TechBrief

The Advancing Steel and Concrete Bridge Technology to Improve Infrastructure Performance Program is a cooperative agreement between a university consortium consisting of Lehigh University (lead), the University of Delaware, Portland State University, University of Buffalo, Modjeski & Masters, and Corven Engineering. Its purpose is to advance the state-of-the art technologies to improve the condition and durability of the nation's bridges and highway structures with a focus on implementable technologies that address high priority needs. The agreement is managed by the Federal Highway Administration Office of Bridge Technology.

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Performance of Concrete Highway Bridge Decks using Nationwide Condition Data

This Technical Brief provides an overview of the work completed under Task 10 of the cooperative agreement entitled "Advancing Steel and Concrete Bridge Technology to Improve Infrastructure Performance Program". The objective of the research performed under Task 10 was to determine how National Bridge Inventory (NBI) condition ratings could best be used to study the influence of parameters that govern concrete highway bridge deck performance.

Introduction

Concrete highway bridge deck repair and rehabilitation are the most common cause for bridge work. Figure 1 shows an example of a bridge deck with significant deterioration in the form of delaminations. In order to optimize preservation activities and use available monies effectively, a solid understanding of the parameters that affect the performance of concrete bridge decks is critical. The presented research developed a nationwide database based on National Bridge Inventory (NBI) condition ratings and other critical parameters that were computed by the authors, referred to as the Nationwide Concrete Highway Bridge Deck Performance Inventory (NCBDPI) database (Ghonima et al., 2018). Two performance parameters were computed from the available concrete bridge deck condition ratings: time-in-condition rating (TICR) and deterioration rate (DR). Following the aggregation of all parameters in the NCBDPI database, filtering, and preprocessing were performed. Two analysis methods were evaluated to study bridge deck performance. This Technical Brief is an excerpt of the Internal Final Report (Ghonima et al., 2018).

Figure 1. Example of a concrete bridge deck showing significant deterioration in the form of corrosion and delaminations. Photo courtesy by Thomas Schumacher.

Research Overview

The main objective of this research was to evaluate the use of NBI condition ratings to study concrete bridge deck performance. This research was subdivided into four subtasks. Subtask 1 included an in-depth literature review of reported research on concrete bridge deck durability and service-life models. In Subtask 2, key parameters found to influence durability were identified in the literature. Subtask 3 summarizes the capabilities and limitations of two service-life prediction software packages. As part of Subtask 4, a nationwide database was created that includes identified parameters and two performance parameters were computed: time-in-condition rating (TICR) and deterioration rate (DR). Two analyses were implemented and evaluated to study the relationship between influence and performance parameters: binary logistic regression and Bayesian survival analysis. Please see the internal final report for details regarding all aspects of the work performed (Ghonima et al., 2018).

Bayesian survival analysis is highlighted in this Technical Brief (see Section “Data Analysis”) as it was found most practical and useful for an owner or agency to study concrete bridge deck performance.

Background

Concrete Bridge Decks

Bridge decks are a critical element of a bridge as they support and distribute vehicle loads to the superstructure. However, because of the requirements of this role, bridge decks are exposed to severe exposure conditions. According to the National Cooperative Highway Research Program (NCHRP) Synthesis Report 333, concrete bridge deck deterioration is one of the leading causes of structural deficiency in bridges (NCHRP, 2004). In addition, the preservation of concrete bridge decks is both costly and disruptive to highway systems. Therefore, developing optimal preservation decisions for concrete bridge decks is key in keeping bridges and highways in good repair. In order to develop effective preservation schedules, the factors affecting bridge deck performance need to be understood.

In this document, the term “maintenance” is used for any action that increases the condition rating (CR) of the bridge deck. Preservation includes both rehabilitation and certain maintenance actions, but not replacement (FHWA, 2018). Technically, certain maintenance actions do not increase the condition of a bridge deck instantaneously (e.g. washing) but they may still have an effect on the performance, and hence decrease the rate of deterioration.

National Bridge Inventory

The collapse of the Silver Bridge in Ohio in 1967 resulted in a congressional mandate to all the State DOTs in the 1970s to establish a unified method of National Bridge Inspection Standards (NBIS) for all the public highway bridges across the country with a span length of more than 20 ft (6.10 m). The associated data consisting of 116 items are stored in the National Bridge Inventory (NBI) and represent one of the most comprehensive sources of bridge information. Each of the fifty States, the District of Columbia, and the Commonwealth of Puerto Rico submit their substructure, superstructure, and deck condition ratings (CR), which are determined by trained bridge inspectors, every two years. These ratings are then compiled in the NBI and made available to the public. The data are used by the FHWA in their biannual report of bridge condition and performance to Congress.

Based on the 2017 NBI census there are 615,002 bridges in the US (FHWA, 2017). Finally, the NBI database allows the State DOTs to monitor bridge performance and conditions and help identify if and what preservation actions should be taken. The NBI's 116 items can be categorized as follows (FHWA, 1995):

- Items 1–27: General description and administrative information
- Items 28–42: Functional or operational (capacity) information, design load
- Items 43–44: Structure/design/construction type and material of construction
- Items 45–56: Span information, geometric information, and clearance dimensions (no Item 57)
- Items 58–70: Structural condition and bridge loading information
- Items 71–72: Waterway and approach data (no Items 73–74)
- Items 75–97: Inspector's work recommendations and projected costs
- Items 98–116: Other information of various categories.

