Bridge Deterioration Models and Rates

Requested by
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Executive Summary

Background

The California Department of Transportation (Caltrans) is seeking to revise and update bridge deterioration models and user costs to ensure that resources to maximize bridge service life are expended appropriately. Past efforts to analyze deterioration using bridge inspection data have been inconclusive as work to maintain the bridges offsets the deterioration. Additional research focused on more advanced methodologies and state of the practice would provide better predictions of bridge needs for both state and locally owned bridges in California. Updated deterioration rates and models could inform bridge performance targets for the next State Highway System Management Plan and transportation asset management plan, and for eventual use in the bridge management system software for improved bridge network- and project-level decisions.

To assist Caltrans in gathering information about bridge deterioration models and rates, CTC & Associates surveyed state departments of transportation (DOTs) expected to have experience with bridge deterioration forecasting models; a selected group of seven state DOTs that have recently conducted research in this area; manufacturers of bridge deterioration modeling products; and a consultant that uses bridge deterioration modeling products. Twenty-nine state DOTs responded to the survey in addition to two vendors (IDS and Mayvue Solutions) and the consultant (Paul D. Thompson). A literature search was also conducted to identify publicly available national and international research and other sources that describe bridge deterioration models and rates.

Summary of Findings

State Survey of Practice

An online survey was distributed to members of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Bridges and Structures expected to have experience developing bridge deterioration models and rates. A separate survey was distributed to the selected group of seven state DOTs that have recently conducted research in this area. From the initial group of state DOTs, 18 agencies reported on their experience developing bridge deterioration models; seven agencies do not use bridge deterioration forecasting models. From the selected group of state DOTs, four agencies reported on their efforts to implement their research.

System Description

Respondents described several models and methodologies used by their agencies to determine bridge deterioration. Of the 22 respondents, nine reported using commercial products that had been customized for their agencies, six agencies use multiple tools, four agencies use models that were developed in-house, two agencies use models that were developed as part of university research projects, and one agency uses a commercial off-the-shelf project. Table ES1 provides an overview of state DOT bridge deterioration model use.

Table ES1. Overview of State DOT Bridge Deterioration Model Use

Model Type	State	Product/Vendor (If Applicable)
Commercial Off-the-Shelf Product	Tennessee	AASHTOWare BrM/AASHTO
Customized Commercial Product	Arkansas, Delaware, Iowa, Louisiana, New Jersey, Rhode Island, South Dakota, Washington, West Virginia	*Arkansas*. dTIMS/Deighton Associates Limited *Delaware*. AASHTOWare BrM/AASHTO *Iowa*. NBI Optimizer/Infrastructure Data Solutions, Inc. (IDS) *Louisiana*. AASHTOWare BrM/AASHTO *New Jersey*. AASHTOWare BrM/AASHTO *Rhode Island*. AASHTOWare BrM/AASHTO *South Dakota*. AASHTOWare BrM/AASHTO *Washington*. AASHTOWare BrM/AASHTO *West Virginia*. dTIMS/Deighton Associates Limited
In-House Model	Kansas, Oregon, Virginia, Wyoming	*Kansas.* N/A *Oregon*. N/A *Virginia*. N/A *Wyoming*. N/A
Multiple Models	Colorado, Florida, Illinois, Indiana, Michigan, Wisconsin	*Colorado*: • In-house tool: Asset Investment Management System (AIMS) • dTIMS/Deighton Associates Limited *Florida*: • In-house deterioration model • AASHTOWare BrM/AASHTO *Illinois*: • In-house deterioration model • AASHTOWare BrM/AASHTO *Indiana*: • In-house deterioration model • dTIMS/Deighton Associates Limited *Michigan*: • In-house deterioration model • AASHTOWare BrM/AASHTO *Wisconsin*. N/A
University Research	New York, North Carolina	*New York*. N/A *North Carolina*. N/A

N/A Not available.

Applications and Processes

The bridge deterioration models used by agencies responding to the survey support a number of applications and processes. The applications most frequently cited by respondents were:

- Long-range budget planning (20 agencies).
- Project scoping and/or planning (15 agencies).
- Life cycle cost analyses (13 agencies).

Material evaluation and resource demand models were cited least frequently (three agencies). Several respondents provided additional information about the applications and processes supported by their models:

- *Arkansas*. dTIMS is used to calculate asset value based on depreciated replacement cost in the agency's transportation asset management plan.
- *Delaware*. AASHTOWare BrM is used to prioritize annual bridge work needs.
- *Indiana*. In addition to dTIMS, the agency uses a scoping application developed by Deighton to streamline its scoping process. The scoping application interacts with other applications through the agency's data warehouse.
- *Iowa*. The agency uses NBI Optimizer to promote funding needs to state commissioners.
- *New Jersey*. AASHTOWare BrM provides risk-based analysis.

Other Model Parameters

The models used by all agencies except Oregon DOT can be adjusted for specific variables or parameters. The most frequently cited parameters reported by respondents were:

- Superstructure material type (18 agencies).
- Age (17 agencies).
- Condition rating and use of deck overlays (16 agencies each).
- Deck wearing surface (12 agencies).
- Average daily traffic (ADT), climatic conditions and highway functional class (11 agencies each).

Cited least frequently were approach surface (one agency), maximum span length (two agencies), number of spans (two agencies) and skew angle (two agencies).

Bridge Elements

Models used by all agencies responding to the survey include the deck, superstructure and substructure. Other bridge elements accommodated by models include barrier walls (Michigan); culverts (Delaware, Illinois, Kansas, Michigan, New Jersey and Virginia); national- or agency-defined elements (Delaware, New Jersey, South Dakota and Wisconsin); and wearing surfaces (Indiana and Washington).

<u>Modeling Practices and Analysis</u>

Maintenance Treatments

The models from nearly one-half of the agencies (10) responding to the survey account for specific bridge maintenance treatments. Treatments cited by respondents include bridge washing (Rhode Island), deck seals and treatments (Colorado and South Dakota), joint replacements (Colorado), overlays (Arkansas and Michigan), rehabilitation (Colorado and Wyoming), and schedule- and condition-based treatments (Illinois).

Benefits of Specific Maintenance Treatments

Six transportation agencies have developed an approach to isolate the benefit of specific bridge maintenance treatments and their impact on the deterioration rate:

- *Arkansas*. Summation over time of the difference in action and no action.

- *Kansas*. Action/benefit models based on the utility theory for the specific preservation actions in place.
- *Michigan*. Most deck treatments but not all maintenance actions. The condition impact of these actions is based on the rating before the maintenance treatment was made.
- *North Carolina*. Past inspection reviews of previous maintenance activities used to estimate the standard National Bridge Inventory (NBI) improvement or delay in deterioration.
- *South Dakota*. An approach only for treatments that have defined benefits.
- *West Virginia*. Ability to select between 14 treatment actions based on a set of trigger conditions.

The Indiana DOT respondent noted that the agency's optimization model does not capture maintenance activities, however, most of those activities would trigger a hold on the component age when the activity is applied. For example, with thin epoxy overlays, the condition state of the bridge deck is not reset; instead, the agency holds the age of the deck for a set number of years (added life).

Impact on Asset Management Practices

Modeling in 13 agencies has resulted in changes to business processes or practices specific to asset management. The most frequently cited processes or practices were budgeting (four agencies), project prioritization (three agencies), and preservation and rehabilitation (three agencies). Respondents also pointed to the value of data-driven decisions for inventory needs (Iowa) and preservation planning (New Jersey). In Indiana, asset engineers receive all dTIMS results so that they can select the best strategy for a given bridge instead of applying one strategy to the entire network. In Colorado, modeling hasn't impacted business processes or practices recently, but is used annually to determine asset management budgets. Other states, including Illinois, Kansas and West Virginia, have only begun to incorporate modeling and were unable to evaluate impacts.

Impact of 2014 National Highway System Bridge Requirement

Twenty agencies described the effects that the Federal Highway Administration's (FHWA's) 2014 National Highway System bridge requirement has had on their agencies. Eight agencies reported that the requirement had a limited impact (West Virginia); no change (Arkansas, Illinois, Iowa, Louisiana, Rhode Island and Wyoming); or was not applicable (New Jersey). Agencies reporting effects of the requirement were primarily related to excluding element-level data (Colorado and Michigan), increased data collection (Florida and Wisconsin), and modeling challenges (Delaware and Virginia).

<u>Research Implementation</u>

Transportation agencies in four states—Florida, Indiana, Michigan and North Carolina—discussed recently conducted research into bridge deterioration models and rates. Models represented were:

- AASHTOWare Bridge Management (BrM) (Florida).
- dTIMS (Indiana).
- In-house model (Michigan).
- University research (North Carolina).

Among the topics addressed were the degree to which each agency has implemented the research findings, the effectiveness of the new model and enhancements that are needed to improve the model's performance.

Three agencies (Indiana, Michigan and North Carolina DOTs) reported complete implementation of their models; Florida DOT's implementation is only partially complete. Respondents from all of these agencies reported that the anticipated results were consistent with the measured outcomes. Among the potential enhancements to the model are capturing more element-level data (Indiana); expanding the model to include ancillary treatments and maintenance elements (Indiana); creating additional models that consider environmental exposure, ADT and other inventory factors (Michigan); and conducting research on deterioration of specific material types in elements (North Carolina). Florida DOT only recently finished its second cycle of inspections using the new elements and needs to analyze the results to determine if the model is performing as predicted.

System Assessment and Analysis

Key Successes

Providing or improving asset management related projections is one of the most significant successes with using bridge deterioration modeling according to responding agencies (Illinois, North Carolina, Oregon, South Dakota and Virginia). Other key successes include justifying bridge investments (Indiana, Iowa, Kansas and Michigan) and validating other data or observations (Florida and New York).

Modeling Challenges

Data management can be challenging, according to five respondents, including data inconsistencies (Oregon), reliable cost–benefit information (Colorado), and cleaning and uncensoring data (Indiana). Three agencies noted model deficiencies as challenging, including models that do not directly account for specific maintenance and preservation actions (New York), limitations that make it difficult to simulate varying conditional scenarios for funding levels (North Carolina) and models that are too conservative (West Virginia). A lack of resources was also reported by three agencies, including the time to implement new ideas (Arkansas) and staffing (Iowa).

Best Practices

Simplicity was the most frequently recommended best practice for using bridge deterioration models (Arkansas, Indiana, Michigan and New York). Practices related to staffing resources were also recommended: using in-house staff members to conduct the modeling so that they can increase their understanding of the system's capabilities and performance, and also because familiarity with the agency's bridges allows them to make better decisions about modeling criteria (Iowa); using a data analyst to perform modeling and forecasting (Kansas); and coordinating with bridge design and maintenance staff for project selection (Louisiana). Other best practices recommended by respondents were awareness of data variability (Oregon) and knowing that data is subjective (Wyoming); developing models that consider the unique environmental conditions and risks of the area (Florida and Illinois); verifying models for accuracy (Rhode Island and Wisconsin); and taking preliminary measures to prepare for deterioration modeling, such as reading available research (Indiana).

Agencies Not Using Bridge Deterioration Modeling

Seven state transportation agencies have not adopted a model to forecast deterioration in bridges: Massachusetts, Mississippi, Montana, Nevada, New Hampshire, North Dakota and South Carolina. Though indicating that his agency has not adopted a deterioration model, the North Dakota DOT respondent noted that the agency manipulates deterioration curves resident in the AASHTOWare BrM software based on inventory performance and engineering judgment. Agency modifications include changes to network policies, NBI conversions and deterioration rates.

Methods or practices used by the other agencies to assess bridge condition include condition ratings (Nevada); engineering judgment (Montana and North Dakota); inspection reports (Massachusetts, Mississippi, Montana, Nevada, North Dakota and South Carolina); and load ratings (South Carolina). New Hampshire DOT's current methodology involves categorizing bridges using current NBI ratings taken from inspection data gathered every two years; bridges are then placed on two lists: maintenance and preservation or rehabilitation and replacement. Each bridge is ranked based on a weighting/scoring system that considers various factors such as condition, type, size, importance and risk. The ranked lists are reviewed by a committee of bridge engineers and business analysts to make any needed adjustments before the lists are used to inform agency investment and construction decisions.

Current and Future Research Activities and Interests

Thirteen of the 29 state transportation agency respondents described their involvement in current or ongoing research in bridge deterioration modeling. Activities are primarily related to membership in the following national programs:

- AASHTO Transportation System Preservation Technical Services Program (TSP2) working groups (Arkansas, Indiana, Michigan, South Dakota and Virginia).
- FHWA Long-Term Bridge Performance (LTBP) Program (Arkansas).
- National Cooperative Highway Research Program (NCHRP) domestic scans (Virginia).
- AASHTOWare BrM Technical Advisory Group (Virginia).
- Transportation Pooled Fund (TPF) Program study (Illinois, Indiana, Iowa, Kansas, Michigan, North Dakota, South Dakota and Wisconsin).

Other current activities include involvement in state transportation agency initiatives (Florida and New Hampshire) and university research (Colorado and Montana).

Respondents expressed interest in future research efforts associated with deterioration modeling:

- Supplements to AASHTOWare BrM processes (Mississippi).
- Design improvements (South Carolina).
- Modeling that incorporates a health index to forecast performance and the impacts of funding decisions (Oregon).
- Scope development, project management and implementation of results into the asset management module once they are developed (New York).

Survey of Vendors

Two vendors—IDS and Mayvue Solutions—described products that their companies manufacture in support of bridge deterioration modeling by state DOTs. IDS manufactures Bridge Optimizer (customized for the U.S. National Bridge Inventory schema and marketed as NBI Optimizer) and Asset Optimizer. Because both products implement the same modeling methodology, the respondent only described modeling approaches and features of Asset Optimizer, a cloud-based solution that supports the development and management of optimized long-range cross-asset programs. Mayvue Solutions shared information about AASHTO's AASHTOWare BrM.

Product Functionality

Applications and Processes

In terms of the applications and processes allowed by each product, AASHTOWare BrM is the more robust product, supporting legislative reporting, life cycle cost analyses, long-range budget planning, material evaluation, and project scoping and planning. Asset Optimizer supports life cycle cost analyses and long-range budget planning along with a range of other applications such as predictive modeling, data analytics and cross-asset budget trade-off analysis. Neither product supports resource demand models.

Bridge Elements and Product Parameters

Products from both vendors can analyze decks, superstructures and substructures. In addition, both products support NBI deterioration and National Bridge Element/element deterioration, and can be adjusted for other variables, such as ADT, deck wearing surface, highway functional class and superstructure material type. For developing predictive models, the Asset Optimizer can accommodate any parameter that has adequate historical data. Since AASHTOWare BrM allows for user-defined formula modifications, it can model deterioration curves with available data.

Product Practices and Analysis

Bridge Maintenance Treatments

Both products can accommodate specific bridge maintenance treatments. IDS products consider specific rehabilitation/maintenance or functional improvement treatments by defining the incremental improvements expected on each of the deterioration parameters. The products can also specify the constraints or criteria governing the applicability of any treatment. Constraints were also defined in cases where application of a specific action is dependent on prior treatments applied in preceding years. AASHTOWare BrM models the deterioration of each element on each structure; each treatment can affect the elements differently. Treatments can be considered in isolation or in combination.

Isolating the Benefit of Bridge Maintenance Treatments

Asset Optimizer and AASHTOWare BrM are capable of isolating the benefit of each bridge maintenance treatment and its impact on the deterioration rate. AASHTOWare BrM considers the impact of a treatment individually or in combination with other treatments. IDS products define the impact of each treatment on each deterioration parameter or performance variable. Examples of improvements include higher condition ratings for bridge elements, improved load rating and improved deck geometry. The improvements often depend on a number of factors such as the physical characteristics of the bridge or the current condition rating.

Survey of Consultant

An online survey was distributed to Paul D. Thompson, who described three products used to support bridge deterioration modeling by state DOTs:

- **Custom development using AASHTOWare BrM data, SQL and Excel.** In this project, the consultant developed a bridge deterioration model for Florida DOT. In a subsequent project, the consultant updated the model for the 2015 AASHTO elements
- **National Bridge Investment Analysis System (NBIAS).** In this FHWA project, the consultant developed national deterioration models using a custom methodology based on Pontis data sets of 15 states.
- **Methodology for estimating life expectancies of highway assets.** This NCHRP project developed a methodology for estimating life expectancies of highway assets for use in life cycle cost analyses supporting management decision-making.

The consultant is currently pilot testing an open-source spreadsheet developed for the long-range renewal planning of transportation structures.

Product Functionality

Applications and Processes

The three models described by the consultant support applications and processes related to life cycle cost analyses, long-range budget planning and resource demand models. The Florida DOT and NBIAS models also support legislative reporting. Material evaluation is only supported in the methodology created for NCHRP.

Bridge Elements and Product Parameters

All models can analyze decks, superstructures and substructures, and the Florida DOT and NBIAS models can analyze all NBI elements. The Florida DOT model can also analyze a large number of agency-defined elements for movable bridges, retaining walls, sign structures, high-mast light poles and traffic signal mast arms.

The three models can adjust for climatic conditions, condition rating, deck wearing surface, superstructure material type and use of deck overlays. None of the models can be adjusted for approach surface, design load, design type, maximum span length, number of spans, rebar coating and skew angle.

Product Practices and Analysis

Bridge Maintenance Treatments

The Florida DOT and NBIAS models take into account specific bridge maintenance treatments:

- *Florida DOT model*: The treatment effectiveness model was developed using a database of past projects and the observed changes in element condition.
- *NBIAS model*: Treatment effectiveness models are available for replacement, rehabilitation, preservation and routine maintenance.

Isolating the Benefit of Bridge Maintenance Treatments

Both the Florida DOT and NBIAS models use life cycle cost analysis to quantify the benefit for each specific bridge maintenance treatment and its impact on the deterioration rate. The methodology created for NCHRP does not provide a process for isolating the benefit of bridge maintenance treatments.

Related Research and Resources

The tables beginning on page 12 summarize the publications and other resources highlighted in this Preliminary Investigation in these topic areas:

- Multiple or unspecified models.
- Artificial neural network models.
- Mechanistic models.
- Probabilistic models.
- Regression models.
- Stochastic models.
- International research.
- Commercial products.
- Related resources.

Gaps in Findings

While the survey received a robust response, other state DOT research programs may have adopted a model for forecasting bridge deterioration. Reaching out to agencies not responding to the survey may yield additional findings. Though some respondents provided a fairly significant level of detail in their survey responses, guidance about agency policies and practices for using bridge deterioration models was limited. Caltrans could benefit from targeted follow-up inquiries that seek more details about models and practices that appear to be the most readily adaptable to the Caltrans environment.

Next Steps

Moving forward, Caltrans could consider:

- Engaging with state transportation agency respondents about the models and methodologies used in these states to consider how they might be adapted to meet Caltrans' needs.
- Consulting with the respondents from Colorado, Delaware, Illinois, Kansas and Wisconsin DOTs for documentation related to these agencies' policies and practices.
- Reviewing the research implementation efforts of Florida, Indiana, Michigan and North Carolina DOTs for details about model effectiveness and potential enhancements that would improve model performance.
- Examining the models and methodologies described by the vendors and consultant for additional relevance to Caltrans' applications.
- Reviewing the extensive resources identified in the literature search that include state transportation agency guidance and research on several models along with information about commercial products.

Multiple or Unspecified Models

Publication or Project (Year)	State or Category	Excerpt From Abstract or Description of Resource
NCHRP Report 713: Estimating Life Expectancies of Highway Assets, Volume 1: Guidebook (2012)	National Guidance	Provides a methodology for estimating the life expectancies of major types of highway system assets for use in life cycle cost analyses that support management decision-making.
National-Scale Bridge Element Deterioration Model for the USA (2018)	National Guidance	Describes algebraic methods developed in research for Florida and Virginia used to process element inspection data into transition probability matrices. Also examines the transformation of the resulting models for compatibility with the latest inspection manuals used in federal bridge condition reporting requirements.
Descriptive and Predictive Deep Learning Analytical Tools for Enhanced Bridge Management: Bridge Subtyping and Bridge Deterioration Forecasting (Research in Progress)	Multiple States	Seeks to develop "bridge deterioration forecasting (for predictive analysis of the bridge data to accurately identify quantitative descriptors for the structure deterioration state (e.g., condition ratings) as well as any possible anomalies in the deterioration pattern of the bridge structure)." Completion date: July 2022.
Bridge Element Deterioration for Midwest States (Research in Progress)	Multiple States (Pooled Fund Study)	Seeks to use historic Midwest DOT bridge data related to element-level deterioration, operation practices, maintenance activities and historic design/construction details to develop deterioration curves. Completion date: December 2021.
Deterioration Models for Prediction of Remaining Useful Life of Timber and Concrete Bridges: A Review (2020)	Multiple States	Presents a "critical review of different bridge deterioration models highlighting the advantages and limitations of each model." Deterministic and stochastic models are applied to timber highway bridge superstructure using NBI condition data for bridges in Florida, Georgia, South Carolina and North Carolina.
Migration Probability Matrix for Bridge Element Deterioration Models (2017)	Florida	Describes a migration probability matrix "developed to encapsulate the differences in definitions between Florida's bridge element inspection data" and a new manual based on the 2013 AASHTO Manual for Bridge Element Inspection.
Implementation of the 2013 AASHTO Manual for Bridge Element Inspection (2016)	Florida	Provides details of the migration probability matrix summarized in the previous citation.
Enhancement of the FDOT's Project Level and Network Level Bridge Management Analysis Tools: Final Report (2011)	Florida	Describes Florida DOT's investigation of several modeling issues that were not possible during earlier Pontis implementation work.
Bridge Model Validation at Indiana Department of Transportation (2017)	Indiana	Presents a model validation method to validate the agency's deterioration models in a manner that can be adopted by other agencies wishing to validate their own models.

Publication or Project (Year)	State or Category	Excerpt From Abstract or Description of Resource
Bridge Deterioration Models to Support Indiana's Bridge Management System (2016)	Indiana	Describes development of "families of curves representing deterioration models for bridge deck, superstructure and the substructure" using NBI condition ratings as the response variable.
A Process for Systematic Review of Bridge Deterioration Rates (2016)	Michigan	Establishes a process through which trends in bridge deterioration rates can be evaluated at regular intervals. Changes that occurred in bridge condition ratings were aggregated in five-year bands; deterioration curves for each of these five-year periods were computed using the Markov deterioration modeling method.
Development of Deterioration Curves for Bridge Elements in Montana (Research in Progress)	Montana	Seeks to develop deterioration models specific to Montana's five transportation districts; identify data that could be used to improve the accuracy of the deterioration curves; and compare results from Montana-specific data with data from the NBI. Completion date: July 2022.
Bridge Element Deterioration Rates (2009)	New York	Presents results from an extensive filtering/reconditioning of inspection data. Describes the development of methods and a computer program to calculate deterioration rates for bridge elements using Markov chain and Weibull-based approaches.
Deterioration Rates of Typical Bridge Elements in New York (2010)	New York	Describes findings appearing in the 2009 report cited above, including case studies showing that element deterioration rate information can be used to determine the expected service life of different bridge elements under a variety of external factors.
Determination of Bridge Deterioration Models and Bridge User Costs for the NCDOT Bridge Management System (2015)	North Carolina	Provides updated deterioration models and a "unique statistical regression methodology." Results include probabilistic deterioration models "that provide significantly improved predictive accuracy and precision over prior deterministic models."
Development of a Robust Framework for Assessing Bridge Performance Using a Multiple Model Approach (2019)	Texas	Presents a simple approach to multiple model deterioration modeling for bridges by identifying common points between deterioration model approaches and combining the results at these points.
The Evolution of Structure Asset Management in Wisconsin: Practice and Research (2017)	Wisconsin	Describes the Wisconsin Structures Asset Management System (WiSAMS), which relies heavily on inventory and inspection data and uses a set of rules and deterioration modeling to determine current and future optimal work.
Developing Deterioration Models for Wyoming Bridges (2016)	Wyoming	Presents deterioration models developed using stochastic and deterministic models. Uses a new method using least absolute shrinkage and selection operator (LASSO) regression to eliminate human bias in explanatory variable selection.

Artificial Neural Network Models

Publication or Project (Year)	State	Excerpt From Abstract or Description of Resource
Development and Validation of Deterioration Models for Concrete Bridge Decks; Phase 1: Artificial Intelligence Models and Bridge Management System (2013)	Michigan	Documents the development and evaluation of artificial neural network models to predict the condition ratings of concrete highway bridge decks in Michigan using historical condition assessments in the NBI database.
Artificial Neural Network Model of Bridge Deterioration (2010)	Wisconsin	Uses statistical analysis to identify 11 significant factors influencing deterioration and develops an artificial neural network model to predict associated deterioration.

