Probability of Transition to Poor Condition for Bridges in Virginia

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report summarizes the findings of a study that was developed by the Virginia Department of Transportation (VDOT) to understand the likelihood that the general condition rating of any particular bridge will fall over a given time period. The proposed methodology can be used for all types of bridges with various condition ratings to calculate the likelihood of transition to a lower condition rating. The study focused on bridges that are proposed for inclusion in the first year of Virginia's federally-funded Infrastructure Investment and Jobs Act (IIJA) program. It was of interest to predict the percentage of bridges in poor condition (i.e. Min GCR<5) in the foreseeable future. This allows VDOT to allocate resources to those bridges that are in need of funding from the IIJA program.

The proposed methodology defines a variable called Time in Condition Rating (TICR), which shows the time that a given component will remain in a given general condition rating. The Weibull distribution parameters are then calculated to estimate the probability of transitioning from a higher GCR to a lower GCR.

The result of the analysis revealed that approximately 7 out of 10 bridges in the IIJA program which currently have a min GCR of 5 will be in poor condition in the next four years. Likewise approximately 1 out of 5 bridges which currently have a min GCR of 6 will be in poor condition in the next four years.

The proposed methodology allows VDOT to more effectively allocate resources so that the appropriate treatments are applied to the appropriate bridges at the appropriate time. Such models also allow Virginia to establish budgets, predict conditions, and set performance goals.

1.0 INTRODUCTION

This report summarizes the findings of a study that was developed by VDOT to understand the likelihood that a bridge will fall from fair to poor condition. The study uses Virginia's database of historical bridge condition data to understand past behavior and deterioration rates. Probabilities that a bridge will transition from one general condition rating to a lower general condition rating are presented. The study is applicable to various types of bridges; however, this report emphasizes bridges with steel girders and concrete decks.

The investigation was performed to assist VDOT in its prediction of future bridge conditions, but also in support of the federally-funded Infrastructure Investment and Jobs Act (IIJA) program. One of the goals of the IIJA program is to fund fair bridges that are at risk of becoming poor in 3 years.

An underlying assumption of the study is that future behavior will be predicted by the performance of the structure in the past. This assumption tends to under-predict future deterioration rates with respect to the age of the Virginia bridge inventory. The study uses bridge condition data from the past 26 years, but in that time the average age of bridge inventory in Virginia has increased from in comparison with 26 years ago. It could reasonably be assumed that condition-based deterioration will be more rapid as an inventory ages. Accordingly, past behavior, based on the performance of younger bridges, might show slower deterioration rates than what can be expected in the future.

At the same time, past behavior may over-predict future deterioration rates due to the improvement of bridge treatments of the past two decades. Virginia has been slowly but steadily improving its bridge treatments, technology, and construction methods to slow the deterioration rates of new bridges and existing bridges after repair. These improvements include durable materials and techniques that increase the service lives of bridges post-treatment.

Investigation of the dual inventory characteristics of increased average age and improved materials/technology are beyond the scope of this study, but they could be the subject of a future effort to further refine the predictive models presented herein.

Virginia has a keen interest in understanding the likelihood that a bridge will fall from fair to poor condition. Reliable predictive models allow Virginia to more effectively direct resources so that the appropriate treatments are applied to the appropriate bridges at the appropriate time. Such models also allow Virginia to establish budgets, predict conditions, and set performance goals.

The primary objectives of this study are explained below.