Parameters Considered in this Research

21 parameters were extracted from the NBI and an additional four were computed by the research team, and collected in the Nationwide Concrete Highway Bridge Deck Performance Inventory (NCBDPI) database (Ghonima et al., 2018). These are parameters selected by the research team after performing a review of durability and service-life literature on concrete bridge decks:

- NBI Item 3 – Country (Parish) Code
- NBI Item 8 – Structure Number
- NBI Item 21 – Maintenance Responsibility
- NBI Item 26 – Functional Classification of Inventory Route
- NBI Item 28 – Lanes on Structure
- NBI Item 43a – Structural Material/Design
- NBI Item 43b – Type of Design and/or Construction
- NBI Item 58 – Deck Condition Rating (CR)
- NBI Item 91 – Designated Inspection Frequency
- NBI Item 107 – Deck Structure Type
- NBI Item 108a – Type of Wearing Surface
- NBI Item 108b – Type of Membrane
- NBI Item 108c – Deck Protection
- Average Daily Truck Traffic (ADTT) – Calculated based on NBI Item 109
- Deck Area – This parameter was computed by multiplying two NBI parameters (NBI Item 49 x NBI Item 51)
- Climatic Region – assigned using the International Energy Conservation Code (IECC) also used by the FHWA Long Term Bridge Performance (LTBP) program
- Distance to Seawater – based on the coastline and bridge location of NBI Items 16 and 17
- Bridge Age – based on NBI Items 27 and 106

Several additional parameters have been documented in the literature (e.g. NCHRP, 2004) to affect the performance of concrete bridge decks such as depth of concrete cover, concrete permeability, concrete mix, exposure to deicers, freeze-thaw cycles, etc. Unfortunately, these parameters could not be incorporated because they are either not available or not recorded in a consistent and accessible format. Also, they might only be documented from the design phase, as specified values, rather than as-built values obtained from field measurements (e.g. concrete cover). Finally, even when information is available, it can be in different formats, depending on the standard used (e.g. concrete permeability can be tested according to ASTM C1202 at 28, 56, or 90 days, or even using a different test method). However, it would be straightforward to expand the database developed in this research in the future should such or other information become available.

Bridge Deck Condition Ratings

Bridge deck condition ratings (CR) are stored under NBI Item 58. Using the FHWA recording and coding guide (FHWA, 1995), concrete bridge decks are inspected for cracking, spalling, leaching, chloride contamination, potholing, delamination, and full or partial depth failures (see Table 1). It should be noted that Table 1 is an example and there are some differences in how States interpret the condition ratings for bridge decks. Studying the effect this might have on the data was outside of the scope of this research. When inspecting a bridge deck, the condition of the wearing surface, joints, expansive devices, curbs, sidewalks, parapets, bridge rails, and scuppers are not taken into consideration, nor may they affect the CR of a deck. The influence of a deck on the superstructure or vice versa (e.g., rigid frame, slab, or box girder) is not taken into consideration; the rating is based on the condition of the deck only. Finally, if the deck is covered by an asphalt layer, the condition is estimated based on the condition of the visible portion of the superstructure and the deck's underside (Ghonima et al., 2018).

Table 1. Description of concrete bridge deck condition rating (CR) for the example of Minnesota Department of Transportation (MnDOT, 2016).

Code	This rating should reflect the overall general condition of the deck (or slab) - this includes the underside of the deck and the wearing surface. The condition of railings, sidewalks, curbs, expansion joints, and deck drains are not considered in this rating.
9	Excellent Condition: Deck is in new condition (recently constructed)
8	Very Good Condition: Deck has very minor (and isolated) deterioration. Minor cracking, leaching, scale, or wear (no delamination or spalling).
7	Good Condition: Deck has minor (or isolated) deterioration. Minor cracking, leaching, scale, or wear (isolated spalling/delamination).
6	Satisfactory Condition: Deck has minor (or isolated) deterioration • Concrete: moderate cracking, leaching, scale, or wear (minor spalling and/or delamination).
5	Fair Condition: Deck has moderate deterioration (repairs may be necessary). Extensive cracking, leaching, scale, or wear (moderate delamination or spalling).
4	Poor Condition: Deck has advanced deterioration (replacement or overlay should be planned). Advanced cracking, leaching, scale, or wear (extensive delamination or spalling) - isolated full-depth failures may be imminent.
3	Deck has severe deterioration - immediate repairs may be necessary. Severe cracking, leaching, delamination, spalling or full-depth failures may be present.
2	Critical Condition: Deck has failed - emergency repairs are required.
1	"Imminent" Failure Condition: Bridge is closed - corrective action is required to open to restricted service.
0	Failed Condition: Bridge is closed - deck replacement is necessary.

