# Introduction

## Societal Context

In 1908, Henry Ford’s first Model T rolled off the assembly line. Less than 20 years later an estimated 15 million Model T cards had been sold. By 1956 there we more than 65 million registered vehicles on America’s roads (FHWA, 2012). That same year Congress enacted the Federal-Aid Highway Act, creating what is now known as the interstate highway system. Over the next half-century, the number of vehicles swelled to 240 million as a generation of Americans returned from World War II to a relatively unscathed nation, rich with natural resources, and an industrial complex created in a large part by the war effort that would fuel economic development for the next several decades.

Just as America experienced a cultural and transportation transformation in the 1950’s, so too is our current transportation system on the verge of major transformation. New technologies (automated vehicles, electric cars) promise to dramatically alter the way Americans and American goods travel.

Furthermore, the demand on our transportation systems will continue to increase. America’s population will grow by 70 million and freight volume will increase by more than 40 percent by 2045 (*Beyond Traffic 2045*, 2017). This will require an increase in infrastructure capacity by building new roads, bridges, and other facilities; as well as maintaining existing infrastructure to ensure continued use and extend service life.

## Current State of Transportation Infrastructure

However, providing funding for these projects presents a continuing challenge. Federal fuel taxes per gallon has not increased since 1993. Improved vehicle fuel economy reduces fuel consumption on a per vehicle basis, further reducing the revenue from gas taxes. Inflation continues to degrade the purchasing power of transportation funds and states are increasingly using debt to fund transportation projects.

At the same time, it is becoming more costly to maintain transportation systems as many of America’s roadways and bridges, many of which were constructed in the 1950s and 1960s, are nearing or have exceeded their design lifespan. Of the 611,845 public road bridges, 58,791 were classified as structurally deficient in the 2015 National Bridge Inventory (NBI), and another 84,124 were classified as functionally obsolete. In recent years more than 15 percent of state capital spending on highways has gone to bridge rehabilitation and replacement.

The changing societal expectations related to infrastructure stewardship and the new demands emerging from connected vehicles cannot be met by the current practice of bridge engineering. Cost-effectively addressing the challenges associated with the aging U.S. bridge stock necessitates a more accurate, quantitative and objective understanding of bridge performance and deterioration. Without the ability to forecast performance and distinguish between over- and under-performing bridges, the paradigms of life-cycle analysis and asset management will remain on the sidelines. Although the qualitative and empirical approaches that define today’s bridge engineering practice have served the profession well over the past five decades, they are wholly incapable of operating under the current fiscal pressures or answering the calls for more efficient and transparent resource allocation.

## Key Knowledge Gap: Influence of Trucks on Bridge Performances

Principal among the shortcomings of current design and assessment approaches is their inability to accurately address the effects of trucks, which provide the primary means of freight transportation for distances under 750 miles and may present the largest demands a bridge will experience, on bridge performance. While the trucking industry continues to push for heavier vehicle limits, the latest design codes (LRFD) are producing more flexible bridges with reduced reserve capacity. The reduction in conservatism can only be justified if the assumptions inherent to our design and evaluation methodologies are made more certain. However, the simple live-load models and analysis methods currently used in design are unable to accurately predict live-load responses, address limit states related to reliability and resilience, or assess the performance of in-service bridges.

Our lack of understanding of how trucks influence bridge performance also represents a key barrier to meeting the needs of emerging connected vehicle technology, specifically truck platooning (which will likely be one of the first applications of connected vehicles). Truck platooning is driven by safety and energy efficiency concerns and involves virtually connecting trucks into a train with extremely small headway in between vehicles. This not only drastically changes the level of live load on bridges (and violates many of the underlying assumptions associated with design and assessment live load models), it creates a more steady-state dynamic loading, which cannot simply be accounted for with an amplification factor. To inform platooning policies and avoid potentially costly unintended consequences, better understanding of how trucks influence bridge performance is needed.

## Overview of Vehicle-Bridge Interaction

Of particular interest in both of these regards is dynamic vehicle-bridge interaction (VBI). VBI refers to a complex dynamic loading condition which refers to the scenario in which one dynamic system (vehicle) traverses a second dynamic system (bridge), thereby exciting the response of the second system which, in turn, influences the response of the former system. To date, most of the work in this area has focused on railway bridges where such dynamic interactions have resulted in significant consequences. The 1847 collapse of the Dee Bridge in England prompted some of the earliest work examining the dynamic effects of moving loads (Willis, 1849). In the case of highway bridges, the lack of repetitive, steady-state-type loading, together with the large safety factors historically employed, have prevented the issues of dynamic interaction from being considered of great consequence. However, changing societal expectations and emerging technologies may provide scenarios in which the dynamic interaction produces amplified bridge responses and demand better understanding of VBI.

