Bridge Model Validation at Indiana DOT

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ABSTRACT

The Indiana Department of Transportation (INDOT) 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 US as well diminished confidence in the BMS results precipitated INDOT management to re-evaluate some facets of the BMS, such as the deterioration models, to ensure that the results are still dependable. In 2016, INDOT 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 polices, 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 INDOT, and then 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 INDOT used in a manner that can be adopted by other agencies who wish to validate their own deterioration models.

Keywords: Bridge management, bridge deterioration models, model development, model validation, asset management.

INTRODUCTION

The Indiana Department of Transportation (INDOT) has had a bridge management system (BMS) since 1982. This system has undergone several enhancements over the years, with the most recent major one in 2008 and it is still in use today.

Recent changes to the bridge inspection standards in the US as well diminished confidence in the BMS results precipitated INDOT management to re-evaluate some facets of the BMS, such as the deterioration models, to ensure that the results are still dependable.

In 2016, INDOT began two separate but complimentary projects: the first was to commission a research project to develop new deterioration models for several main bridge components, and the second was to develop the next generation of the BMS, which included new treatments and new deterioration models.

A critical aspect for a BMS is having a high degree of confidence and reliability in the generated results. In order to achieve this, the results must be validated against real world outcomes. The BMS results are generated by predicting bridge condition into the future, along with defining the agency's business practices regarding treatment interventions. To have confidence in the results, one must have confidence in the prediction models. This paper discusses a subsequent project undertaken by the author's firm for INDOT to validate the current bridge models used by the BMS.

PROBLEM STATEMENT

In 2016, INDOT received the results of a research project undertaken by Purdue University to develop deterioration models for the State's bridges for the deck, superstructure, and substructure components. In 2016, INDOT contracted Deighton Associates Limited to develop their next generation BMS. One aspect of this project was to use INDOT's BMS to validate the predictive accuracy of the models and quantify any deviation of actual measurements of condition from the predicted baseline. This validation, along with establishing a *procedure* that can be used by INDOT to validate deterioration models into the future as required, were the two primary objectives of this project.

DETERIORATION MODEL DEVELOPMENT

In 2015/2016, INDOT, in cooperation with Federal Highway Administration and the US Department of Transportation, commissioned Purdue University to conduct a Joint Transportation Research Program to develop new bridge deterioration models in support of INDOT's Bridge Management System.

Deterioration models establish the current and future deterioration patterns of bridge elements over time. A bridge management system that is equipped with reliable deterioration models can assist bridge engineers with the tasks associated with long-term programming, planning, and needs assessment at both the project and network levels. At the project level, bridge engineers can use these models to track the physical condition of the bridge deck, superstructure, and substructure, and thereby provide guidance in predicting the year at which a component's condition reaches agency-specified thresholds for rehabilitation or replacement. At the network level, bridge engineers use these deterioration models to measure the accumulated repair needs of the individual bridge components that, combined with activity cost models, can determine the system-wide financial needs over a specified future time horizon. Deterioration models also play key roles in other agency business processes, such as highway cost allocation and asset valuation. These functions are facilitated when the bridge manager is capable of *reliably* predicting the physical condition of each bridge component at any future date.

The bridge deterioration models currently used in the Indiana BMS were first developed over two decades ago. Since then, there have been significant changes in construction techniques and technologies, materials, condition inspection methods, and loading patterns. The past few decades have also seen advancements in statistical techniques for data analysis and model building. In addition, there has been a surge in data resources in terms of the volume and variety of data types and items, and data integrity and reliability. For example, data on truck volumes and climatic conditions are more readily available, making it possible to develop models that account for these deterioration factors. These challenges and opportunities combined indicate that now is an opportune time to develop new models to address the current modelling needs of INDOT bridge managers.

Deterioration models are often developed separately for many State DOTs for the wearing course, deck, superstructure, and substructure. For the wearing course, INDOT recently developed deterioration curves; however, the decades-old models continue to be used for the remaining components. Therefore, INDOT commissioned the research study to update the deterioration models for the remaining components (1).

Study Objectives and Scope

The two main objectives of the Purdue research project were to: develop a set of bridge condition deterioration curves on the basis of the physical and operational characteristics, climate, and truck traffic, and identify the factors that influence bridge component deterioration and measure the direction and strength of the influence of each factor (1).

As stated earlier, one of the objectives of the Deighton project was to validate the predictive accuracy of the deterioration models that resulted from the research project.

The Purdue research study was directed to address only the bridges located on the state highway system (interstates, U.S. roads, and state roads). These bridges were placed into "families" based on their material type, functional class, and administrative/climatic region, and were calibrated for each family. Bridges on local routes were excluded (1).