Data Analysis

Data Pre-Processing and Filtering

Before the data from the NBI database could be analyzed, several preprocessing steps were necessary to deal with missing data and inconsistencies found in the reported NBI bridge deck condition ratings (CR). Additionally, the following two parameters were used as filters:

- NBI Item 42a – Type of Service on Bridge: to **exclude** non-highway bridges.
- NBI Item 107 – Deck Structure Type: to **exclude** any non-concrete bridge decks.

The created Nationwide Concrete Highway Bridge Deck Performance Inventory (NCBDPI) database includes NBI data from 1992 to 2014 including 150,136 unique concrete highway bridge decks. Details regarding pre-processing and filtering can be found in Ghonima et al. (2018).

Bayesian Survival Analysis

Performance Parameter

Based on the bridge deck condition ratings (CR) available in the NBI database (Item 58) the following bridge deck performance parameter, which represents the dependent variable, was computed: time-in-condition rating (TICR). TICR is defined as the duration of time (in years) a CR remains constant. Fig. 2 shows sample CR for three fictitious concrete bridge decks for the period 1992 to 2014, as studied in this research. Cases where the CR increases are assumed to indicate human intervention in form of actions that improve the condition of the deck (referred to as maintenance). Two types of TICR data exist: uncensored and censored. Examples of these are labeled in Fig. 2. Censoring occurs for four reasons: (1) data is censored, as its CR prior to 1992 is unknown, (2) data is censored as its value after 2014, is unknown, (3) data is censored due to missing observations, and (4) data is censored due to an increase in CR from one year to the next, which is considered maintenance, as defined above.

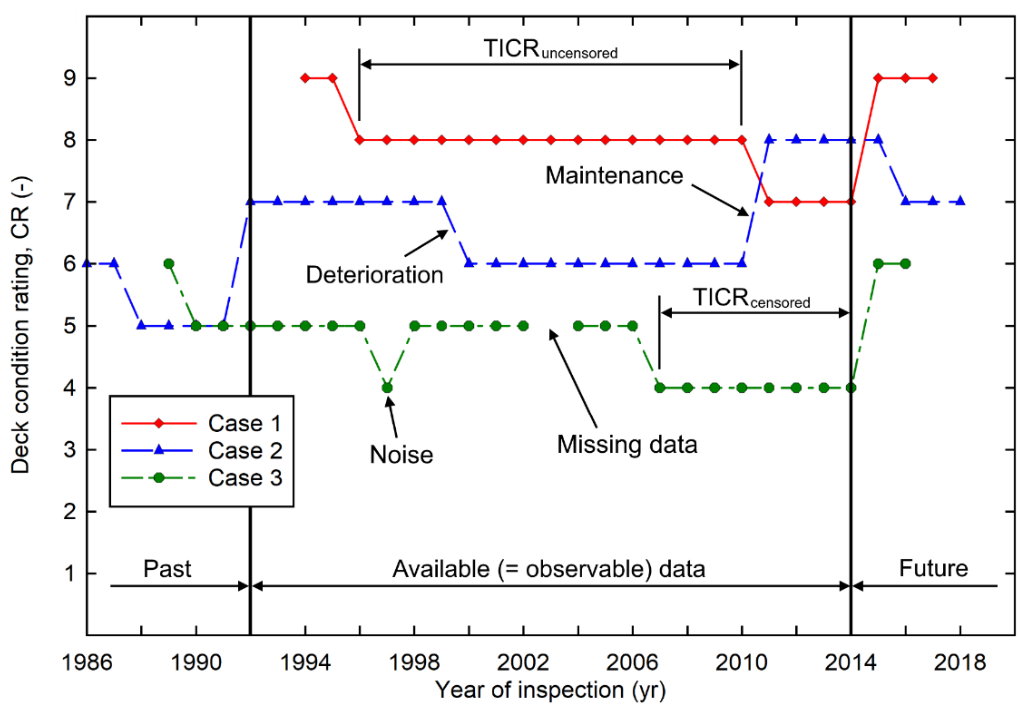

Figure 2. Sample bridge deck condition ratings (CR) for three fictitious concrete bridge decks. One uncensored and one censored TICR are shown as examples. Note that spikes like the one shown in 1999 were considered noise and the data point having CR = 4, in this case, was replaced by CR = 5.

Fig. 3 shows a histogram of the TICR performance parameter for all highway concrete bridges in the US and all TICR observations extracted from the NCBDPI (= 150,136 data points). It can be observed that the dataset contains a significant number of censored data; in fact over 2/3 of the TICR observations experienced some type of censoring. Omitting such data or not properly treating them can introduce bias in statistical estimators such as mean, variance, etc. In particular, if censored data were discarded, the TICR would be underestimated, as bridges that experience slower deterioration are more likely to have censored observations. The way TICR data were treated in this study is analogous to patient observations in the medical field where a doctor is able to observe a patient only over a certain time frame.

