# Developing Wyoming Specific Bridge Deterioration Models for Bridge Management


WYDOT Sponsor
Paul Cortez
Wyoming Department of Transportation
Bridge Program
5300 Bishop Blvd
Cheyenne, Wyoming, 82009
(307) 777-4049



Principal Investigator
Marc Maguire
Utah State University
Civil and Environmental Engineering
4110 Old Main Hill
Logan, Utah
435-797-1139



Submitted to
Wyoming Department of Transportation
Programming Research unit
5300 Bishop, Blvd.
Cheyenne, Wyoming, 82009

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### A. Problem Statement

Like the rest of the nation, Wyoming Department of Transportation (WYDOT) has bridges are in need of rehabilitation or may benefit from a preservation technique such as deck sealing. Bridge managers need tools to make decisions about intervention so funds can be allocated accordingly, now and in the future. The WYDOT bridge section needs specific techniques, taking advantage of Wyoming specific data, to predict deterioration so funds can be appropriately distributed. Condition data has been collected for the National Bridge Inventory since 1983 and element level inspection data since 1996. Using this data, an accurate state-of-the-art bridge management system can be developed.

The purpose of this project is to investigate relationships between bridge deterioration, design, and environmental factors and develop design and maintenance strategies in response to the findings. The main objective of the project is to develop deterministic and/or probabilistic deterioration models for Wyoming bridges based on historical and geometric data. The impact of several factors found and known to be important to deterioration, and outlined in more detail below, will be considered in developing these models.

The data from the study can be used to find statistical trends that affect bridge performance in Wyoming. Furthermore, the study will be able to identify differences in performance between various subpopulations through a rigorous statistical analysis. Additionally, the performances in past or current inspections methods and/or design details may be identified.

### B. Background and Literature Review

The goal of infrastructure preservation is to cost-effectively and efficiently improve asset performance, as measured by attributes such as service life (Primer, 1999). Current bridge management systems use deterministic or Markov chain or semi-Markov process to predict future performance and service life. Many states have successfully developed deterioration models for their inventory. In all cases, this requires intensive investigation into the available state compiled condition information. Ng and Moses (1999) outlined how the semi-Markov process could be used to determine the minimum-cost for bridge elements in Indiana. Arawal et al. (2010) developed a Weibull based approach for New York bridges. Determining the effectiveness of one method (e.g., deterministic versus Markov based) was the focus of several research projects (e.g., Morcous et al. 2002, Thomas 2011, Sobanjo et al. 2010, Arawal et al. 2010).

The development of these models requires information regarding the past performance of the assets to be compiled and analyzed. Wyoming bridges have been inspected and the data regarding their geometry, function, environment and condition is available, but must be statistically analyzed.

Bridge designers and managers have access to several sources of information about bridges, however, they are scattered and not easily compiled for analysis. The National Bridge Inventory (NBI) contains easy to access information about condition rating and some geometric details, but provides limited details on many bridge details. Bridge designers have access to paper or electronic plans for bridges, but the design geometry is time consuming to extract and work with. Furthermore, environmental data is available through many sources, but not compiled, but through this research will be considered.

In an unpublished pilot study by the Principal Investigator (PI), sixteen steel bridges were selected near Washington DC to determine structural factors affecting deterioration and to develop a deterministic (i.e., without regard to inherent probability) deterioration model. This study is an example of the direction of the proposed project and relates well to the Wyoming inventory, which contains mostly steel bridges. Data from the National Bridge Inventory (NBI), plans, and inspection reports were collected from each bridge. Inspection reports typically provide qualitative data, which is difficult to quantify for data analysis, but contained some quantifiable data. However, quantitative use of most information in the inspection reports will be difficult. For the preliminary study, element level inspection was not considered because the selected bridges had very similar deck element condition levels. Without a wide range of deterioration, the analysis will not yield significant results. The proposed study will incorporate a wider range of bridges (data points) so element level data will be a focus because of its typically higher accuracy and fidelity.

Finite element analyses, using the beam offset model (Zhang 2008), were incorporated to determine structural factors which affected the deterioration (as determined from NBI data). The finite element models and mechanical models were used to estimate stress based deterioration, combined with diffusion based deterioration models (Balakumaran, 2012) and environmental factors. Deterministic deterioration models were developed and trends in structural factors affecting performance were identified.

