# 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 where a spring-mass-damper (truck) traverses a second spring-mass-damper (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. Characterize the mechanisms behind the dynamic interaction and identify the influential parameters by leveraging finite element (FE) simulation tools,
2. Identify more accurate methodologies for predicting dynamic amplification, and
3. Identify bridge vulnerabilities associated with truck platooning and make recommendations related to implementation strategies and policies.

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., 2013). 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.

Finally, the validated models were used to simulate platooning scenarios to investigate the effect of repeated vehicles. The number of repeated vehicles and vehicle spacing were investigated.