Numerical Train-Structure Interaction Analysis of a Floating Bridge and its Correlation with Full-Scale Test

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Objective:

1. Numerical train-structure interaction analysis of a floating bridge
2. Numerical analysis of a multi-movement rail joint and Track Bridge System designed for the bridge
3. Truck load test Results
4. Component test results of the Track Bridge
5. Full-scale in-track test results of the Track Bridge

Contents

Introduction

- Built in 1989, the widest and fifth-longest floating bridge in the world

- Carries westbound and reversible lanes of Interstate 90 between Seattle and Mercer Island, Washington.

- Length: 5,811 feet (1772 m)

- The south reversible express lanes are being converted to light rail permanent way in 2015.

East Link Project Features

- Installation of Light Rail Transit Tracks (LRT) on the floating bridge with no precedent in the civil engineering practice

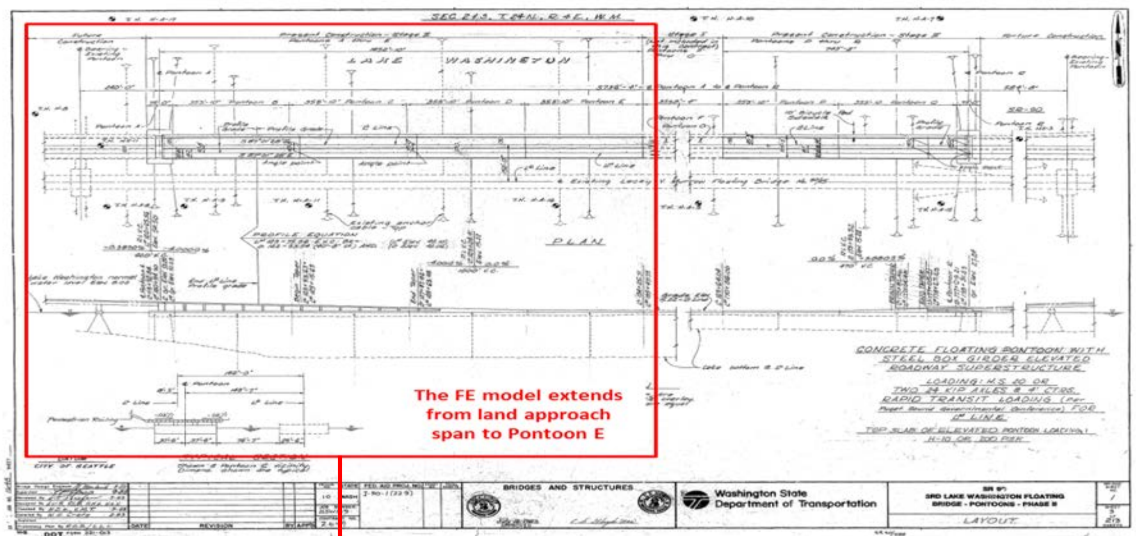
- Design of a Track Bridge (TB) system to accommodate multidimensional movements at the existing expansion joints

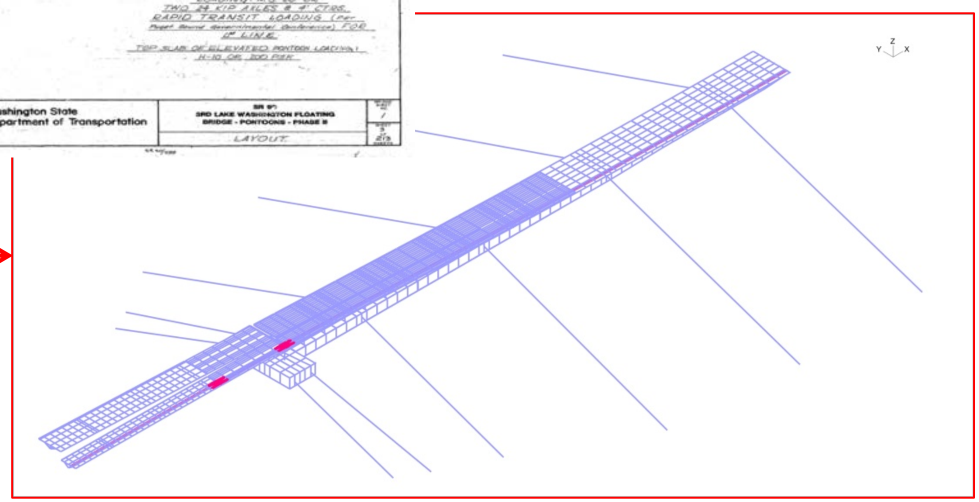
- Detailed finite element modeling of the floating bridge, train and TBs

Bridge Model Development

The FE model of the bridge includes:

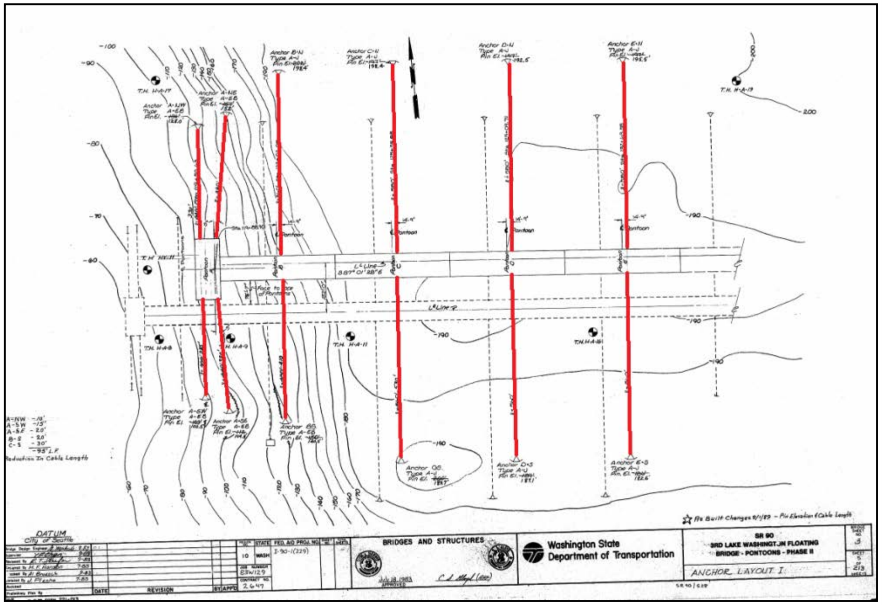
- Approach, transition and floating spans of the west side of the bridge with total length of 2100 feet (640m)

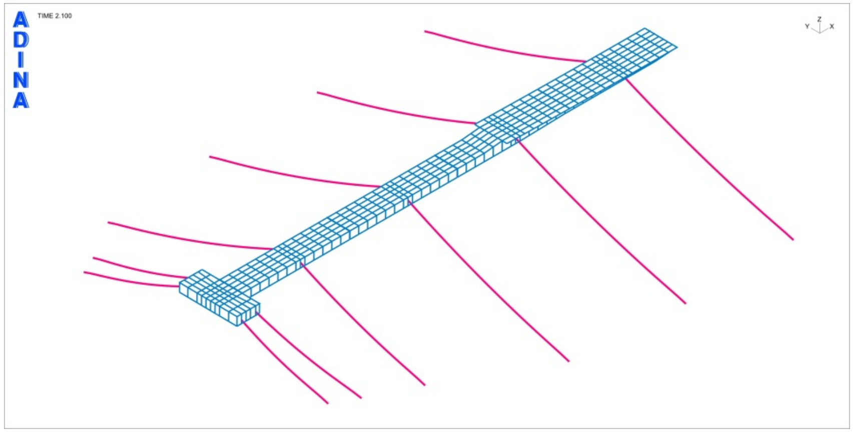




Anchors and Floatation

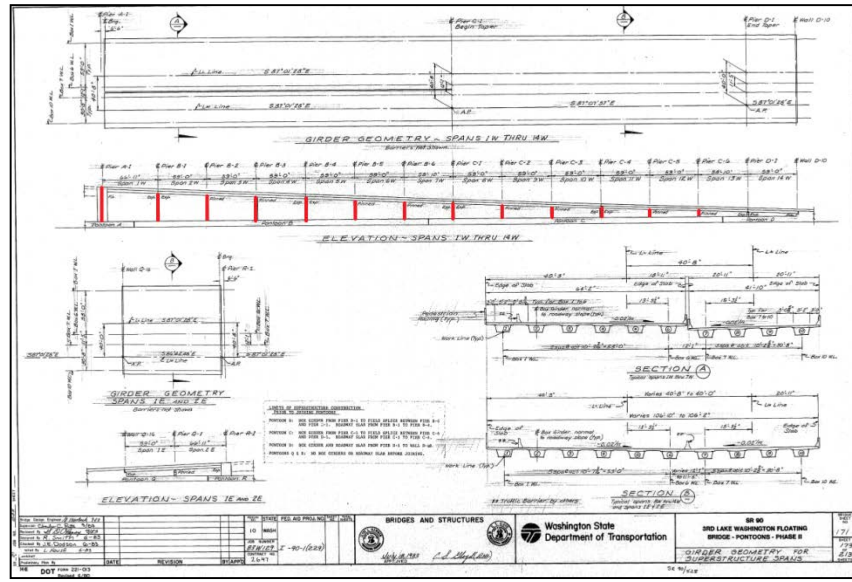
Anchors (beam elements with large displacements)
15 beam element for anchors at A-1
20 beam elements for the rest of anchors
Compression-only springs to simulate water

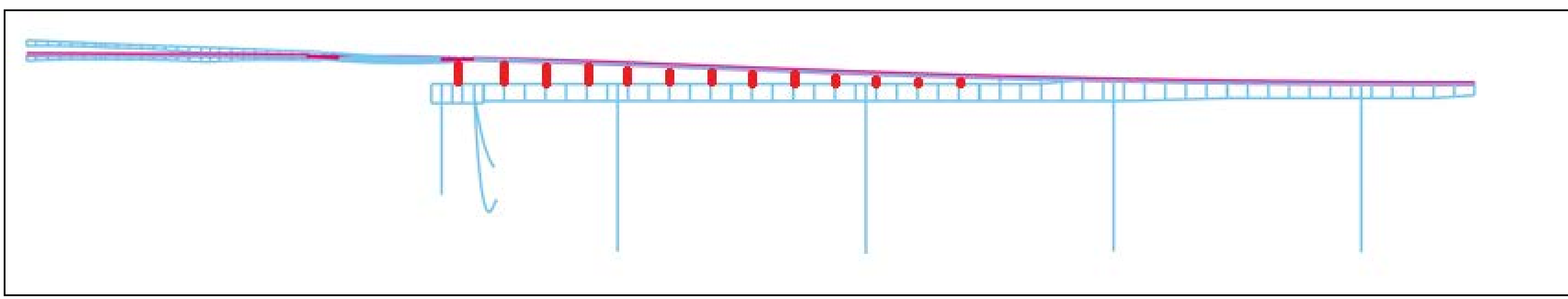




Piers

- Piers (Linear Elastic Beam Elements)
- Integral Connection between Piers and Pontoons

