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Evaluation of Illinois Bridge Deterioration Models

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16. Abstract

The National Bridge Inventory bridge inspection system ranks the condition of bridge components on a scale of zero to nine. The resulting condition ratings represent an important element considered in deciding measures for bridge maintenance, repair, and rehabilitation. Thus, forecasting future condition ratings well is critical to reliable planning for these activities and estimating the costs. The Illinois Department of Transportation currently has deterministic models for this purpose. This study's objective is to review the current models using condition rating histories gathered from 1980 to 2020 in Illinois for the following bridge components: deck, superstructure, substructure, culvert, and deck beam. The results show the current Illinois Department of Transportation models are inadequate in forecasting condition ratings, producing overestimates of the transition times between two condition rating levels for these components / systems, except for the deck beam, which is underestimated. It is recommended that the mean transition times found in this study from condition rating histories are used to replace the current models as a short-term solution. Further research is recommended to develop probabilistic models as a long-term solution to address observed significant variation or uncertainty in condition rating and transition times between condition rating levels.

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EXECUTIVE SUMMARY

Roadway bridge structures in Illinois are inspected on a biennial basis for their safe operation in the transportation infrastructure, some of which may need more frequent inspections. One of the inspection results is the National Bridge Inventory (NBI) condition rating (CR). The historical CR data for each bridge represents important information used for decision-making for bridge maintenance, repair, and rehabilitation (MR&R). The CR histories focused herein were for the following bridge components in Illinois: deck, superstructure, substructure, culvert with shallow fill less than 2 feet, culvert with fill equal to or greater than 2 feet, and deck beam. Accordingly, the Illinois Department of Transportation (IDOT) also uses models to forecast the evolution of bridge CR for planning and cost estimation.

The objective of this project was to review IDOT's current deterioration models using the available CR histories. This data set spanned from 1980 to 2020. The results showed the current IDOT models mostly overestimated the CR transition time and the life of the Illinois bridge components / systems identified above, except the deck beam. For several cases (superstructure, substructure, and culvert with fill equal to or greater than 2 feet), the overestimation / forecast appeared to be excessive. Indiana, the most compatible neighboring state to Illinois in terms of climate, served as a benchmark for Illinois. The deterioration curves based on historical CRs between Illinois and Indiana were close or very close to each other. Both were away or far away from Illinois' current models. Variation among the regions was well noticeable, indicating the need for regional deterioration models as opposed to statewide models.

Accordingly, regional deterioration models based on the cumulated CR histories are recommended for use in Illinois. This measure would make the forecast more consistent with recorded MR&R practice. In addition, probabilistic NBI deterioration models, including standard deviation, are recommended to account for the observed uncertainties and variations. An example application using the Weibull distribution is also presented in this report. Enhanced models for all bridge components and culvert systems using this approach are recommended for development in future studies to fully account for the observed randomness of CR values in the cumulated histories of past decades.

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CHAPTER 1: INTRODUCTION

As part of the effort to maintain bridge structures in the United States for an acceptable level of service, bridges are monitored through a periodical inspection program. The interval of these inpections is mandated at a maximum of two years. When needed, this interval can be as short as six months. For example, those bridges identified as fracture critical structures are inspected more frequently than two-year intervals. Namely, those bridges with conditions more uncertain with respect to their possibly adverse developments are monitored more closely. When needed, these bridges may be subject to special measures, such as immediate repair or strengthening as well as closure to traffic.

Bridge condition rating (CR) as a result of these inspections has two scale systems in Illinois. The first is the National Bridge Inventory (NBI) system, which ranks the condition of bridge components on a scale of zero to nine (i.e., from the poorest to the best) (FHWA, 1995). The targeted bridge components are aggregated by deck, superstructure, and substructure for recording purposes, etc., without further describing more details such as a joint or a beam. The second is the National Bridge Element (NBE) system, which is now used in the AASHTOWare bridge management (BrM) system, previously the Pontis system. There are three to five levels or states of condition, depending on the bridge element (AASHTO 2019). The elements can be more detailed bridge components, such as an expansion joint, concrete beam, steel beam, and paint on steel beam. This second system started in the 1990s or even later, depending on when the bridge owner adopted Pontis or BrM.

