THE UNIVERSITY OF ALABAMA AT BIRMINGHAM

NCTSPM
NATIONAL CENTER FOR TRANSPORTATION SYSTEMS PRODUCTIVITY AND MANAGEMENT

Simulation of Bridge Responses to Heavy Vehicles

Presented By

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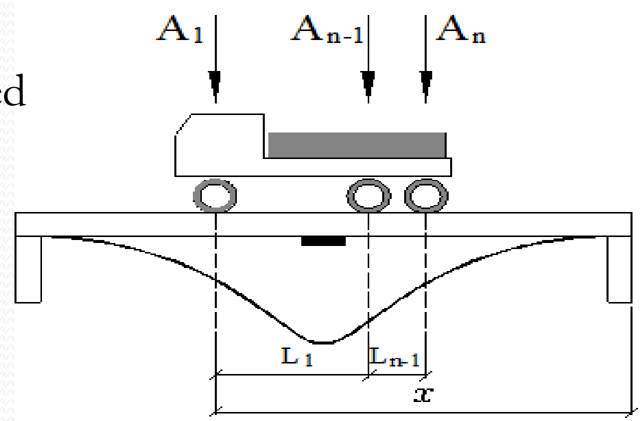
Research Background

- As per US Department of Transportation there are 600,000 bridges
  - 11% structurally deficient
  - 13% functionally obsolete
- Condition of the bridges determined by load rating factor
- Advanced system to monitor the bridge for enforcement and safety assessment
  - Bridge Weigh In Motion (B-WIM)

Federal Highway Administration (FHWA), US Department of Transportation, www.fhwa.dot.gov/bridge/nbi/defbr11.cfm, Accessed on December 9, 2012
American Association of State Highway and Transportation Officials (2010), AASHTO LRFD bridge design specifications, 4th Edition, Washington, DC.
A bill to amend title 23, United States Code, with respect to vehicle weight limitations applicable to the Interstate System, and for other purposes, S 3705, www.govtrack.us/congress/bills/111/s3705, Accessed on October 11, 2012.

Principles of Moses' algorithm

- Inverse type of analysis
- Structures response in terms of bending moment is measured
- Influence lines are obtained for the vehicle load
- Live load is calculated inversely



$$M_E(t) = A_1 I(x) + A_2 I(x - L_1) + A_3 I(x - L_1 - L_2)$$

Limitations of Moses' algorithm

- Moses' algorithm uses simplified formulae
- Not effective for long span, wide bridges, irregular road surface profiles
- Vehicle is assumed to have uniform speed

Moving Force Identification (MFI) algorithm

- Alternative Approach for Moses' algorithm
- Equation of motion

$$[M]_{(n\times n)}\{\ddot{x}\}_{(n\times 1)} + [C]_{(n\times n)}\{\dot{x}\}_{(n\times 1)} + [K]_{(n\times n)}\{x\}_{(n\times 1)} = [T]_{(n\times s)}\{f(t)\}_{(s\times 1)}$$

Where,

M – mass matrix, C – damping matrix, K – stiffness matrix, x – displacement,

x (dot) – velocity, x(dot dot) – acceleration, T – corresponding location

- Finite element modeling for mass matrix, stiffness matrix, and damping matrix
- Potential of considering all dynamic forces in the system using Sophisticated FE simulations
  - Including mass, springs and dampers
  - Vehicle to bridge interaction
  - Dynamics associated with road surface roughness

Law, S.S. and Zhu, X.Q. (2000), "Study on different beam models on moving force identification", Journal of Sound and Vibration, Vol. 234, No.4, pp. 661–679
Yu, L. and Chan, T.H.T. (2003a), Identification of multi-axle vehicle loads on bridges, Journal of Vibration and Acoustics (ASME), Vol. 126, pp. 17–26
Yu, L. and Chan, T.H.T. (2003b), "Moving force identification based on the frequency–time domain method", Journal of Sound and Vibration, Vol. 261, pp. 329–349
O'Connor, C. and Chan, T.H.T. (1988a), Dynamic wheel loads from bridge strains, Journal of Structural Engineering, ASCE, Vol.114, No.8, August, pp.1703–1723
O'Connor, C. and Chan, T.H.T. (1988b), Wheel loads from bridge strains: Laboratory studies, Journal of Structural Engineering, ASCE, Vol.114, No.8, August, pp.1724-1740

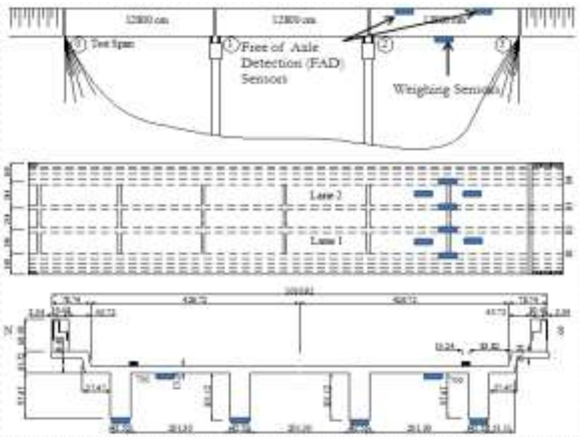
Challenges involved in the current FE model for application of Advanced MFI algorithm

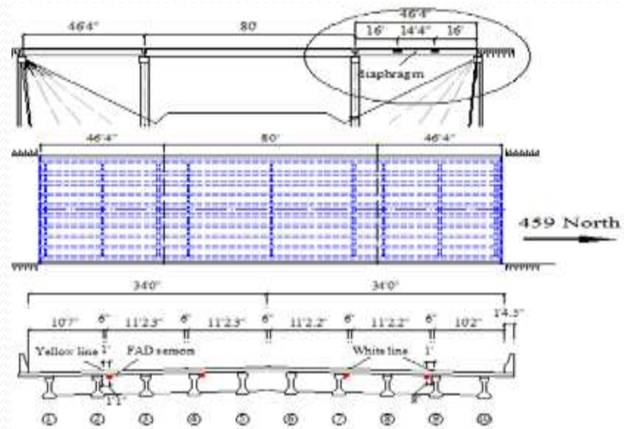
- **Oversimplified Finite Element Models**
- **Truck properties**
  - Effect of suspension and damping, mass distribution, tire pressure and tire rotation
- **Dynamic vehicle to bridge interaction**
  - Effect of vertical mass movement , vibration, deflection due to mass
  - Effect of surface irregularities and gap
- **Physical parameters**
  - Truck transverse position, slab camber, boundary conditions,
  - Roughness of road surface, friction and drag forces
- **Multiple Presence**
  - B-WIM failed to determine vehicular characteristics
  - Axle detection for more than two vehicles over the bridge

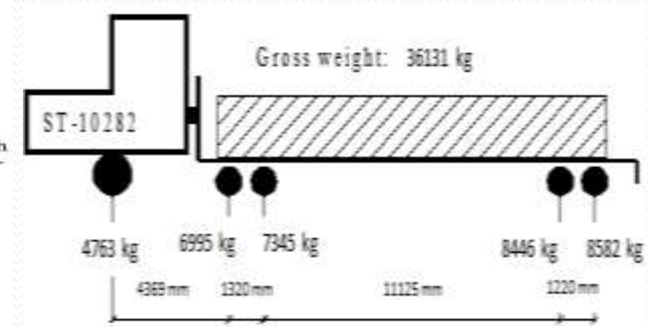
O'Brien E.J., Quilligan, M.J. and Karoumi, R. (2006), "Calculating an influence line form direct measurements", Proceedings of the Institution of Civil engineers, Bridge engineering, Vol.159, Issue 1, March, pp.31-34

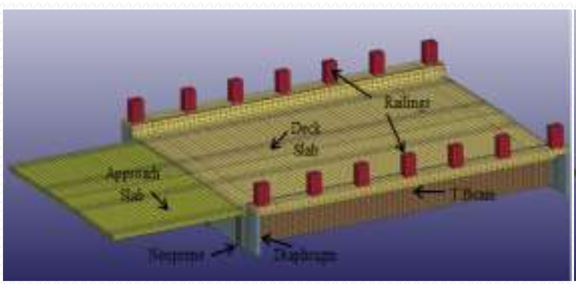
Zhao Hua (2010), Bridge Weigh-In-Motion for Bridge Safety and Maintenance, PhD Dissertation, Department of Civil Construction and Environmental Engineering, the University of Alabama at Birmingham, Birmingham, AL.

