I’d like to thank my family and friends for their good humor and support during this endeavor. I am especially grateful to my friends and colleagues, John DeVitis, David Masceri, Nick Romano and Dom Wirkijowski for their extensive help over these several years.

# Table of Contents

[Acknowledgements ii](#_Toc5807946)

[Table of Contents iii](#_Toc5807947)

[List of Tables vi](#_Toc5807948)

[List of Figures ix](#_Toc5807949)

[Abstract xx](#_Toc5807950)

Chapter 1: Introduction 1

Societal Context 1

Current State of Transportation Infrastructure 1

Key Knowledge Gap: Influence of Trucks on Bridge Performances 2

Overview of Vehicle-Bridge Interaction 3

Research Objectives and Scope 5

Summary of Thesis Chapters 6

[Chapter 2: Literature Review 12](#_Toc5807951)

[Dynamic Amplification in Bridge Codes 12](#_Toc5807952)

[Experimental Evaluation of Amplification Factors 13](#_Toc5807953)

[Modeling Vehicle-Bridge Interaction 15](#_Toc5807954)

[Influential Parameters for Dynamic Amplification 18](#_Toc5807955)

[Effects of Platooned Vehicles 21](#_Toc5807956)

[Bridge Vibration Limits 22](#_Toc5807957)

[Knowledge Gaps 23](#_Toc5807958)

[Part 1: Understanding vehicle-bridge interaction and dynamic amplification 25](#_Toc5807959)

[Chapter 1.1: Description of Case Structure 29](#_Toc5807960)

[Chapter 1.2: Preliminary Modeling of test structure 33](#_Toc5807961)

[Chapter 1.3: Phase 1 Testing 39](#_Toc5807962)

[Chapter 1.4: Phase 2 Testing 46](#_Toc5807963)

[Chapter 1.5: Phase 3 Testing 82](#_Toc5807964)

[Chapter 1.6: VBI Model Validation 102](#_Toc5807965)

[Chapter 1.7: Part 1 Summary and Conclusions 127](#_Toc5807966)

[Part 2: Estimating Dynamic Amplification 128](#_Toc5807967)

[Chapter 2.1: Components of Vehicle Bridge Interaction 130](#_Toc5807968)

[Chapter 2.2: In-Situ Measurement 132](#_Toc5807969)

[Chapter 2.3: Model-Based Simulation 141](#_Toc5807970)

[Chapter 2.4: Simplified Model Formulation 146](#_Toc5807971)

[Chapter 2.5: IRI & Other Vehicle-Only Models 174](#_Toc5807972)

[Chapter 2.6: VBI Mechanisms and Parameters 177](#_Toc5807973)

[Chapter 2.7: Part 2 Summary and Conclusions 195](#_Toc5807974)

[Part 3: Applications in Vehicle-Bridge Interaction 197](#_Toc5807975)

[Chapter 3.1: Remediation and Smoothness Criteria 198](#_Toc5807976)

[Chapter 3.2: Multiple Vehicles 203](#_Toc5807977)

[Chapter 3.3: Part 3 Conclusions and Future Work 218](#_Toc5807978)

[List of References 221](#_Toc5807979)

# List of Tables

[Table 1.1.1: NBI Details of Case Structure 32](#_Toc5705345)

[Table 1.2.1: Cross-Girder Boundary Conditions (Nodal Restraints) 35](#_Toc5705346)

[Table 1.3.1: Testing Equipment Model Info 41](#_Toc5705347)

[Table 1.4.1: Phase 2 Testing Equipment Details 49](#_Toc5705348)

[Table 1.4.2: Phase 2 Testing Weather Conditions 53](#_Toc5705349)

[Table 1.4.3: Model Parameter Values 75](#_Toc5705350)

[Table 1.4.4: Frequency of Mode Shapes from Experimental Data and FEA 75](#_Toc5705351)

[Table 1.4.5: LRFD flexural ratings using refined analysis for 0.4 of span length 78](#_Toc5705352)

[Table 1.4.6: Operational vs Rating Bridge Responses (Midspan, Bottom-Flange) 78](#_Toc5705353)

[Table 1.4.7: Live Load and Impact Factors 80](#_Toc5705354)

[Table 1.5.1: Phase 3 Test Equipment Model Specifications 86](#_Toc5705355)

[Table 1.5.2: Test Vehicle Wheel Weights 87](#_Toc5705356)

[Table 1.5.3: Meta Data for Test Runs 88](#_Toc5705357)

[Table 1.5.4: Ames Model 8300 Profiler Specifications 88](#_Toc5705358)

[Table 1.5.5: RMS Values for (Run 6) Truck Acceleration Before and On Bridge 92](#_Toc5705359)

[Table 1.5.6: Girders Reported Corresponding to Lane of Travel 101](#_Toc5705360)

[Table 1.6.1: Displacement Comparison for Different Representations of Diaphragms 106](#_Toc5705361)

[Table 1.6.2: Diaphragm Equivalent Beam Element Section Properties 106](#_Toc5705362)

[Table 1.6.3: Pedestal Beam Element Attributes 106](#_Toc5705363)

[Table 1.6.4: Pedestal Element End Releases (Translational) 107](#_Toc5705364)