Mechanistic Models

Publication or Project (Year)	State	Excerpt From Abstract or Description of Resource
Investigation of Mechanistic Deterioration Modeling for Bridge Design and Management (2017)	Colorado	Describes a mechanistic model developed to predict corrosion and concrete cracking as a function of material and environmental inputs.

Probabilistic Models

Publication or Project (Year)	State or Category	Excerpt From Abstract or Description of Resource
Time-Based Modeling of Concrete Bridge Deck Deterioration Using Probabilistic Models (Research in Progress)	Pennsylvania	Seeks to develop a "robust, self-learning, probabilistic model to predict the service life of concrete bridge decks and subsequently other infrastructure components." Completion date: August 2020.
Risk-Based Life-Cycle Management of Deteriorating Bridges (2019)	University Transportation Center Research	Presents an integrated probabilistic framework for quantifying the risk of bridge failure due to flood events when considering climate change.

Regression Models

Publication or Project (Year)	State or Category	Excerpt From Abstract or Description of Resource
Can Interdependency Considerations Enhance Forecasts of Bridge Infrastructure Condition? Evidence Using a Multivariate Regression Approach (2020)	General Research	Explores the efficacy of using a multivariate three-stage least squares model to describe the interdependencies of bridge components and to quantify the effects of other explanatory factors on the components' deterioration.

Publication or Project (Year)	State or Category	Excerpt From Abstract or Description of Resource
Regression Model Evaluation for Highway Bridge Component Deterioration Using National Bridge Inventory Data (2016)	General Research	Compares several regression models for highway bridge component rating over time using an external validation procedure and a traditional apparent model evaluation method based on the goodness-of-fit to data.
Statistical Forecasting of Bridge Deterioration Conditions (2020)	Ohio	Describes development of a forecasting model that predicts future bridge deterioration conditions based on the bridge characteristics. Identifies the bridge characteristics that are statistically significant variables that explain variations in bridge deterioration.

Stochastic Models

Publication or Project (Year)	State or Category	Excerpt From Abstract or Description of Resource
Stochastic Regression Deterioration Models for Superstructure of Prestressed Concrete Bridges in California (2019)	California	Uses the NBI for California, regression technique and Monte Carlo simulation to build models for predicting the superstructure condition of four structure types—slab, stringer/multibeam or girder, T-beam, and box beam or girder.
Stochastic Analysis and Time-Based Modeling of Concrete Bridge Deck Deterioration (2018)	Pennsylvania	Uses semi-Markov time-based model based on accelerated failure time Weibull fitted-parameters to estimate the transition probabilities and sojourn times for the deterioration of concrete bridge decks.
Development of Age and State Dependent Stochastic Models for Improved Bridge Deterioration Prediction (Research in Progress)	University Transportation Center Research	Seeks to develop general age- and state-dependent stochastic deterioration models using inspection data for improved element-level condition deterioration prediction of bridges. Expects to establish a Bayesian framework to facilitate calibration of the deterioration models incorporating inspection data and various uncertainties. Completion date: July 2022.

International Research

Publication or Project (Year)	Excerpt From Abstract or Description of Resource
Incorporating the Effects of Climate Change Into Bridge Deterioration Modeling: The Case of Slab-on-Girder Highway Bridge Deck Designs Across Canada (2020)	Uses mechanistic approaches to simulate crack initiation and crack growth to illustrate the sensitivity of bridge deck deterioration and design service life to changes in bridge deck design and a changing climate across major cities in Canada.
Predictive Group Maintenance Model for Networks of Bridges (2020)	Describes an approach that prioritizes the maintenance of multisystem multicomponent networks of bridges using a deterioration model of components with uncertainty.

Publication or Project (Year)	Excerpt From Abstract or Description of Resource
A Computerized Hybrid Bayesian-Based Approach for Modelling the Deterioration of Concrete Bridge Decks (2019)	Presents an automated defect-based tool to predict the future condition of bridge decks by calibrating the Markovian model based on a hybrid Bayesian-optimization approach. Results show the proposed model outperformed some commonly utilized deterioration models related to three performance indicators (root-mean squared error, mean absolute error and chi-squared statistic).
Finite Element–Based Machine-Learning Approach to Detect Damage in Bridges Under Operational and Environmental Variations (2019)	Uses a hybrid technique that integrates model- and data-based approaches into structural health monitoring. Data recorded in situ under normal conditions were combined with data obtained from finite-element simulations of more extreme environmental and operational scenarios and entered into the training process of machine-learning algorithms for damage detection.
Expert Judgement Based Maintenance Decision Support Method for Structures With a Long Service-Life (2019)	Introduces an expert judgment-based condition over time assessment method that quantifies the uncertainty regarding the period that is required for structural assets to deteriorate to a given condition.
Assessing Transition Probability of Bridge Deterioration Using Dempster–Shafer Theory of Evidence (2017)	Introduces a novel method based on the theory of evidence for bridge deterioration modeling through expert judgment.
Development of Hybrid Optimisation Method for Artificial Intelligence Based Bridge Deterioration Model–Feasibility Study (2013)	Compares bridge deteriorations using optimization and without optimization. Sufficient data was obtained to prove that optimization—a hybrid method of case-based reasoning and genetic algorithm—was effective.

Commercial Products

Publication or Project (Year)	Excerpt From Abstract or Description of Resource
AASHTOWare Bridge Management (undated)	Serves as a one-stop location for all AASHTOWare BrM software information: news/updates, support, training and other product information.
Implementation of AASHTOWare Bridge Management 5.2.3 to Meet Agency Policies and Objectives for Bridge Management and Address FHWA Requirements (2017)	Serves as a high-level guide to the functionality and bridge management modules in the AASHTOWare BrM software package.
The Use of Element Level Data and Bridge Management Software in the Network Analysis of Big Bridges (2017)	Investigates inspection practices, management strategies and analysis systems currently employed for big bridges, and includes a framework for modifications to the AASHTOWare BrM software.
dTIMS for Asset Management (undated)	Provides information about dTIMS and related modules, including Business Analytics, Operations Management and Business Intelligence.

Publication or Project (Year)	Excerpt From Abstract or Description of Resource
Colorado DOT: Integration of Multiple Asset Classes Eliminating a Siloed Asset Management Approach (undated)	Describes Colorado DOT's Asset Investment Management System (AIMS) and how it uses dTIMS cross-asset optimization functionality.
NBI Optimizer: Optimal Bridge Programming (2012-2016)	Describes the cloud-based software as a service (SaaS) application that provides analytics functions, reports, maps, charts, plans, dashboard and documents.

Related Resources

Publication or Project (Year)	State	Excerpt From Abstract or Description of Resource
Bridge Management and Scoping (undated)	Michigan	Provides links to resources that address condition rating and measurement.
New Jersey Transportation Asset Management Plan (2019)	New Jersey	Establishes objectives and investment strategies to manage the condition of New Jersey's pavements and bridges.
The RhodeWorks Tolling Program (undated)	Rhode Island	Describes "a unique approach to repairing bridges by tolling only specific types of tractor trailers. The tolls collected at each location in Rhode Island will go to repair the bridge or bridge group associated with that toll location."

Detailed Findings

Background

The California Department of Transportation (Caltrans) is responsible for overseeing the design, construction, operation and maintenance of more than 13,000 bridges in California. In the past, bridge deterioration rates have been developed based on historical data and bridge inspection reports to assess performance management for both a good to fair and a fair to poor condition deterioration at the network level. As asset management practices improve, there is a need for revised and updated bridge deterioration models and user costs to ensure that resources are expended appropriately to maximize bridge service life. In addition, using bridge inspection data to analyze deterioration has been inconclusive as work to maintain the bridges offsets the deterioration. Advanced techniques need to be investigated to determine deterioration while considering ongoing maintenance.

Caltrans is seeking information from other state departments of transportation (DOTs) about their knowledge and experience with bridge deterioration models and rates. Caltrans is also interested in learning from state DOTs that have recently implemented bridge deterioration model research to determine the degree of implementation and model effectiveness. Additional research focused on more advanced methodologies and state of the practice would provide better prediction of bridge needs for both state and locally owned bridges in California. These updated deterioration rates and models could be used to inform bridge performance targets for the next State Highway System Management Plan and transportation asset management plan, and for eventual use in the bridge management system software for improved bridge network- and project-level decisions.

To assist Caltrans in this information-gathering effort, CTC & Associates surveyed:

- State transportation agencies expected to have experience developing bridge deterioration models and rates.
- Seven state DOTs that have recently conducted research in this area.
- Manufacturers of bridge deterioration modeling products:
    - AgileAssets, Inc.
    - Bentley Systems, Inc.
    - Infrastructure Data Solutions (IDS).
    - Mayvue Solutions.
- A consultant who uses bridge deterioration modeling products: Paul D. Thompson.

Twenty-nine state DOTs responded to the survey in addition to two vendors (IDS and Mayvue Solutions) and the consultant (Paul D. Thompson). A literature search supplemented the results of these surveys. The search examined publicly available national and international research and other sources that describe bridge deterioration models and rates. Findings from these efforts are presented in this Preliminary Investigation in four areas:

- Survey of state practice.
- Survey of vendors.
- Survey of consultant.
- Related research and resources.

Survey of State Practice

An online survey was distributed to members of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Bridges and Structures expected to have experience developing bridge deterioration models and rates. A separate survey was distributed to the selected group of seven state DOTs that have recently conducted research in this area. Questions from both surveys are provided in Appendix A. The full text of survey responses is presented in a supplement to this report.

Summary of Survey Results

State transportation agencies participating in the surveys are listed below in three categories: agencies that have adopted a model to forecast deterioration in bridges, agencies that have conducted research in this area and agencies that have not adopted a model. Twenty-five state transportation agencies from the initial group responded to the survey; 18 of these agencies reported on their experience developing bridge deterioration models. Four agencies from the selected group of DOTs responded to the survey and reported on their efforts to implement research results.

Agencies Using Bridge Deterioration Forecasting Models

- Arkansas.
- Colorado.
- Delaware.
- Illinois.
- Iowa.
- Kansas.
- Louisiana.
- New Jersey.
- New York.
- Oregon.
- Rhode Island.
- South Dakota.
- Tennessee.
- Virginia.
- Washington.
- West Virginia.
- Wisconsin.
- Wyoming.

Agencies Conducting Bridge Deterioration Modeling Research

- Florida.
- Indiana.
- Michigan.
- North Carolina.

Agencies Not Using Bridge Deterioration Forecasting Models

- Massachusetts.
- Mississippi.
- Montana.
- Nevada.
- New Hampshire.
- North Dakota.
- South Carolina.

Survey results from the state transportation agencies that use bridge deterioration models and that have conducted research in this area are summarized below in the following topic areas:

- System description.
- Modeling practices and analysis.
- Research implementation (selected DOTs only).
- System assessment and analysis.

Feedback from agencies that have not adopted a model to forecast deterioration in bridges is presented in **Alternatives to Using Bridge Deterioration Modeling** beginning on page 40. **Current Research Activities and Interests**, beginning on page 40, includes information about respondents' involvement in or awareness of research and other activities related to bridge deterioration modeling.

System Description

Description of Model

Twenty-two respondents described several models and methodologies used by their agencies to determine bridge deterioration as well as the type of model used (a model that was developed in-house, a commercial off-the-shelf product, a commercial product that has been customized for the agency or other type). Agency practices that support the use of the model were also provided.

Of the 22 respondents, nine reported using commercial products that had been customized for their agencies, and six reported using multiple tools. AASHTO's AASHTOWare Bridge Management (BrM) modeling product is most commonly used (10 agencies) followed by in-house tools (five agencies), dTIMS (Deighton's Total Infrastructure Management System) by Deighton Associates Limited (four agencies) and NBI Optimizer by IDS (one agency). Table 1 summarizes survey responses.

The respondent from Washington State DOT, which uses AASHTOWare BrM, reported that bridge deterioration modeling is an evolving process as the agency is currently adopting a bridge condition model that uses inspection reports, engineering judgment and historical repair records. Data required to accomplish this task may have to be bolstered and added. The agency has been given certain requirements for bridge inspection and data gathering that do not always fulfill additional mandates. Improvements to the model will be made during a second iteration. New Jersey DOT is awaiting the following new enhancements to AASHTOWare BrM: life cycle plans, risk-based preservation program and a revised program optimizer.

Iowa DOT is developing models in AASHTOWare BrM. The agency has been using a proprietary system to determine overall inventory needs, but has not used the output to determine individual bridge projects. Engineering judgment is used for programming individual projects. Currently the agency is using AASHTOWare BrM with condition ratings but is planning to use AASHTOWare BrM for modeling development in the near future. The respondent noted that it will take more time to develop models using element data.

Table 1. Overview of State DOT Bridge Deterioration Models

State	Model Type	Product Name/Vendor (If Applicable)	Model Description/Agency Practice
Arkansas	Customized commercial product	dTIMS Deighton Associates Limited	Model logic applies National Bridge Inventory (NBI) condition ratings and considers how those ratings have changed.
Colorado	Multiple models	In-house tool: Asset Investment Management System (AIMS) dTIMS Deighton Associates Limited	The agency has implemented the in-house-developed AIMS, which "predicts the long-term performance of each asset given various budget scenarios," in dTIMS to conduct analysis. Current efforts:

State	Model Type	Product Name/Vendor (If Applicable)	Model Description/Agency Practice
			• Using deterioration curves developed in Python code. • Working to update deterioration curves using results of university research.
Delaware	Customized commercial product	AASHTOWare BrM AASHTO	• Uses AASHTOWare BrM modules for bridge database, inspection and modeling. • Conducts data analysis of historical Pontis/AASHTOWare BrM element and NBI condition data along with expert solicitation of experienced bridge design, inspection and maintenance staff.
Florida	Multiple models	In-house deterioration model AASHTOWare BrM AASHTO	• Deterioration models developed through research conducted by Florida State University. • AASHTOWare BrM software enhanced with results of agency research.
Illinois	Multiple models	In-house deterioration model AASHTOWare BrM AASHTO	• In-house deterioration models based on condition ratings for deck, superstructure, substructure and culvert. • Uses AASHTOWare BrM, customized by Mayvue Solutions, which has default deterioration models. • Future modifications will be conducted by the agency or assisted by Mayvue.
Indiana	Multiple models	In-house deterioration model dTIMS Deighton Associates Limited	• Uses dTIMS for network optimization and to process deterioration curves developed in-house. • Deterioration curves developed in-house using commercial software for coding. Curves are processed inside dTIMS during network optimization analysis. • Other software such as R statistical software (https://www.r-project.org/) and Python (https://www.python.org/) automate cleaning and uncensoring of historic component conditions. • Deterioration modeling classified as ordinary regression of condition. After cleaning, uncensoring and clustering the data, the model regresses each condition state residency time to a Weibull distribution. Using threshold values and this Weibull distribution, the model establishes predicted residency time. Using all conditions' residency times, data is regressed into a logistic shape.
Iowa	Customized commercial product	NBI Optimizer Infrastructure Data Solutions, Inc. (IDS)	• Uses modeling system to determine overall inventory needs. • Individual projects programmed using engineering judgment based on inspection documentation and local knowledge of maintenance crews.

State	Model Type	Product Name/Vendor (If Applicable)	Model Description/Agency Practice
Kansas	In-house model	N/A	• Spreadsheet-based models use Markov chain modeling with Monte Carlo simulations. • Considering adaptation of in-house models to AASHTOWare BrM.
Louisiana	Customized commercial product	AASHTOWare BrM AASHTO	• Uses component-level deterioration and NBI deterioration models. • Previously used Pontis.
Michigan	Multiple models	In-house deterioration model AASHTOWare BrM AASHTO	• Uses Markov deterioration modeling method in in-house model. • Implements in-house-developed deterioration model in AASHTOWare BrM to help with structure prioritization and project programming. • Uses deterioration rates to assist in predicting future funding needs.
New Jersey	Customized commercial product	AASHTOWare BrM AASHTO	Calibrates two models to determine bridge deterioration: • Component-level deterioration based on bridge NBI component ratings. • Element-level deterioration based on element condition states.
New York	University research	N/A	Uses Weibull analysis in modeling developed by City College of New York.
North Carolina	University research	N/A	• Uses deterministic modeling of NBI components. • Prepared to implement probabilistic modeling of NBI components.
Oregon	In-house model	N/A	Estimates dwell times for deck, superstructure and substructure NBI ratings and uses these to perform high-level analyses.
Rhode Island	Customized commercial product	AASHTOWare BrM AASHTO	None provided.
South Dakota	Customized commercial product	AASHTOWare BrM AASHTO	Uses element- and component-level deterioration models.
Tennessee	Commercial off-the-shelf product	AASHTOWare BrM AASHTO	None provided.
Virginia	In-house model	N/A	Uses general condition rating (GCR) component deterioration (time in GCR) and element-level deterioration models.
Washington	Customized commercial product	AASHTOWare BrM AASHTO	• Uses AASHTOWare BrM customized for the agency using parameters developed in-house. • Agency has compiled raw data and is estimating bridge element deterioration using statistical methods.

State	Model Type	Product Name/Vendor (If Applicable)	Model Description/Agency Practice
West Virginia	Customized commercial product	dTIMS Deighton Associates Limited	• Conducts inspections on a designated frequency and applies condition codes for deck, superstructure and substructure. • Uses a composite weight in dTIMS Business Analytics software.
Wisconsin	Multiple models	Not provided.	• Uses a deterministic trend with time series in condition state for NBI and Markov chain process. • Applies Weibull distribution and analysis for element-level deterioration.
Wyoming	In-house model	N/A	Applies durational analysis in certain NBI ratings.

N/A Not available.

Applications and Processes

The bridge deterioration models used by agencies responding to the survey support a number of applications and processes. The applications most frequently cited by respondents were:

- Long-range budget planning (20 state transportation agencies).
- Project scoping and/or planning (15 state transportation agencies).
- Life cycle cost analyses (13 state transportation agencies).

Material evaluation and resource demand models were cited least frequently (three respondents). Table 2 summarizes the applications and processes supported by agency models.

Table 2. Applications and Processes Supported by State DOT Models

Model/ Model Type	State	Legislative Reporting	Life Cycle Cost Analyses	Long Range Budget Planning	Material Evaluation	Project Scoping and/or Planning	Resource Demand Models
AASHTOWare BrM	Delaware		X	X		X	
	Florida			X	X	X	
	Illinois		X	X		X	X
	Louisiana		X	X			
	New Jersey		X	X	X	X	
	Rhode Island	X	X	X		X	
	South Dakota	X	X	X		X	X
	Tennessee		X	X			
	Washington	X	X	X		X	
dTIMS (Deighton)	Arkansas					X	X
	Colorado			X			
	Indiana	X	X	X		X	
	West Virginia		X	X		X	

Model/ Model Type	State	Legislative Reporting	Life Cycle Cost Analyses	Long Range Budget Planning	Material Evaluation	Project Scoping and/or Planning	Resource Demand Models
In-House Model	Kansas			X		X	
	Michigan	X		X		X	
	Oregon	X					
	Virginia	X	X	X	X	X	
	Wyoming	X	X	X		X	
Multiple Models	Wisconsin			X		X	
NBI Optimizer (IDS)	Iowa			X			
University Research	New York			X			
	North Carolina	X	X	X			
	Total	**9**	**13**	**20**	**3**	**15**	**3**

Several respondents provided additional information about the applications and processes supported by their models:

- *Arkansas*. dTIMS is used to calculate asset value based on depreciated replacement cost in the agency's transportation asset management plan.
- *Delaware*. AASHTOWare BrM is used to prioritize annual bridge work needs.
- *Indiana*. In addition to dTIMS, the agency uses a scoping application developed by Deighton to streamline its scoping process. The scoping application interacts with other applications through the agency's data warehouse.
- *Iowa*. The agency uses NBI Optimizer to promote funding needs to state commissioners.
- *New Jersey*. AASHTOWare BrM provides risk-based analysis.

Other Model Parameters

Only Oregon DOT's in-house model cannot be adjusted for specific variables or parameters. The models used by all other state transportation agencies responding to the survey can be adjusted for a variety of parameters. The most frequently cited parameters reported by respondents were:

- Age.
- Condition rating.
- Superstructure material type.
- Use of deck overlays.

Approach surface, maximum span length, number of spans and skew angle were cited least frequently. Table 3 summarizes the parameters that can be used with agency models.

Table 3. Variables or Parameters Accommodated by Agency Model

Model/Model Type	State	Age	Approach Surface	Average Daily Traffic (ADT)	Average Daily Truck Traffic (ADTT)	Climatic Conditions	Condition Rating
AASHTOWare BrM	Delaware				X		X
	Florida	X				X	X
	Illinois	X				X	X
	Louisiana	X				X	
	New Jersey	X		X	X	X	X
	Rhode Island	X		X	X		
	South Dakota	X		X	X	X	X
	Tennessee						X
	Washington	X		X	X	X	X
dTIMS (Deighton)	Arkansas	X					X
	Colorado						X
	Indiana	X		X	X	X	X
	West Virginia	X	X	X	X	X	X
In-House Model	Kansas	X					
	Michigan	X					
	Virginia	X				X	X
	Wyoming			X	X		X
Multiple Models	Wisconsin	X		X	X		X
NBI Optimizer (IDS)	Iowa	X		X			X
University Research	New York	X		X		X	
	North Carolina	X		X	X	X	X
	Total	**17**	**1**	**11**	**10**	**11**	**16**

Table 3. Variables or Parameters Accommodated by Agency Model, continued

Model/Model Type	State	Deck Wearing Surface	Design Load	Design Type	Highway Functional Class	Location*	Maximum Span Length
AASHTOWare BrM	Delaware		X	X	X		
	Florida						
	Illinois	X			X	X	
	Louisiana	X					
	New Jersey	X	X	X	X	X	X
	Rhode Island				X	X	
	South Dakota	X		X			
	Tennessee	X					
	Washington	X					

Model/Model Type	State	Deck Wearing Surface	Design Load	Design Type	Highway Functional Class	Location*	Maximum Span Length
dTIMS (Deighton)	Arkansas						
	Colorado						
	Indiana	X		X	X	X	
	West Virginia	X	X	X	X	X	X
In-House Model	Kansas				X		
	Michigan	X					
	Virginia	X		X		X	
	Wyoming						
Multiple Models	Wisconsin	X	X	X	X	X	
NBI Optimizer (IDS)	Iowa	X			X		
University Research	New York			X	X		
	North Carolina				X	X	
	Total	**12**	**4**	**8**	**11**	**8**	**2**

*Respondents were provided with location-related examples (e.g., National Highway System, urban, waterway).

Table 3. Variables or Parameters Accommodated by Agency Model, continued

Model/Model Type	State	Number of Spans	Rebar Coating	Skew Angle	Superstructure Material Type	Use of Deck Overlays
AASHTOWare BrM	Delaware		X			X
	Florida		X		X	X
	Illinois				X	X
	Louisiana				X	X
	New Jersey	X	X	X	X	X
	Rhode Island				X	
	South Dakota		X		X	X
	Tennessee				X	X
	Washington		X		X	X
dTIMS (Deighton)	Arkansas				X	X
	Colorado					
	Indiana		X		X	X
	West Virginia	X	X	X	X	X
In-House Model	Kansas				X	
	Michigan				X	X
	Virginia		X		X	X
	Wyoming				X	X
Multiple Models	Wisconsin				X	X
NBI Optimizer (IDS)	Iowa		X			X

Model/Model Type	State	Number of Spans	Rebar Coating	Skew Angle	Superstructure Material Type	Use of Deck Overlays
University Research	New York				X	
	North Carolina				X	
	Total	**2**	**9**	**2**	**18**	**16**

Indiana DOT noted that some of the parameters described in Table 3 are addressed when data is clustered before the agency analyzes for the deterioration curve. Other variables are included as triggers and resets inside dTIMS. The agency can enhance its model as necessary to include other variables that address additional treatments and reset values.

Other variables and parameters reported by respondents include

- Deck area (New Jersey).
- Deck geometry (Iowa).
- Element defect flags (Washington).
- Fracture-critical (Delaware).
- High-cost bridges (New Jersey).
- Historical classification (Delaware).
- Marine environment (Virginia).*
- Number of historical overlays (Wyoming).
- Operating capacity (Iowa).
- Presence of expansion joints (Virginia).*
- Protective coating (Washington).
- Scour-critical (Delaware).
- Structure type (Kansas).

* Virginia DOT has calibrated these parameters to a certain degree and has begun implementing them.

<u>Bridge Elements</u>

Models used by all agencies participating in the survey include the deck, superstructure and substructure. Table 4 summarizes other bridge elements described by respondents.

