Ph.D. Research Proposal

Doctoral Program in Civil Engineering

Understanding Vehicle-Bridge Interaction through Field Measurements and Model-Based Simulations

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Abstract

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. Principal among the shortcomings of current design and assessment approaches is their inability to accurately address the effects of trucks (perhaps the largest demands bridges experience) on the dynamics of the coupled vehicle-bridge system (vehicle-bridge interaction) and consequently on bridge performance. Furthermore, this lack of understanding represents a key barrier to meeting the needs of emerging connected vehicle technology, specifically truck platooning. Truck platooning, which involves virtually connecting trucks into a train with extremely small headway between vehicles, not only drastically changes the level of live load on bridges, but it also creates a more steady-state dynamic loading that cannot simply be accounted for with an amplification factor.

The objectives of this research are to (1) characterize the parameters that exert significant influence over the level of vehicle-bridge interaction (VBI), (2) identify any shortcomings with current design and assessment methodologies related to their treatment of dynamic amplification and propose modifications, and (3) identify bridge vulnerabilities associated with truck platooning and make recommendations related to implementation strategies and policies.

Field testing will be performed, whereby an in-service bridge and a vehicle are instrumented, and responses from both are captured synchronously while the vehicle is traversing the bridge. The resulting data will then be used to inform and "calibrate" FE models, thus ensuring that the models can accurately simulate VBI. Once confidence in the FE models is established, objectives (2) and (3) can be achieved through parametric studies and simulation of platooning scenarios. Parameters to be investigated will include road profile roughness, vehicle speed, bridge configurations (span length/width, girder spacing, skew, bridge type, etc.), and dynamic characteristics (e.g. modal frequencies, mode shapes, and damping of natural modes of vibration).

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Introduction

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 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. Principal among the shortcomings of current design and assessment approaches is their inability to accurately address the effects of trucks (perhaps the largest demands bridges experience) on bridge performance.

In addition to this desire for improved stewardship, 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.

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, with the changing societal expectations and emerging technologies, better understanding of VBI has become of critical importance.

To address VBI for highway bridges the proposed 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 any shortcomings with current design and assessment methodologies and propose modifications, and

(3) Identify bridge vulnerabilities associated with truck platooning and make recommendations related to implementation strategies and policies.

These objectives will be realized by using data from field testing to inform and "calibrate" FE models, thus ensuring that the models can accurately simulate VBI. Once confidence in the FE models is established, objectives (2) and (3) can be achieved through parametric studies and simulation of platooning scenarios.

Intellectual Merit

The intellectual merit of the proposed research lies in a more thorough understanding of VBI, its mechanisms, and how to appropriately account for those mechanisms in simulation. This knowledge will be leveraged to develop more accurate methods of calculating the true response of a structure to moving loads and to identify the characteristics of bridges that may exhibit problematic dynamic amplifications due to VBI.

Broader Impacts

The primary broader impact of the proposed research involves equipping bridge owners and managers with a better understanding of the nature of truck demands on bridges. This improved understanding will allow for a better measure the structure's performance as well as improved deterioration predictions. This, in turn, will lead to more accurate design specifications and fewer structures that are vulnerable to excessive dynamic responses. Furthermore, the ability to accurately simulate the effects of repeated vehicles on bridges will improve truck platooning policy and reduce the likelihood of any negative, unintended consequences of platooning on long-term bridge performance and safety.

State of the Art Review

Structural analysis of traffic loading on bridges is performed primarily for the purposes of design or evaluation. The methods of analysis and technological tools historically available have limited the analyses to evaluate the traffic as static loads (i.e. location and magnitude of load remain constant with time), rather than as moving masses where the true response of the structure is actually due to the interaction of the two dynamic systems. The industry accounts for this disparity by applying a factor to the static load or response, thereby attempting to increase the calculated response to match that which the bridge may actually experience under moving vehicles.

In this paper, the factor may be referred to as an impact factor (IM) or dynamic amplification factor (DAF). The factors can be defined as follows:

$$IM = \frac{Dynamic\ Response - Static\ Response}{Static\ Response}$$

$$DAF = \frac{Dynamic\ Response}{Static\ Response}$$

Therefore, the IM is just $DAF - 1$. The total live load response can be computed by the following:

$$LL = (1 + IM) * R_{sta} \quad \text{or} \quad LL = DAF * R_{sta}$$

Where R_{sta} is the static load effect which is amplified by (1 + IM) or the DAF.

The magnitude of this factor (IM or DAF) differs depending on the reference code being used, but in many cases, has been developed from extensive surveying of existing structures and the amplifications they experience.

Dynamic Amplification in Bridge Codes

The various design and evaluation codes handle dynamic amplification in slightly different ways, but they all specify a factor that is to be applied to the loading model. In the current AASHTO (2017) *LRFD Bridge Design Specification* the impact factor is 0.33. The British code includes an IM of 0.25 in its two design load models.

The factors specified by the Ontario and Canadian Highway design codes are dependent on the number of vehicle axles, with lower factors for more axles. A factor of 0.25 is specified for vehicles with 3 or more axles. Similarly, the Australian code specifies factors based on load type. An impact factor of 0.4 is specified for wheel and axle loads, and 0.35 for triaxle truck and lane load.

The Chinese code's factors are a function of bridge's first natural frequency, with a lower bound of 0.05 and an upper bound of 0.45. A bridge with a first natural frequency below 5 Hz would have a specified impact factor less than 0.25.

The New Zealand, European, and Japanese codes all specify factors as a function of bridge span length with the factors decreasing with increased span length. The New Zealand code has a maximum IM of 0.30 for span lengths less than 12 meters. The equation for IM specified by the Japanese code is different for different bridge types. A steel or RC bridge with a span length of 40 feet for instance would be assigned an IM equal to 0.32.