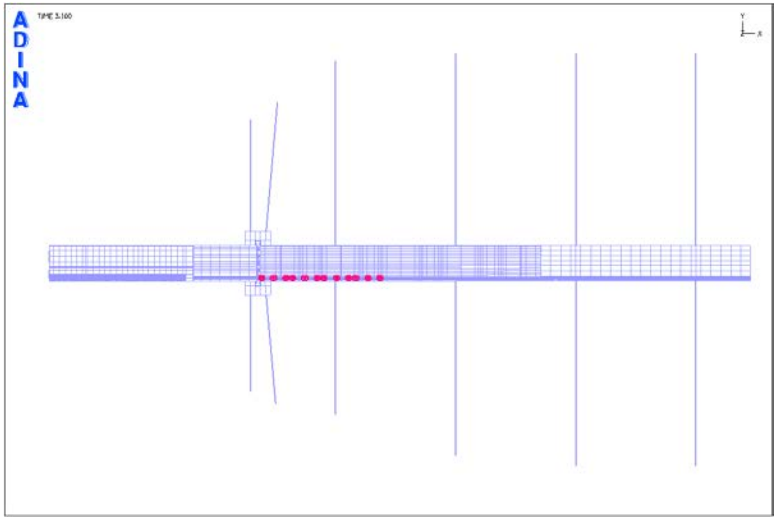


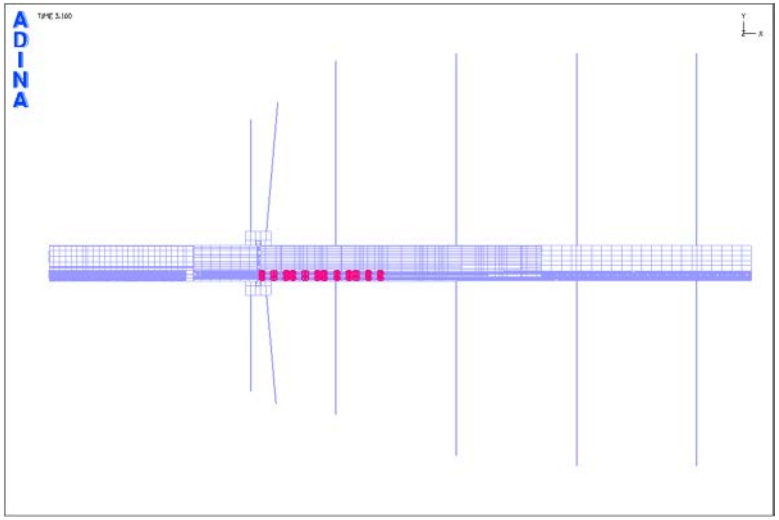


Bridge model validation based on physical test results

- A set of full scale load tests on the I-90 bridge simulating train loading (WSDOT and KPFF Consultants).
- Four flatbed trucks that were loaded to approximate the weight of a train.
- Two loading cases were used for the purpose of calibration and validation of the FE model of the bridge

Case S8: Four trucks simulating a train parked on the south side of the floating bridge





Case S7: Two sets of four trucks simulating two trains parked parallel

Bridge Model Development

Bridge FE model validation based on physical test results

- Measured parameters
  - Anchor cable forces
  - deck vertical movements
  - Pontoon rotations

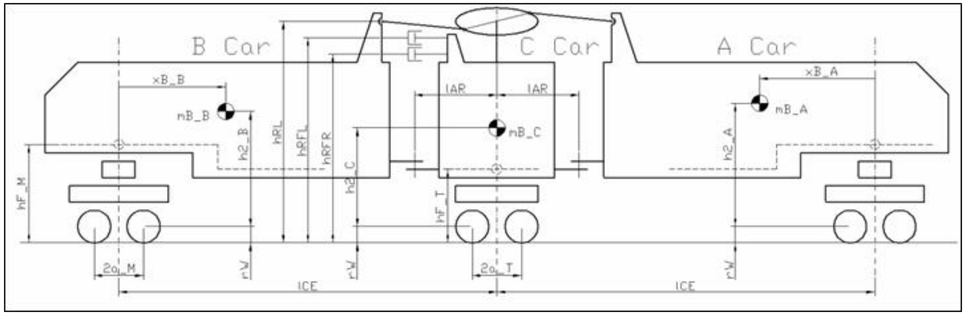
- Updating parameters
  - Initial strains of the cables (to achieve measured cable forces)
  - Stiffness of the elements connecting adjacent pontoons

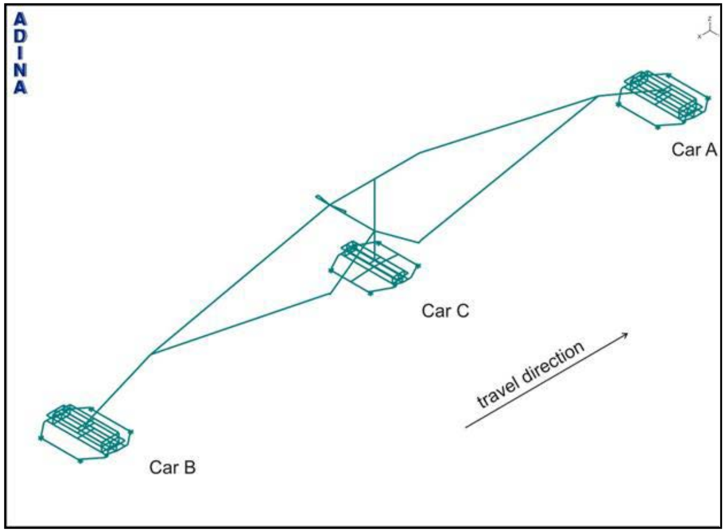
- Case S8: Used to calibrate the FE model
- Case S7: Used to validate the calibrated model

Loading	Case	Pontoon Connection Stiffness (Kips/ft)	Deck Ver. disp. in (cm)	Pontoon A Rot. (degrees)	Pontoons A&B Rel. Disp. In
S8	FE3	1.5E5	4.15	0.16	0.04
	Exp1	-	4.10	0.18	-
S7	FE4	1.5E5	7.40	0.25	0.058
	Exp2	-	7.50	0.29	-

LRV Model Development

- Light Rail Vehicle: A three-section passenger vehicle with articulation joints between the bodies
- Finite element model includes: Car bodies, Bolsters, Bogies, axles, axle Boxes and Wheels Connections
- The primary suspension system: A set of springs representing longitudinal, vertical, and lateral stiffness as well as damping characteristics of the system
- The secondary suspension system: an air suspension consisting of airbags and air reservoirs which were simulated by nonlinear springs and dashpots





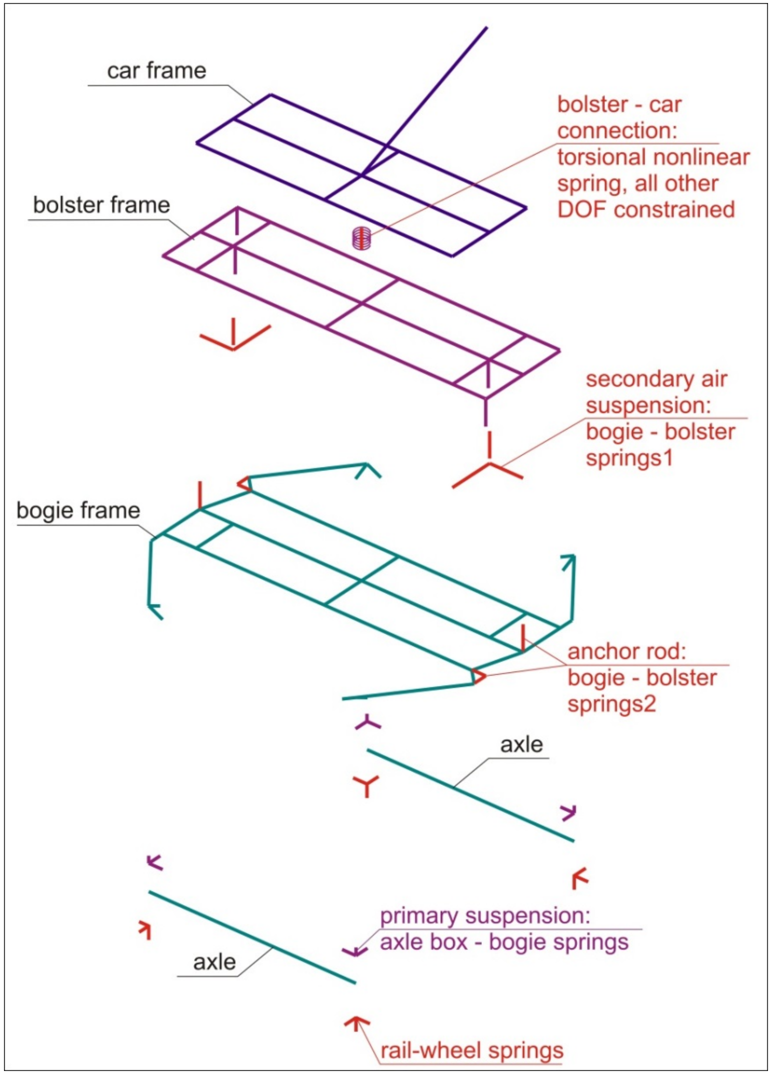
LRV Model Development

Car Body to Bolster Connection
Torsional Springs

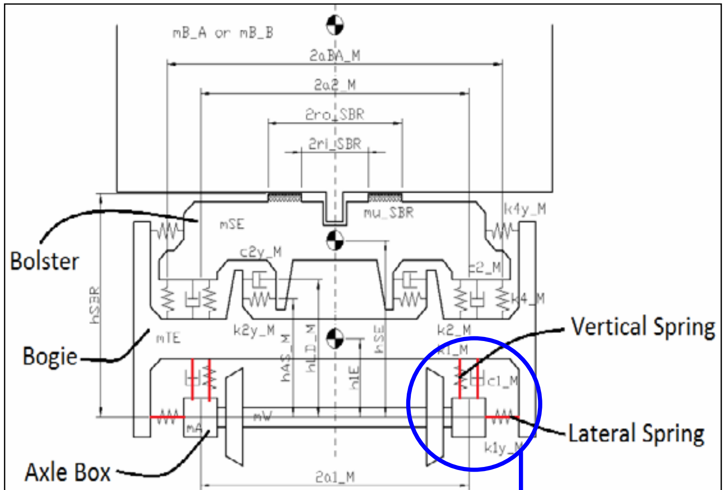
Bolster to Bogie Connection
Secondary Air Suspension
Anchor Rods

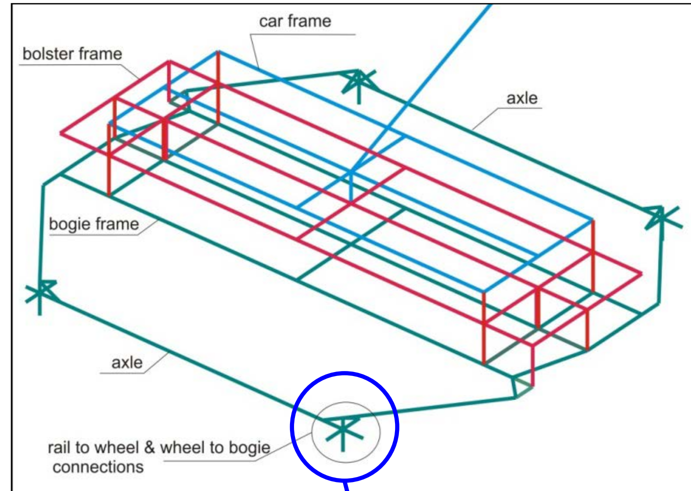
Bogie to Axle Box Connection
Primary Suspension
Axle Link (for Car C only)

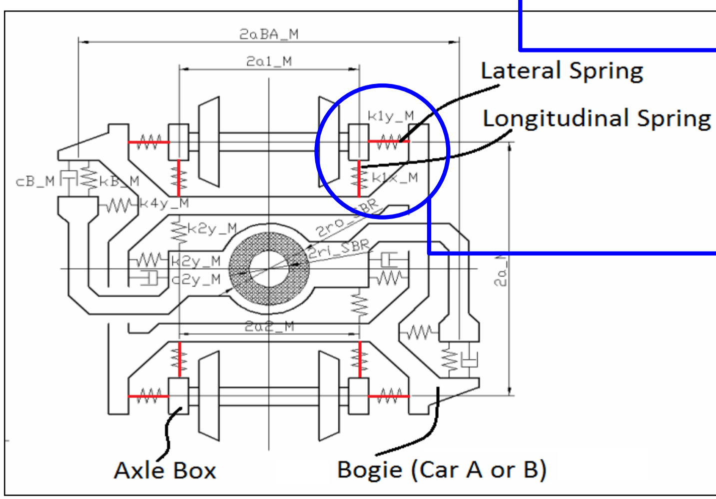
Inter-car Connection
Articulation Damping
Inter-car Z-link
Articulation Bushing