The amplification of bridge responses due to dynamic response is termed “dynamic amplification” and quantifies the inability of static analyses to predict the maximum response of a dynamic system. It is expressed as a ratio of maximum dynamic response to static response. For a bridge, moving vehicles excite the coupled system resulting in bridge motion which in turn causes member level responses unequal to those that would result from the force of the vehicles’ weight alone (static).

For many civil applications, static analyses have proven adequate for determining the demands of structures. Structures often remain near enough to a motionless state that the structure can be described as a static system, and the resulting error from employing this assumption can be accounted for with a small increase in the factor of safety. However, in some cases, the excitation of the bridge mass results in appreciable bridge motion.

Live load demands have historically been estimated using static analysis. The dynamic amplification factor that should be used depends on the design specification with jurisdiction. According to AASHTO, a maximum factor of 1.33 is to be used (1.75 for joints). However, there have been numerous reports of bridges experiencing dynamic amplification well in excess of this number, thereby suggesting that the old assumptions are no longer conservative for every bridge. We are therefore compelled as designers, builders and operators to identify the shortcomings of old assumptions and develop more accurate methods as required.

## Research Objectives and Scope

Given the above discussion, this research has adopted the following three primary objectives:

1. Establish the mechanisms that result in levels of VBI that render the common static live load model unconservative,
2. For the cases identified in (1) develop and validate a practical approach to estimating the effects of truck loads inclusive of VBI, and
3. Identify bridge vulnerabilities associated with truck platooning and make recommendations related to how VBI should be estimated and mitigated.

These objectives were realized by taking an inductive approach whereby a structure exhibiting large dynamic responses was investigated to identify and characterize the mechanisms and parameters influential to VBI using the Structural Identification (StId) framework (Çatbaş et al., 2013b). Field testing of this structure was performed to obtain measurement of operational responses. These responses would provide quantification of the bridge’s dynamic behavior and provide data to inform and “calibrate” FE models, thus ensuring that the models could accurately simulate VBI.

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.

## Summary of Thesis Chapters

### Chapter 2: Literature Review

Presented in this chapter is an overview of current engineering practice as it relates to dynamic amplification and vehicle-bridge interaction. Dynamic amplification factors as specified by different design codes are presented as well as a brief summary of dynamic amplification factors determined through field testing. Methods for modeling vehicle-bridge interaction are also presented, including profile generation with the ISO 8608 standard. The effect of vehicle, bridge and road surface parameters have been the subject of many previous studies. Their conclusions are summarized. The effect of repeated vehicles (platoons) on bridge responses has not been extensively researched, however, similar loading is experienced by railway bridges. The work in this area is summarized. Finally, human perception of bridge vibrations is reviewed, as well as the attempts of design codes to limit vibrations that cause user discomfort.

### Part 1: Understanding Vehicle Bridge Interaction and Dynamic Amplification

This first part details the experimental testing and investigation of a real bridge and documents the knowledge gained from such efforts. A total of three field tests were carried out. These tests provided quantitative measure of the bridge dynamic behavior and indicated that this bridge was experiencing dynamic amplification as high as 2.0. The recorded responses were also utilized for the validation of FE models and VBI simulation methods.

### Chapter 3: Description of Case Structure

This chapter provides a detailed description of the 11-span viaduct that was subjected to multiple field tests. The structure was selected for investigation due to the large vibrations reported by motorists and was therefore suspected of exhibiting high dynamic amplification.

### Chapter 4: Preliminary Modeling of Test Structure

As a first step in investigating the behavior of the test structure, an element-level 3D FE model was constructed. The details of this model and the process of its construction are documented.

### **Chapter 5: Phase 1 Testing**

The purpose of the first phase of testing was to identify which portions of the structure were experiencing the greatest vibration and should receive further testing. Design of the instrumentation plan and test activities are documented. The results of the testing are presented which indicated that all instrumented locations are experiencing similar levels of vibration. Spans 7 and 8 were subsequently chosen for further testing.

### Chapter 6: Phase 2 Testing

The purpose of this phase of testing was to characterize the superstructure using operational dynamic data and to quantify the dynamic amplification experienced by the bridge during typical traffic conditions. Design of the instrumentation plan and test activities are documented. The resulting data is processed and interpreted to estimate the in-situ dynamic amplification and identify the structure’s operational mode shapes and corresponding frequencies. The extracted modal parameters were used to update and validate the 3D FE model.

### Chapter 7: Phase 3 Testing

This phase of testing was designed to provide a more thorough understanding of the coupled behavior of bridge and vehicle by capturing the motion of the bridge and a vehicle synchronously. Design of the instrumentation plan and test activities are documented. The resulting data demonstrated that a single truck is capable of inducing vibrations in the bridge that lead to dynamic amplification of bridge responses. Understanding of the mechanisms and influential parameters associated with dynamic amplification could not be directly interpreted from the test data.

