# Table of Contents

[Acknowledgements ii](#_Toc5635009)

[Table of Contents iii](#_Toc5635010)

[List of Tables v](#_Toc5635011)

[List of Figures viii](#_Toc5635012)

[Abstract xix](#_Toc5635013)

[Introduction 1](#_Toc5635014)

[Societal Context 1](#_Toc5635015)

[Current State of Transportation Infrastructure 1](#_Toc5635016)

[Key Knowledge Gap: Influence of Trucks on Bridge Performances 2](#_Toc5635017)

[Overview of Vehicle-Bridge Interaction 3](#_Toc5635018)

[Research Objectives and Scope 5](#_Toc5635019)

[Part 1: Understanding vehicle-bridge interaction and dynamic amplification 6](#_Toc5635020)

[Chapter 1: Description of Case Structure 10](#_Toc5635021)

[Chapter 2: Preliminary Modeling of test structure 14](#_Toc5635022)

[Chapter 3: Phase 1 Testing 20](#_Toc5635023)

[Chapter 4: Phase 2 Testing 27](#_Toc5635024)

[Chapter 5: Phase 3 Testing 62](#_Toc5635025)

[Chapter 6: VBI Model Validation Simulation 82](#_Toc5635026)

[Part 1 Summary and Conclusions 107](#_Toc5635027)

[Part 2: Estimating Dynamic Amplification 108](#_Toc5635028)

[Chapter 1: Components of Vehicle Bridge Interaction 110](#_Toc5635029)

[Chapter 2: In-Situ Measurement 112](#_Toc5635030)

[Chapter 3: Model-Based Simulation 120](#_Toc5635031)

[Chapter 4: Simplified Model Formulation 125](#_Toc5635032)

[Chapter 5: IRI & Other Vehicle-Only Models 152](#_Toc5635033)

[Chapter 6: VBI Mechanisms and Parameters 155](#_Toc5635034)

[Part 2 Summary and Conclusions 173](#_Toc5635035)

[Part 3: Applications in Vehicle-Bridge Interaction 174](#_Toc5635036)

[Chapter 1: Remediation and Smoothness Criteria 175](#_Toc5635037)

[Chapter 2: Multiple Vehicles 180](#_Toc5635038)

[Part 3 Conclusions and Future Work 194](#_Toc5635039)

[List of References 196](#_Toc5635040)

# List of Tables

[Table 1.1.1: NBI Details of Case Structure 13](#_Toc5632710)

[Table 1.2.1: Cross-Girder Boundary Conditions (Nodal Restraints) 16](#_Toc5632711)

[Table 1.3.1: Testing Equipment Model Info 22](#_Toc5632712)

[Table 1.4.1: Phase 2 Testing Equipment Details 30](#_Toc5632713)

[Table 1.4.2: Phase 2 Testing Weather Conditions 33](#_Toc5632714)

[Table 1.4.3: Model Parameter Values 55](#_Toc5632715)

[Table 1.4.4: Frequency of Mode Shapes from Experimental Data and FEA 55](#_Toc5632716)

[Table 1.4.5: LRFD flexural ratings using refined analysis for 0.4 of span length 58](#_Toc5632717)

[Table 1.4.6: Operational vs Rating Bridge Responses (Midspan, Bottom-Flange) 58](#_Toc5632718)

[Table 1.4.7: Live Load and Impact Factors 60](#_Toc5632719)

[Table 1.5.1: Phase 3 Test Equipment Model Specifications 66](#_Toc5632720)

[Table 1.5.2: Test Vehicle Wheel Weights 67](#_Toc5632721)

[Table 1.5.3: Meta Data for Test Runs 68](#_Toc5632722)

[Table 1.5.4: Ames Model 8300 Profiler Specifications 68](#_Toc5632723)

[Table 1.5.5: RMS Values for (Run 6) Truck Acceleration Before and On Bridge 73](#_Toc5632724)

[Table 1.5.6: Girders Reported Corresponding to Lane of Travel 81](#_Toc5632725)

[Table 1.6.1: Displacement Comparison for Different Representations of Diaphragms 86](#_Toc5632726)

[Table 1.6.2: Diaphragm Equivalent Beam Element Section Properties 86](#_Toc5632727)