Sample Outcome of Deterioration Model Development

Six deterioration models were built for bridge decks, six for substructure, and 42 for superstructure. It was found that the best models were either exponential or polynomial of the second or third order. The influential variables were found to be as follows:

- deck age in years (AGE),
- interstate location (1 if located on Interstate, 0 Otherwise) (INT),
- angle of skew (SKEW),
- bridge length (LENGTH),
- type of service under bridge (SERVUNDER),
- number of spans in main unit (SPANNO),
- freeze index in 1,000s of degree-days (FRZINDX),
- average annual number of freeze-thaw cycles (NRFTC),
- average annual daily truck traffic in 1000s (ADTT), and,
- deck protection (1 with protective system, 0 otherwise), (DECKPROT).

For the purposes of this paper, two curves will be isolated further and validated against actual inspections performed by INDOT: deck condition for NHS pavements in Northern Indiana (Deck 1) and substructure condition for NHS pavements in Central Indiana (Sub 2) (1). These two curves (Deck 1 and Sub 2) are shown in Equations 1 and 2 and graphically shown in Figure 1 and Figure 2 respectively (DCR is Deck Condition Rating, SUBCR is Substructure Condition Rating):

$$\mathrm{DCR} = 8.55637 - 0.24129\bullet\mathrm{AGE} + 0.0096\bullet\mathrm{AGE}^2 - 0.0001667\bullet\mathrm{AGE}^3 - 0.04301\bullet\mathrm{SERVUNDER} - 0.01218\bullet\mathrm{SPANNO} + 0.51375\bullet\mathrm{DECKPROT} - 0.05182\bullet\mathrm{FRZINDX} - 0.01872\bullet\mathrm{ADTT} \qquad (1)$$

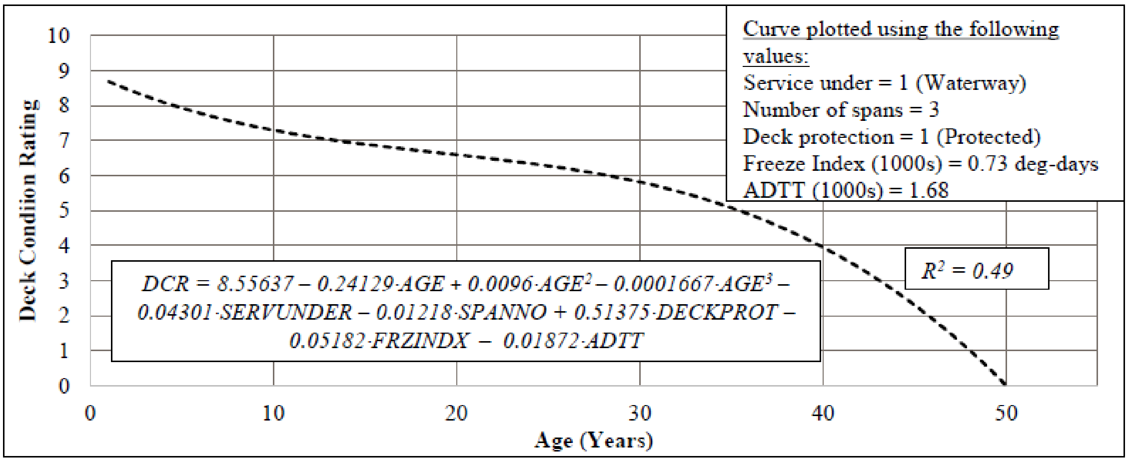

Figure 1: Example Plot of the Bridge Deck Deterioration Model - Northern Districts, NHS

$$SUBCR = 8.25023 – 0.10552•AGE + 0.00274 •AGE^2 – 0.00002766•AGE^3 – 0.03816•INT – 0.008212•SERVUNDER – 0.00045568•LENGTH – 0.00648•NRFTC \quad (2)$$