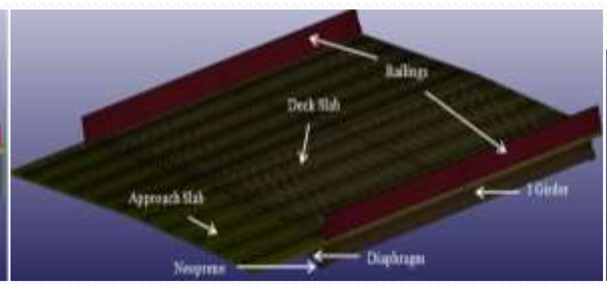
Task 1 – Experimental test and FE Validation of Bridges, Vehicle

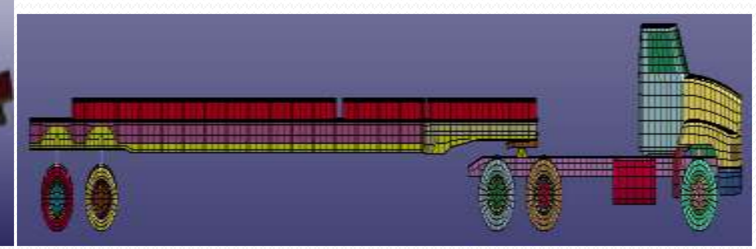


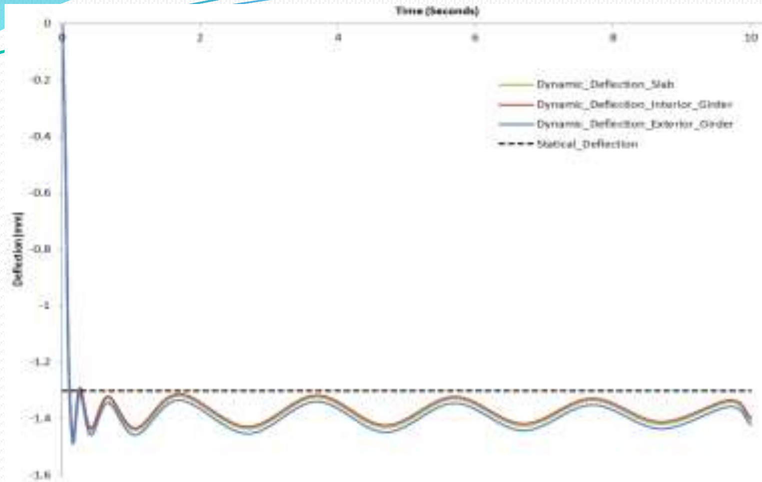


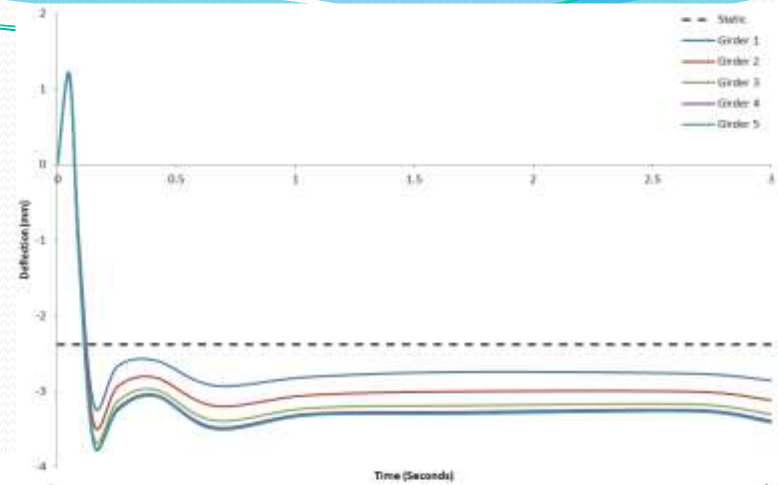


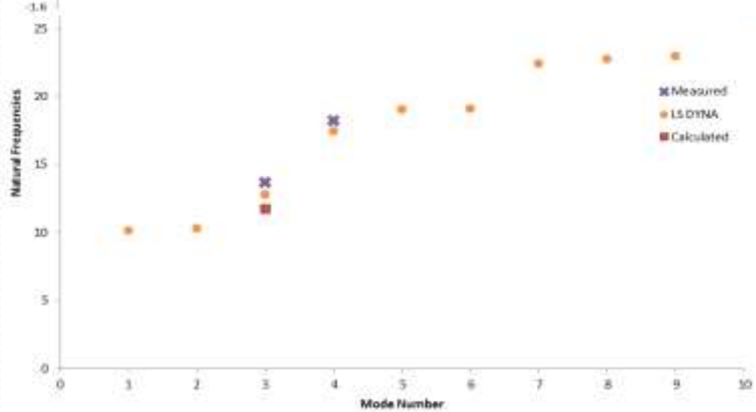


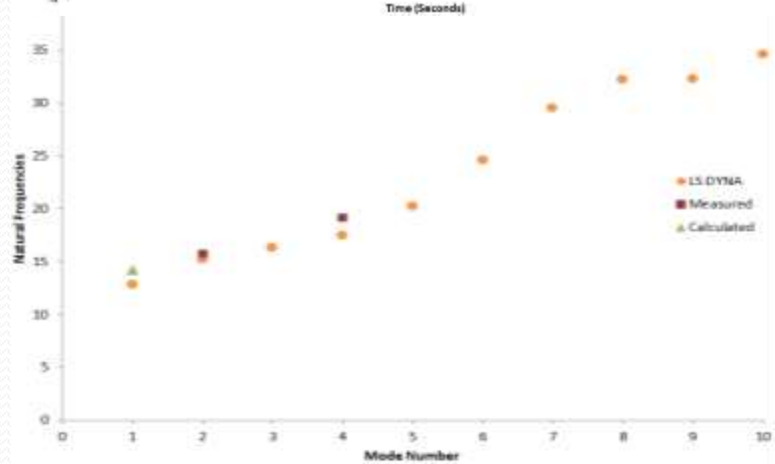





Time (Seconds)
Deflection (mm)
Dynamic_Deflection_Slab
Dynamic_Deflection_Interior_Girder
Dynamic_Deflection_Exterior_Girder
Statical_Deflection


Static
Girder 1
Girder 2
Girder 3
Girder 4
Girder 5
Deflection (mm)
Time (Seconds)


Natural Frequencies
Measured
LS DYNA
Calculated
Mode Number


Natural Frequencies
LS DYNA
Measured
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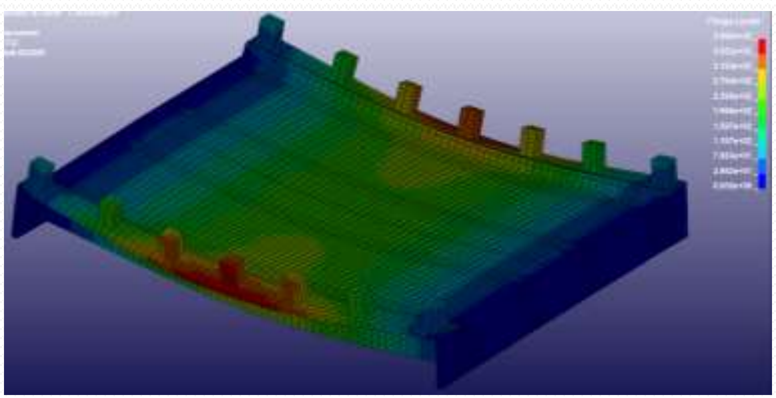
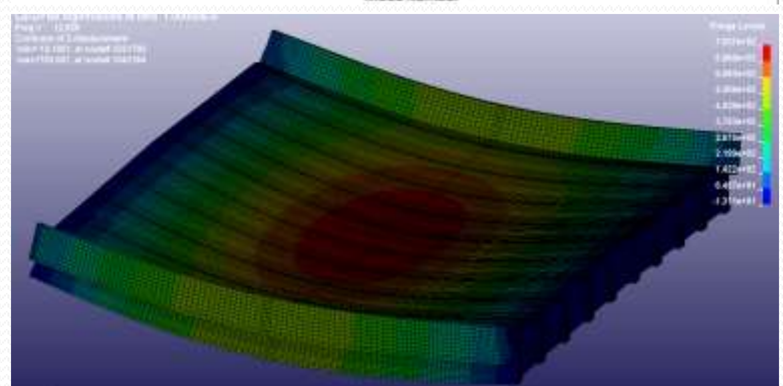
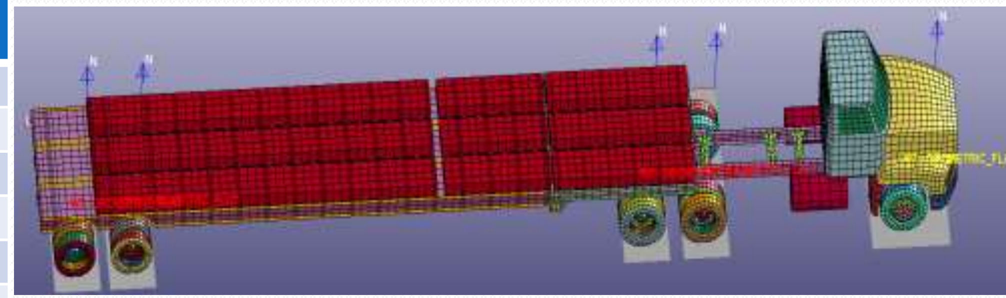
Mode Number