[Table 1.6.5: Cross-Girder Boundary Node Restraints 107](#_Toc5705365)

[Table 1.6.6: Influence of Mesh Size on Model Responses 108](#_Toc5705366)

[Table 1.6.7: Comparison of Experimental and FE (LUSAS) Mode Shape Frequencies 110](#_Toc5705367)

[Table 1.6.8: Parameter Values for Initial Vehicle Model 112](#_Toc5705368)

[Table 1.6.9: SDOF Vehicle Model Final Parameter Values 115](#_Toc5705369)

[Table 1.6.10: Mean Absolute Errors for Experiment vs Simulation 120](#_Toc5705370)

[Table 1.6.11: Error of Maximum Responses for Experiment vs Simulation 120](#_Toc5705371)

[Table 2.2.1: Displacement and Stress Equations for Point Load and Sinusoidal Distributed Load 133](#_Toc5705372)

[Table 2.4.1: Beam and Sprung Mass Parameter Values for Validation Simulations 158](#_Toc5705373)

[Table 2.4.2: Difference between FEM Predicted Midspan Displacement with Varied Time-Step Size 159](#_Toc5705374)

[Table 2.4.3: Differences between FEM and State-Space Displacement Predictions 160](#_Toc5705375)

[Table 2.4.4: Differences between FEM Displacement Predictions with 1 Mode and 5 Modes 162](#_Toc5705376)

[Table 2.4.5: Midspan Stiffness Values for 140 ft. Bridge Models 165](#_Toc5705377)

[Table 2.4.6: Midspan Stiffness Values for 100 ft. Bridge Models 165](#_Toc5705378)

[Table 2.4.7: Midspan Stiffness Values for 40 ft. Bridge Models 166](#_Toc5705379)

[Table 2.4.8: State-Space Beam Parameters 167](#_Toc5705380)

[Table 2.4.9: SDOF Vehicle Model Parameters 167](#_Toc5705381)

[Table 2.4.10: 2.8 Hz SDOF Vehicle Model Parameters 168](#_Toc5705382)

[Table 2.4.11: Profile Parameters for Performance Assessment Study 168](#_Toc5705383)

[Table 2.4.12: Moving Mass Simulation Decisions 169](#_Toc5705384)

[Table 2.6.1: Coupled and Decoupled Model Parameters 180](#_Toc5705385)

[Table 2.6.2: Difference between Predicted Midspan Displacement for Coupled and Decoupled Models 182](#_Toc5705386)

[Table 2.6.3: Bridge Attributes for Parametric Study 185](#_Toc5705387)

[Table 2.6.4: Vehicle Attributes for Parametric Study 186](#_Toc5705388)

[Table 2.6.5: Frequency Factor for Maximum Amplification 190](#_Toc5705389)

[Table 3.1.1: Simulation Parameters for Smoothing Studies 200](#_Toc5705390)

[Table 3.2.1: Vehicle Parameters for Traffic Simulations 204](#_Toc5705391)

[Table 3.2.2: Traffic Pattern Parameters 205](#_Toc5705392)

[Table 3.2.3: Maximum Responses from Traffic Simulations 205](#_Toc5705393)

[Table 3.2.4: Single Vehicle Responses for Vehicles 3 and 5 207](#_Toc5705394)

[Table 3.2.5: Maximum Responses for Final Vehicle Loading Event 209](#_Toc5705395)

# List of Figures

[Figure 1.0.1: Diagram of StID Framework 26](#_Toc5705396)

[Figure 1.1.1: Elevation View of Case Structure 29](#_Toc5705397)

[Figure 1.1.2: Schematic of Case Structure Elevation 29](#_Toc5705398)

[Figure 1.1.3: Cross-Section Diagram of Case-Structure from Construction Documents 30](#_Toc5705399)

[Figure 1.1.4: View of Case Structure from Underside Featuring Deck Separation 30](#_Toc5705400)

[Figure 1.1.5: Schematic of Case Structure Typical Girder Layout with Numbered Girders 31](#_Toc5705401)

[Figure 1.1.6: View of Case Structure Bearings 32](#_Toc5705402)

[Figure 1.2.1: Schematic of Generic Element-level FEM Model 33](#_Toc5705403)

[Figure 1.2.2: Illustration of Element-Level Representation of 3D Geometry 34](#_Toc5705404)

[Figure 1.2.3: Illustration of FE Representation of Connectivity between Girders and Cross-Girders 36](#_Toc5705405)

[Figure 1.2.4: Apriori FEM Mode 1 – 2.37 Hz 37](#_Toc5705406)

[Figure 1.2.5: Apriori FEM Mode 2 – 2.73 Hz 37](#_Toc5705407)

[Figure 1.2.6: Apriori FEM Mode 3 – 3.22 Hz 37](#_Toc5705408)

[Figure 1.2.7: Apriori FEM Mode 4 – 3.71 Hz 37](#_Toc5705409)

[Figure 1.2.8: Apriori FEM Mode 5 – 3.77 Hz 37](#_Toc5705410)

[Figure 1.2.9: Apriori FEM Mode 6 – 4.22 Hz 37](#_Toc5705411)

[Figure 1.2.10: Apriori FEM Mode 7 – 4.25 Hz 38](#_Toc5705412)