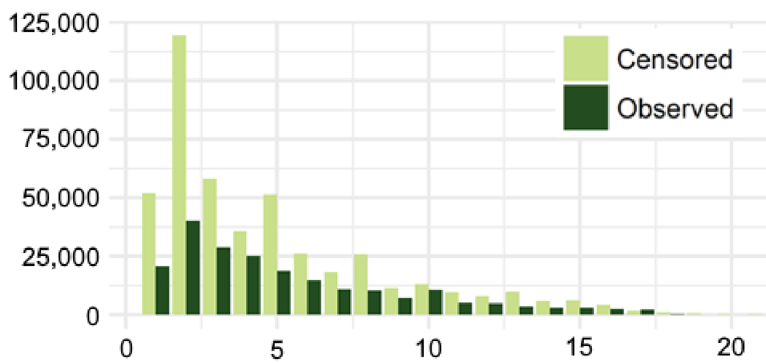

Figure 3. Histogram of TICR (years) performance parameter for all TICR (on *x*-axis). Counts (on *y*-axis) for observed and censored data are shown separately for comparison.

Methodology

Bayesian survival analysis was utilized because it can handle censored data. For details regarding methodology see Ghonima et al. (2018). For bridge data, censorship occurs because we often do not observe the actual time until a bridge deck CR changes, but rather we observe a minimum bound for the time-in-condition rating (TICR). For example, we observe a bridge in CR = 5 during 1992 and 1993, but we do not know if the bridge was in CR = 5 in 1991 or before that, hence, this bridge's TICR observation is at least two years, or TICR $\geq$ 2 years. Recall the doctor - patient analogy drawn earlier; some patient survival times are not observed because the period of observation concludes prior to observing the outcome. Censoring is not something typically considered in civil engineering applications although it directly applies to TICR data for bridge decks. However, it does have a measurable effect on any analysis and excluding it significantly underestimates the TICR and survival probabilities.

The influence parameters, or independent variables, are assumed to come from a Weibull distribution, which is commonly used to model deterioration and aging processes. The advantage of this distribution is that it can account for the increasing failure rates with increasing age.

In this study, Bayesian survival analysis is used to compute the probability that the condition rating (CR) of a bridge deck with specific characteristics remains the same (i.e. survives) as a function of the time-in-condition rating (TICR).

Histograms of the selected modeled covariates (or independent variables) are shown in Fig 4. Censored data (shown in light green) are TICR observations where only a minimum bound for TICR are available, while observed (or uncensored) data (shown in dark green) are occurrences of TICR where the change in condition is due to deterioration (i.e. decrease in CR). Note that excluding censored observations would throw away over 2/3 of the dataset.