This study focuses on the NBI CR system. In this direction, IDOT has included the following bridge components / systems in its CR histories: deck, superstructure, substructure, culvert with shallow fill (< 2 feet), culvert with deep fill (≥ 2 feet), and deck beam. For planning purposes, IDOT uses deterioration models based on CR to forecast and perform other associated management activities such as cost estimation. Table 1 presents the current IDOT models for the identified bridge components / systems. They are given in transition time (in number of years) between every two CR levels. For example, the transition time from a CR of 4 to 3 for a deck is estimated at five years in Table 1. In the table, 9999 indicates no available model, because no or little data are available to support an estimated transition time for the case. Transitions from a CR of 2 and below belong to this category. The objective of this study is to review and evaluate the current models using the available CR histories from inspections. The models' ability to forecast or predict is focused on herein.

Table 1. Current IDOT Deterioration Models for Bridge Components / Systems

NBI	Deck	SuperStr	DeckBeam	SubStr	Culvert_LowFill	Culvert_HighFill
0	9999	9999	9999	9999	9999	9999
1	9999	9999	9999	9999	9999	9999
2	9999	9999	9999	9999	9999	9999
3	2.6	4	1.5	4	4	5.8
4	5	7	4.5	8	6	8
5	14	16	6.4	14.5	9	12
6	10	14	10	18.5	16	20
7	15	18	3.25	19	18	20
8	3	12.5	3.5	15.5	18	18
9	1	1	1	1	1	1

CHAPTER 2: STATE OF THE ART AND PRACTICE

This study surveyed the practices of state bridge owners in the focused area. Only two critical questions were included in the questionnaire in order to receive a prompt response and most relevant information. The questions were given as follows:

> Question 1. Does your agency use condition rating deterioration models to forecast future condition ratings and/or expected lives for bridges and/or their components?
>
> Question 2. If you answered “Yes” above, could you please share the models for any of the following items:
>
> - Deck, Superstructure
> - Precast Prestressed Concrete Deck Beam Superstructure
> - Substructure and Culverts (fill depth less than 2 feet and fill depth greater than or equal to 2 feet)
>
> When providing models, please indicate whether they are for the entire state or a portion of the state (such as a region or district in the state). Also, please provide a copy of or a link to the report documenting the models’ development, if such a report exists.

The questionnaire was issued by the IDOT Technical Review Panel (TRP) of this project to the state members of the AASHTO Standing Committee on Research (SCOR). The responses were also gathered by the TRP. A total of 13 states responded within the 30-day deadline; Table 2 summarizes the results. The responding states included most of those neighboring Illinois, which is considered very helpful.

Table 2. Summary of State Survey

State	**DE**	**DC**	**IN**	**KY**	**MI**	**MN**	**MO**	**MT**	**NE**	**OH**	**WA**	**WI**	**WY**
Deterioration models available?	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes
State or region based?	State	State	Region	State	State	State	N/A	N/A	State	State	N/A	State	State

The results reveal that most states that responded to the questionnaire have bridge deterioration models, except Missouri, Montana, and Washington. However, Missouri and Montana are in the process of developing their models at the time they responded to the questionnaire. In addition, the available models are mostly for the entire state, except Indiana, which has regional models within the state. The regions are referred to as north, central, and south.

Indiana is a neighboring state to Illinois with a similar spread in latitude. Its climate condition is also similar to that of Illinois, offering an opportunity to compare and benchmark Indiana's models with Illinois' deterioration models. This is reported in Chapter 4.

The survey also identified several studies for the responding states, which represent the state of the art and practice. These studies are briefly discussed below, along with other relevant publications identified by the research team.

Phares et al. (2004) conducted a study on the variation of CR at the FHWA Turner-Fairbanks Highway Research Center. Forty-nine experienced bridge inspectors from 25 states participated in the study. They were given the same seven bridges in the local area and completed their respective inspections of the bridges without interaction with other participating teams. The researchers analyzed the CRs obtained by the inspection teams to observe possible variations for their respective bridges. A wide spread of CR values was found. For example, for Bridge B521, the deck CR values were between 3 and 7, the superstructure values between 4 and 8, and the substructure values between 3 and 7. Note that the transition times between two CR levels are functions of CR. As a result, it should not be a surprise to observe equally wide or further wider variation in the transition times.