[Figure 1.2.11: Apriori FEM Mode 8 – 4.58 Hz 38](#_Toc5705413)

[Figure 1.3.1: Schematic of Sensor Locations at a Given Pier Location 40](#_Toc5705414)

[Figure 1.3.2: Schematic Showing Piers Chosen for Instrumentation 40](#_Toc5705415)

[Figure 1.3.3: Accelerometer (PCB 393A03) with Magnetic Base (PCB 080A54) 40](#_Toc5705416)

[Figure 1.3.4: Top View of Mode 4 (3.71 Hz) 41](#_Toc5705417)

[Figure 1.3.5: Underside View of Mode 4 (3.71Hz) 41](#_Toc5705418)

[Figure 1.3.6: Transverse Acceleration Time Histories 42](#_Toc5705419)

[Figure 1.3.7: Comparison of Vertical Acceleration RMS for Different Piers 43](#_Toc5705420)

[Figure 1.3.8: Comparison of Transverse Acceleration RMS for Different Piers 43](#_Toc5705421)

[Figure 1.3.9: Comparison of Longitudinal Acceleration RMS for Different Piers 44](#_Toc5705422)

[Figure 1.4.1: Accelerometer Installation Locations for Phase 2 Testing 47](#_Toc5705423)

[Figure 1.4.2: Strain Gauge Installation Locations for Phase 2 Testing 48](#_Toc5705424)

[Figure 1.4.3: Photo Featuring Sensor Installation with Boom Lift 50](#_Toc5705425)

[Figure 1.4.4: Typical Accelerometer Installation on Steel Girder with Magnetic Base 51](#_Toc5705426)

[Figure 1.4.5: Typical Strain Gauge Installation on Steel Girder with Epoxied Mounting Blocks 52](#_Toc5705427)

[Figure 1.4.6: Event Acceleration Time History for Girder 5 at Middle of Span 7 53](#_Toc5705428)

[Figure 1.4.7: Frequency response of 6th order Elliptic filter 55](#_Toc5705429)

[Figure 1.4.8: Filtered Event Acceleration Time History for Girder 5 at Middle of Span 7 55](#_Toc5705430)

[Figure 1.4.9: Filtered Acceleration Time History for Girder 5 at the Middle of Span 7 56](#_Toc5705431)

[Figure 1.4.10: Count of Acceleration Exceedance Events over 4.5 Hours 56](#_Toc5705432)

[Figure 1.4.11: PSD Estimate of Girder Accelerations 57](#_Toc5705433)

[Figure 1.4.12: Performance of "Omega" Method for Data Without Low-Frequency Content 58](#_Toc5705434)

[Figure 1.4.13: Performance of “Modified Omega” Method 59](#_Toc5705435)

[Figure 1.4.14: Displacement for Event as Estimated by “Omega Arithmetic” for Girder 5 at Middle of Span 7 60](#_Toc5705436)

[Figure 1.4.15: Parent FFT of Displacement Estimate by “Omega” Methods for Girder 5 at Middle of Span 7 60](#_Toc5705437)

[Figure 1.4.16: Strain Time History for Girders 4 and 5 at the Middle of Span 7 61](#_Toc5705438)

[Figure 1.4.17: High-strain event occurrence count over 24 hours 62](#_Toc5705439)

[Figure 1.4.18: Frequency Response for Elliptic Filter (1.5 Hz Cutoff) 63](#_Toc5705440)

[Figure 1.4.19: Comparison of Simulated Static Midspan Moment and Low-Pass Filtered Moment 63](#_Toc5705441)

[Figure 1.4.20: Filtered and Raw Strain for Girder 5 Bottom Flange at Middle of Span 7 64](#_Toc5705442)

[Figure 1.4.21: Live-Load Deflection Components for 2-Span Continuous Bridge 65](#_Toc5705443)

[Figure 1.4.22: Extrapolated Strain in Top of Deck at Midspan over Girder 4 65](#_Toc5705444)

[Figure 1.4.23: Strain Time History for Girder 4 Bottom Flange at 2’ West of Cross-Girder 7 (Neg. Mom. Region) 66](#_Toc5705445)

[Figure 4.24: CMIF Singular Values with Peaks Identified 70](#_Toc5705446)

[Figure 1.4.25: Experimental Mode 1 – 2.00 Hz 70](#_Toc5705447)

[Figure 1.4.26: Experimental Mode 4 – 2.44 Hz 70](#_Toc5705448)

[Figure 1.4.27: Experimental Mode 7 – 2.83 Hz 71](#_Toc5705449)

[Figure 1.4.28: Experimental Mode 12 – 3.56 Hz 71](#_Toc5705450)

[Figure 1.4.29: Comparison of Experimental and A-priori FEM Mode 1 Shape 72](#_Toc5705451)

[Figure 1.4.30: Experimental Mode 1 – 2.00 Hz 73](#_Toc5705452)

[Figure 1.4.31: Experimental Mode 4 – 2.44 Hz 73](#_Toc5705453)

[Figure 1.4.32: Experimental Mode 7 – 2.83 Hz 73](#_Toc5705454)

[Figure 1.4.33: Experimental Mode 9 – 3.20 Hz 73](#_Toc5705455)

[Figure 1.4.34: Experimental Mode 12 – 3.56 Hz 74](#_Toc5705456)