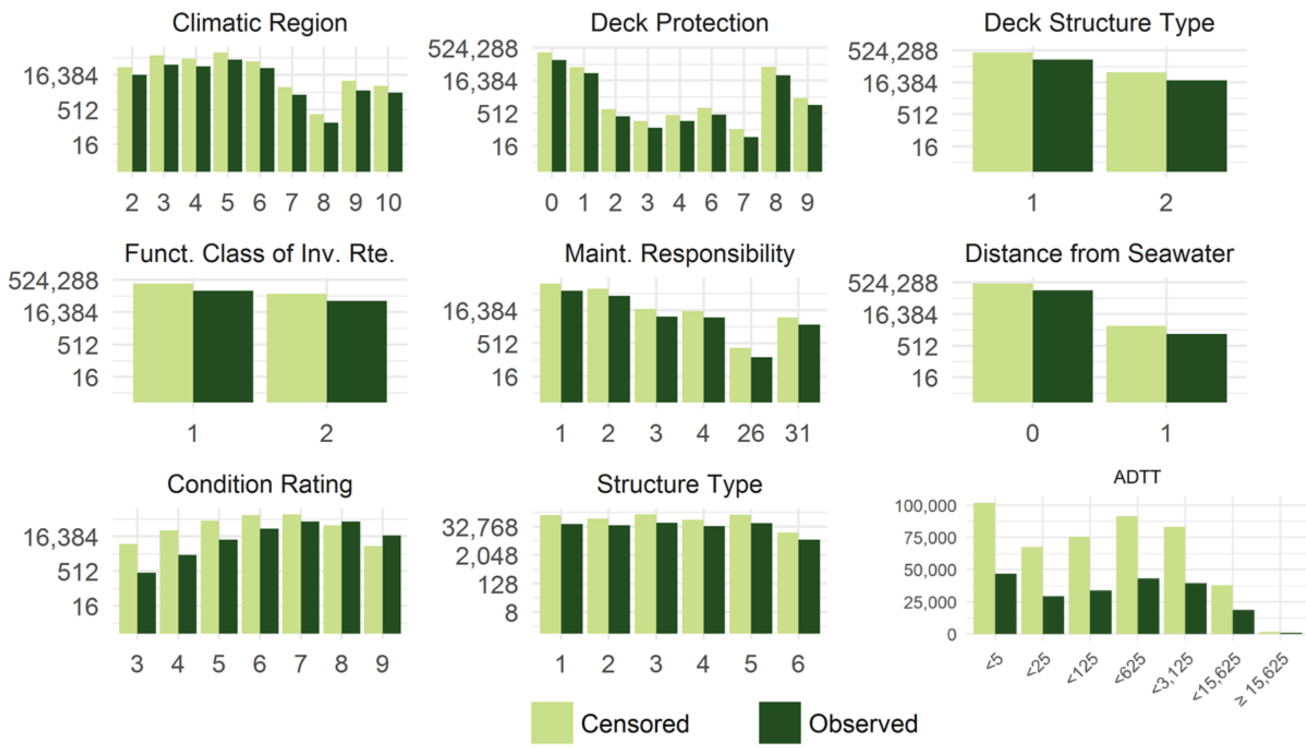

Figure 4. Histograms of used model parameters and their categories. To display the large differences in magnitude of the counts for the various parameters in the data, a log-scale is used for the y-axis (except for ADTT) – enabling, for example, the 450 observations in IECC Climatic Region 8 to be displayed alongside the 222,254 observations in IECC Climatic Region 5. The meaning of the x-axis category codes are provided in Figs. 5 through 9, for additional codes see Ghonima et al, 2018.

Survival Curves

After the survival analysis is completed, so-called survival curves can be plotted. Survival curves for five select parameters (i.e. CR, Climate Zone, ADTT, Deck Protection, and Structure Type) are presented and discussed in Figs. 5 to 9. These curves represent mean estimates and provide the probability that a concrete bridge deck is assigned the same CR (i.e. survives) the following year as a function of TICR. A description of how survival curves are computed and additional curves can be found in the final research report (Ghonima et al., 2018). Unless noted otherwise, the curves assume a hypothetical bridge deck with the following parameters (category codes are given in parentheses):

- Condition Rating CR = 7
- ADTT = 100
- IECC Climatic Region = Cold (5)
- Deck Protection = None (0)
- Deck Structure Type = Concrete Cast-in-Place (1)
- Distance from Seawater > 3 km (1)
- Functional Class = Urban (2)
- Maintenance Responsibility = State Highway Agency (1)
- Structure Type = Steel – Simple Span (3)

Fig. 5 compares mean survival curves for different condition ratings (CR). A clear trend can be observed for higher CR to be associated with lower survival probabilities. In other words, a CR = 9 (i.e. brand-new condition) is much more difficult to maintain over time than is, say, a CR = 4 (i.e. advanced deterioration condition). It should be noted that this differs from what the authors (and other researchers) have found previously, when censoring was not considered, i.e. when all data was treated as uncensored. Qualitatively, the survival probabilities would fall much quicker and TICR would be underestimated, i.e. deck deterioration would be overestimated. The reason for this is that the Bayesian survival analysis discussed here is capable of considering censored data, i.e. data that cannot be fully observed (Fig. 2).

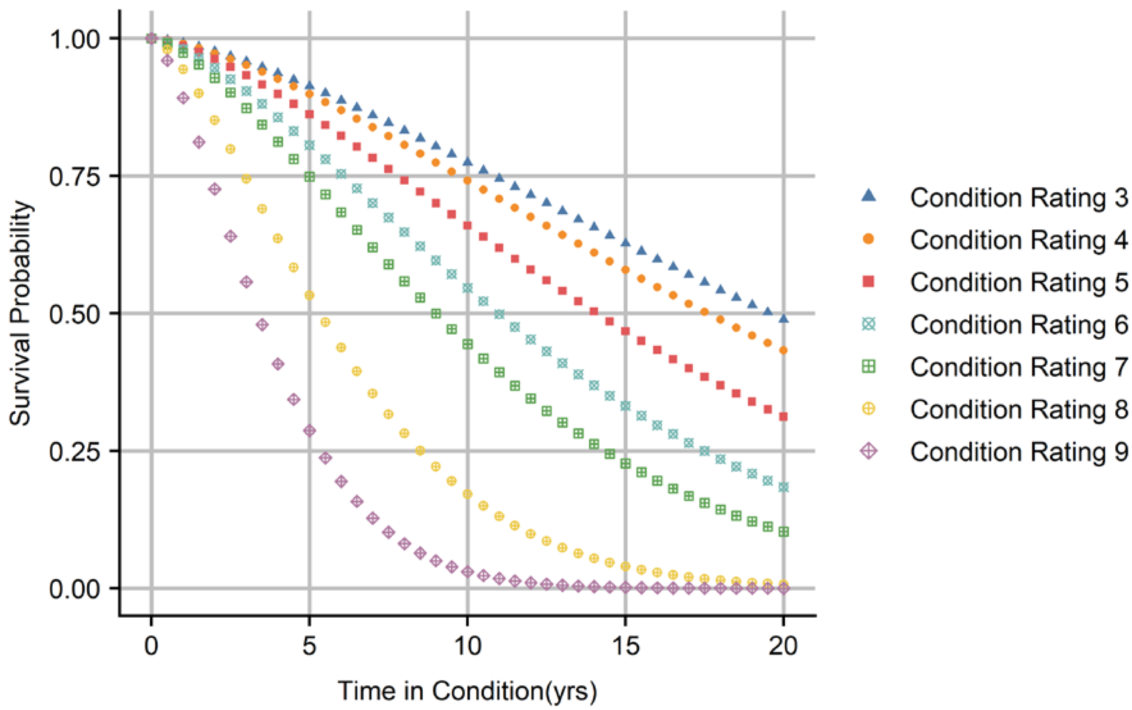

Figure 5. Mean survival curves for bridge deck CR values.