As mentioned in Chapter 1, BrM uses a different CR system from the NBI system. It also uses a probabilistic approach for forecasting. The so-called Markov chain model was started in the 1980s (Fu & Moses, 1986; Fu, 1987) for bridge component deterioration modeling. Instead of projecting exactly how many years it may take for a bridge component to deteriorate to the next condition level, the Markovian model produces the chances (probabilities) of such an evolution. This idea has been implemented in BrM and Illinois practice. Given the observed wide variation in CR and the transition time, this probabilistic approach has a strong merit to be applied here in Illinois. Note also that the concept of Markovian modeling has been improving for realistically modeling bridge element evolution (Fu and Devaraj 2008, Fu 2010).

Kelley (2016) proposed a process for the Michigan Department of Transportation to evaluate the trends in bridge deterioration rates at regular intervals to identify the effectiveness of preventive maintenance and other actions. The process appears to be applicable for both CR of the NBI and NBE (i.e., BrM) systems. The median is used for assessing deterioration rates, acknowledging the variation in CR values.

Nelson (2014) conducted a study on NBI bridge deck deterioration rates for the Minnesota Department of Transportation using decades of reinforced concrete deck inspection CR histories of approximately 2,600 bridges. Deck deterioration rates were determined by the length of time bridge decks stay, or drop, at NBI CR. These factors were considered in affecting the rate of bridge deck deterioration: type of reinforcement (black, epoxy-coated top, and all epoxy coated), presence of concrete overlay, average daily traffic, presence of 3 inches of cover to the top mat of reinforcement, superstructure material, and location.

Hatami and Morcous (2011) reported that the Nebraska bridge management system used the previous national average deterioration rates for modeling and forecasting. These simple models were one CR drop in the deck's CR every eight years and one drop in the superstructure's and substructure’s CR every 10 years. Their study was to develop deterioration models based on CR histories obtained from bridge inspections between 1998 and 2010. The impact of governing factors is considered in developing the models, such as structure type, deck type, wearing surface, deck protection, average daily traffic, average daily truck traffic, and the highway district.

Hunt et al. (2011) conducted a study for the Ohio Department of Transportation on bridge component deterioration rates. The study applied statistical analysis and modeling of the bridge management system data to provide insights to the rate of degradation and maintenance requirement of bridges under different environmental conditions, locations, and other factors. Age resetting algorithms and Markov models were utilized to develop operational performance indices forecasting for general appraisal, wearing surface, floor condition, and protective coating systems.

CHAPTER 3: ILLINOIS BRIDGE CONDITION RATING DATA AND ANALYSIS APPROACH

IDOT provided Illinois' bridge CR data to the research team for this project. The data included inspection results spanning from 1980 to 2020. The data set included items such as district, structure number (SN), inspection date, status, structure length, year of original construction, highway system, whether the bridge is on the national highway system (NHS), whether the bridge is a major structure (i.e., a larger structure), CR, etc. Table 3 presents the typical appearance of a data set.

Table 3. Typical Items of IDOT Bridge CR Histories

District	SN	InspDate	Status	LengthTotal	OriginalConstructionYear	System	NHS	IsMajor	DeckCondition
1	0169714	1/1/1980	1	83.0	1958	Toll	Yes	0	9
1	0169718	1/1/1980	1	215.0	1958	Toll	Yes	0	9
1	0169721	1/1/1980	1	365.0	1958	Toll	Yes	0	9
1	0169724	1/1/1980	1	178.0	1958	Toll	Yes	0	9
1	0169743	9/18/1980	1	180.0	1958	Toll	Yes	0	8
1	0169744	9/18/1980	1	180.0	1958	Toll	Yes	0	8
1	0169746	9/17/1980	1	150.0	1958	Toll	Yes	0	6
1	0169749	9/16/1980	1	184.0	1958	Toll	Yes	0	6
1	0169750	9/16/1980	1	184.0	1958	Toll	Yes	0	6
1	0169751	9/15/1980	1	282.0	1958	Toll	Yes	0	6

The data set was first sorted according to bridge, so that the historical CRs for each bridge were obtained. These histories were then classified into one of four exclusive categories regarding the CR behavior over time.