The equation specified by the European code differs dependent on the number of lanes. For a single-lane bridge, the impact factor may range from 0.4 to 0.7, while that for a two-lane bridge ranges from 0.1 to 0.3.

Experimental Evaluation of Amplification Factors

A large number of field tests were carried out in various countries over the years, in-part, for the development of bridge design codes. In the 1950's, AASHTO sponsored a major investigation, for which 18 newly constructed bridges were selected for the purpose of testing and determining the dynamic effects of moving vehicles on the bridges. This study concluded that the dynamic amplification generally increases with increased vehicle speed, is sensitive to vehicle suspension performance, and that the initial oscillations of the vehicle are responsible for a large amount of uncertainty in the dynamic response of the bridge. The maximum dynamic amplification factor recorded from these tests was 1.63 for displacements and 1.41 for strains, however, 95% of the measured amplification factors fell below the value specified by the current code at the time. (Paultre, Chaallal, and Proulx 1992)

In 1956 and 1957, field tests were completed on 52 bridges in Canada, with specific attention paid to dynamic amplification. Amplification factors were observed as high as 1.75, while values near 1.30 were more typical. These tests concluded that the amplification factors were higher for flexible bridges and were greatly affected by the road surface roughness and irregularities on the bridge as well as approach. In fact, Write and Green recommended that irregularities in the road profile should be eliminated, as this was more influential on dynamic amplification than the many other structural parameters considered (Paultre, Chaallal, and Proulx 1992). Additional tests were carried out in Canada in the 1970s and 1980s. Amplifications factors were obtained as high as

1.85 with higher factors obtained from bridges with first fundamental frequencies of 2 to 5 Hz. Similar results were obtained from field tests of more than 200 bridges in Switzerland, with amplification factors as high as 1.7 for bridges with a first fundamental frequency between 2 and 4 Hz. (Deng et al. 2015)

A more recent field test was completed in Florida of a 3-span prestressed multi-girder bridge. Amplification factors were determined experimentally by measuring the bridge response from loaded five-axle trucks. The amplification factors for one truck was found to be 1.82 while that for two trucks was found to be 1.50 and were observed at higher speeds (80 km/h). The authors were able to reasonably reproduce the bridge response recorded in the field by using FE simulation and incorporating the measured road profile of the approach. By comparing responses with and without road profile, the authors were able to show that road surface irregularities have a significant impact on dynamic amplification. (Kwasniewski, Wekezer, et al. 2006)

Modeling Vehicle-Bridge Interaction

While much can be gleaned from experimental investigations, they are often expensive, and require a large amount of resources and time. For this reason, analytical methods are often employed, especially where a large number of situations need to be investigated (i.e. parametric studies).

In early studies, vehicle-bridge interaction was analyzed by representing the bridge as a beam, and the vehicles as point forces or point masses moving across the beam (Willis 1849). As computational tools advanced, bridge models gained complexity and are now commonly modeled as grillage models (Ashebo, Chan, and Yu 2007) or full 3D FE models (Kwasniewski, Li, et al. 2006). Similarly, the vehicle models have advanced to multiple degrees of freedom (DOF). The minimum vehicle model is composed of a single sprung-mass system (Y.-B. Yang, Lin, and Yau 2004). It often consists of a single DOF, but may have two if the wheel weight and tire stiffness is to be modeled separately from the suspension system. Two dimensional models can also be used, whereby each axle is represented by a sprung-mass system that may optionally be connected (Chatterjee, Datta, and Surana 1994). Finally, a full 3D model of the vehicle may be constructed, for which the vehicle body is modeled as a rigid mass (or multiple connected masses) with multiple DOF, and the suspension system will be modeled as lumped masses connected to the vehicle body and bridge surface via spring-dashpots elements (E. J. OBrien et al. 2010).

In some cases, the effect of traffic is considered, and multiple vehicle models are employed in the analysis. The traffic parameters (e.g. weights, spacing, speed, etc.) can be obtained directly from weigh-in-motion (WIM) data but are often generated using statistical methods, whereby the distributions of traffic parameters are derived from WIM data or from traffic flow simulations. The traffic model is then formed using Monte Carlo methods. (Caprani 2012; Zhang, Vrouwenvelder, and Wardenier 2001)

The interface between the traffic/vehicles and structure is the road surface. The motion of the vehicle tires over the bridge is dictated by the geometry of that surface (i.e. road profile). Therefore, it is important that it be included in any modeling effort. The profile can be specified in 1D (i.e. an elevation dimension specified for every unit length of the bridge) or 2D, whereby the profile is provided for multiple wheel lines (Liu, Huang, and Wang 2002). The road profile can be generated from field measurements of an actual roadway, or computer generated. For the latter case, the profile is often generated with the Power Spectral Density (PSD) function (Honda, Kajikawa, and Kobori, n.d.). Standards have been developed for the function parameters based on road roughness categories, and while the profiles generated using these standards are useful, Loprencipe and Zoccali argue that they are no substitute for in-situ measurements when the behavior of a specific vehicle and structure is being investigated (2017).

There are different methods of solving the vehicle-bridge system, depending partially on the modeling methods employed. For simpler models, the equations of motion of both the vehicle and bridge can be explicitly derived. Their interaction can then be solved by coupling the equations or by using an iterative approach. For the coupled method, the equations of motion of the two systems are assembled into single mass, damping, and stiffness matrices for each time step (Kim, Kawatani, and Kim 2005). Alternatively, for the iterative approach, the bridge and vehicle equations of motion are solved separately, and the force and displacement results of each used in the solution of the other (Wang and Huang 1992). The process is therefore repeated until convergence is achieved. Modal superposition can be used in the iterative approach and is also used in many commercially available FE software packages to drastically reduce the computational burden of solving the bridge response compared to time-step solutions (Au, Cheng, and Cheung 2001b; Y. B. Yang and Lin 2005).