[Table 1.6.3: Pedestal Beam Element Attributes 86](#_Toc5632728)

[Table 1.6.4: Pedestal Element End Releases (Translational) 87](#_Toc5632729)

[Table 1.6.5: Cross-Girder Boundary Node Restraints 87](#_Toc5632730)

[Table 1.6.6: Influence of Mesh Size on Model Responses 88](#_Toc5632731)

[Table 1.6.7: Comparison of Experimental and FE (LUSAS) Mode Shape Frequencies 90](#_Toc5632732)

[Table 1.6.8: Parameter Values for Initial Vehicle Model 92](#_Toc5632733)

[Table 1.6.9: SDOF Vehicle Model Final Parameter Values 95](#_Toc5632734)

[Table 1.6.10: Mean Absolute Errors for Experiment vs Simulation 100](#_Toc5632735)

[Table 1.6.11: Error of Maximum Responses for Experiment vs Simulation 100](#_Toc5632736)

[Table 2.2.1: Displacement and Stress Equations for Point Load and Sinusoidal Distributed Load 113](#_Toc5632737)

[Table 2.4.1: Beam and Sprung Mass Parameter Values for Validation Simulations 137](#_Toc5632738)

[Table 2.4.2: Difference between FEM Predicted Midspan Displacement with Varied Time-Step Size 138](#_Toc5632739)

[Table 2.4.3: Differences between FEM and State-Space Displacement Predictions 139](#_Toc5632740)

[Table 2.4.4: Differences between FEM Displacement Predictions with 1 Mode and 5 Modes 141](#_Toc5632741)

[Table 2.4.5: Midspan Stiffness Values for 140 ft. Bridge Models 143](#_Toc5632742)

[Table 2.4.6: Midspan Stiffness Values for 100 ft. Bridge Models 144](#_Toc5632743)

[Table 2.4.7: Midspan Stiffness Values for 40 ft. Bridge Models 144](#_Toc5632744)

[Table 2.4.8: State-Space Beam Parameters 145](#_Toc5632745)

[Table 2.4.9: SDOF Vehicle Model Parameters 146](#_Toc5632746)

[Table 2.4.10: 2.8 Hz SDOF Vehicle Model Parameters 146](#_Toc5632747)

[Table 2.4.11: Profile Parameters for Performance Assessment Study 146](#_Toc5632748)

[Table 2.4.12: Moving Mass Simulation Decisions 147](#_Toc5632749)

[Table 2.6.1: Coupled and Decoupled Model Parameters 157](#_Toc5632750)

[Table 2.6.2: Difference between Predicted Midspan Displacement for Coupled and Decoupled Models 160](#_Toc5632751)

[Table 2.6.3: Bridge Attributes for Parametric Study 163](#_Toc5632752)

[Table 2.6.4: Vehicle Attributes for Parametric Study 164](#_Toc5632753)

[Table 2.6.5: Frequency Factor for Maximum Amplification 168](#_Toc5632754)

[Table 3.1.1: Simulation Parameters for Smoothing Studies 177](#_Toc5632755)

[Table 3.2.1: Vehicle Parameters for Traffic Simulations 181](#_Toc5632756)

[Table 3.2.2: Traffic Pattern Parameters 182](#_Toc5632757)

[Table 3.2.3: Maximum Responses from Traffic Simulations 182](#_Toc5632758)

[Table 3.2.4: Single Vehicle Responses for Vehicles 3 and 5 184](#_Toc5632759)

[Table 3.2.5: Maximum Responses for Final Vehicle Loading Event 186](#_Toc5632760)

# List of Figures

[Figure 1.0.1: Diagram of StID Framework 7](#_Toc5633036)

[Figure 1.1.1: Elevation View of Case Structure 10](#_Toc5633037)

[Figure 1.1.2: Schematic of Case Structure Elevation 10](#_Toc5633038)

[Figure 1.1.3: Cross-Section Diagram of Case-Structure from Construction Documents 11](#_Toc5633039)

[Figure 1.1.4: View of Case Structure from Underside Featuring Deck Separation 11](#_Toc5633040)

[Figure 1.1.5: Schematic of Case Structure Typical Girder Layout with Numbered Girders 12](#_Toc5633041)