Table 4. Other Bridge Elements Included in Agency Models

Bridge Element	State (Model)	Description
Barrier Walls	Michigan (in-house model)	N/R
Culverts	• Delaware, Illinois, New Jersey (AASHTOWare BrM) • Kansas, Michigan, Virginia (in-house model)	*Kansas*. NBI 62. *Virginia*. Including concrete and steel.
Defects	Washington (AASHTOWare BrM)	N/R
Elements: Agency-Defined	• Delaware, New Jersey (AASHTOWare BrM) • Wisconsin (multiple models)	*Wisconsi*n. All national- and agency-defined elements.
Elements: National-Defined	• South Dakota (AASHTOWare BrM) • Wisconsin (multiple models)	*South Dakota.* Deterioration of AASHTO elements. *Wisconsin*. All national- and agency-defined elements.
Protective Coatings	Washington (AASHTOWare BrM)	N/R
Rails	Delaware (AASHTOWare BrM)	N/R

Bridge Element	State (Model)	Description
Wearing Surfaces	• Indiana (dTIMS (Deighton)) • Washington (AASHTOWare BrM)	N/R

N/R No response.

Modeling Practices and Analysis

Maintenance Treatments

The models from nearly one-half of the agencies (10) responding to the survey account for specific bridge maintenance treatments. Respondents described some of these treatments, including bridge washing, deck seals, joint replacement and overlays. Table 5 summarizes survey responses.

Although Indiana DOT currently does not include maintenance activities in its model, it has the capability to do so and has made capturing maintenance activities and ancillary treatments for the model a long-range goal. All results from dTIMS, including all strategies for each bridge, bridge history and component ages, are provided to asset engineers. This information allows engineers to determine whether the best option for a given bridge is the best option for the entire network, particularly when overall budget constraints are considered. Also, scoring sheets used by Indiana DOT's asset engineers use the three- and five-year deteriorated values within the scoring computations.

Table 5. Modeling Specific Maintenance Treatments

Maintenance Treatment	State (Model)	Description
Bridge Washing	Rhode Island (AASHTOWare BrM)	Treatment added as two-year protective system.
Deck Seals and Treatments	• Colorado (dTIMS (Deighton)) • South Dakota (AASHTOWare BrM)	• *Colorado.* Deck seals. • *South Dakota*. Deck treatments that don't improve condition can be modeled to reset the time in that condition.
Joint Replacements	Colorado (dTIMS (Deighton))	N/R
Overlays	• Arkansas (dTIMS (Deighton)) • Michigan (in-house model)	*Arkansas*: • Polymer overlay holds deck deterioration for 12 years. • Hydro-demolition with overlay improves deck condition. *Michigan*. Life expectancy and impact of epoxy overlays considered. For the deck rating, will add 5 years to the expected time to poor.

Maintenance Treatment	State (Model)	Description
Other	• Colorado (dTIMS (Deighton)) • Illinois, Washington (AASHTOWare BrM) • North Carolina (university research) • Wyoming (in-house model)	*Colorado.* Rehabilitation. *Illinois*. Schedule- and condition-based treatments. *North Carolina*. Estimated rating improvements or delay in deterioration defined for every treatment in bridge management system. Treated element will either have an improved NBI rating or delayed deterioration (for a specified duration). *Wyoming*. Model validates condition improvement by comparing rehabilitation projects.

N/R No response.

Benefits of Specific Maintenance Treatment

Respondents from six transportation agencies have developed an approach to isolate the benefits of specific bridge maintenance treatments and their impact on the deterioration rate:

- In Arkansas, the benefit is summation over time of the difference in action and no action.
- Kansas DOT has developed action/benefit models based on the utility theory for the specific preservation actions in place.
- Michigan DOT has quantified most of the deck treatments but not all maintenance actions. The condition impact of these actions is based on the rating before the maintenance treatment was made.
- North Carolina DOT uses past inspection reviews of previous maintenance activities to estimate the standard NBI improvement or delay in deterioration.
- South Dakota DOT has developed an approach only for treatments that have defined benefits.
- West Virginia DOT's model can select between 14 treatment actions based on a set of trigger conditions.

Indiana DOT's optimization model does not capture maintenance activities, however, most of those activities would trigger a hold on the component age when the activity is applied. For example, with thin epoxy overlays, the condition state of the bridge deck is not reset; instead, the agency holds the age of the deck for a set number of years (added life). The respondent from Virginia DOT noted that developing an approach is a "work in progress."

Impact on Asset Management Practices

Thirteen agencies described how modeling has resulted in changes to business processes or practices specific to asset management. The most frequently cited processes or practices were related to budgeting (four agencies), project prioritization (three agencies), and preservation and rehabilitation (three agencies). Other respondents pointed to the value of data-driven decisions for inventory needs (Iowa) and preservation planning (New Jersey). Indiana DOT's asset engineers receive all dTIMS results so that they can select the best strategy for a given bridge instead of applying one strategy to the entire network. Although modeling at Kansas DOT is in the early stages, the respondent reported that he can "foresee changes" in how candidates are prioritized for specific actions and how the benefits of future actions are evaluated.

Less specific impacts were also described. For example, the Colorado DOT respondent noted that modeling hasn't impacted business processes or practices recently, but is used annually to determine asset management budgets. Illinois, Kansas and West Virginia DOTs have only begun to incorporate modeling. The Illinois and West Virginia DOT respondents were unsure about specific impacts.

Table 6 summarizes survey results from agencies experiencing a change to business processes or practices as a result of modeling.

Table 6. Impact of Modeling on Business Processes and Practices

Business Process/Practice	State (Model)	Description
Budgeting	• Colorado, Indiana (dTIMS (Deighton)) • Delaware (AASHTOWare BrM) • Michigan (in-house model)	*Colorado*. Modeling is used on an annual basis to assist in determining asset management budgets. *Delaware*. Forecasting future budget needs and performance measure expectations for different funding scenarios. *Indiana*. Selecting the best strategy for a given bridge instead of applying one strategy to the entire network when considering budget constraints. *Michigan*. Predicting future condition based on the proposed work to determine future funding needs.
Decision-Making	• Iowa (NBI Optimizer) • South Dakota (AASHTOWare BrM)	*Iowa*. Using data-driven evidence instead of engineering judgment to determine inventory needs. *South Dakota*. Using optimization results to support maintenance decisions.
Inspection Process	• Indiana (dTIMS (Deighton)) • Delaware (AASHTOWare BrM)	*Delaware*. Slightly modifying the inspection process for a few elements. *Indiana*. Using the 3- and 5-year deteriorated values within the scoring sheet computations.
Preservation and Rehabilitation	• Arkansas (dTIMS (Deighton)) • New Jersey, Rhode Island (AASHTOWare BrM) • Wyoming (in-house model)	*Arkansas*. Shifting to more preservation (polymer overlays) and rehabilitation (hydro-demolition with overlays). *New Jersey*. Implementing data-driven preservation planning. *Rhode Island*. Focusing on preservation activities through the RhodeWorks 10-year program. *Wyoming*. Increasing focus on bridge rehabilitation.
Project Prioritization	• Kansas, Michigan (in-house models) • Wisconsin (multiple models)	*Kansas*. Anticipating how candidates are prioritized for specific actions and how the benefits of future actions are evaluated.

Business Process/Practice	State (Model)	Description
		Michigan. Predicting when bridges will go to a poor state so work can be prioritized to maintain a good to fair condition of the network. *Wisconsin*. Achieving more systematic project programming and certification of proposed work.
Other	• Virginia (in-house model) • Washington (AASHTOWare BrM)	*Virginia*. Shifting performance measures from poor to average GCR weighted by a user importance factor. *Washington*. Adding additional defects to the agency's element list.

Impact of 2014 National Highway System Bridge Requirement

In 2014, the Federal Highway Administration (FHWA) began requiring state transportation agencies to collect element-level data for National Highway System (NHS) bridges as a supplement to NBI data submission. Twenty agencies responding to the survey described the effects that this requirement has had on their agencies. Eight agencies reported that the requirement had a limited impact (West Virginia); no change (Arkansas, Illinois, Iowa, Louisiana, Rhode Island and Wyoming); or was not applicable (New Jersey). Agencies reporting effects of the requirement described the exclusion of element-level data, increased data collection and modeling challenges. State agency descriptions of the effects are summarized in Table 7 by topic.

Table 7. Impact of 2014 NHS Bridge Requirement on Deterioration Analysis

Impact	State (Model)	Description
Data Challenges	• Kansas (in-house model) • Washington (AASHTOWare BrM)	*Kansas*. The agency's data collection methodology for bridge decks changed significantly, resulting in a discontinuity in historic data. (Kansas DOT has collected commonly recognized (CoRE) element-level bridge data since the 1990s.) Kansas DOT will continue using the NBI data set until it has collected sufficient data, when it will incorporate bridge deterioration models for elements into its asset management system. *Washington*. The requirement makes the new directive easier, but may lack some data required to fully implement deterioration modeling analysis.
Element-Level Data Excluded	• Colorado, Indiana (dTIMS (Deighton)) • Michigan (in-house model)	*Indiana*. Element-level data (NHS only) is currently not used when developing deterioration curves or inside dTIMS. The current model is only effective at the network level, predicting overall budgets and percent spending toward certain work types. The agency understands that it must improve to 100% element level to make its model a better predictor at the bridge level. *Michigan*. The agency does not have deterioration models for elements. It currently uses the elements to support a proposed fix or to validate other attributes about the bridge. Michigan DOT is part of a pooled fund research project to develop deterioration models for elements (see Table 11, page 41).

Impact	State (Model)	Description
Increased Data Collection	• Florida (AASHTOWare BrM) • Wisconsin (in-house model)	*Florida*. The agency will use the new data collected to validate and enhance deterioration models by conducting another research project with Florida State University, which will validate the data. *Wisconsin*. The agency currently collects more specific condition data, however, it was developed before many DOTs used asset management. There is a need for better development of refined element deterioration relationships for elements.
Modeling Challenges	• Delaware (AASHTOWare BrM) • Virginia (in-house model)	*Delaware*. The agency has been collecting Pontis element data since 1991-1992. Delaware does not agree with a number of changes with some of the 2014 National Bridge Elements (NBEs); these changes make it harder to model and assign costs (e.g., piles are now on each element (the agency had been inspecting them as a linear foot element in Pontis), the paint element). *Virginia*. Calibrating element models has become extremely difficult. CoRe element data does "marry well with NBE data," which makes the NBE approach more rational and "a good long-term change."
No Change/ Limited Impact/ Not Applicable	• Arkansas, West Virginia (dTIMS (Deighton)) • Illinois, Louisiana, New Jersey, Rhode Island (AASHTOWare BrM) • Iowa (NBI Optimizer) • Wyoming (in-house model)	**No change:** • *Arkansas, Louisiana*. Details not provided. • *Illinois*. Currently the agency is transitioning from an agency-defined element set (greater than 100) to the AASHTO Manual for Bridge Element Inspection elements with only five agency-defined elements. • *Iowa*. Although the agency has not used element data for modeling, it has been collecting data for over 20 years. Inspectors had to be trained on the new elements, but they were already familiar with the concept. Inspection software had to be modified to account for the new elements; element data was not translated into the new format. • *Rhode Island*. A full element inspection has always been conducted. • *Wyoming*. The model uses NBI component condition ratings. **Limited impact:** • *West Virginia*. Only element data for NHS bridges is collected. The agency may modify the model to account for element data. **Not applicable:** • *New Jersey*. The agency, which initiated the deterioration model after 2014, uses Migrator to convert CoRe elements into NBEs.
Other	• New York, North Carolina (university research) • Oregon (in-house model) • South Dakota (AASHTOWare BrM)	*New York*. The agency is currently developing new deterioration models. Before adopting the AASHTO element-based inspection system, it had been using a state-specific inspection system. *North Carolina*. Future goals include developing deterioration rates based on historical inspection data. The current method reflects NBI inspection ratings. *Oregon*. Health index information is incorporated to empirically estimate a more refined remaining service life. *South Dakota*. The agency models element deterioration.

Related Resources

Respondents from Florida, Michigan, New Jersey, New York State, North Carolina and Rhode Island DOTs offered guidance about agency policies and practices for using bridge deterioration models and rates. These resources are cited in the **Related Research and Resources** section of this Preliminary Investigation, beginning on page 52. Listed below is a sampling of this guidance:

- *Florida*: Implementation of the 2013 AASHTO Manual for Bridge Element Inspection (2016).
- *Michigan*: Bridge Management and Scoping (undated).
- *New Jersey*: New Jersey Transportation Asset Management Plan (2019).
- *North Carolina*: Determination of Bridge Deterioration Models and Bridge User Costs for the NCDOT Bridge Management System (2015).
- *Rhode Island*: The RhodeWorks Tolling Program (undated).

Colorado, Delaware and Illinois DOTs are currently developing guidance. Documentation from Indiana, Wisconsin and Kansas DOTs is available upon request. The respondents from Indiana and Wisconsin DOTs would prefer to discuss the inherent factors and limitations of their models before providing information; the Kansas DOT respondent noted that formal policies are still being developed, but the agency could share an outline of the methodology.

Research Implementation

Four state transportation agencies—Florida, Indiana, Michigan and North Carolina—have recently conducted research into bridge deterioration models and rates. Respondents from these four states discussed this research, describing the degree to which each agency has implemented the research findings, the effectiveness of the new model and enhancements that are needed to improve the model's performance.

Indiana, Michigan and North Carolina DOT respondents indicated complete implementation of their models; Florida DOT's implementation is only partially complete. Respondents from all of these agencies reported that the anticipated results were consistent with the measured outcomes. The case studies below summarize survey responses.

Florida Department of Transportation

Topic	Description
Model	AASHTOWare BrM
Level of Implementation	Partial implementation. The agency is still calibrating the modeling results and comparing them with current practices.
Model Effectiveness	• Results are realistic and expected. • The model doesn't consider planned projects.
Potential Enhancements	Unknown. The agency only recently finished its second cycle of inspections using the new elements and needs to analyze the results to determine if the model is performing as predicted.

Indiana Department of Transportation

Topic	Description
Model	dTIMS (Deighton)
Level of Implementation	Complete implementation into score sheets and the dTIMS model. • Score sheets play a significant role in final project selection but more and more emphasis is being placed on network optimization. • Final project selection is backfed into dTIMS for evaluation and comparison against dTIMS forecasted program.
Model Effectiveness	The model is very effective. Even with bad predictions, staff can quickly determine if the cause is bad data in its Bridge Inspection Application System (BIAS) database, limitations of its business rules (triggers and resets) or limitations of using component-level data. Since all strategies that are generated are shared, if an asset engineer develops a strategy that dTIMS does not, the problem is with agency data or a deficiency with the business rules, which is accommodated by correcting the data or enhancing the rules.
Potential Enhancements	• Capture more data, such as element-level data. • Expand the model to include ancillary treatments and maintenance elements.

Michigan Department of Transportation

Topic	Description
Model	In-house model
Level of Implementation	Complete. Deterioration rates have been implemented in the project prioritization and scoping process to help identify bridge condition and when maintenance is required. Deterioration rates are also used to predict funding needs. Deterioration models have been implemented in AASHTOWare BrM to help with structure prioritization and project programming.
Model Effectiveness	The agency has "relative confidence" in the models. But because they were calculated using a statewide approach that did not consider environmental impacts, results are taken with a "relative grain of salt." For future planning as a state, the models are effective but when looking at specific regions, they have some degree of variability. The agency needs to generate additional models that support varying bridge conditions throughout the state.

Potential Enhancements	Create additional models that consider environmental exposure, ADT and other inventory factors.

North Carolina Department of Transportation

<u>**Topic**</u>	<u>**Description**</u>
Model	University research
Level of Implementation	Complete. The agency's most recent research findings are fully implemented in its bridge management system.
Model Effectiveness	The models are generally effective at showing deterioration at the structure level. However, the agency should exercise caution when using the models to make decisions at a system level.
Potential Enhancements	When refining deterioration rates, university or industry research on deterioration of specific material types in elements would be helpful when included with historical element ratings.

System Assessment and Analysis

<u>Key Successes</u>

Twenty of the 22 state transportation agencies using bridge deterioration modeling described the successes experienced with these models. (New Jersey DOT is currently recalibrating its deterioration model.) Among the most significant successes reported by these agencies were providing or improving projections (Illinois, North Carolina, Oregon, South Dakota and Virginia); justifying bridge investments (Indiana, Iowa, Kansas and Michigan); and validating other data or observations (Florida and New York). After using deterioration models in its asset management program for more than 10 years, New York State DOT found that the models accurately represent what is observed in the field. Table 8 summarizes survey results.

Table 8. Successes With Bridge Deterioration Models

Modeling Success	State	Description
Identifies Future Data Needs	Washington	Data is in better alignment. The agency also better understands what further data may be required.
Improves Bridge Condition	Wyoming	Deterioration models, improvement models, cost models and optimization algorithms have helped the agency greatly reduce the percentage of bridges in poor condition.
Improves Scoping	Wisconsin	Project scoping is improved and the agency has a better understanding of future investment needs.
Justifies Bridge Investments	Indiana, Iowa, Kansas, Michigan	*Indiana*. Using dTIMS as a network optimization tool along with the deterioration model provides a more consistent mechanism for documenting the decision-making process and justifying these decisions. While the agency doesn't always use the recommended strategies, it can post-analyze decisions in terms of cost and forecast network health. *Iowa*. Modeling provides a longer range forecast that helps with bridge funding and allows the agency to overlay bridge funding with pavement needs.

Modeling Success	State	Description
		Kansas. In 2010, the agency used system-level deterioration models to justify bridge replacement and maintenance funding for the transportation program. *Michigan*. Modeling has supported the agency's funding needs and project selection process. It has also allowed the agency to move toward a more data-centric business process.
Provides/Improves Projections	Illinois, North Carolina, Oregon, South Dakota, Virginia	*Illinois*. Modeling allowed the agency to begin planning and programming preservation activities and also aided in planning and programming rehabilitation and replacement. *North Carolina*. Models indicate future replacement and preservation needs. *Oregon*. High-level model provides a basis for objectively forecasting bridge conditions. *South Dakota*. Modeling can furnish transportation asset management program projections. *Virginia*. Modeling provides better projections.
Provides Needed Data	Colorado, Louisiana	*Colorado.* Data-driven decisions can be made about practices that need to be implemented now to ensure the longevity of inventory. *Louisiana*. Implementing the deterioration models allowed the agency to achieve usable bridge management system analysis.
Validates Other Data/Observations	Florida, New York	*Florida.* Modeling allows the agency to match the prioritization conducted by districts based on their knowledge of area bridges. *New York*. Models accurately represent what is observed in the field.
Other	Arkansas, Delaware, Rhode Island, West Virginia	*Arkansas*. Modeling seems reasonable. *Delaware*. The agency has successfully developed deterioration models for common bridge type such as culverts, reinforced concrete slabs, multisteel beam and prestressed concrete multibeam bridges. *Rhode Island*. Rhode Island has used inspection data collected since 1995 to determine actual bridge deterioration rates. *West Virginia*. Modeling provides a foundation for building an asset management system.

Key Challenges

These 20 agencies also described challenges experienced with bridge deterioration models. Data management was cited most frequently by respondents (five agencies), including data inconsistencies (Oregon) and cost–benefit information (Colorado). Three agencies noted model deficiencies, including models that do not directly account for specific maintenance and preservation actions (New York) and models that are too conservative (West Virginia). Lack of resources was also reported by three agencies, including the time to implement new ideas (Arkansas) and staffing (Iowa). Table 9 summarizes survey responses.

Table 9. Bridge Deterioration Model Challenges

Modeling Challenge	State	Description
Continuity of Expertise	Kansas, Louisiana	*Kansas*: • Previous methodologies were ineffective: Spreadsheets became outdated once the expert left, and AASHTOWare's Pontis was cumbersome and did not produce logical results. • AASHTOWare BrM is still cumbersome yet has enough flexibility to meet the agency's needs. *Louisiana*. Experience needed to develop models is in short supply. The agency has relied on studies from similar peer states.
Data Collection	Virginia	The agency does not collect sufficient data to explain the volatility in the results. More data items would explain much of this volatility.
Data Management	Colorado, Indiana, New Jersey, Oregon, Washington	*Colorado.* Determining state-specific deterioration curves, obtaining reliable cost–benefit information for treatment type and tracking actual work performed on structures are challenging. *Indiana*. Cleaning and uncensoring data were challenging. Next, the agency will expand its model to address ancillary treatments, which will allow removing inherent ancillary treatment from the current deterioration models to "see the full story." *New Jersey*. Converting deterioration of elements in the component rating (converted) with respect to the actual component condition. *Oregon.* Data inconsistencies; AASHTOWare BrM has not allowed the agency to implement the management model. *Washington.* The agency is retrofitting and defining data from historical procedures that don't always fit the current model. (Its database only stores inspection data to the early 2000s.)
Data Variability	Wyoming	NBI condition ratings were calculated from CoRe elements, which resulted in very conservative ratings. This condition, combined with inconsistent inspector ratings, created a highly variable data set to develop deterioration models. These models can be variable for some structures, which sometimes results in recommending the too harsh or too lenient future treatment.
Insufficient Data	Michigan, Wisconsin	*Michigan*. There is enough information for common inventory filters but insufficient data to model typical inventory items. *Wisconsin*: • More data is needed to refine curves for various elements and environment conditions. • Getting partners and stakeholders to buy in to a new approach to managing assets is also challenging.
Lack of Resources	Arkansas, Iowa, South Dakota	*Arkansas*. Finding time to implement new ideas is challenging. *Iowa*: • The agency has insufficient personnel to manage its modeling system. • Relying on consultants to run the software makes it difficult to achieve desired results.

Modeling Challenge	State	Description
		• Adequate resources are unavailable to review output and make runs as needed. *South Dakota*. Accommodating additional work with limited resources is challenging.
Model Deficiencies	New York, North Carolina, West Virginia	*New York*: • Models do not directly account for specific maintenance and preservation actions. • A change in inspection system to AASHTO-element-based system necessitated new model development. *North Carolina*. Limitations imposed by using three NBI component ratings make it difficult to simulate varying conditional scenarios for funding levels. *West Virginia*. Models may be too conservative. Adjusting models for different climatic conditions can be challenging.
Model Use	Florida, Illinois	*Florida*. The agency still needs to expand its understanding of the model software and its capabilities. *Illinois*. Assumptions are made if components (such as decks, superstructures, substructures or culverts) exceed typical number of years in a specific condition rating category. The agency's multiyear plan is "very sensitive to this."
Other	Delaware, Rhode Island	*Delaware*. Modeling is challenging for elements or bridge types that are less common in the state (such as timber, cable stay and steel truss bridges). *Rhode Island*. Changes in new preservation maintenance activities resulted from the skill deterioration model.

Best Practices

Simplicity was the most frequently recommended best practice for using bridge deterioration models (Arkansas, Indiana, Michigan and New York). Practices related to staffing resources were also recommended (Iowa, Kansas and Louisiana). The respondent from Kansas DOT reported that in an ideal world, a data analyst would do most of the modeling. He added that the "level and type of analysis for forecasting future conditions requires a very specialized skill set, more like an actuary or academic than a bridge engineer. As bridge engineers we strive to get the 'right' answer, knowing what control we have over the uncertainties. Forecasting requires an acknowledgment that we are really just guessing."

Other best practices recommended by respondents were data variability (Oregon and Wyoming), model specificity (Florida and Illinois), model verification (Rhode Island and Wisconsin) and preliminary measures (Indiana and North Carolina). Table 10 summarizes survey results.

Table 10. Best Practices in Bridge Deterioration Modeling

Best Practice	State	Description
Consistent Practices	Washington	Be consistent with inspection processes and data gathering from year to year.