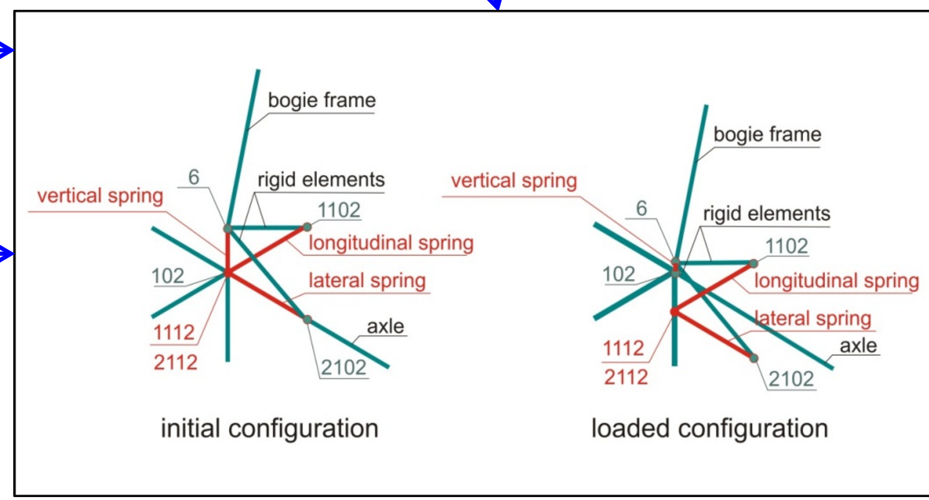


Bogie to Axle Box Connection (Primary Suspension)



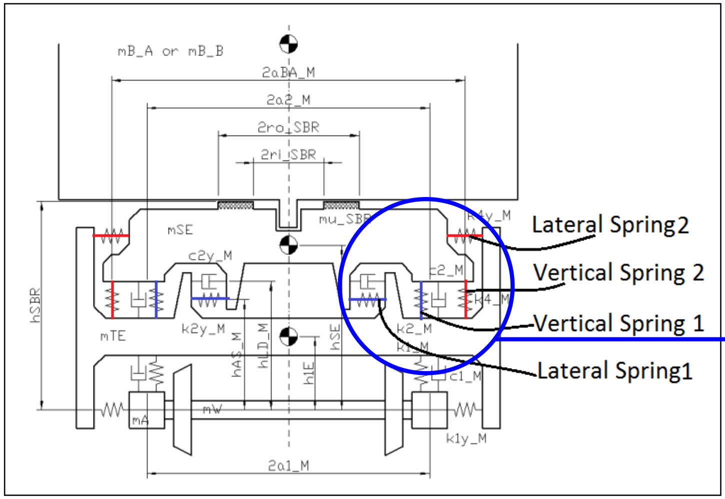


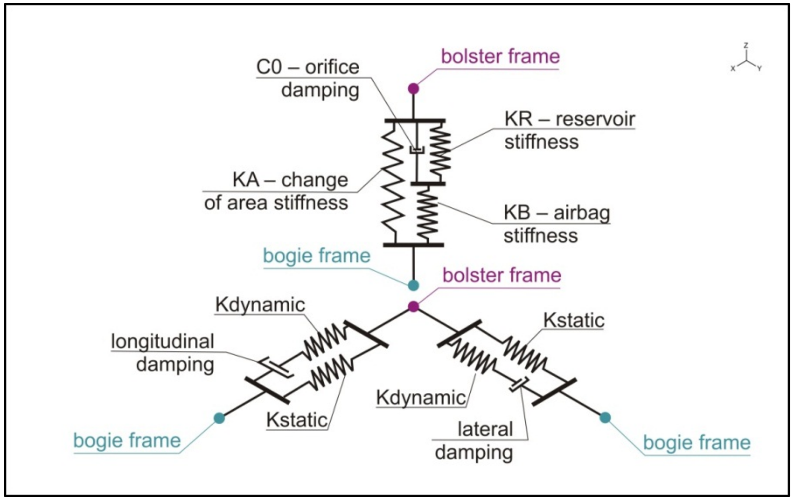


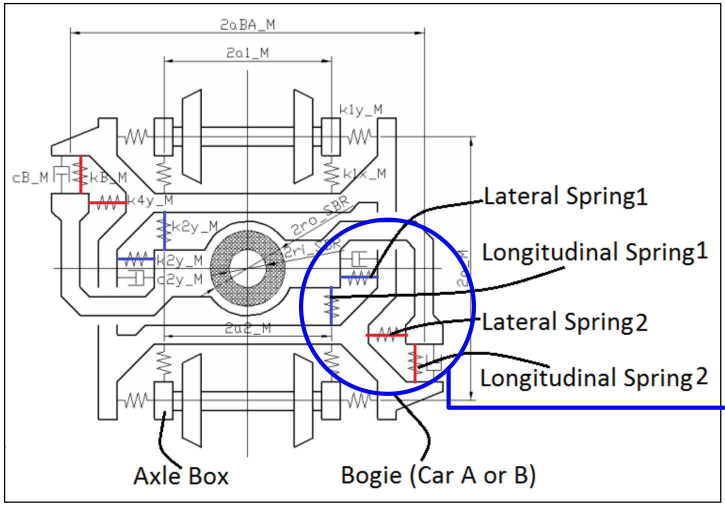


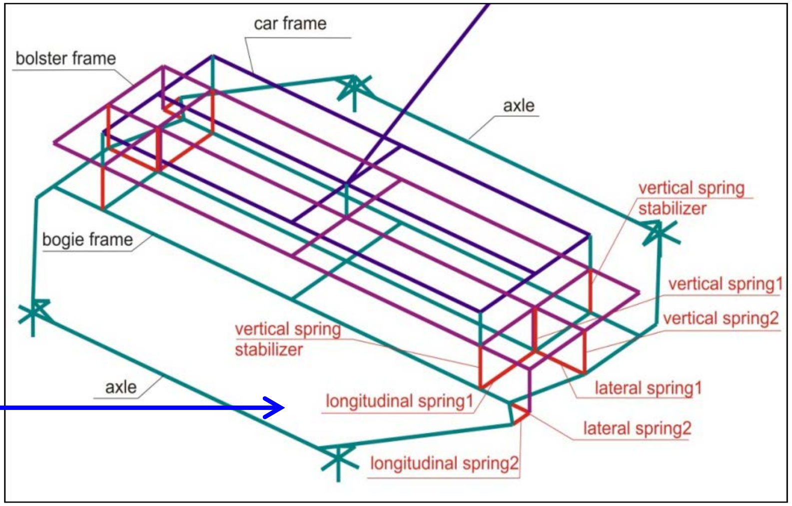
LRV Model Development

Bolster to Bogie Connection (Secondary Suspension)

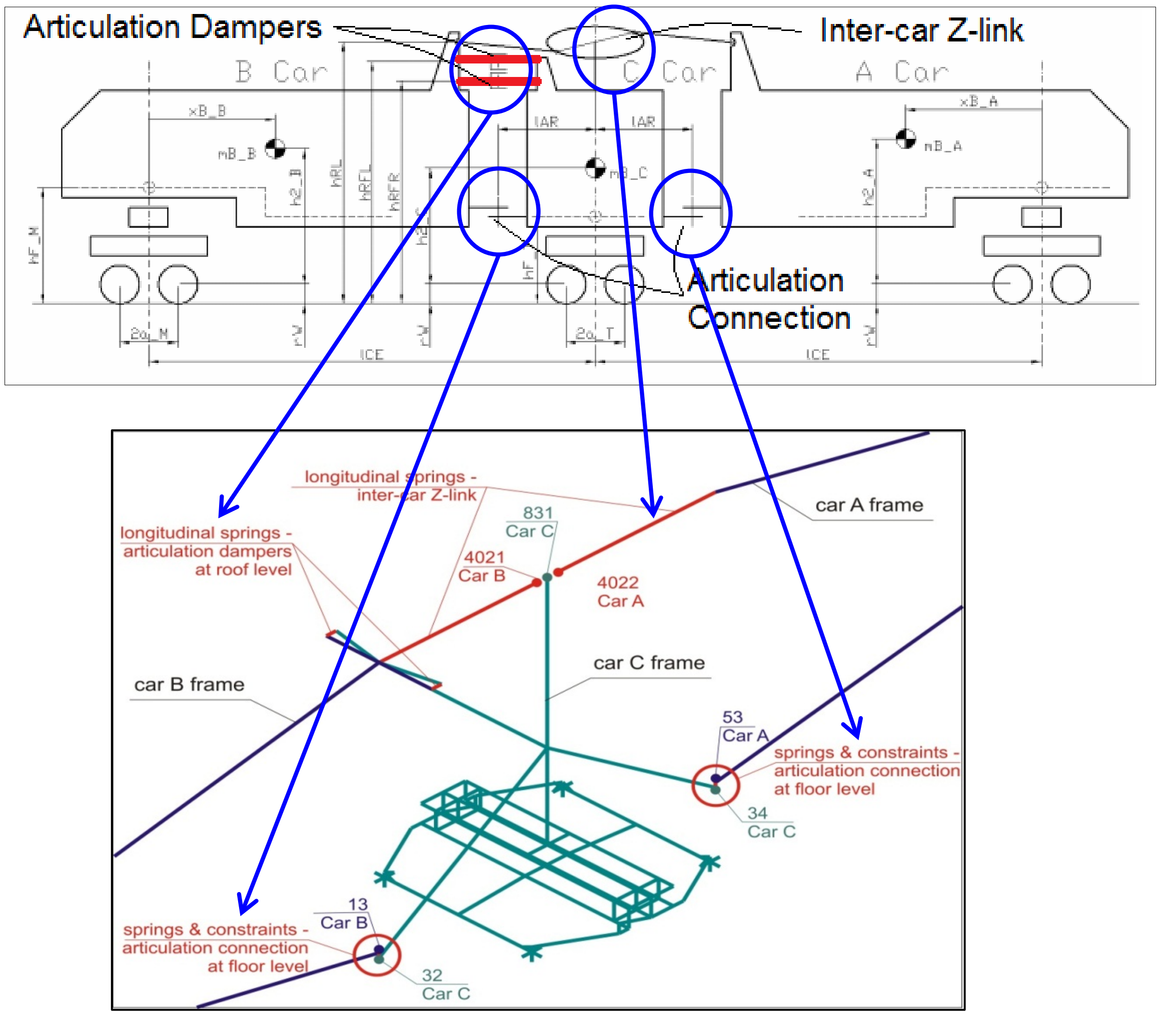








Car Frames A and B to C Connection



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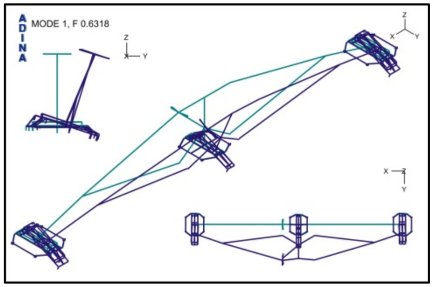
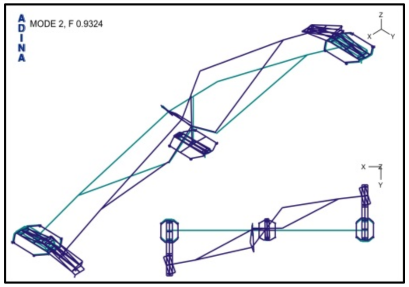
LRV Model Development

