William W. Hay Railroad Engineering Seminar Series

"Structural Engineering Research for Railroad Bridge Performance Assessment"

James M. LaFave, PhD, PE

Associate Professor & Chair of the CEE Structures Group

Department of Civil & Environmental Engineering (CEE)

University of Illinois

Friday, November 2nd, 2012

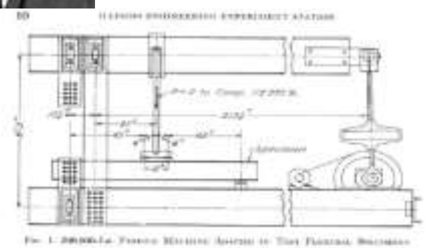
Facilities

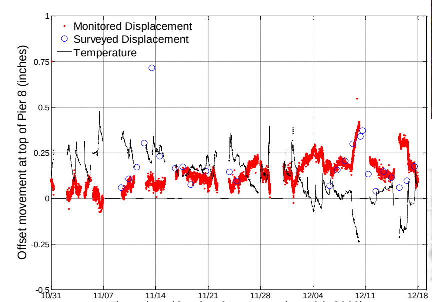
Railroads

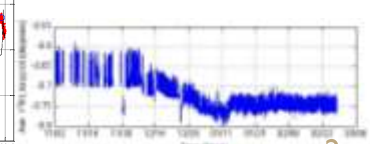
Introduction – 100 Years of Railroad Bridge Research at the University of Illinois

1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020

FIG. 7. VIEW OF TESTING MACHINE WITH AUXILIARY APPARATUS TESTS IN ALTERNATE TENSION AND COMPRESSION







Abrams

Andrawes

Duarte

Elnashai

Fahnestock

Gardoni

The University of Illinois at Urbana-Champaign

Department of Civil and Environmental Engineering

Structural Engineering

Kuchma

LaFave

Lopez-Pamies

Masud

Paulino

Song

Spencer

Research Interests of the Structures Faculty

- Buildings, bridges, and other civil structures
- Steel, concrete, masonry, wood, composites
- Design codes and procedures
  - Serve on specification committees on steel, concrete, masonry
- Earthquakes, wind, blast, fire
- Experimental testing
- New construction, repair and retrofit
- Soil-structure interaction
- Structural stability and collapse
- Large-scale numerical simulations
- Finite and boundary element methods
- Computational mechanics algorithms
- Fracture mechanics and fatigue
- Optimization of structures
- Fluid-structure interaction
- Functionally graded materials
- Structural health monitoring
- Structural control and smart materials
- Risk and reliability
- Inverse analysis problems

In 2012, from the very practical …
to the research frontier!

Some Examples of Recent Illinois CEE Structures Research Related to Railroads

- **Prof. Dan Kuchma → "Testing for Strength Evaluation of Aging Concrete Railroad Deck Beams"**
- **Prof. Larry Fahnestock → "Improved Bolted Connections for Special Trackwork (w/ a Focus on Crossing Diamonds)"**
- **Prof. Bill Spencer → "Wireless Structural Health Monitoring of the *Government Bridge*"**
- **Prof. Bassem Andrawes → "Improved Concrete Railroad Tie Design and Performance"**
- **Prof. Jim LaFave → "Bridge Performance Assessment Using Simplified Field Monitoring"**

AAR Technology Scanning
University of Illinois at Urbana-Champaign (UIUC)

"BRIDGE PERFORMANCE ASSESSMENT USING SIMPLIFIED FIELD MONITORING"

Background:

- Ongoing need for repair or replacement.
- Limited access to bridges during train traffic.
- Year-to-year degradation cannot be measured.

Improving bridge management by:

- Measuring changes in bridge performance.
- Using sensors to collect data that can become part of the bridge record.
- Assisting bridge repair prioritization with data.

STRUCTURAL ENGINEERING

RAILTEC

Background	Preliminary Work
Motivation	Monitoring Approach
Bridge Field Experiments	Displacement Measurements
Analysis	Displacement Estimation
Other Field Results	Steel Bridges
Discussion	Conclusions

Preliminary Work – Survey-Based Study & Railroad Bridge Classification

2010-2011: Railroad Structural Engineering – Survey of Current Research Needs

Conducted at the University of Illinois to determine current research interests & needs related to railroad bridges and structural engineering.

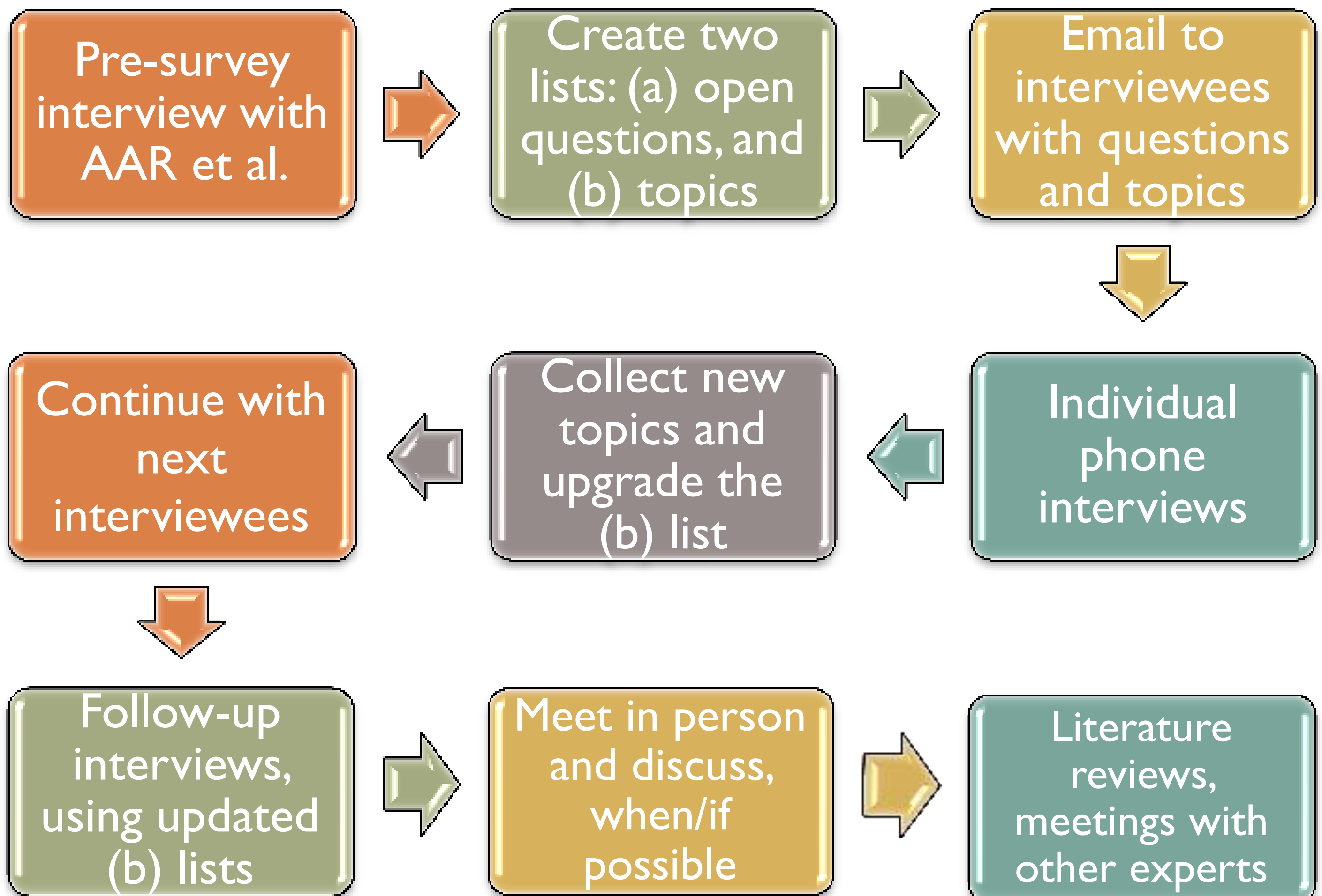
Motivation

- In October of **1987**, the U of I had hosted the "**National Workshop on Railway Bridge Research Needs**".
- To identify the most important research topics of the day regarding railroad bridges and structural engineering.
- **Related research activity** was limited between 1970 and 1990, but it **increased** considerably between 1990 and 2005 (Byers and Otter, 2006).

Objective

- To help **prioritize** railroad bridge structural engineering research topics, as identified by members of the North American railroad bridge structural engineering community.
- 20+ years now after that workshop, some sort of a **new "meeting"** has been needed to best identify and prioritize current research needs.

Survey Methodology



Survey Population

Representative Group from Both the Railroad Bridge and Structural Engineering Communities			
Work experience (3-60 years)	Industry (Government, Engineering Firms, Railroads)	Field of Expertise (Design, Construction, Rating, Management)	Involvement (AREMA, other Engineering Societies)

Results – Current Research Needs

Research Areas Proposed

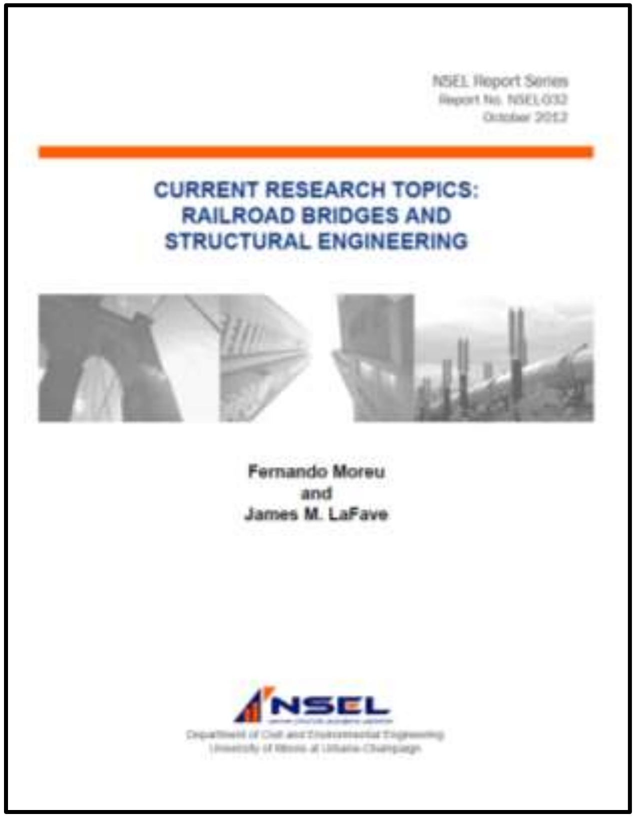
22 Main Research Topics

Related Literature Reviews

New Topics Collected

6 Top Current Research Topics

https://www.ideals.uiuc.edu/handle/2142/34749



RT&S Magazine (September 2011)

2011 TOPICS	2011 RANKING
Deflection measurements	1
High speed trains	2
Long-span bridges	3
Approaches	4
Longitudinal forces	5
New design loads	6

1987 TOPICS	1987 RANKING
Field stress measurements	1
Investigate impact factor and effects	2
Fatigue life	3
Determine longitudinal forces	4
Develop better analysis for design	5
Timber non-destructive testing	6

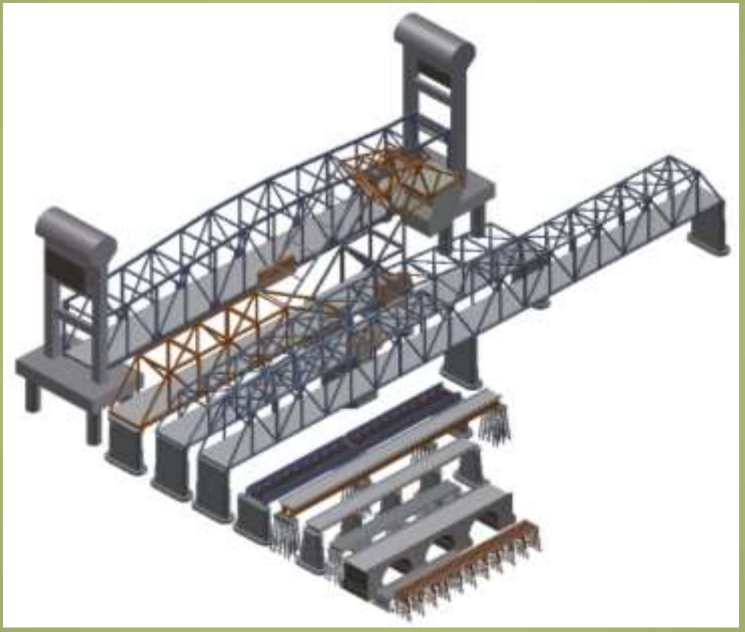
AAR Technology Scanning -- University of Illinois at Urbana-Champaign
"BRIDGE PERFORMANCE ASSESSMENT USING SIMPLIFIED FIELD MONITORING"

2011

Which parameter should be measured for structural monitoring assessments of railroad bridges?