Best Practice	State	Description
Data Variability	Oregon, Wyoming	*Oregon*. Be aware of the variability in agency data. Review the output from all modeling to assess reasonableness. *Wyoming*. Know that inspection data is subjective. Deterioration models are only as reliable as the data received.
Documentation	Colorado	Gather thorough documentation for any assumptions made when creating the models.
Frequency of Analysis	Michigan	Consider varying time blocks. Michigan DOT analyzes based on a five-year block, which allows for similar bridge inspection techniques and oftentimes the same inspector for more reliable data from year to year.
Future Plans	New Jersey	• Use element-level deterioration models to identify future preservation projects. • Use component-level deterioration models to identify future rehabilitation/ replacement projects.
Impact of Data	Indiana	Examine the impacts of various data clusters to the final deterioration curves.
Model Specificity	Florida, Illinois	*Florida*. Develop models that are specific to the state and consider the unique environmental conditions and risks. *Illinois*. Develop separate models for precast prestressed concrete box beams and major bridges, and models based on climatic zones.
Model Verification	Rhode Island, Wisconsin	*Rhode Island.* Use an agency-specific deterioration rate based on inspection instead of expert elicitation or engineering judgment. *Wisconsin.* Verify theoretical models with deterministic models for accuracy.
Preliminary Steps	Indiana, North Carolina	*Indiana.* Read available National Cooperative Highway Research Program (NCHRP) and Transportation Research Board (TRB) publications regarding deterioration models. *North Carolina*. When initially setting structures on the deterioration curve, consider how long the structure has been at its current element rating to prevent like structures from deteriorating at the same rate (which is a problem specific to deterministic models).
Simplicity	Arkansas, Indiana, Michigan, New York	*Arkansas.* Keep it simple. Check results to see if they make sense. *Indiana*. Start with simplified models. Debug and then enhance to more complicated models. *Michigan*. Start simple: Perform the common inventory items first and then expand to other items. *New York*. Try to be as simplistic as possible.
Staffing Resources	Iowa, Kansas, Louisiana	*Iowa*. Use in-house staff to run the modeling to better understand system capabilities and performance. In-house staff can make better decisions about modeling criteria because they understand the agency's bridges. *Kansas*. Consider hiring a data analyst to do the bulk of the modeling. This level and type of analysis for forecasting future conditions requires a very specialized skill set, more like an actuary or academic then a bridge engineer. *Louisiana*. Coordinate with bridge design and maintenance for project selection.
Sufficient Data	Virginia	"Believe the no." The agency believes that more data items would explain much of the volatility.
Work Requirements	Indiana	Understand the level of work required to clean and uncensor data.

Best Practice	State	Description
Other	Oregon	Include only the elements that actually reflect bridge deterioration, not those that are only indicators of condition (e.g., asphalt wearing surfaces).

Alternatives to Using Bridge Deterioration Modeling

Of the 29 state DOTs responding to the survey, seven have not adopted a model to forecast deterioration in bridges:

- Massachusetts.
- Mississippi.
- Montana.
- Nevada.
- New Hampshire.
- North Dakota.
- South Carolina.

Note: Though indicating that his agency has not adopted a deterioration model, the North Dakota DOT respondent briefly described his agency's use of AASHTOWare BrM to model bridge deterioration.

Respondents described other methods or practices used to assess bridge condition:

- Condition ratings (Nevada).
- Engineering judgment (Montana and North Dakota).
- Inspection reports (Massachusetts, Mississippi, Montana, Nevada, North Dakota and South Carolina).
- Load ratings (South Carolina).

Two respondents described current practices in more detail:

- *New Hampshire*. The agency's current methodology involves categorizing bridges using current NBI ratings taken from inspection data gathered every two years and then preparing two lists:
    - Maintenance and preservation.
    - Rehabilitation and replacement.

  Each bridge is assigned a rank based on a weighting/scoring system that takes into account various factors such as condition, type, size, importance and risk. A committee of bridge engineers and business analysts reviews the ranked lists to make any needed adjustments before the lists are used to inform agency investment and construction decisions.
- *North Dakota*. The agency manipulates deterioration curves resident in the AASHTOWare BrM software based on inventory performance and engineering judgment. Agency modifications include changes to network policies, NBI conversions and deterioration rates.

Current Research Activities and Interests

Involvement in Ongoing Research

Respondents from 13 of the 29 agencies participating in the survey described their involvement in current or ongoing research in bridge deterioration modeling, primarily through membership in national programs, such as working groups in the AASHTO Transportation System Preservation Technical Services Program (TSP2), FHWA's Long-Term Bridge Performance (LTBP) Program and Transportation Pooled Fund (TPF) Program studies. Respondents also reported involvement in state initiatives and university research. Table 11 summarizes survey results.

Table 11. Involvement in Bridge Deterioration Modeling Research

Involvement	State	Description
National Programs	Arkansas, Indiana, Michigan, South Dakota, Virginia	• **AASHTO TSP2 Working Groups** https://tsp2bridge.pavementpreservation.org/national-working-groups/ ○ Bridge Management System (BMS) Working Group *From the work scope*: Promote the development/adoption of best practices for BMS to extend the service life of bridges and demonstrate the value of preservation. Develop general guidance and examples to help practitioners nationwide identify best practices for BMS that meet the needs of the agency and establish a process that makes implementation less intimidating. Monitor and share the national development of management systems as they evolve. *Members*: ▪ Arkansas (follows working group activities). ▪ Virginia (co-chair of working group). ○ Midwest Bridge Preservation Partnership (MWBPP) https://tsp2bridge.pavementpreservation.org/midwest-mwbpp/action-committees/ According to survey respondents, the MWBPP recently awarded a contract to a consultant to research data from the combined 12 member states and develop sustainable deterioration curves. *Leaders*: Nebraska, Wisconsin. • **FHWA LTBP Program** https://highways.dot.gov/research/long-term-infrastructure-performance/ltbp/long-term-bridge-performance *From the web site*: The LTBP Program is a long-term research effort … to collect high-quality bridge data from a representative sample of highway bridges nationwide that will help the bridge community to better understand bridge performance. *Member*: Arkansas (follows program activities). • **NCHRP 20-68A U.S. Domestic Scan 20-01, Successful Approaches to Utilizing Bridge Management Systems for Strategic Decision Making in Asset Management Plans** https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=1570 (scroll to "Scan 20-01") *From the web site*: [The scan] will explore how agencies effectively integrate BMS data into their transportation asset-management plans (TAMP) to preserve and improve the condition of the assets and the performance of their system.

Involvement	State	Description
		Member: Virginia. • **Optimization Module for AASHTOWare BrM Technical Advisory Group** *Member*: Virginia. • **TPF 5(432), Bridge Element Deterioration for Midwest States** https://www.pooledfund.org/Details/Study/655 *From the objectives*: This effort will pool data and through the analysis and research processes create results that will improve accuracy of various bridge management and asset management applications that the member DOTs use (AASHTOWare BrM, Agile Assets and others). The study is expected to conclude December 2021. See **Related Research and Resources**, page 53, for a study description. *Members*: Illinois, Indiana, Iowa, Kansas, Michigan, North Dakota, South Dakota, Wisconsin (lead agency).
State Initiatives	Florida, New Hampshire	*Florida*. The agency will be developing new research to fine-tune agency models. *New Hampshire*. An effort recently initiated to significantly expand the agency's bridge management system includes in-house development of models by agency engineers and business system analysts. Still in the early stages of development, modeling is expected to provide data for life cycle cost analyses, long-range budget planning and project planning.
University Research	Colorado, Montana	*Colorado*. The agency is working with the University of Colorado at Denver to develop new state-specific deterioration curves. *Montana*. A research project in progress will develop bridge deterioration models for Montana. See **Related Research and Resources**, page 57, for a description of this research effort.
Other	Delaware, Massachusetts, New Jersey	*Delaware*. Aware of other research efforts by other DOTs and universities. *Massachusetts.* The agency is gathering data that will be supplied to a consultant for reevaluation of the progression of bridge condition based on historical information. *New Jersey*. Involved in machine learning to correlate NBI versus element-level models.

Interest in Future Research

Respondents expressed interest in future research efforts associated with deterioration modeling:

- Supplements to AASHTOWare BrM processes (Mississippi).
- Scope development, project management and implementation of results into the asset management module once they are developed (New York).
- Modeling that incorporates a health index that forecasts performance to illustrate the impacts of funding decisions (Oregon).
- Design improvements (South Carolina).

Illinois DOT has collected element-level inspection data for many years and condition rating data even longer to determine how bridges deteriorate in the state. However, the respondent noted that the agency is always interested in obtaining additional information from other state transportation agencies. The respondent from Kansas DOT is interested in research and articles associated with bridge asset management, and tries to direct a portion of the agency's annual research budget to following research in this area.

Survey of Vendors

An online survey was distributed to the following vendors to inquire about the products that their companies manufacture to support bridge deterioration modeling by state DOTs:

- AgileAssets, Inc.
- Bentley Systems, Inc.
- IDS (Infrastructure Data Solutions).
- Mayvue Solutions.

The survey questions are provided in Appendix A. The full text of survey responses is presented in a supplement to this report.

Summary of Survey Results

Two vendors—IDS and Mayvue Solutions—responded to the survey. Both companies manufacture products to support bridge deterioration modeling by state DOTs. Information provided by these vendors is summarized below in the following topic areas:

- Product descriptions.
- Product functionality.
- Product practices and analysis.

Supplementary resources provided by the vendors are summarized in this section. Additional details are available in **Related Research and Resources** beginning on page 52.

Product Descriptions

IDS

The IDS respondent noted that the company offers Bridge Optimizer and Asset Optimizer to support bridge deterioration modeling. (Bridge Optimizer is customized for the NBI schema and is marketed as NBI Optimizer.) Because both products implement the same modeling methodology, only Asset Optimizer is described. Modeling approaches and other features about Asset Optimizer are summarized in Table 12.

Table 12. IDS Asset Optimizer: Product Information

Topic	Description
Product Description	A cloud-based solution that supports the development and management of optimized long-range cross-asset programs. The software implements unique predictive analytics and multiobjective optimization algorithms to enable trade-off analysis and project selection across entire asset portfolios, including bridges, pavement and traffic management. The optimization algorithm ensures the selection of projects that maximize assets performance, minimize the risk and minimize life cycle costs.
Approaches	• **Supervised Learning Method.** A multivariate inductive supervised learning technique is used to model the deterioration of bridge elements. This approach is based on a statistical learning theory with two main features: It does not assume any prior knowledge of the deterioration function, and it can efficiently account for a wide range of explanatory

Topic	Description
	variables. Deterioration models are constructed using training data examples derived from historical data records (for example, NBI databases) and represented as pairs of input–output mappings. The learning algorithm infers, or discovers, the deterioration distribution function that closely captures the underlying dependencies between bridge attributes (as input or explanatory variables) and bridge component or element condition (as output or dependent variable). • **Regression Modeling.** Deterioration models are defined based on analyzing distributions of the bridge component waiting time in each condition grade and investigating a number of functional forms (such as Weibull, exponential or polynomial). The distribution that shows better correlation (or goodness of fit) with historical data and provides reasonable and acceptable predictions with respect to the observed history will be selected. By examining the goodness of fit of these distributions (measured by the root-mean-square error), the best distribution parameters can be defined.
Reducing Problem Dimensionality	To reduce the number of explanatory variables, the bridge data set could be subdivided into a number of groups (or cohorts) that are assumed to have somewhat homogeneous characteristics in terms of their deterioration rate. Groups can be defined based on user-defined criteria such as functional class (or route type), service type, material, structure type and deck type. Deterioration models are then developed for each of the bridges and bridge elements in each of the defined groups.
Predictions Using Incremental Recursive Approach	The defined deterioration models based on these methods represent an average distribution (or deterioration trend) of a specific bridge component (in a specific bridge group). But in reality, individual components are rarely identical and often deteriorate at different rates due to a wide range of factors, which would cause these components with identical parameters to deteriorate at different rates. The deterioration models are then used to predict the change in a bridge component condition starting from an initial state. The initial condition state for each component is typically set to the values recorded in the most recent data set (for example, the most recent NBI data). Starting from an initial state, the defined models are then used in an incremental recursive manner to predict future values, where the value in a specific year is calculated based on the initial value known or calculated at a previous year.
State DOTs Using This Product*	• Caltrans. • Iowa DOT.
Additional Information	The IDS bridge deterioration modeling approach tries to overcome some of the inherent difficulties of deterioration modeling (e.g., high dimensionality and imprecise or incomplete data) as well as known limitations in current approaches (such as Markov models). It also tries to minimize the need for subjective judgment or expert opinion by using available historical data as often as possible. Based on its experience with machine learning inductive models, this approach seems very promising. However, more research is needed to improve model robustness and ensure wider application and user acceptance.

*As reported by the vendor.

Mayvue Solutions

Table 13 presents product information about AASHTOWare BrM. (*Note*: The respondent indicated that the company offered another product to support bridge deterioration modeling by state DOTs but did not provide information about additional products.)

Table 13. AASHTOWare Bridge Management: Product Information

Topic	Description
Product Description	• Models bridge deterioration. • Identifies projects to meet performance outcomes. • Makes long-term projections.
State DOTs Using This Product*	44 state DOTs, including Caltrans.
Additional Information	Caltrans, as a member agency of AASHTO, already licenses AASHTOWare BrM and uses it regularly for signs and tunnels. But the agency may utilize fewer aspects of the bridge modeling functions, which are AASHTOWare BrM's strongest features. AASHTOWare and Mayvue are available to provide demonstrations, training, support and setup help as needed.

*As reported by the vendor.

Product Functionality

<u>Applications and Processes</u>

Table 14 shows the applications and processes supported by vendor products. AASHTOWare BrM supports legislative reporting, life cycle cost analyses, long-range budget planning, material evaluation, and project scoping and planning. Asset Optimizer supports a range of applications not specified in the survey, including predictive modeling, data analytics and cross-asset budget trade-off analysis. Note that neither product supports resource demand models.

Table 14. Applications or Processes Supported by Product

Product/ Vendor	Legislative Reporting	Life Cycle Cost Analyses	Long Range Budget Planning	Material Evaluation	Project Scoping/ Planning	Other	Description
Asset Optimizer **IDS**		X	X			X	• Scenario trade-off analysis. • Predictive modeling. • Multiyear program development. • Program management. • Needs management. • Data analytics, geographic information system (GIS integration, dashboards, reporting. • Cross-asset budget trade-off analysis.
AASHTOWare BrM **Mayvue Solutions**	X	X	X	X	X	X	Supports application needs of AASHTO partners.

Bridge Elements and Product Parameters

Products from both vendors can analyze decks, superstructures and substructures. In addition, both products support NBI deterioration and NBE deterioration.

In addition, both vendor products can be adjusted for specific variables or parameters, such as ADT, deck wearing surface, highway functional class and superstructure material type. For developing predictive models, the Asset Optimizer can accommodate any parameter that has adequate historical data. Since AASHTOWare BrM allows for user-defined formula modifications, it can model deterioration curves with available data. Table 15 presents the variables and parameters supported by the vendor products.

Table 15. Variables or Parameters Accommodated by Model

Product/ Vendor	Age	Approach Surface	ADT	ADTT	Climatic Conditions	Condition Rating	Deck Wearing Surface	Design Load	Design Type	Highway Functional Class	Location
Asset Optimizer **IDS**	X		X	X		X	X	X	X	X	X
AASHTOWare BrM **Mayvue Solutions**	X	X	X	X	X	X	X	X	X	X	X

Table 15. Variables or Parameters Accommodated by Model, continued

Product/ Vendor	Maximum Span Length	Number of Spans	Rebar Coating	Skew Angle	Super structure Material Type	Use of Deck Overlays	Other	Description
Asset Optimizer **IDS**	X	X		X	X	X	X	For developing predictive models, any parameter with adequate historical data accommodated. (*Note*: Assumptions made when data is limited or not available.)
AASHTOWare BrM **Mayvue Solutions**	X	X	X	X	X	X	X	User-defined formula modifications of deterioration curves allow modeling any available data.

Product Practices and Analysis

Bridge Maintenance Treatments

IDS and Mayvue Solutions products can accommodate specific bridge maintenance treatments:

IDS products consider specific rehabilitation/maintenance or functional improvement treatments by defining the incremental improvements expected on each of the defined deterioration parameters. The products can also specify the constraints or criteria governing the applicability of any treatment. Constraints were also defined in cases where application of a specific action is dependent on prior treatments applied in preceding years.

AASHTOWare BrM models the deterioration of each element on each structure, and each treatment can have different effects on those elements. These treatments can be considered in isolation or in combination.

Isolating the Benefit of Bridge Maintenance Treatments

Both vendors reported that their products provide a process for isolating the benefit of each bridge maintenance treatment and its impact on the deterioration rate. The respondent from Mayvue Solutions reiterated AASHTOWare BrM's ability to consider the impact of a treatment individually or in combination with other treatments. The IDS respondent noted that the company's products can define the impact of each treatment on each deterioration parameter or performance variable. Examples of improvements include higher condition ratings for bridge elements, improved load rating and improved deck geometry. The improvements often depend on a number of factors such as the physical characteristics of the bridge or the current condition rating.

Product Documentation

Resources provided by IDS describe a dynamic programming-based multiobjective optimization approach that generates global optimal network-level, long-range bridge improvement programs. Included is a case study using this approach to develop a 20-year improvement and replacement program for Iowa DOT. Mayvue Solutions provides access to AASHTOWare BrM formulas in the software's technical manual. These publications are cited in **Related Research and Resources**, beginning on page 68. Below is an abbreviated listing of the citations:

- *IDS*:
    - Cloud-Based Scalable Software for Optimal Long-Range, Network-Level Bridge Improvement Programming (2017).
    - Multi-Objective Optimization for Long-Range Bridge Improvement Programming: Iowa DOT Case Study (2018).
- *Mayvue Solutions*: AASHTOWare Bridge Management (undated).

Survey of Consultant

An online survey was distributed to Paul D. Thompson to inquire about the bridge deterioration models that the consultant uses. The survey questions are provided in Appendix A. The full text of survey responses is presented in a supplement to this report.

Summary of Survey Results

The consultant described three products that have been used to support bridge deterioration modeling by state DOTs:

- Custom development using AASHTOWare BrM data, SQL and Excel (Florida DOT).
- Custom development using Pontis data sets from 15 states (FHWA).
- Methodology for estimating life expectancies of highway assets (NCHRP).

The consultant noted that he has completed similar research for Alabama and Kansas DOTs. Information about these projects may be obtained from the following DOT representatives:

- Alabama: Eric Christie, 334-242-6281, christiee@dot.state.al.us.
- Kansas: John Culbertson, 785-296-5510, john.culbertson@ks.gov.

He is in the pilot testing phase of developing an open-source spreadsheet for the long-range renewal planning of transportation structures. (See *Related Resources* below for the introduction to the draft user's manual.) The tool is being used on several projects for deterioration forecasting, life cycle cost analysis and generation of investment candidates for network-level applications. The calculations are similar to AASHTOWare BrM but because it is purpose-built for network-level analysis, it is faster, easier to implement and more customizable. Full release is planned for early 2021, at which time the plan is to offer the product for download at no charge.

Related Resource:

> **Introduction**, *StruPlan: Open-Source Long-Range Renewal Planning for Transportation Structures,* Draft User's Manual, Paul D. Thompson, June 2020.
> See Attachment A.
> *From the introduction*: StruPlan is an open-source long-range renewal planning spreadsheet for transportation structures. Using bridge management system data and models, it produces a network level 10-year spending plan, with forecasts of condition and performance, based on an optimized selection of preservation, rehabilitation and reconstruction activities. Parameters governing costs, deterioration and treatment selection can be fine-tuned to fit the needs of each agency and program. All substantive calculations and results are readily visible on Excel worksheets, where they can be examined, tested and modified.

Information about the three products described by the consultant is summarized below in the following topic areas:

- Product descriptions.
- Product functionality.
- Product practices and analysis.

Supplementary resources provided by the consultant are summarized in this section. Additional details are available in **Related Research and Resources** beginning on page 52.

Product Descriptions

Tables 16 through 18 summarize project information for each product developed by the consultant, including the owner of each project.

Table 16. Product 1: Custom Development Using AASHTOWare BrM

Topic	Description
Product	Custom development of deterioration model parameters using AASHTOWare BrM data, SQL, Excel and other common tools.
Project Description	Develop bridge deterioration model for Florida DOT.
Project Owner	Florida DOT
Additional Information	In a subsequent project, the consultant updated these models for the 2015 AASHTO elements (see Implementation of the 2013 AASHTO Manual for Bridge Element Inspection in **Related Research and Resources**, page 54). *Contact*: Chris Laughlin, Florida DOT, 850-410-5514, christopher.laughlin@dot.state.fl.us.

Table 17. Product 2: Custom Development Using Pontis Data From Selected States

Topic	Description
Product	National Bridge Investment Analysis System
Project Description	Develop national deterioration models using a custom methodology from the contributed Pontis data sets of 15 states.
Project Owner	Ross Crichton, FHWA Office of Policy, 202-366-5027, ross.crichton@dot.gov.
Additional Information	NBIAS software and user's manual are available from Ross Crichton, FHWA.

Table 18. Product 3: Estimating Life Expectancies of Highway Assets

Topic	Description
Product	Estimating Life Expectancies of Highway Assets
Project Description	Develop a methodology for estimating life expectancies of highway assets for use in life cycle cost analyses supporting management decision-making.
Project Owner	NCHRP
Additional Information	NCHRP Report 713: Estimating Life Expectancies of Highway Assets, Volume 1: Guidebook (see **Related Research and Resources**, page 52).

Product Functionality

<u>Applications and Processes</u>

All models described by the consultant support a number of applications and processes, particularly life cycle cost analyses, long-range budget planning and resource demand models.

Material evaluation is least likely to be supported. Table 19 summarizes the applications and processes supported by these products.

Table 19. Applications and Processes Supported by Consultant Products

Product	Legislative Reporting	Life Cycle Cost Analyses	Long Range Budget Planning	Material Evaluation	Project Scoping/ Planning	Resource Demand Models	Other	Description
Product 1	X	X	X		X	X	X	• Priority-setting • Programming
Product 2	X	X	X			X	X	Report to the Congress on the conditions and performance of the nation's roads, bridges and transit.
Product 3		X	X	X	X	X		None provided.

Bridge Elements and Product Parameters

All products described by the consultant can analyze decks, superstructures and substructures. Products 1 and 2 also analyze all NBI elements. In addition, Product 1 can analyze a large number of agency-defined elements for movable bridges, retaining walls, sign structures, high-mast light poles and traffic signal mast arms.

The variables and parameters most likely to be supported by the three products are climatic conditions, condition rating, deck wearing surface, superstructure material type and use of deck overlays. None of the models allow for approach surface, design load, design type, maximum span length, number of spans, rebar coating and skew angle. Table 20 summarizes the variables and parameters supported by these products.

Table 20. Variables or Parameters Accommodated by Consultant Products

Product	Age	ADT	ADTT	Climatic Conditions	Condition Rating	Deck Wearing Surface	Highway Functional Class	Location
Product 1				X	X	X		X
Product 2	X	X	X	X	X	X	X	X
Product 3	X	X		X	X	X		

Table 20. Variables or Parameters Accommodated by Consultant Products, continued

Product	Superstructure Material Type	Use of Deck Overlays	Other	Description
Product 1	X	X	X	Element-level model.
Product 2	X	X		None provided.
Product 3	X	X		None provided.

Product Practices and Analysis

Bridge Maintenance Treatments

Product 1 and Product 2 take into account specific bridge maintenance treatments:

- *Product 1*: Treatments affect future costs and changes in condition. The treatment effectiveness model was developed using a database of past projects and the observed changes in element condition.
- *Product 2*: Treatment effectiveness models are available for replacement, rehabilitation, preservation and routine maintenance.

Isolating the Benefit of Bridge Maintenance Treatments

Both Product 1 and Product 2 use life cycle cost analysis to quantify the benefit for each specific bridge maintenance treatment and its impact on the deterioration rate. Product 3 does not provide a process for isolating the benefit of bridge maintenance treatments.

Product Documentation

Resources provided by the consultant describe bridge management analysis tools developed through various projects. These publications are cited in **Related Research and Resources**, beginning on page 52. Below is an abbreviated listing of the citations:

- Enhancement of the FDOT's Project Level and Network Level Bridge Management Analysis Tools: Final Report (2011).
- National-Scale Bridge Element Deterioration Model for the USA (2018).
- NCHRP 713: Estimating Life Expectancies of Highway Assets, Volume 1: Guidebook (2012).

Related Research and Resources

A literature search of recent publicly available resources identified publications and resources that are organized into the following topic areas:

- Multiple or unspecified models.
- Artificial neural network models.
- Mechanistic models.
- Probabilistic models.
- Regression models.
- Stochastic models.
- International research.
- Commercial products.
- Related resources.

Multiple or Unspecified Models

National Guidance

NCHRP Report 713: Estimating Life Expectancies of Highway Assets, Volume 1: Guidebook, Paul D. Thompson, Kevin Ford, Mohammad Arman, Samuel Labi, Kumares Sinha and Arun Shirole, 2012.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_713v1.pdf
From the abstract: This two-volume report provides a methodology for estimating the life expectancies of major types of highway system assets, in a form useful to state departments of transportation (DOTs) and others, for use in life cycle cost analyses that support management decision making. Volume 1 is a guidebook for applying the methodology in DOT asset management policies and programs. Volume 2 describes the technical issues and data needs associated with estimating asset life expectancies and the practices used in a number of fields—such as the energy and financial industries—to make such estimates.