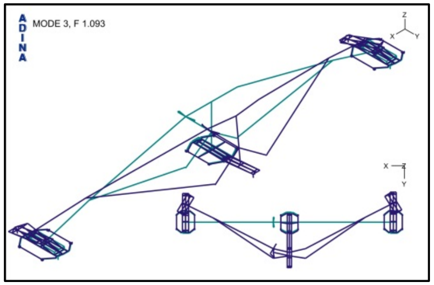
Mode Number	Frequency (Hz)	MPF-X (%)	MPF-Y (%)	MPF-Z (%)	Description
1	0.632	0.0	62.0	0.0	In-phase roll (lower center)
2	0.932	0.0	0.0	0.0	In-phase yaw
3	1.093	0.0	0.1	0.0	Out-of-phase yaw
4	1.202	0.0	0.0	73.9	In-phase bounce
5	1.267	4.8	0.0	0.5	Out-of-phase bounce
6	1.368	0.9	0.0	4.5	Out-of-phase bounce: car C moves in opposite direction from cars A and B
7	1.641	0.0	15.3	0.0	In-phase roll (upper center)
8	1.854	93.5	0.0	0.0	In-phase surge (all cars longitudinal motion)
9	2.150	0.0	0.0	0.0	Zig-zag yaw & out-of-phase roll (Car C is still)
10	4.615	0.0	0.0	0.0	Out-of-phase roll (lower center) & out-of-phase yaw
11	6.025	0.0	0.0	0.0	Zig-zag yaw & out-of-phase roll (Car C yaw)
12	6.624	0.0	0.0	0.0	Car B bogie pitch
13	6.634	0.0	0.0	0.0	Car A bogie pitch
14	7.484	0.0	0.0	0.0	Car C bogie pitch
15	8.235	0.0	0.0	4.2	Car A bounce
16	8.242	0.0	0.0	5.7	Car B bounce
17	9.589	0.0	11.2	0.0	In-phase bogie sway: Car A and B bogies lateral motion
18	9.589	0.0	2.2	0.0	Out-of-phase bogie sway: Car A and B bogies lateral motion
19	11.663	0.0	0.0	0.0	Out-of-phase pitch & car B bogie surge
20	12.349	0.1	0.0	0.0	In-phase pitch & out-of-phase car bogie surge



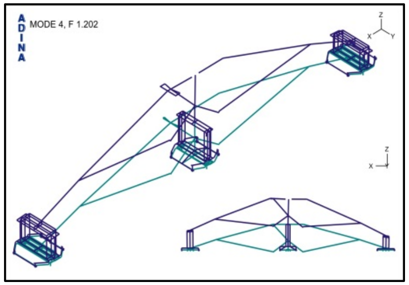
Mode 1
In-phase roll (lower center)



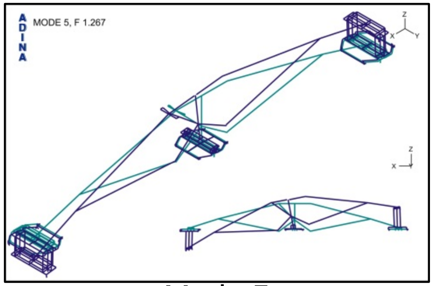
Mode 2
In-phase yaw



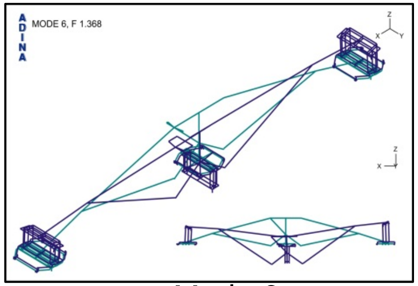
Mode 3
Out-of-phase yaw



Mode 4
In-phase bounce



Mode 5
Out-of-phase bounce

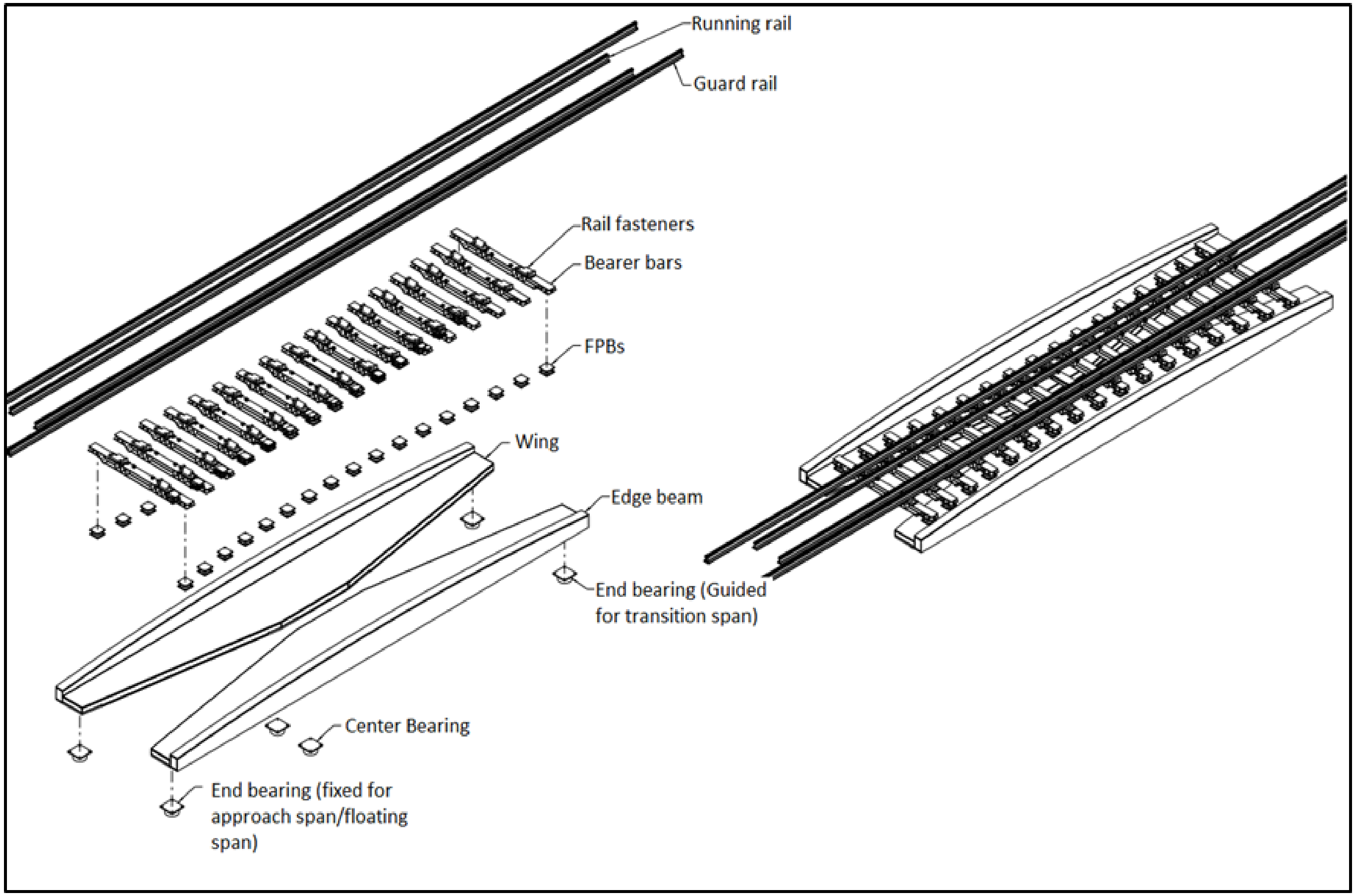


Mode 6
Out-of-phase bounce
Car C moves in opposite direction

TB Model Development

Track Bridge (TB) components

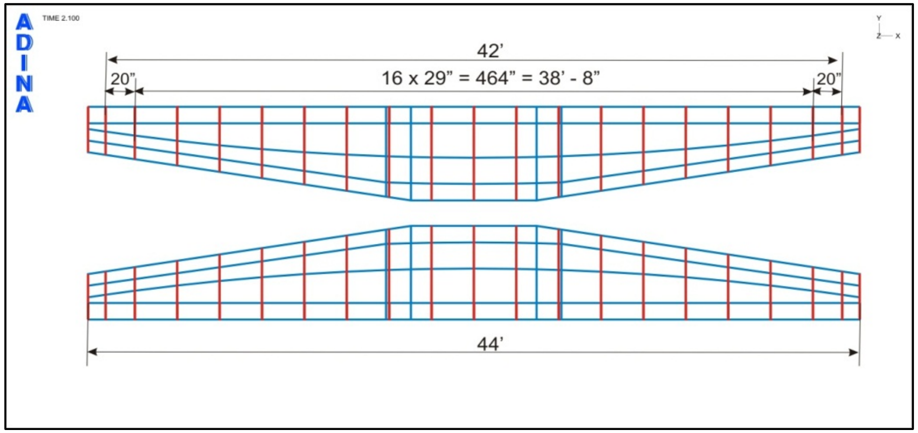
- Wings, Edge Beams, Stiffeners, Bearer Bars, FPBs, Rail fasteners

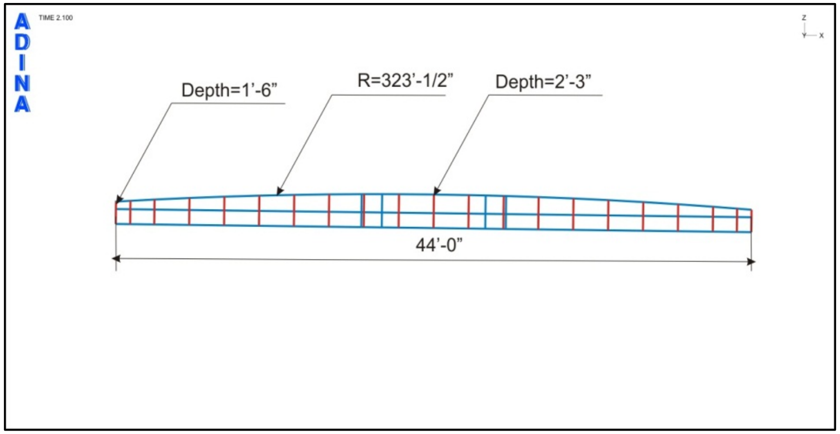


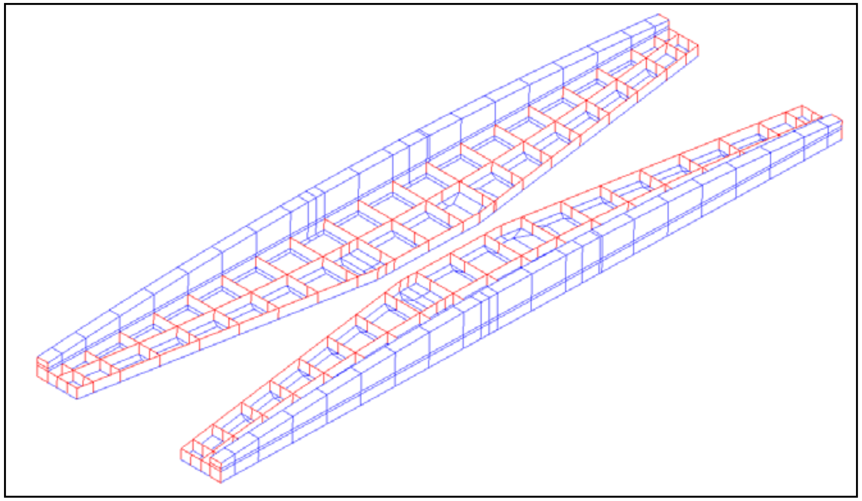
TB Model Development

FE model of the TB

- Wings (shell elements)
- Edge Beams (shell elements)
- Vertical Stiffeners (shell elements)