Objectives:

- Develop cumulative density functions for all types of bridges that predict the probability that the general condition rating will change in a given year. Develop separate curves for decks, superstructures, and substructures.
- Determine the probability that the bridges currently proposed for the IIJA program will fall into poor condition (formerly structurally deficient, or SD) in a given time period (e.g. 4 years)

2.0 BACKGROUND

VDOT has the goal of sustaining the condition of its bridge inventory for the foreseeable future. In order to better understand the condition of its bridges, VDOT follows FHWA's convention for categorizing bridges into condition categories of "good", "fair", and "poor" as indicated in Table 1. Bridges are inspected in accordance with the requirements of the National Bridge Inspection Standards (NBIS). During each safety inspection each of the bridge's major components (deck, superstructure, substructure, or culvert) is assigned a general condition rating (GCR) of between 0 (failed) and 9 (excellent). GCR designations are defined by FHWA and are published in VDOT's *Inventory and Appraisal Coding Guide for Virginia's Structures*. Structures are assigned condition categories as indicated below. These condition categories are defined by the minimum general condition rating of each bridge components, which is assigned to each bridge during its routine safety inspection.

Table 1- FHWA definitions for bridge condition

Condition Category	Range Of General Condition Ratings
Good	**Minimum GCR ≥ 6**
Fair	**Minimum GCR = 5**
Poor	**Minimum GCR ≤ 4**

In recent years Virginia has made a concerted effort to reduce the number of poor structures (formerly referred to as *structurally deficient* structures) in the inventory of the Structure and Bridge Division. This has led to a substantial reduction in the percentage, count, and deck area of poor bridges in Virginia, as shown in Figure 1.

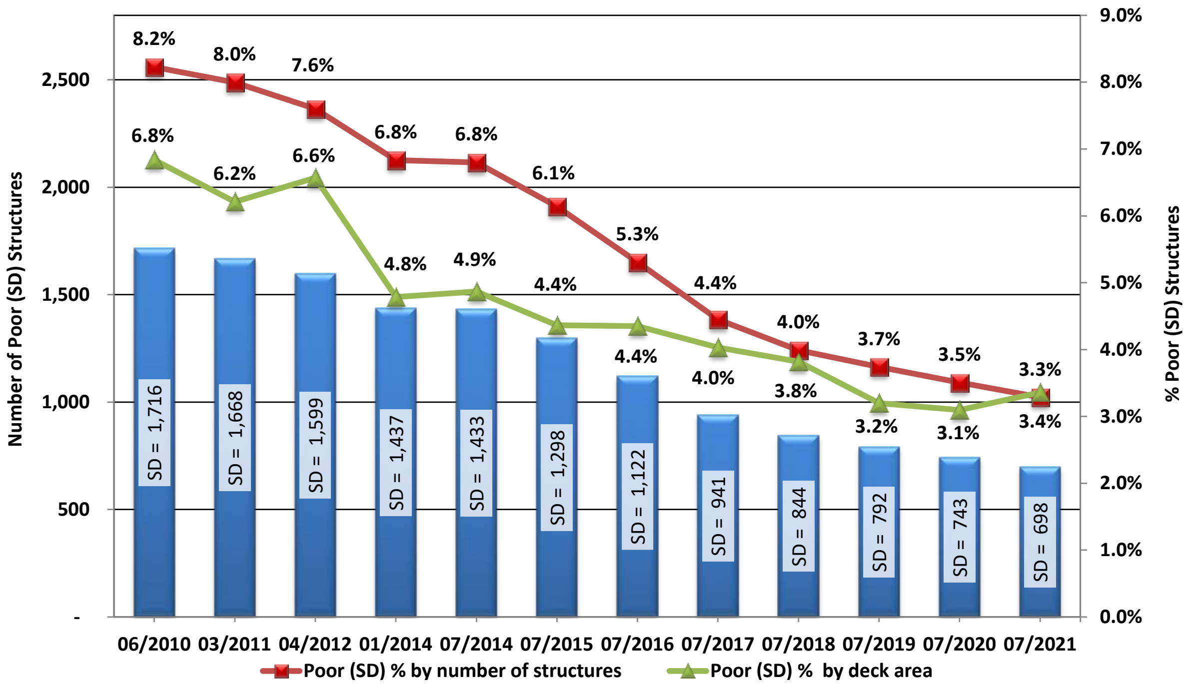

Figure 1: Multi-Year Performance History of Poor (Formerly Referred to as Structurally Deficient) Structures on All Systems