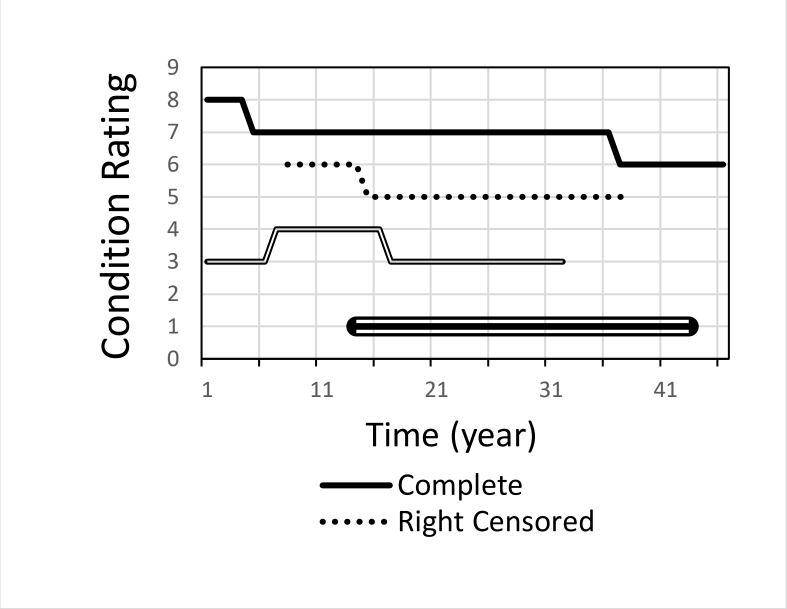

Figure 1. Chart. Categories of CR histories.

The first category is referred to as a complete history. Namely, the history has recorded continued CR deteriorations from one level to another, and then further one or more levels lower. This case is shown in Figure 1 as the top solid line. The second category is referred to as a right censored history, because there is only one first drop in CR. The lower level of CR has not registered another drop. As such, it is not conclusive as to how long the second level of CR has lasted. This case is indicated in Figure 1 as the dotted line. It was excluded in the comparison of CR histories with the current IDOT deterioration models shown in Table 1.

The third category is more complicated, involving CR increase. Such increases may be due to improvement work such as resurfacing or overlay of the bridge for improved ride. However, these factors are beyond the scope of this study on deterioration. This case is shown in Figure 1 as the double line. The last category is referred to as an incomplete history, without change in CR. It is displayed in Figure 1 as the triple line. This case did not register a change in CR. It was, thus, unable to contribute to the review of current deterioration models reported herein.

Depending on the bridge component / system (i.e., deck, superstructure, substructure, either culvert type, or deck beam), approximately 20% to 30% of the CR histories belong to the complete data category, 40% to 50% to the unsure, 15% to 30% to the right censored, and 10% to the incomplete. Because of this study’s limited scope, only the data belonging to the complete category have been used in the analysis and results reported herein.

The provided CR data identified the district in which each bridge is located. Figure 2 presents the nine districts and five regions in Illinois. One of the tasks of this project was to examine the current IDOT deterioration models’ reliability for regions to see if regional models would be justifiable to adopt. This would be a change from the current statewide models applied for all regions.