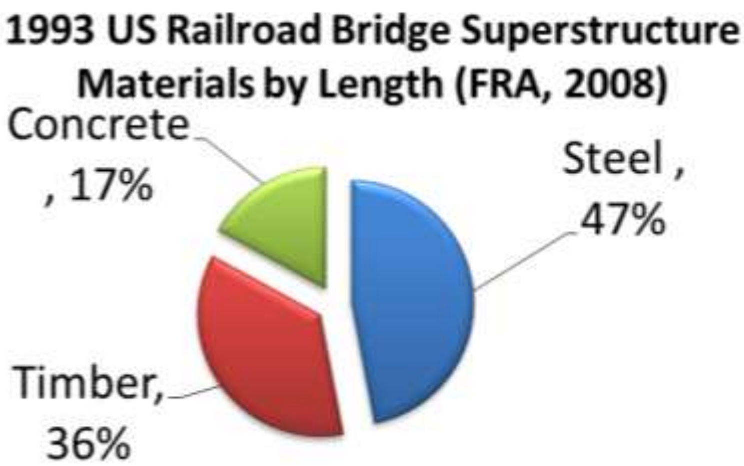
TOPICS	RANKING
Deflection measurements	1
High speed trains	2
Long span bridges	3
Approaches	4
Longitudinal forces	5
New design loads	6

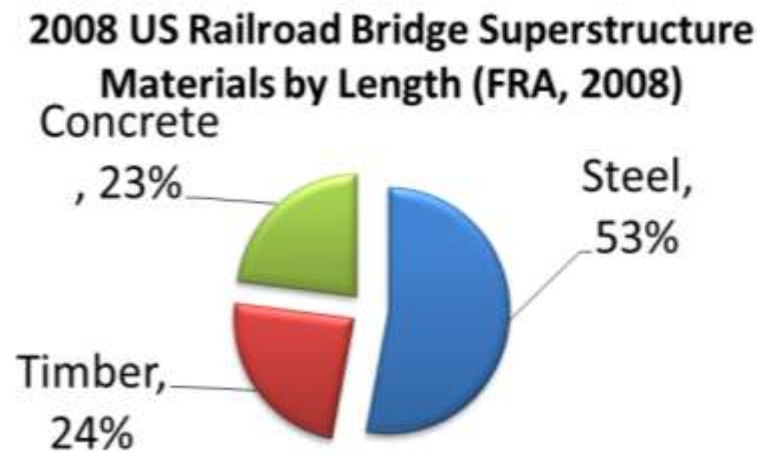
Which part of the bridges should be monitored? What to monitor?



U.S. Railroad Bridge Classification

Current Railroad Bridge Inventory





- Significant decrease in timber railroad bridges
- Replacement of timber railroad brides is a priority (40% of bridge "maintenance" budget for some Class I railroads today)
- Importance of railroad bridge classification for bridge maintenance and railroad management in general
- Other references: Parsons Brinckerhoff Quade & Douglas, Inc. (1980), Mee et al. (1994), AREMA Committee 10 Structures Maintenance & Construction (2008), and the International Heavy Haul Association (IHHA, 2009).

FRA (2008). "Railroad Bridge Integrity Working Group Upgrade". RSAC, Railroad Bridge Working Group, Railroad Bridge Working Group Report: Final Report and Recommendations, Presentations, September 10.
Parsons Brinckerhoff Quade & Douglas, Inc. (1980). "Track and Bridge Maintenance Research Requirements". U. S. Department of Transportation, Federal Railroad Administration. Report Number FRA/ORD-80/11, March.
AREMA Committee 10 Structures Maintenance & Construction, (2008). AREMA Bridge Inspection Handbook, Lanham, MD.
IHHA (2009). "Guidelines to Best Practices for Heavy Haul Railway Operations. Infrastructure Construction and Maintenance Issues". D. & F. Scott Publishing, Inc., International Heavy Haul Association, 656 pp.

Railroad Bridge Classification

Performance challenges

Current concerns from railroad bridge management departments

Current SHM applications that could better measure & assist in the decisions associated to the management of these specific bridge types

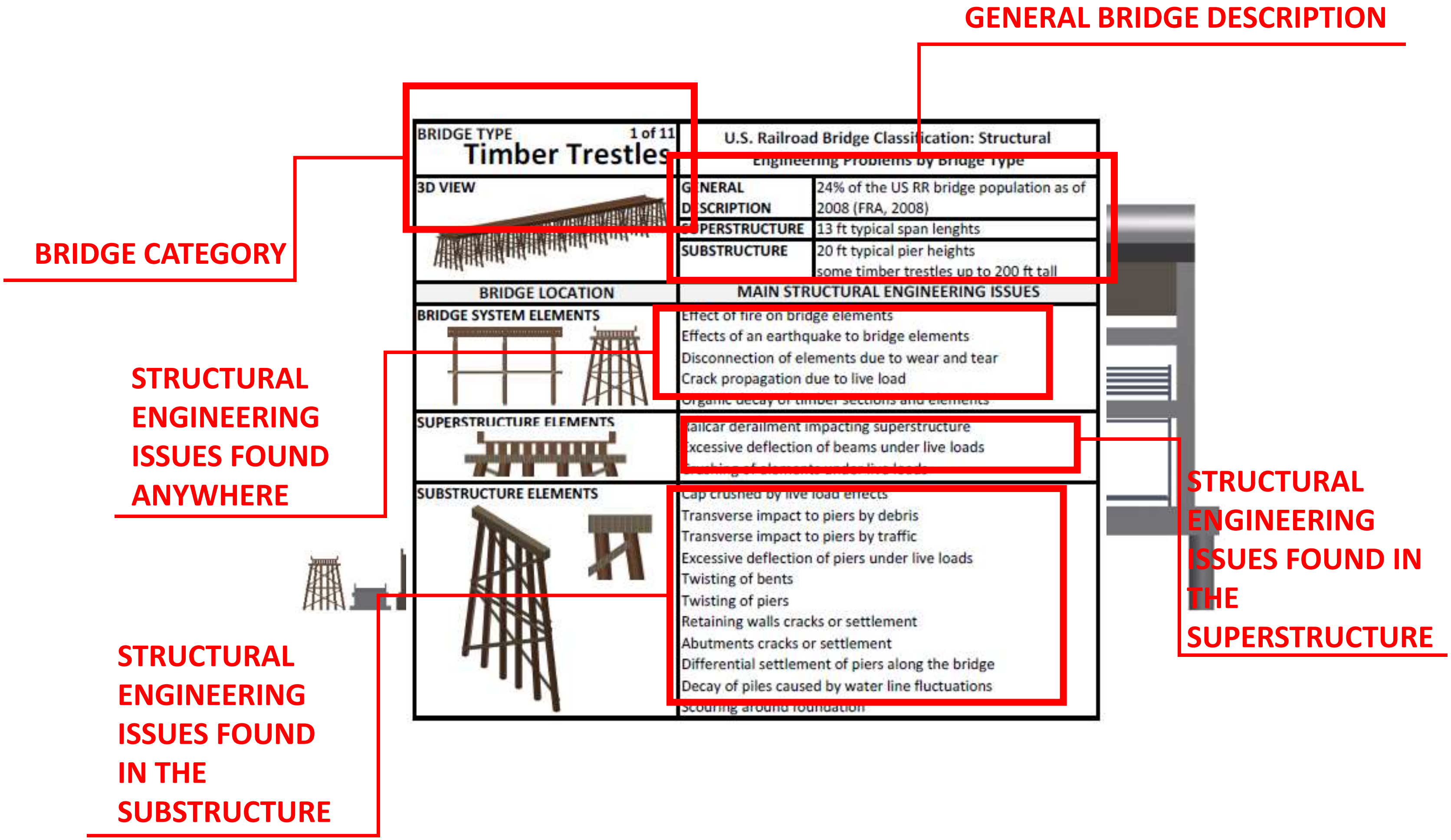
Timber	Timber Trestles
Concrete	Reinforced Concrete Bridges
	Arch Bridges (including Masonry)
	Prestressed Concrete Bridges
Steel	Steel Beams
	Deck Plate Girders
	Through Plate Girders
	Truss Bridges
Movable	Swing Span Bridges
	Bascule Span Bridges
	Vertical Lift Span Bridges

- 11 different categories of railroad bridges
- Based primarily on:
  - Superstructure properties
  - Past studies related to bridge monitoring and bridge inspection, or
  - Railroad bridge maintenance in a more general sense
- Past SHM railroad bridge studies mostly directed toward accident prevention, and not so much toward maintenance (Mee et al., 1994; Otter et al., 2012)

Mee, B. et al. (1994). "Overview of Railroad Bridges and Assessment of Methods to Monitor Railroad Bridge Integrity". U.S. Department of Transportation Federal Railroad Administration, Washington D.C.

Otter, D., Joy, R., Jones, M.C., and Maal, L. (2012). "Needs for Bridge Monitoring Systems Based on Railroad Bridge Service Interruptions". Transportation Research Board 91st Annual Meeting Proceedings, January.

North American Railroad Bridge Classification for Assessment & Monitoring



BRIDGE TYPE 1 of 11 Timber Trestles	U.S. Railroad Bridge Classification: Structural Engineering Problems by Bridge Type	
3D VIEW	GENERAL DESCRIPTION	24% of the US RR bridge population as of 2008 (FRA, 2008)
	SUPERSTRUCTURE	13 ft typical span lenghts
	SUBSTRUCTURE	20 ft typical pier heights some timber trestles up to 200 ft tall
BRIDGE LOCATION	MAIN STRUCTURAL ENGINEERING ISSUES	
BRIDGE SYSTEM ELEMENTS	Effect of fire on bridge elements Effects of an earthquake to bridge elements Disconnection of elements due to wear and tear Crack propagation due to live load Organic decay of timber sections and elements	
SUPERSTRUCTURE ELEMENTS	Railcar derailment impacting superstructure Excessive deflection of beams under live loads Crushing of elements under live loads	
SUBSTRUCTURE ELEMENTS	Cap crushed by live load effects Transverse impact to piers by debris Transverse impact to piers by traffic Excessive deflection of piers under live loads Twisting of bents Twisting of piers Retaining walls cracks or settlement Abutments cracks or settlement Differential settlement of piers along the bridge Decay of piles caused by water line fluctuations Scouring around foundation	

STRUCTURAL ENGINEERING ASSOCIATION OF AMERICAN RAILROADS RAILTEC

AAR Technology Scanning -- University of Illinois at Urbana-Champaign

"BRIDGE PERFORMANCE ASSESSMENT USING SIMPLIFIED FIELD MONITORING"

2012

Review of existing literature and applications of structural monitoring to railroads, highways & other lifelines to select monitoring tools

Priority toward simplified, portable, autonomous (wireless) sensors

Explore the applicability of available (and emerging) measurement techniques for railroad bridges, including proposals for specific parameters to be measured

Displacements at specific locations could be a bridge performance parameter

We propose using accelerometers for reference-free displacement estimation of railroad bridge deflections under railroad traffic.

Displacement as a Simple Bridge Performance Parameter

Displacement as a performance parameter (possible indirect measure of bridge "health")

- *Monitoring bridge displacements may help assess bridge performance*
- *Measuring peak displacements and time histories under trains*
- *Both for short- and long-term assessment*

Current methods to monitor displacement require a fixed point and are expensive.