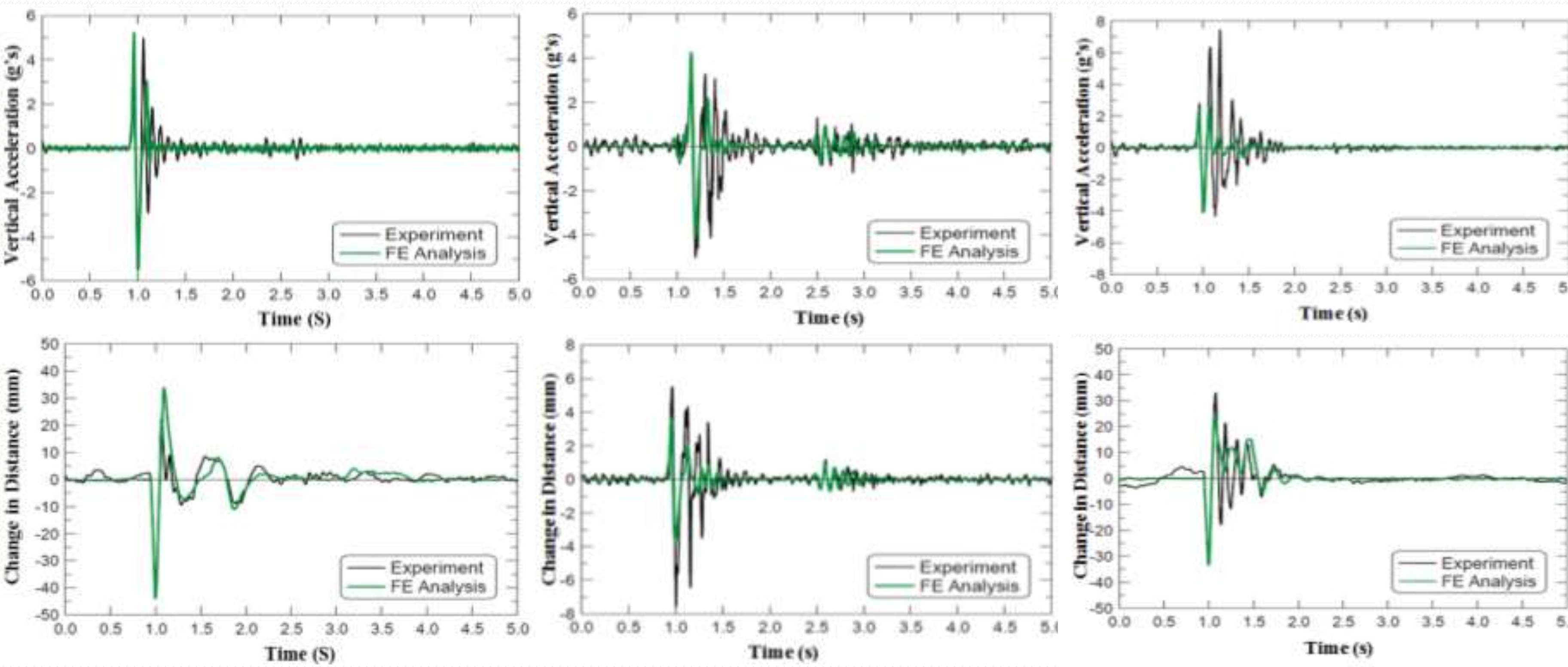


Mass Distribution of Heavy Vehicle – Using Rigid Wall Forces

Axle Type	Measured Load (N)	FE Model Load (N)	Relative Error (%)
Front Axle	46725	47456	1.56
Rear Axle 1	68553	68680	0.18
Rear Axle 2	72977	75984	4.12
Trailer Axle 1	82767	81800	-1.16
Trailer Axle 2	84101	87095	3.56
All Axles	355123	361015	1.65



Suspension parameters of Heavy Vehicle – Using Strain gages and accelerometers



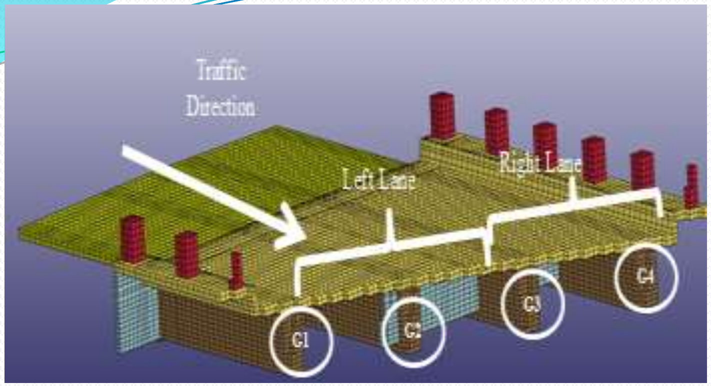
Task 2 – Dynamic Vehicle to Bridge Interaction using B-WIM and FE

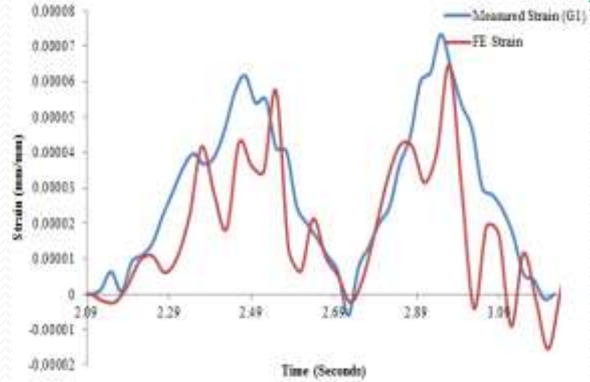
Heavy Vehicle to Bridge Interaction -

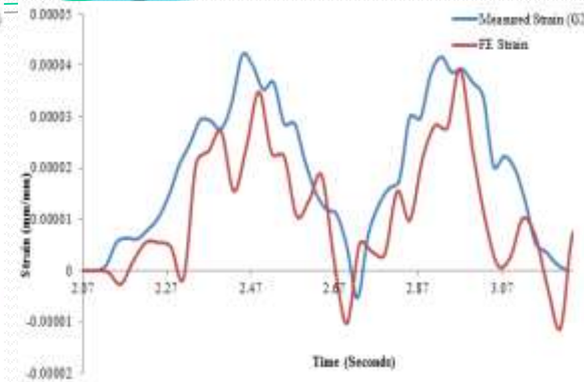
- AASHTO LRFD code specifies live load based on impact factor
  - Common impact factor for all the bridges regardless of nature of vehicular traffic
  - Do not account for vertical movement of the vehicles, vibrations
  - Do no account for suspension and damping parameters of the vehicles
- To observe the response of bridge under moving heavy vehicle loads and vibrations
- To simulate the FE model and validate the FE response with experimental B-WIM test

Considerations for the simulation-

- CONTACT_SURFACE_TO_SURFACE – for smooth transition of wheel over the bridge
- Transient dynamic analysis with truck velocity 55 mph
- Strain gages in the left and right lane and under the girders