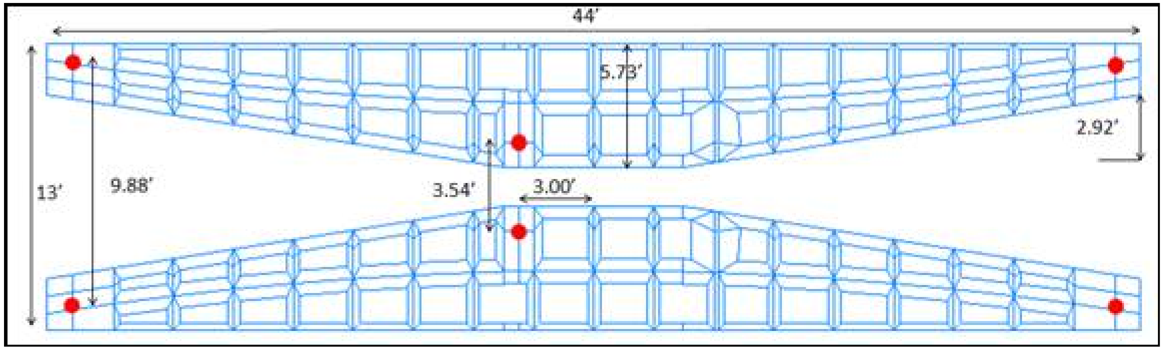


TB Model Development

TB Boundary Conditions

- At center support, the support is only vertical
- At floating end, the support is fixed in all three translational DOFs
- At transition span, the support is fixed in transverse and vertical (longitudinal is free)
- All rotational DOFs are free

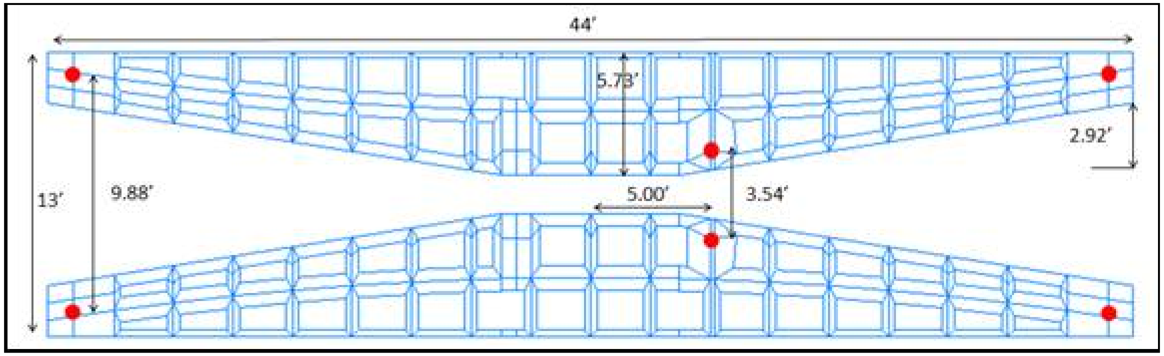
West Approach
(west)



Exterior Joint

Transition end
(west)

Transition end
(west)

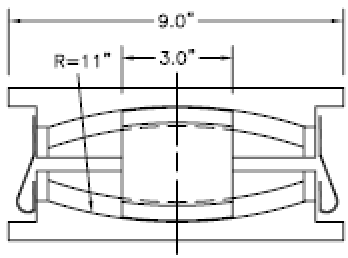


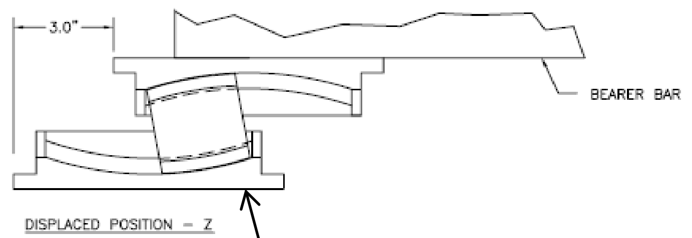
Interior Joint

Floating end
(east)

Double Friction Pendulum Bearing (FPB)

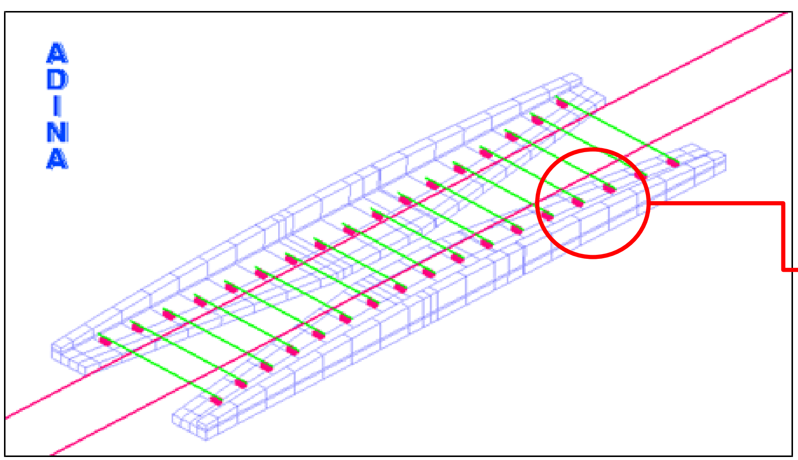
- Supports bearer bars at their ends
- Provides limited transverse movement of the rails

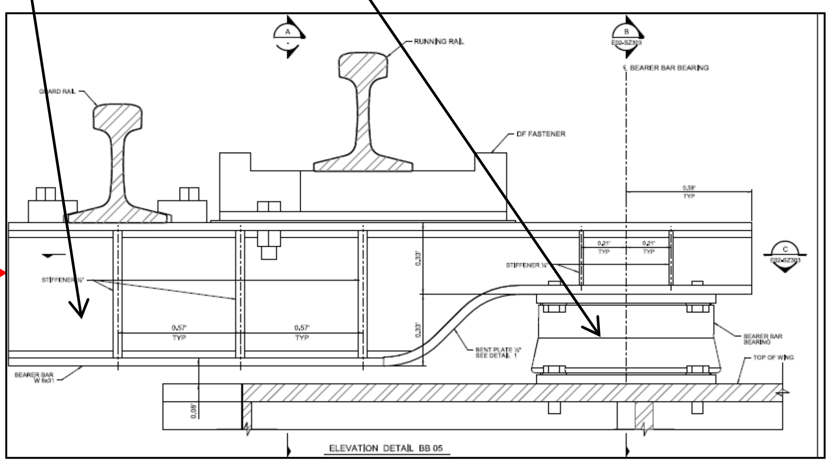




Bearer bar

Double FPB

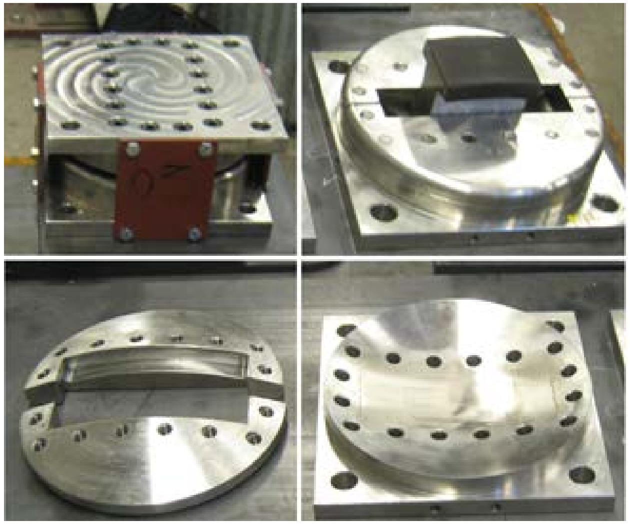


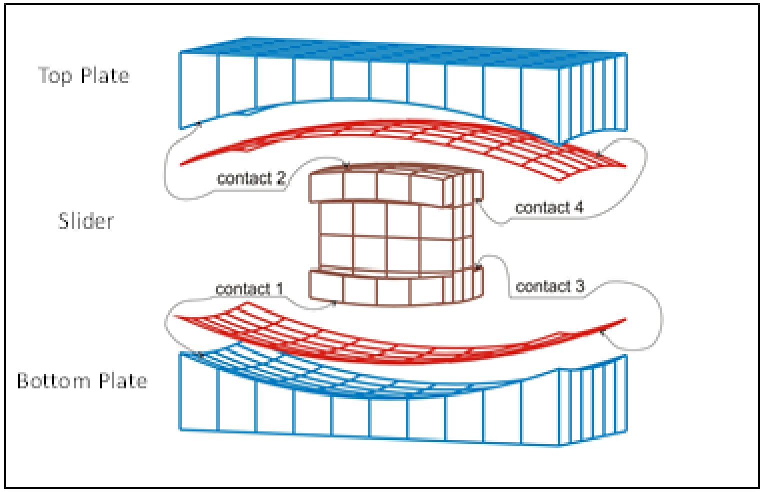


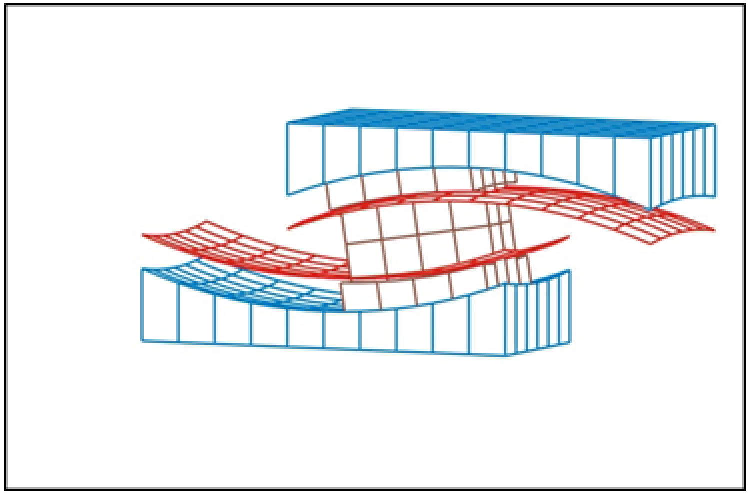
TB Model Development

Double Friction Pendulum Bearing (FPB)

- The bottom and top plates and slider
- The slots are modeled with shell elements
- Four contact surfaces



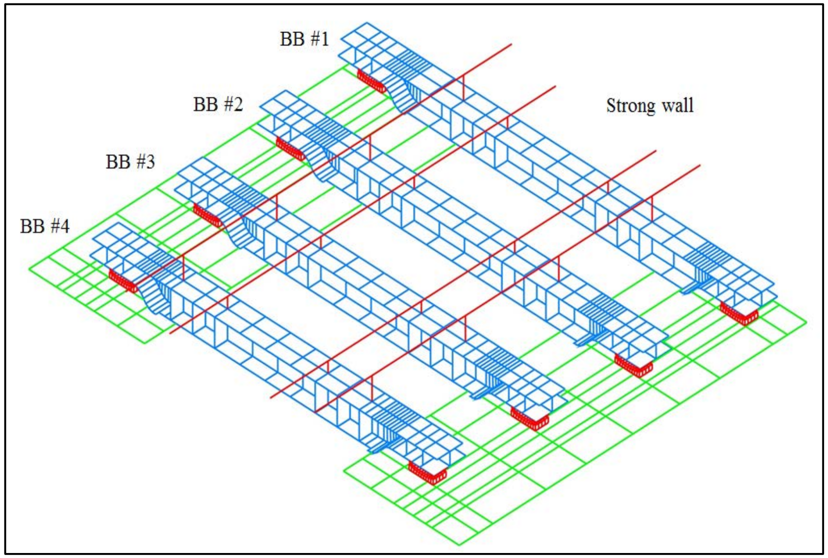


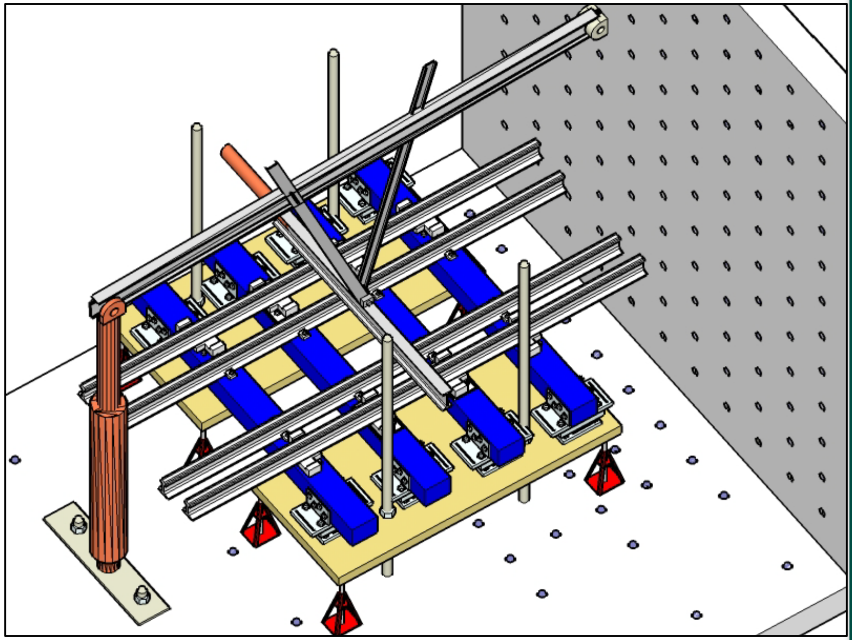


TB Component Test

Track Bridge Component Test (University of Washington)