Now that these gains have been made it is important that Virginia sustain its recent progress, and in order to do so, VDOT has embarked on a program that shifts its investment strategy from "worst first" to a more balanced approach, emphasizing both replacement of poor bridges and restoration/preservation of bridges in fair condition. In 2019, VDOT performed its *Comprehensive Review (VDOT 2019)*, which found that Virginia could sustain its inventory for approximately 50 years at an acceptable level of service if the funding balance were changed to 75% for preservation and 25% for replacement. The study found that this can be done with current funding levels, as long as the funding is adjusted for inflation.

As can be seen from Figure 2, the reduction in the number and area of poor bridges in Virginia has coincided with an increase in the number and area of fair bridges.

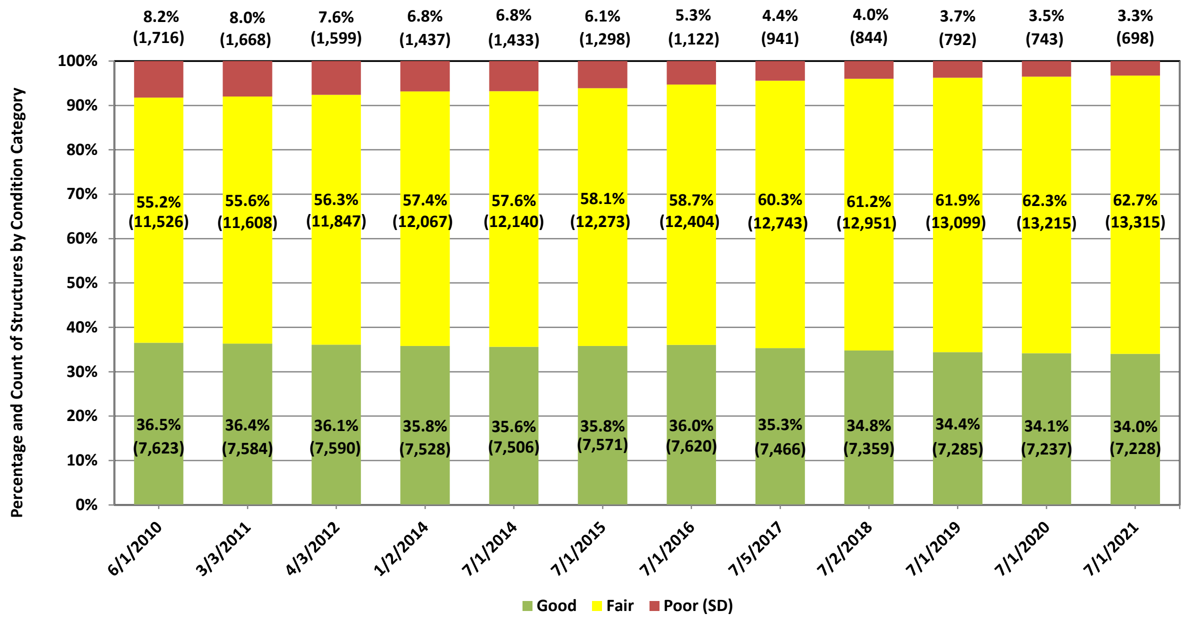

Figure 2: Virginia Structures in Good, Fair, and Poor (Formerly Referred to as Structurally Deficient) Condition. 12 Year Trend

Database Preparation

This analysis was conducted by studying the general condition ratings of NBI bridges in VDOT's bridge inventory by following the process described below:

1. Prepare data needed for analysis using NBI database. Currently between 1992-2017 (26 years)
2. Build a database that shows sequences of GCRs for deck, superstructure, substructure, culverts, and minimum GCR
3. Select the number of years to "trim". Since data sets are incomplete (no data prior to 1992 and after 2017), there is a need to enhance the quality of the database by trimming data for entering and leaving the time interval. The study selected 5 years as the appropriate number for trimming. This 5 year was selected based on a technical paper in the ASCE journal of bridge engineering (Nasrollahi et al (2014)).
4. Develop a probabilistic model such as Weibull distribution. Estimate distribution parameters for time in condition rating (TICR). Note that TICR represents a variable that shows the time that a given component will remain in a given general condition rating.