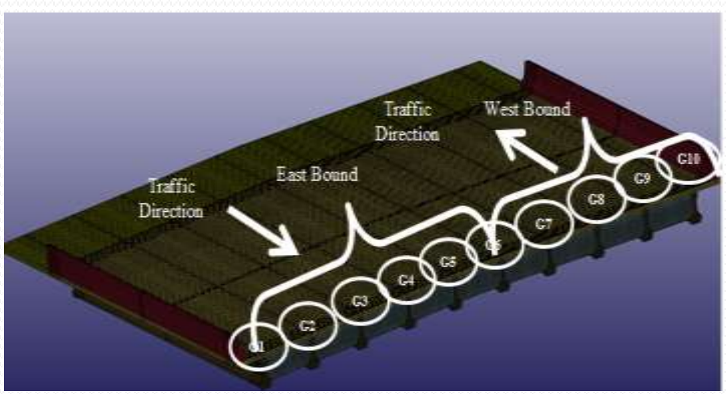


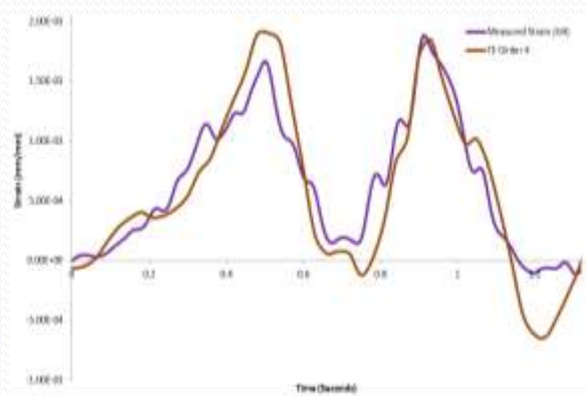
Weighing Sensor Location for US 78

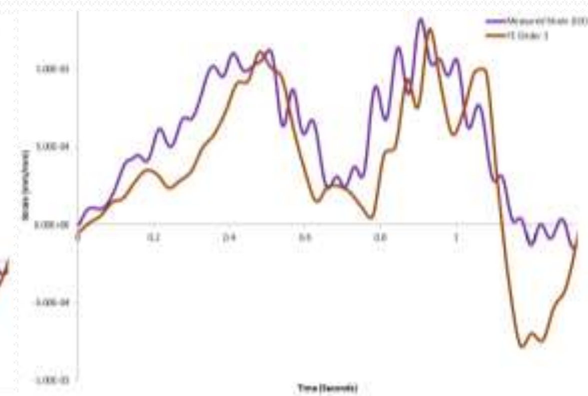
- Under G1, G2, G3 and G4
- Truck in Left Lane
- Comparison for G1 and G2 only

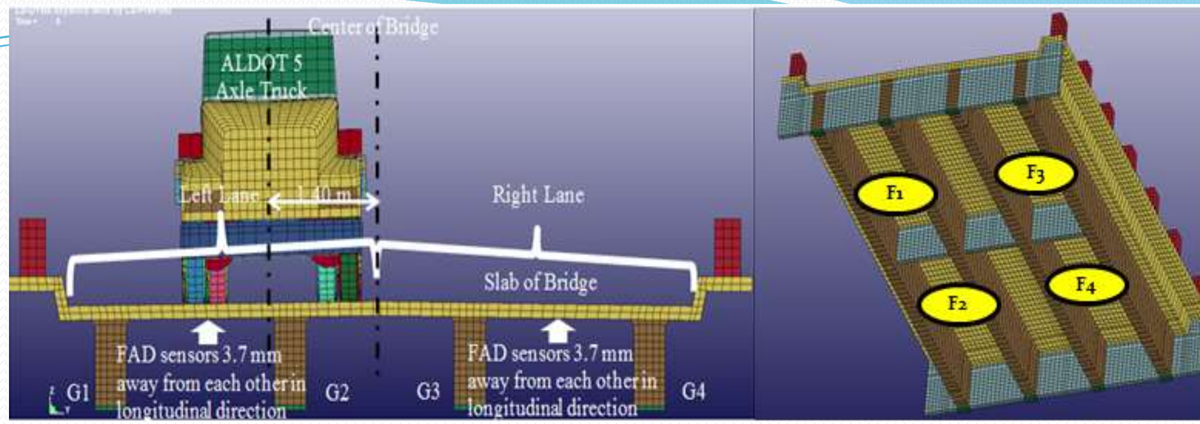
Weighing Sensor Location for I 459

- Under G3, G4, G5 and G6
- Truck in East Bound Fastest Lane
- Comparison for G4 and G5 only

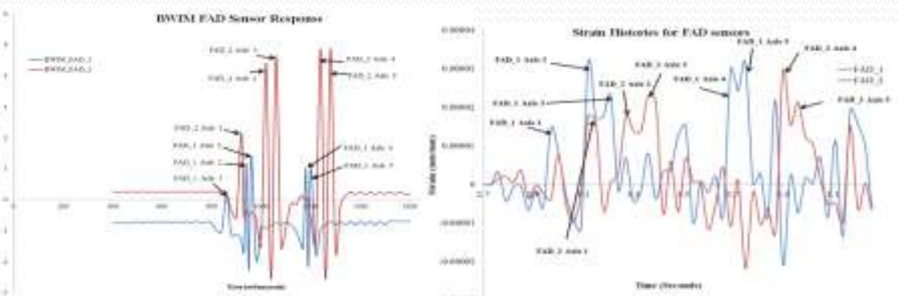




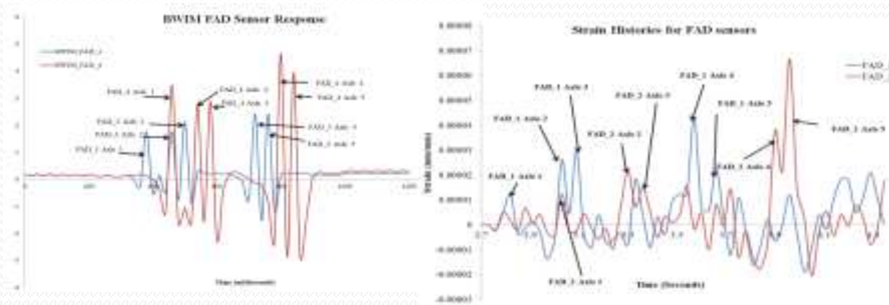




Location of FAD Sensors on US-78



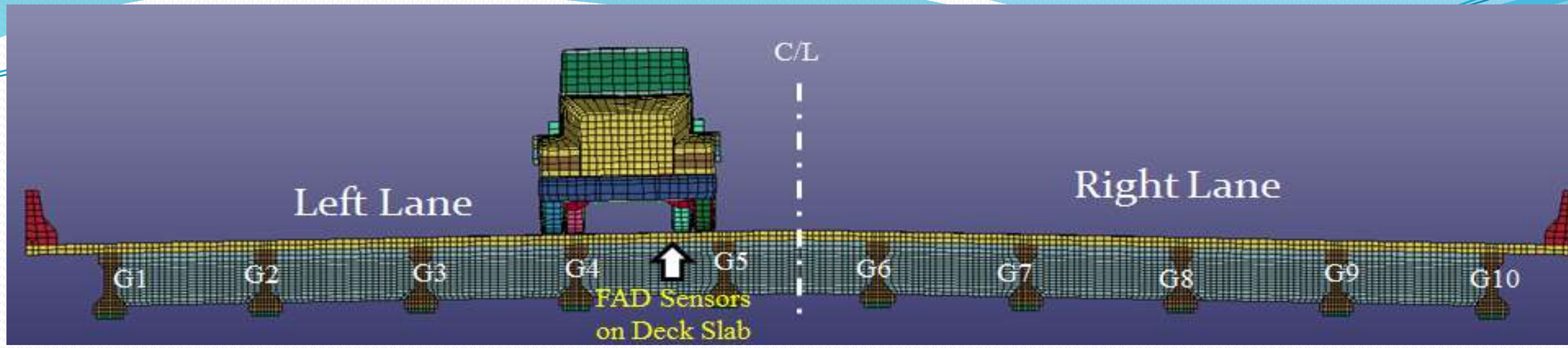
FAD Sensor Response of US 78 Bridge (Left Lane)



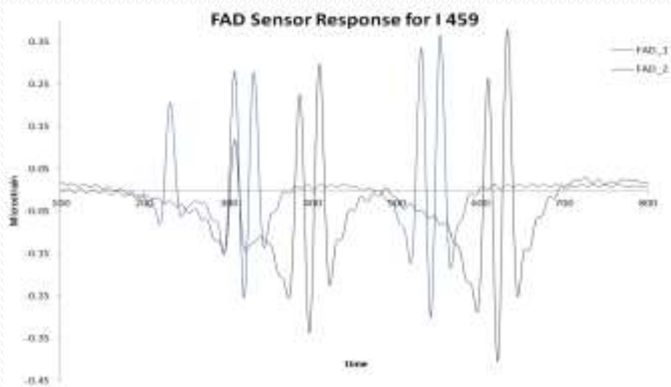
FAD Sensor Response of US 78 Bridge (Right Lane)

Summary of parameters of truck using FE and B-WIM

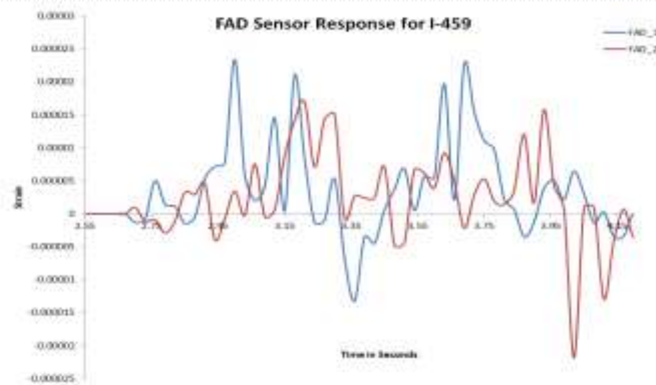
Method	T1 (s)	T2 (s)	D (m)	V (m/s)	A1-A2 (m)	A2-A3 (m)	A3-A4 (m)	A4-A5 (m)
BWIM	0.83	0.97	3.65	26.07	3.65	1.04	7.82	1.56
FE	2.97	3.12	3.65	24.33	4.13	1.70	11.67	1.45
Measured	-	-	3.65	24.58	4.27	1.32	11.54	1.22