To give an example of how to interpret a survival curve plot, Fig. 6 is used. The question can be asked: What are the probabilities that a concrete bridge deck will be assigned a CR = 7 for more than 10 years, i.e. TICR ≥ 10 yr, for ADTTs of 10 and 10,000? Answer: The probabilities that a concrete bridge deck is assigned CR = 7 with a TICR ≥ 10 yr are 48.8% and 35.3% for ADTT = 10 and 10,000, respectively, which is a 13.5% difference in survival probability. From Fig. 6, it is also obvious that lower ADTT lead to higher survival probabilities, i.e. a lower chance that a bridge deck is assigned a lower CR, which makes sense.

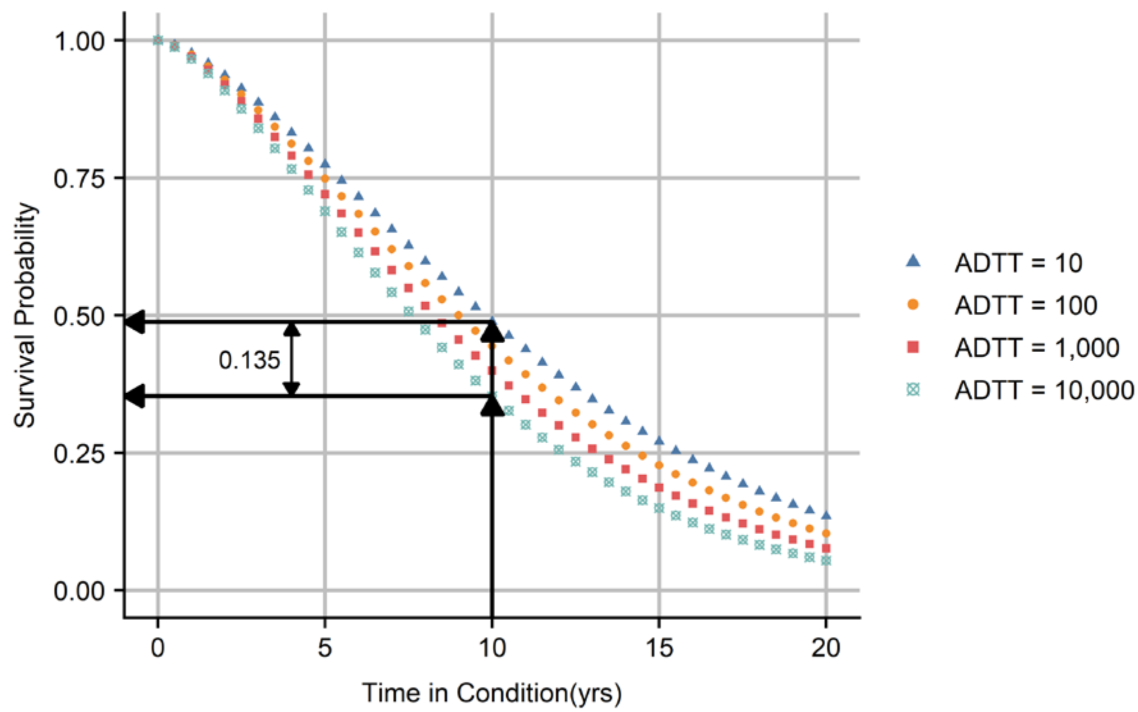

Figure 6. Mean survival curves for select ADTT values. Note: arrows correspond to example discussed in the text.