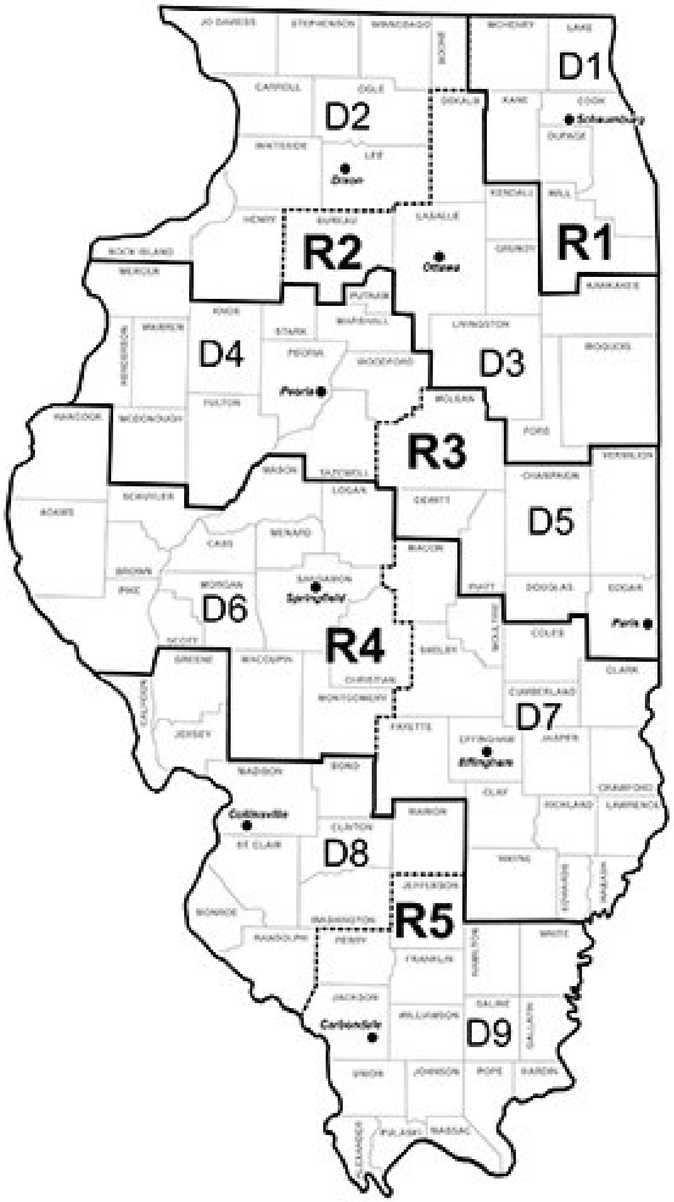

Figure 2. Photo. Nine districts and five regions in Illinois.

CHAPTER 4: ANALYSIS AND RESULTS

TRANSITION TIME BETWEEN TWO CONDITION RATING LEVELS

According to the current deterioration models in Table 1, the analysis first focused on the transition times between CR levels. Given the inspection dates in the CR data (Table 3), the transition time from one CR to a lower CR is computed in years, equal to the total number of days between the two inspections divided by 365 days per year. The results are presented below for each component / system.

Deck

A comparison of the analysis results for the deck are presented in Table 4. The first column is the CR level interval. The second column displays the current IDOT model in number of years taken from Table 2. The third column includes the analysis results of the Illinois State histories provided to this project, in terms of mean and standard deviation (Stdev). Comparison of this column with the second column, the IDOT deterministic model, is a focus of this study. This comparison also offers information on variation in the CR histories. This variation is relatively significant compared with the mean value. The next two columns show the mean and Stdev for the five regions in comparison with the state mean and Stdev, as well as IDOT's current deterministic models in the second column.

The comparison in Table 4 stops at CR 2 to 1, because no historical data are available in the provided data. Starting from CR 4 to 3 downward, available data become sparse. As such, the number of data points (i.e., number of structures or histories) is indicated there, highlighting the need for additional care for comparison. This is especially important when involving the regional data and results. The regional data integrate to the state data. Therefore, when the total number of data points for the state is small, each of the five regions will have a further smaller data set, making each region's results likely less reliable. The number of data points also reduces with CR. Namely, fewer data points are available at CR 8 to 7 compared with CR 9 to 8, at CR 7 to 6 compared with CR 8 to 7, etc. This is generally true for other bridge components (superstructure and substructure) and structure systems (culverts).

The variation in the transition times is also significant. For example, for Region 3 at CR 9 to 8, the Stdev/Mean = 2.52/3.07 = 82%. As a reference, the bridge's live load effect (truck load effect) has been found to have this ratio at about 20% to 30%, depending on the site. This significant variation appears to be due to the variation in CR, as presented in Phares et al. (2004) and noted above.

In addition, the current IDOT model seen in Table 4 is unable to forecast well compared with the means from the CR histories. For the deck, the prediction is off for individual transition times, either underestimating or overestimating, sometimes by a large amount. For example, for CR 8 to 7, the model predicts three years, but the mean from the histories is 9.21 years. For CR 5 to 4, the model predicts 14 years, but the historical data give only 7.53 years. This also highlights inadequate capability of the deterministic model; it is unable to account for variations seen in the CR histories. When MR&R is planned pertaining to current CR and its trend of evolution to the next level, a realistic and reliable forecast of CR to the next level can be critical. The current model's ability to forecast appears to be inadequate.