[Figure 1.4.35: Experimental Mode 13 – 3.56 Hz 74](#_Toc5705457)

[Figure 1.4.36: Experimental Mode 1 – 2.00 Hz 76](#_Toc5705458)

[Figure 1.4.37: Updated FEM Mode 1 – 2.00 Hz 76](#_Toc5705459)

[Figure 1.4.38: Experimental Mode 4 – 2.44 Hz 76](#_Toc5705460)

[Figure 1.4.39: Updated FEM Mode 3 – 2.28 Hz 76](#_Toc5705461)

[Figure 1.4.40: Experimental Mode 7 – 2.83 Hz 76](#_Toc5705462)

[Figure 1.4.41: Updated FEM Mode 5 – 3.06 Hz 76](#_Toc5705463)

[Figure 1.4.42: Experimental Mode 9 – 3.20 Hz 77](#_Toc5705464)

[Figure 1.4.43: Updated FEM Mode 6 – 3.17 Hz 77](#_Toc5705465)

[Figure 1.4.44: Experimental Mode 12 – 3.56 Hz 77](#_Toc5705466)

[Figure 1.4.45: Updated FEM Mode 7 – 3.68 Hz 77](#_Toc5705467)

[Figure 1.4.46: Experimental Mode 13 – 3.56 Hz 77](#_Toc5705468)

[Figure 1.4.47: Update FEM Mode 8 – 3.68 Hz 77](#_Toc5705469)

[Figure 1.4.48: Human Perception to Vibrations (Reiher and Meister, 1931) 80](#_Toc5705470)

[Figure 1.5.1: Test Truck Instrumentation Layout 84](#_Toc5705471)

[Figure 1.5.2: Span 2 Instrumentation Layout 84](#_Toc5705472)

[Figure 1.5.3: Spans 3 & 4 Instrumentation Layout 85](#_Toc5705473)

[Figure 1.5.4: Spans 7 & 8 Instrumentation Layout 85](#_Toc5705474)

[Figure 1.5.5: Photo of Test Truck 87](#_Toc5705475)

[Figure 1.5.6: Truck Raw Acceleration Time History for Run 6 89](#_Toc5705476)

[Figure 1.5.7: PSD Estimate of Test Truck Acceleration (Full Bandwidth) 89](#_Toc5705477)

[Figure 1.5.8: PSD Estimate of Test Truck Acceleration (<10 Hz) 90](#_Toc5705478)

[Figure 1.5.9: Frequency response of 6th order Elliptic filter 91](#_Toc5705479)

[Figure 1.5.10: Filtered Truck Acceleration Time History (Before and On Bridge) 91](#_Toc5705480)

[Figure 1.5.11: Filtered Truck Acceleration Time History for Period before Bridge (A) 92](#_Toc5705481)

[Figure 1.5.12: Filtered Truck Acceleration Time History for Period on Bridge (B) 92](#_Toc5705482)

[Figure 1.5.13: PSD Estimate for Acceleration from Front Sensors, On and Off Bridge 93](#_Toc5705483)

[Figure 1.5.14: PSD Estimate for Acceleration from Rear Sensors, On and Off Bridge 94](#_Toc5705484)

[Figure 1.5.15: PSD Estimate from Truck Acceleration 95](#_Toc5705485)

[Figure 1.5.16: RMS of Filtered Truck Acceleration while on Bridge versus Truck Speed 96](#_Toc5705486)

[Figure 1.5.17: Acceleration Time History (Filtered) for Girder 5 at the Middle of Spans 2 97](#_Toc5705487)

[Figure 1.5.18: Acceleration Time History (Filtered) for Girder 5 at the Middle of Spans 3 & 4 97](#_Toc5705488)

[Figure 1.5.19: Acceleration Time History (Filtered) for Girder 5 at the Middle of Spans 7 & 8 98](#_Toc5705489)

[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 98](#_Toc5705490)

[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 99](#_Toc5705491)

[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 99](#_Toc5705492)

[Figure 1.5.23: RMS of Filtered Midspan Acceleration of Span 2 100](#_Toc5705493)

[Figure 1.5.24: Average RMS Value for Filtered Midspan Acceleration of Spans 3 & 4 100](#_Toc5705494)

[Figure 1.6.1: Schematic of Plate Eccentric-Beam FEM Model 103](#_Toc5705495)

[Figure 1.6.2: Plate Eccentric-Beam Representation and 3D Rendering with Assigned Eccentricities 104](#_Toc5705496)

[Figure 1.6.3: Diagram of FE Representation of Diaphragms 105](#_Toc5705497)

[Figure 1.6.4: LUSAS FEM Mode 1 – 1.98 Hz 108](#_Toc5705498)

[Figure 1.6.5: Experimental Mode 1 – 2.00 Hz 108](#_Toc5705499)

[Figure 1.6.6: LUSAS FEM Mode 3 – 2.45 Hz 109](#_Toc5705500)

[Figure 1.6.7: Experimental Mode 7 – 2.83 Hz 109](#_Toc5705501)

[Figure 1.6.8: Connectivity at discontinuous joints 111](#_Toc5705502)

[Figure 1.6.9: Measured Profile 112](#_Toc5705503)