### Chapter 8: VBI Model Validation

It was the goal of the simulation efforts presented in this section to identify the bridge and vehicle attributes that were responsible for the observed bridge vibrations and dynamic amplification. The process of constructing and validating a model that was capable of reproducing the responses observed in the field is documented. The model was found to adequately predict the responses measured in the field when the bridge roadway profile was included in simulations.

### Part 2: Estimating Dynamic Amplification

This part summarizes the various methods of predicting dynamic amplification using both experimental and analytical methods. These methods are time-consuming to perform and require considerable expertise. Therefore, a simplified model is proposed that reduces the bridge and vehicle to two degrees of freedom. The ability of this model to predict dynamic amplification is assessed by comparing its predictions to those obtained from 3D FE models. The simplified model as well as the 3D FE models are further used to investigate the parameters that are influential to dynamic amplification.

### Chapter 10: Components of Vehicle Bridge Interaction

This chapter provides a brief summary of vehicle-bridge interaction distilled into its most basic components. Therefore, the bridge and vehicle are visualized as two dynamic systems coupled at the point of contact between wheel and bridge roadway. This representation is used to identify those components which must be considered when investigating VBI and must be included in any analytical representation of VBI.

### Chapter 11: In-Situ Measurement

This chapter provides methods of estimating dynamic amplification of existing structures with field testing, including load testing and operational monitoring. It is shown that amplification factors determined from displacement measurements will be greater than those determined from strain measurements. Brief guidance is also provided for the measurement of the bridge roadway profile for use in VBI simulations.

### Chapter 12: Model-Based Simulation

This chapter provides an analytical approach to estimating dynamic amplification using finite element analysis. Common structural model types are presented, and guidance is provided for modeling the vehicle. Brief guidance is also provided for the validation and implementation of analytical models for simulating VBI.

### Chapter 13: Simplified Model Formulation

This chapter details the development of a simplified model for estimating dynamic amplification. This model reduces the bridge to a single beam and a single degree of freedom through generalized coordinates. The vehicle is also modeled as a single degree of freedom. The equations of motion for the coupled system are provided as well as a state-space representation of the system. Validation of the model is presented. Performance of the model is assessed by comparing dynamic amplification predictions to those obtained from 3D FE models.

### Chapter 14: IRI & Other Vehicle-Only Models

This chapter demonstrates the shortcomings of common profile roughness metrics in predicting dynamic amplification by examining the correlation between FE predicted dynamic amplification and IRI values, ISO 8608 parameters, and responses from quarter-car simulations. All of these models fail to consider the bridge and ultimately fail at reliably indicating dynamic amplification.

### Chapter 15: VBI Mechanisms and Parameters

This chapter examines the parameters influential to dynamic amplification through simulation studies. The effect of coupling the vehicle and bridge systems in analysis is first investigated. These studies suggest that coupling of the systems serves to reduce the contact force and bridge response. Multiple parametric studies are performed to investigate the interdependency of parameters influential to dynamic amplification. These studies confirm that maximum bridge response occurs when the vehicle and bridge natural frequencies are close to matching. The importance of profile location in simulations is also demonstrated.

### Part 3: Applications in Vehicle-Bridge Interaction

The simulation tools demonstrated in Part 1 and developed in Part 2 are leveraged in this part to address some of the challenges facing bridges associated with VBI.

### Chapter 17: Remediation and Smoothness Criteria

This chapter addresses profile roughness by examining rolling straightedge criteria. Various straightedge limits are used to modify a real (measured) profile and the effect of these modifications on dynamic amplification is quantified. It is shown that rolling straightedge criteria with common limits (i.e. 1/8 to ¼ inch deviation over 10 to 16 feet) are not effective at reducing dynamic amplification. It is further shown that the straightedge length should be at least 16 feet (4.88 m) for a deviation limit of 1/8th inch (0.318 cm), and at least 30 feet (9.14 m) for a deviation limit of ¼ inch (0.635 cm).

### Chapter 18: Multiple Vehicles

This chapter seeks to identify the effect of multiple vehicles on dynamic amplification and provide guidance on how the effect of multiple vehicles should be considered when it is impractical to perform VBI simulation (i.e. static analysis). This is accomplished by first examining the effects of a few traffic patterns and then extended to truck platoons. The simulation studies show that traffic and truck platoons can result in increased dynamic amplification because even a single previous truck can induce the bridge conditions (motion) that result in increased dynamic response. Furthermore, as spacing between vehicles decreases and more vehicles are present on the bridge, the static load effect increases, but the dynamic amplification will likely be less than what would occur for a single vehicle.