Motivation for reference-free displacements

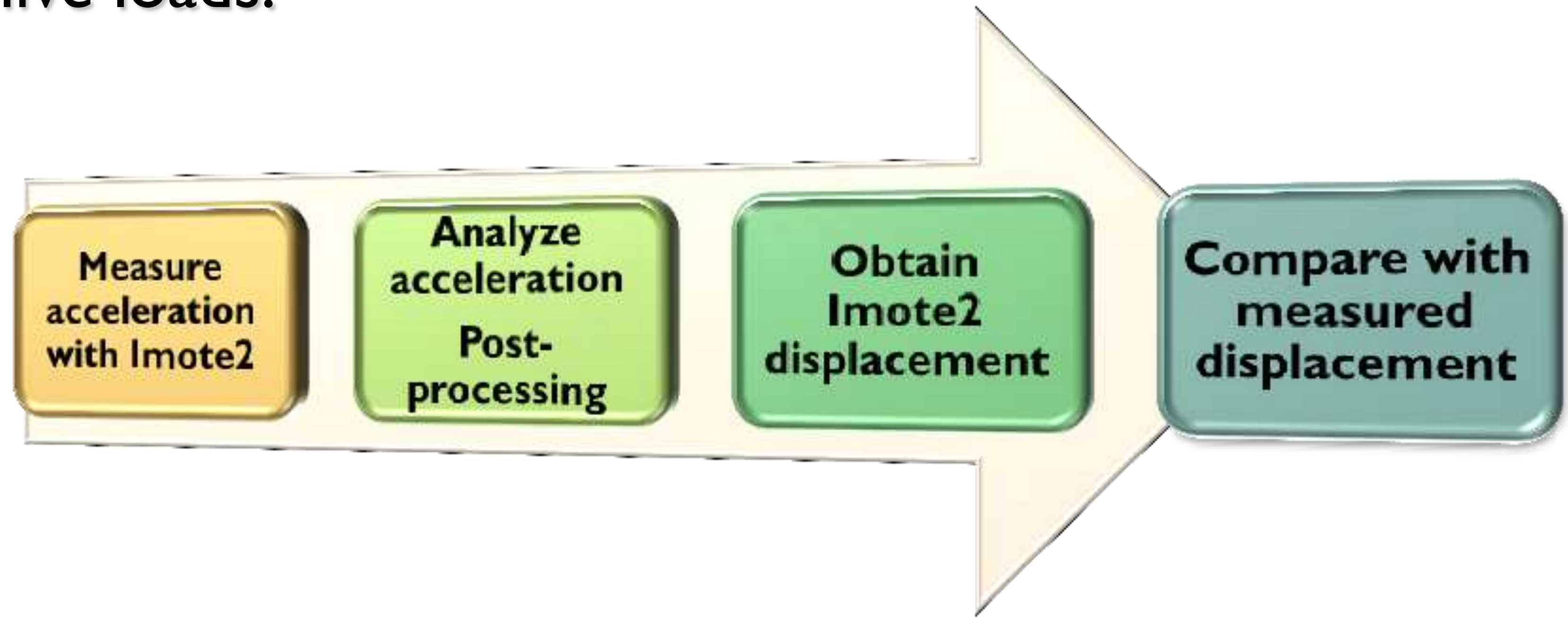
- *Accelerations are easy to record, and don't require a fixed point*
- *Lee et al. (2010) proposed a displacement estimation from accelerations*
- *Laboratory experiments have validated that wireless sensors can estimate displacements from accelerations*
- *Goal: a "reference-free" displacement estimation method for railroad bridges*

ISM400 board stacked on Imote2

Sensor enclosure assembly

Research goal

Use (wireless) sensors to obtain reference-free displacement measurements of railroad bridges under live loads.



Field Experiments → Measuring both wired and Imote2 (wireless) accelerations, and LVDT displacements, under trains to validate estimations.

STRUCTURAL ENGINEERING ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

RAILTEC

Field Experiments to Explore the Validity of Displacement to Measure Bridge Performance (Especially from Acceleration Measurements)

Field Implementation

NEES NSEL SSTL CN BNSF RAILWAY

- Identified (with Class I railroads) **nearby bridges** for potential test-bed sensing implementation.
- Integrate this AAR project with ***CN*** and BNSF bridges by identifying some current **pressing problems** from the railroad bridge managerial point of view on specific Class I railroads.
- Field monitoring.

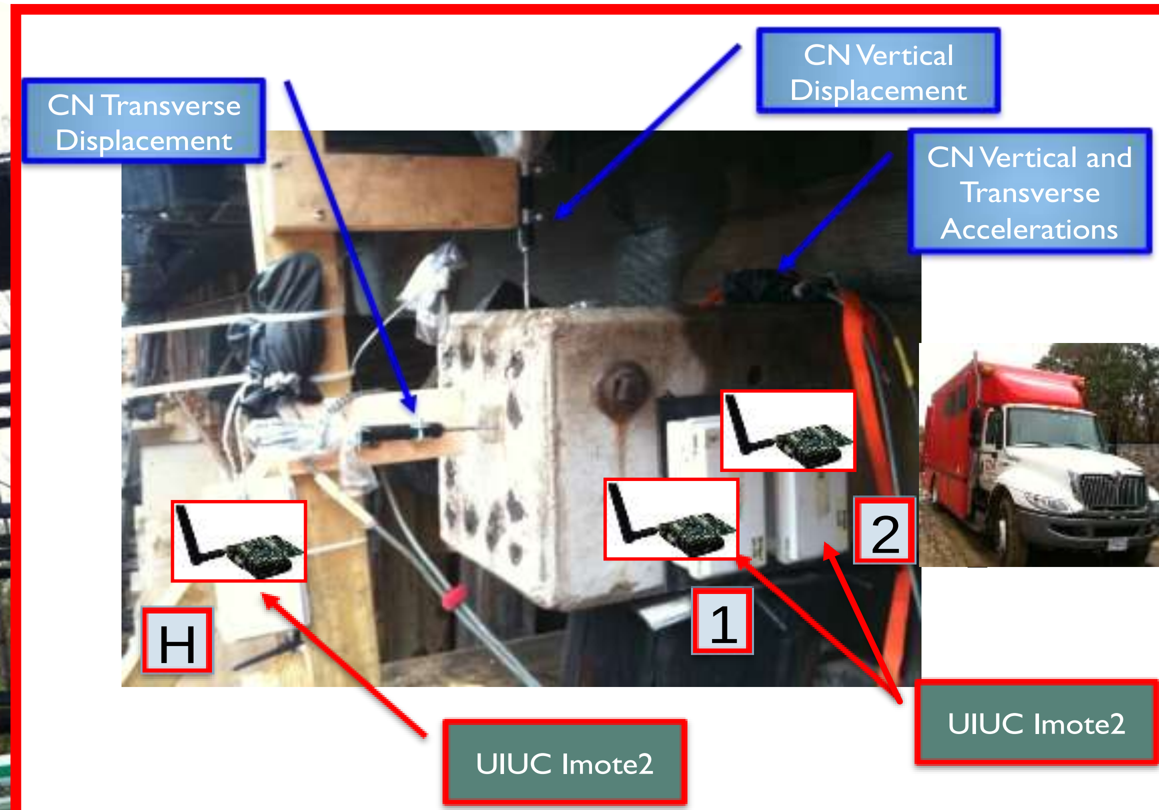
STRUCTURAL ENGINEERING RAILTEC

STRUCTURAL ENGINEERING ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

RAILTEC

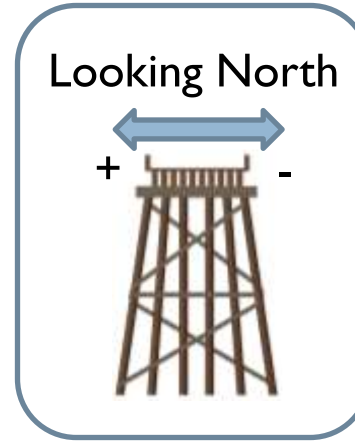
1. **CN Timber Trestle**
2. BNSF Steel Old Pinned – Truss
3. New BNSF Bridge

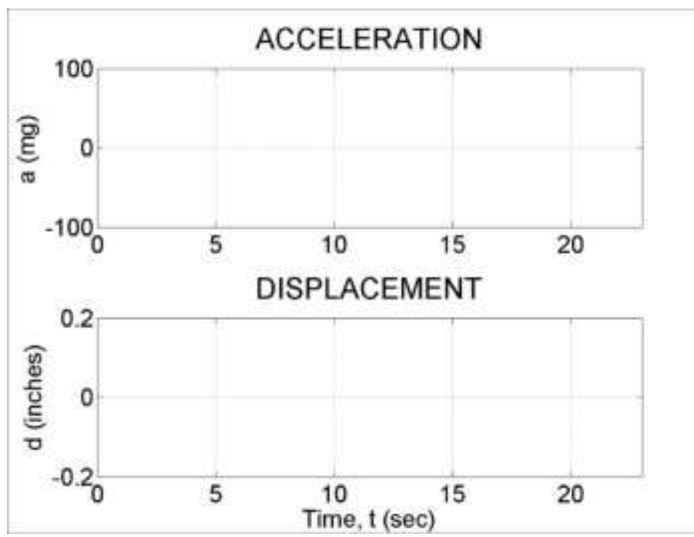
Experimental Setup (@ South Trestle)



- 2 LVDTs (1 vertical, 1 horizontal) for displacements
- 1 biaxial accelerometer for accelerations
- 2 Imote2s attached to pier cap (tri-axial acceleration)
- 1 Imote2 attached to the scaffolding (tri-axial acceleration)
- Measured 10 work trains (WT) and 4 regular trains

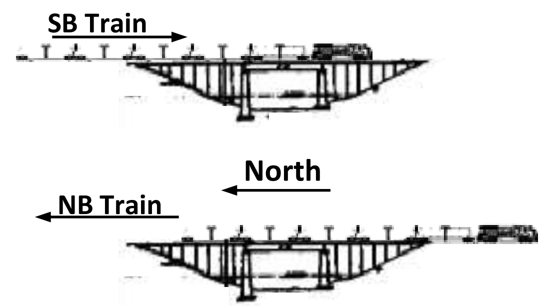
Measured Lateral (Transverse) Displacement Data





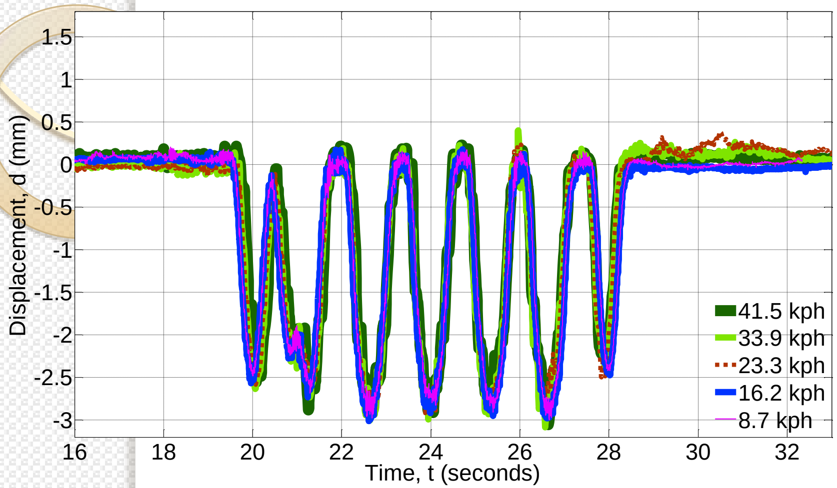
10 Work Trains in Total

Time	Work Train
9:55	Arrived to the site
10:40	5MPH SB
10:50	5MPH NB
11:00	10MPH SB
11:12	10MPH NB
11:17	15MPH SB
11:27	15MPH NB
11:32	20MPH SB
11:41	20MPH NB
11:47	25MPH SB
11:56	25MPH NB