For example, the biggest factor found to affect deterioration was first fundamental frequency as determined from the finite element models. As presented in Figure 1, there is some correlation between first frequency and rate of degradation, with low frequency bridges (long period) degrading more rapidly than higher frequency bridges. Note the low correlation of determination. This seemingly poor correlation is a manifestation of the high scatter in the condition rating of the bridges and the relatively few data points. This scatter can be mitigated by investigating a much higher number of structures, as will be proposed for WYDOT bridges.

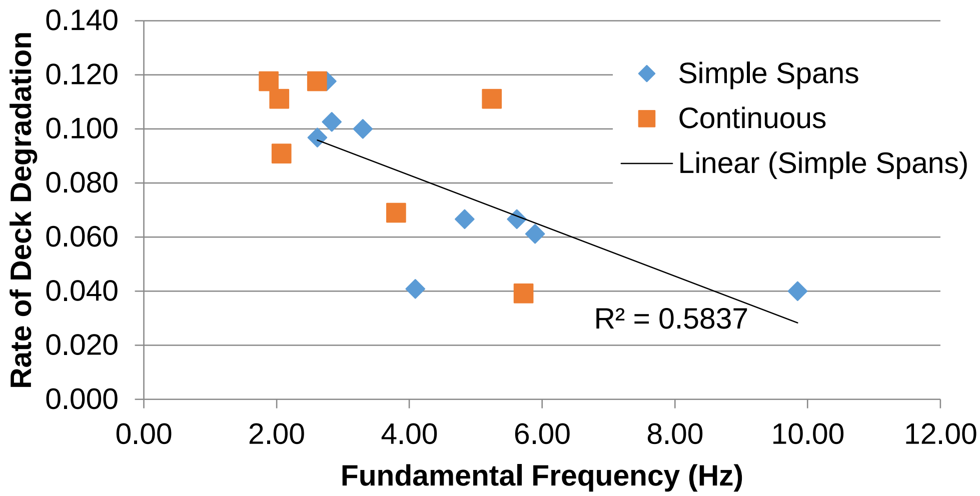


*Figure 1 – Rate of Degradation versus Fundamental Frequency*

Using the various factors identified as affecting deterioration rate an example deterministic model was created using multivariable linear regression:

$$DDRate = \frac{6.66 * Hz}{10^3} + \frac{7.37 * TPY}{10^6} + \frac{1.47 * LSH}{10} + \frac{2.61 * GS}{10^2} - 0.184727$$

This equation predicts the straight line degradation rate (DDRate), intended for use over a short period of time, but incorporated geometric factors like natural frequency (Hz), trucks per year (TPY), longitudinal shrinkage stress (LSH) and girder spacing (GS). This equation takes into account several factors that traditional deterministic condition models do not, which typically focus only on time for various bridge subsets (Hatami and Morcous 2011).

The preliminary study investigated the use of easily obtained information relating to structural performance and deterioration. The results of this very small study will inform the methods used in proposed study for data collection and analysis, but not necessarily the methods used for deterioration modeling. The presented study was not taken past determining a deterministic model, incorporating only a small number of factors. The proposed study will investigate several factors for several structure types and investigate the goodness of fit of both deterministic and stochastic deterioration modeling.

### C. Study Objectives

The proposed study will focus on developing deterministic and Markov based deterioration models for WYDOT bridges. To reach this goal, several objectives must be completed.

<u>*Objective 1: Collect Data Relevant to the Study.*</u> Data must be collected from all sources available including NBI data, element level inspection data, inspection reports, plans,

past maintenance actions and environmental information. Of course, any additional information the RAC and champion deem necessary will also be incorporated.

*<u>Objective 2: Analyze the Collected Data for Factors Affecting Condition.</u>* Statistical analyses will be performed on the collected WYDOT inventory data. The data analysis will allow the researchers to identify design, response and environmental parameters associated with deterioration.

*<u>Objective 3: Develop Deterioration Models.</u>* Using the results from the data analysis in Objective 3, deterioration models will be developed. The focus will be on developing Pontis (a common bridge management system) compatible deterioration models (Markov based) and deterministic models to inform maintenance decision making.

*<u>Objective 4: Implement and Report Results.</u>* Compile the results obtained from the previous objectives and develop a comprehensive report on the work performed. A major part of writing the report will be working directly with the WYDOT bridge office and champion to develop ways the generated deterioration models will be useful to them. Implementation is the primary objective of this research and ideally be immediately used by WYDOT bridge managers.