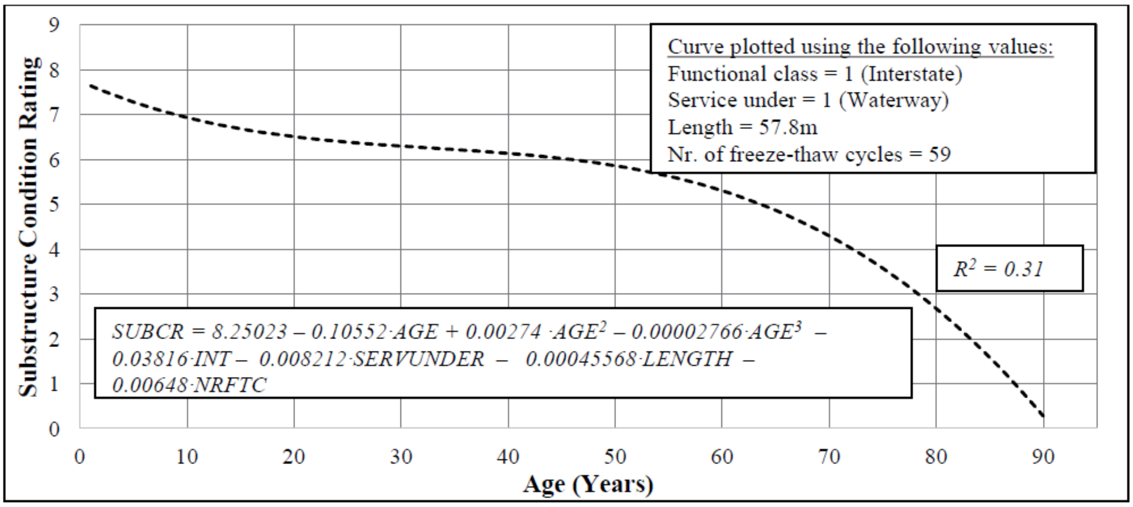

Figure 2: Example Plot of the Substructure Deterioration Model – Central Districts, NHS

DETERIORATION MODEL VALIDATION

The process of validating the deterioration models is crucial to the ultimate credibility of the results of the BMS, since the results are directly based and attributable to the accuracy of the models. This section details the methodology used in the Deighton project for validating the models for INDOT.

Approach

The approach consists of six basic steps. The BMS plays a critical role in the validation, as it is through the use of the BMS that the automated analysis can take place. The steps used in this approach are (see Figure 3):

(1) Use the BMS to go back in time and capture the condition of the bridge network for a specific point in time,

(2) Capture the actual work done by INDOT in the BMS from that historical point in time to current time,

(3) Define the deterioration models that are to be validated in the BMS,

(4) Run an analysis using the BMS from that historical point in time to current time,

(5) Review the results of the historical analysis and compare to the actual, current bridge condition, and,

(6) Quantify any variances between predicted and actual. Refine the deterioration models as required and re-define the models in the BMS.