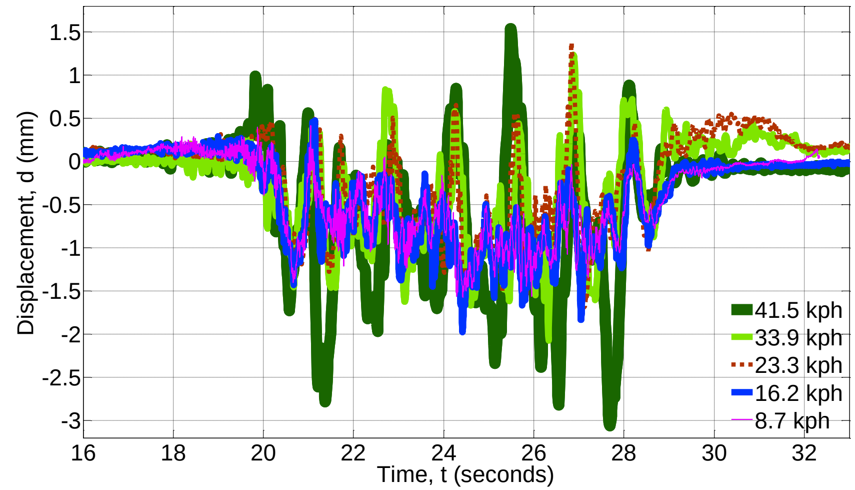


Measured Displacements (mm) vs. Train Speed

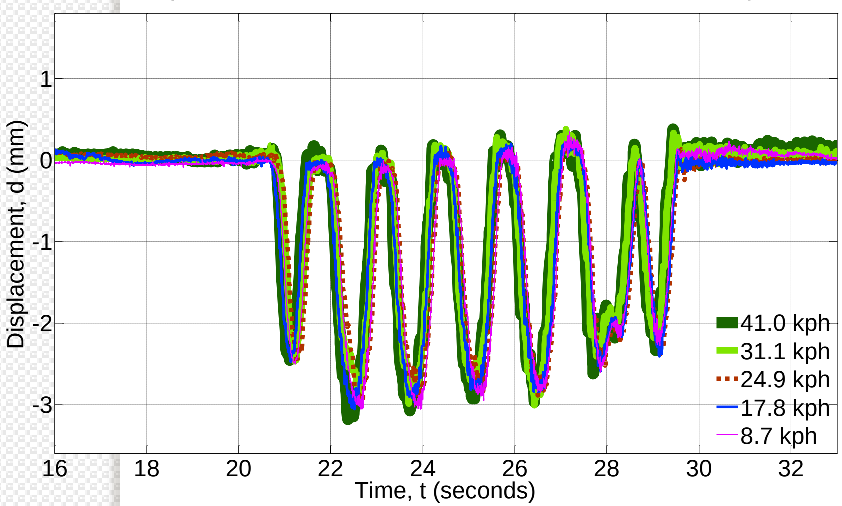
Vertical Displacements under Southbound Work Trains (SB WTs)



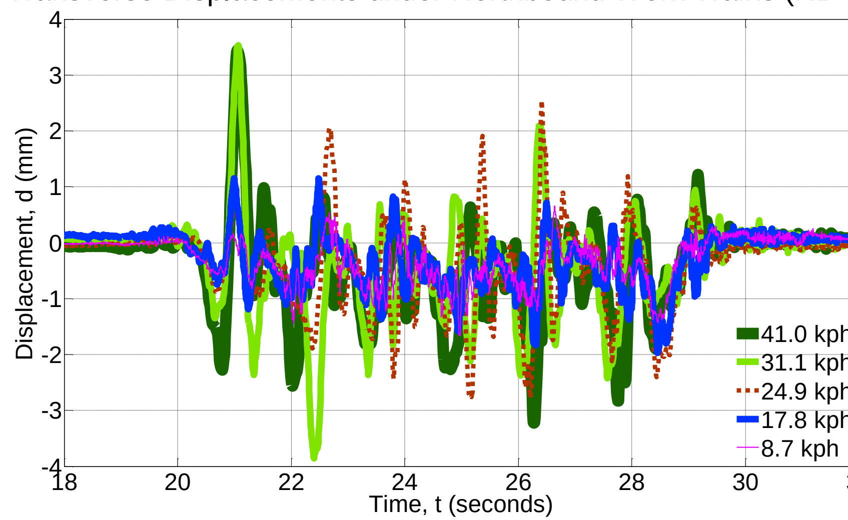
Transverse Displacements under Southbound Work Trains (SB WTs)



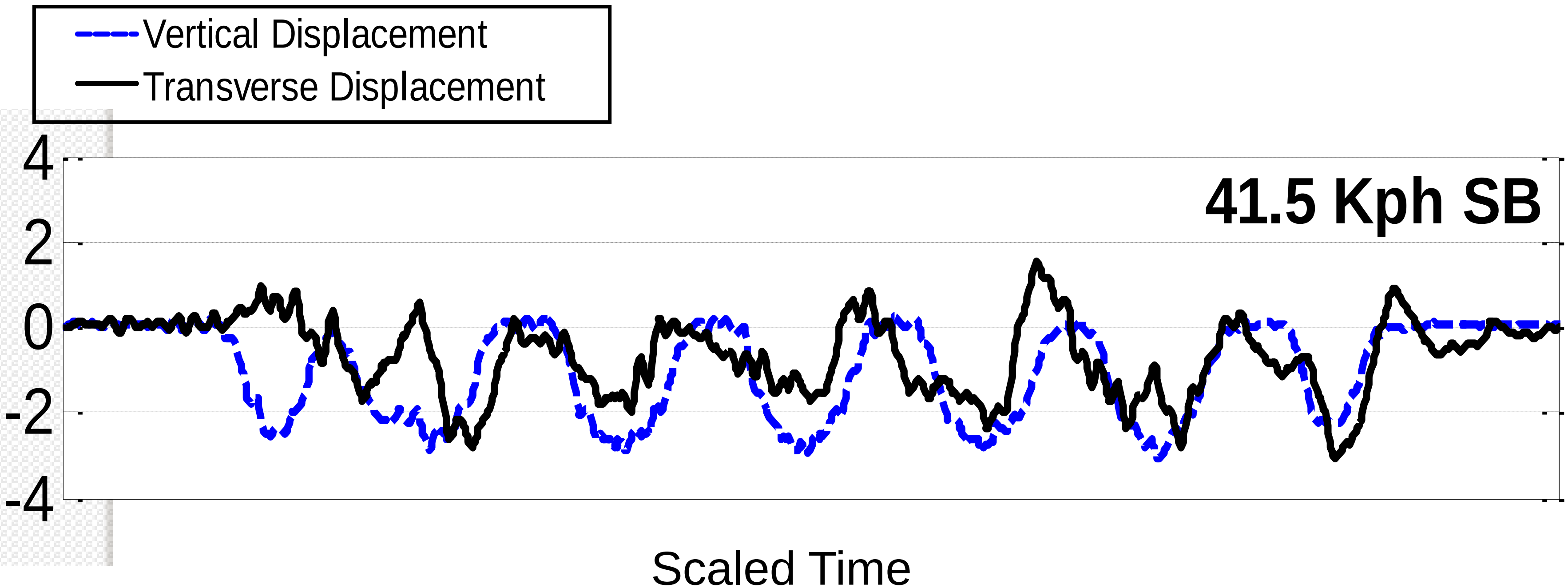
Vertical Displacements under NorthBound Work Trains (NB WTs)



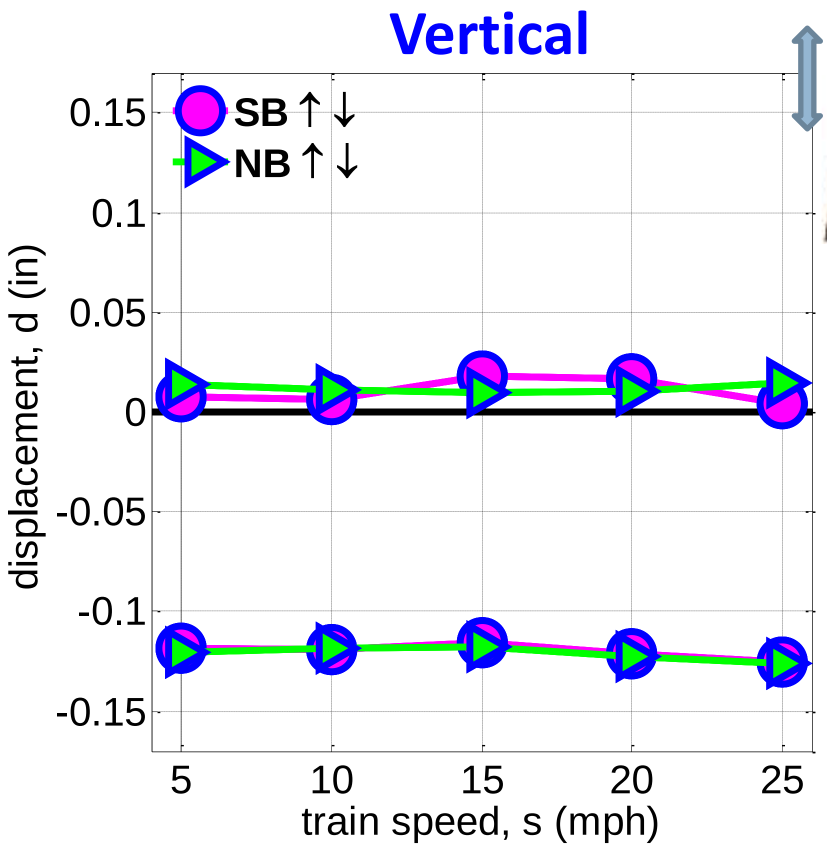
Transverse Displacements under Northbound Work Trains (NB WTs)

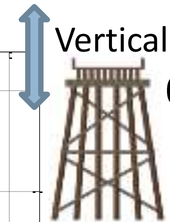


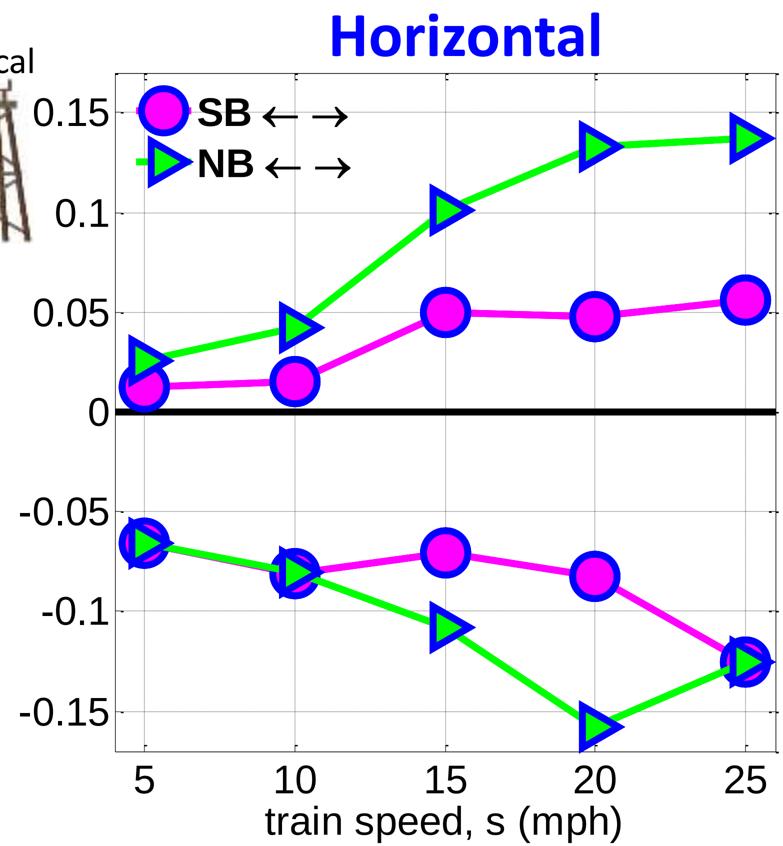
Measured Displacements (mm) vs. Time (for a 25 mph WT)

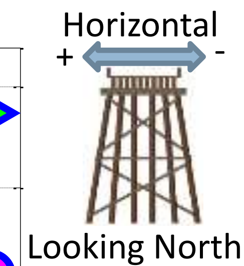


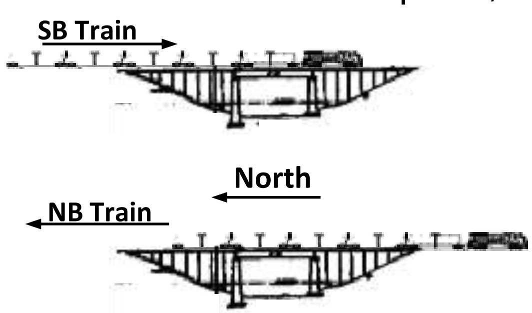
Measured Maximum Displacements vs. Train Speed