"National-Scale Bridge Element Deterioration Model for the USA," Paul D. Thompson, *Proceedings of the International Conference for Bridge Maintenance, Safety, and Management*, 2018.
See Attachment B.
From the abstract: The Federal Highway Administration of the United States uses its National Bridge Investment Analysis System (NBIAS) to develop needs estimates and report on the conditions and performance of the nation's 600,000 bridges and culverts. The system's deterioration model was recently updated to be consistent with the most recent bridge element inspection standards. A data set containing nearly 3 million element inspection records was stratified into nine climate zones according to average temperatures and moisture in each county of the United States. Algebraic methods developed in research for Florida and Virginia were used to process the element inspection data into transition probability matrices. The resulting models were then transformed for compatibility with the latest inspection manuals used in federal bridge condition reporting requirements. The product represents the first time there has been a true nationwide element level deterioration model for bridges in the United States.

Multiple States

Research in Progress: Descriptive and Predictive Deep Learning Analytical Tools for Enhanced Bridge Management: Bridge Subtyping and Bridge Deterioration Forecasting, Mountain-Plains Consortium, start date: February 2020; expected completion date: July 2022.
Project description at https://www.mountain-plains.org/research/details.php?id=513
From the project description: While in the past various data-driven deterioration models are proposed in the literature to model bridge deterioration, these models either suffer from low

accuracy or are too complex to be applicable. Moreover, they only address the problem of deterioration forecasting. Recently deep learning is shown to significantly outperform other analytical modeling methodologies in a variety of application domains. In this study, the team proposes to develop two analytical tools based on deep learning models for enhanced bridge management. The proposed tools will address the problems of bridge subtyping (for descriptive analysis of inspection data to effectively categorize bridges to groups based on their performance characteristics and behavioral trends), and bridge deterioration forecasting (for predictive analysis of the bridge data to accurately identify quantitative descriptors for the structure deterioration state (e.g., condition ratings) as well as any possible anomalies in the deterioration pattern of the bridge structure).

Research in Progress: Bridge Element Deterioration for Midwest States, Transportation Pooled Fund Study Number TPF-5(432), start date: December 2019; expected completion date: December 2021.
Project description at https://www.pooledfund.org/Details/Study/655
From the project description: The objective of this pooled fund research is to have multiple Midwest DOTs pool resources and historic Midwest DOT bridge data related to element level deterioration, operation practices, maintenance activities and historic design/construction details. This data will provide the basis for research to determine deterioration curves. A select number of deterioration curves will provide needed utility for the time-dependent deterioration of bridge elements to be used in making estimates of future conditions and work actions. This effort will pool data and through the analysis and research processes create results that will improve accuracy of various bridge management and asset management applications that the member DOTs use (BrM, Agile Assets and other[s]).

"Deterioration Models for Prediction of Remaining Useful Life of Timber and Concrete Bridges: A Review," Ishwarya Srikanth and Madasamy Arockiasamy, *Journal of Traffic and Transportation Engineering*, Vol. 7, Issue 2, pages 152-173, April 2020.
Citation at http://www.sciencedirect.com/science/article/pii/S2095756419301084
From the abstract: Bridge deterioration models are used for prioritization and maintenance of bridges. These models can be broadly classified as deterministic and stochastic models. There are mechanistic models (or physical models) as well as artificial intelligence (AI)-based models, each of which can be stochastic or deterministic in nature. Even though there are several existing deterioration models, [the] state-based stochastic Markov chain-based model is widely employed in bridge management programs. This paper presents a critical review of different bridge deterioration models highlighting the advantages and limitations of each model. The models are applied to some case studies of timber superstructure and concrete bridge decks. Examples are illustrated for arriving at bridge deterioration models using deterministic, stochastic and artificial neural network (ANN)-based models based on [N]ational [B]ridge [I]nventory (NBI) data. The first example is based on deterministic model and the second on stochastic model. The deterministic model uses the NBI records for the years 1992–2012, while the stochastic model uses the NBI records for one year (2011–2012). The stochastic model is [a] state-based Markov chain model developed using transition probability matrix (TPM) obtained by percentage prediction method (PPM). The two deterioration models (i.e., deterministic and stochastic models) are applied to timber highway bridge superstructure using NBI condition data for bridges in Florida, Georgia, South Carolina and North Carolina. The illustrated examples show that the deterministic model provides higher accuracy in the predicted condition value than the stochastic Markov chain-based model. If the model is developed based on average of transition probabilities considering the data for the period 1992[–]2012, the prediction accuracy of [the] stochastic model will improve. Proper data filtering of condition records aids in improving the accuracy of the deterministic models. The third example illustrates

the ANN-based deterioration model for reinforced concrete bridge decks in Florida based on the NBI condition data for the years 1992–2012. The training set accuracy and testing set accuracy in the ANN model are found to be 91% and 88%, respectively. The trained model is utilized to generate missing condition data to fill the gaps due to irregular inspections of concrete bridges. This paper also discusses [the] scope for future research on bridge deterioration modeling.

Florida

"Migration Probability Matrix for Bridge Element Deterioration Models," Paul D. Thompson, *Transportation Research Circular E-C224*: *Eleventh International Bridge and Structures Management Conference*, pages 137-152, November 2017.
http://onlinepubs.trb.org/onlinepubs/circulars/ec224.pdf
From the abstract: Element-level bridge inspection data suitable for deterioration models have been collected by most state department of transportation (DOTs) since the mid-1990s, but in 2013 AASHTO significantly modified the inspection process. FHWA has proposed adding the modified inspection language to the National Bridge Inventory in compliance with element inspection requirements in 23 USC 144(b). This presents a serious problem for all DOTs because none yet have sufficient element inspection data under the 2013 AASHTO manual to support deterioration modeling.

Research completed in 2016 for the Florida DOT suggests one readily implementable solution to this problem. A migration probability matrix was developed to encapsulate the differences in definitions between Florida's bridge element inspection data gathered under AASHTO's 1998 Guide to Commonly Recognized Structural Elements, and the new 2016 Florida DOT inspection manual, which is based on the 2013 AASHTO Manual for Bridge Element Inspection. Deterioration models previously developed using the older data can be easily multiplied by this migration probability matrix to develop reasonable models that are compatible with inspection data gathered under the new manual. Ultimately this migration matrix can be validated and improved once sufficient element inspection data are gathered under the new manual.

Related Resource:

> **Implementation of the 2013 AASHTO Manual for Bridge Element Inspection**, John O. Sobanjo and Paul D. Thompson, Florida Department of Transportation, July 2016.
> https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/research/reports/fdot-bdv30-977-07-rpt.pdf
> *From the executive summary*:
>
> > **Deterioration model migration**
> > New transition times were developed using a set of probabilistic correspondences between CoRe element condition states and the new state definitions—a migration probability matrix—to yield a deterioration model for every element in the new FDOT [Florida DOT] Manual. The result can be imported directly into the new PON_MOD_DETER table in AASHTOWare Bridge Management once it is ready. An Excel file containing this information was delivered during the study. The biggest shortcoming with the new models is the fact that the migration probability matrix had to be developed from judgment. Once FDOT completes a year or two of inspections under the new manual, a better approach will be possible. The most recent CoRe element inspection on each bridge can be projected forward two years using the CoRe element deterioration model. Then a migration probability matrix can be computed by comparing the new inspections against the projected estimates, using an algebraic method similar to the one-step method (Sobanjo and Thompson, 2011). In the longer term, after two or

more complete cycles of inspections are completed under the new manual, a new set of deterioration models can be developed as was done in the 2011 study.

Enhancement of the FDOT's Project Level and Network Level Bridge Management Analysis Tools: Final Report, John Sobanjo and Paul D. Thompson, Florida Department of Transportation, 2011.
https://rosap.ntl.bts.gov/view/dot/18692
From the abstract: Over several years, the Florida Department of Transportation (FDOT) has been implementing the AASHTO Pontis Bridge Management System to support network-level and project-level decision making in the headquarters and district offices. … With the success of these previous research efforts, FDOT further investigated several additional modeling issues that were not possible during earlier Pontis implementation work. First, a sensitivity analysis was performed on the Project Level Analysis Tool (PLAT) and Network Analysis Tool (NAT), as well as a comparison made between the PLAT and NAT models and the National Cooperative Highway Research Program (NCHRP) Report 590, which explored the criteria used for priority setting and resource allocation. The analysis suggested priority enhancements to PLAT/NAT, including improved deterioration and cost models, and multi-objective optimization. Secondly, an improved version of the NBI Translator has been developed and implemented using two years of bridge inspection data from the Florida bridge inventory. A stand-alone computer program was developed, as well as a Microsoft Excel spreadsheet version of the Translator program written in Visual Basic for Applications (VBA), which was incorporated into the PLAT. Next, the research developed improved deterioration, action effectiveness and cost models for Pontis and the PLAT. A new, simplified procedure was developed for estimating one-step Markovian models that produces usable results with significantly smaller sample sizes than traditional regression. As the fifth accomplishment, models were developed for estimating user costs at bridge sites where no detour is considered. Several existing user cost models were reviewed in the study, including some traditional roadway-based models and the previous FDOT user cost model for bridges. New accident models were formulated based on Florida crash data at bridge sites for years 2003 through 2007, including the following: binomial logistic regression, Poisson regression and negative binomial regression models.

Indiana

"Bridge Model Validation at Indiana Department of Transportation," Gary Ruck and Kate Francis, *Transportation Research Circular E-C224*: *Eleventh International Bridge and Structures Management Conference*, pages 21-29, November 2017.
http://onlinepubs.trb.org/onlinepubs/circulars/ec224.pdf
From the abstract: The Indiana Department of Transportation (DOT) has had a bridge management system (BMS) since 1982. This system has undergone several enhancements since its inception, with the most recent major one in 2008.

Recent changes to bridge inspection standards in the United States as well [as] diminished confidence in the BMS results precipitated Indiana DOT management to re-evaluate some facets of the BMS, such as the deterioration models, to ensure that the results are still dependable. In 201[6], Indiana DOT began a project to validate the current bridge models used by the BMS. The results of this project and the framework used to validate the deterioration models will be discussed.

Deterioration models used by a management system should be validated on a recurring basis. A continuous validation process ensures that results produced by the models remain accurate and reliable as dependent factors change over time: inspection methods, treatment technologies, maintenance policies, traffic volumes and composition. The model validation method established an historical analysis baseline. Results were then generated based on the actual bridge rehabilitation and maintenance work performed by Indiana DOT and compared to the present day bridge condition. Variances between predicted and actual conditions were evaluated and modifications to the bridge models were addressed.

This paper will present the method Indiana DOT used in a manner that can be adopted by other agencies who wish to validate their own deterioration models.

Bridge Deterioration Models to Support Indiana's Bridge Management System, Milhan Moomen, Yu Qiao, Bismark R. Agbelie, Samuel Labi and Kumares C. Sinha, Indiana Department of Transportation, February 2016.
https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=3113&context=jtrp
From the abstract: The bridge deterioration models that are currently in use in the Indiana [b]ridge [m]anagement [s]ystem were developed over two decades ago. Since then, significant changes have taken place in inspection methods, technologies used [and] advanced statistical tools for data analysis. Also, because of the lack of reliable data, such items as the truck traffic and climate conditions were not included in past modeling efforts. In recent years, these obstacles have been minimized and therefore, there is an opportunity to update the deterioration models for the various bridge components. In addressing this research need, the present study developed families of curves representing deterioration models for bridge deck, superstructure and the substructure. The National Bridge Inventory database was used, and the models use the NBI condition ratings as the response variable. The model families were categorized by administrative region, functional class and superstructure material type. The explanatory variables include traffic volume and truck traffic, design type and climatic condition, and design features. Deterministic and probabilistic models were developed.

Michigan

A Process for Systematic Review of Bridge Deterioration Rates, Robert Kelley, Michigan Department of Transportation, March 2016.
https://www.michigan.gov/documents/mdot/A_Process_for_Systematic_Review_of_Bridge_Deterioration_Rates_522422_7.pdf
From the report's purpose and background: The purpose of this report is to establish a process through which trends in bridge deterioration rates can be evaluated at regular intervals. These periodic reviews will show whether preventive maintenance and other small actions taken on bridges are becoming more or less effective over time. This process is fairly simple, can be thoroughly documented and is easily replicated.

Bridge condition is reported to the Federal Highway Administration (FHWA) using two rating methods—the National Bridge [Inventory] (NBI) [c]ondition [r]atings and the National Bridge Element (NBE) ratings. Since NBE data is only in its second year of collection, there is insufficient data at this time to use NBE data to either compute deterioration rates or evaluate trends in these rates and therefore the NBI condition ratings (deck, superstructure and substructure ratings for bridges; culvert rating for culverts) were used in this report.

When a bridge condition rating is compared to the rating of the same component a year later, there are only three possibilities: Either the rating increased, stayed the same, or the rating decreased due to deterioration. Those with a rating increase are assumed to have received rehabilitation or replacement actions. Since the purpose of the report is to study the effectiveness of maintenance actions, those with rating increases are ignored in the calculations.

The changes that occurred in these ratings in a given year were aggregated in five[-]year bands and the deterioration curves for each of these five[-]year periods were computed using the Markov deterioration modeling method.

Montana

Research in Progress: Development of Deterioration Curves for Bridge Elements in Montana, Montana Department of Transportation, start date: March 2020; expected completion date: July 2022.
Project description at https://trid.trb.org/View/1658980
From the project description: This proposed research is in response to the Federal Highway Administration's (FHWA's) objective of implementing a transportation management plan for the National Highway System (NHS). One of the standards that state departments of transportation must meet is the development and operation of a bridge management system that includes deterioration forecasting for all NHS bridge assets. The Montana Department of Transportation uses two analysis programs for this purpose: the FHWA's National Bridge Investment Analysis System (NBIAS) and the Bridge Data Analytics Tool, which is currently under development. Both of these tools require deterioration curves for different bridge elements (bridge deck, superstructure and substructure). The objective of the proposed research is to 1) develop deterioration models specific to Montana's five transportation districts using inspection data related to time-dependent element deterioration, operation practices and annual average daily traffic, 2) identify existing or new data that could be used to improve the accuracy of the deterioration curves, and 3) compare the results from Montana-specific data with data from the National Bridge Inventory to identify similarities and differences in the deterioration models.

New York

Bridge Element Deterioration Rates, Anil K. Agrawal, Akira Kawaguchi and Zheng Chen, New York State Department of Transportation, March 2009.
https://www.dot.ny.gov/divisions/engineering/technical-services/trans-r-and-d-repository/C-01-51_Final%20Report_March%202009.pdf
From the abstract: The objective of this research project has been to carry out an extensive filtering/reconditioning of inspection data, identify methods to calculate deterioration rates for bridge elements and develop a computer program to calculate deterioration rates for bridge elements. Several filters have been developed and implemented to remove inspection data affected by rehabilitation, inspector subjectivity, sudden drop in ratings because of vehicle/vessel collision, and miscoding of inspection rating. In addition to filters described above, reconditioning algorithms have been developed to remove erroneous data because of reconstruction of bridge elements before the inspection data became available starting in 1981. The filtered inspection data show predominantly deteriorating behavior representing actual deterioration process. In order to investigate effects of numerous factors, e.g., AADTT [annual average daily truck traffic], climate, DOT regions, ownership, design types, etc., on the deterioration rates, a versatile cascading approach has been developed to classify bridge elements on the basis of selected factors. The cascading approach generates classes of bridges based on the classification factors selected. These classes can be analyzed to calculate deterioration rates. A computer program has been developed to calculate deterioration rates by Markov [c]hain and Weibull-based approaches. The computer program uses an updateable inspection database and generates quadratic equations of desired orders for deterioration rates. A detailed case study has been carried out to compare Markov chain and Weibull-based approaches for deterioration rates. Since the Weibull-based method utilizes actual scatter in duration data for a particular rating and considers this duration as a random variable, it has been found to be more reliable for calculating deterioration rates for bridge elements. Hence,

deterioration curves and equations using the Weibull-based method have been generated and are presented for use.

Related Resource:

"Deterioration Rates of Typical Bridge Elements in New York," A.K. Agrawal, A. Kawaguchi and Z. Chen, *Journal of Bridge Engineering*, Vol. 15, Issue 4, July 2010. Citation at https://ascelibrary.org/doi/10.1061/%28ASCE%29BE.1943-5592.0000123
From the abstract: The New York State Department of Transportation (NYSDOT) maintains an inventory of over 17,000 highway bridges across the state. These bridges are inspected biennially or more often as necessary. Bridge inspectors are required to assign a condition rating for up to 47 structural elements of each bridge, including 25 components of each span of a bridge, in addition to the general components common to all bridges. The bridge condition rating scale ranges from 7 to 1; 7 being new and 1 being in failed condition. These condition ratings may be used to calculate the deterioration rates for each bridge element, while considering the effects of key factors, such as the bridge material type, on the deterioration rates. This paper describes an approach based on the Weibull distribution to calculate the deterioration rates of typical bridge elements in New York State using historical bridge inspection data and compares the results with those using the traditionally used Markov chains approach. It is observed that the Weibull-based approach performs better in terms of the observed conditions than the traditionally used Markov chains approach for developing deterioration curves for different bridge elements. Both Markov chains and Weibull-based approaches have been incorporated into a computer program that generates the deterioration curves for specific bridge elements based on historical NYSDOT bridge inspection data dating back to 1981. Case studies on the deterioration rates of various bridge elements in New York State are presented to demonstrate the two approaches. The case studies show that the element deterioration rate information can be used to determine the expected service life of different bridge elements under a variety of external factors.

North Carolina

Determination of Bridge Deterioration Models and Bridge User Costs for the NCDOT Bridge Management System, Tara L. Cavalline, Matthew J. Whelan, Brett Q. Tempest, Raka Goyal and Joshua D. Ramsey, North Carolina Department of Transportation, October 2015.
https://connect.ncdot.gov/projects/research/RNAProjDocs/2014-07FinalReport.pdf
From the abstract: The objectives of this project were to provide NCDOT [North Carolina DOT] with revised, updated deterioration models and user cost tables for use in the BMS [bridge management system] software. Existing data in NCDOT's BMS were reviewed and steps to address data anomalies were identified and implemented. Updated deterministic deterioration models were developed for the existing data on the family level, with components grouped into families using established *a priori* classifications.

Additionally, a unique statistical regression methodology applying survival analysis techniques to better address characteristics of the historical condition rating data was developed and resulted in probabilistic deterioration models for bridge components and culverts that provide significantly improved predictive accuracy and precision over prior deterministic models. These models include transition probability matrices that account for the effects of design, geographic and functional characteristics on deterioration rates over different condition ratings. These models were found to provide significantly improved prediction accuracy and precision over typical planning horizons used in network analysis. However, while this advanced model was found to best fit the historical condition rating data and provide unique insight on factors influencing deterioration over the life cycle of each bridge component, it was also discovered that a simplified implementation of the probabilistic deterioration model was able to achieve similar performance without rigorously incorporating the effects of external factors on deterioration rates.

To aid in implementation and technology transfer, a software application was developed to facilitate routine updating of both the deterministic and probabilistic deterioration models. Preliminary work to evaluate the relative impact of individual maintenance activities on element condition ratings was performed, including the development of histograms of condition rating changes from prior actions to aid in development of action effectiveness models. Inputs and methodologies utilized to compute user costs in NCDOT's BMS were updated and enhanced using relevant, current resources that were locally or regionally sourced when possible. Specifically, the updates and enhancements to the user cost models address average daily traffic (ADT) growth rates, vehicle operating cost, vehicle distribution, vehicle weight distribution, vehicle height distribution, accident injury severity, accident cost, and an equation useful in forecasting the number of annual bridge-related crashes.

Texas

Development of a Robust Framework for Assessing Bridge Performance Using a Multiple Model Approach, Jeffrey Weidner, Jin Collins, Mariana Benitez, Mubarak Adesina and Christian Lozoya, Center for Advanced Infrastructure and Transportation, Rutgers University, May 2019.
https://rosap.ntl.bts.gov/view/dot/48948
From the abstract: This project presents a simple approach to multiple model deterioration modeling for bridges by identifying common points between deterioration model approaches and combining the results at these points. Inclusion of other data sources into this framework was explored, and an ontology of these sources and their relationships was developed. The results showed fairly close performance between individual models and combined models when considering a population of bridges in Texas using the National Bridge Inventory data—a resource that Texas would like to make better use of. This performance is a result of the bridges selected via identification of explanatory variables, which are assumed through engineering judgment to drive deterioration—a practice that is common in nearly all of the literature. Future work includes exploring more robust ways of identifying explanatory variables.

Wisconsin

"The Evolution of Structure Asset Management in Wisconsin: Practice and Research," Joshua Dietsche, *Transportation Research Circular E-C224*: *Eleventh International Bridge and Structures Management Conference*, pages 3-18, November 2017.
http://onlinepubs.trb.org/onlinepubs/circulars/ec224.pdf
From the abstract: Beginning in the early 2000s, the Wisconsin Department of Transportation (DOT) Bureau of Structures began a concerted effort to develop processes and tools to help manage the Wisconsin structures inventory. The first major step was the development of a data management tool, the Highway Structures Information System [HSIS]. This application provides Wisconsin DOT with a means to collect, store and manage structure inventory, design, rating and inspection data.

A second step was aimed at documenting and standardizing bridge preservation practices across the state. Organizationally, Wisconsin DOT divides the state into five regions. Each has their own maintenance, planning and scoping staff, with oversight from Wisconsin DOT central office. To promote consistency amongst the regions, Wisconsin DOT created the Bridge Preservation Policy Guide. This guide provides an inventory of preservation actions and also addresses goals, objectives and performance measures. The aim is to lay the groundwork for more consistent bridge work activities (maintenance, rehabilitation, replacement) around the state.

Most recently, Wisconsin DOT has focused on developing a tool to provide recommendations for current and future bridge work actions. The result of this work is the Wisconsin Structures Asset Management System (WiSAMS). WiSAMS relies heavily on the inventory data and inspection data stored in HSIS and uses a set of rules and deterioration modeling to determine current and future optimal work. The WiSAMS rules are a logical extension of policy in the Bridge Preservation Policy Guide.

Wyoming

Developing Deterioration Models for Wyoming Bridges, Minwoo Chang and Marc Maguire, Wyoming Department of Transportation, May 2016.
https://rosap.ntl.bts.gov/view/dot/31036
From the abstract: Deterioration models for the Wyoming Bridge Inventory were developed using both stochastic and deterministic models. The selection of explanatory variables is investigated and a new method using [l]east [a]bsolute [s]hrinkage and [s]election [o]perator (LASSO) regression to eliminate human bias in explanatory variable selection. The cross validation technique is used to determine the minimum number of explanatory variables. The relative significance of candidate variables is used to rank the explanatory variables in hierarchical order. The deterministic deterioration models are developed by using curve-fitting methods for the mean of bridge ages for each condition rating. In order to improve the accuracy in the model, bridges are split into the multiple subsets using first two explanatory variables for deck, superstructure and substructure. Although the deterministic deterioration model is insufficient to predict condition ratings for a specific bridge, it is worthy to observe a general feature of how the functionality of bridges becomes worse over time. The stochastic models are developed to capture the uncertainty in the deterioration process using the Markov chain. The transition probability matrix is estimated using percentage prediction method, which counts the numbers corresponding to the element of transition probability matrix. The same subsets used in the deterministic deterioration models are considered. For each subset, zoning technique is used such that the bridge data is grouped for every 30 years to estimate transition probability matrix separately. The source codes are provided for the future update of bridge inventory and stochastic deterioration models. A computer program is used [to] develop and plot deterioration models. A simple guideline is also included so that the user can access the source codes conveniently.

Artificial Neural Network Models

Michigan

Development and Validation of Deterioration Models for Concrete Bridge Decks; Phase 1: Artificial Intelligence Models and Bridge Management System, Emily K. Winn and Rigoberto Burgueño, Michigan Department of Transportation, June 2013.
https://www.michigan.gov/documents/mdot/RC-1587A_435817_7.pdf?20131004091451
From the abstract: This research documents the development and evaluation of artificial neural network (ANN) models to predict the condition ratings of concrete highway bridge decks in Michigan. Historical condition assessments chronicled in the [N]ational [B]ridge [I]nventory (NBI) database were used to develop the ANN models. Two types of artificial neural networks[—] multi-layer perceptrons [MLPs] and ensembles of neural networks (ENNs)[—]were developed

and their performance was evaluated by comparing them against recorded field inspections and using statistical methods. The MLP and ENN models had an average predictive capability across all ratings of 83% and 85%, respectively, when allowed a variance equal to bridge inspectors. A method to extract the influence of parameters from the ANN models was implemented and the results are consistent with the expectations from engineering judgment. An approach for generalizing the neural networks for a population of bridges was developed and compared with Markov chain methods. Thus, the developed ANN models allow modeling of bridge deck deterioration at the project (i.e., a specific existing or new bridge) and system/network levels. Further, the generalized ANN degradation curves provided a more detailed degradation profile than what can be generated using Markov models. A bridge management system (BMS) that optimizes the allocation of repair and maintenance funds for a network of bridges is proposed. The BMS uses a genetic algorithm and the trained ENN models to predict bridge deck degradation. Employing the proposed BMS leads to the selection of optimal bridge repair strategies to protect valuable infrastructure assets while satisfying budgetary constraints. A program for deck degradation modeling based on trained ENN models was developed as part of this project.

