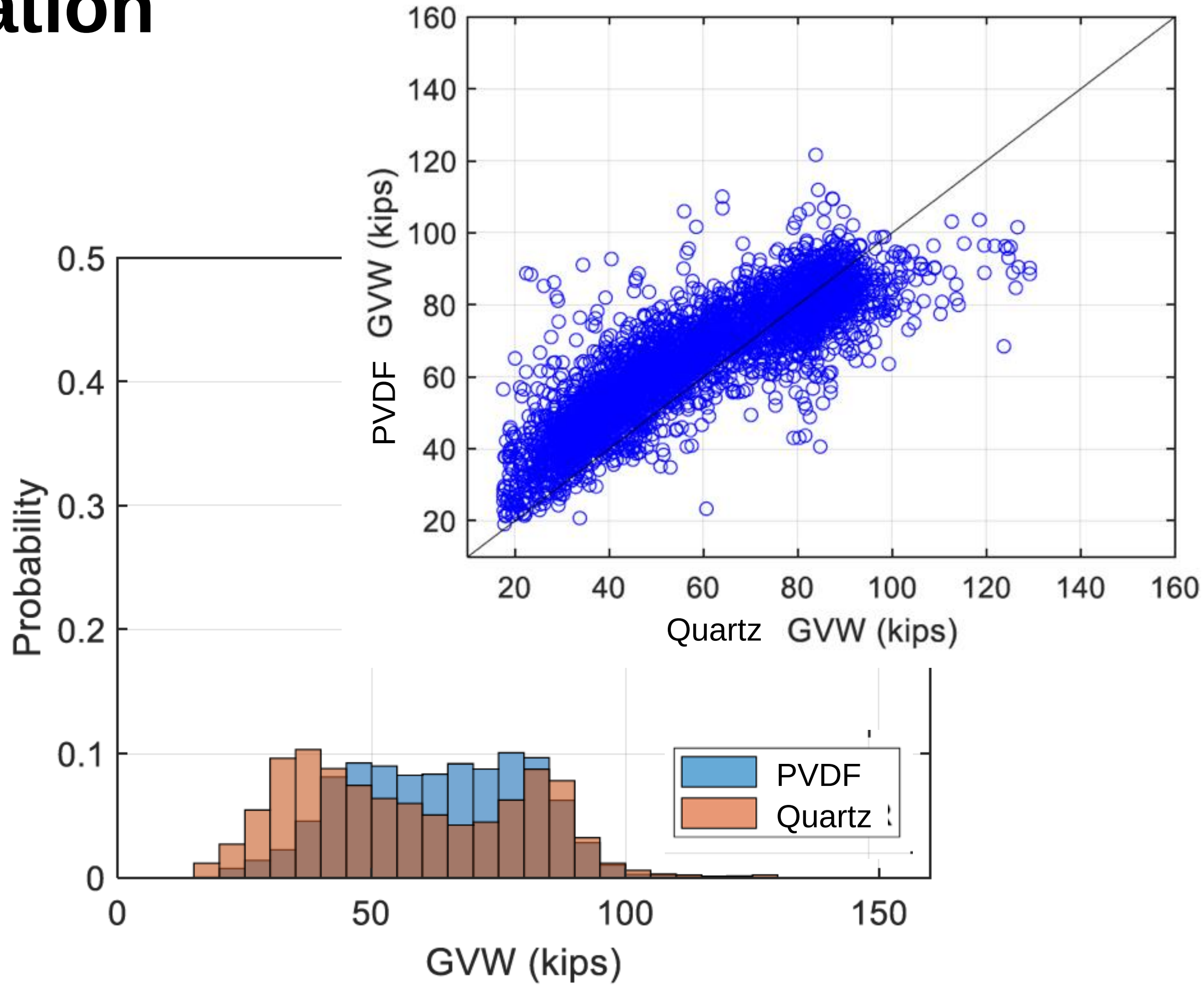




PVDF Sensors



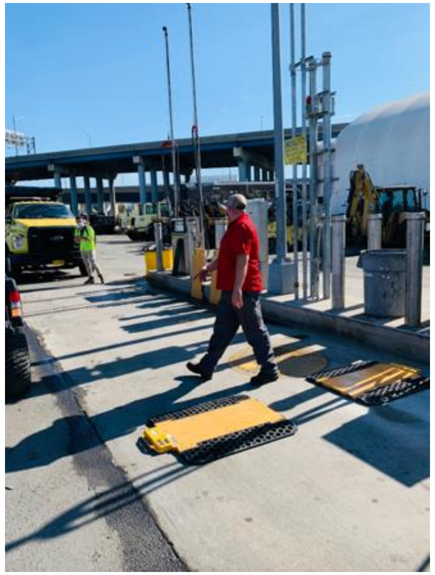
Quartz Sensors



- PVDF sensors are less accurate than Quartz.
- PVDF overestimates for lighter truck and underestimates for heavy trucks.