3.0 WEIBULL DISTRIBUTION

This study uses a methodology that was initially introduced by a paper entitled *"Estimating Inspection Intervals for Bridges Based on Statistical Analysis of National Bridge Inventory Data"* in the in the peer-reviewed *ASCE Journal of Bridge Engineering* (Nasrollahi et al (2014)).

It has been found that the Weibull distribution provides the best fit for TICR and ultimately to predict changes in the general condition ratings of bridges. (Equation 1 shows the Weibull distribution formula.

$$f(t) = \frac{\beta(t-\delta)^{\beta-1}}{\theta^{\beta}} \exp\left[-\left(\frac{t-\delta}{\theta}\right)^{\beta}\right], t > \delta \quad \textbf{(Equation 1)}$$

Where,

β= shape parameter;

θ =scale parameter;

δ= location parameter.

The Weibull distribution has the following two characteristics:

- In the Weibull distribution, the scale parameter is known as the characteristic life; this is a point that 63.2 percent of the population fails by the characteristic life point regardless of the value of shape parameter (β)
- When the beta value is between 1 and 3.6, the Weibull distribution approximates the lognormal distribution.
- For wearing out process, the value of beta is greater than 1.
- Location parameter is zero for bridge deterioration models.

4.0 Cumulative Density Functions

The cumulative-density function (CDF) is the area under the probability density function (PDF) up to a particular time, T. The CDF shows the probability that the condition rating will change before a specific time, as shown in (Equation 2.

$$F(t) = \int_{\infty}^{t} \left[\frac{\beta (t-\delta)^{\beta-1}}{\theta^{\beta}} e^{\left[(t-\delta)/\theta \right]^{\beta}} \right] dt = 1 - e^{-\left[(t-\delta)/\theta \right]^{\beta}} \qquad \textbf{(Equation 2)}$$

In order to enhance the accuracy of models, the Weibull parameters were calculated for different categories of structures considering the type of superstructure and deck. For instance, Figures 3 through 5 below, show the Weibull PDF for steel bridges with concrete decks. In these figures, the term CRX-B-D refers to data for a bridge deck with a general condition rating X. In addition, the estimated values of δ and β are shown on the right side of the chart for condition ratings of 4 to 8 respectively.