Wisconsin

"Artificial Neural Network Model of Bridge Deterioration," Ying-Hua Huang, *Journal of Performance of Constructed Facilities*, Vol. 24, Issue 6, December 2010.
Citation at https://ascelibrary.org/doi/abs/10.1061/(ASCE)CF.1943-5509.0000124
From the abstract: Accurate prediction of bridge condition is essential for the planning of maintenance, repair and rehabilitation. An examination of the assumptions (for example, maintenance independency) of the existing Markovian model reveals possible limitations in its ability to adequately model the procession of deterioration for these purposes. This study uses statistical analysis to identify significant factors influencing the deterioration and develops an application model for estimating the future condition of bridges. Based on data derived from historical maintenance and inspection of concrete decks in Wisconsin, this study identifies 11 significant factors and develops an artificial neural network (ANN) model to predict associated deterioration. An analysis of the application of ANN finds that it performs well when modeling deck deterioration in terms of pattern classification. The developed model has the capacity to accurately predict the condition of bridge decks and therefore provide pertinent information for maintenance planning and decision making at both the project level and the network level.

Mechanistic Models

Colorado

Investigation of Mechanistic Deterioration Modeling for Bridge Design and Management, Kyle Nickless and Rebecca Atadero, Colorado Department of Transportation, April 2017.
https://rosap.ntl.bts.gov/view/dot/32595
From the abstract: The ongoing deterioration of highway bridges in Colorado dictates that an effective method for allocating limited management resources be developed. In order to predict bridge deterioration in advance, mechanistic models that analyze the physical processes causing deterioration are capable of supplementing purely statistical models and addressing limitations associated with bridge inspection data and statistical methods. A review of existing analytical models in the literature was conducted. Due to its prevalence throughout the state of Colorado and frequent need for repair, corrosion-induced cracking of reinforced concrete (RC) decks was selected as the mode of deterioration for further study. A mechanistic model was developed to predict corrosion and concrete cracking as a function of material and

environmental inputs. The model was modified to include the effects of epoxy-coated rebar, waterproofing membranes, asphalt overlays, joint deterioration and deck maintenance. Probabilistic inputs were applied to simulate inherent randomness associated with deterioration. Model results showed that mechanistic models may be able to address limitations of statistical models and provide a more accurate and precise prediction of bridge degradation in advance. Preventive maintenance may provide longer bridge deck service life with fewer total maintenance actions than current methods. However, experimental study of specific deterioration processes and additional data collection are needed to validate model predictions. Maintenance histories of existing bridges are necessary to predicting bridge deterioration and improving bridge design and management in the future.

Probabilistic Models

Pennsylvania

Note: Although the completion date for the following project has passed, the status is listed as active.

Research in Progress: Time-Based Modeling of Concrete Bridge Deck Deterioration Using Probabilistic Models, Center for Integrated Asset Management for Multimodal Transportation Infrastructure Systems, start date: March 2019, expected completion date: August 2020.
Project description at https://trid.trb.org/View/1590669
From the project description: The goal of the proposed research is to develop a robust, self-learning, probabilistic model to predict the service life of concrete bridge decks and subsequently other infrastructure components. The model will originate from the existing performance data for 22,000 bridge decks in the state of Pennsylvania and will utilize advanced statistical tools, including machine learning systems and Bayesian probabilistic networks. The newly developed tool will allow [s]tate [d]epartments of [t]ransportation to A) accurately predict the lifetime of concrete bridge decks and B) establish more efficient and accurate management decisions, resulting in an increased longevity of the [n]ation's infrastructure.

University Transportation Center Research

Risk-Based Life-Cycle Management of Deteriorating Bridges, Mohamed Soliman, Omid Khandel and Julie Ann Hartell, Southern Plains Transportation Center, March 2019.
https://rosap.ntl.bts.gov/view/dot/41982
From the abstract: A proper maintenance and repair strategy for extending the service life of deteriorating bridges can be achieved through comprehensive risk-based approaches. Since flood frequency is expected to change as a result of global climate change, proper prediction of future flood hazard becomes an essential task. In addition, flood occurrence generally increases the rate of riverbed erosion, which causes the formation of scour and increases the risk of bridge failure. The scour formation highly depends on the type of bridge foundation and the river characteristics. This report presents an integrated probabilistic framework for quantifying the risk of bridge failure due to flood events considering climate change. An analytical model is integrated into a probabilistic simulation process to quantify the time-variant performance of bridge foundations under flood and flood[-]induced scour. The effect of adopted global climate scenarios on the failure risk under flood exposure is also investigated.

Regression Models

General Research

"Can Interdependency Considerations Enhance Forecasts of Bridge Infrastructure Condition? Evidence Using a Multivariate Regression Approach," Steven M. Lavrenz, Tariq Usman Saeed, Jackeline Murillo-Hoyos, Matthew Volovski and Samuel Labi, *Structure and Infrastructure Engineering*: *Maintenance, Management, Life-Cycle Design and Performance*, Vol. 16, Issue 8, pages 1177-1185, August 2020.
Citation at https://doi.org/10.1080/15732479.2019.1693606
From the abstract: In recent years, there has been an increasing trend toward viewing complex infrastructure systems in a holistic manner, to better understand their behavior. This paper extends the holism concept to facilitate comprehension of the deterioration of the three bridge components: the deck, superstructure and substructure. The hypothesis is that these bridge components deteriorate, not in isolation, but collectively as a system of systems, and therefore their deterioration exhibits substantial interdependency. To investigate these interdependencies, this paper uses National Bridge Inventory (NBI) data. The paper explores the efficacy of using a multivariate three-stage least squares (3SLS) model to describe these interdependencies and to quantify the effects of other explanatory factors on the deterioration of these components. The results of the 3SLS model are compared to traditional linear models estimated using ordinary least squares (OLS) to demonstrate the 3SLS model's ability to return more precise estimates of bridge deterioration effects. The results show that the 3SLS model statistically outperforms the OLS models by an average of 104% and 173%, based on root mean square error and mean absolute percentage error, respectively. These results support the hypothesis that bridge components exhibit system-of-systems behavior as their deterioration levels are influenced by the condition of each other. The results also suggest that such holistic nature can be captured using a simultaneous equation model.

"Regression Model Evaluation for Highway Bridge Component Deterioration Using National Bridge Inventory Data," Pan Lu, Shiling Pei and Denver Tolliver, *Journal of the Transportation Research Forum*, Vol. 55, Issue 1, pages 5-16, Spring 2016.
https://trforum.org/wp-content/uploads/2016/10/2016v55n1_01_HwyBridge.pdf
From the abstract: Accurate prediction of bridge component condition over time is critical for determining a reliable maintenance, repair and rehabilitation (MRR) strategy for highway bridges. Based on bridge inspection data, regression models are the most widely adopted tools used by researchers and state agencies to predict future bridge condition (FHWA 2007). Various regression models can produce quite different results because of the differences in modeling assumptions. The evaluation of model quality can be challenging and sometimes subjective. In this study, an external validation procedure was developed to quantitatively compare the forecasting power of different regression models for highway bridge component deterioration. Several regression models for highway bridge component rating over time were compared using the proposed procedure and a traditional apparent model evaluation method based on the goodness-of-fit to data. The results obtained by applying the two methods are compared and discussed in this paper.

Ohio

"Statistical Forecasting of Bridge Deterioration Conditions," M. Ilbeigi and M. Ebrahimi Meimand, *Journal of Performance of Constructed Facilities*, Vol. 34, Issue 1, February 2020.
Citation at https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29CF.1943-5509.0001347
From the abstract: The objective of this study is to create a forecasting model that predicts future bridge deterioration conditions based on the bridge characteristics. Historical data of more than 28,000 bridges in the state of Ohio from 1992 to 2017 were used to create an ordinal regression model to statistically examine effects of bridge characteristics on variations in bridge condition and predict future bridge conditions. The outcomes of this study indicate that bridge characteristics such as age, ADT [average daily traffic], deck area, structural material, deck material, structure system, maximum length of span and current condition of the bridge are statistically significant variables that explain variations in bridge deterioration. The results of the forecasting process show that the created ordinal regression model can statistically predict future bridge conditions precisely.

Stochastic Models

California

"Stochastic Regression Deterioration Models for Superstructure of Prestressed Concrete Bridges in California," Sahar Hasan and Emad Elwakil, *Journal of Structural Integrity and Maintenance*, Vol. 4, Issue 2, pages 97-108, 2019.
Citation at https://doi.org/10.1080/24705314.2019.1603194
From the abstract: At the beginning of 2018 about 6% of California's bridges [were] structurally deficient, and approximately 17% of California's bridges [were] estimated to cost about $12.2 billion for repairs. The subjectivity in determining the condition rating is an imprecise process and may significantly affect the maintenance process, which may vary from inspector to another. Most research works (*sic*) in prestressed concrete bridges condition rating has focused predominantly on modeling and has neglected to study the effect of non-periodical maintenance on condition rating. This study aims to identify the variables affecting superstructure deterioration and build models for predicting the superstructure condition. This paper has used National Bridge Inventory for California [s]tate in order to build models for predicting the superstructure condition of four structure types ([s]lab; [s]tringer/[multibeam] or [g]irder; T-[b]eam; and [b]ox [b]eam or [g]irder) using [r]egression technique and Monte Carlo simulation. This research shows the impact of eight significant variables on the superstructure deterioration with high coefficient of determination (R^2 = 86%). The developed models have been validated with a satisfactory result [93%] using Average Validity Percentage method. The developed models will help departments of transportation and infrastructure agencies to predict the condition rating and prioriti[ze] the maintenance process for bridges.

Pennsylvania

"Stochastic Analysis and Time-Based Modeling of Concrete Bridge Deck Deterioration," Amir Manafpour, Ilgin Guler, Aleksandra Radlinska, Farshad Rajabipour and Gordon Warn, *Journal of Bridge Engineering*, Vol. 23, Issue 9, September 2018.
Citation at https://ascelibrary.org/doi/abs/10.1061/(ASCE)BE.1943-5592.0001285
From the abstract: Adequate prediction of the concrete bridge deck deterioration rate is necessary for maintenance and rehabilitation decisions. The stochastic deterioration of bridge decks can be most accurately modeled with a time-based probabilistic approach. In this work, a semi-Markov time-based model, based on accelerated failure time (AFT) Weibull fitted-

parameters, was used to estimate the transition probabilities and sojourn times for the deterioration of concrete bridge decks. Approximately 30 years of in-service performance data for over 22,000 bridges in Pennsylvania were used in the model development. The proposed approach attempts to relate deck deterioration rates to various explanatory factors, such as structural system attributes, average daily traffic (ADT), route type and environmental conditions. The following factors were found to be statistically significant with respect to the rate of bridge deck deterioration: type of rebar protection, continuous versus simply supported spans, overall bridge deck length, number of spans, bridge location, type of overlay, and whether or not the deck was located on interstate routes. Furthermore, the effects of remediation on bridge deck deterioration and service life were also evaluated and quantified, based on in-service performance data.

University Transportation Center Research

Research in Progress: Development of Age and State Dependent Stochastic Models for Improved Bridge Deterioration Prediction, Mountain-Plains Consortium, start date: November 2017; expected completion date: July 2022.
Project description at https://www.mountain-plains.org/research/details.php?id=433
From the project description: More general stochastic models that can capture the nonhomogeneous nature of the deterioration process are needed, and so are calibration approaches that can establish proper transition probability matrices. In terms of inspection data, most of the states have been collecting some element-level bridge condition data (Rehm 2013). Although there is more than a decade of inspection data (Farrar and Newton 2014; Rehm 2013), the data have not been fully utilized. One key issue that needs to be addressed is the large variability/uncertainty in the inspection data (stemming from various sources). One contributing source is the subjectivity of the inspection process. For example, it has been reported in (Graybeal et al. 2003) that out of the assigned condition ratings for the same structure by 49 bridge inspectors from 25 state departments only 68% of them fall within ±1 interval around the mean while an interval of ±2 would be needed to capture 95% of the assigned ratings. How to incorporate the uncertainties in the inspection data in a systematic way is an important issue that needs to be addressed to establish more robust deterioration models. This aspect has not been explicitly considered. Research is needed in how to effectively leverage the inspection data to establish better deterioration models and to predict bridge conditions at the element level to guide cost-effective maintenance decision-making. Overall, there is a need to develop systematic and robust approaches that can extract useful and accurate information from the inspection data and can accommodate more general models for the deterioration process. To address the above challenges, this project aims to develop general age[-] and state[-]dependent stochastic deterioration models using inspection data for improved element-level condition deterioration prediction of bridges. Also, a Bayesian framework will be established to facilitate systematic and robust calibration of the deterioration models incorporating the inspection data and various uncertainties.

International Research

"Incorporating the Effects of Climate Change Into Bridge Deterioration Modeling: The Case of Slab-on-Girder Highway Bridge Deck Designs Across Canada," Geoffrey Guest, Jieying Zhang, Rebecca Atadero and Hamidreza Shirkhani, *Journal of Materials in Civil Engineering*, Vol. 32, Issue 7, July 2020.
Citation at https://doi.org/10.1061/(ASCE)MT.1943-5533.0003245
From the abstract: Climate change is expected to impact both the operational and structural performance of infrastructure such as buildings, roads and bridges. However, infrastructure

design guides widely rely on historical climate data, if any, for informing design requirements. The goal of this research was to explore a methodology for modeling bridge deck design against corrosion attack in a changing climate. Three deterioration stages were simulated to understand the time to deck failure. Corrosion initiation of reinforcing steel was considered by utilizing a deterministic diffusion-based model predicting the time to reinforcement corrosion initiation. Crack initiation and crack growth were also simulated using mechanistic approaches to illustrate the sensitivity of bridge deck deterioration and design service life to changes in bridge deck design and a changing climate across major cities in Canada. The findings indicate that a changing climate has the potential to significantly alter the service life of a bridge deck, but the effect is strongly dependent on the durability design of the bridge deck. It is recommended that bridge designers strive to utilize mechanistic-empirical models that incorporate high-resolution climate data as inputs for better understanding changes in deterioration as a consequence of a nonstationary climate.

"Predictive Group Maintenance Model for Networks of Bridges," Georgios M. Hadjidemetriou, Xiang Xie and Ajith K. Parlikad, *Transportation Research Record 2674*, Issue 4, pages 373-383, April 2020.
Citation at https://doi.org/10.1177/0361198120912226
From the abstract: Recent progress in the monitoring and prediction of the condition of infrastructure using sensing technologies has motivated researchers and infrastructure owners to explore the benefits of asset predictive maintenance, as an alternative to reactive maintenance. However, the application of predictive group maintenance for multi-system multi-component networks (MSMCN) has not received much attention in the literature or in practice. The paper presents an approach that prioritizes the maintenance of MSMCN of bridges, using a deterioration model of components with uncertainty, a life cycle cost model, a predictive model for the optimal time for maintenance based on the latest inspection, a group maintenance model to reduce setup cost, and a scheduling model considering budget constraints. This model has been applied to a network of 15 bridges constituted by multiple heterogeneous components, and, compared with the Structures Investment Toolkit, it showed potential for a substantial decrease in maintenance costs, thus highlighting the practical significance of the presented approach.

"A Computerized Hybrid Bayesian-Based Approach for Modelling the Deterioration of Concrete Bridge Decks," Eslam Mohammed Abdelkader, Tarek Zayed and Mohamed Marzouk, *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, Vol. 15, Issue 9, pages 1178-1199, September 2019.
Citation at https://doi.org/10.1080/15732479.2019.1619782
From the abstract: This article presents an automated defect-based tool to predict the future condition of the bridge decks by calibrating the Markovian model based on a hybrid Bayesian-optimization approach. The in-state probabilities are demonstrated in the form of posterior distributions, whereas the transition from a condition state to the next lower state is a function of the severities of five types of bridge defects. In the present study, the Bayesian belief network is employed to construct the likelihood function by modeling the dependencies between the bridge defects. The maximum entropy optimization is incorporated to compute the missing conditional probabilities. The proposed approach utilizes Markov chain Monte Carlo Metropolis-Hastings algorithm to derive the posterior distributions. Finally, a stochastic optimization model is designed to build a variable transition probability matrix for each five-year zone via genetic algorithm. An automated tool is programmed using C#.net programming language to facilitate the implementation of the developed deterioration model by the users. Results show that the proposed model outperformed some commonly utilized deterioration models as per three

performance indicators, which are root-mean squared error, mean absolute error [and] chi-squared statistic.

“Finite Element–Based Machine-Learning Approach to Detect Damage in Bridges Under Operational and Environmental Variations,” Eloi Figueiredo, Ionut Moldovan, Adam Santos, Pedro Campos and João C.W.A. Costa, *Journal of Bridge Engineering*, Vol. 24, Issue 7, July 2019.
Citation at https://doi.org/10.1061/(ASCE)BE.1943-5592.0001432
From the abstract: In the last decades, the long-term structural health monitoring of civil structures has been mainly performed using two approaches: model based and data based. The former approach tries to identify damage by relating the monitoring data to the prediction of numerical (e.g., finite-element) models of the structure. The latter approach is data driven, where measured data from a given state condition are compared to the baseline or reference condition. A challenge in both approaches is to make the distinction between the changes of the structural response caused by damage and environmental or operational variability. This issue was tackled here using a hybrid technique that integrates model- and data-based approaches into structural health monitoring. Data recorded in situ under normal conditions were combined with data obtained from finite-element simulations of more extreme environmental and operational scenarios and input into the training process of machine-learning algorithms for damage detection. The addition of simulated data enabled a sharper classification of damage by avoiding false positives induced by wide environmental and operational variability. The procedure was applied to the Z-24 Bridge, for which [one] year of continuous monitoring data were available.

“Expert Judgement Based Maintenance Decision Support Method for Structures With a Long Service-Life,” C.J.A. Ter Berg, G. Leontaris, M. van den Boomen, M.T.J. Spaan and A.R.M. Wolfert, *Structure and infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, Vol. 15, Issue 4, pages 492-503, April 2019.
Citation at https://doi.org/10.1080/15732479.2018.1558270
From the abstract: The optimal moment at which maintenance activities should be performed on structures with long service-life to guarantee the required quality of service is hard to define, due to uncertainties in their deterioration processes. Most of the developed methods and concepts use historical data to predict the deterioration process with deterministic values as a result. Some researchers recognise that probabilistic deterioration models are required for life-cycle models but in practice, however, historical data are often scarce. Moreover, the available data often only inform about a short period of time, while maintenance strategies, technologies, materials and external circumstances change over time. Therefore, the required probabilistic deterioration models cannot be retrieved and remain unproven in life-cycle modelling so far. Hence, this article introduces an expert judgement[-]based [c]ondition [o]ver [t]ime [a]ssessment method that quantifies the uncertainty regarding the period that is required for structural assets to deteriorate to a given condition. The proposed method utilises Cooke’s classical model, which makes use of knowledge and experience of experts, who are weighed according to their performance in judging uncertainty, to assess this period. A bridge-based experiment shows that the proposed method has the potential to provide a means to effectively plan maintenance.

“Assessing Transition Probability of Bridge Deterioration Using Dempster–Shafer Theory of Evidence,” Saleh Abu Dabous, *Bridge Structures: Assessment, Design and Construction*, Vol. 12, Issue 3-4, pages 97-106, 2017.
Citation at https://trid.trb.org/view/1474124
From the abstract: This paper introduces a novel method based on the theory of evidence for bridge deterioration modeling through expert judgment elicitation. The advantages of the theory

of evidence over the traditional probability theory are discussed and the process for the theory implementation is demonstrated with a case study to validate the application of Dempster–Shafer theory of evidence to estimate the transition probabilities. Based on the results, the theory of evidence is proposed as a scientific expert judgement elicitation technique in the area of bridge condition rating and deterioration modeling. Expert judgment elicitation and theory of evidence application hold potential in the field of bridge management and require further investigation and research.

"Development of Hybrid Optimisation Method for Artificial Intelligence Based Bridge Deterioration Model—Feasibility Study," Daniel Callow, Jaeho Lee, Michael Blumenstein, Hong Guan and Yew-Chaye Loo, *Automation in Construction*, Vol. 31, pages 83-91, May 2013.
Citation at https://www.sciencedirect.com/science/article/abs/pii/S0926580512002117
From the abstract: A long-term performance bridge, i.e., deterioration, model is the most crucial component [of bridge management systems] and decides level of reliability of long-term bridge needs. Recent development of an AI [artificial intelligence] based bridge deterioration model was undertaken to minimise these shortcomings. However, this model is computationally costly due to the process of [n]eural [n]etwork, generating a large data output. To improve the neural network process, optimisation is required. The hybrid optimisation method is proposed in this paper to filter out feasible condition ratings as input for long-term prediction modelling.

Highlights

- A comparison of bridge deteriorations, one with optimisation and the other without.
- The optimisation is a hybrid method of case-based reasoning and genetic algorithm.
- The outcome provided sufficient data that proved the optimisation was effective.

Commercial Products

AASHTOWare Bridge Management

AASHTOWare Bridge Management, American Association of State Highway and Transportation Officials, undated.
https://www.aashtowarebridge.com/
From the web site: AASHTOWare's efforts are headed by a [t]ask [f]orce comprised of [s]tate bridge engineering and information technology professionals. This [t]ask [f]orce manages the product and the contractor's efforts on behalf of AASHTO and the user community in order to ensure development, maintenance and support of the software meets the needs and requirements of current bridge owners in [s]tate and local agencies, governmental organizations such as the FHWA and private consultants.

The latest official release of BrM is 6.2, which was accepted by the TAG [Technical Advisory Group] and approved by the [t]ask [f]orce for release in August 2019. Agencies wishing to install and use this version should contact the contractor via email or phone call to request the software.

"Implementation of AASHTOWare Bridge Management 5.2.3 to Meet Agency Policies and Objectives for Bridge Management and Address FHWA Requirements," Joshua Johnson and Zac Boyle*, Transportation Research Circular E-C224*: *Eleventh International Bridge and Structures Management Conference*, pages 188-212, November 2017.
http://onlinepubs.trb.org/onlinepubs/circulars/ec224.pdf
This conference paper offers a high-level guide of the functionality and bridge management modules in BrM 5.2.3.

The Use of Element Level Data and Bridge Management Software in the Network Analysis of Big Bridges, Bradly C. Croop, Paul Thompson, Tess Ahlborn, Colin N. Brooks, Jay Puckett, Maxwell Fyrster, Thomas P. Murphy, Maria Lopez and David M. Banach, TPF Study TPF-5(308), October 2017.
https://www.pooledfund.org/Document/Download/7769
This is the final report of Transportation Pooled Fund Study TPF-5(308), The Use of Bridge Management Software in the Network Analysis of Big Bridges, led by Michigan DOT. *From the abstract*:

> The project goals are to investigate the inspection practices, management strategies and analysis systems currently employed for Big Bridges and to suggest modifications, improvements and recommendations for enhancement. Currently, Big Bridges are treated the same as smaller or less-complex bridges within existing bridge management programs and software packages. This simplistic approach is suboptimal for Big Bridges that are composed of various structure types that function more as a network of adjacent structures with complex interactions between various components. Several products, recommendations, documents and guidelines were developed as part of this study, including recommended additions and changes to the list of currently recognized AASHTO National Bridge Elements and Bridge Management Elements contained in the AASHTO Manual for Bridge Element Inspection; guidelines for the breakdown of Big Bridges into smaller units; a methodology for the inspection and collection of element level data; a framework for modifications to the AASHTOWare BrM software; recommended approaches for asset management, including adapting and supplementing existing tools as a part of network level decision making; a recommended migration path to location aware recording of damage instances while maintaining long-term cost analysis; and recommendations for future research.

dTIMS

dTIMS for Asset Management, Deighton Associates Limited, undated.
https://www.deighton.com/
This web site provides information about dTIMS and related modules, including Business Analytics, Operations Management and Business Intelligence.

Related Resource:

> **Colorado DOT: Integration of Multiple Asset Classes Eliminating a Siloed Asset Management Approach**, Deighton Associates Limited, undated.
> https://www.deighton.com/other-cdot
> This web page briefly describes Colorado DOT's Asset Investment Management System and how it completes a cross-asset analysis and optimization using dTIMS cross-asset optimization functionality.