Influential Parameters for Dynamic Amplification

Many analytical and experimental studies throughout the past several decades have investigated which parameters are influential to dynamic amplification. These parameters have included: road surface condition, bridge span length and natural frequency, bridge type, vehicle speed, and vehicle weight and suspension characteristics. Of these, research has shown that road surface condition, vehicle speed, and vehicle weight and suspension type have the most effect on dynamic amplification. Although some codes include span length or first natural frequency in their calculations of IM, studies have shown poor correlation between either of these parameters and dynamic amplification. Furthermore, although bridge type may have a significant impact of the dynamic behavior of a bridge, there are a wide variety of bridge types and even more varied structural characteristics within each type. (Deng et al. 2015)

Vehicle Parameters

Vehicle speed has been shown to have a significant effect on dynamic amplification. Generally higher amplification factors result from higher speeds. In some studies, it has been shown that there is a critical speed for which the amplification factor is a maximum (González et al. 2010). However, although the various studies generally agree that vehicle speed is an important factor, the proposed relationships between vehicle speed and amplification factors is inconsistent, suggesting that this relationship is complicated and dependent on other factors (Deng et al. 2015). Similarly, vehicle mass and suspension characteristics have been shown to effect dynamic amplification, but again, no definitive relationship has been established. However, studies generally agree that the amplification factors decrease with increased vehicle weight and damping and with decreased suspension stiffness (Green, Cebon, and Cole 1995; Nassif and Nowak 1995).

Road Surface Roughness

Previous studies have examined the impact that the road surface has on impact factors. Many analytical studies have shown that a rough road surface may result in higher dynamic amplification. However, the studies do not agree on the significance of the effect road surface has on dynamic amplification, which is likely due to variety of bridge types and geometry, road profiles, and model types employed.

Most analytical studies have used a single-line beam model in which the width of the bridge is reduced to a single beam with appropriate mass and stiffness. Some of the earliest simulation work was done by Aramraks at Purdue University. In his research, single span, 2-span and 3-span bridges were represented as single-line beam models. Surface roughness was idealized as a number of half sine waves, resulting in beam accelerations as much as 10 times those obtained with a smooth road surface (Aramraks 1975).

As computing technology has progressed, more complex simulations have been carried out. A simply supported box girder was modeled with a moving mass over a rough road surface that was simulated by using PSD functions to produce a more realistic road profile, and obtained dynamic amplification factors (DAF) as high as 3.0 (Inbanathan and Wieland 1987). Simulations of a 3-span continuous box-girder bridge (modeled as a beam) for a rough road surface generated a maximum DAF of 2.3 (Law and Zhu 2005).

Chatterjee et al. used a single line girder model of a continuous bridge, and showed that for certain combinations of speed and frequency ratios between the vehicle and structure, the DAF could exceed 4.0 (Chatterjee, Datta, and Surana 1994). The effect of long term deflections in addition to road surface roughness was investigated for a simple span and a 3-span prestressed concrete bridge and it was concluded that the long-term deflections had negligible effect on amplification factors, but the road surface roughness could cause amplification factors in excess of 2.0 (Au, Cheng, and Cheung 2001a).

The effect of road surface on bridge responses was further investigated with 3-dimensional FE models. Kou and DeWolf modeled a 4-span continuous plate-girder bridge, and examined the effect of smooth road surface versus 0.5 inch and 1 inch amplitude roughness and concluded that the road roughness had negligible effect on bridge deflections (Kou and DeWolf 1997). In contrast, 3-D FE simulations of a 3-span non-continuous bridge by Li et al. showed that the surface roughness had a large effect on dynamic amplification, especially with increased speed. Based on simulation efforts, a maximum dynamic amplification of nearly 3.0 was reported for poor road condition and at 70 mph, while a DAF of only 1.2 was recorded from field measurements of the bridge (H. Li, Wekezer, and Kwasniewski 2008).

Indeed, the dynamic amplification factors obtained from field measurements are consistently lower than the factors suggested by analytical research and have similarly wide variation from bridge to bridge. Cooper instrumented two bridges in England and recorded a maximum DAF of 1.42. Cooper also created a probabilistic model of DAF based on field measured road roughness and span length that suggests a maximum mean DAF of 1.27 (Cooper 1997). Park et al. examined the effect of road roughness on dynamic amplification by testing 25 highway bridges in South Korea. None of the bridges exhibited amplification factors greater than 1.25, but their results clearly showed that the amplification factors increased with the International Roughness Index (IRI) (Park, Shin, and Chung 2005). However, further research suggests that no single measure of road roughness can accurately predict DAF because of the many other influential parameters that contribute to DAF (i.e. bridge geometry, mass and stiffness; vehicle dynamic properties; vehicle speed; etc.). (E. OBrien, Li, and González 2006; Y. Li, OBrien, and González 2006).

Effects of Platooned Vehicles

Much research has focused on the load effect of congested traffic on bridges, whereby larger loads are applied to the structure due to the increased number of vehicles present. The increased load is exacerbated by the tendency of long lines of trucks to form (Han et al. 2015). While any traffic pattern of repeated trucks is often referred to as truck platoons, in this research platoons will refer to trucks that are virtually coupled by wireless communication and sensing that allows on-board computers to control headway and speed. Some research has looked into how this headway should be controlled to reduce congestion (Lipari, Caprani, and OBrien 2017), but little work has been done to understand the dynamic effect of platooned trucks on highway bridges.