Location of FAD Sensors on I 459



FAD Sensor Response of I 459 Bridge (Left Lane)



FAD Sensor FE Response of I 459 Bridge (Left Lane)

Summary of parameters of truck using FE and B-WIM

Method	T1 (s)	T2 (s)	D (m)	V (m/s)	A1-A2 (m)	A2-A3 (m)	A3-A4 (m)	A4-A5 (m)
BWIM	0.12	0.306	4.37	24.27	4.53	0.73	4.85	0.53
FE	**3.00**	**3.18**	**5.1**	**28.33**	**4.24**	**1.69**	**12.74**	**1.70**
Measured	-	-	3.65	24.58	4.27	1.32	11.54	1.22

- **Dynamic heavy vehicle to bridge interaction**
  - Validation using field calibrated data
  - Using FE simulation, reliable weighing sensor response
  - Successful axle detection using FAD sensor (When single truck present over bridge)

- **Disadvantages of dynamic heavy vehicle to bridge interaction using full 3D FE model**
  - FAD sensor did not show consistent peak values for both bridges
  - Total number of elements are 82669 and 314422 and therefore not possible to use in MFI algorithm
  - Dynamic properties used for MFI are not possible to extract from current model
  - Higher simulation time of 12 hours and 18 hours respectively for US 78 and I 459

Task 3 – Simplified Vehicle to Bridge Interaction FE Simulation

1) Simplified 5 Axle ALDOT Beam Mass Truck (5A-BM) model for ALDOT 5 Axle Truck and its validation

2) Approaches for FE Simulations

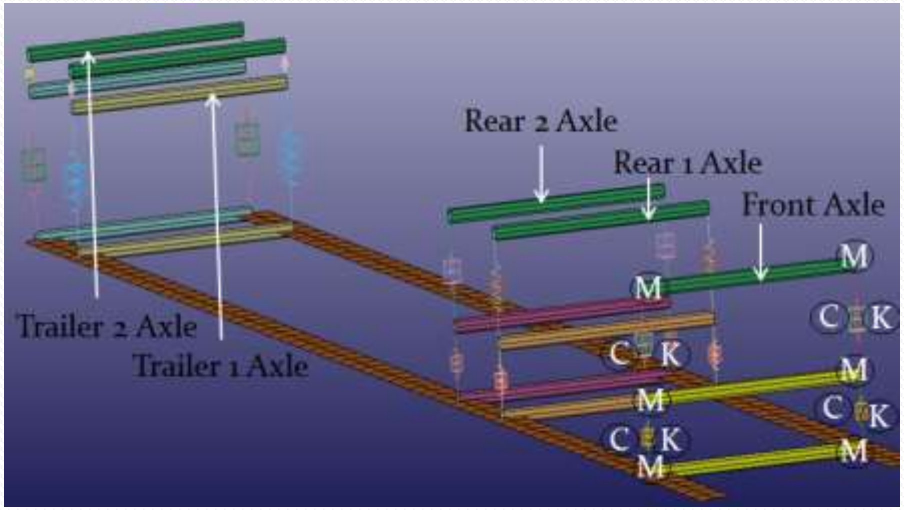
1. Approach 1: 5A-BM-3D Solid Bridge
2. Approach 2: 5A-BM-Composite Bridge
3. Approach 3: 5A-BM-Shell Beam Bridge
4. Approach 4: 5A-BM-Large Shell Beam Bridge

3) Effect of surface roughness

*Only US 78 is considered for Simplified Vehicle to Bridge Interaction FE Simulation in this presentation

1) Simplified 5 Axle ALDOT Beam Mass Truck (5A-BM) model for ALDOT 5 Axle Truck and its validation

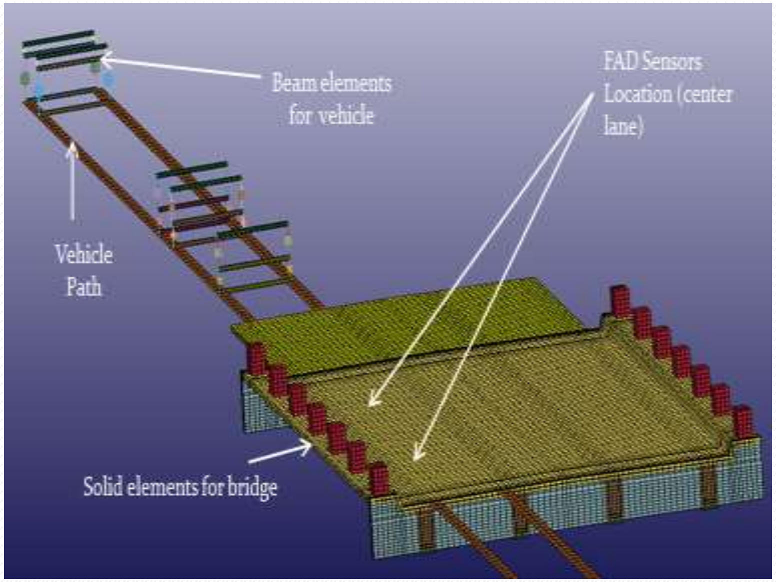
- 30 mass elements (M), 20 discrete elements for each suspension (K) and damping (C).
- Only axles are considered and the frame of the truck removed for analysis

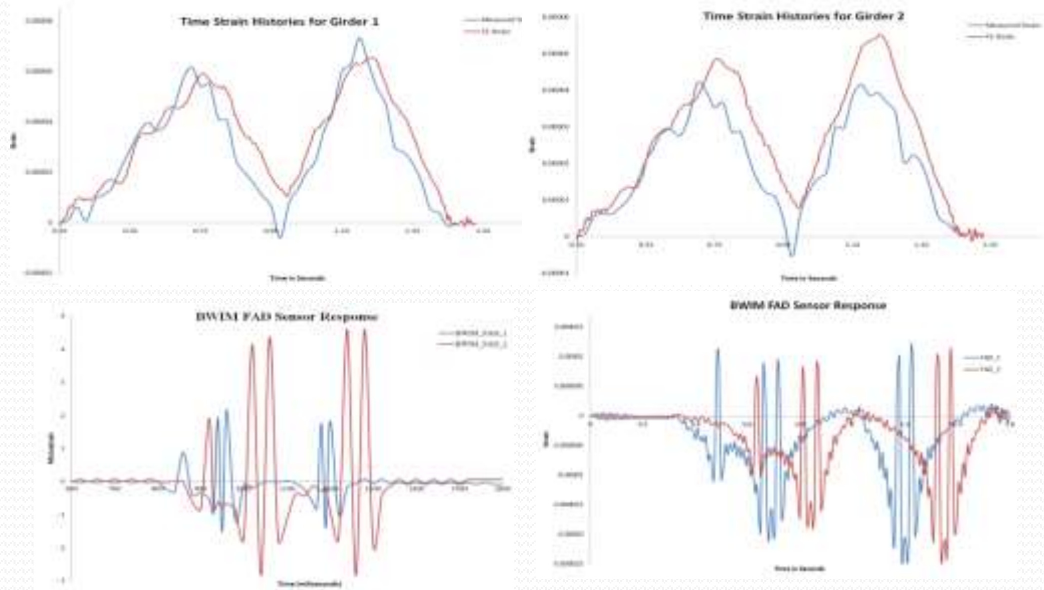


Axle No.	Axle Type	Measured Load (N)	FE Model Load (N)	Relative Error (%)
1	Front Axle	46725	45834	1.90
2	Rear Axle 1	68553	66405	3.13
3	Rear Axle 2	72977	70240	3.75
4	Trailer Axle 1	82767	80641	2.56
5	Trailer Axle 2	84101	82628	1.75
Gross Reaction	All Axles	355123	345748	2.63