NBI Optimizer

NBI Optimizer: Optimal Bridge Programming, Infrastructure Data Solutions, Inc., 2012-2016.
https://ids.consulting/solutions/nbi-optimizer/
From the web site: NBI Optimizer high-performance high-availability cloud-based [s]oftware as a Service (SaaS) application provides bridge managers with 24/7/365 access to a comprehensive NBI data repository and a rich set of analytics functions, reports, maps, charts, plans, dashboard, and documents from anywhere using a web browser. NBI Optimizer provides unique capabilities to analyze and visualize historical patterns in the physical and performance characteristics of individual bridges, groups of bridges, or the entire inventory.

"Cloud-Based Scalable Software for Optimal Long-Range, Network-Level Bridge Improvement Programming," Mahmoud Halfawy, *Transportation Research Record 2612*, Vol. 1, pages 132-140, January 2017.
Citation at https://journals.sagepub.com/doi/10.3141/2612-15
From the abstract: This paper presents a novel dynamic programming-based multiobjective optimization approach that is capable of generating global optimal network-level, long-range bridge improvement programs. The algorithm considers three objectives: the minimization of system-level risk, the maximization of system-level condition and the minimization of life-cycle costs, subject to agency-defined constraints and planning scenarios. The algorithm efficiently explores the enormous search space to find optimal project lists for each year in the planning horizon under any given scenario. Alternative planning scenarios are defined to quantify the impact of different investment levels on system-level performance metrics and to determine the investment required to achieve the desired performance and risk targets.

Related Resource:

> **"Multi-Objective Optimization for Long-Range Bridge Improvement Programming: Iowa DOT Case Study,"** Mahmoud Halfawy and Scott Neubauer, *TRB 97th Annual Meeting Compendium of Papers*, Paper #18-03551, 2018.
> Citation at https://trid.trb.org/view/1495851
> *From the abstract*: This paper presents a case study in the application of a novel multi-objective optimization approach to develop [a] 20-year improvement and replacement program for approximately 3,200 Iowa state-owned bridges. The optimization model considers three competing objectives: minimization of system-level risk, maximization of system-level condition, and minimization of costs, subject to a set of agency-defined constraints. A range of alternative actions are considered including preservation, rehabilitation, functional improvement, and replacement actions. Annual optimal project lists are generated for a set of planning scenarios. Two types of scenarios were considered: (1) budget scenarios to evaluate the impact of funding levels on systemwide condition and risk measures; and (2) performance target scenarios to evaluate budget requirements to achieve certain performance objectives in terms of system-wide condition or risk measures. The paper presents a step-by-step description of the methodology including deterioration modeling, risk analysis, definition of alternative actions and the trade-off analysis of planning scenarios.

Related Resources

Michigan

Bridge Management and Scoping, Michigan Department of Transportation, undated.
https://www.michigan.gov/mdot/0,4616,7-151-87728_87844_87847_70814---,00.html
Links to resources on this web page include the Project Scoping Manual, which addresses condition rating and measurement systems in Chapter 4, and the Bridge Capital Scheduled Maintenance Manual.

New Jersey

New Jersey Transportation Asset Management Plan, New Jersey Department of Transportation, August 2019.
https://www.state.nj.us/transportation/about/asset/pdf/NJ_2019_TAMP_FHWA.pdf
From the executive summary: The New Jersey Transportation Asset Management Plan (TAMP) is a risk-based plan for highway asset preservation. The TAMP describes the policies, procedures, data, and tools used to preserve pavement and bridge assets on the National Highway System (NHS) for various asset owners and the State Highway System (SHS) managed by New Jersey Department of Transportation (NJDOT). It establishes objectives and investment strategies to manage the condition of New Jersey's pavements and bridges. The NJDOT pavement and bridge management systems are used in the TAMP process to determine the most cost-effective allocation of resources among different types of preservation and rehabilitation approaches across the life cycle of pavement and bridge assets.

Rhode Island

The RhodeWorks Tolling Program, Rhode Island Department of Transportation, undated.
http://www.dot.ri.gov/tolling/index.php
From the web page: The RhodeWorks bridge tolling program is a unique approach to repairing bridges by tolling only specific types of tractor trailers. The tolls collected at each location in Rhode Island will go to repair the bridge or bridge group associated with that toll location.

The tolling program is part of the RhodeWorks legislation, which became law in February of 2016 as a way to rebuild Rhode Island's infrastructure. RhodeWorks provides for the planning, execution, management and funding to bring the state's roads and bridges into a state of good repair by 2025. The full budget for RhodeWorks is about $4.9 billion over ten years and about one tenth of that amount will come from the tolling program. The RhodeWorks law prohibits tolls on cars and small trucks.

Contacts

CTC contacted the individuals below to gather information for this investigation.

State Agencies

Arkansas

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Appendix A: Survey Questions

The following surveys were distributed to state departments of transportation (DOTs) expected to have experience with bridge deterioration modeling, selected state DOTs that had recently completed research on this topic, and vendors and consultants familiar with bridge deterioration models.

State Departments of Transportation Survey

The following survey was distributed to state DOT members of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Bridges and Structures.

Caltrans Survey on Bridge Deterioration Models and Rates

Note: The response to the question below determined how a respondent was directed through the survey.

(Required) Has your agency adopted a model to forecast deterioration in bridges?

Response Options:

- No (Directed the respondent to the **Agencies Without a Bridge Deterioration Model** section of the survey.)
- Yes (Directed the respondent to the **Agencies With a Bridge Deterioration Model** section of the survey.)

Agencies Without a Bridge Deterioration Model

1. What other methodologies or techniques does your agency use to assess bridge condition (such as inspection reports or engineering judgment)?
2. Is your agency considering adopting a model or other methodologies to assess bridge deterioration?
    - No
    - Yes (Please briefly describe your agency's plans.)

Note: After responding to the questions below, the respondent was directed to the **Wrap-Up** section of the survey.

Agencies With a Bridge Deterioration Model

System Description

1. What model or methodologies does your agency use to determine bridge deterioration?
2. Who developed the model?
    - We use a model developed in-house.
    - We use a commercial off-the-shelf product.
    - We use a commercial product that is customized for our agency.
    - Other (Please describe the model developer.)

2A If your agency is using a commercial product, what are the names of the model and the vendor providing it?

3. Please indicate the applications or processes that are supported by the model. (Please select all that apply.)
   - Legislative reporting
   - Life cycle cost analyses
   - Long-range budget planning
   - Material evaluation
   - Project scoping and/or planning
   - Resource demand models
   - Other (Please describe the other applications or process.)

4. Can the model be adjusted for specific variables or parameters?
   - No (Please skip to Question 5.)
   - Yes (Please answer Question 4A below)

4A. Please select all model parameters that apply.
   - Age
   - Approach surface
   - Average daily traffic (ADT)
   - Average daily truck traffic (ADTT)
   - Climatic conditions
   - Condition rating
   - Deck wearing surface
   - Design load
   - Design type
   - Highway functional class
   - Location (National Highway System, urban, waterway)
   - Maximum span length
   - Number of spans
   - Rebar coating
   - Skew angle
   - Superstructure material type
   - Use of deck overlays
   - Other (Please describe other model parameters.)

5. What bridge elements are included in the model? Please select all that apply.
   - Deck
   - Superstructure
   - Substructure
   - Other (Please describe other bridge elements.)

System Practices and Analysis

1. Does the model take into account specific bridge maintenance treatments?
   - No
   - Yes (Please describe how the model accounts for these treatments.)

2. Has your agency developed an approach for isolating the benefit for each specific bridge maintenance treatment and its impact on the deterioration rate?
   - No
   - Yes (Please describe this approach.)

3. Has your agency's modeling resulted in any changes to business processes or practices specific to asset management?
   - No
   - Yes (Please describe these changes.)

4. Please briefly describe how the 2014 requirement to collect element level bridge inspection data for National Highway System bridges has affected your agency's analysis of bridge deterioration. Include in your description any changes made to accommodate the new requirement.

5. If available, please provide links to documentation that describes your agency's policies and practices for using bridge deterioration models and rates. Send any files not available online to carol.rolland@ctcandassociates.com.

System Assessment

1. What successes has your agency experienced in connection with bridge deterioration models?
2. What challenges has your agency experienced in connection with bridge deterioration models?
3. What best practices do you recommend that other agencies consider when using bridge deterioration models?
4. Please provide links to documents associated with your agency's bridge model (other than those you have already provided). Send any files not available online to carol.rolland@ctcandassociates.com.

Wrap-Up

1. Are you involved in or aware of current or ongoing research in this area?
   - No
   - Yes

1A. What is your involvement or interest in this research related to bridge deterioration?

2. Please use this space to provide any comments or additional information about your previous responses.

Selected Group of State Departments of Transportation Survey

In addition to completing the previous survey, the selected group of state DOTs responded to the following questions about the implementation of their research.

System Implementation

1. To what degree has your agency implemented the findings from its recent research on bridge deterioration modeling (for example, partial, complete)?
2. Please describe the effectiveness of the model.
3. Are the anticipated results from the research consistent with measured outcomes?
   - Yes
   - No

3A. Please describe any enhancements, updates or other considerations that are needed to improve the model's performance.

Vendor Survey

Note: The response to the question below determined how a respondent was directed through the survey.

(Required) Does your company manufacture products to support bridge deterioration modeling by state departments of transportation (DOTs)?

- No (Directed the respondent to the **Wrap-Up** section of the survey.)
- Yes (Directed the respondent to the sections below.)

Bridge Deterioration Model Product Descriptions

The next section of the survey asks you to describe the bridge deterioration modeling products that your firm offers. The survey gives you the opportunity to describe two different products. If your firm offers more than two bridge deterioration modeling products, please describe the **two most frequently used products**.

<u>Bridge Deterioration Model Product 1</u>

Product Description

1. Please describe the product that your company offers for bridge deterioration modeling.
2. What state DOTs are using this product?
3. Please indicate the applications or processes that are supported by the product. (Please select all that apply.)
    - Legislative reporting
    - Life cycle cost analyses
    - Long-range budget planning
    - Material evaluation
    - Project scoping and/or planning
    - Resource demand models
    - Other (Please describe the other applications or process.)

4. Can the product be adjusted for specific variables or parameters?
    - No (Please skip to Question 5.)
    - Yes (Please answer Question 4A below)

4A. Please select all product parameters that apply.
- Age
- Approach surface
- Average daily traffic (ADT)
- Average daily truck traffic (ADTT)
- Climatic conditions
- Condition rating
- Deck wearing surface
- Design load
- Design type
- Highway functional class
- Location (National Highway System, urban, waterway)
- Maximum span length
- Number of spans
- Rebar coating
- Skew angle
- Superstructure material type
- Use of deck overlays
- Other (Please describe other product parameters.)

5. What bridge elements are included in the product? Please select all that apply.
    - Deck
    - Superstructure
    - Substructure
    - Other (Please describe other bridge elements.)

Product Practices and Analysis

1. Does the product take into account specific bridge maintenance treatments?
    - No
    - Yes (Please describe how the product accounts for these treatments.)
2. Does the product provide a process for isolating the benefit for each specific bridge maintenance treatment and its impact on the deterioration rate?
    - No

- Yes (Please describe this process.)

3. If available, please provide links to documentation that describes this bridge deterioration model. Send any files not available online to carol.rolland@ctcandassociates.com.
4. (Required) Does your company offer another product to support bridge deterioration modeling by state DOTs?
   - No (Directed the respondent to the **Wrap-Up** section of the survey.)
   - Yes (Directed the respondent to **Bridge Deterioration Model Product 2** questions.)

Wrap-Up

Please use this space to provide any comments or additional information about your previous responses.

Consultant Survey

Note: The response to the question below determined how a respondent was directed through the survey.

(Required) Does your organization use products and services to support bridge deterioration modeling by state departments of transportation (DOTs)?

- No (Directed the respondent to the **Wrap-Up** section of the survey.)
- Yes (Directed the respondent to the sections below.)

Bridge Deterioration Model Product Descriptions

The next section of the survey asks you to describe the bridge deterioration modeling products and services that your firm uses. The survey gives you the opportunity to describe three different products or services. If your firm has used more than three bridge deterioration modeling products or services, please describe the three most frequently used products or services.

Bridge Deterioration Modeling Product/Service 1

Product Description

1. Please provide the following information about the product or service that your organization uses:
   - Project description
   - Project owner (such as a state DOT or other transportation-related agency; please include contact information)
   - Name of product or service used in the project
   - Vendor
2. Please indicate the applications or processes that are supported by the product or service. (Please select all that apply.)
   - Legislative reporting
   - Life cycle cost analyses
   - Long-range budget planning
   - Material evaluation
   - Project scoping and/or planning
   - Resource demand models

- Other (Please describe the other applications or process.)

3. Can the product or service be adjusted for specific variables or parameters?
   - No (Please skip to Question 4.)
   - Yes (Please answer Question 3A below)

3A. Please select all product parameters that apply.

- Age
- Approach surface
- Average daily traffic (ADT)
- Average daily truck traffic (ADTT)
- Climatic conditions
- Condition rating
- Deck wearing surface
- Design load
- Design type
- Highway functional class
- Location (National Highway System, urban, waterway)
- Maximum span length
- Number of spans
- Rebar coating
- Skew angle
- Superstructure material type
- Use of deck overlays
- Other (Please describe other product parameters.)

4. What bridge elements are included in the product? Please select all that apply.
   - Deck
   - Superstructure
   - Substructure
   - Other (Please describe other bridge elements.)

Product Practices and Analysis

1. Does the product or service take into account specific bridge maintenance treatments?
   - No
   - Yes (Please describe how the product or service accounts for these treatments.)
2. Does the product provide a process for isolating the benefit for each specific bridge maintenance treatment and its impact on the deterioration rate?
   - No
   - Yes (Please describe this process.)
3. If available, please provide links to documentation that describes this bridge deterioration product or service. Send any files not available online to carol.rolland@ctcandassociates.com.
4. (Required) Does your organization use another product or service to support bridge deterioration modeling by state DOTs?
   - No (Directed the respondent to the **Wrap-Up** section of the survey.)
   - Yes (Directed the respondent to **Bridge Deterioration Modeling Product/Service 2/Bridge Deterioration Modeling Product/Service 3** questions.)

Wrap-Up

Please use this space to provide any comments or additional information about your previous responses.

DRAFT Users Manual

StruPlan: Open-source long-range renewal planning for transportation structures

Release 1.3

30 June 2020

Paul D. Thompson

Table of Contents

1. Introduction

StruPlan is an open-source long-range renewal planning spreadsheet for transportation structures. Using bridge management system data and models, it produces a network level 10-year spending plan, with forecasts of condition and performance, based on an optimized selection of preservation, rehabilitation, and reconstruction activities. Parameters governing costs, deterioration, and treatment selection can be fine-tuned to fit the needs of each agency and program. All substantive calculations and results are readily visible on Excel worksheets, where they can be examined, tested, and modified. StruPlan is intended to be:

- A flexible and responsive tool to support transportation agency decision making;
- A learning tool for students, analysts, and developers who are new to life cycle cost analysis and bridge management systems; and
- A research tool for testing of new models and planning methods.

StruPlan can augment an agency's existing bridge management system by providing the transparency, analysis speed, and flexibility necessary for network-level decision support. It is meant to assist in the following business processes:

- Transportation Asset Management Plan (TAMP) development, to define state of good repair, 10-year performance targets, and 10-year spending plans;
- TAMP implementation, supporting tracking and adjustment of targets and spending plans proactively;
- Long-range needs analysis, and development of levels of service consistent with available resources, under scenarios and policies that minimize long-term cost;
- Capital budgeting and programming in cross-asset decision making processes, using priority-setting methods based on long-term social cost minimization;
- Development of preservation policies that minimize long-term costs, and application of those policies to specific structures.

StruPlan does not replace a bridge management system (BMS), but adds new capabilities that current BMS either do not have, or that are prohibitively difficult, time-consuming, or inflexible in today's systems. It adds value to BMS.

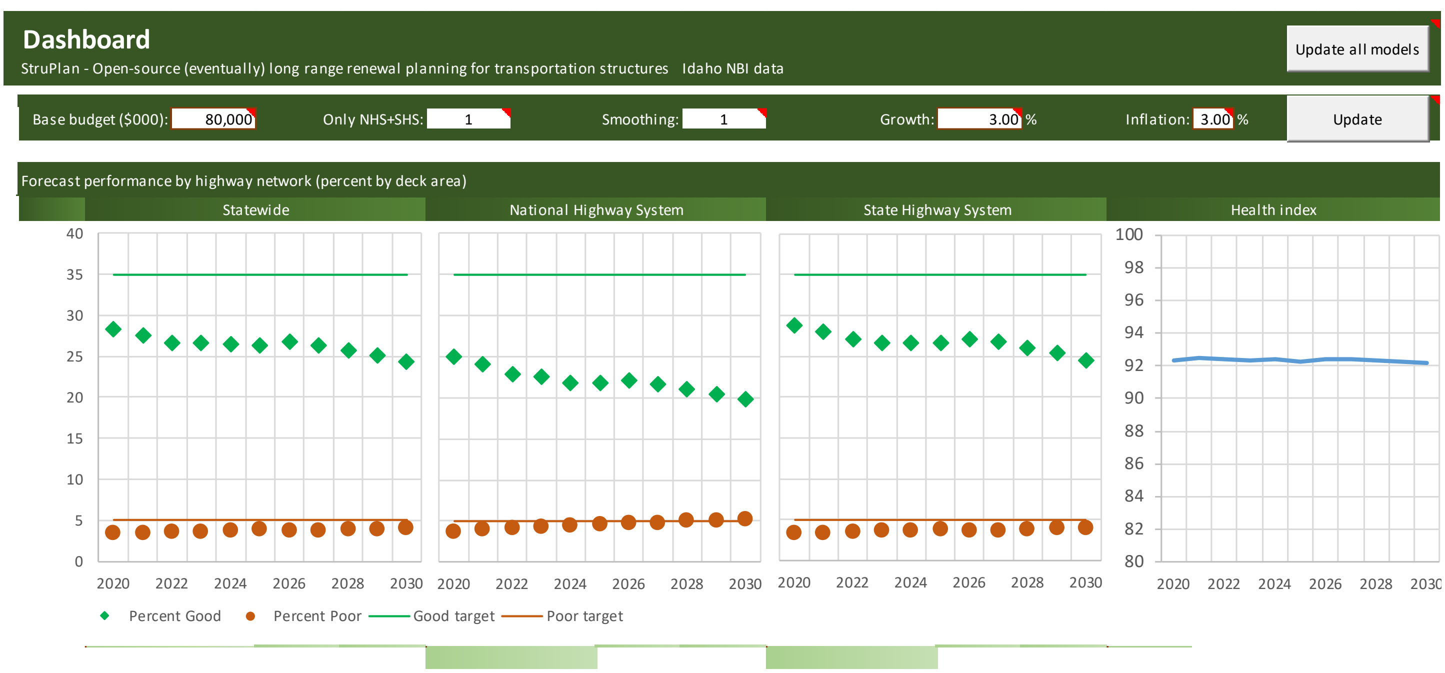

Figure 1. Dashboard display of medium-term condition forecasts

1.1 Overview of capabilities

Data can be loaded into StruPlan using copy/paste, or imported from a source spreadsheet. The source file can be exported from a database or downloaded from the Federal Highway Administration (FHWA) web site at **https://www.fhwa.dot.gov/bridge/nbi/ascii2018.cfm#del**. The model can work with any type of infrastructure that is inspected using an element and condition state system, in the same form as the AASHTO Manual for Bridge Element Inspection (AASHTO 2019). Models are provided from published sources for bridge deterioration, life cycle cost, functional needs, scour risk, social cost, and federal Transportation Performance Management (TPM) measures. The quantitative parameters for these models are from published sources, and can be updated using data commonly found in BMS. Any aspect of the model can be enhanced using alternative sources or new research over time.

Through its analytical process, StruPlan produces the following basic outputs:

- Identification of the treatment on a given structure in a given year, that minimizes long-term cost, selected from four general approaches: do-nothing, preservation, rehabilitation, or reconstruction;
- Programmatic estimate of the initial cost of the treatment, including direct and indirect costs;
- Forecast condition with and without the treatment, in the form of health index and the federal TPM measures %Good and %Poor by deck area;
- Improvement in safety and/or mobility as a result of functional improvement and risk mitigation;
- Savings in social costs related to detours, crashes, and pollutant emissions;
- Total long-term agency and social cost savings for prioritization;
- Network summary of conditions, performance, and expenditures consistent with the optimized strategy under funding constraints.

All infrastructure management system models attempt to strike a balance among several important considerations, including transparency, execution time, cost, level of detail, realism, data requirements, performance metrics, and flexibility. StruPlan is designed to focus on speed, transparency, and flexibility. The level of detail and data requirements are kept minimal, consistent with the needs of a network level model. This is complementary to the more detailed models often found in bridge management systems. The functionality of StruPlan is confined to a few basic models that are most important at the network level:

- Data preparation
  - Importing of bridge and element data
  - Data clean-up, de-metrication, generic model selection to get started
- Modeling of planning metrics
  - Generation of element families (protective elements and their parents)
  - Long-term cost analysis and treatment selection
  - Forecasting of %Good and %Poor from element/state forecasts
  - Functional needs (safety, mobility, sustainability, risk)
- Support for planning decisions
  - Generation of annual work candidates
  - Prioritization within funding constraints
  - Forecasting of outcomes and spending plans

1.2 Element families

Bridge element inspection data include protective elements, such as wearing surfaces and coatings, and an association with a substrate element that is protected. StruPlan ties these elements together for long-term cost analysis, so the condition of protective elements contributes to long-term benefits and affects the choice of treatment. In addition, StruPlan models the potential effect of expansion joint seal condition on deterioration rates of other bridge elements.

Elements are combined into a smaller number of groups that share the same deterioration model, the same potential protective elements, and the same treatment characteristics. Each element group has a set of models:

- A long-term deterioration model in the form of a Markov model, the most common type of deterioration model in bridge management systems (Mirzaei et al 2014);
- A medium-term (10-year) deterioration model that is a hybrid of Weibull and Markov models, to make it age-sensitive (Sobanjo and Thompson 2011);
- Protection factors that govern the effect of protective elements on the associated substrate elements;
- Long-term and medium-term unit cost models, expressed in a generic form that allows combining of dissimilar measurement units;
- Medium-term model of indirect (fixed) costs that are not dependent on bridge conditions;
- A model of treatment effectiveness.

If the imported data have bridges divided into structure units or spans, StruPlan performs its medium-term analysis also at this level of detail.

1.3 Long-term cost analysis

The long-term cost analysis in StruPlan simulates each element group and environment under a variety of scenarios of protective system effectiveness and initial treatment alternative. It is a network-level model that simulates an entire population of bridge elements and produces results in the form of unit long-term costs. Later in the medium-term model, the unit long-term costs are scaled to the size of each bridge and combined according to the forecast condition of the element and its protective elements.

Annual conditions and costs in the long-term are forecast year-by-year over 75 years using a Markov Chain. Sensitivity analysis research with these models has shown that conditions converge to a steady state within 75 years under any realistic set of deterioration and cost parameters. After 75 years, the remaining long-term costs are estimated using a perpetuity model. All costs are discounted to present value using an agency-specified discount rate.

The results of all scenarios of element group, protection effectiveness, and treatment are gathered in a single table of network unit long-term cost factors, which is the main product of the StruPlan long-term model. A sensitivity analysis worksheet helps the analyst to visualize the effect of bridge age on the selection of treatment.

1.4 Forecasting of %Good and %Poor

Federal TPM measures are relatively new (FHWA 2017), and do not yet have proven forecasting models. Since reliable deterioration models are based on element level data, it is desirable to have a model that builds on element forecasting to predict the federal measures. Element condition state data are exponentially distributed, but TPM data are categorical at the bridge level (Good, Fair, or Poor). One modeling approach that is compatible with these forms of data and has worked well in research so far, is a Weibull survival model. This model relates the fraction in condition state 1 to the probability of being in Good condition; and likewise links states 3 and 4 to Poor condition.

StruPlan includes worksheet formulas and a VBA module to use maximum likelihood estimation, built on Excel's Solver tool, to develop best-fit parameters of these Weibull models. The procedure is simple but gives useful forecasts. It should be regarded as experimental so far, until more agencies have experience with it.

1.5 Functional needs and risk

Departments of Transportation in Florida (Thompson et al 1999, Sobanjo and Thompson 2004 and 2013), North Carolina (O'Connor and Hyman 1989), and Georgia (Garrow and Sturm 2013) have done a significant amount of research on bridge functional deficiencies and risk. The models are simple but very useful because they rely on data that are readily available in BMS.

To analyze the effects of clearance and load restrictions, the models estimate the fraction of truck traffic exceeding any given level of height or weight. To analyze the effects of substandard width or approach alignment, the models estimate the relative increase in crashes. For scour, the models estimate the probability of bridge failure. All of these were derived by researchers through field data collection and historical research. The AASHTO Red Book (AASHTO 2010) provides economic parameters to estimate the user cost savings if deficiencies are corrected, considering costs of accidents, travel time, and vehicle operations. Public health costs related to excess pollutant emissions (not including carbon dioxide) are also estimated (Thompson et al 2016).