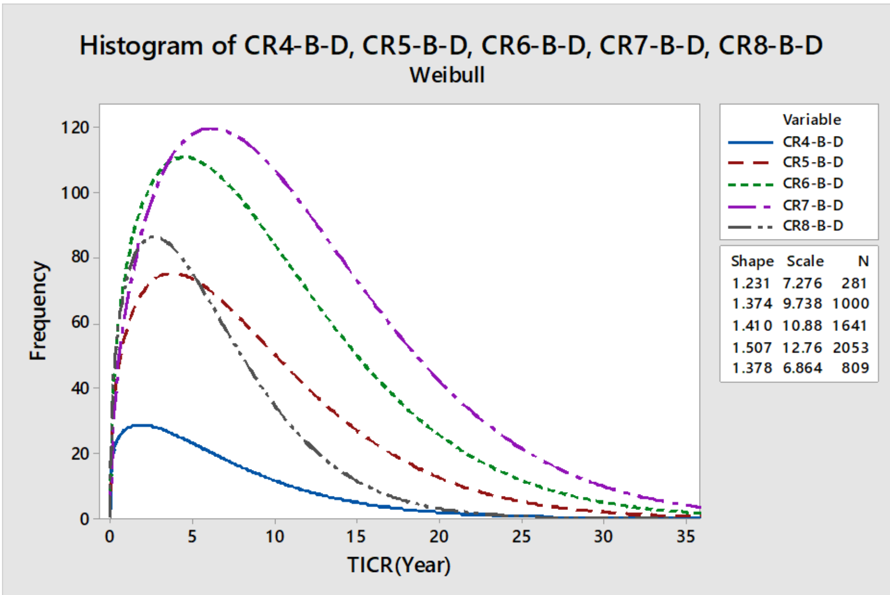

Figure 3- Probability Density Function for Deck GCRs for Bridges with Steel Girders and a Concrete Deck

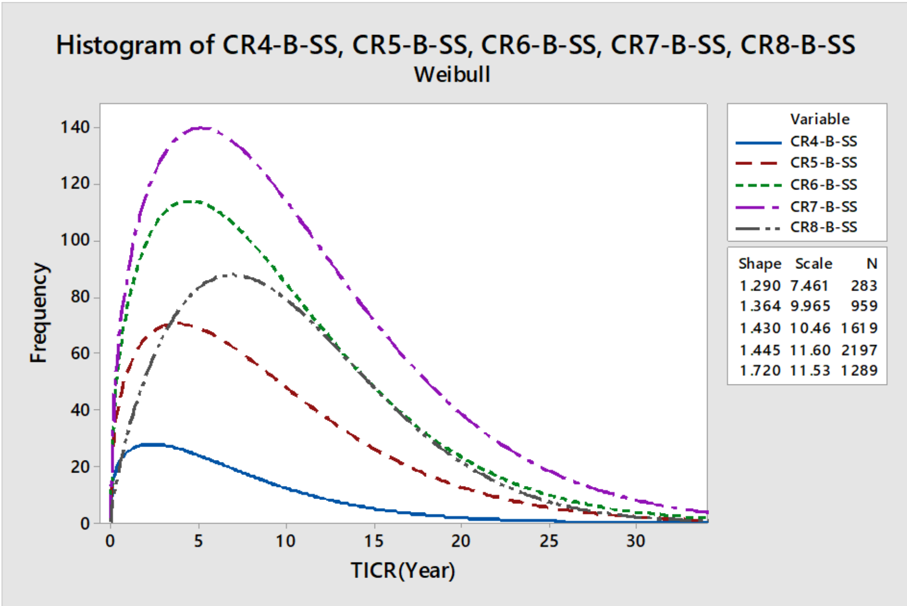

Figure 4- Probability Density Function for Superstructure GCRs for Bridges with Steel Girders and a Concrete Deck

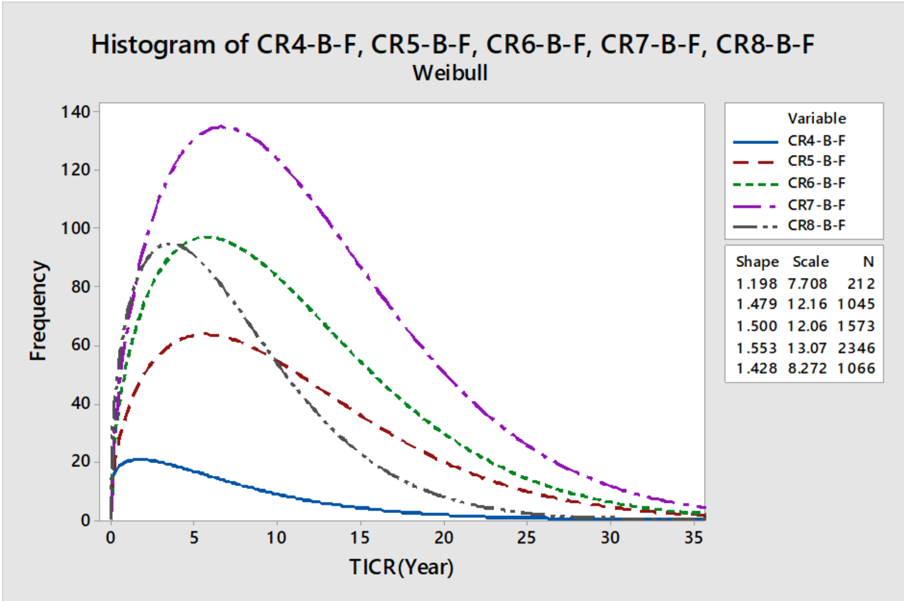

Figure 5- Probability Density Function Substructure GCRs for Bridges with Steel Girders and a Concrete Deck

