National-scale bridge element deterioration model for the USA

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

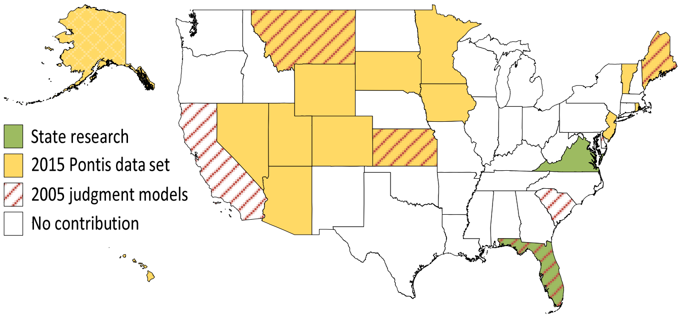

Figure 1. Sources of data

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.

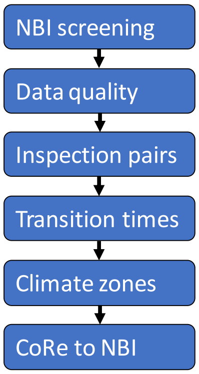

Figure 2. Model development process

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.

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.

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

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