- Test set-up built at the University of Washington, Seattle
- Four bearer bars seating on Friction Pendulum Bearing
- Steel plates representing wings of the TB

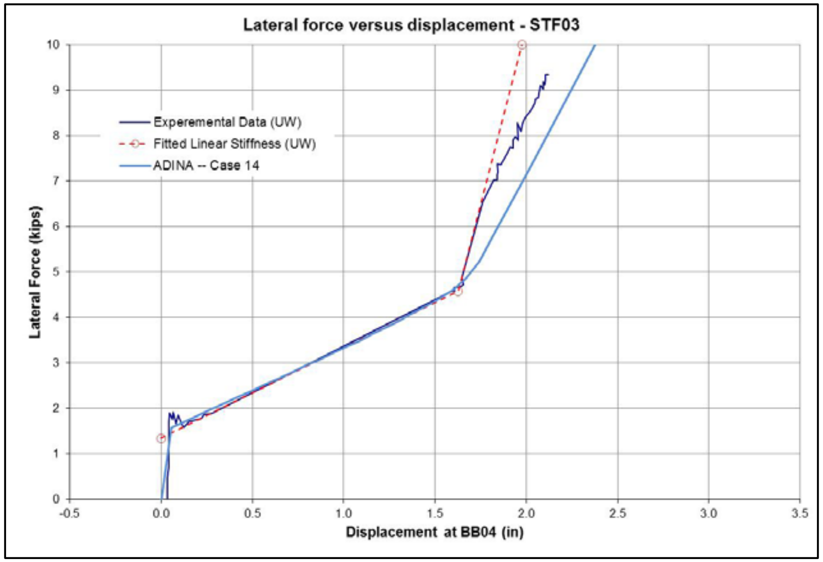




TB Component Test

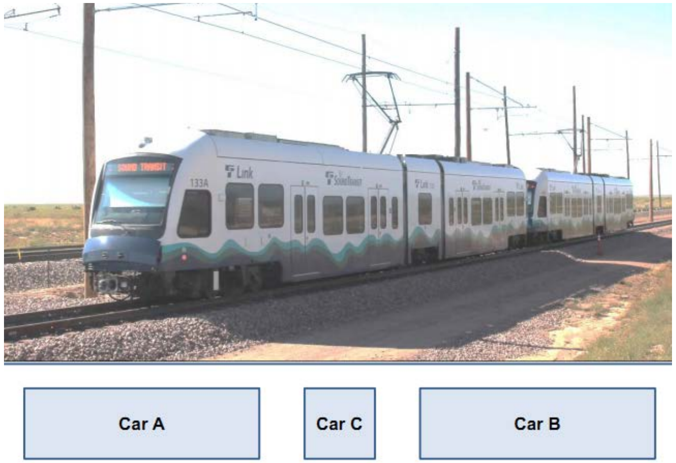
Track Bridge Component Test

- Loading
  - Prescribed displacements applied to the supports to provide 4% initial slope
  - Lateral and vertical load of 3.85 Kips and 28 Kips were applied to the rail on top of BB4
- Result
  - Lateral displacement (BB4) versus lateral force



TB Full-Scale Tests

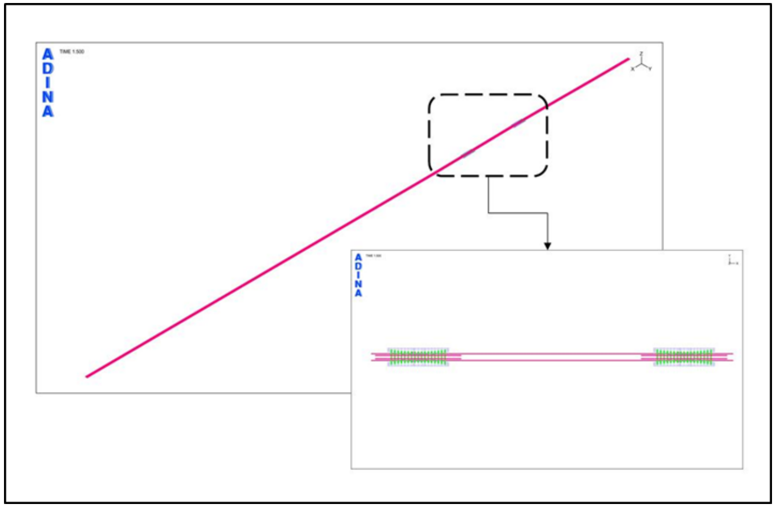
TB Test Set up at Transportation Technology Center Inc. (TTCI)

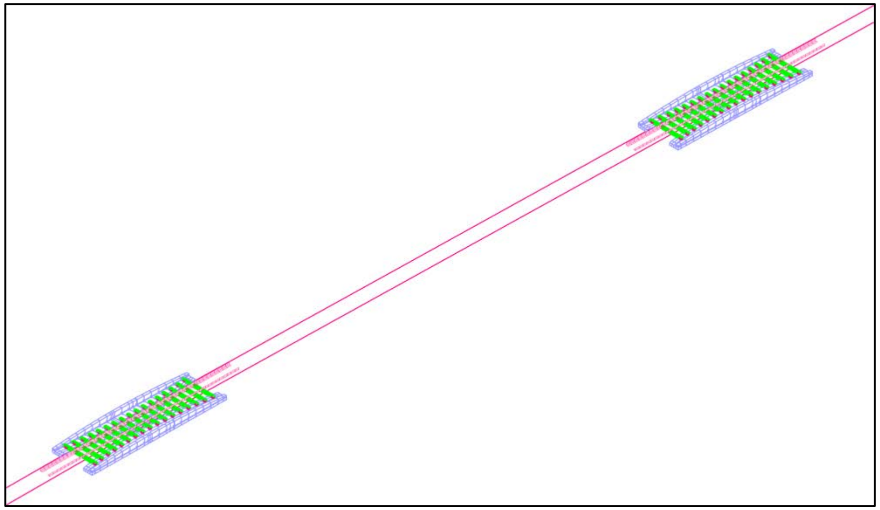


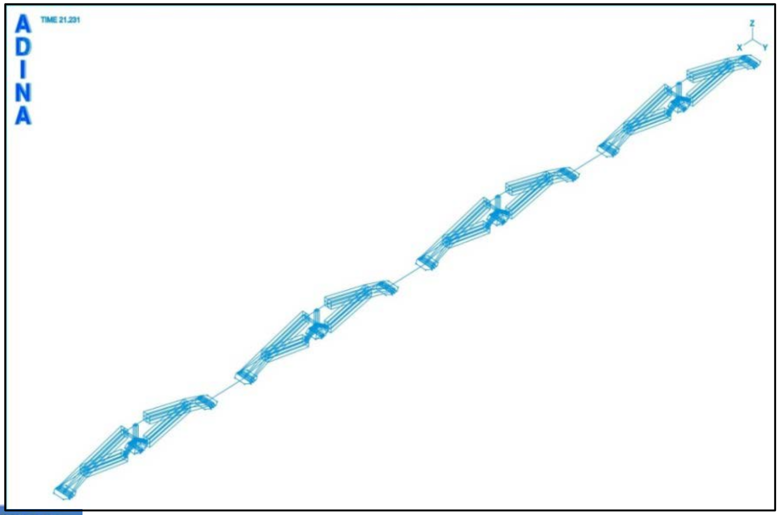
Phase	Case	Moving Direction	Front car	Rear car
1	1	North bound	AW0	AW0
	2	North bound	AW0	AW3
	3	South bound	AW0	AW0
	4	South bound	AW3	AW0
2	5	North bound	AW0	AW0
	6	North bound	AW0	AW3
	7	South bound	AW0	AW0
	8	South bound	AW3	AW0
3	9	North bound	AW0	AW0
	10	North bound	AW0	AW3
	11	South bound	AW0	AW0
	12	South bound	AW3	AW0

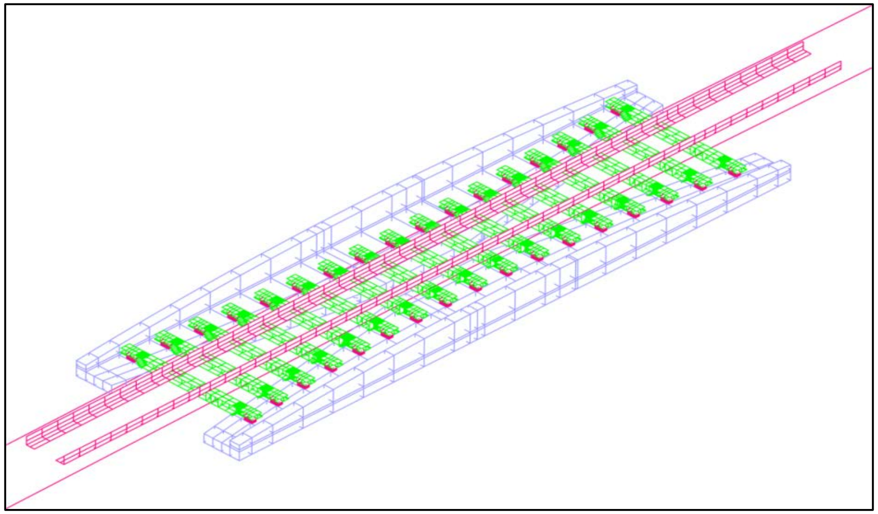
TB Full-Scale Tests

Finite Element Model of the TB Test Set up









TB Full-Scale Test Results (TTCI)

- Overall dynamic response match
- Spikes related to measurement anomaly
- Slight differences in weight distribution

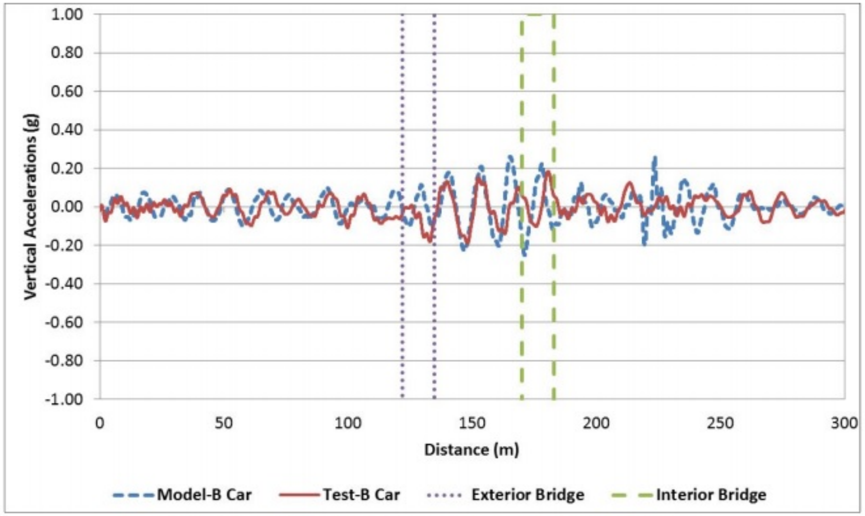


Figure 22. Vertical accelerations measured in the B-car

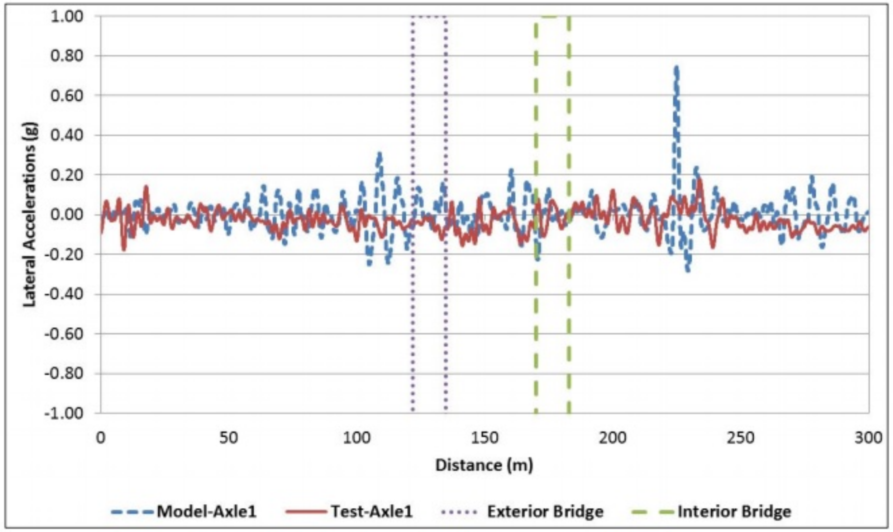


Figure 24. Lateral accelerations measured at axle 1

TB Full-Scale Test Results (TTCI)