[Figure 1.6.10: Comparison of span 3 midspan acceleration for simulations with and without a profile included 114](#_Toc5705504)

[Figure 1.6.11: Comparison of truck vertical acceleration for simulations with and without a profile included 114](#_Toc5705505)

[Figure 1.6.12: Experiment vs Simulation for Vehicle Acceleration for Run 14 over Bridge (Raw Data) 116](#_Toc5705506)

[Figure 1.6.13: Filtered Experimental Vehicle Acceleration for Run 14 over Bridge 117](#_Toc5705507)

[Figure 1.6.14: Experiment vs Simulation for Vehicle Acceleration for Run 14 over Bridge (Filtered and Decimated) 118](#_Toc5705508)

[Figure 1.6.15: “Warped” Experimental and Simulated Truck Acceleration from DTW 119](#_Toc5705509)

[Figure 1.6.16: Experiment vs Simulation for Span 2 Midspan Acceleration of Girder 8 for Run 14 (Filtered and Decimated) 121](#_Toc5705510)

[Figure 1.6.17: Experiment vs Simulation for Span 3 Midspan Acceleration of Girder 8 for Run 14 (Filtered and Decimated) 121](#_Toc5705511)

[Figure 1.6.18: Experiment vs Simulation for Span 7 Midspan Acceleration of Girder 8 for Run 14 (Filtered and Decimated) 122](#_Toc5705512)

[Figure 1.6.19: Experiment vs Simulation for Vehicle Acceleration for Run 3 over Bridge (Filtered and Decimated) 122](#_Toc5705513)

[Figure 1.6.20: Experiment vs Simulation for Span 2 Midspan Acceleration of Girder 8 for Run 3 (Filtered and Decimated) 123](#_Toc5705514)

[Figure 1.6.21: Experiment vs Simulation for Span 3 Midspan Acceleration of Girder 8 for Run 3 (Filtered and Decimated) 123](#_Toc5705515)

[Figure 1.6.22: Experiment vs Simulation for Span 4 Midspan Acceleration of Girder 8 for Run 3 (Filtered and Decimated) 124](#_Toc5705516)

[Figure 1.6.23: Experiment vs Simulation for Span 7 Midspan Acceleration of Girder 8 for Run 3 (Filtered and Decimated) 124](#_Toc5705517)

[Figure 1.6.24: Simulated Bridge Midspan Displacement Amplification Time History 125](#_Toc5705518)

[Figure 1.6.25: Simulated Bridge Midspan Moment Amplification Time History 125](#_Toc5705519)

[Figure 1.6.26: Maximum Displacement Amplification for Varying Speeds 126](#_Toc5705520)

[Figure 2.1.1: Schematic of Combined Vehicle and Bridge Systems 130](#_Toc5705521)

[Figure 2.2.1: Additional Amplification as a Function of Bridge Inertial Force 134](#_Toc5705522)

[Figure 2.4.1: Diagram of Simplified 2-DOF Model 146](#_Toc5705523)

[Figure 2.4.2: Diagram of Single-Span 2-DOF Model 148](#_Toc5705524)

[Figure 2.4.3: Diagram of 2-Span 2-DOF Model 152](#_Toc5705525)

[Figure 2.4.4: Difference between FEM Predicted Midspan Displacement with Varied Time-Step Size 159](#_Toc5705526)

[Figure 2.4.5: Comparison of Single-Span Beam Model Displacement Simulations 160](#_Toc5705527)

[Figure 2.4.6: Comparison of 2-Span Beam Model Displacement Simulations 160](#_Toc5705528)

[Figure 2.4.7: First Two Mode Shapes for 2-Span Continuous Beam 161](#_Toc5705529)

[Figure 2.4.8: FEM Displacement Predictions with 1 Mode and 5 Modes for 2-span Continuous Beam 162](#_Toc5705530)

[Figure 2.4.9: Performance of 2DOF State-Space Models for Predicting Dynamic Amplification 171](#_Toc5705531)

[Figure 2.4.10: Performance of 2DOF State-Space Model Grouped by Vehicle 172](#_Toc5705532)

[Figure 2.5.1: Performance on ISO 8608 Parameters for Predicting Dynamic Amplification 174](#_Toc5705533)

[Figure 2.5.2: Performance of IRI for Predicting Dynamic Amplification 175](#_Toc5705534)

[Figure 2.5.3: Performance of Quarter-Car Vehicle Model for Predicting Dynamic Amplification 176](#_Toc5705535)

[Figure 2.6.1: Diagram of Decoupled Model 177](#_Toc5705536)

[Figure 2.6.2: Diagram of Coupled 2-DOF Model 178](#_Toc5705537)

[Figure 2.6.3: Displacement Predicted by Coupled Model and Decoupled Model 180](#_Toc5705538)

[Figure 2.6.4: Difference between Displacement from Coupled Model and Uncoupled Model as a Percent of Maximum 181](#_Toc5705539)

[Figure 2.6.5: Difference between Contact Force from Coupled Model and Uncoupled Model as a Percent of Vehicle Weight 181](#_Toc5705540)

[Figure 2.6.6: Free Decay of Vehicle Contact Force 183](#_Toc5705541)

[Figure 2.6.7: Effect of Vehicle Forcing Frequency on Bridge Displacement and Vehicle Contact Force 185](#_Toc5705542)