The probability of transition from one condition rating to a lower condition rating is calculated using the CDF formula shown in Equation 2. A built-in assumption is that GCRs go to the next lower GCR (e.g. from GCR 8 to GCR 7). Also, any component has been in its current condition for a certain amount of time, and this must be taken into account for calculating the transition probability from the current GCR to the next lower GCR. Therefore, it is necessary to add the term *T* to (Equation 3.

$$\boldsymbol{F(t) = 1 - e^{-\left[{(t-\delta)}/{\theta}\right]^{\beta}} = 1 - e^{-\left[{(t+T)}/{\theta}\right]^{\beta}}}$$ **(Equation 3)**

Where,

T is the number of years in the last (or current) condition rating.

Because the transition probability for each condition rating is statistically independent of other condition ratings, the transition probability can be calculated using (Equation 4.

$$P(A_{9\,to\,8} \cap A_{8\,to\,7} \cap A_{7\,to\,6} \cap A_{6\,to5} \cap A_{5\,to\,4}) = P(A_{9\,to\,8}) \times P(A_{8\,to\,7}) \times P(A_{7\,to\,6}) \times P(A_{6\,to5}) \times P(A_{5\,to\,4})$$

(Equation 4)

Where: $P(A_{x\ to\ y})$= is the transition probability that a component with a general condition rating of “x” goes to general condition rating of “y”

Because each bridge component may have a different GCR, the transition probabilities within four years are calculated for each component and then the maximum likelihood is selected as the transition probability as shown in (Equation 5.

$$\boldsymbol{P = Min(P_{deck}, P_{superstructure}, P_{substructure})}$$ **(Equation 5)**

Where,

P_{deck} is the probability of transition from the current deck’s GCR to CGR of 4;

$P_{superstructure}$ is the probability of transition from the current superstructure’s GCR to CGR of 4;

$P_{substructure}$ is the probability of transition from the current substructure’s GCR to CGR of 4.

5.0 RESULTS

The study evaluated the 295 bridges originally proposed for inclusion in the IIJA program (*nb: this list has been reduced since the original start of the IIJA program*). 156 of these bridges currently have a minimum general condition rating of 5, and on average there is a 67.7% chance based on count or 71.6% weighted by deck area of falling into poor condition within the next 4 years if other interventions are not undertaken. In other words, approximately 7 out of 10 bridges which currently have a min GCR of 5 are predicted to be in poor condition in the next four years. Likewise, 115 of the 295 bridges currently have a minimum general condition rating of 6, and on average there is a 16.9% chance based on count or 17.9% weighted by deck area of falling into poor condition within the next 4 years if other interventions are not undertaken. In other words, approximately 1 out of 5 bridges which currently have a min GCR of 6 will be in poor condition in the next four years.

The proposed methodology in this report allows VDOT to more effectively allocate resources so that the appropriate treatments are applied to the appropriate bridges at the appropriate time. Such models also allow Virginia to establish budgets, predict conditions, and set performance goals.

6.0 REFERENCES

Virginia Department of Transportation (VDOT 2019), "MAINTENANCE AND OPERATIONS COMPREHENSIVE REVIEW 2019" , retrieved on 1/11/2022 at https://www.virginiadot.org/projects/resources/legstudies/Maintenance_and_Operations_Comprehensive_Review_%E2%80%93_2019.pdf

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