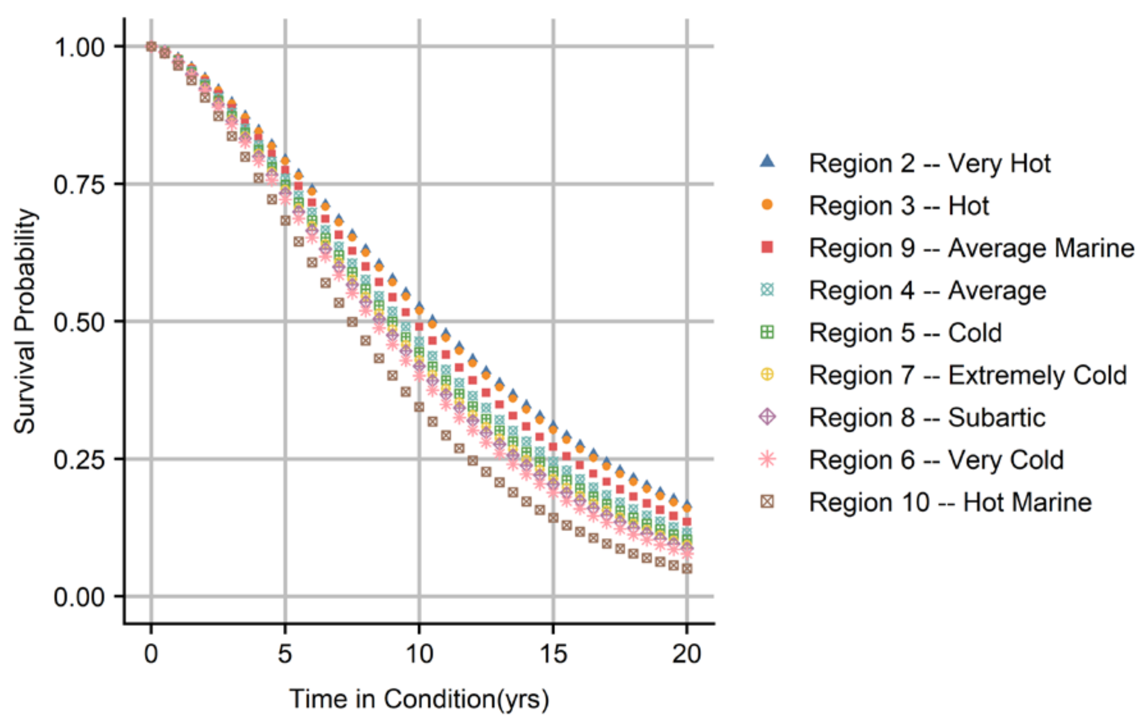

Figure 7. Mean survival curves for IECC Climatic Regions.

Fig. 7 shows the effect of different environments following IECC Climatic Regions. Overall, it can be observed that hotter climates are associated with higher mean survival probabilities, which is reasonable. As an exception, the lowest survival probability is associated with Region 10 (hot marine).

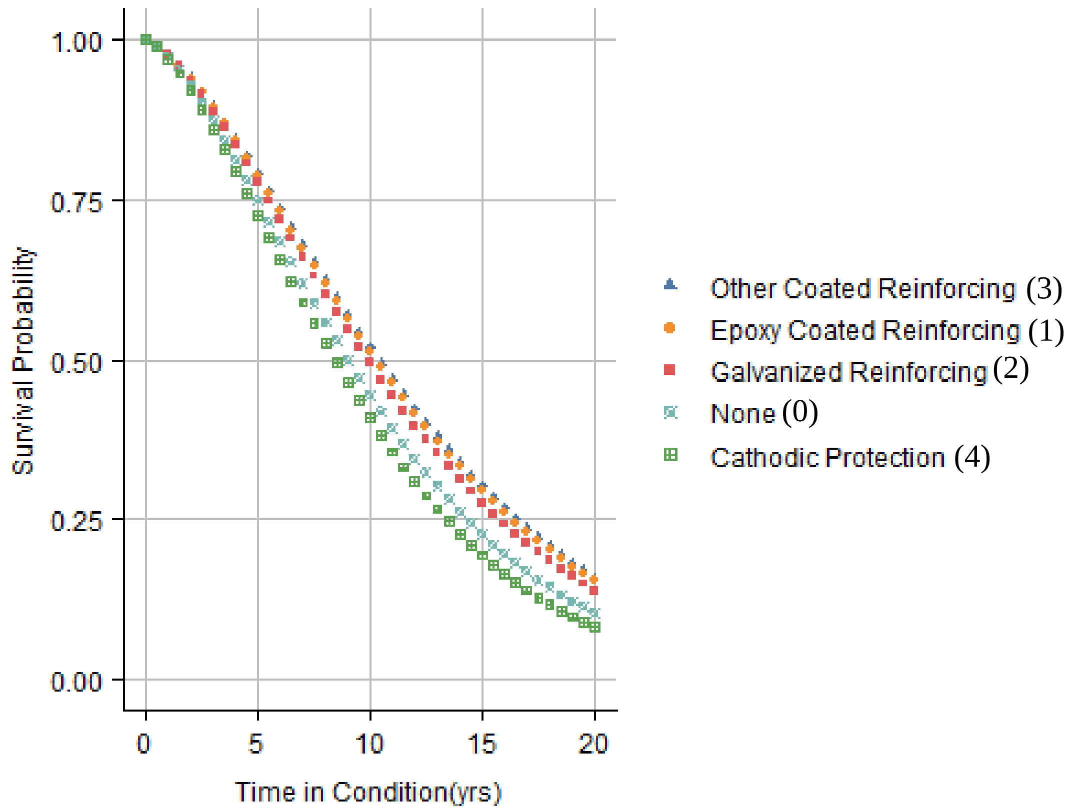

Figure 8. Mean survival curves for parameter "Deck Protection". Category codes in parentheses.

In Fig. 8, the effect of protective measures on survival probabilities is illustrated. As can be observed, some protective measures appear more helpful than others. For example, both epoxy-coated as well as galvanized rebars appear to increase mean survival probability compared to when black rebars (identified as "None") are used.