[Figure 2.6.8: Effect of Bridge and Vehicle Frequency on Bridge Displacement and Vehicle Contact Force (1/4) 186](#_Toc5705543)

[Figure 2.6.9: Effect of Bridge and Vehicle Frequency on Bridge Displacement and Vehicle Contact Force (2/4) 187](#_Toc5705544)

[Figure 2.6.10: Effect of Bridge and Vehicle Frequency on Bridge Displacement and Vehicle Contact Force (3/4) 187](#_Toc5705545)

[Figure 2.6.11: Effect of Bridge and Vehicle Frequency on Bridge Displacement and Vehicle Contact Force (4/4) 188](#_Toc5705546)

[Figure 2.6.12: Effect of Bridge and Vehicle Frequency on Bridge Displacement and Vehicle Contact Force (Total) 188](#_Toc5705547)

[Figure 2.6.13: Effect of Vehicle Frequency as a Fraction of Bridge Natural Frequency on Bridge Displacement Amplification. 190](#_Toc5705548)

[Figure 2.6.14: Profiles with Matching Frequency Content but Different Phase Angle Distribution 191](#_Toc5705549)

[Figure 2.6.15: Bridge Displacement for Profiles with Different Phase Distribution 192](#_Toc5705550)

[Figure 2.6.16: Effect of Profile Position on Bridge Displacement Amplification 192](#_Toc5705551)

[Figure 3.1.1: Effect of Smoothing (1/8" over 10ft.) on Real Profile 199](#_Toc5705552)

[Figure 3.1.2: Effect of Smoothing (1/4" over 30ft.) on Real Profile 199](#_Toc5705553)

[Figure 3.1.3: Comparison of Bridge Dynamic Amplification with Rough Profile and with Smoothed Profile 200](#_Toc5705554)

[Figure 3.1.4: Effect of Smoothing Parameters on Dynamic Amplification 201](#_Toc5705555)

[Figure 3.2.1: Span-1 response to traffic pattern no. 1 206](#_Toc5705556)

[Figure3. 2.2: Span-2 response to traffic pattern no. 2 206](#_Toc5705557)

[Figure 3.2.3: Time History of Bridge Displacement for Last Vehicle in Traffic Patterns 207](#_Toc5705558)

[Figure 3.2.4: Span-1 Response to final vehicle (#5) in traffic pattern 1 208](#_Toc5705559)

[Figure 3.2.5: Span-2 Response to final vehicle (#5) in traffic pattern 2 208](#_Toc5705560)

[Figure 3.2.6: Effect of Number of Sequential Vehicles on Bridge Response 211](#_Toc5705561)

[Figure 3.2.7: Response summary for 140ft single-span model 212](#_Toc5705562)

[Figure 3.2.8: Response summary for 100ft single-span model. 212](#_Toc5705563)

[Figure 3.2.9: Response Summary for 140ft 2-Span Model (Span 1) 214](#_Toc5705564)

[Figure 3.2.10: Response Summary for 140ft 2-Span Model (Span 2) 214](#_Toc5705565)

[Figure 3.2.11: Span 2 Displacement Time History for Varied Platoon Headway Spacing 215](#_Toc5705566)