In contrast, the problem has been extensively studied for railway bridges, where train cars present regular wheel spacing, vehicle spacing, and weight (Bolotin and Armstrong 1965; Kurihara and Shimogo 1978; Yeong-Bin Yang, Yau, and Hsu 1997; J. Li and Su 1999). Research has shown that railway bridges are susceptible to large dynamic amplifications (Wu, Yang, and Yau 2001), and that the amplification is dependent on such parameters as wheel spacing, train speed, bridge span length, and bridge first fundamental frequency (Majka and Hartnett 2008; Kwark et al. 2004).

However, while the loading conditions of railway bridges are similar to that induced by platooned trucks, the structural system is markedly different. The tracks of railway bridges are often isolated from the structure by ballast, providing different load distribution and significantly higher damping than is accomplished by the deck of a highway bridge. Furthermore, the track of a railway bridge is typically smoother and with fewer irregularities than a highway bridge roadway.

Bridge Vibration Limits

The dynamic effect of traffic on bridges is not just of concern for amplification factors or strength limit states (i.e. rating factor). Excessive vibrations may result in reduced fatigue life, as the vibrations can result in more stress cycles per loading event. Furthermore, structural vibrations should be limited so as not to upset the bridge users.

Past studies have looked at what constitutes objectionable vibrations and the characteristics that influence a human's perception of those vibrations. In general, these studies concluded that as the displacement and frequency increase, the vibration is considered more intolerable to users. However, there is no single parameter that can predict a human's perception of a given vibration (Gaunt and Sutton 1981). Some of the earliest work on this topic was carried out by Reiher and Meister. They developed sensitivity curves by subjecting people to vertical harmonic vibration (Reiher and Meister 1931). These sensitivity curves still provide an acceptable characterization of human perception to vibrations.

AASHTO bridge specifications state that bridges should be designed to avoid psychological effects and that acceleration is the primary factor for human sensitivity to bridge deformations, but fails to provide any specific limits for vibrations (AASHTO

1998). Instead they placed limits on span-to-depth ratios and live load deflections in hopes that this would prevent unsatisfactory dynamic behavior. The Ontario Highway Bridge Design Code of 1983 introduced a new serviceability limit state that was meant to control vibrations that would be objectionable to pedestrians by restricting deflections based on the first frequency of the structure (Csagoly and Dorton 1978). The Eurocode also advises bridge designers to limit vibrations to avoid the discomfort to users, but again, fails to provide guidance as to how that may be accomplished (BS 2006).

Knowledge Gaps

Much research has been devoted to understanding the factors that affect dynamic amplification and to the development of methods for calculating it. However, numerous bridges have been identified as having amplifications far outside those predicted by established methods, thus suggesting there are mechanisms whose effect on dynamic behavior is still poorly understood. Even though past studies have identified influential parameters that may contribute to the apparent outliers, there has been no consensus on how to incorporate those parameters into dynamic response predictions. This is due, in part, to the failure of studies to consider all influential parameters simultaneously and thus their interdependency. Furthermore, much of the previous research considered only simple loading models (i.e. design trucks) that cannot possibly account for the variety of vehicles that any given bridge experiences every day. With the advancement of computational tools and processing power, a comprehensive parametric study is only recently feasible.

Dynamic amplification factors, due to the nature of their formulation, are incapable of accurately predicting the amplification of a wide range of structures. They were developed by applying statistical methods to a population of bridges that were selected for investigation, and therefore, while they aim to provide a reasonable upper bound on amplification for design purposes, cannot be expected to remain accurate for every single bridge in the population. Furthermore, there is no assurance that the chosen sample sets are representative of the entire bridge stock, nor can it be assumed that the characteristics of the entire bridge stock are time invariant.

There is therefore a need, in the interest of developing methods whose range of applicability includes a larger portion of the bridge stock, to investigate the effect and interdependency of a more comprehensive set of parameters and to identify and characterize those bridges that are "outliers" and non-conservative. This understanding can be leveraged to develop a mechanistic modeling approach capable of accurately predicting the dynamic amplification of a wide range of bridges (as opposed to relying on a statistical approach that aims to characterize a reasonable upper bound). Furthermore, changes in bridge design, loading, maintenance practices, etc. and their influence on population characteristics should be considered in an effort to ensure resulting methods will continue to be applicable.

As truck platoons are introduced to America's highways, the lack of understanding of vehicle-bridge interaction could further threaten the bridge stock. To date, research on the impact of repeated vehicles has been limited to railway bridges, for which the loading and structural characteristics are significantly different. Before this novel mode of transportation is implemented, investigation of its impact on bridge response should be conducted for which the bridge and load patterning are represented in a manner that is realistic of actual structures and truck platoon scenarios.

Research Objectives and Approach

The research will fall into three broad categories:

1. Characterize the mechanisms behind the dynamic interaction and identify the influential parameters by leveraging finite element (FE) simulation tools,
2. Identify any shortcomings with current design and assessment methodologies and propose modifications, and
3. Identify bridge vulnerabilities associated with truck platooning and make recommendations related to implementation strategies and policies.

The research will take an inductive approach, whereby efforts will first focus on understanding the phenomenon of vehicle-bridge interaction by investigating a specific structure with unusually large dynamic amplifications. The resulting knowledge and tools will be leveraged to generate generalized conclusions about dynamic amplification for typical highway bridges and mechanistic models for its simulation.

Understanding vehicle-bridge interaction

Operational structural monitoring along with finite element simulation will be used to explore the principles and mechanisms behind dynamic amplification. The process of structural identification will be leveraged to incorporate sensing data from a real structure into an FE model. That process will first be conducted to obtain a model that is an accurate representation of the bridge. It will be conducted a second time to ensure the model can accurately simulate a moving vehicle and its interaction with the bridge.

A variety of sensors will be used to capture the acceleration and strain of the structure under operating conditions. Care will be taken to sample at rates high enough to capture the modes of interest and avoid aliasing. From the gathered data and through modal processing methods the shapes and frequencies of the natural modes of vibration of the structure will be computed. Strain readings will be analyzed to determine the operational stress of the bridge and estimate the dynamic amplification.

