Ph.D. Research Proposal

**Doctoral Program in Civil Engineering**

**Influential Parameters Leading to Large Dynamic Amplification of Bridges**

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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 (i.e. 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 will seek to: (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.

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. Finally, the research will provide a better understanding of the impact that platooned trucks have on a bridge.

The primary broader impact of the proposed research is the ability for bridge owners and managers to make better decisions. Better understanding of bridge response to traffic allows for a better measure the structure’s performance as well as improved deterioration predictions. It is further hoped that this improved understanding will lead to more accurate design specifications and fewer structures that are vulnerable to excessive dynamic responses. Furthermore, the knowledge of the effect of repeated vehicles on bridges can be included in truck platooning policy, thus ensuring that bridges are not overstressed by this novel mode of transportation.

# State of the Art

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). The industry accounts for this disparity by applying a factor to the static load or response, thereby attempting to increase the calculated response to that which the bridge would actually experience from moving vehicular loads.

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:

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

or

Where Rsta 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 () *LRFD Bridge Design Specification* the impact factor is dependent on road surface roughness, ranging from 0.1 to 0.3. The AASHTO () *Manual for Bridge Evaluation* specifies an impact factor of 0.33.

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 British code includes an IM of 0.25 in its two design load models.

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 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, whereby 18 bridges were constructed 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 initial oscillations of the vehicle produce 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 typically observed. 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 et al. 2006)

## 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 is a wide variety of bridge types and even more varied structural characteristics within each type. (Deng et al. 2015)

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. 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 a complicated one 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 soft suspension with high damping (Green, Cebon, and Cole 1995; Nassif and Nowak 1995).

## Influence of Road Surface Roughness on Dynamic Amplification

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 how much road surface effects 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 evolved, 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 power spectral density functions to produce a more realistic road profile, and obtained dynamic amplification factors (DAF) as high as 3 (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 (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. The study 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 (Au, Cheng, and Cheung 2001).

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 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 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.) (OBrien, Li, and González 2006; Y. Li, OBrien, and González 2006).

## Modeling Vehicle-Bridge Interaction

## Bridges with Excessive Vibrations

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 measure 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 performance. 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).

# Research Objectives and Approach

The research will fall into three broad categories:

1. Understand dynamic amplification and the mechanisms that govern it
2. Propose modifications to current design and assessment methodologies
3. Examine the impact of repeated vehicles on dynamic amplification

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 the bridge stock.

## Understanding dynamic amplification

Structural health 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 utilized to capture the acceleration and strain of the structure under operating conditions. Care must 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 calculated. 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. 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 “calibrating” the model with 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 truly representative of the actual structure and capable of accurately simulating VBI.

The testing scenario will be simulated by running a spring-mass-damper system that matches mass and frequency of the test truck across the model of the bridge. The goal is to produce responses similar to those witnessed during the test. In the event that matching responses are not readily produced, the model of the bridge and the truck will be adjusted.

Once the field test observations can be reproduced, features of the model will be changed or removed in an effort to find out to which parameters large dynamic amplifications are sensitive. The hope is to find out what types of bridges are vulnerable to this phenomenon and how to prevent it or modify existing structures to eliminate the phenomenon. These parameters will consist of characteristics of the structure, vehicle/traffic, and road surface.

## Adressing current design and assessment methodologies

Results of the parametric study will be examined and “rules-of-thumb” for calculating dynamic response of bridges will be developed. These will be compared to current design and assessment specifications and appropriate modifications will be proposed. Furthermore, the methods used for analyzing moving loads will be reviewed and other, simpler methods will be formulated and evaluated in an effort to identify a simpler method that is still able to accurately predict a bridge’s dynamic response to moving vehicles. It is hoped, that for certain scenarios, an acceptable modelling method can be used that the “typical” engineer could understand and implement.

The proposed methodologies will be demonstrated on a bridge that exhibited problematic dynamic amplifications.

## Impact of platooning on bridge responses

The models developed for the simulating VBI will be used to simulate platooned trucks. The model will be selected such that its parameters correspond to large dynamic response. This will result in a model that is most sensitive to the platooning parameters. These platooning 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 what combination of parameters result 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.