- Simulation tend to over predict the ride quality
- More conservative

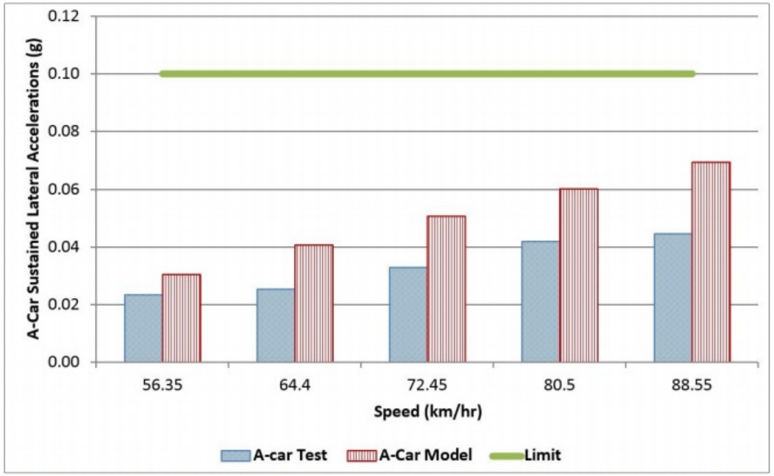


Figure 25. Ride quality — comparison of simulated lateral accelerations with test results

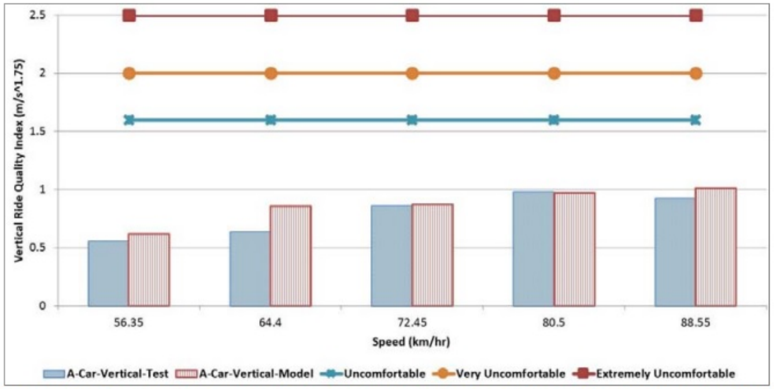
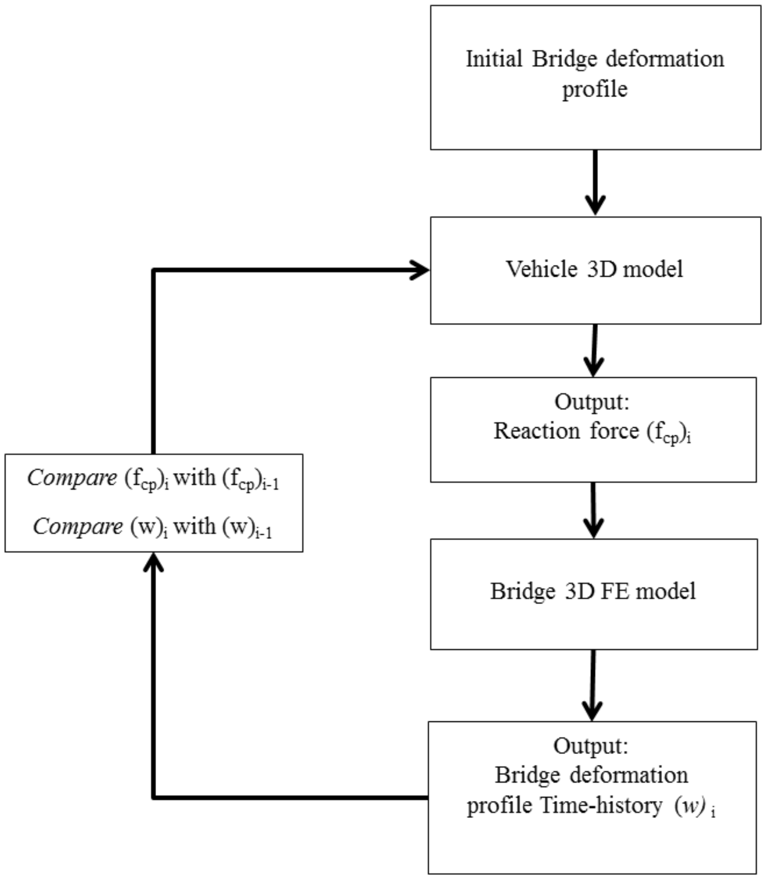
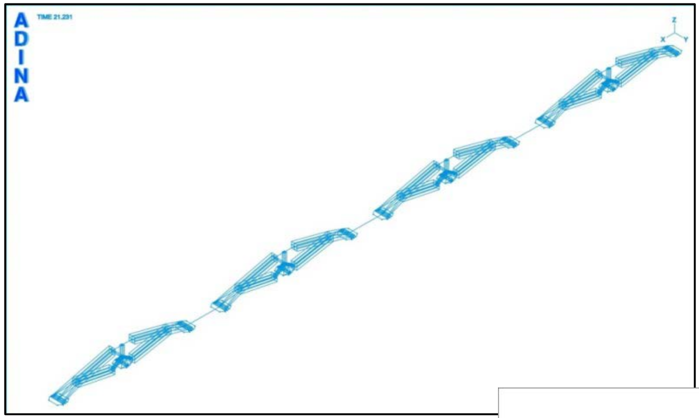


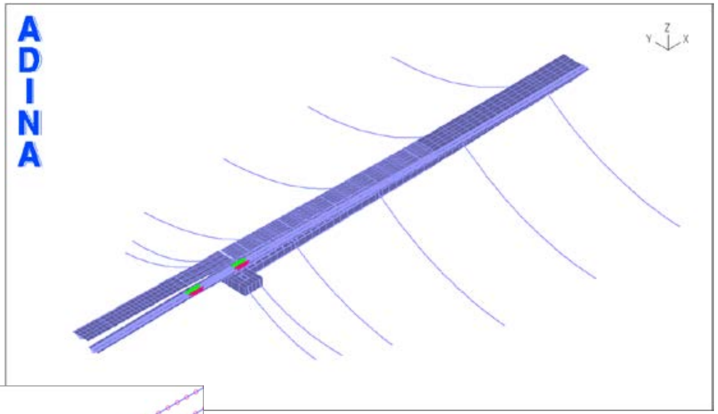
Figure 26. Ride quality — comparison of simulated vertical accelerations with test results

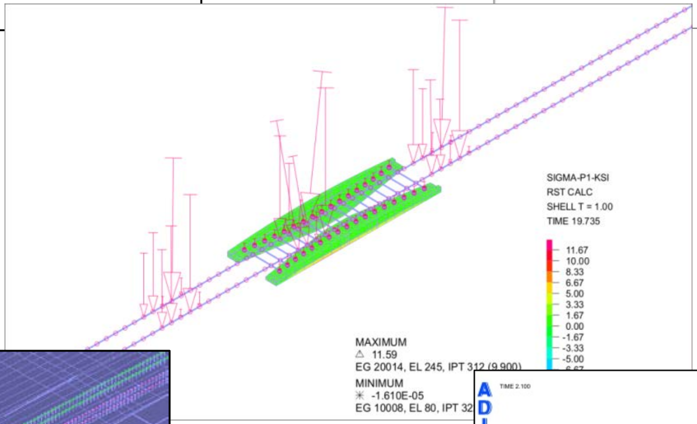
Train-Structure Interaction Analysis

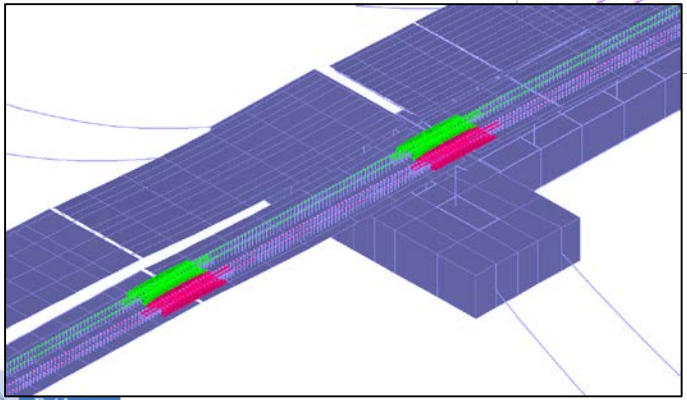


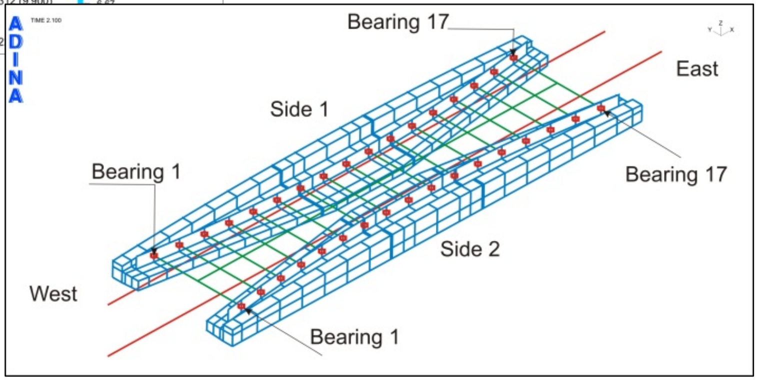
Train-Structure Interaction Analysis Results











Train-Structure Interaction Analysis Results

Loading Scenarios

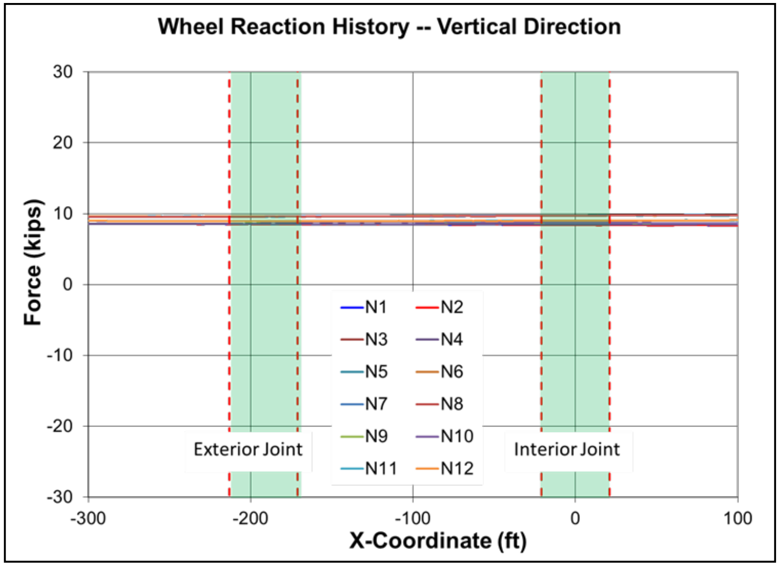
Run ID	Index	Bridge movement	Loading	Moving Direction	# of Consists	Loaded Track
1	1B	Case0	AW0	East to West	2	One
2	1S1	Case5	AW0	East to West	2	One
3	1S2	Case5	AW0	East to West	4	One
4	2S	Case5	AW0	West to East	4	One
5	4S	Case5	AW3	West to East	4	One
6	5S	Case5	AW3	East to West	4	One
7	3S	Case5	AW0	Both	4	Two
8	8S	Case5	AW3	Both	4	Two
8R	8SR	Case5	AW3	Both	4	Two