2) Approaches for FE Simulations

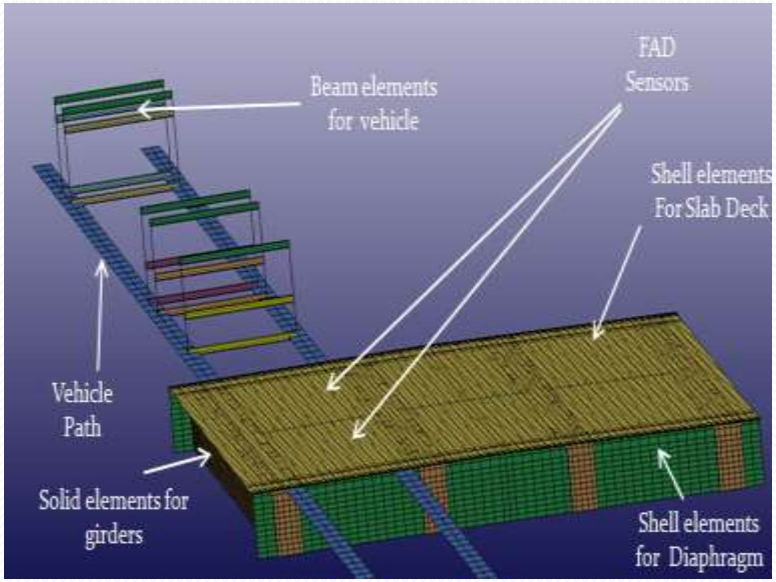
1. Approach 1: 5A-BM-3D Solid Bridge

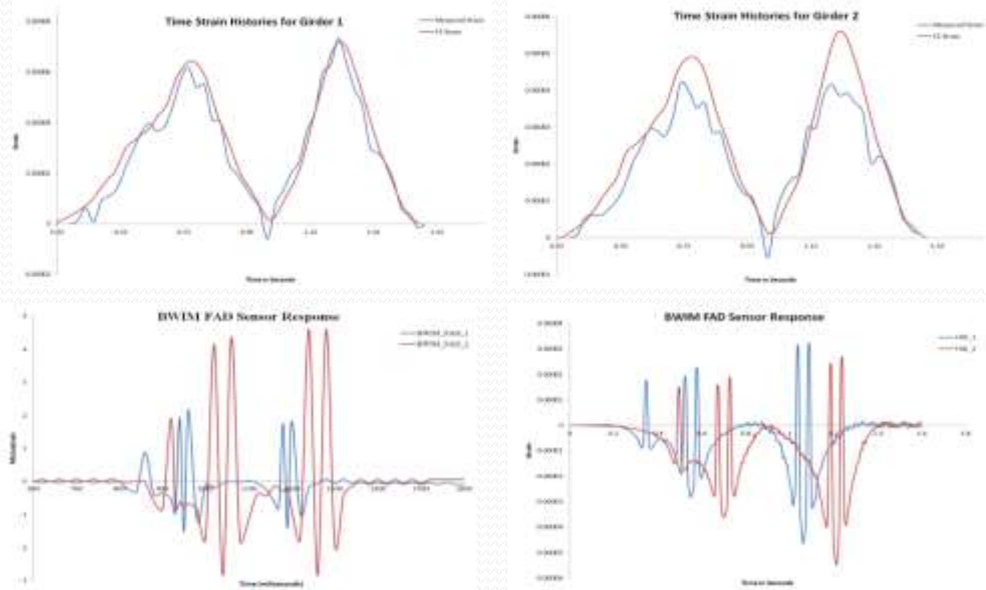




- Rail elements for the predefined path of the vehicle and solid elements for 3D bridge
- Weighing sensor for Girder 1shows comparable results with the experimental values
- Successful axle detection using FAD sensor (When single truck present over bridge)
- Simulation time reduced to 15 minutes compared to 12 Hours
- Number of elements – 60396
- Dynamic properties used for MFI are not possible to extract from current model

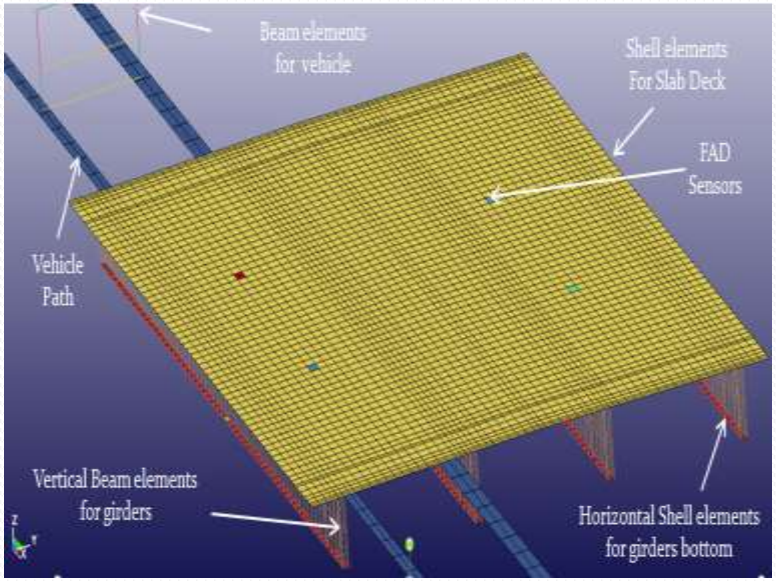
2. Approach 2: 5A-BM-Composite Bridge

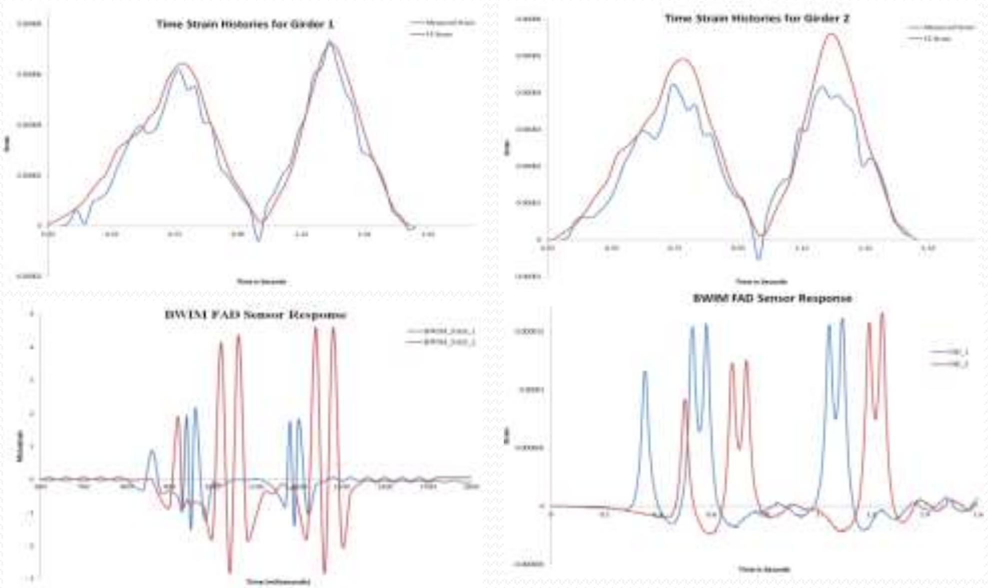




- Solid elements for Girder and Diaphragm, Shell elements for slab
- Weighing sensor for Girder 1show comparable results with the experimental values
- Successful axle detection using FAD sensor (When single truck present over bridge)
- Simulation time reduced to 9 minutes compared to 12 Hours
- Number of elements – 22195
- Dynamic properties used for MFI are not possible to extract from current model