[Figure 1.1.6: View of Case Structure Bearings 13](#_Toc5633042)

[Figure 1.2.1: Schematic of Generic Element-level FEM Model 14](#_Toc5633043)

[Figure 1.2.2: Illustration of Element-Level Representation of 3D Geometry 15](#_Toc5633044)

[Figure 1.2.3: Illustration of FE Representation of Connectivity between Girders and Cross-Girders 17](#_Toc5633045)

[Figure 1.2.4: Apriori FEM Mode 1 – 2.37 Hz 18](#_Toc5633046)

[Figure 1.2.5: Apriori FEM Mode 2 – 2.73 Hz 18](#_Toc5633047)

[Figure 1.2.6: Apriori FEM Mode 3 – 3.22 Hz 18](#_Toc5633048)

[Figure 1.2.7: Apriori FEM Mode 4 – 3.71 Hz 18](#_Toc5633049)

[Figure 1.2.8: Apriori FEM Mode 5 – 3.77 Hz 18](#_Toc5633050)

[Figure 1.2.9: Apriori FEM Mode 6 – 4.22 Hz 18](#_Toc5633051)

[Figure 1.2.10: Apriori FEM Mode 7 – 4.25 Hz 19](#_Toc5633052)

[Figure 1.2.11: Apriori FEM Mode 8 – 4.58 Hz 19](#_Toc5633053)

[Figure 1.3.1: Schematic of Sensor Locations at a Given Pier Location 21](#_Toc5633054)

[Figure 1.3.2: Schematic Showing Piers Chosen for Instrumentation 21](#_Toc5633055)

[Figure 1.3.3: Accelerometer (PCB 393A03) with Magnetic Base (PCB 080A54) 21](#_Toc5633056)

[Figure 1.3.4: Top View of Mode 4 (3.71 Hz) 22](#_Toc5633057)

[Figure 1.3.5: Underside View of Mode 4 (3.71Hz) 22](#_Toc5633058)

[Figure 1.3.6: Transverse Acceleration Time Histories 23](#_Toc5633059)

[Figure 1.3.7: Comparison of Vertical Acceleration RMS for Different Piers 24](#_Toc5633060)

[Figure 1.3.8: Comparison of Transverse Acceleration RMS for Different Piers 24](#_Toc5633061)

[Figure 1.3.9: Comparison of Longitudinal Acceleration RMS for Different Piers 25](#_Toc5633062)

[Figure 1.4.1: Accelerometer Installation Locations for Phase 2 Testing 28](#_Toc5633063)

[Figure 1.4.2: Strain Gauge Installation Locations for Phase 2 Testing 29](#_Toc5633064)

[Figure 1.4.3: Photo Featuring Sensor Installation with Boom Lift 30](#_Toc5633065)

[Figure 1.4.4: Typical Accelerometer Installation on Steel Girder with Magnetic Base 31](#_Toc5633066)

[Figure 1.4.5: Typical Strain Gauge Installation on Steel Girder with Epoxied Mounting Blocks 32](#_Toc5633067)

[Figure 1.4.6: Event Acceleration Time History for Girder 5 at Middle of Span 7 33](#_Toc5633068)

[Figure 1.4.7: Frequency response of 6th order Elliptic filter 35](#_Toc5633069)

[Figure 1.4.8: Filtered Event Acceleration Time History for Girder 5 at Middle of Span 7 35](#_Toc5633070)

[Figure 1.4.9: Filtered Acceleration Time History for Girder 5 at the Middle of Span 7 36](#_Toc5633071)

[Figure 1.4.10: Count of Acceleration Exceedance Events over 4.5 Hours 36](#_Toc5633072)

[Figure 1.4.11: PSD Estimate of Girder Accelerations 37](#_Toc5633073)

[Figure 1.4.12: Performance of "Omega" Method for Data Without Low-Frequency Content 38](#_Toc5633074)

[Figure 1.4.13: Performance of “Modified Omega” Method 39](#_Toc5633075)

[Figure 1.4.14: Displacement for Event as Estimated by “Omega Arithmetic” for Girder 5 at Middle of Span 7 40](#_Toc5633076)

[Figure 1.4.15: Parent FFT of Displacement Estimate by “Omega” Methods for Girder 5 at Middle of Span 7 40](#_Toc5633077)