Table 4. Transition Time Comparison between Models and Histories for Deck

CR	Model	State Data	Regional Data	
		Mean/Stdev	Mean/Stdev	Region
	(yrs)	(yrs/yrs)	(yrs/yrs)	
9 to 8	1	2.81/2.15	1.92/1.15	1
			2.69/2.15	2
			3.07/2.52	3
			3.12/2.05	4
			3.28/2.31	5
8 to 7	3	9.21/6.49	6.59/4.89	1
			8.73/6.09	2
			9.16/6.31	3
			11.54/6.87	4
			10.34/7.17	5
7 to 6	15	10.45/7.27	11.67/7.19	1
			10.84/7.58	2
			8.74/6.70	3
			10.43/7.39	4
			11.11/7.25	5
6 to 5	10	8.35/6.11	10.00/5.99	1
			9.52/7.61	2
			6.88/4.68	3
			7.78/5.81	4
			8.74/6.54	5
5 to 4	14	7.53/5.43	7.93/6.17	1
			9.73/7.38	2
			6.26/4.08	3
			8.52/5.86	4
			7.49/4.65	5
4 to 3	5	6.07/4.67	2.00/0.02	1
		(37 data points)	10.99/8.21	2
			6.02/4.03	3
			N/A*	4
			3.49/1.05	5
3 to 2	2.6	3.91/4.36	N/A*	1
		(2 data points)	N/A*	2
			3.91/4.36	3
			N/A*	4
			N/A*	5

*N/A = Inadequate data

Table 4 also shows the regional means and Stdevs to be away from the state mean and Stdev, respectively. This highlights the need for regional models, instead of a single state model for all regions, which has been the practice for decades. There may be other factors influencing these behaviors in different regions. For the deck, such possible factors may be vehicle / truck traffic, total vehicle / truck traffic volume over the transition time, number of freeze-thaw cycles, other weather-related parameters, black or coated rebars, top concrete cover depth, etc. These factors have not been included in this study due to its limited scope.

Table 5 offers a comparison for the total transition time, which is the sum of all transition times. Only those transitions for which there are some historical data available are included in this sum. For a fair comparison, only the corresponding transitions in the current deterministic models are included in Table 5. In particular, Table 5 stops at CR 4 to 3, beyond which data become clearly inadequate. The current deterministic models also stop at this transition as do the regional data–based sums.

In addition, Table 5 indicates Region 4 is unable to provide a result for the last transition, CR 4 to 3. In other words, the mean and Stdev values in Table 5 can be compared directly with each other and the deterministic sum for the current IDOT model, excluding Region 4. Nevertheless, the Region 4 values have only one case missing out of six: CR 4 to 3. Therefore, the Region 4 results in Table 5 may still serve as an approximate comparison with the last transition missing. This transition may last about six years, the state mean transition time in Table 4.

Table 5 also shows that the current model overestimates the life by 8% (=48/44.42-1), according to the mean of statewide histories. For Regions 1 and 3, however, the current deterministic model overforecasts by about 20%. In contrast, the model underforecasts Region 3's mean by 9%. Again, this behavior of missing the mean is likely due to the observed large variation in the CR histories. To that end, a probabilistic approach to the forecast would be able to explicitly account for the variation and enhance forecast reliability.

Table 5. Total Transition Time Comparison between Models and Histories for Deck

Model	**State Data**	**Regional Data**	
	Mean	Mean	Region
(yrs)	(yrs)	(yrs)	
48	44.42	40.11	1
		52.50	2
		40.13	3
		41.39*	4
		44.45	5

*CR 4 to 3 has inadequate data, not contributing to this sum.

Superstructure

Table 6 provides the same comparison as Table 4 but for the bridge superstructure. A major difference in this comparison from that of the deck is that the current deterministic models overestimate the transition times, except the first transition, CR 9 to 8. Note that according to IDOT personnel, by definition CR 9 is supposed to be for the first year of the bridge's life. However, inspectors have used CR 9 beyond the first year, resulting in the current model underestimating the transition time. This extended transition time for CR 9 is seen in all components / systems studied in this project: deck, superstructure, substructure, the two culvert types, and deck beam. If inspectors' perceptions about and use of CR 9 cannot be effectively changed, then the IDOT model for this transition will need to change to model what realistically happens in the inspection and the recorded CR.