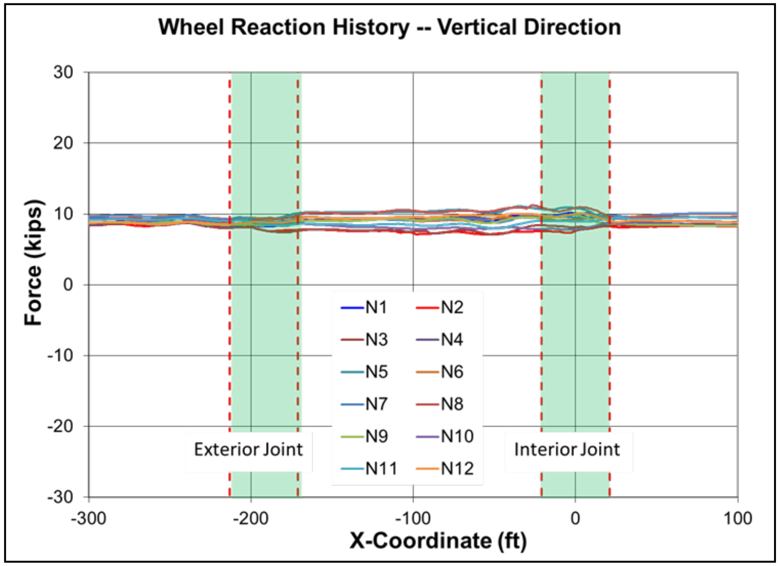
	Speed (MPH)	Pitch degree	Yaw degree	Roll degree
Case 0 (Neutral)	55	0.0	0.0	0.0
Case 1 (Service)	55	0.5 down	0.0	0.0
Case 2 (Service)	55	0.5 down	0.1	0.0
Case 3 (Service)	55	0.5 down	0.0	0.7
Case 5 (Service-all)	55	0.5 down	0.1	0.7
Case 9a (Restricted)	55	1.0 down	0.5	1.0
Case 9b (Restricted)	40	1.0 down	0.5	1.0
Case 9c (Restricted)	20	1.0 down	0.5	1.0

Train-Structure Interaction Analysis Results

Wheel Reactions

Run ID	Index	South Track (Kips)		North Track (Kips)	
		Vertical	Transverse	Vertical	Transverse
1	1B	9.76	0.07	-	-
2	1S1	10.96	1.47	-	-
3	1S2	10.98	1.46	-	-
4	2S	10.84	1.20	-	-
5	4S	14.82	1.29	-	-
6	5S	14.74	1.56	-	-
7	3S	10.97	1.47	10.62	1.26
8	8S	14.82	1.57	14.46	1.33
8R	8SR	14.82	1.57	14.46	1.33



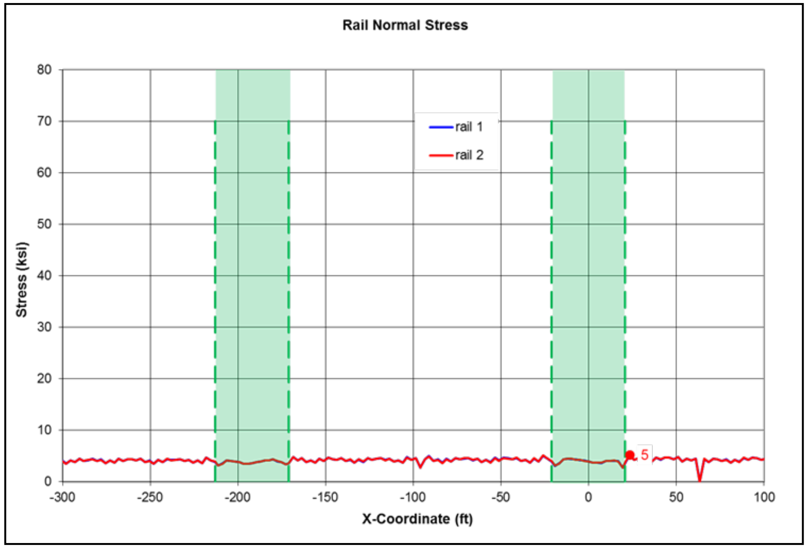


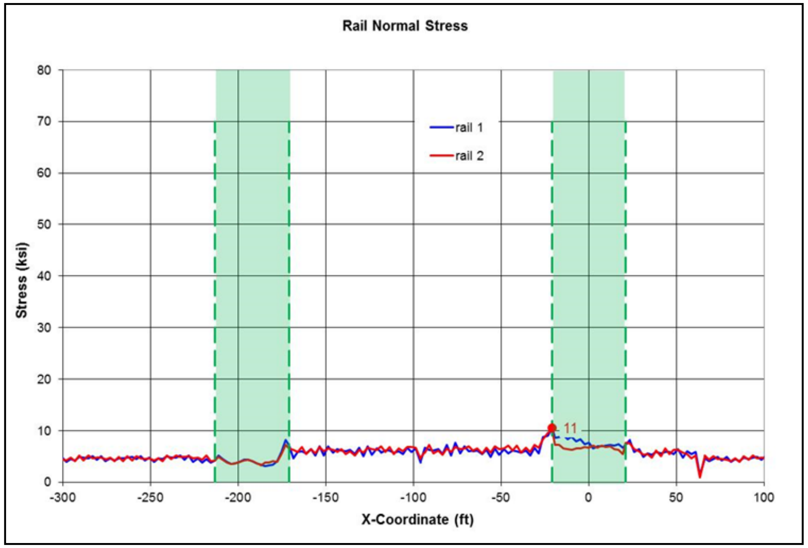
Vertical wheel reaction for Run #1 and Run #2

Train-Structure Interaction Analysis Results

Rail Stress

Run ID	Index	South Track (Ksi)		North Track (Ksi)	
		Average	Maximum	Average	Maximum
1	1B	4	5	-	-
2	1S1	6	11	-	-
3	1S2	6	11	-	-
4	2S	6	10	-	-
5	4S	7	11	-	-
6	5S	7	12	-	-
7	3S	6	11	6	9
8	8S	7	12	7	10
8R	8SR	7	12	7	10



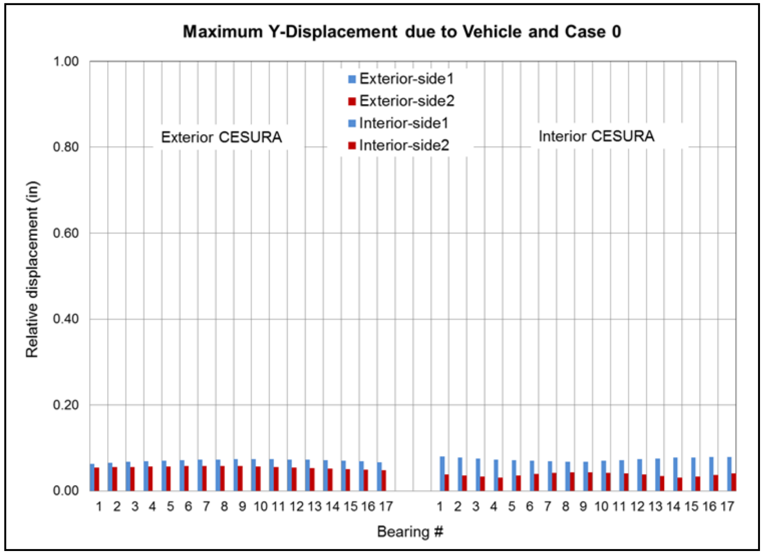


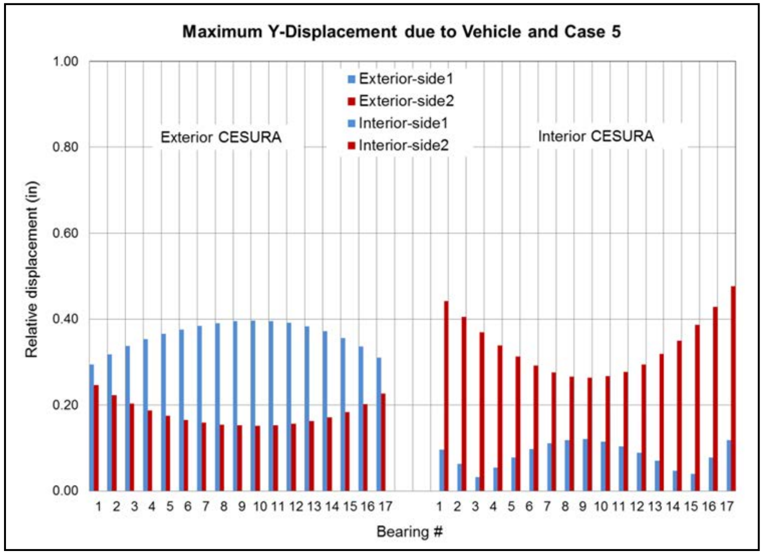
Rail Stress for Run #1 and Run #2

Train-Structure Interaction Analysis Results

Lateral Bearer Bars Movement

Run ID	Index	South Track							
		Exterior TB (in)				Interior TB (in)			
		Case	Train	Residual	Case+Train	Case	Train	Residual	Case+Train
1	1B	0.000	0.074	0.002	0.074	0.000	0.080	0.007	0.080
2	1S1	0.313	0.084	0.019	0.397	0.462	0.085	0.013	0.477
3	1S2	0.313	0.097	0.016	0.409	0.462	0.084	0.014	0.485
4	2S	0.313	0.116	0.039	0.429	0.462	0.094	0.022	0.489
5	4S	0.313	0.146	0.045	0.458	0.462	0.138	0.024	0.494
6	5S	0.313	0.140	0.021	0.452	0.462	0.132	0.015	0.493
7	3S	0.317	0.134	0.034	0.450	0.463	0.133	0.020	0.521
8	8S	0.316	0.185	0.042	0.501	0.463	0.168	0.029	0.519
8R	8SR	0.316	0.186	0.043	0.501	0.463	0.167	0.028	0.518





Maximum Lateral BB Movements for Run #1 and Run #2

Conclusions

1. The FE model of Homer M. Hadley Memorial Bridge incorporates all structural components presented in a detailed way necessary for the design purposes.

2. This is a unique multi-scale finite element model including 68 friction pendulum bearings (10in-diameter) incorporated in the global model of the bridge spanning about 2100 feet.

3. The LRV train was separately modeled as a coupled system with rail, which includes stiffness of the fasteners as well as dynamic characteristics of the vehicle.

4. Due to high efficiency of the developed finite element model of all components of the bridge, detailed analysis of the track bridge components was feasible using computers of regular capacity within reasonable computational time.

5. The bridge model was analyzed for a set of loading scenarios including different storm conditions and train speeds. Stress distribution in the track bridge components, rail stresses and bearer bar movements extracted for each loading scenarios, were found to be in the acceptable range.

6. Validation:
   a) The analytical model was calibrated and validated with the measured data from the bridge.
   b) The analytical results were validated with a component test performed at the University of Washington.
   c) Full scale tests were performed at TTCI facility to verify the dynamic behavior of the TB system