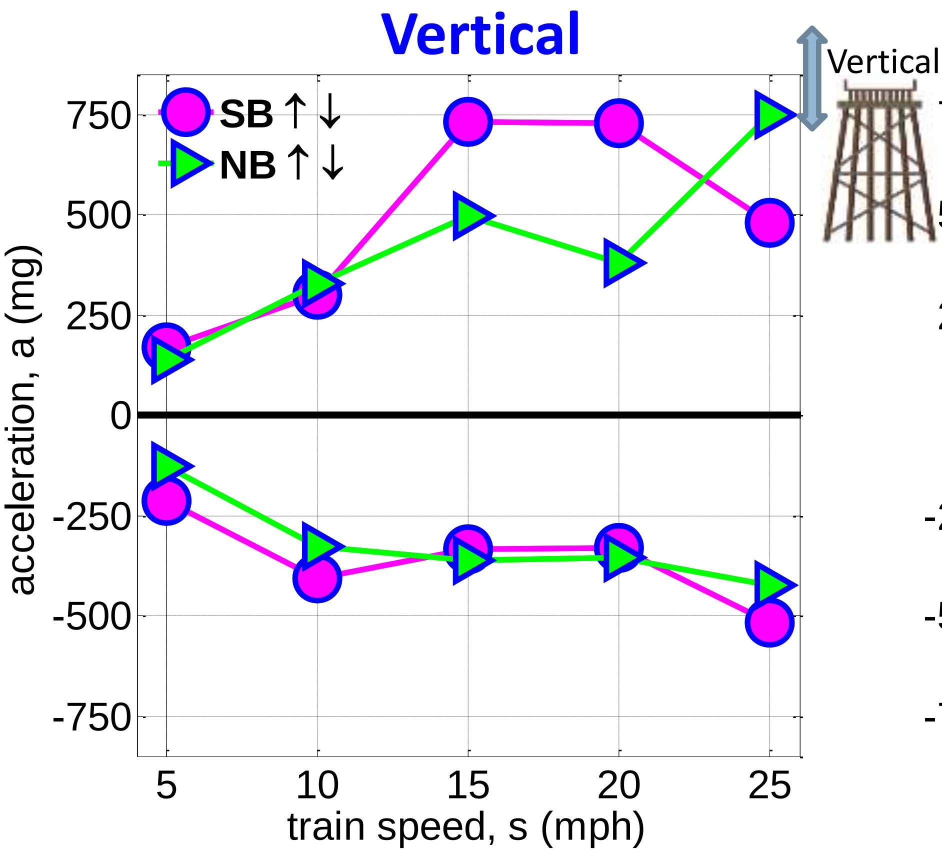


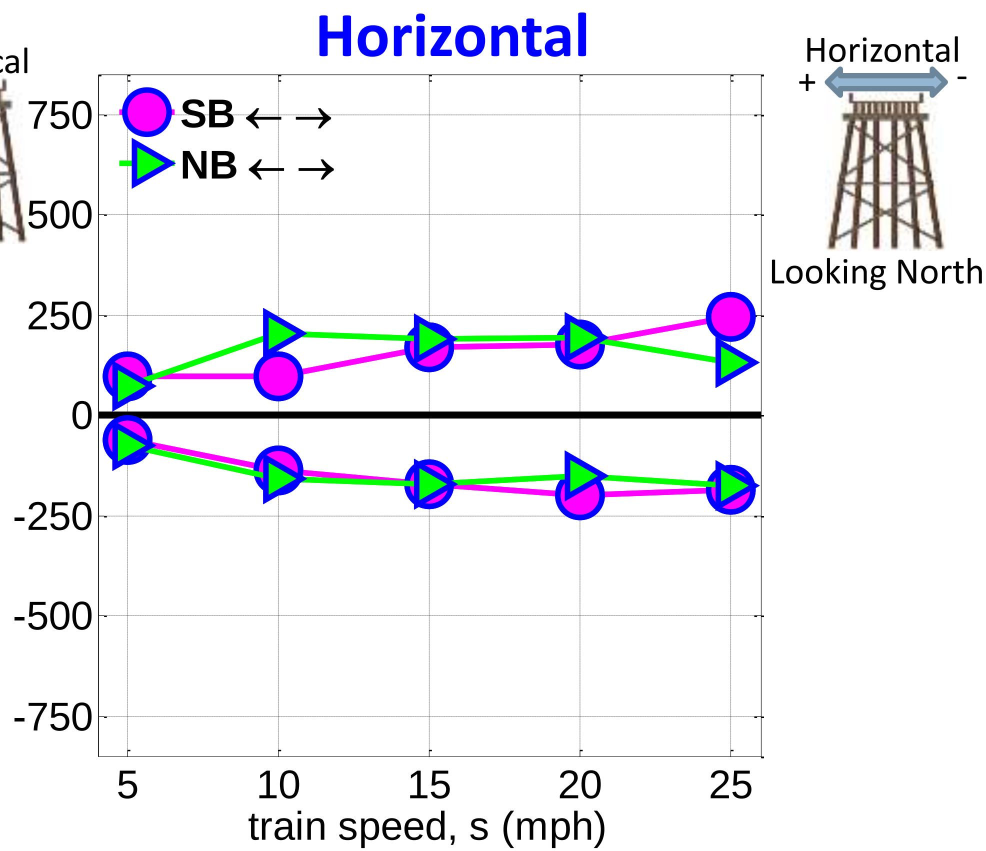


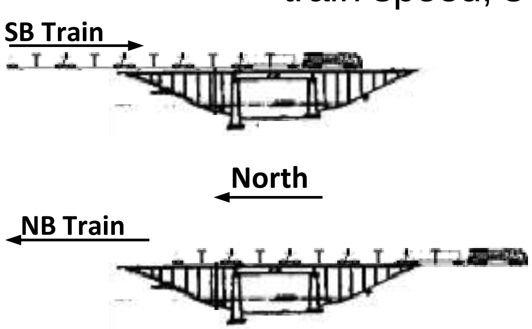


- ❑ Vertical displacements are independent of train speed
- ❑ Horizontal displacements increase with train speed
- ❑ Train response when over a bridge can be controlled with slow orders , which would appear to control lateral (and not vertical) performance of timber pile bents

Vertical & Horizontal Accelerations vs. Train Speed

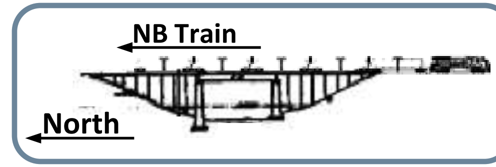


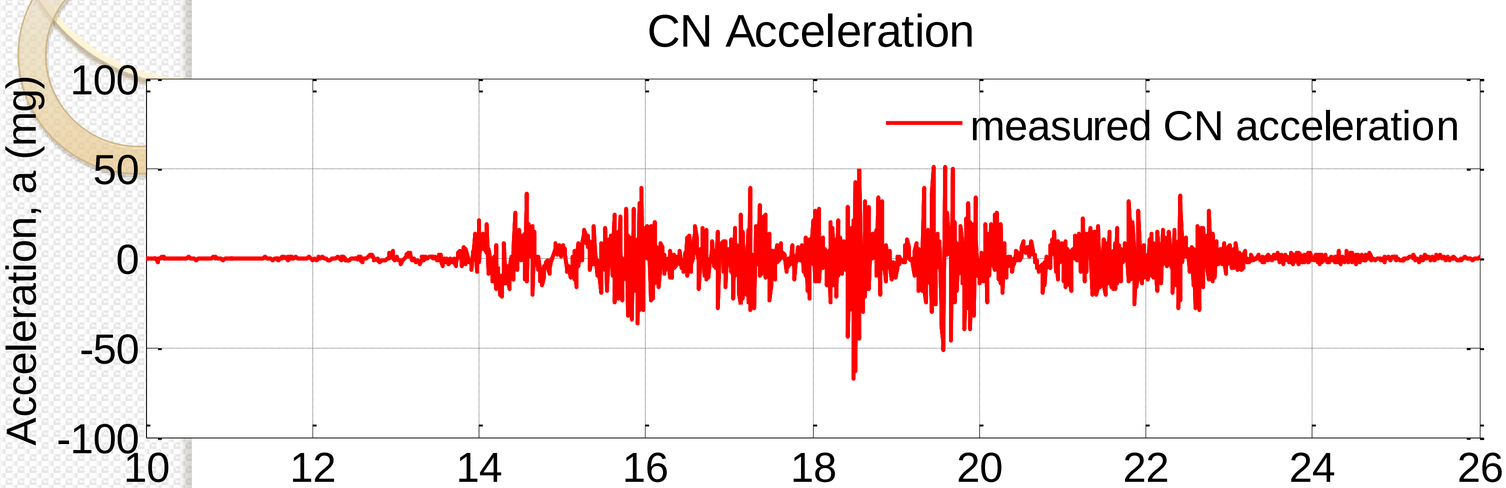


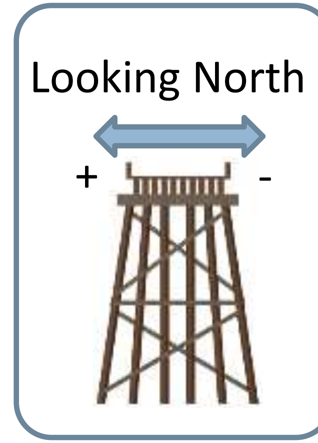


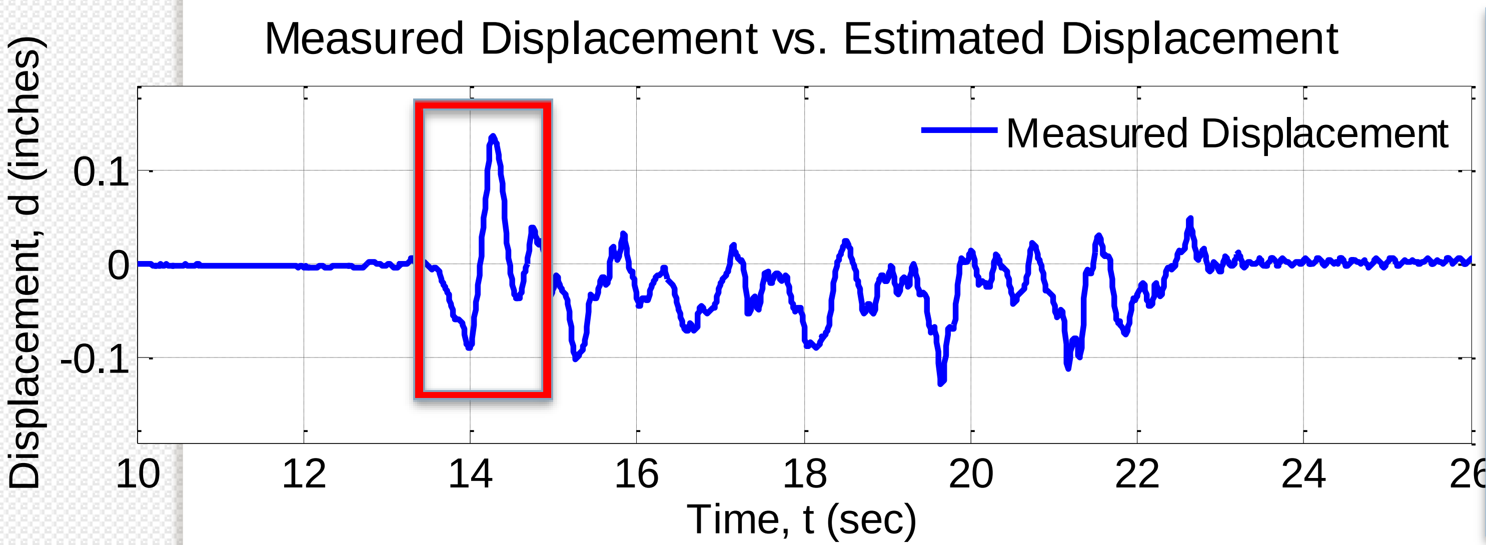
- Accelerations increase from 5 mph to 15 mph
- After 15 mph, accelerations do not clearly increase
- Maximum accelerations don’t seem to have the same trend as maximum displacements
- Transverse displacements increase with speed and might be useful to quantify bridge performance