Characterization of a test vehicle moving over the bridge will occur by instrumenting a fully loaded truck and the bridge simultaneously. The accelerations of the test vehicle will provide information on the vehicle-bridge interaction as well as be used to calculate the truck's first mode of vibration which can be used to characterize the vehicle's suspension.

The FE models will be constructed based on construction documents that detail the geometry and material of the various bridge components. Uncertainties in the model (e.g. material properties, connections, support conditions, etc.) will be addressed by correlating and updating the model based on the test results, whereby model properties will be altered until the simulation results align with the test results. In this way we can be confident that the FE model is representative of the actual structure and capable of accurately simulating VBI.

The VBI testing scenario will be simulated by running a spring-mass-damper system that matches the mass and frequency of the test truck across the model of the bridge. The goal is to produce responses similar to those observed during the test. In the event that matching responses are not readily produced, the model of the bridge and the truck will again be adjusted with a particular focus on inclusion of any potential mechanisms that may have been ignored or discounted.

Once the field test observations can be reproduced, features of the model will be changed or removed in an effort to find out which parameters have the largest influence on dynamic amplification. These parameters represent those mechanisms that effect dynamic amplification and require further investigation. It is anticipated that these parameters may consist of characteristics of the structure, vehicle/traffic, and road surface.

The hope is to find out which types of bridges are vulnerable to objectionable levels of amplification and how to prevent it or modify existing structures to mitigate this behavior.

Addressing current design and assessment methodologies

Parametric studies will be performed on those parameters that were previously identified as influential. Results of the parametric study will be examined to judge the accuracy of current methods for calculating amplification factors. "Rules-of-thumb" for calculating dynamic response of bridges will be developed in cases where the current methodologies fall short. Furthermore, the methods used for analyzing moving loads will be reviewed and alternative methods will be evaluated in an effort to identify a simpler, yet still effectual method. It is hoped, that for certain scenarios, there will exist an acceptable modelling method that would be sufficiently efficient to be implemented regularly in practice.

Impact of platooning on bridge responses

The models developed for simulating VBI will be used to simulate platooned trucks. They will possess those characteristics that correspond to large dynamic response, resulting in models that are sensitive to the platooning parameters. A parametric study will be conducted to determine what combination of parameters results in increased stress in the structure and should be avoided. Additional parametric studies will be conducted to understand how the structural characteristics influence the "problematic" platooning parameters. Once complete, the results of this parametric study will be condensed into a set of policy recommendations related to the influence of truck platooning on the long-term performance of bridges.

Work Plan

Research Strategy

The overall research strategy is organized into five phases as shown in Figure 1 below.

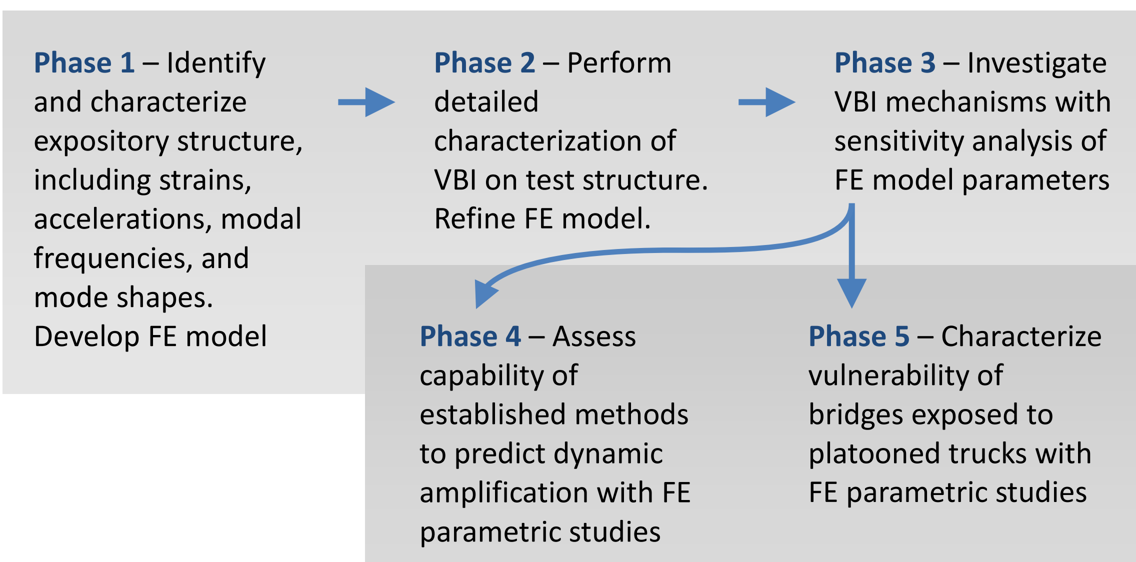


Figure 1: Schematic of Research Organization

Phase 1 – Preliminary Field Characterization

As a first step, an existing structure will be located for which vehicle loading produces dynamic responses at a level that can be easily detected by sensors and thus suitable for investigating VBI. If a proposed structure is found to possess the desired attributes, it will be characterized through the process of structural identification. Therefore, a variety of sensors will be placed on the bridge to record operational strains and accelerations, and an FE model will be developed that is a "digital twin" of a real structure.

Task 1.a. *Perform preliminary field test of proposed bridge to determine which regions experience the largest vibrations.* Accelerometers will be installed on the bridge at various locations to determine the nature of dynamic response and which portions of the structure deserve greater scrutiny in future investigations.