[Figure 1.4.16: Strain Time History for Girders 4 and 5 at the Middle of Span 7 41](#_Toc5633078)

[Figure 1.4.17: High-strain event occurrence count over 24 hours 42](#_Toc5633079)

[Figure 1.4.18: Frequency Response for Elliptic Filter (1.5 Hz Cutoff) 43](#_Toc5633080)

[Figure 1.4.19: Comparison of Simulated Static Midspan Moment and Low-Pass Filtered Moment 43](#_Toc5633081)

[Figure 1.4.20: Filtered and Raw Strain for Girder 5 Bottom Flange at Middle of Span 7 44](#_Toc5633082)

[Figure 1.4.21: Live-Load Deflection Components for 2-Span Continuous Bridge 45](#_Toc5633083)

[Figure 1.4.22: Extrapolated Strain in Top of Deck at Midspan over Girder 4 45](#_Toc5633084)

[Figure 1.4.23: Strain Time History for Girder 4 Bottom Flange at 2’ West of Cross-Girder 7 (Neg. Mom. Region) 46](#_Toc5633085)

[Figure 4.24: CMIF Singular Values with Peaks Identified 50](#_Toc5633086)

[Figure 1.4.25: Experimental Mode 1 – 2.00 Hz 50](#_Toc5633087)

[Figure 1.4.26: Experimental Mode 4 – 2.44 Hz 50](#_Toc5633088)

[Figure 1.4.27: Experimental Mode 7 – 2.83 Hz 51](#_Toc5633089)

[Figure 1.4.28: Experimental Mode 12 – 3.56 Hz 51](#_Toc5633090)

[Figure 1.4.29: Comparison of Experimental and A-priori FEM Mode 1 Shape 52](#_Toc5633091)

[Figure 1.4.30: Experimental Mode 1 – 2.00 Hz 53](#_Toc5633092)

[Figure 1.4.31: Experimental Mode 4 – 2.44 Hz 53](#_Toc5633093)

[Figure 1.4.32: Experimental Mode 7 – 2.83 Hz 53](#_Toc5633094)

[Figure 1.4.33: Experimental Mode 9 – 3.20 Hz 53](#_Toc5633095)

[Figure 1.4.34: Experimental Mode 12 – 3.56 Hz 54](#_Toc5633096)

[Figure 1.4.35: Experimental Mode 13 – 3.56 Hz 54](#_Toc5633097)

[Figure 1.4.36: Experimental Mode 1 – 2.00 Hz 56](#_Toc5633098)

[Figure 1.4.37: Updated FEM Mode 1 – 2.00 Hz 56](#_Toc5633099)

[Figure 1.4.38: Experimental Mode 4 – 2.44 Hz 56](#_Toc5633100)

[Figure 1.4.39: Updated FEM Mode 3 – 2.28 Hz 56](#_Toc5633101)

[Figure 1.4.40: Experimental Mode 7 – 2.83 Hz 56](#_Toc5633102)

[Figure 1.4.41: Updated FEM Mode 5 – 3.06 Hz 56](#_Toc5633103)

[Figure 1.4.42: Experimental Mode 9 – 3.20 Hz 57](#_Toc5633104)

[Figure 1.4.43: Updated FEM Mode 6 – 3.17 Hz 57](#_Toc5633105)

[Figure 1.4.44: Experimental Mode 12 – 3.56 Hz 57](#_Toc5633106)

[Figure 1.4.45: Updated FEM Mode 7 – 3.68 Hz 57](#_Toc5633107)

[Figure 1.4.46: Experimental Mode 13 – 3.56 Hz 57](#_Toc5633108)

[Figure 1.4.47: Update FEM Mode 8 – 3.68 Hz 57](#_Toc5633109)

[Figure 1.4.48: Human Perception to Vibrations (Reiher and Meister, 1931) 60](#_Toc5633110)

[Figure 1.5.1: Test Truck Instrumentation Layout 64](#_Toc5633111)

[Figure 1.5.2: Span 2 Instrumentation Layout 64](#_Toc5633112)

[Figure 1.5.3: Spans 3 & 4 Instrumentation Layout 65](#_Toc5633113)