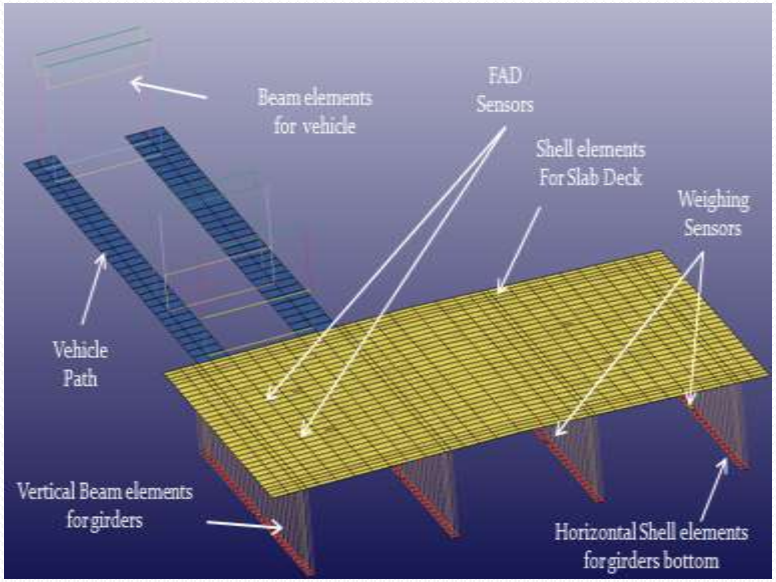
3. Approach 3: 5A-BM-Shell Beam Bridge

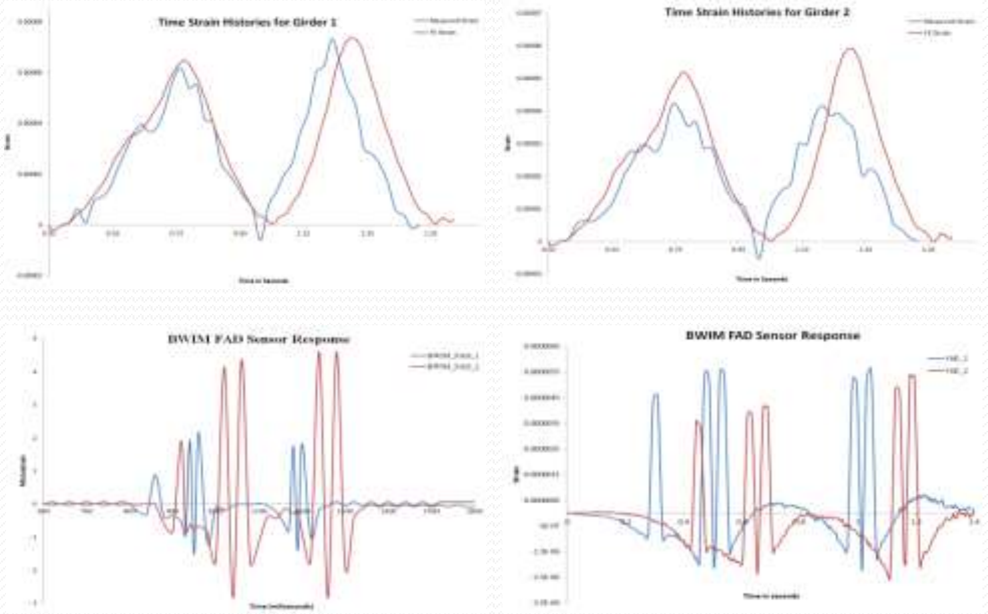




- Beam elements for Girder, shell elements for slab, Girders constrained in lateral direction
- Weighing sensor for Girder 1show comparable results with the experimental values
- Successful axle detection using FAD sensor (When single truck present over bridge)
- Simulation time reduced to 3 minutes compared to 12 Hours
- Number of elements – 13175
- Dynamic properties used for MFI are not possible to extract from current model

4. Approach 4: 5A-BM-Large Shell Beam Bridge





- Beam elements for Girder, shell elements for slab, Girders constrained in lateral direction
- Weighing sensor for Girder 1show comparable results with the experimental values
- The response of the FAD sensors are not sharp due to larger element size
- Simulation time reduced to 1 minutes 30 Seconds compared to 12 Hours
- Number of elements – 2469
- This model will be used for extraction of mass matrix, and stiffness matrix

Extraction of Mass and Stiffness Matrix:

- US 78 bridge with 1942 total number of elements were used for the extraction
- Implicit analysis using Eigenvalue was carried out using LS DYNA
- The mode shapes and natural frequencies were obtained from LS DYNA
- From LS DYNA the output for M and K matrix were obtained
- Rayleigh Damping will be used for obtaining damping (C) matrix

$$\alpha = \frac{2\omega_i \omega_j}{\omega_j^2 - \omega_i^2} \omega_j \xi_i - \omega_i \xi_j$$

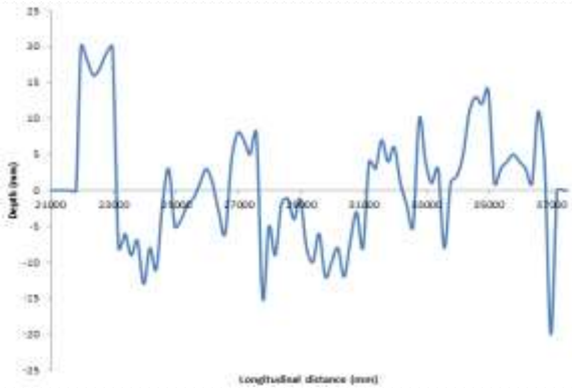
$$\beta = \frac{2}{\omega_j^2 - \omega_i^2} \omega_j \xi_j - \omega_i \xi_i$$

$$\xi = \frac{\alpha}{2\omega_i} + \frac{\beta \omega_i}{2}$$

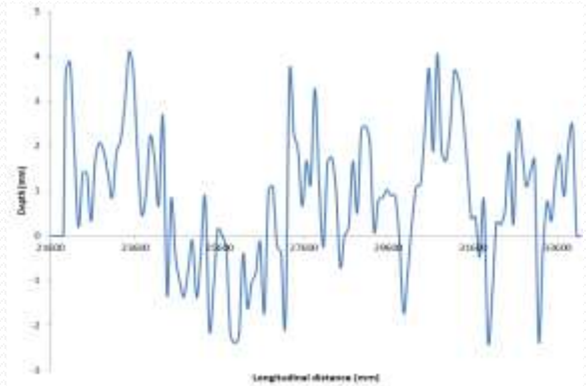
Work is in progress

3) Effect of surface roughness

1. Roughness measured at site by previous researchers
2. AASHTO Road Test Pavement Serviceability Rating as defined in the brackets

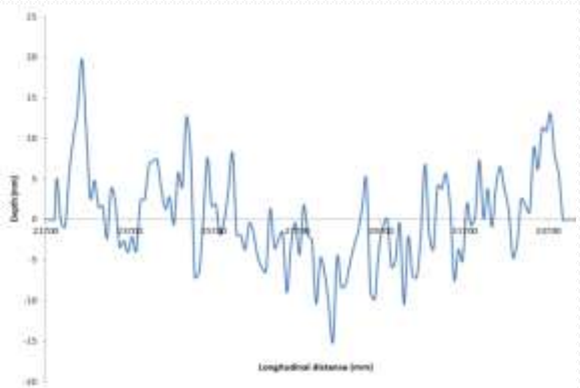


Measured Roughness

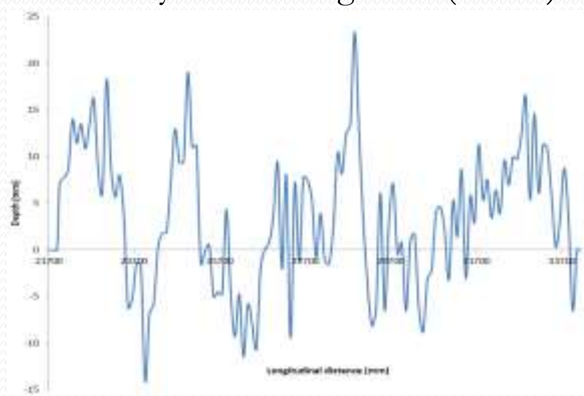


Very Good Roughness (PSR-5)

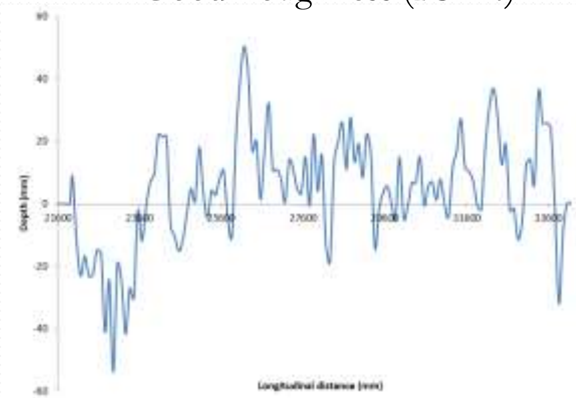
Good Roughness (PSR-4)



Average Roughness (PSR-3)



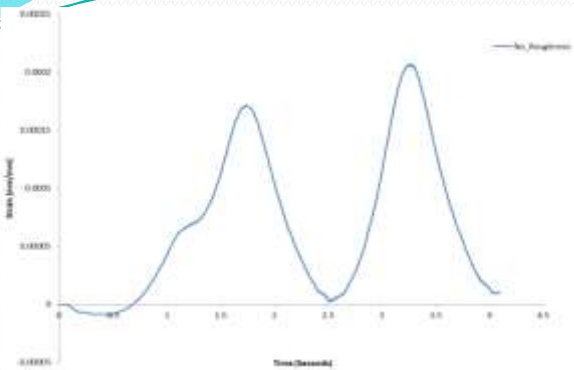
Poor Roughness (PSR-2)