WIM Calibration

- Five (5) trucks were used for calibration of Quartz sensors
  - 2 x Class 9, 1 x Class 6, 2 x Class 5

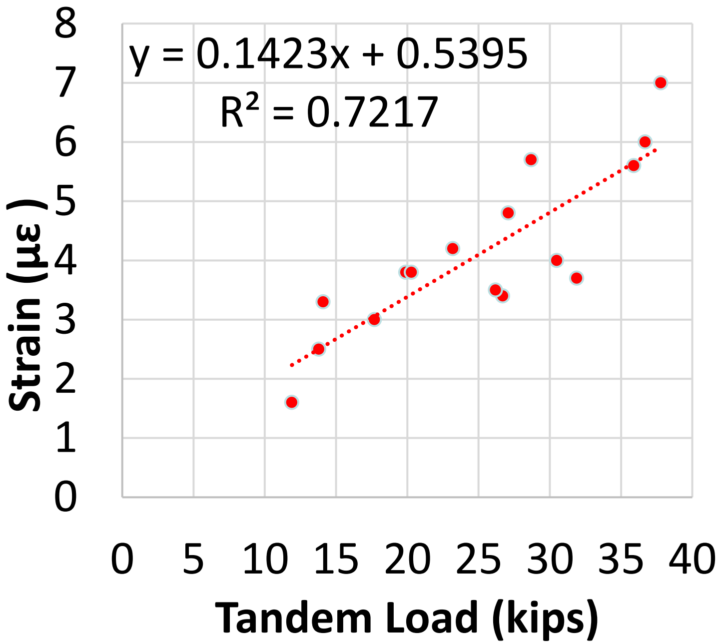


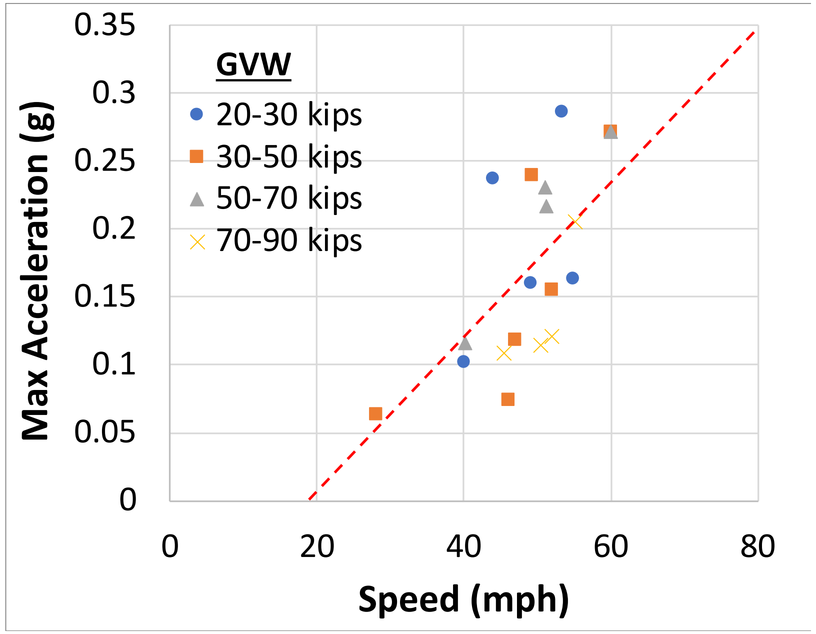
Standards	GVW	Single	Tandem	Wheel
Quartz Results (maximum error, %)	4.4	12.4	7.9	21.9
Compliance (%)	100	100	100	99
ASTM Type III Target	6	15	10	20

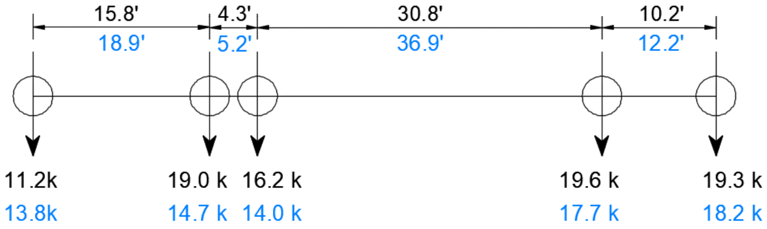
Data Fusion: WIM and SHM

- Regular traffic was used to correlate between SHM and WIM.
  - SHM provides strain and acceleration.
  - WIM provides weight and speeds.

- Weight is directly correlated with strain.
- Speed is directly correlated with acc.







Lessons Learned

- Wireless Sensor
  - Communication range & battery and power consumption
- Rugged DFO
  - Suitable for bridge application and reliable for long-term
- Quartz sensor
  - Highly accurate data for live load spectra
- Fusion of SHM and FEM
  - Calibrate the FEM for predicting future responses and remaining service life.
- Fusion of SHM and WIM
  - Load and resistance of the bridge
  - Understand the factors that affect the structure response.
  - Weight is the key factor for the strain while speed is the key factor for the vibration.

Acknowledgement

- Special Thanks to
  - **NYCDOT** and their engineers, Dawn Harrison, Tanvi Pandya, Paul Schartz, Shane Trotman, Roly Parocco, Rashid Md, and Sunil Desai for their technical support and coordination, and Jess O'Brien and Joseph Brucculeri to provide calibration trucks.
  - **Triple Cantilever Design Joint Venture (TCDJV**) and their engineers, Jeff Carpenter, Rajendra Navalurkar, Andrea Zampieri, Zia Islam, and Amir Zahlan, for their support.
  - **C2SMART/USDOT** Federal Tier I University Transportation Center, with **Shri Iyer as Exec. Director,** for their financial support and excellent coordination/management of the project, research associate, Peng Lou and Wassim Nasreddine, graduate students, (Daniel Ortiz, He Zhang) with the RIME Team to implement new technologies, and
  - **Kistler's** Jess Helmlinger, James Harkin, Alex Schumacher, and Christoph Klauser for their technical support and assistance.
  - Structural Monitoring Solution (SMS)'s Terry Tamutus for their technical support for the rugged FO sensors.

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