Overestimation of the current IDOT model happens quite significantly sometimes. For example, the transition from CR 5 to 4 is forecast by the model at 16 years, but the state mean is only 7.13 years, overestimating by 124%, without mentioning the Stdev at 6.15 years or a coefficient of variation at 86% (=6.15/7.13). Table 6 also displays significant Stdev values for large variation and uncertainty, as seen earlier in Table 4. The table also demonstrates the variations in regions from the state statistics and, thus, a need for regional models.

Table 6. Transition Time Comparison between Models and Histories for Superstructure

CR	**Model**	**State Data**	**Regional Data**	
		Mean/Stdev	Mean/Stdev	Region
	(yrs)	(yrs/yrs)	(yrs/yrs)	
9 to 8	1	3.54/2.73	2.53/1.74	1
			3.19/2.33	2
			3.85/3.51	3
			4.43/2.66	4
			4.07/2.64	5
8 to 7	12.5	9.99/6.38	9.00/5.90	1
			9.31/6.17	2
			9.85/6.93	3
			11.37/6.38	4
			10.99/6.20	5
7 to 6	18	12.81/8.24	10.78/6.91	1
			12.53/8.12	2
			11.84/8.34	3
			15.80/8.87	4
			14.12/8.33	5
6 to 5	14	9.29/6.88	10.88/7.52	1
			9.65/7.57	2
			7.84/6.45	3
			10.48/6.08	4
			8.01/5.85	5
5 to 4	16	7.13/6.15	9.79/7.58	1
			8.57/7.59	2
			4.80/4.11	3
			8.66/5.84	4
			7.61/5.46	5
4 to 3	7	4.40/4.91	5.23/5.68	1
		(43 data points)	7.54/8.15	2
			3.14/2.90	3
			N/A*	4
			4.12/4.84	5
3 to 2	4	3.52/4.12	3.34/2.33	1
		(7 data points)	N/A*	2
			4.25/5.40	3
			N/A*	4
			N/A*	5

*N/A = Inadequate data

Table 7 provides a comparison of the total transition time with historical data, to the extent of available data. In other words, the transitions from CR 3 to 2 and below are excluded, because there are not historical data. The current model overforecasts the state mean by 46%. The worst overforecast for a regional mean is at 66% for Region 3.

Table 7. Total Transition Time Comparison between Models and Histories for Superstructure

Model	State Data	Regional Data	
	(Mean)	(Mean)	Region
(yrs)	(yrs)	(yrs)	
68.5	47.04	48.21	1
		50.79	2
		41.32	3
		50.74*	4
		48.92	5

* CR 4 to 3 has inadequate data, not contributing to this sum.

Substructure

Table 8 is a comparison of the bridge substructure among the current model, state histories, and regional histories. Similar to the bridge superstructure comparison in Table 6, the current model overforecasts each CR transition time. As a result, the total transition time by the current model is a significant overestimate, as seen in Table 9.

Table 8 for the substructure still demonstrates significant variation and uncertainty in the transition times, indicated by the large Stdev values compared with the respective means. Variation in the statistics among the regions are apparent as well, compared to the state statistics.

Table 9 shows the sums of the transition times for the current model, state means, and regional means for comparison. The current model is seen to overforecast the state mean by 47%, and the lowest regional mean by 80%.

Table 8. Transition Time Comparison between Models and Histories for Substructure

CR	Model	State Data	Regional Data	
		Mean/Stdev	Mean/Stdev	Region
	(yrs)	(yrs/yrs)	(yrs/yrs)	
9 to 8	1	3.45/2.67	2.35/1.65	1
			3.16/2.64	2
			3.95/3.36	3
			4.12/2.49	4
			3.86/2.17	5
8 to 7	15.5	11.67/6.72	10.85/6.31	1
			11.84/6.16	2
			10.49/6.41	3
			13.52/7.32	4
			12.86/7.18	5
7 to 6	19	12.38/7.96	11.79/7.38	1
			12.68/8.63	2
			11.72/8.25	3
			14.42/8.99	4
			12.67/6.88	5
6 to 5	18.5	10.07/7.50	8.62/6.53	1
			10.45/8.04	2
			10.05/7.79	3
			13.88/7.12	4
			9.59/7.55	5
5 to 4	14.5	7.63/6.75	7.37/6.10	1
		36 data points	14.52/10.94	2
			5.81/2.24	3
			3.10/1.65	4
			3.93/2.64	5
4 to 3	8	6.89/9.25	1.50/0.70	1
		9 data points	N/A*	2
			4.64/1.33	3
			N/A*	4
			N/A*	5
3 to 2	4	N/A*	N/A*	1
		1 data point	N/A*	2
			N/A*	3
			N/A*	4
			N/A*	5