1.6 Generation of annual work candidates

Analysis at the most detailed level is conducted at the level of structure units and element groups, or SuGrs for short. Each treatment alternative is evaluated for initial cost and long-term cost, in each year of the 10-year period. The calculation uses the results of the network level unit long-term cost model, selecting the treatment with least long-term cost. These results are summed to the bridge level, and there are combined with the results for functional needs and risk. Configurable treatment selection logic in some cases upgrades the work candidate to rehabilitation or replacement based on the type of work needed and its cost.

The final bridge-level treatment decision is returned to the SuGr-level model to make a final forecast of condition outcomes at the end of the 10-year period. At the bridge level, a final determination is made of initial cost, benefit, and outcomes. These are saved for each possible implementation year.

1.7 Prioritization within funding constraints

In the priority-setting model, work candidates compete for a limited budget, which is usually much smaller than the total cost of the candidates. Priority is determined using an incremental benefit/cost ranking, where the benefit of programming a given project in a given year is the avoided long-term cost that would otherwise be incurred if the work had to be delayed until the following year. Bridges which are not selected will deteriorate, increasing the long-term agency cost, and will also continue to incur excess user costs, if any.

Each bridge is selected just once during the ten-year period for a capital project. Routine maintenance activities, usually not programmed on a multi-year basis, are included in the long-term cost calculation and not identified individually.

Agencies can use the model to investigate budgetary scenarios, taking into account inflation and real growth, if any.

1.8 Forecasting of outcomes and spending plans

After application of a budget constraint and prioritizing, StruPlan summarizes the resulting condition and performance outcomes, and the necessary expenditures to achieve those outcomes. Outcomes are reported in terms of the federal TPM measures (%Good and %Poor) and health index. Expenditures are forecast for preservation, rehabilitation, and reconstruction. To support the structure that is common in Transportation Asset Management Plans, separate forecasts and expenditures are provided for the National Highway System and the State Highway System.

National-scale bridge element deterioration model for the USA

P.D. Thompson
Consultant

ABSTRACT: The Federal Highway Administration of the United States uses its National Bridge Investment Analysis System (NBIAS) to develop needs estimates and report on the conditions and performance of the nation's 600,000 bridges and culverts. The system's deterioration model was recently updated to be consistent with the most recent bridge element inspection standards. A data set containing nearly 3 million element inspection records was stratified into nine climate zones according to average temperatures and moisture in each county of the United States. Algebraic methods developed in research for Florida and Virginia were used to process the element inspection data into transition probability matrices. The resulting models were then transformed for compatibility with the latest inspection manuals used in federal bridge condition reporting requirements. The product represents the first time there has been a true nationwide element level deterioration model for bridges in the United States.

1 INRODUCTION

The US Federal Highway Administration uses its National Bridge Investment Analysis System (NBIAS) to develop needs estimates and contribute data to a periodic report on the conditions and performance of the nation's highway and transit infrastructure, including more than 600,000 bridges and culverts (FHWA 2016). NBIAS performs a network-level life cycle cost analysis representing future deterioration and costs at the element level, to estimate the amount of investment in bridge preservation activities that is likely to keep long-term costs to a minimum.

Since the 1970s, states have been required to gather a standardized data set of bridge inventory and biennial inspection data, for submittal to FHWA each April. These are compiled into a National Bridge Inventory (NBI) (FHWA 1995) which provides the source data for the Conditions and Performance Report. Until recently, the NBI had only four data items describing bridge condition:

58 – Deck condition rating
59 – Superstructure condition rating
60 – Substructure condition rating
62 – Culvert condition rating

These four items represent separate parts of a structure, with a focus on the primary load-bearing components. Since the NBI Coding Guide is focused on safety rather than on maintenance needs, certain components having significant maintenance costs (such as expansion joints and paint) receive little or no consideration when assigning a condition rating. Each item is recorded using a coding scheme where 9 is excellent condition and 0 is failed and beyond corrective action. When any of the NBI condition ratings is 4 or below, the bridge is considered "structurally deficient".

Although the FHWA Coding Guide is still mandatory, bridge owners have found that the four condition ratings are insufficient for asset management purposes. They do not provide enough information on the cause of deterioration, to forecast future condition or select appropriate maintenance actions, and they do not provide enough information on the extent of deterioration for cost estimation.

As a result, nearly all bridge management systems worldwide use a more extensive condition description organized according to elements and condition states (Mirzaei et al 2014). In the United States, most of these systems have, until recently, been based on the AASHTO Commonly-Recognized (CoRe) Element Guide (AASHTO 1998). The guide defines 106 common structural elements and provides objective visual language for recognizing 3-5 condition states for each element. Inspectors record the quantity or percentage of each element found to be in each condition state.

Previous versions of NBIAS used 72 of the 106 elements, focusing on the ones believed by FHWA to have some relationship to the criteria used in assessing the four NBI condition ratings. Since the collection of element-level data was optional at the time of NBIAS development, and because there was no process for states to submit such data to FHWA, it was necessary to develop a model to synthesize element data from NBI data. Only the 72 elements were capable of being imputed in this way.

One of the criticisms of the AASHTO CoRe Elements was the lack of detail on bridge decks, and the fact that deterioration processes were often commingled. It was difficult, for example, to separate deterioration of paint systems from deterioration of the underlying steel, or cracking from corrosion. As a result, the AASHTO manual moved toward a standard that makes a separate assessment of each major deterioration process, in order to provide the clearest and most relevant possible distinctions among condition states. This practice was formalized in the 2013 AASHTO Manual for Bridge Element Inspection (AASHTO 2013). Federal rules now mandate the collection and reporting of a subset of the elements defined in the new manual. Designated "NBI Elements," these are shown in Table 1 (FHWA 2014).

In order to prepare the next edition of the Conditions and Performance Report, FHWA wanted to base its analysis on the new catalog of 100 NBI Elements as submitted by the states. To do this, it would be necessary to develop a new bridge element deterioration model compatible with the new data set.

2 SOURCES OF DATA

A major challenge in this effort was the fact that the definitions of NBI elements and condition states was new, so very few studies had yet been undertaken to develop compatible deterioration models. At the time the work was done, only the Florida Department of Transportation had yet completed such models (Sobanjo and Thompson 2016). However, many of the states had long histories, some going as far back as 1995, of bridge inspection using the older CoRe Element manual, and some had developed deterioration models using the older format. These provided some potential sources of data.

2.1 *Model used in earlier NBIAS versions*

A 50-state survey conducted in 2005 identified 15 state Departments of Transportation that had developed bridge element deterioration models and were willing to share them for FHWA use. Most of these models were based on expert judgment, although some of the agencies had used the linear regression procedure within AASHTO's Pontis software to update their judgment-based models to incorporate bridge inspection data.

Table 1. National Bridge Inventory (NBI) Elements

12	Reinforced Conc (R/C) Deck	207	Steel Tower
13	Prestressed (PS) Conc. Deck	208	Timber Trestle
15	PS Concrete Top Flange	210	R/C Pier Wall
16	R/C Top Flange	211	Other Pier Wall
28	Steel Deck - Open Grid	212	Timber Pier Wall
29	Steel Deck - Filled Grid	213	Masonry Pier Wall
30	Steel Deck - Orthotropic	215	R/C Abutment
31	Timber Deck	216	Timber Abutment
38	R/C Slab	217	Masonry Abutment
54	Timber Slab	218	Other Abutments
60	Other Deck	219	Steel Abutment
65	Other Slab	220	R/C Sub Pile Cap
102	Steel Box Girder	225	Steel Pile
104	PS Box Girder	226	PS Concrete Pile
105	R/C Box Girder	227	R/C Pile
106	Other Box Girder	228	Timber Pile
107	Steel Open Girder/Beam	229	Other Pile
109	PS Open Girder/Beam	231	Steel Pier Cap
110	R/C Open Girder/Beam	233	PS Concrete Cap
111	Timber Open Girder	234	R/C Pier Cap
112	Other Girder/Beam	235	Timber Pier Cap
113	Steel Stringer	236	Other Pier Cap
115	PS Concrete Stringer	240	Steel Culvert
116	R/C Stringer	241	R/C Culvert
117	Timber Stringer	242	Timber Culvert
118	Other Stringer	243	Other Culvert
120	Steel Truss	244	Masonry Culvert
135	Timber Truss	245	PS Concrete Culvert
136	Other Truss	300	Strip seal joint
141	Steel Arch	301	Pourable joint
142	Other Arch	302	Compression joint
143	PS Concrete Arch	303	Assy. joint w/ seal
144	R/C Arch	304	Open joint
145	Masonry Arch	305	Assy. joint no seal
146	Timber Arch	306	Other joint
147	Steel Main Cables	310	Elastomeric Bearing
148	Sec Steel Cables	311	Moveable Bearing
149	Other Secondary Cable	312	Enclosed Bearing
152	Steel Floor Beam	313	Fixed Bearing
154	PS Floor Beam	314	Pot Bearing
155	R/C Floor Beam	315	Disk Bearing
156	Timber Floor Beam	316	Other Bearing
157	Other Floor Beam	330	Metal Railing
161	Steel Pin & Hanger	331	R/C Railing
162	Steel Gusset Plate	332	Timber Railing
202	Steel Column	333	Other Railing
203	Other Column	334	Masonry railing
204	PS Concrete Column	510	Wearing surfaces
205	R/C Column	515	Steel coating
206	Timber Column	521	Concrete coating

Each of the 15 states had up to four separate deterioration models representing categories of environmental and operating conditions within their states, in most cases reflecting the use of deicing chemicals and the presence of marine environments. The NBIAS models were organized into nine climate zones, based on rainfall and freeze-thaw experience, using conventions established in the Highway Performance Monitoring System. Each of the more than 3000 counties in the USA is classified into one climate zone. So the researcher developed a correspondence, based on judgment, between geographic states and environments on one hand, and NBIAS climate zones on the other hand.

In this way, a deterioration model was selected for each element and climate zone to populate the NBIAS models starting in 2007. These models have been unchanged in NBIAS since then.

2.2 *Florida and Virginia research*

In 2010 to 2012, the Departments of Transportation of Florida and Virginia developed bridge element deterioration models using large databases of CoRe Element inspections over 12 years or more. The methodology, summarized later in this paper, was developed initially for Florida DOT (Thompson and Sobanjo 2010). These states addressed only three of the nine climate zones, and only the Florida model, at the time, had been migrated to fit the 2013 AASHTO elements. Nonetheless, the earlier studies provided some important lessons:

- There can be important differences between agencies in how the condition state language of the CoRe elements is interpreted. It was found, for example, that Virginia inspectors were reluctant to use the worst defined condition state of each element because they understood this to imply a requirement for a structural analysis. The Florida inspectors did not share that view and were more willing to use all of the defined condition states.
- The Florida research compared the models based on inspection history against earlier models based only on expert judgment. They found that expert judgment was not very accurate, that transition times were under-estimated by a factor of about 2 (Thompson and Sobanjo 2010).

For the current effort, these lessons implied that it would be desirable to base each model on more than one agency's data, and actual inspection history should be relied upon as much as possible, in preference to expert judgment.

2.3 *Collected Pontis data*

Between 2008 and 2015, the FHWA Long-Term Bridge Performance Program (LTBP) gathered Pontis data sets from 23 state DOTs, to help the program with its deterioration research. While the LTBP had not developed a national deterioration model of its own, it was willing to share its data set with the NBIAS project for that purpose. On further analysis it was found that 15 of the data sets could be made compatible with the present study, so a combined database was created from these 15 agencies. The new database contained 66,025 bridge records, 492,661 inspection events, and 2,868,505 element inspection records.

Although this database was apparently of sufficient size for useful analysis, it did not provide uniform coverage of all of the climate zones across the country. In the end, it was necessary to incorporate the earlier Florida and Virginia research, in order to avoid bias against the climate characteristics of the southeast United States. Certain results from the earlier NBIAS models were also used in order to provide reasonable variation in the effect of temperature on deterioration rates, as part of the climate zone model. Figure 1 shows the national coverage of the 50 states from the combination of all three data sources.

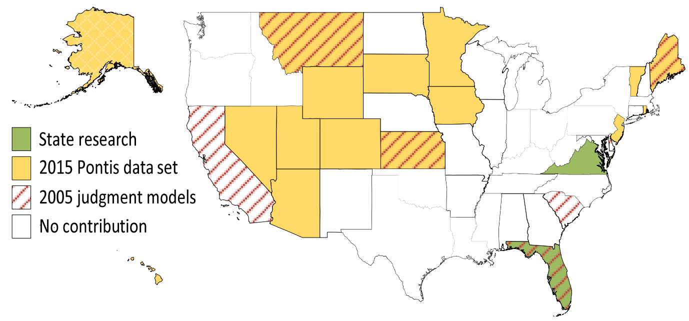

Figure 1. Sources of data

3 MODEL DEVELOPMENT PROCESS

A multi-step process, described in the following sections and summarized in Figure 2, was used to reduce and process the data set, to estimate transition times, to expand the result to nine climate zones, and to make the results compatible with the 2013 AASHTO Manual for Bridge Element Inspection.

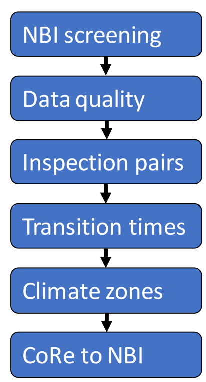

Figure 2. Model development process

3.1 *NBI screening*

The state DOTs have often used their Pontis databases for more than just federally-recognized bridges. As just one example, a recent examination of Florida's database found 36,889 structures, of which fewer than 9,000 are bridges that appear in the National Bridge Inventory. The rest are drainage culverts, sign structures, high-mast light poles, and traffic signal mast arms. For the purpose of the NBIAS analysis, it was necessary to remove certain objects:

- All bridges and culverts less than 20 feet in clear span length along the roadway centerline, and all other structures that do not qualify for the National Bridge Inventory.
- All agency-defined and customized elements.
- Approach slabs, slope protection elements, and any other elements not found in the list of 100 NBI Bridge Elements (FHWA 2014).
- All bridge deck elements that used the temporary 2001 interim revisions to the AASHTO CoRe Elements.

These redactions ensured that the deterioration models would faithfully represent the structures that are addressed in the NBIAS analysis.

3.2 *Data quality checking*

Analysis of the data set found that agencies varied considerably in their ability to maintain uniform quality control on element data. In particular, the first element inspection cycle attempted by each agency, usually in the mid-1990s, was often treated as a practice run for inspectors in training and for field manuals under development, and was not considered reliable by many of the agencies. The first inspection on each bridge was therefore deleted from the data set.

In addition, the first and last years of inspections often covered only a part of the inventory: the first year usually covered one or more pilot districts within the state, and the final year was typically still underway and partially complete at the time the database was obtained from the agency. Since these partial cycles were not likely to be random samples of the inventory, they were deleted.

For element inspections remaining, a variety of quality assurance tests were performed, which resulted in additional deletions. For example, it was required that the quantities of each element inspection in each condition state sum, over all condition states, to the total quantity indicated for the element.

3.3 *Creation of inspection pairs*

A Structured Query Language (SQL) command was used to process all of the remaining element inspections to create a table of inspection pairs. Each inspection pair consisted of two element inspections spaced 2 years apart (plus or minus 6 months). To form a pair, two inspections must match in their element number, environment code, and quantity.

At this stage it is desirable to omit any inspection pairs that have experienced preservation or replacement activity modeled by NBIAS, since the purpose of the analysis is to quantify pure uninterrupted deterioration. Unfortunately, the 15 agencies differed dramatically in their ability to collect work accomplishment data, and few had significant data sets to offer. As a result, the table of inspection pairs was reduced by omitting any bridge inspections where any elements showed an improvement in condition. This is a very imperfect solution, for at least three reasons:

- Preservation actions may have been applied, that did not change the condition state of any of the elements but may have postponed further deterioration of the bridge.
- Even if preservation occurred on some of the elements, the untreated elements should still be useful for deterioration modeling. For example, agencies often perform bridge deck work that does not affect the superstructure or substructure.
- Sometimes conditions appear to improve due to random error, or difference of opinion among inspectors. Filtering out only one direction of random error introduces a statistical bias.

These considerations are likely to affect the accuracy of the resulting models, but no research has been done to quantify the magnitude or direction of the bias. This would be a valuable topic for future research, and is also a factor arguing in favor of improved agency databases and procedures, including contractual requirements, for recording work accomplishments at a sufficient level of detail to identify at least the bridge and elements that were treated.

After creation of inspection pairs, the populations of individual element types in each climate zone were evaluated. It was found that many of the elements were not sufficiently common to produce the 500 inspection pairs that earlier research had found were necessary for a stable model (Thompson and Sobanjo 2010). For each model, it was also necessary to set aside a random sample for validation purposes, further increasing the population requirement. As a result, elements were clustered in order to increase the model populations. This clustering was done by judgment, grouping each uncommon element with a more common element believed to experience the same deterioration rates. This resulted in 30 element groups.

3.4 *Estimation of transition times*

The estimation procedure uses the data set of inspection pairs and the one-step algebraic procedure described in Thompson and Sobanjo (2010).

To set up the estimation of a one-step matrix, the prediction equation is defined as follows:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} & 0 & 0 \\ & p_{22} & p_{23} & 0 \\ & & p_{33} & p_{34} \\ & & & p_{44} \end{bmatrix}^2 \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{1}$$

The element inspection vectors [Y] and [X] are spaced two years apart, but the transition probability matrix [P] is expressed for a one-year transition. Hence, it is applied twice. Writing out the individual equations necessary to calculate [Y] results in:

$$y_1 = x_1 p_{11} p_{11} \tag{2}$$

$$y_2 = x_1 p_{11} p_{12} + x_1 p_{12} p_{22} + x_2 p_{22} p_{22}$$

$$y_3 = x_1 p_{12} p_{23} + x_2 p_{22} p_{23} + x_2 p_{23} p_{33} + x_3 p_{33} p_{33}$$

$$y_4 = x_2 p_{23} p_{34} + x_3 p_{33} p_{34} + x_3 p_{34} p_{44} + x_4 p_{44} p_{44}$$

Since the sum of each row in [*P*] must be 1.0, the following additional equations apply:

$$p_{12} = 1 - p_{11}; \quad p_{23} = 1 - p_{22}; \quad p_{34} = 1 - p_{33} \tag{3}$$

The vectors [*X*] and [*Y*] can be computed from the database of inspection pairs to describe the combined condition of the element before and after. So these quantities are known. Thus the system of seven equations and seven unknowns can be solved algebraically for the elements of [*P*]. First find p_{11} from equation 2, then find p_{12} from equation 3, then p_{22} and p_{23}, and so on in a simple sequence.

A complication arises because the equations are second-order polynomials in p_{ii}, so it is necessary to use the quadratic equation to find the roots. For example, the equation for p_{33} is:

$$p_{33} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{4}$$

$$a = x_3; \quad b = x_2 p_{23}; \quad c = x_1 p_{12} p_{23} + x_2 p_{22} p_{23} - y_3$$

The same pattern of equations and solution methods apply to elements having 3 or 5 condition states as well. Each same-state transition probability p_{ii} is constrained to be in the range from 0 to 1 exclusive. Even though the quadratic equation finds two roots, in practice only one root was in the necessary range. The final transition time is computed from:

$$t = \frac{\log(0.5)}{\log(p_{jj})} \tag{5}$$

The model estimation and evaluation process was automated using Microsoft Excel.

3.5 *Climate zone factors*

NBIAS classifies the more than 3000 counties of the USA into nine climate zones according to moisture and temperature, using the same definitions as the Highway Performance Monitoring System (FHWA 2014) and the existing NBIAS data set. Even though the estimation data set was very large, the analysis found that population sizes were insufficient for the climate zones in the southeastern USA.

Another finding on detailed analysis of the results was that, even though each climate zone was internally consistent, the differences in models from one zone to another, for certain individual element groups, were not always consistent or intuitive. Even though the inconsistencies were statistically significant and based on factual data, the potential use of the model for resource allocation meant that a higher level of consistency was required.

As a result, it was decided to develop two separate but intersecting models: a model giving typical transition times for each element group across all zones, and a separate model for climate zone adjustment factors based on each bridge's location. This had the effect of smoothing the model so that it was always intuitive and consistent, and had the added benefit of boosting the element group populations.

In the end, the element group model was developed entirely from the 15-state data set, supplemented by the Florida and Virginia data. The climate zone factors were also developed from the large data set (not including the Florida and Virginia models), but supplemented by the climate zone factors used in the original NBIAS models. Table 2 shows the final climate zone factors.

Table 2. Climate zone factors

Zone	Moisture	Temperature	Factor
1	Wet	Freeze	0.64
2	Wet	Thaw	0.58
3	Wet	Warm	0.92
4	Damp	Freeze	0.84
5	Damp	Thaw	0.75
6	Damp	Warm	1.20
7	Dry	Freeze	0.94
8	Dry	Thaw	0.84
9	Dry	Warm	1.34

3.6 *Migration of element definitions*

The models developed to this point are all based on AASHTO CoRe elements, using the older element definitions that have 3 to 5 condition states defined for each element. A final step is necessary, therefore, to convert the results to be compatible with the NBI element definitions.

This transformation was accomplished using a migration probability matrix, a probabilistic mapping of each new element condition state to one or more of the old condition states. This mapping was prepared in Florida research using expert judgment, informed by the differences in element condition state language between the old manual and the new one (Sobanjo and Thompson 2016).

In many cases, such as railings, the new manual had exactly the same definitions as the old one, so no change was necessary. Changes were minimal for most concrete elements, because the only change in condition state language was the exposure of reinforcing steel in condition state 2. Other elements had more significant differences. Steel elements, for example, were divided into a substrate element and a coating element. Deck elements also had major changes. The full migration probability matrix and the rationale for each allocation of condition states can be found in Sobanjo and Thompson (2016).

4 FINAL MODEL

Table 3 shows the final model of element group transition times developed in the study. To determine the transition times for a specific element on a given bridge, first determine the corresponding element group for that element, and the specific climate zone for the county in which the bridge is located. The element group determines the transition times to be extracted from Table 3. This is then multiplied by the climate zone factor from Table 2 to yield a final transition time estimate for each condition state.

NBIAS uses these transition times to generate a Markov transition probability matrix as a part of its life cycle cost analysis. The rightmost column in Table 3 shows the median number of years from state 1 to state 4 resulting from the Markov chain calculation.

Table 3. Final element group transition times (years)

Element group	State 1 to State 2	State 2 to State 3	State 3 to State 4	State 1 to State 4
A1 Concrete deck	12	24	24	79
A2 Concrete slab	9	30	17	72
A4 Steel deck	14	8	9	41
A5 Timber deck/slab	10	10	21	53
B1 Strip Seal expansion joint	28	10	10	59
B2 Pourable joint seal	12	6	6	32
B3 Compression joint seal	13	10	10	42
B4 Assembly joint/seal	24	15	15	70
B5 Open expansion joint	22	16	16	70
C1 Uncoated metal rail	18	27	56	127
C2 Coated metal rail	32	22	20	96
C3 Reinforced concrete railing	44	36	28	140
C4 Timber railing	31	9	9	62
C5 Other railing	36	13	13	77
D1 Unpainted steel super/substructure	23	40	40	132
D2 Painted steel superstructure	23	35	12	90
D6 Prestressed concrete superstr	68	40	15	152
D7 Reinforced concrete superstructure	24	40	24	113
D8 Timber superstructure	41	24	13	100
E1 Elastomeric bearings	94	18	18	152
E2 Metal bearings	28	34	34	123
F1 Painted steel substructure	19	30	11	77
F3 Concrete column/pile	38	34	36	140
F5 Concrete abutment	50	57	30	176
F6 Concrete cap	70	73	34	225
F8 Timber substructure	18	31	16	85
G1 Reinforced concrete culverts	37	42	53	170
G2 Metal and other culverts	12	18	31	78
P1 Deck wearing surface	11	32	19	79
P2 Protective coating	17	12	9	50

Median number of years to make the indicated transition

5 CONCLUSIONS

By drawing on the research and data sets of 19 state DOTs, the study was able to produce a nation-wide bridge element deterioration model for the National Bridge Investment Analysis System. Based on historical inspection data, the model avoids some of the problems that have been noted with earlier judgment-based models, particularly under-estimation of transition times noted in Sobanjo and Thompson (2013).

In addition to its use in NBIAS, the model is potentially useful to agencies that are getting started with bridge management and have not yet developed their own models. It may also be useful to researchers who need a national-scale model for life cycle cost analysis or investment analysis, but might not have the resources to develop one of their own.

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