North Bound (NB) 25 MPH WT



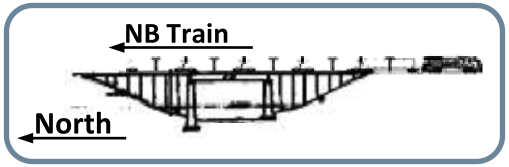


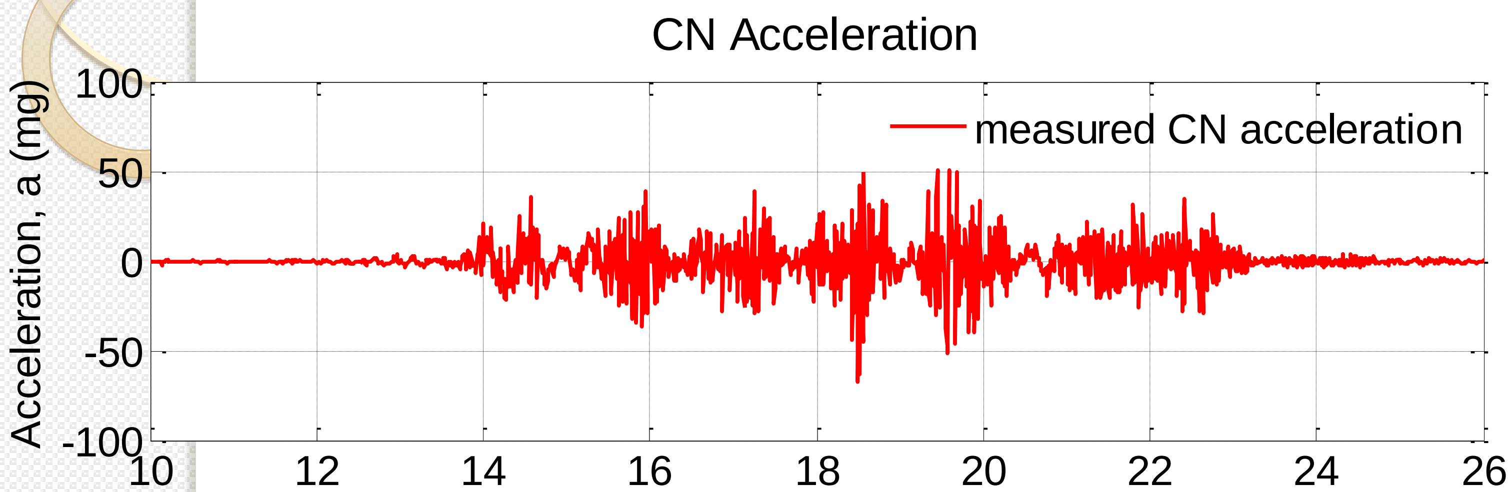


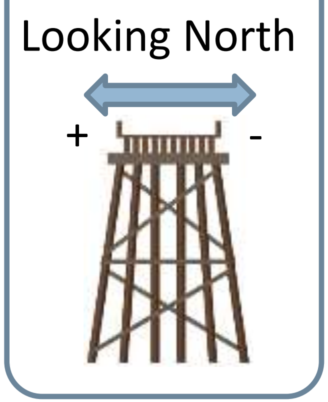


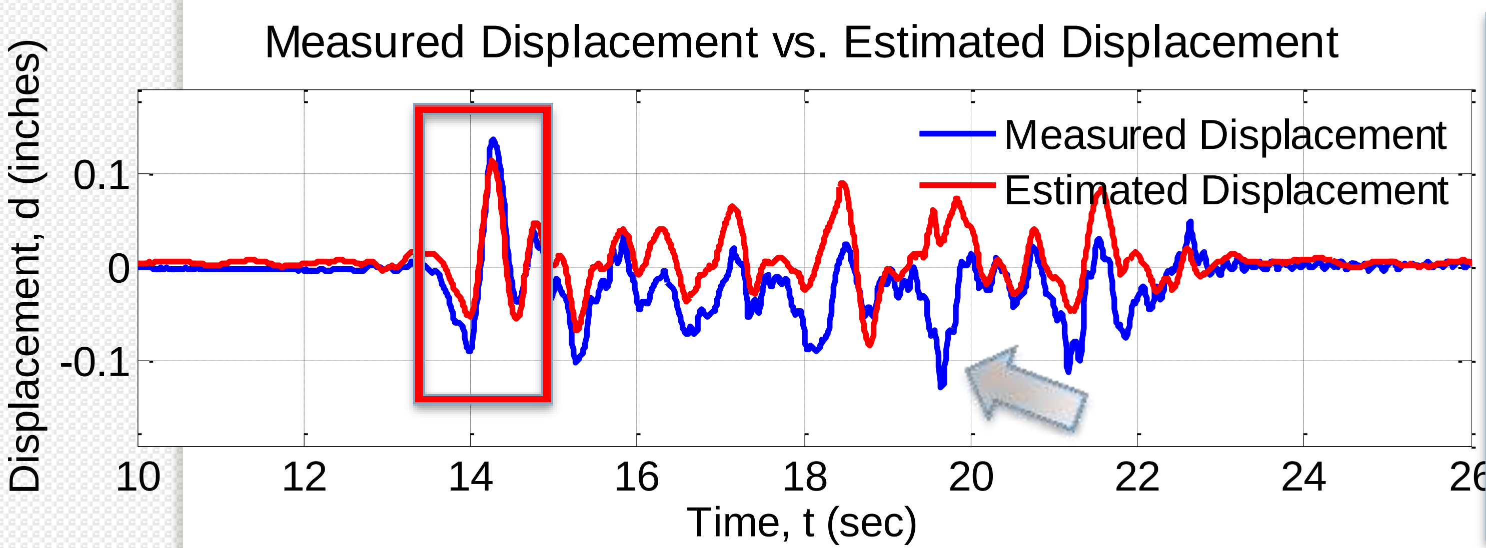
Estimated Displacement can be obtained by double integration of the measured acceleration, and then compared to the measured displacement for validation.

North Bound (NB) 25 MPH WT



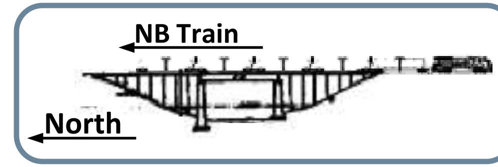


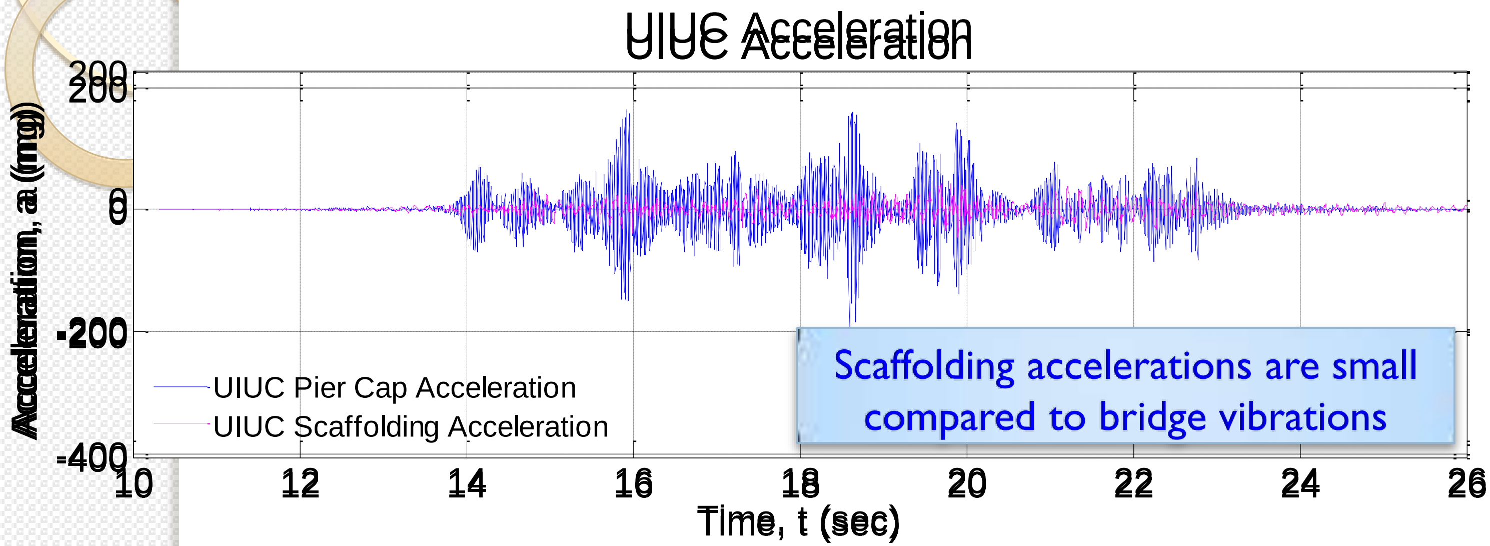




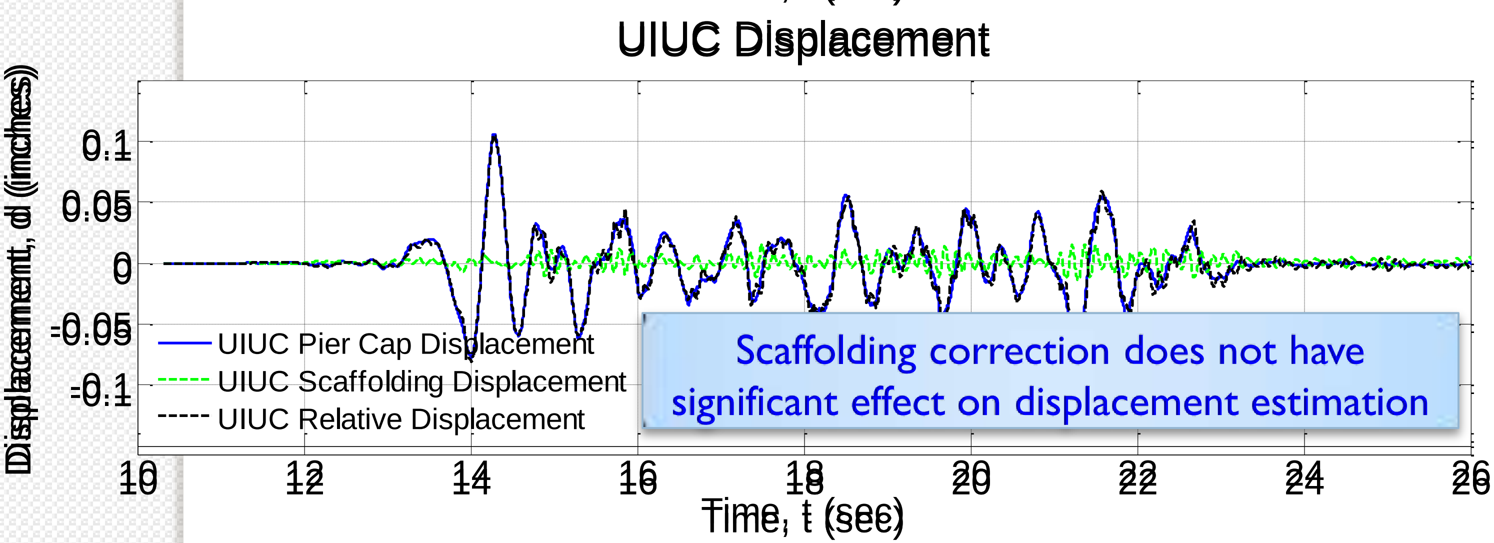
Measured Displacement has a pseudo-static trend (non-symmetric); **Estimated Displacement** does not have such a trend (symmetric).

North Bound (NB) 25 MPH WT

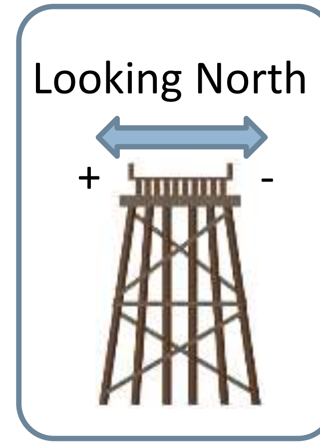




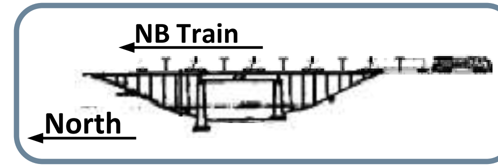
Scaffolding accelerations are small compared to bridge vibrations