# 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. AASHTO, L., 1998. Bridge design specifications. American Association of State Highway and Transportation Officials, Washington, DC.
4. Allemang, R.J., 1999. Vibrations: analytical and experimental modal analysis. Struct. Dyn. Res. Lab. Dep. Mech. Ind. Nucl. Eng. Univ. Cincinnati.
5. Allen, D.E., Rainer, J.H., 1976. Vibration criteria for long-span floors. Can. J. Civ. Eng. 3, 165–173.
6. Aramraks, T., 1975. Highway Bridge Vibration Studies: Interim Report.
7. Ashebo, D.B., Chan, T.H., Yu, L., 2007. Evaluation of dynamic loads on a skew box girder continuous bridge Part I: Field test and modal analysis. Eng. Struct. 29, 1052–1063.
8. Au, F.T.K., Cheng, Y.S., Cheung, Y.K., 2001a. Vibration analysis of bridges under moving vehicles and trains: an overview. Prog. Struct. Eng. Mater. 3, 299–304.
9. Au, F.T.K., Cheng, Y.S., Cheung, Y.K., 2001b. Effects of random road surface roughness and long-term deflection of prestressed concrete girder and cable-stayed bridges on impact due to moving vehicles. Comput. Struct. 79, 853–872.
10. Beyond Traffic 2045, 2017. US DOT.
11. Billing, J.R., 1984. Dynamic loading and testing of bridges in Ontario. Can. J. Civ. Eng. 11, 833–843.
12. Billing, J.R., Green, R., 1984. Design provisions for dynamic loading of highway bridges. Transp. Res. Rec.
13. Bolotin, V.V., Armstrong, H.L., 1965. The dynamic stability of elastic systems. Am. J. Phys. 33, 752–753.
14. BS, 2006. EN-1993-2: Eurocode 3: Design of steel structures-Part 2: Steel Bridges. Br. Stand. Inst. U. K.
15. Canadian Standards Association, 2006. Canadian Highway Bridge Design Code. Mississauga, ON, Canada.
16. Cantieni, R., 1983. Dynamic load tests on highway bridges in Switzerland-60 years experience of EMPA.
17. Caprani, C.C., 2012. Lifetime highway bridge traffic load effect from a combination of traffic states allowing for dynamic amplification. J. Bridge Eng. 18, 901–909.
18. 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.
19. Chang, D., Lee, H., 1994. Impact factors for simple-span highway girder bridges. J. Struct. Eng. 120, 704–715.
20. Chatterjee, P.K., Datta, T.K., Surana, C.S., 1994. Vibration of continuous bridges under moving vehicles. J. Sound Vib. 169, 619–632.
21. Cooper, D.I., 1997. Development of short span bridge-specific assessment live loading. Saf. Bridg. 64–89.
22. Csagoly, P., Dorton, R.A., 1978. The development of the Ontario highway bridge design code. Transp. Res. Rec.
23. 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.
24. Deng, L., Yu, Y., Zou, Q., Cai, C.S., 2015. State-of-the-Art Review of Dynamic Impact Factors of Highway Bridges. J. Bridge Eng. 20, 04014080. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000672
25. 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.
26. European Committee for Standardization (CEN), 2003. Eurocode 1: Actions on structures—Part 2: Trafﬁc loads on bridges. Brussels, Belgium.
27. Fenves, S.J., Veletsos, A.S., Siess, C.P., 1962. Dynamic Studies of the AASHO Road Test Bridges. Highw. Res. Board Spec. Rep. 73.
28. FHWA, 2012. Highway Statistics Summary To 1995.
29. Gaunt, J.T., Sutton, C.D., 1981. Highway bridge vibration studies.
30. González, A., Cantero, D., OBrien, E.J., 2011. Dynamic increment for shear force due to heavy vehicles crossing a highway bridge. Comput. Struct. 89, 2261–2272.
31. González, A., OBrien, E.J., Cantero, D., Li, Y., Dowling, J., Žnidarič, A., 2010. Critical speed for the dynamics of truck events on bridges with a smooth road surface. J. Sound Vib. 329, 2127–2146.
32. Green, M.F., Cebon, D., Cole, D.J., 1995a. Effects of vehicle suspension design on dynamics of highway bridges. J. Struct. Eng. 121, 272–282.
33. Green, M.F., Cebon, D., Cole, D.J., 1995b. Effects of vehicle suspension design on dynamics of highway bridges. J. Struct. Eng. 121, 272–282.
34. Han, W., Wu, J., Cai, C.S., Chen, S., 2015. Characteristics and Dynamic Impact of Overloaded Extra Heavy Trucks on Typical Highway Bridges. J. Bridge Eng. 20, 05014011. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000666
35. Honda, H., Kajikawa, Y., Kobori, T., n.d. Spectra of Road Surface Roughness on Bridges. J. Struct. Div. 108, 1956–1966.
36. Huang, D., Wang, T.-L., Shahawy, M., 1995. Dynamic behavior of horizontally curved I-girder bridges. Comput. Struct. 57, 703–714.
37. Huang, D., Wang, T.-L., Shahawy, M., 1993. Impact studies of multigirder concrete bridges. J. Struct. Eng. 119, 2387–2402.
38. Huang, D., Wang, T.-L., Shahawy, M., 1992. Impact analysis of continuous multigirder bridges due to moving vehicles. J. Struct. Eng. 118, 3427–3443.
39. Inbanathan, M.J., Wieland, M., 1987. Bridge vibrations due to vehicle moving over rough surface. J. Struct. Eng. 113, 1994–2008.
40. Japan Road Association (JRA), 1996. Speciﬁcations for highway bridges. Part 1: Common speciﬁcations. Tokyo.
41. Kim, C.W., Kawatani, M., Kim, K.B., 2005. Three-dimensional dynamic analysis for bridge–vehicle interaction with roadway roughness. Comput. Struct. 83, 1627–1645.
42. 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.
43. Kou, J.-W., DeWolf, J.T., 1997. Vibrational behavior of continuous span highway bridge—influencing variables. J. Struct. Eng. 123, 333–344.