[Figure 1.5.4: Spans 7 & 8 Instrumentation Layout 65](#_Toc5633114)

[Figure 1.5.5: Photo of Test Truck 67](#_Toc5633115)

[Figure 1.5.6: Truck Raw Acceleration Time History for Run 6 69](#_Toc5633116)

[Figure 1.5.7: PSD Estimate of Test Truck Acceleration (Full Bandwidth) 70](#_Toc5633117)

[Figure 1.5.8: PSD Estimate of Test Truck Acceleration (<10 Hz) 70](#_Toc5633118)

[Figure 1.5.9: Frequency response of 6th order Elliptic filter 71](#_Toc5633119)

[Figure 1.5.10: Filtered Truck Acceleration Time History (Before and On Bridge) 71](#_Toc5633120)

[Figure 1.5.11: Filtered Truck Acceleration Time History for Period before Bridge (A) 72](#_Toc5633121)

[Figure 1.5.12: Filtered Truck Acceleration Time History for Period on Bridge (B) 72](#_Toc5633122)

[Figure 1.5.13: PSD Estimate for Acceleration from Front Sensors, On and Off Bridge 73](#_Toc5633123)

[Figure 1.5.14: PSD Estimate for Acceleration from Rear Sensors, On and Off Bridge 74](#_Toc5633124)

[Figure 1.5.15: PSD Estimate from Truck Acceleration 75](#_Toc5633125)

[Figure 1.5.16: RMS of Filtered Truck Acceleration while on Bridge versus Truck Speed 76](#_Toc5633126)

[Figure 1.5.17: Acceleration Time History (Filtered) for Girder 5 at the Middle of Spans 2 77](#_Toc5633127)

[Figure 1.5.18: Acceleration Time History (Filtered) for Girder 5 at the Middle of Spans 3 & 4 77](#_Toc5633128)

[Figure 1.5.19: Acceleration Time History (Filtered) for Girder 5 at the Middle of Spans 7 & 8 78](#_Toc5633129)

[Figure 1.5.20: PSD Estimate for Acceleration of Girder 5 at the Middle of Span 2 over Period That Truck is on the Span 78](#_Toc5633130)

[Figure 1.5.21: PSD Estimate for Acceleration of Girder 5 at the Middle of Spans 3 & 4 over Period the Truck is on the Spans 79](#_Toc5633131)

[Figure 1.5.22: PSD Estimate for Acceleration of Girder 5 at the Middle of Spans 7 & 8 over Period the Truck is on the Spans 79](#_Toc5633132)

[Figure 1.5.23: RMS of Filtered Midspan Acceleration of Span 2 80](#_Toc5633133)

[Figure 1.5.24: Average RMS Value for Filtered Midspan Acceleration of Spans 3 & 4 80](#_Toc5633134)

[Figure 1.6.1: Schematic of Plate Eccentric-Beam FEM Model 83](#_Toc5633135)

[Figure 1.6.2: Plate Eccentric-Beam Representation and 3D Rendering with Assigned Eccentricities 84](#_Toc5633136)

[Figure 1.6.3: Diagram of FE Representation of Diaphragms 85](#_Toc5633137)

[Figure 1.6.4: LUSAS FEM Mode 1 – 1.98 Hz 88](#_Toc5633138)

[Figure 1.6.5: Experimental Mode 1 – 2.00 Hz 88](#_Toc5633139)

[Figure 1.6.6: LUSAS FEM Mode 3 – 2.45 Hz 89](#_Toc5633140)

[Figure 1.6.7: Experimental Mode 7 – 2.83 Hz 89](#_Toc5633141)

[Figure 1.6.8: Connectivity at discontinuous joints 91](#_Toc5633142)

[Figure 1.6.9: Measured Profile 92](#_Toc5633143)

[Figure 1.6.10: Comparison of span 3 midspan acceleration for simulations with and without a profile included 94](#_Toc5633144)

[Figure 1.6.11: Comparison of truck vertical acceleration for simulations with and without a profile included 94](#_Toc5633145)

[Figure 1.6.12: Experiment vs Simulation for Vehicle Acceleration for Run 14 over Bridge (Raw Data) 96](#_Toc5633146)

[Figure 1.6.13: Filtered Experimental Vehicle Acceleration for Run 14 over Bridge 97](#_Toc5633147)