Task 1.b. *Design and perform field test of selected portion/portions of the test bridge.* The instrumentation plan will be designed to capture the maximum responses while providing adequate spatial distribution to characterize the shape of natural modes of vibration (mode shape) and nature of interaction between superstructure and substructure. Both acceleration and strain will be monitored. Accelerometers will be installed with magnets and will be sampled with a National Instruments (NI) portable acquisition system, while the strain gauges will be attached with epoxy and sampled with a Campbell acquisition system. Because, of the likely lack of power infrastructure on site, batteries will be used to power the acquisition systems.

Task 1.c. *Process and Interpret data acquired from field test.* Characterization of vibrations will include examination of the frequency content by computing the spectral density, identification of mode shapes and corresponding frequencies through the use of the complex mode indicator function (CMIF), and comparison with comfort limit states. Dynamic amplification will be estimated by using pass band filtering techniques on the strain data, to isolate the static response from the total response.

Task 1.d. *Create, validate and calibrate FE model/models of the structure.* Models with varying levels of resolution and complexity may be required for different purposes. The model will be error screened and validated by comparing behavior of model to that which would be expected for the structural form and to those observed in the field. Model calibration will be completed by deliberately adjusting model parameters until sufficient agreement is found between predicted and measured mode shapes and natural frequencies (while simultaneously using a parameter set that is plausible based on heuristics).

Task 1.e. *Use the model to assess structural condition and performance (e.g. load rating).* Investigate possible mechanisms for atypical dynamic behavior if present. Some of these may become apparent from model anomalies or disparities that must be addressed as part of the calibration process. The model will further be used to examine the influence of unique bridge characteristics to the observed structural behavior.

Phase 2 – Detailed Field Characterization

With a thorough understanding of the structure, further investigation will seek to characterize the vehicle-bridge interaction. This will include field testing whereby both the viaduct and a vehicle will be instrumented, and responses from both will be captured synchronously while the vehicle is traversing the viaduct. Additional models and new model types may be developed as required such that an analytical model is obtained that is able to simulate the test scenario.

Task 2.a. *Identify appropriate FE software and create a model that is capable of simulating moving vehicle loads and resulting structural response*. Calibrate the model with data from previous test. The model will be created so as to have matching mode shapes, frequencies, and mass distribution. Simulations with varying traffic conditions will be performed as an initial attempt at reproducing the observed operational responses.

Task 2.b. *Design and perform field test of the viaduct with known loading.* This will require instrumentation of both the structure and a test vehicle with synchronous capture of data. The static weight of the vehicle will be measured by placing truck scales under the wheels. Accelerometers will be positioned at the four corners of the dump bucket so that the "roll", "bounce", and "pitch" modes of motion can be captured and characterized. The instrumented vehicle will traverse the viaduct at a variety of speeds and under different traffic conditions. The bridge will be instrumented such that its activated modes of vibration can be characterized at different locations along the aqueduct.

Task 2.c. *Process and interpret data acquired from field test.* The magnitude and frequency content of test vehicle's motion on and off the viaduct and the corresponding structural vibrations will be examined. The effect of the different crossings on the nature of bridge vibrations will be examined by comparing the captured time histories.

Task 2.d. *Measure the profile of the bridge road surface and that of the approaches.* A reputable company will be located that is capable of measuring the roadway profile with sufficient resolution and accuracy and at an acceptable price and subsequently contracted. As a result, the roadway profile of every lane will be delivered and formatted such that it can be incorporated into FE simulations.

Task 2.e. *Simulate test scenarios and compare model results with experimental responses.* The test vehicle will be modeled as a spring-mass-damper. The mass of the system will be determined from the weights measured in the field, and the spring stiffness will be calculated from the measured first natural frequency of the test vehicle. Effort will be made to recreate the magnitude and pattern of vehicle and viaduct accelerations. The uncertain bridge and vehicle parameters will be adjusted to bring the model results in line with the test results. The "uniqueness" of the final model will be assessed by exploring the variety of parameter combinations that produce matching responses.

Phase 3 – Identification of VBI Parameters

Once a model is obtained that is reasonably capable of recreating those responses measured in the field, various model parameters will be adjusted to identify those to which dynamic amplification is sensitive. These parameters are indicative of the structural and vehicle mechanisms that govern the distinctive behavior observed.

Task 3.a. *Reduce model complexity while maintaining accurate VBI simulation,* in an effort to reduce computational requirements for the large number of simulation runs that are anticipated. This will focus on reducing the geometric complexity of the model. For instance, the substructure can be reduced to springs and support conditions at the ends of the girders, and the superstructure can be reduced to a grillage or single-line-girder model. For any reduction attempts, a control simulation of VBI that was used in Task 2 will be run and the responses compared to those from the unaltered model. The trial model will be rejected if compared responses differ. A passing model with the least complexity will be selected for further parametric studies.

Task 3.b. *Identify model properties to which dynamic amplification is sensitive.* Identify all model parameters that have any significant level of uncertainty, as well as any parameters that could vary from bridge to bridge (e.g. vehicle weight, vehicle speed, road surface roughness, bridge material properties, bridge support conditions). The selected parameters will be altered to see if they have any effect on the dynamic amplification. An attempt will then be made to reduce the total number of parameters by eliminating extra properties that have "overlapping" representation of mechanisms. For instance, bridge deck thickness influences both the mass of the deck, as well as the stiffness. It is better to uniquely target these mechanisms with the deck material density and modulus. In this way the minimum set of parameters will be selected that can account for all influential mechanisms.

Task 3.c. *Develop parameter ranges that are appropriate for future parametric studies of dynamic amplification.* The chosen set of parameters will be adjusted incrementally and the control moving vehicle load case as well as a natural frequency solver will be run so as to develop sensitivity curves. The very nature of some parameters may restrict their range. For the rest, the range will be those values within the sensitive range.