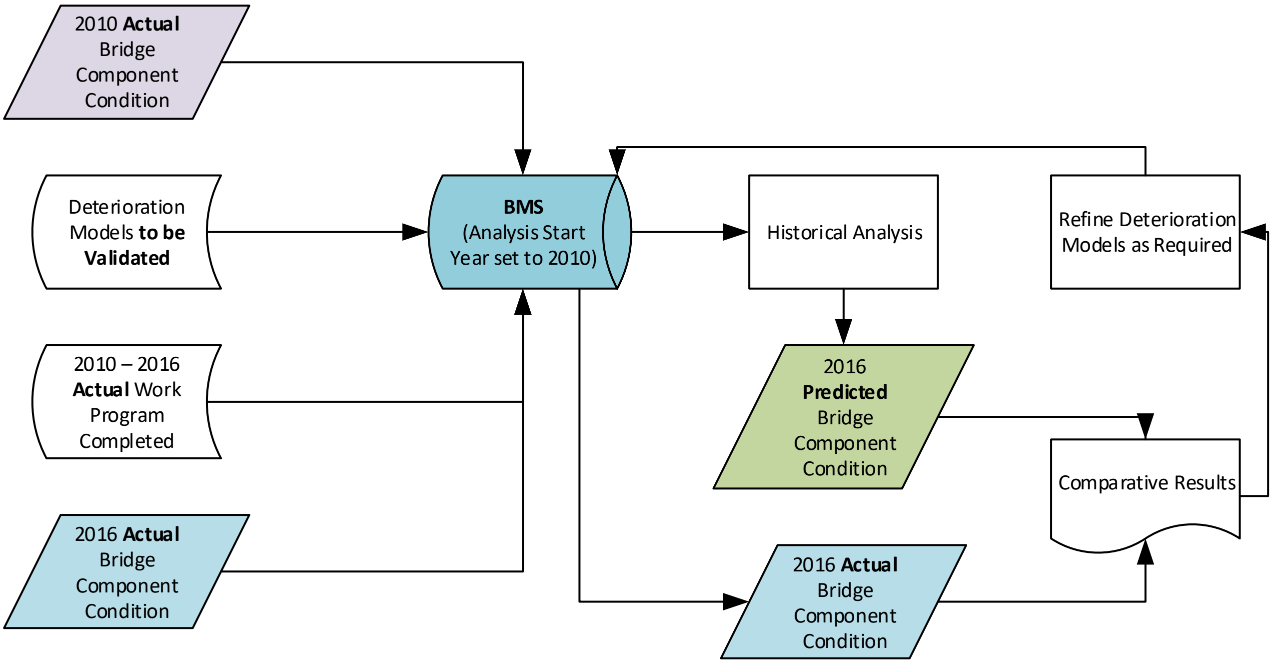

Figure 3: Overview of Model Validation Process

Bridge Management System

The BMS used by INDOT is dTIMS by Deighton Associates Limited. A BMS is critical to the model validation process because it provides an agency with the ability to run automated analyses and compare results quickly. It is essential that a BMS should allow for:

- Flexibility of setting a start date for the analysis,
- Multiple key performance indicators to be analysed,
- Capture of actual work done by the agency,
- Running an analysis from a historical point in time to current time, and,
- Comparison of predicted condition values to actual values.

Turning Back the Clock

The first step in the validation process is to choose a historical point in time that is far enough in the past to allow for ample deterioration of the major bridge components, but not too far so that capturing the *actual* work done between the historical point and current time is an overly onerous process. For the purpose of this exercise, the historical point in time selected was 2010.

The objective is to make the "current" time in the BMS to be 2010, and then capture the *actual* bridge component conditions *as they were* in 2010. In essence, you "turn back the clock" in the BMS to 2010.

For the Deighton project, INDOT provided the bridge conditions for deck, superstructure, substructure, and wearing surface as they were in 2010. This data was loaded into the BMS and the start time for the analysis was set to 2010.

Capturing Actual Work Done

Next, the actual bridge projects that INDOT performed between 2010 and 2016 were loaded into the BMS. These are recorded as committed projects, since the work was actually done. The premise is to start the analysis beginning in 2010 and commit or force the BMS to select the actual work done between 2010 and 2016 but ***no*** additional projects. In this way, the BMS is replicating the history that has taken place between 2010 and 2016, and also capturing the actual improvements in bridge condition that resulted from the historical work performed by INDOT.

Defining Deterioration Models in the BMS

The deterioration models that are to be validated are defined in the BMS for each of the components. That is, the equations presented earlier (Equations 1 and 2) plus the equations for all other components and families of bridges are defined within the BMS. In this way, the condition projections made by the BMS will be based on the deterioration models that are *to be validated*.

A Historical Analysis

At this point in the validation process, the basic building blocks are in place in the BMS and it can now be used to predict the bridge component condition into the future and select bridge rehabilitation projects. The projections will follow the "to be validated" deterioration curves and the bridge projects that are selected are the actual projects performed by INDOT. When the BMS selects a bridge project, the bridge components are improved in condition based on the treatment resets programmed in to the BMS. So, when a deck replacement project is selected by the BMS for example, the deck condition rating and the wearing surface condition are improved, whereas the substructure and superstructure ratings are unaffected.

It is important to note that the *only* projects the BMS is selecting are the ones that were *actually* performed by INDOT and no others.

The premise of this analysis is that for every bridge in the network, its *predicted* condition in the BMS in 2016 is based on the "to be validated" deterioration models, and the actual work that has been performed from 2010 to 2016. We call this the *predicted* condition. This condition is one of the two important parameters required to validate the deterioration models.

The second parameter is the actual bridge component condition. The 2016 actual bridge condition data is loaded into the BMS. This is called the *actual* condition since it is based on the actual bridge inspections that have taken place. Once both the predicted and the actual bridge conditions are derived or captured in the BMS, the comparison can occur. The model validation process is summarized in Figure 3.

Reviewing the Results

To review the results, one must compare the predicted bridge condition with the actual bridge condition. The comparison can be performed for individual bridges or for a group of bridges. An additional benefit of this comparison with an individual bridge is that you can review each specific bridge component condition and determine the variance between the predicted and the actual values.

The results were reviewed for bridges where work was done between 2010 and 2016, and for bridges where no work at all was done. In the first case, an additional outcome is that you can also validate the treatment resets in the BMS against what actually occurred for the bridge. Both comparisons are valid and each provides a different perspective on the results.

Comparisons for *groups* of bridges are also useful for quantifying variances, and are sometimes more useful for this purpose than for individual bridges since the nuances of each bridge does not affect the comparison. The following results are based on the models presented in Equations 1 and 2 and the validation exercise. These figures focused initially on those structures that did *not* have work done to them during the study period. This allowed the comparisons between predicted and actual to focus only on actual deterioration and not on the effects of a work program. Additional comparisons were made using bridges that also had work performed but those comparisons are outside the scope of this paper.