44. Kurihara, M., Shimogo, T., 1978. Vibration of an elastic beam subjected to discrete moving loads. J. Mech. Des. 100, 514–519.
45. Kwark, J.W., Choi, E.S., Kim, Y.J., Kim, B.S., Kim, S.I., 2004. Dynamic behavior of two-span continuous concrete bridges under moving high-speed train. Comput. Struct. 82, 463–474.
46. Kwasniewski, L., Li, H., Wekezer, J., Malachowski, J., 2006a. Finite element analysis of vehicle–bridge interaction. Finite Elem. Anal. Des. 42, 950–959.
47. Kwasniewski, L., Wekezer, J., Roufa, G., Li, H., Ducher, J., Malachowski, J., 2006b. Experimental evaluation of dynamic effects for a selected highway bridge. J. Perform. Constr. Facil. 20, 253–260.
48. Law, S.S., Zhu, X.Q., 2005. Bridge dynamic responses due to road surface roughness and braking of vehicle. J. Sound Vib. 282, 805–830.
49. Leonhardt, F., 1988. Cracks and Crack Control in Concrete Structures. PCI J. 33, 124–145. https://doi.org/10.15554/pcij.07011988.124.145
50. Li, H., Wekezer, J., Kwasniewski, L., 2008. Dynamic response of a highway bridge subjected to moving vehicles. J. Bridge Eng. 13, 439–448.
51. Li, J., Su, M., 1999. The resonant vibration for a simply supported girder bridge under high-speed trains. J. Sound Vib. 224, 897–915.
52. Li, Y., OBrien, E., González, A., 2006. The development of a dynamic amplification estimator for bridges with good road profiles. J. Sound Vib. 293, 125–137.
53. Lipari, A., Caprani, C.C., OBrien, E.J., 2017. Heavy-Vehicle Gap Control for Bridge Loading Mitigation. IEEE Intell. Transp. Syst. Mag. 9, 118–131.
54. Liu, C., Huang, D., Wang, T.-L., 2002. Analytical dynamic impact study based on correlated road roughness. Comput. Struct. 80, 1639–1650.
55. Loprencipe, G., Zoccali, P., 2017. Use of generated artificial road profiles in road roughness evaluation. J. Mod. Transp. 25, 24–33. https://doi.org/10.1007/s40534-017-0122-1
56. Majka, M., Hartnett, M., 2008. Effects of speed, load and damping on the dynamic response of railway bridges and vehicles. Comput. Struct. 86, 556–572.
57. McGetrick, P., Kim, C.-W., González, A., 2013. Dynamic axle force and road profile identification using a moving vehicle. Int. J. Archit. Eng. Constr. 2, 1–16.
58. Ministry of Transport of the People’s Republic of China (MTPRC), 2004. General code for design of highway bridges and culverts. Beijing.
59. Nassif, H.H., Nowak, A.S., 1995. Dynamic Effect Of Truck Loads On Girder Bridges, in: Proceedings of the International Symposium on Heavy Vehicle Weights and Dimensions. Road Transport Technology. pp. 383–387.
60. New Zealand Transport Agency (NZTA), 2013. Bridge Manual. Wellington, New Zealand.
61. OBrien, E., Li, Y., González, A., 2006. Bridge roughness index as an indicator of bridge dynamic amplification. Comput. Struct. 84, 759–769.
62. OBrien, E.J., Cantero, D., Enright, B., González, A., 2010. Characteristic dynamic increment for extreme traffic loading events on short and medium span highway bridges. Eng. Struct. 32, 3827–3835.
63. OBrien, E.J., Keenahan, J., 2015. Drive-by damage detection in bridges using the apparent profile. Struct. Control Health Monit. 22, 813–825.
64. O’Brien, E.J., McGetrick, P., González, A., 2014. A drive-by inspection system via vehicle moving force identification. Smart Struct. Syst. 13, 821–848.
65. Park, Y.S., Shin, D.K., Chung, T.J., 2005. Influence of road surface roughness on dynamic impact factor of bridge by full-scale dynamic testing. Can. J. Civ. Eng. 32, 825–829.
66. Paultre, P., Chaallal, O., Proulx, J., 1992. Bridge dynamics and dynamic amplification factors-a review of analytical and experimental findings. Can. J. Civ. Eng. 19, 260–278.
67. Reiher, H., Meister, F.J., 1931. The effect of vibration on people. Forsch. Auf Dem Geb. Ingenieurwesens 2, 381–386.
68. Romano, N., Masceri, D., Moon, F., Samtani, N., Murphy, T., de Murphy, M.L., 2017. Bridge Superstructure Tolerance to Total and Differential Foundation Movements.
69. Schwarz, M., Laman, J.A., 2001. Response of prestressed concrete I-girder bridges to live load. J. Bridge Eng. 6, 1–8.
70. Tyan, F., Hong, Y.-F., Tu, S.-H., Jeng, W.S., 2009. Generation of random road profiles. J. Adv. Eng. 4, 1373–1378.
71. Wang, T.-L., Huang, D., 1992. Cable-stayed bridge vibration due to road surface roughness. J. Struct. Eng. 118, 1354–1374.
72. White, D.W., 2012. Guidelines for analysis methods and construction engineering of curved and skewed steel girder bridges. Transportation Research Board.
73. 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.
74. Wright, D.T., Green, R., 1964. Highway Bridge Vibrations: Part II, Ontario Test Programme. Department of Civil Engineering, Queen’s University.
75. Wu, Y.-S., Yang, Y.-B., Yau, J.-D., 2001. Three-dimensional analysis of train-rail-bridge interaction problems. Veh. Syst. Dyn. 36, 1–35.
76. Yang, Y.B., Lin, C.W., 2005. Vehicle–bridge interaction dynamics and potential applications. J. Sound Vib. 284, 205–226.
77. Yang, Y.-B., Lin, C.W., Yau, J.D., 2004. Extracting bridge frequencies from the dynamic response of a passing vehicle. J. Sound Vib. 272, 471–493.
78. Yang, Y.-B., Yau, J.-D., Hsu, L.-C., 1997. Vibration of simple beams due to trains moving at high speeds. Eng. Struct. 19, 936–944.
79. Zhang, Q.-L., Vrouwenvelder, A., Wardenier, J., 2001. Dynamic amplification factors and EUDL of bridges under random traffic flows. Eng. Struct. 23, 663–672.