# Work Plan

## Task 1 – Field testing and simulation of test structure

As a first step to investigating VBI, an FE model will be developed that is a “digital twin” of a real structure. This will be accomplished by performing structural identification, whereby data from the real structure is used to influence and “calibrate” a model. Therefore, a variety of sensors will be placed on the bridge to record operational strains and accelerations.

1. Perform preliminary field test of viaduct to determine which regions experience the largest vibrations. Accelerometers will be installed on the bridge at various locations along its entire length. The magnitude of these responses, relative to one another, will be used to determine which portions of the structure will receive greater scrutiny in future investigations.
2. Design and perform field test of selected portion/portions of viaduct. Instrumentation plan will be designed to capture maximum response 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.
3. Process and Interpret data acquired from field test. Characterization of vibrations will include computation of mode shapes and corresponding frequencies, examination of the frequency content, and evaluation of strength, service and comfort limit states. Dynamic amplification will be estimated by utilizing data filtering methods.
4. Create, validate and calibrate FE model/models of the structure. Models with varying level of resolution and complexity may be required for different purposes. 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.
5. Use model to assess structural condition and performance. Investigate possible mechanisms for vibration levels. Examine degree of conservatism lost due to amplification factors greater than assumed for design.

## Task 2 – Refinement of FE simulation with VBI data

Additional testing and simulation will attempt to answer those questions about dynamic amplification that were not adequately answered by Task 1. 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 required that are better able to simulate the test scenario. The model will be leveraged to identify the manner of loading that contributes to dynamic amplification and the structural parameters that affect it.

1. Identify appropriate FE software and create appropriate model that is capable of simulating moving vehicle loads and resulting structural response and is calibrated with data from previous test.
2. 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 instrumented vehicle will traverse the viaduct at a variety of speeds and under different traffic conditions.
3. Process and Interpret data acquired from field test. Examine magnitude and frequency content of test vehicle’s motion on and off the viaduct. Examine magnitude and frequency content of the structure’s vibrations when the test vehicle is on and off the bridge, and the nature of the vibrations for different crossings of the test vehicle.
4. 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 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.
5. Simulate test scenarios and compare model results with experimental responses. Effort will be made to recreate the magnitude and pattern of vehicle and viaduct accelerations.

## Task 3 – Identify influential mechanisms to VBI

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.

1. Reduce model complexity while maintaining accurate VBI simulation. 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 trials, 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.
2. 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. These parameters might include: vehicle weight, vehicle speed, road surface roughness, bridge material properties, bridge support conditions. Each of these parameters will be altered to see if they have any effect on the dynamic amplification.
3. Develop parameter ranges that are appropriate for any future parametric studies of dynamic amplification. An attempt will first be made to reduce the total number of parameters by eliminating extraneous properties that target the same mechanism. 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. The final 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 in the sensitive range.
4. Examine and refine sensitivity plots. This will constitute the first effort to identify trends in dynamic amplification. 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 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 the parameter into amplitude and frequency content categories that describe the density of imperfections of different wavelength. 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 4 –

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.

1. Parametric study focusing on the amplification factor
2. Identify for which structures is the current AASHTO IM (0.33) or other common factors inadequate. Identify those parameters to which dynamic amplification is sensitive. Design a parametric study that samples those parameters, Identify ranges of bridge and vehicle parameters for which amplification factors exceed specified values.
3. Examine trends to identify better methods of predicting amplification factors
4. If no clear trends may be observed, or if the identified trends only work for a subset of bridges, other analysis 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. Look into simpler methods of simulation that can produce the same results as the more complex modeling already used. Single-line and grillage models will be examined compared to full 3D FE models. Vehicle acceleration due to roadway profile alone will be solved independently and the resulting accelerations applied as loads to the structure to see if vehicle-bridge interaction needs to be explicitly modeled.
5. Identify special loading scenarios (i.e. platooning) that may result in large vibrations. FE simulation tools will be used to demonstrate how this scenario can be analyzed and the conditions to be avoided so as to limit vibrations.
6. How should IM testing be conducted. Demonstrate how dynamic behavior led to damage of a bridge. A bridge that was previously tested will be reexamined to determine if the vibrations induced by traffic resulted in a crack of the concrete pier.

## Schedule

# Chapter 5 Current Progress

# Chapter 6 Conclusions

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