## D. Study Benefits

Predicting anticipated spending and funding allocations is important to the year to year operation of WYDOT. This study will give the WYDOT Bridge Program the ability to predict bridge maintenance actions with better accuracy, which will save WYDOT capital and/or allow for more efficient allocation of their limited funds.

Determining possible design practices which contribute to deterioration can have an immediate impact on future designs. By identifying past engineering changes and their effect on deterioration rate, current designers continue or discontinue certain details which are effecting deterioration, or develop improved details.

## E. Applicable Questions

Below are questions requested to be answered by the WYDOT research center:

***a. Are there any potential barriers to implementation (e.g. material, technology, vendors, legal/regulatory, public perception)?***

No.

***b. For each potential barrier, are strategies to mitigate potential barriers identified and presented?***

N/A.

***c. What is the expected timeframe for implementation?***

Implementation should begin prior to project completion and is expected to take up to six months. See Table 1.

***d. Does the project involve action on Federal lands or other condition that will require NEPA documentation (e.g. Categorical Exclusion or Environmental Assessment)?***

No.

***e. What are the major uncontrollable factors and/or unknowns in the project such as weather, wildlife, material properties, traffic, etc?***

Unknowns involve weather associated with travel to allow for regular meetings with the Champion. Additionally, there is some small degree of uncertainty associated with available information and access to that information.

***f. Are their contingencies to address these uncontrollable factors and unknowns in the proposal and are there additional costs if there are delays due to uncontrollable variables such as weather?***

Weather contingencies include rescheduling as appropriate. Data access contingencies will involve working around access issues with Utah State University and WYDOT information technology employees. Neither of these contingencies are expected to require additional cost.

***g. Should the project be segmented into phases with go-no/go decision points based on known unknowns (e.g. technology, partnerships, regulatory)?***

The project does not have any known unknowns that will require a decision to continue or suspend the project. Furthermore, the data collection will be finished and the analysis just begun at the project midpoint. Creating a go-no/go decision point will result in no deliverables to WYDOT if the project is suspended in the middle.

***h. If the project involves evolution of one or more technologies, is a technology roadmap provided showing how these technologies fit together?***

All technologies used in the research, and the results of the research, will be easy to access technology familiar to WYDOT personnel.

## F. Statement of Work

The following work plan will be followed during the course of the proposed project.

### Objective 1: Collect Data Relevant to Study.

***Introduction.*** Collecting data and compiling it into a useable form is an integral part of this research and will likely require the most time. Currently, the largest compilation of data (NBI) contains much information that is not necessary and is often separate from element level inspection data, environmental data and other data types.

***Condition data collection.*** Information contained in element level inspections and NBI condition ratings are not always together. The goal of this research is to allow the two measures of condition to work together. Considering the relative amount of NBI data (30 years) versus element level condition data (20 years), the proposed models will likely rely on both. Furthermore, the data contained, which can be qualitative and difficult to use, will be considered. Condition data can be collected for every bridge in the WYDOT inventory.

***Environmental Data.*** There are several locations to acquire historical data regarding environmental. Several government websites compile environmental statistics by zip code or even triangulated based on geographical coordinates. The National Oceanographic and Atmospheric Association also has historical data tabulated from several weather stations throughout Wyoming. The latter provides very in depth information that may not be ideal for use with the current, program, but it will be investigated. The type of information investigated will be temperature ranges, solar radiation, precipitation and humidity. Environmental data can be collected for every bridge in the WYDOT inventory.

***Geometric and Material Data.*** WYDOT engineers will have knowledge of when design changes occurred over time, like when concrete mixtures changes and when different steel types were used. This type of information will be invaluable study and will be solicited immediately. Data on the structure itself can be extracted from the bridge rating system database to be considered for model development. Furthermore, WYDOT has archived plan sets from which geometric information can be extracted for use if the data is rating database is not enough. Determining what geometric factors effect deterioration can be a great benefit to WYDOT design and maintenance engineers. Geometric and material data can be collected for a large number if not all of WYDOT bridges. The actual number will be decided upon discussion with WYDOT engineers and preliminary investigation into the easily available data.

### Objective 2: Analyze Collected Data for Factors Affecting Condition.

***Introduction.*** Following data collection, the PI will work on identifying specific parameters that affect deterioration. It is imperative the data be filtered appropriately to delineate between bare deck bridges and those that have undergone some form of preservation treatment.