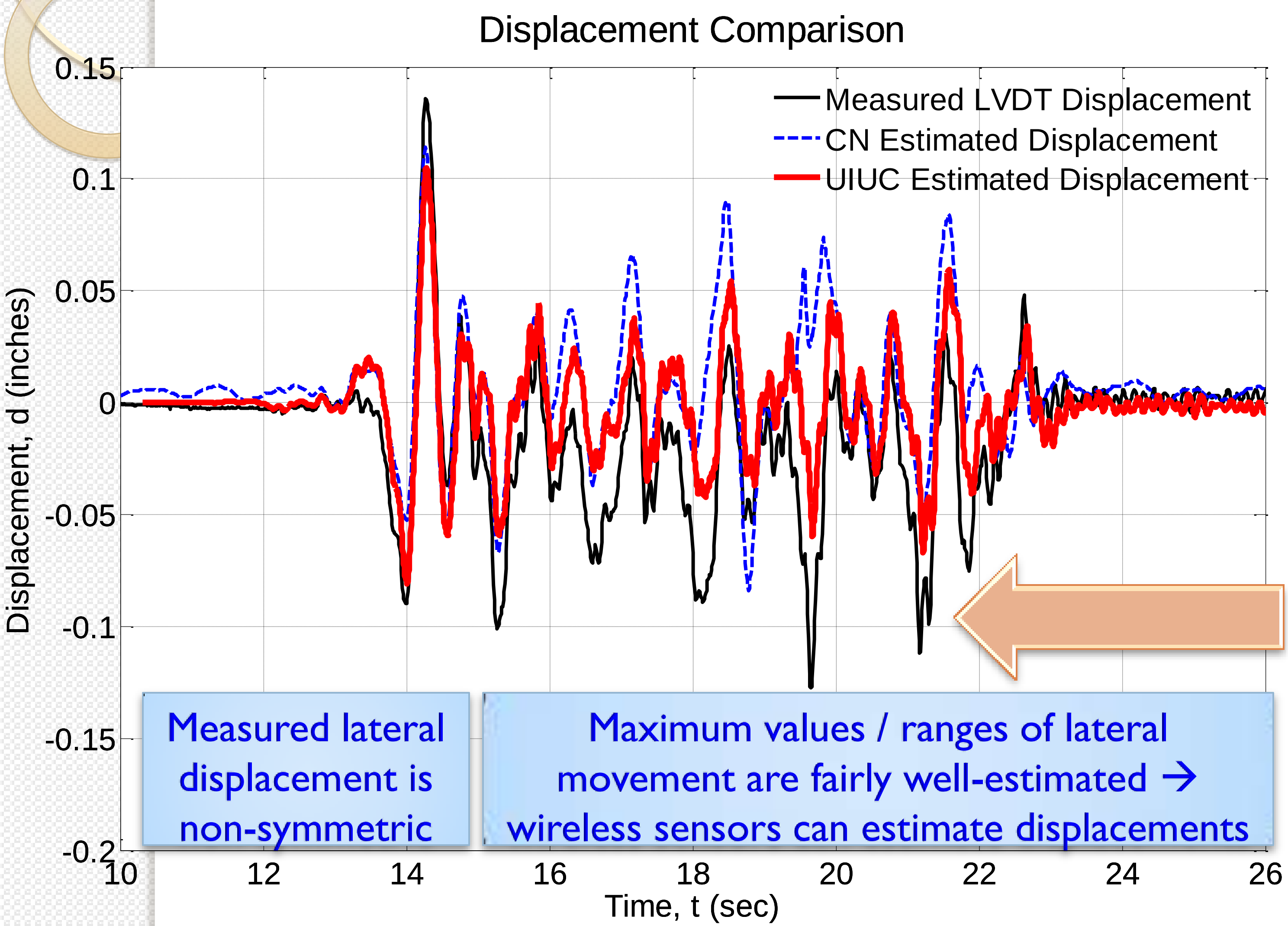


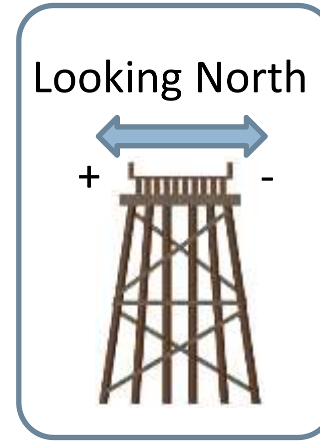
Scaffolding correction does not have significant effect on displacement estimation



North Bound (NB) 25 MPH WT





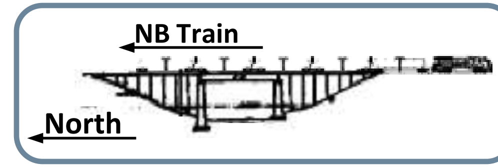


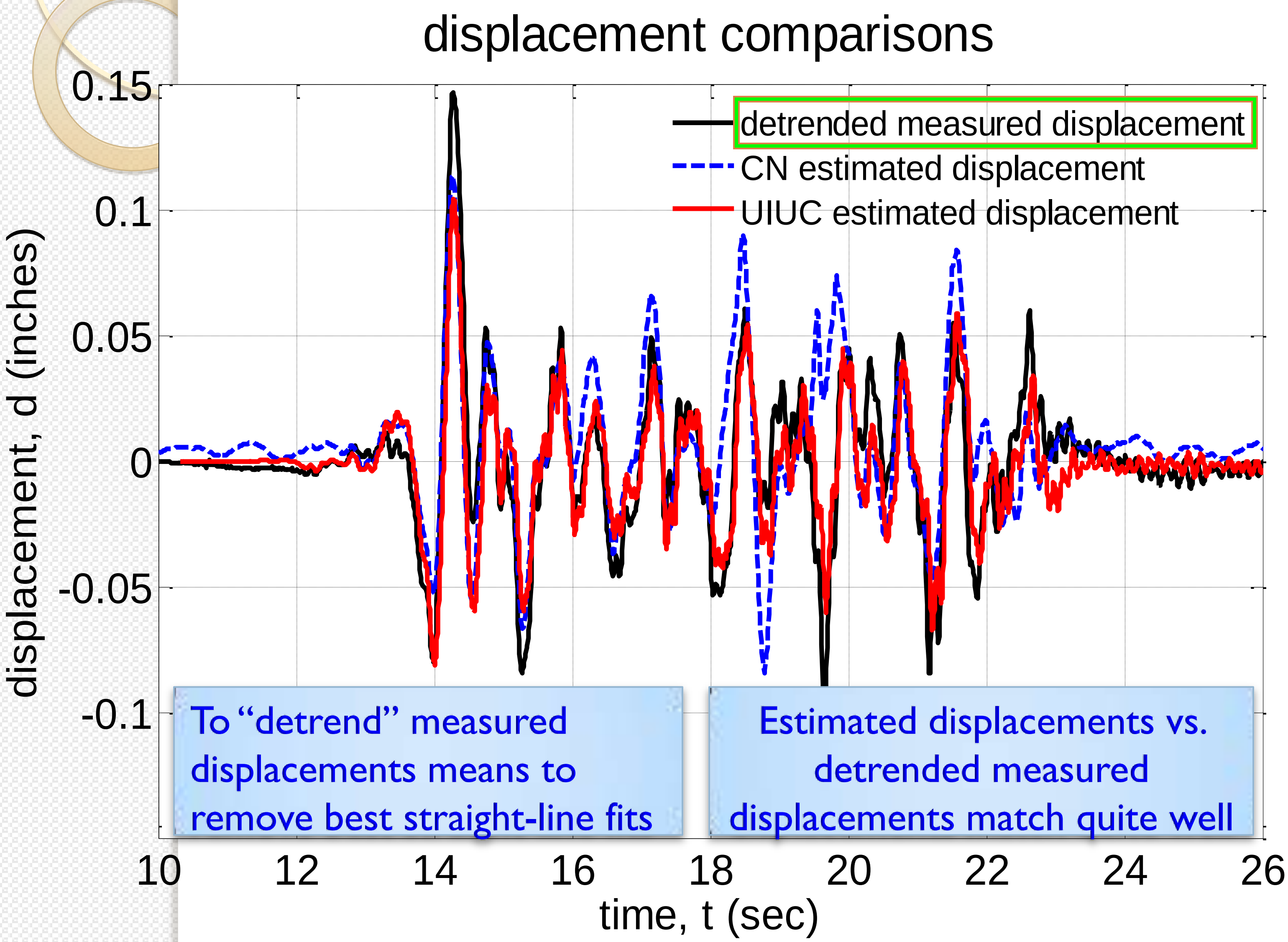
Measured lateral displacement is non-symmetric

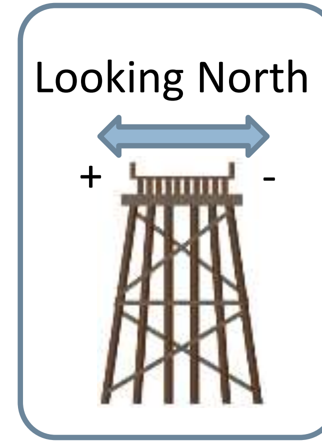
Maximum values / ranges of lateral movement are fairly well-estimated → wireless sensors can estimate displacements

Measured pseudo-static trend could be removed by “detrending” measured displacements

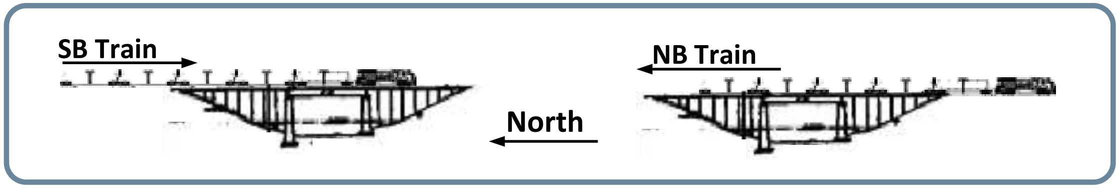
North Bound (NB) 25 MPH WT

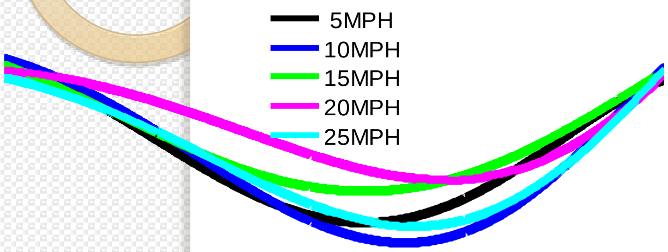




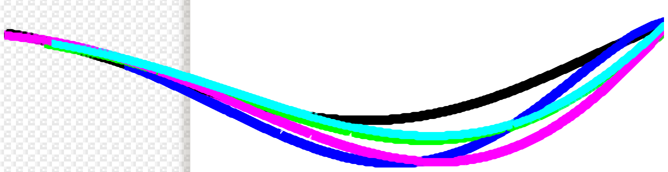


Total Range Displacement Estimation (Max. Peak-to-Peak Displacements)

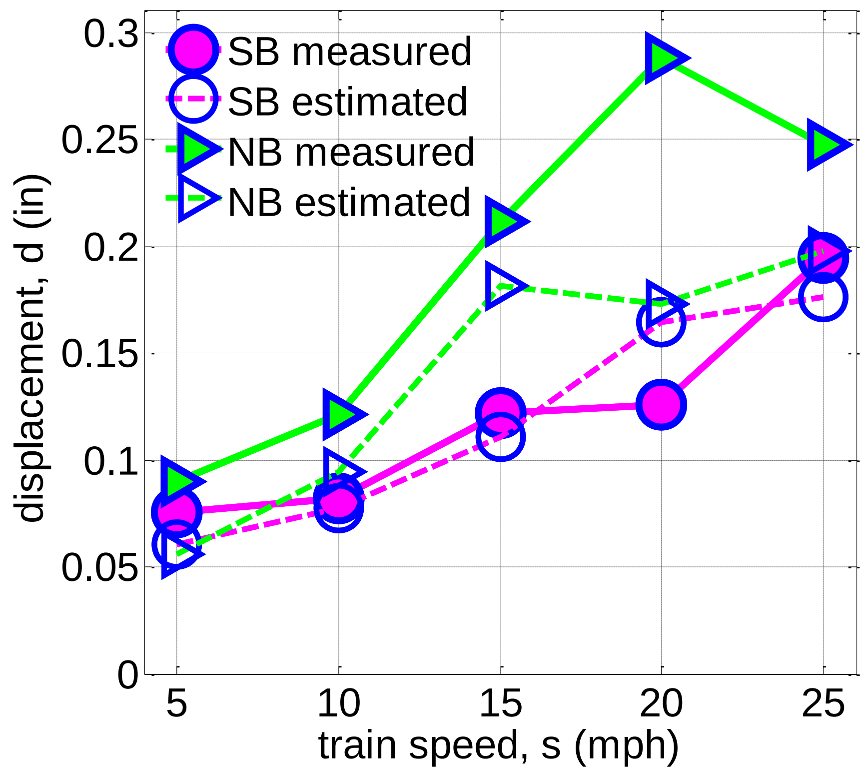


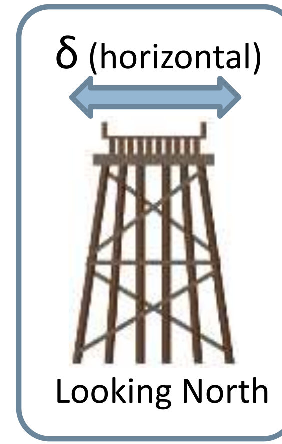


Max. **SB** pseudo-static horizontal = 0.05”