Task 3.d. *Examine and refine sensitivity plots.* This will constitute the first effort to identify trends in dynamic amplification through regression analysis. In some cases the parameters may be combined into a single variable. For example, it might be advantageous to plot responses versus the first natural frequency, which is largely a function of longitudinal stiffness and bridge mass. Furthermore, some parameters may require further investigation, especially when they are more complicated than a single scalar value. For example, the road surface profile can have numerous configurations. One approach may be to separate this parameter into categories that describe the density of imperfections of different wavelengths through spectral density terms. Those parameters that exhibit no effect on dynamic amplification will be discarded. Through this effort a final set of parameters will be collected and their sensitive ranges established.

Task 3.e. *Document the final set of parameters and their relation to vehicle or structural mechanisms.* Identify design and management decisions that have an effect on those mechanisms.

Phase 4 – Assessment of Current Approaches to Dynamic Amplification

The dynamics of bridges and vehicle-bridge interaction is given little attention in current design and evaluation codes. Most only account for it by applying a factor to the static load effects and by limiting deflections to reduce excessive vibrations. This task will examine the shortcomings of these methodologies and determine how the dynamic amplification may be more accurately predicted.

Task 4.a. *Design and perform a parametric study of the amplification factor.* A parameter sampling scheme will be selected that can efficiently cover the parameter space. Latin hypercube sampling will be used for continuous scalar valued parameters. Full factorial sampling could be used for categorical parameters, but this sampling scheme would unnecessarily and drastically increase the number of test cases. Therefore, a fractional factorial design will be utilized, which still exposes information of the parameters' level of influence on the amplification factor and their interaction, but with much fewer test cases. The final sampling scheme will be a combination of the two statistical methods and will be used to create a population of parameter sets. Models for each parameter set will be constructed by applying the parameter values to the FE model, which will be subsequently run and results collected. Results will be collected for both VBI simulation and natural frequency. Post processing will produce any response quantities not immediately produced by the FE solver, such as amplification factors. All data will be organized, tabulated and saved in a manner that is accessible for future plotting/interpretation efforts.

Task 4.b. *Identify structures for which the current AASHTO IM factor (0.33) or other common factors are inadequate.* Data from the previous task will be leveraged to identify trends. Samples with amplification factors greater than 0.33 and those less than 0.33 will be broken into separate series. A statistical hypothesis testing method, known as ANOVA, will first be used to decipher differences in the two populations (i.e. do they belong to the same parent population), and which parameters should be investigated in more depth. For those parameters which are selected to bear further scrutiny, individual statistical tests will be performed to identify parameter ranges that lead to a bridge with an amplification factor greater than 0.33. If no trends can be observed, the models will be reexamined in an effort to identify new characteristics to include in the statistical analyses.

Task 4.c. *Identify better methods of predicting amplification factors.* If the previous task reveals shortcomings in the current dynamic amplification methodologies (i.e. any amplifications values exceeded 0.33), regression analysis will be performed in an effort to develop an equation or set of rules that can more accurately predict dynamic amplification. Consideration will be paid to the spatial distribution of amplification factors, and whether the amplification factor equations can adequately capture that distribution. An attempt will be made to at least identify a simple relationship for the maximum amplification factor. Other methods will be identified as necessary for amplification factors at other locations on the structure or for other response types.

Task 4.d. *Identify alternative methods of modeling vehicle-bridge interaction.* If no simple relationships are found as part of the previous task, or if the identified relationships only apply to a subset of bridges, other analysis methods will be required. They would also be required whenever a more accurate simulation of VBI is desired for a specific structure. Therefore, regardless of the outcomes of the previous task, simpler simulation methods will be explored that can be easily implemented by an engineer with run-of-the-mill FE software and produce conservative results that are comparable to the full simulation used in the parametric study. This will include consideration of simpler FE models, such as single-line and grillage models. Furthermore, an attempt will be made to simplify the modeling of the interaction by splitting the analysis into vehicle response due to the roadway profile alone and the structural response due to the forces resulting from the vehicle response.

Phase 5 – Investigation of Truck Platoons

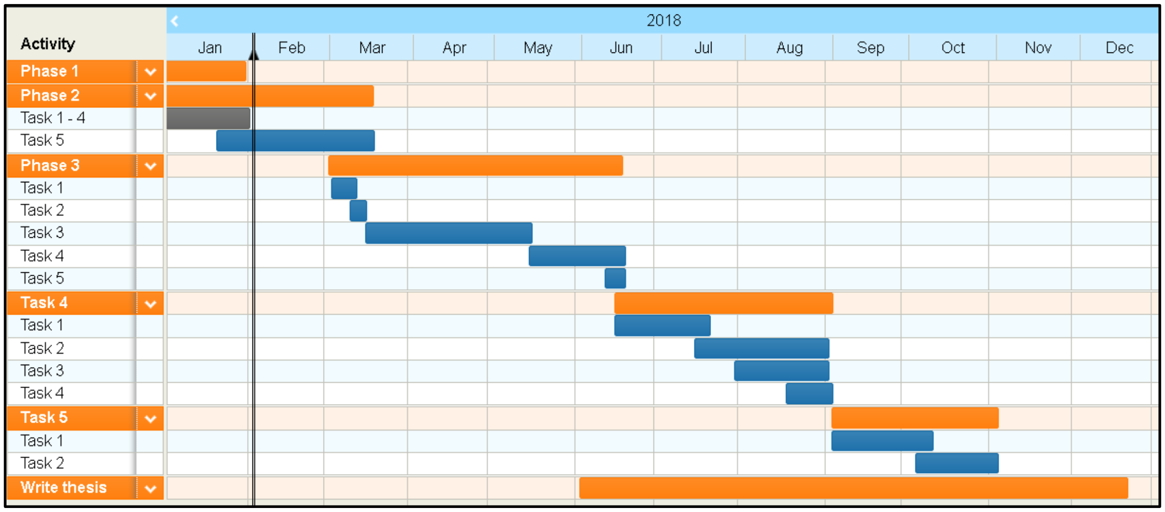
The models developed for the previous parametric study will be used to simulate platooned trucks. The goal is to identify the vulnerability of a given bridge to large dynamic responses under platooned trucks, as well as the platoon parameter ranges that would greatly reduce the effect on even the most vulnerable of bridges.