Figure 4: Predicted Deck and Substructure Deterioration versus Actual Inspections

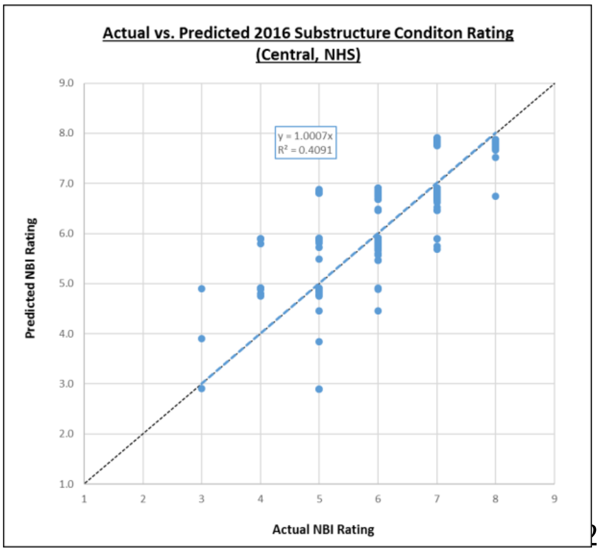

Figure 5:Predicted Substructure Deterioration versus Actual Inspections for Central Districts, NHS

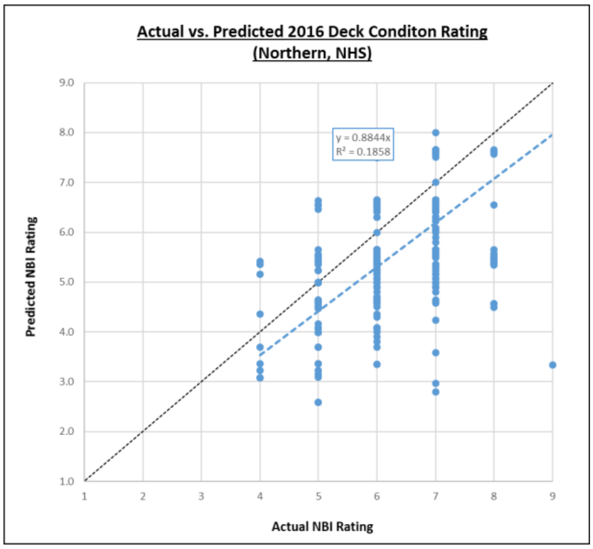

Figure 6: Predicted Deck Deterioration versus Actual Inspections for Northern Districts, NHS

Figure 4 shows the 2010 and 2016 actual inspections along with the original deterioration model used in the BMS and the new Purdue model for both Deck and Substructure components for all INDOT bridges. In both cases, the actual value is greater than predicted. This difference is exacerbated because the inspection ratings are always whole numbers.

Figure 5 and Figure 6 show the actual ratings versus the predicted ratings for 2016 for Substructure (Central Indiana, NHS) and for Deck (Northern Indiana, NHS) respectively. It is evident that there is a moderate degree of scatter in both plots. The blue dotted line represents the trend line of the points. In Figure 5, the trend line is on top of the 45° line indicating a very good *overall* correlation between actual and predicted. However, Figure 6 shows the majority of the points below the 45° line, indicating a more aggressive rate of deterioration with the curve than the actual inspections. This is corroborated with the trend line being below the 45° line.

RECOMMENDATIONS

The authors of this paper recommend that an agency maintain historical condition records and an accurate history of actual work completed, implement a BMS, conduct a model deterioration validation exercise every five years or when new models are developed or there are changes in condition data collection protocols, and revise deterioration models accordingly based on the results of the validation exercise.

CONCLUSIONS

This paper has presented a framework and methodology that was used at INDOT to validate bridge deterioration models. The main conclusion of this exercise is ***not*** to comment on the accuracy of the bridge models that were developed for INDOT, but rather that bridge deterioration models ***must*** be validated so that the *results* from the BMS can be validated and hence provide the *consumers* of the results with a higher degree of confidence. This framework can be adopted by other agencies that have a BMS or any asset management system so they can validate their own asset deterioration models. The process presented is repeatable and defendable and hence can withstand a high degree of scrutiny.

Any agency that is using an asset management system and has not put their own deterioration models through a similar validation exercise runs the risk of not being able to defend the results of the management system with a high degree of confidence, and hence may be in danger of tarnishing their credibility along with the credibility of the asset management system.

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