***Regression analysis.*** Regression techniques will be used to identify parameters that are affecting deterioration of various components. By identifying factors affecting deterioration, subsets of bridges can be selected which will have different deterioration rates. This investigation will focus on the entire bridge set and various subsets for which there is more information. By dividing the whole into subsets the developed deterioration models can be applied with more precision. Bridges will likely be divided into smaller subsets based on construction material, location, or any other subset identified as important. In addition to identifying subsets, this analysis can identify certain design details like natural frequency (see Background section) or reinforcing bar cover depth or deck reinforcing patterns that can be taken into account for future designs.

**Objective 3: Develop Deterioration Models**

***Introduction.*** After collection of data and determining the important factors affecting deterioration, developing deterioration models will be possible. Initial focus will be placed on bare decks, various preservation practices, because the bridge deck is typically the most important deteriorating component. Superstructure and substructures at a macro and at an element level will be investigated. Both deterministic and stochastic condition models will be developed to determine performance and utility of each to WYDOT engineers.

***Deterministic Models.*** Deterministic models depend on mathematical or statistical formula for a relationship between factors affecting bridge condition (Hatami and Morcous 2011). The proposed deterministic models will be developed using single or multi-variable regression to determine the goodness of fit to some amount of explanatory variables, as determined from several analyses in Objective 2. In general deterministic methods predict well short-term but struggle for long periods.

***Stochastic Models.*** Stochastic models are being increasingly used in several applications, the most common technique for infrastructure deterioration is the Markov decision process. A state-based deterioration technique will be will be developed using a set of explanatory variables like structure type, truck traffic and environment. The bridge conditions will be defined as different Markovian states, in which there is a probability of the bridge element deteriorating from one state to another. After compiling these probabilities into what is known as a transition matrix, WYDOT can then input into the Pontis bridge management system or a custom system of their choice. Transition matrices can be generated from the condition data using a regression based optimization method that minimizes the differences between a regression curve that best fits the condition data.

### Objective 4: Implement and Report Results.

***Introduction.*** Implementing the deterioration models from Objective 3 into WYDOT's bridge management system will help the bridge section to WYDOT make timely and economical decisions. For this reason the final objective will be to package the final product – the deterioration models – in an easy to use and modify way for WYDOT bridge section for their incorporation into their current bridge management system or in another system of their choice. In tandem with implementation will be writing the final report outlining the methodology, findings and how to update with future information.

***Implementation.*** The PI will work closely with WYDOT bridge managers to implement the results as soon as possible. Implementation will consist of incorporating the developed deterioration models into the WYDOTs bridge management system. This will result in an immediate impact to WYDOT bridge section resources, WYDOT as a whole and ultimately, the state of Wyoming.

***Report.*** Writing will begin upon completion of Objective 3 and in tandem with implementation. Care will be taken to explicitly describe the work in terms familiar with WYDOT such that they could reproduce the work and modify results at a later date.

### Work Schedule

The anticipated schedule is presented in Table 1. It is expected the PI in combination with a PhD student will perform the majority of the work. An undergraduate student will be hired to perform data collection. Funding for undergraduate student will be supplemented using internal Utah State University funding. The project is estimated to require two years to complete. The project will commence upon receipt of funding.

*Table 1 – Task Timeline and Assignments*

| Tasks | Year 1 | | | | Year 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| Objective 1: Data Collection | ■ | ■ | ■ | | | | | |
| Objective 2: Data Analysis | | ■ | ■ | ■ | ■ | | | |
| Objective 3: Deterioration Models | | | | | ■ | ■ | ■ | |
| Objective 4: Implement and Report | | | | | | | ■ | ■ |

### Cost Estimate

The proposed project budget can be found in Table 2. Graduate student salary and PI time make of the most of project direct costs. An undergraduate student will be hired during the first summer of the project and will work on Objective 1 under supervision of the PI and graduate student. Travel is included for face-to-face visits with the WYDOT Bridge Section during various phases of the project and for technology transfer. The project is expected to take two years. Please see Appendix A for a fiscal year breakdown in a format similar to that of the draft WYDOT proposal writing guidelines.