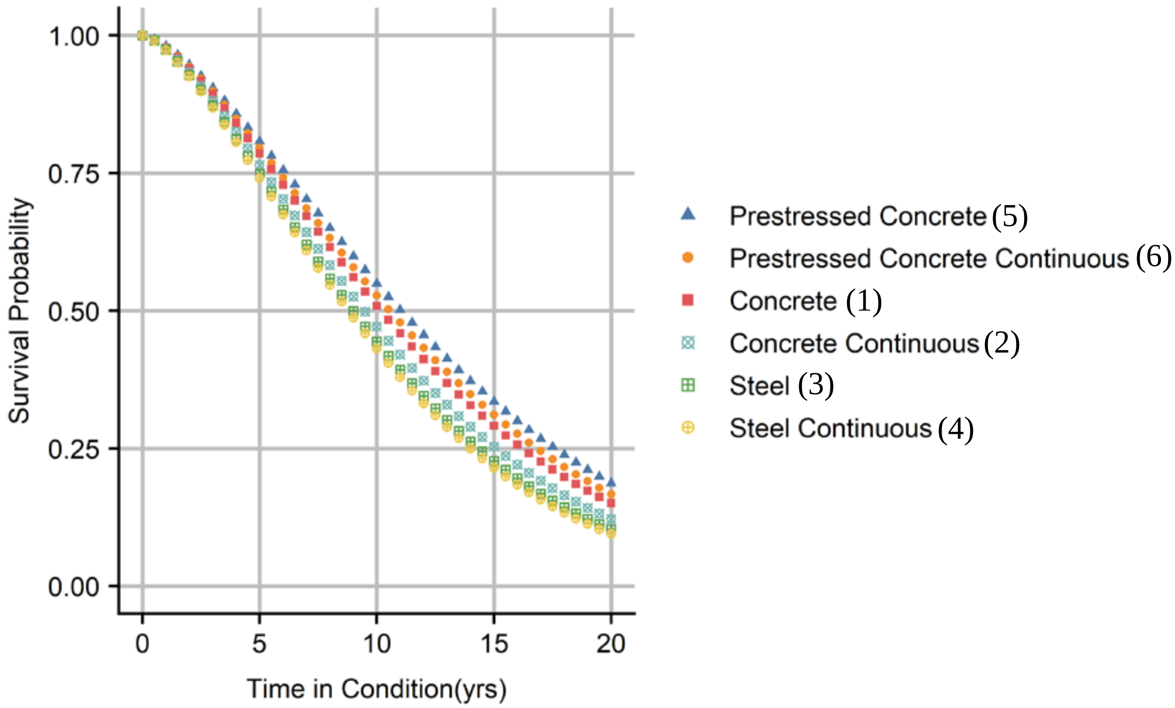

Figure 9. Mean survival curves for parameter "Structure Type". Category codes in parentheses.

Finally, Fig. 9 shows the effect of the type and material of the structure supporting the bridge deck on its performance. Overall, it can be observed that simple-span bridges have bridge decks with higher mean survival probabilities compared to continuous span bridges. This can be explained by the fact that simple-spans do not have negative bending regions which can results in deck tension stresses and thus the bridge deck is less likely to develop cracking due to traffic loading. In terms of material of the supporting structure, prestressed concrete appears to perform better than steel and reinforced concrete.

Summary and Conclusions

The research performed as part of Task 10 created a nationwide database for concrete highway bridge deck performance data based on the National Bridge Inventory (NBI) and used it to establish relationships between deck performance and time-in-condition ratings (TICR) as well as deterioration rates (DR). Two types of analyses were implemented, which can both be used to help an owner or agency in the process of prioritizing bridge deck preservation work. Bayesian survival analysis was found particularly useful in that it produces survival curves that are illustrative and of practical value. This analysis also offers a path for future bridge performance research to include censored observations. Instead of excluding large amounts of observations or treating them as uncensored, partial observations of TICR survival times can be parsimoniously included in studies that examine the effects of various parameters. In the presented analysis, more accurate estimates of bridge deck performance are enabled by not only leveraging the sheer size of the NBI, but also extracting valuable information from censored data that would otherwise have been excluded from the study.

Overall findings regarding concrete bridge deck performance that are independent of the analysis used can be summarized as follows:

- A clear trend was found for higher CR to be associated with lower survival probabilities, or lower TICR.
- Warmer climatic regions have higher TICR, and hence higher survival probabilities, compared

to colder regions.

- Increasing ADTT leads to decreasing TICR, or lower survival probabilities, indicating the positive correlation between higher truck traffic and increased deterioration.
- Both coated as well as galvanized rebars increase mean survival probability, or increase TICR, compared to when black rebars are used.
- Simple span bridges have higher TICR, or higher survival probabilities, than continuous bridges since they do not have a negative bending region that causes tension in the bridge deck.

Future work includes adding construction-related parameters such as early-age concrete properties and actual rebar cover, environmental exposure parameters such as freeze-thaw cycles and use of deicers, as well as utilizing more sophisticated modeling accounting for multiple independent variables simultaneously, including individual bridge propensities to deteriorate and state-level effects on rating consistency, and exploring more causal explanations of observed deterioration.

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Contact — For more information, contact:
Federal Highway Administration (FHWA)
Office of Bridges and Structures, Reggie Holt - reggie.holt@dot.gov

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