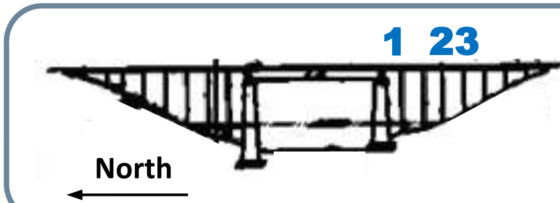
Max. **NB** pseudo-static horizontal = 0.04”



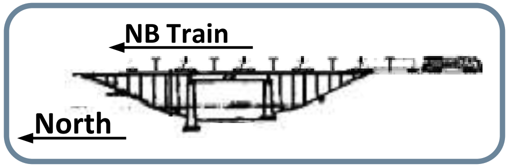


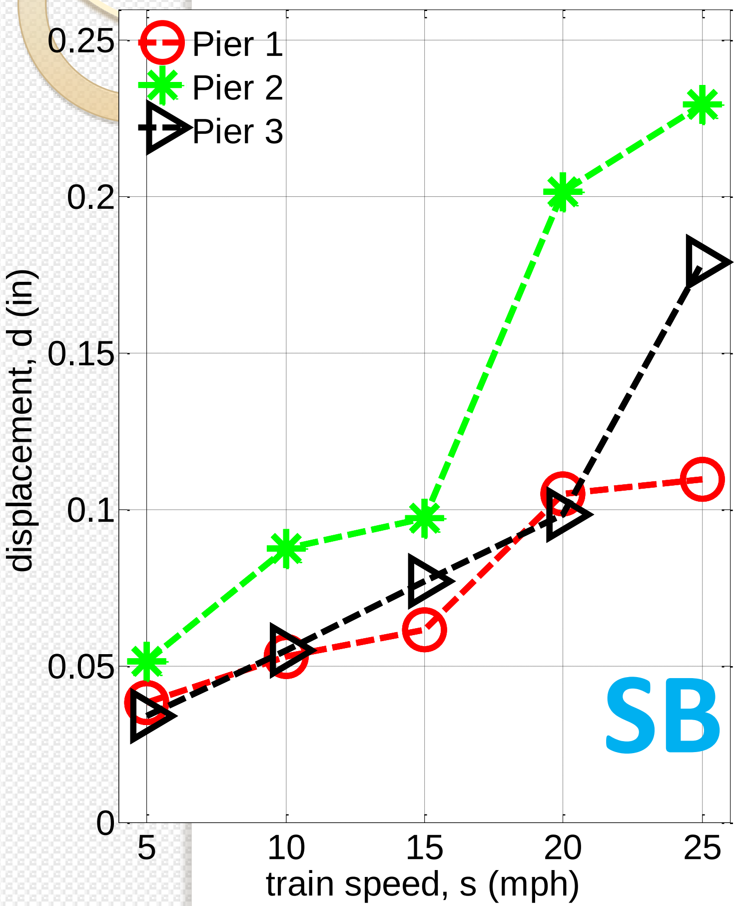
- Except for the 20 mph train, the displacement range estimates improve with higher velocities (in percentage)
- The pseudo-static component definitely appears to affect the accuracy of these lateral displacement range estimations

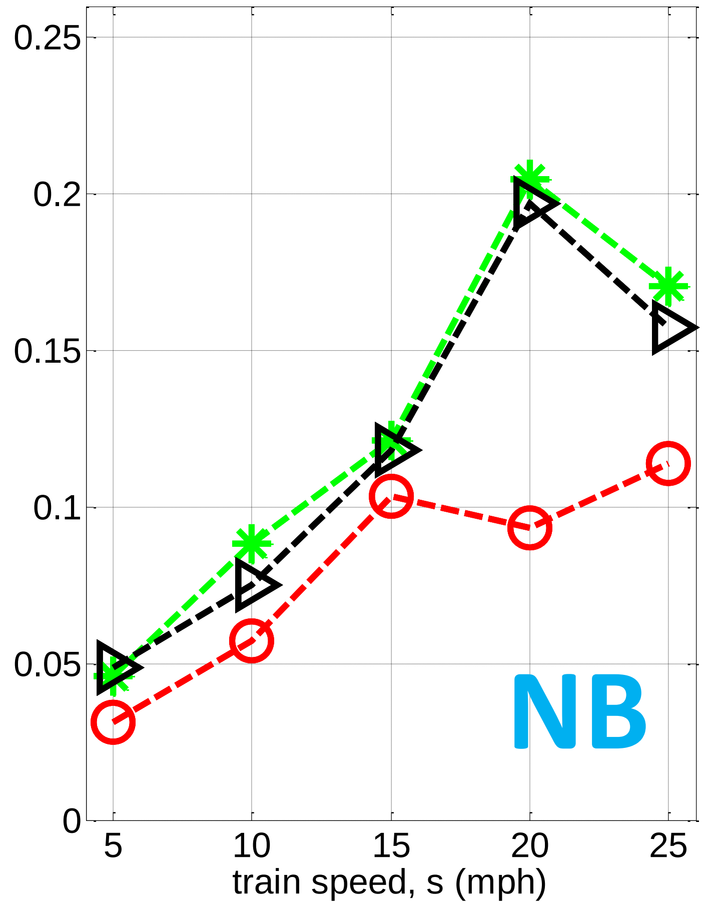
Piers 2 and 3 Estimated Displacements

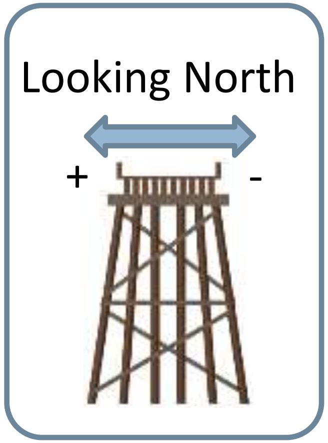


Max. Displacement Estimates for Different Piers (from CN Wired Accelerometers)



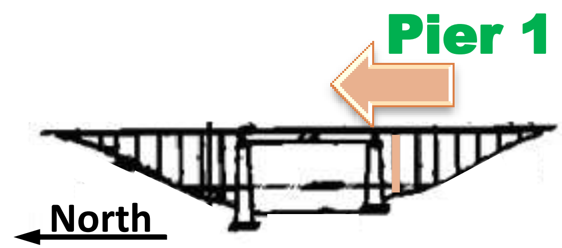






These estimated maximum displacements, even with their limitations, can perhaps assist in identifying piers with larger displacements!

Longitudinal Displacements Were Also Estimated, from UIUC Imote2 Accelerations

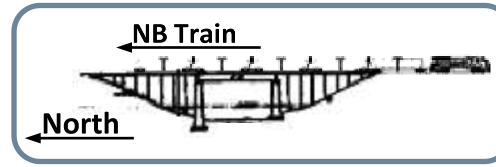


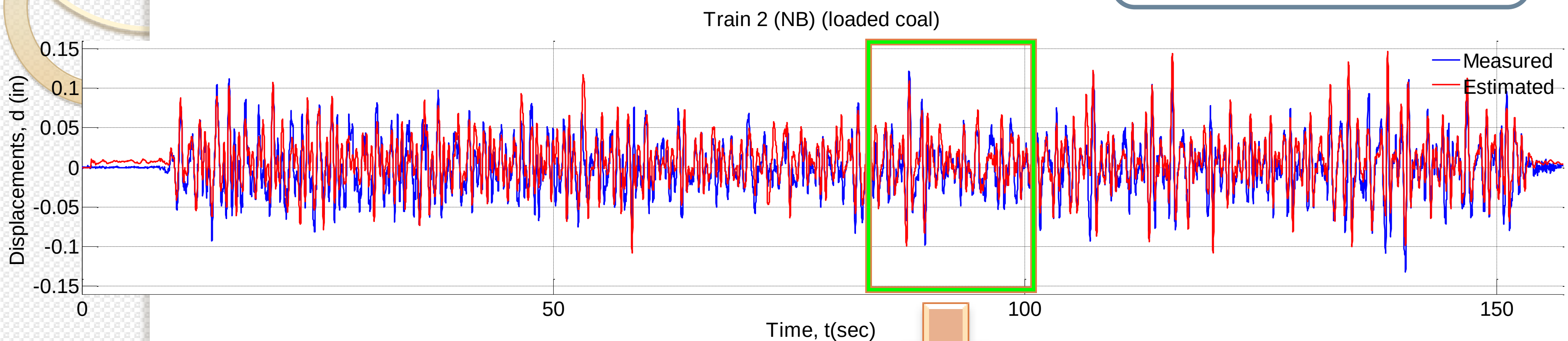
	5	10	15	20	25
SB	0.055	NA	0.257	0.207	0.197
NB	0.014	0.093	0.242	0.195	0.393

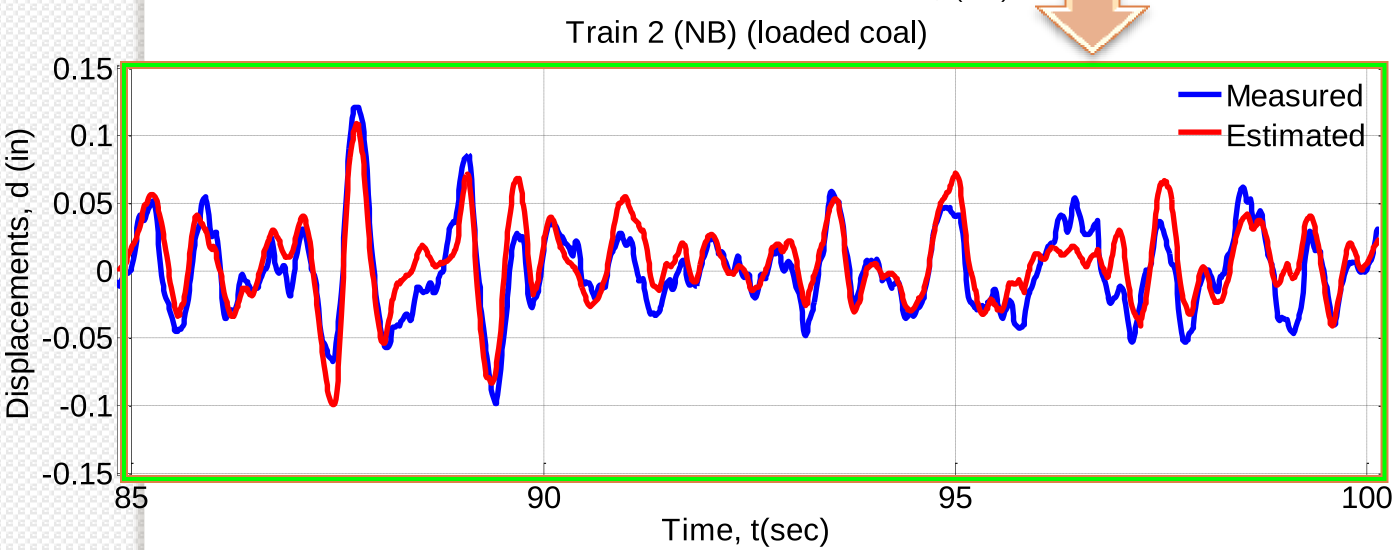
- ❑ Larger longitudinal displacements / ranges than in the transverse direction
- ❑ Maximum estimated values were always toward the South (independent of traffic direction)

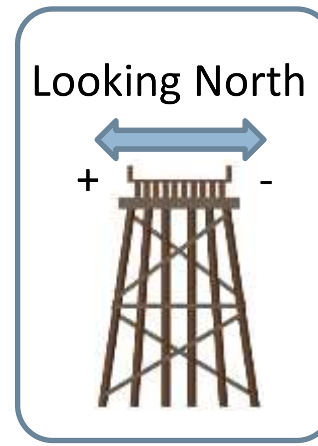
Loaded Train Measurements

Dynamic Displacement Estimates (Regular Train)









- The estimation of displacements / ranges from accelerations is also possible with in-service trains.

Summary & Conclusions

- The ability to make reference-free displacement measurements could be a promising contribution to an existing railroad bridge structural engineering research need
- For the timber trestle measured under work trains, lateral displacements increased with speed
- Displacements have been estimated from accelerations, with comparable results for the dynamic range of both work trains and in-service trains
- Other results from a 250 ft steel truss also showed good reference-free estimations of displacements from accelerations
- Strain measurements collected with wireless smart sensors were able to identify different train loading conditions at a steel truss bridge, and incorporating strain / tilt measurements could address the pseudo-static trend issue

Acknowledgments:

-- Graduate Research Assistant → Fernando Moreu

-- CN → Hoat Le et al.

-- Smart Structures Technology Lab → Prof. Bill Spencer et al.

-- AAR Tech Scanning Program → Dave Davis et al.