[Figure 1.6.14: Experiment vs Simulation for Vehicle Acceleration for Run 14 over Bridge (Filtered and Decimated) 98](#_Toc5633148)

[Figure 1.6.15: “Warped” Experimental and Simulated Truck Acceleration from DTW 99](#_Toc5633149)

[Figure 1.6.16: Experiment vs Simulation for Span 2 Midspan Acceleration of Girder 8 for Run 14 (Filtered and Decimated) 101](#_Toc5633150)

[Figure 1.6.17: Experiment vs Simulation for Span 3 Midspan Acceleration of Girder 8 for Run 14 (Filtered and Decimated) 101](#_Toc5633151)

[Figure 1.6.18: Experiment vs Simulation for Span 7 Midspan Acceleration of Girder 8 for Run 14 (Filtered and Decimated) 102](#_Toc5633152)

[Figure 1.6.19: Experiment vs Simulation for Vehicle Acceleration for Run 3 over Bridge (Filtered and Decimated) 102](#_Toc5633153)

[Figure 1.6.20: Experiment vs Simulation for Span 2 Midspan Acceleration of Girder 8 for Run 3 (Filtered and Decimated) 103](#_Toc5633154)

[Figure 1.6.21: Experiment vs Simulation for Span 3 Midspan Acceleration of Girder 8 for Run 3 (Filtered and Decimated) 103](#_Toc5633155)

[Figure 1.6.22: Experiment vs Simulation for Span 4 Midspan Acceleration of Girder 8 for Run 3 (Filtered and Decimated) 104](#_Toc5633156)

[Figure 1.6.23: Experiment vs Simulation for Span 7 Midspan Acceleration of Girder 8 for Run 3 (Filtered and Decimated) 104](#_Toc5633157)

[Figure 1.6.24: Simulated Bridge Midspan Displacement Amplification Time History 105](#_Toc5633158)

[Figure 1.6.25: Simulated Bridge Midspan Moment Amplification Time History 105](#_Toc5633159)

[Figure 1.6.26: Maximum Displacement Amplification for Varying Speeds 106](#_Toc5633160)

[Figure 2.1.1: Schematic of Combined Vehicle and Bridge Systems 110](#_Toc5633161)

[Figure 2.2.1: Additional Amplification as a Function of Bridge Inertial Force 114](#_Toc5633162)

[Figure 2.4.1: Diagram of Simplified 2-DOF Model 125](#_Toc5633163)

[Figure 2.4.2: Diagram of Single-Span 2-DOF Model 127](#_Toc5633164)

[Figure 2.4.3: Diagram of 2-Span 2-DOF Model 131](#_Toc5633165)

[Figure 2.4.4: Difference between FEM Predicted Midspan Displacement with Varied Time-Step Size 137](#_Toc5633166)

[Figure 2.4.5: Comparison of Single-Span Beam Model Displacement Simulations 138](#_Toc5633167)

[Figure 2.4.6: Comparison of 2-Span Beam Model Displacement Simulations 139](#_Toc5633168)

[Figure 2.4.7: First Two Mode Shapes for 2-Span Continuous Beam 140](#_Toc5633169)

[Figure 2.4.8: FEM Displacement Predictions with 1 Mode and 5 Modes for 2-span Continuous Beam 140](#_Toc5633170)

[Figure 2.4.9: Performance of 2DOF State-Space Models for Predicting Dynamic Amplification 149](#_Toc5633171)

[Figure 2.4.10: Performance of 2DOF State-Space Model Grouped by Vehicle 150](#_Toc5633172)

[Figure 2.5.1: Performance on ISO 8608 Parameters for Predicting Dynamic Amplification 152](#_Toc5633173)

[Figure 2.5.2: Performance of IRI for Predicting Dynamic Amplification 153](#_Toc5633174)

[Figure 2.5.3: Performance of Quarter-Car Vehicle Model for Predicting Dynamic Amplification 154](#_Toc5633175)

[Figure 2.6.1: Diagram of Decoupled Model 155](#_Toc5633176)

[Figure 2.6.2: Diagram of Coupled 2-DOF Model 156](#_Toc5633177)