Task 5.a. *Identify platoon parameter values that result in maximum bridge response and maximum dynamic amplification.* Models from Task 4 that exhibited the maximum and minimum dynamic responses will be selected for this investigation; thereby providing models that are sensitive to the platooning parameters as well as capable of bounding the range of platoon impact. The platoon parameters will include principally vehicle spacing and speed. Secondary parameters will include vehicle weights, and suspension stiffness and damping. A parametric study will be conducted to determine the combination of parameters that results in maximum stress in the structure (i.e. the “worst-case” platoon). Additional studies will be conducted to examine the response of other bridge models to the “worst-case” platoon and any relationships between the bridge characteristics and the platoon parameters that produce the “worst-case” response condition (e.g. does optimal vehicle spacing depend on bridge span length).

Task 5.b. *Identify platoon parameters that most effectively reduce dynamic effects and bridge responses.* Platoon parameters will be investigated that are under operator control. The parametric study from the previous sub-task will be reused. Additional data will be gathered as necessary to fully characterize the parameter space resulting in minimal dynamic response (i.e. create and run additional models). The ideal range of platoon parameters will thus be identified as well as the relative “return-on-investment” of making different platoon management decisions.

Task 5.c. *Develop truck platooning policy recommendations.* Practices (such as platooning, bridge maintenance and bridge design) will be identified that correspond to the parameters obtained in the previous task. Those that can be practically implemented will be compiled and summarized as recommended policies.

Schedule



Current Progress

Research on this topic began in April of 2016 after PennDOT mentioned in a meeting that they had a bridge which was believed to have vibration issues because motorists were frequently reporting "abnormal" vibrations. The bridge, to which they referred, is an 11 span steel viaduct that carries the Schuylkill Expressway (I-76) over a flood plain near Bala Cynwyd, Pennsylvania. In July of 2016, two field tests were performed on the bridge, whereby accelerations and strains of the structure were recorded under operational conditions over a period lasting more than 12 hours. These field tests revealed that all regions of the bridge that were instrumented were experiencing large amplitude vibrations (>0.25 g) that were associated with significant deflections (≈1/2 in.). This type of vibration is considered disturbing by many human comfort criteria. The strain records revealed the bridge was experiencing large amplitude stress cycles (3-6 ksi). Furthermore, a comparison of the filtered strain response to the raw strain record, suggests the vibrations are leading to large dynamic amplifications (≈2.0).

An FE model of a 2-span segment was constructed and calibrated with the mode shapes and frequencies computed with the acceleration data. The *a priori* model required little adjustment to align it with the experimental results. Furthermore, the calibrated model revealed no structural deficiencies or abnormalities. The increased amplification factor resulted in lower bridge ratings, but they remained greater than 1.0. Model simulations further revealed that the cross girder effectively transmits vibrations, thus exciting modes of vibration in the unloaded span. This explains why motorists, stopped in traffic on one side of the bridge, can still perceive large vibrations.

It became evident that more complex simulation would be required if the observed structural behavior was to be fully understood. A new FE software was acquired (LUSAS) that is capable of simulating a sprung mass (or multiple sprung masses) moving on top of the model of the structure. Initial modeling efforts revealed that there were too many unknown variables in this more complex system, and that further field testing would be required to gather more information on the structure, the vehicle and their interaction.

In June of 2017, another field test was performed, whereby both a loaded dump truck and the viaduct were instrumented and data recorded. Testing revealed that the test truck had significantly larger accelerations when traversing the bridge and that those accelerations increased with the vehicle's speed. Similarly, the bridge responded with increased vibrations as soon as the test truck entered the corresponding span. However, even with known vehicle weight, speed, suspension parameters, and a structural model that confidently represents the bridge, the FE simulations were unable to recreate those responses measured in the field.

Further simulations were performed in an effort to identify those parameters that were influential and still poorly understood.   As a result it was found that the roadway profile was the principle influential parameter, and required accurate measurement for there to be any hope of simulations matching the experimental responses. Therefore, RWS Consulting was contracted to measure the roadway profile, which was completed on November 11, 2017.

One of the measured profiles was included in some initial simulations, and the resulting responses agree well with those observed during the field test. Further model adjustments and simulations will be explored to ensure the model can accurately represent the mechanisms involved with vehicle-bridge interaction.

Conclusions

The current body of knowledge in bridge design and assessment is incapable of properly considering vehicle-bridge interaction and wholly inadequate at determining the effect of truck platoons on bridges. Previous research may agree on the maximum dynamic amplification that can be expected for a typical bridge, but provides little insight on the mechanisms that influence dynamic amplification and the characteristics of a bridge that may exhibit excessive amplifications

The current state of this research had resulted in the following main conclusions.

- The test bridge is experiencing vibrations that violate human comfort criteria

- The observed dynamic amplifications exceed that specified by AASHTO
- The bridge appears free of abnormalities and is in good functioning order
- A vehicle experiences higher vibration when on the bridge and at higher speeds
- The bridge is readily excited by even a single vehicle
- The roadway profile has a great effect on the response of a traversing vehicle

Accurate simulation of the test vehicle traversing the bridge is the next step to understanding VBI. A firm understanding of the mechanisms that effect VBI and how they should be modeled will be essential to performing meaningful parametric studies.

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