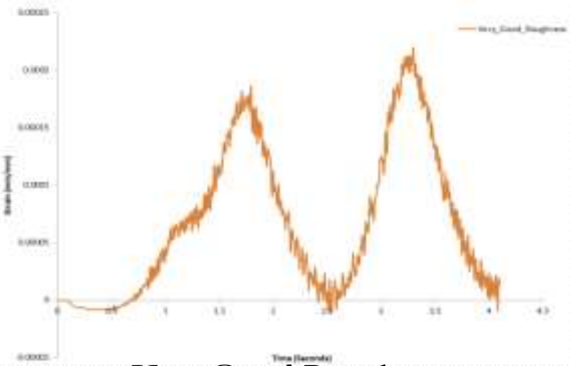
Very Poor Roughness (PSR-1)

http://classes.engr.oregonstate.edu/cce/winter2012/ce492/Modules/09_pavement_evaluation/09-2_body.htm
Journal of Bridge Engineering, Characteristics and dynamic impact of overloaded extra-heavy trucks on typical highway bridges

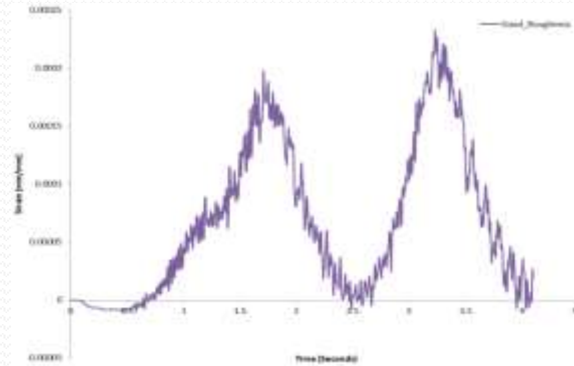
Effect of surface roughness:- Response of Girder 1



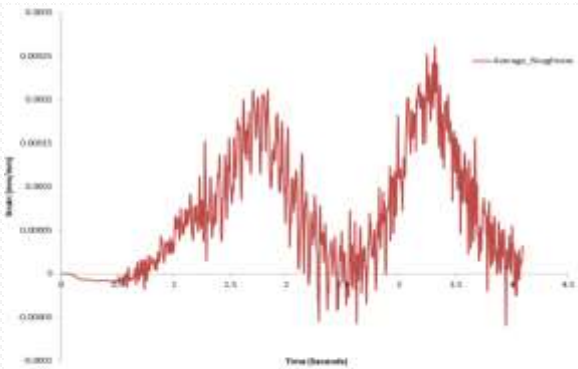
No Roughness



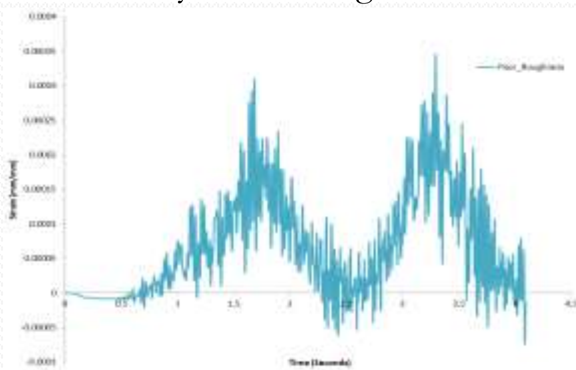
Very Good Roughness



Good Roughness

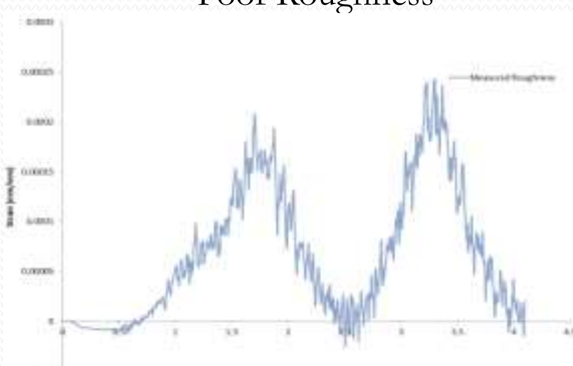


Average Roughness



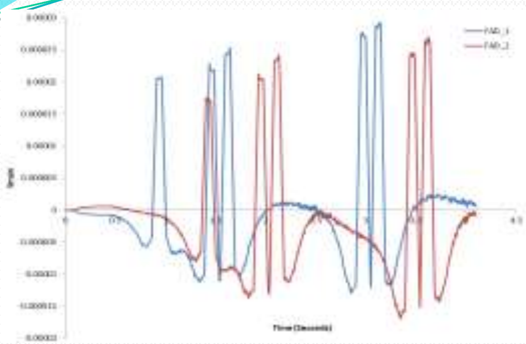
Poor Roughness

Very Poor Roughness

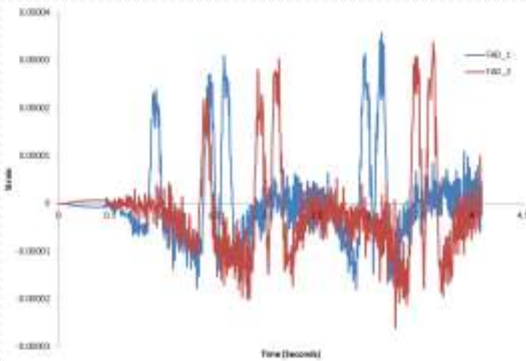


Measured Roughness

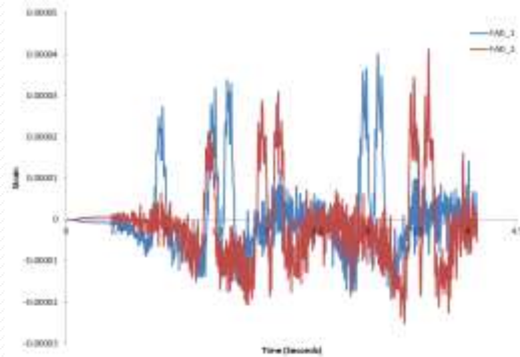
Effect of surface roughness:- FAD Sensor Response



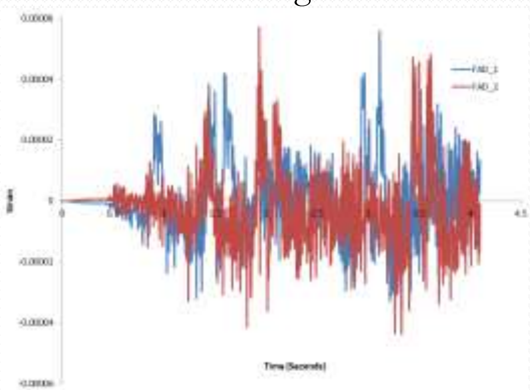
No Roughness



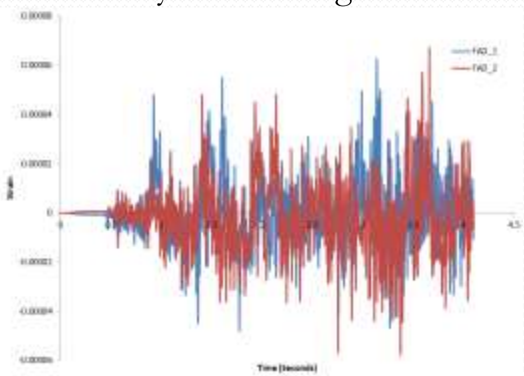
Very Good Roughness



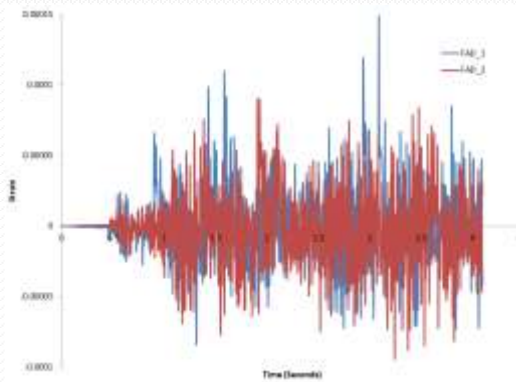
Good Roughness



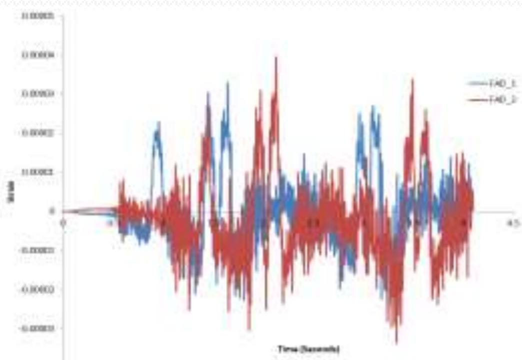
Average Roughness



Poor Roughness



Very Poor Roughness



Measured Roughness

Thank You!

Questions?