[Figure 2.6.3: Displacement Predicted by Coupled Model and Decoupled Model 158](#_Toc5633178)

[Figure 2.6.4: Difference between Displacement from Coupled Model and Uncoupled Model as a Percent of Maximum 159](#_Toc5633179)

[Figure 2.6.5: Difference between Contact Force from Coupled Model and Uncoupled Model as a Percent of Vehicle Weight 159](#_Toc5633180)

[Figure 2.6.6: Free Decay of Vehicle Contact Force 161](#_Toc5633181)

[Figure 2.6.7: Effect of Vehicle Forcing Frequency on Bridge Displacement and Vehicle Contact Force 163](#_Toc5633182)

[Figure 2.6.8: Effect of Bridge and Vehicle Frequency on Bridge Displacement and Vehicle Contact Force (1/4) 164](#_Toc5633183)

[Figure 2.6.9: Effect of Bridge and Vehicle Frequency on Bridge Displacement and Vehicle Contact Force (2/4) 165](#_Toc5633184)

[Figure 2.6.10: Effect of Bridge and Vehicle Frequency on Bridge Displacement and Vehicle Contact Force (3/4) 165](#_Toc5633185)

[Figure 2.6.11: Effect of Bridge and Vehicle Frequency on Bridge Displacement and Vehicle Contact Force (4/4) 166](#_Toc5633186)

[Figure 2.6.12: Effect of Bridge and Vehicle Frequency on Bridge Displacement and Vehicle Contact Force (Total) 166](#_Toc5633187)

[Figure 2.6.13: Effect of Vehicle Frequency as a Fraction of Bridge Natural Frequency on Bridge Displacement Amplification. 168](#_Toc5633188)

[Figure 2.6.14: Profiles with Matching Frequency Content but Different Phase Angle Distribution 169](#_Toc5633189)

[Figure 2.6.15: Bridge Displacement for Profiles with Different Phase Distribution 170](#_Toc5633190)

[Figure 2.6.16: Effect of Profile Position on Bridge Displacement Amplification 170](#_Toc5633191)

[Figure 3.1.1: Effect of Smoothing (1/8" over 10ft.) on Real Profile 176](#_Toc5633192)

[Figure 3.1.2: Effect of Smoothing (1/4" over 30ft.) on Real Profile 176](#_Toc5633193)

[Figure 3.1.3: Comparison of Bridge Dynamic Amplification with Rough Profile and with Smoothed Profile 177](#_Toc5633194)

[Figure 3.1.4: Effect of Smoothing Parameters on Dynamic Amplification 178](#_Toc5633195)

[Figure 3.2.1: Span-1 response to traffic pattern no. 1 183](#_Toc5633196)

[Figure3. 2.2: Span-2 response to traffic pattern no. 2 183](#_Toc5633197)

[Figure 3.2.3: Time History of Bridge Displacement for Last Vehicle in Traffic Patterns 184](#_Toc5633198)

[Figure 3.2.4: Span-1 Response to final vehicle (#5) in traffic pattern 1 185](#_Toc5633199)

[Figure 3.2.5: Span-2 Response to final vehicle (#5) in traffic pattern 2 185](#_Toc5633200)

[Figure 3.2.6: Effect of Number of Sequential Vehicles on Bridge Response 187](#_Toc5633201)

[Figure 3.2.7: Response summary for 140ft single-span model 188](#_Toc5633202)

[Figure 3.2.8: Response summary for 100ft single-span model. 189](#_Toc5633203)

[Figure 3.2.9: Response Summary for 140ft 2-Span Model (Span 1) 190](#_Toc5633204)

[Figure 3.2.10: Response Summary for 140ft 2-Span Model (Span 2) 191](#_Toc5633205)

[Figure 3.2.11: Span 2 Displacement Time History for Varied Platoon Headway Spacing 192](#_Toc5633206)

The validated models were subsequently leveraged to investigate the effect of various mechanisms and parameters on VBI and dynamic amplification. These parameters included roadway profile, vehicle suspension parameters, and bridge dynamic characteristics. Armed with this knowledge, methods for predicting dynamic amplification were assessed and a new simplified model was developed that can be easily implemented by practicing engineers.