*Table 2 – Proposed Project Budget*

| Number | Description | Unit Cost | | Count | Total Cost |
|---|---|---|---|---|---|
| 1 | Principal Investigator Time | $ 5,556 | per month | 2 | $ 11,112 |
| 2 | Principal Investigator Benefits | $ 2,539 | per month | 2 | $ 5,078 |
| 3 | Undergraduate Student Wages | $ 10 | per hour | 300 | $ 3,000 |
| 4 | Undergraduate Student Benefits | $ 0.79 | per hour | 300 | $ 237 |
| 5 | Graduate Student Wages | $ 16,200 | per year | 2 | $ 32,400 |
| 6 | Graduate Student Benefits | $ 1,718 | per year | 2 | $ 3,436 |
| 7 | Travel | $ 2,500 | lump | 1 | $ 2,500 |
| 8 | Materials | $ 1,000 | per year | 2 | $ 2,000 |
| 9 | **Direct Costs** | | | | $ 59,762 |
| 10 | **Indirect Costs** | | | | $ 23,212 |
| 11 | **Total Project Costs** | | | | $ 82,973 |

### G. Change Order Information and Agreements

Utah State University and the PI agree to submit changes to the contract or requests for additional funds to be submitted in writing to the Research Advisory Committee (RAC). Similarly, changes in scope of work or work schedule will be communicated to the Center and the RAC.

### H. Implementation Process

All research findings will be communicated directly with the WYDOT bridge section champion and the RAC. These findings will result in direct improvements to bridge management practices at WYDOT. The findings will be packaged in such a way that they can be immediately implemented, like a program or spreadsheet that will be customized with the aide of the WYDOT champion, Paul Cortez.

### I. Technology Transfer

Because the results of the findings will be of most interest to WYDOT bridge managers and employees, the research results will be mostly used in-house. At least one publication will be prepared for a national journal and/or conference, which will inform other states of the progress made on the state-of-the-art bridge management techniques employed in the proposed research.

### J. Special Requirements

The PI and graduate student will need access to plan sets and other maintenance records, at the discretion of the WYDOT bridge section and champion.

### K. References

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## L. Appendix A: Fiscal Year Budget Breakdown

Note that some values are outside of the lower and upper ranges specified by WYDOT. The direct costs are low, because Utah State University indirect rate is higher than the bounds presented. For this reason, the PI has reduced cost in other areas, specifically, tuition for the student will be sought elsewhere. There is little equipment specified on the project, only a statistical software package (JMP). Similarly, costs for report generation are expected to be low as most will be covered by PI and graduate student salary. The majority of travel will be to meet with WYDOT engineers for project discussion and for technology transfer.

| | Year 1 | Year 2 | Total Projected Project Costs | Percentage of Overall Project Budget | Indicator | Lower Range | Upper Range |
|---|---|---|---|---|---|---|---|
| **Direct Costs** | **$ 31,225** | **$ 28,537** | **$ 59,761** | 72% | * | 81% | 96% |
| ***Total Personnel Costs*** | **$ 24,756** | **$ 21,756** | **$ 46,511** | 56% | | 44% | 72% |
| Principal Investigator | $ 5,556 | $ 5,556 | $ 11,111 | 13% | | 12% | 46% |
| Other Personnel | $ 19,200 | $ 16,200 | $ 35,400 | 43% | | 23% | 44% |
| Fringe Benefits | $ 4,469 | $ 4,281 | $ 8,750 | 11% | | 5% | 12% |
| Research Travel | $ 1,000 | $ 1,000 | $ 2,000 | 3% | | 2% | 10% |
| Report Generation | $ - | $ 500 | $ 500 | 1% | * | 2% | 11% |
| Equipment | $ 1,000 | $ 500 | $ 1,500 | 2% | * | 3% | 30% |
| Others | $ - | $ - | $ - | 0% | * | 2% | 9% |
| **Technology Transfer** | $ - | $ 500 | $ 500 | 1% | | 1% | 5% |
| Conferences | $ - | $ - | $ - | 0% | * | 1% | 3% |
| Miscellaneous Travel | $ - | $ 500 | $ 500 | 1% | | 1% | 11% |
| **Indirect Costs** | $ 12,128 | $ 11,084 | $ 23,212 | 28% | * | 12% | 17% |
| Project Administration | $ - | $ - | $ - | 0% | * | 1% | 8% |
| Overhead | $ 12,128 | $ 11,084 | $ 23,212 | 28% | * | 12% | 17% |
| **Total Fiscal Year 1 Costs** | | | **$ 43,353** | **52%** | | | |
| **Total Fiscal Year 2 Costs** | | | **$ 39,621** | **48%** | | | |
| **Total Project Costs** | | | **$ 82,973** | **100%** | | | |