# List of References

1. AASHTO, 2018. Manual for Bridge Evaluation, 3rd ed. American Association of State Highway and Transportation Officials, Washington, D.C.
2. AASHTO, 2014. AASHTO LRFD Bridge Design Specifications, 7th ed. American Association of State Highway and Transportation Officials, Washington, DC.
3. Allemang, R.J., 1999. Vibrations: analytical and experimental modal analysis. Struct. Dyn. Res. Lab. Dep. Mech. Ind. Nucl. Eng. Univ. Cincinnati.
4. Allen, D.E., Rainer, J.H., 1976. Vibration criteria for long-span floors. Can. J. Civ. Eng. 3, 165–173.
5. Beyond Traffic 2045, 2017. . US DOT.
6. Billing, J.R., 1984. Dynamic loading and testing of bridges in Ontario. Can. J. Civ. Eng. 11, 833–843.
7. Billing, J.R., Green, R., 1984. Design provisions for dynamic loading of highway bridges. Transp. Res. Rec.
8. Cantieni, R., 1983. Dynamic load tests on highway bridges in Switzerland-60 years experience of EMPA.
9. Çatbaş, F.N., Kijewski-Correa, T., Aktan, A.E., 2013a. Structural identification of constructed systems. ASCE Rest. VA.
10. Çatbaş, F.N., Kijewski-Correa, T., Aktan, A.E., 2013b. Structural identification of constructed systems: approaches, methods, and technologies for effective practice of St-Id. American Society of Civil Engineers.
11. Deng, L., Cai, C.S., 2010. Development of dynamic impact factor for performance evaluation of existing multi-girder concrete bridges. Eng. Struct. 32, 21–31.
12. Ding, L., Hao, H., Zhu, X., 2009. Evaluation of dynamic vehicle axle loads on bridges with different surface conditions. J. Sound Vib. 323, 826–848.
13. FHWA, 2012. Highway Statistics Summary To 1995.
14. Green, M.F., Cebon, D., Cole, D.J., 1995. Effects of vehicle suspension design on dynamics of highway bridges. J. Struct. Eng. 121, 272–282.
15. Huang, D., Wang, T.-L., Shahawy, M., 1995. Dynamic behavior of horizontally curved I-girder bridges. Comput. Struct. 57, 703–714.
16. Huang, D., Wang, T.-L., Shahawy, M., 1992. Impact analysis of continuous multigirder bridges due to moving vehicles. J. Struct. Eng. 118, 3427–3443.
17. Kim, C.-W., Kawatani, M., Kwon, Y.-R., 2007. Impact coefficient of reinforced concrete slab on a steel girder bridge. Eng. Struct. 29, 576–590.
18. Kwasniewski, L., Wekezer, J., Roufa, G., Li, H., Ducher, J., Malachowski, J., 2006. Experimental evaluation of dynamic effects for a selected highway bridge. J. Perform. Constr. Facil. 20, 253–260.
19. Leonhardt, F., 1988. Cracks and Crack Control in Concrete Structures. PCI J. 33, 124–145. https://doi.org/10.15554/pcij.07011988.124.145
20. Li, H., Wekezer, J., Kwasniewski, L., 2008. Dynamic response of a highway bridge subjected to moving vehicles. J. Bridge Eng. 13, 439–448.
21. Reiher, H., Meister, F.J., 1931. The effect of vibration on people. Forsch. Auf Dem Geb. Ingenieurwesens 2, 381–386.
22. Romano, N., Masceri, D., Moon, F., Samtani, N., Murphy, T., de Murphy, M.L., 2017. Bridge Superstructure Tolerance to Total and Differential Foundation Movements.
23. Schwarz, M., Laman, J.A., 2001. Response of prestressed concrete I-girder bridges to live load. J. Bridge Eng. 6, 1–8.
24. Wang, T.-L., Huang, D., 1992. Cable-stayed bridge vibration due to road surface roughness. J. Struct. Eng. 118, 1354–1374.
25. White, D.W., 2012. Guidelines for analysis methods and construction engineering of curved and skewed steel girder bridges. Transportation Research Board.
26. Willis, R., 1849. The effect produced by causing weights to travel over elastic bars. Rep. Comm. Appoint. Inq. Appl. Iron Railw. Struct. Append. HM Station. Off. Lond. UK.