*N/A = Inadequate data

Table 9. Total Transition Time Comparison between Models and Histories for Substructure

Model	State Data	Regional Data	
	Mean	Mean	
(yrs)	(yrs)	(yrs)	Region
76.5	52.09	42.48	1
		52.65*	2
		46.66	3
		49.04*	4
		42.91*	5

*CR 4 to 3 has inadequate data, not contributing to this sum.

Culvert with Fill Less than 2 Feet

Table 10 presents a comparison of the current deterministic model, state history, and regional history for culverts with fill less than 2 feet. The current model overforecasts for more transition time cases than underforecasts. The overestimation of the current model occurs at the middle range of CR (CR 8 to 7, CR 7 to 6, and CR 6 to 5) and underestimation happens at the later stage (CR 5 to 4 and CR 4 to 3). Because the middle range is longer than the later range, overforecasting is more significant than underforecasting. As a result, Table 11 shows that the overestimated total transition time by the current model is outstanding. Significant variation or outstanding Stdev values are still seen in this case, as shown in Table 10.

Table 10. Transition Time Comparison between Models and Histories for Culvert with Fill Less than 2 Feet

CR	Model	State Data	Regional Data	
		Mean/Stdev	Mean/Stdev	Region
	(yrs)	(yrs/yrs)	(yrs/yrs)	
9 to 8	1	2.93/2.06	2.40/2.24	1
			3.53/2.18	2
			2.69/1.95	3
			2.79/1.69	4
			2.68/2.05	5
8 to 7	18	10.33/6.57	8.36/5.43	1
			11.96/6.63	2
			10.01/6.47	3
			10.52/7.43	4
			8.81/5.61	5
7 to 6	18	11.88/7.60	10.62/6.90	1
			11.03/7.35	2
			12.07/7.99	3
			14.03/7.93	4
			13.15/8.09	5

CR	Model	State Data	Regional Data	
		Mean/Stdev	Mean/Stdev	Region
	(yrs)	(yrs/yrs)	(yrs/yrs)	
6 to 5	16	12.56/8.34	13.53/8.92	1
			13.12/7.61	2
			10.47/8.52	3
			13.61/7.56	4
			13.93/9.15	5
5 to 4	9	11.10/9.06	11.87/10.66	1
			N/A*	2
			6.62/4.13	3
			16.68/7.25	4
			5.27/5.68	5
4 to 3	6	10.15/10.39	N/A*	1
		(3 data points)	N/A*	2
			N/A*	3
			N/A*	4
			N/A*	5
3 to 2	4	N/A*	N/A*	1
		(1 data point)	N/A*	2
			N/A*	3
			N/A*	4
			N/A*	5

*N/A = Inadequate data

Table 11. Total Transition Time Comparison between Models and Histories for Culvert with Fill Less than 2 Feet

Model	State Data	Regional Data	
	Mean	Mean	Region
(yrs)	(yrs)	(yrs)	
62	48.8	46.78	1
		39.64*	2
		41.86	3
		57.63	4
		43.84	5

*CR 5 to 4 has inadequate data, not contributing to this sum.

Culvert with Fill Equal to or Greater than 2 Feet

Table 12 presents a comparison of the current deterministic model, state history, and regional history for culverts with a deeper fill. For all cases with historical data, the current model overforecasts, except the first transition from CR 9 to 8. These overforecasts appear very significant. For example, CR 8 to 7 is overforecast by about 75%. Because of these overforecasts, the current model significantly overestimates the total transition time, as seen in Table 13.

Table 12 also exhibits large variations as usual from the mean values in the state and regional histories of CR, as also seen for other components / structures above. This phenomenon is apparently inherent due to the uncertainty in CR inspection results.

Table 12. Transition Time Comparison between Models and Histories for Culvert with Fill Equal to or Greater than 2 Feet

CR	**Model**	**State Data**	**Regional Data**	
		Mean/Stdev	Mean/Stdev	Region
	(yrs)	(yrs/yrs)	(yrs/yrs)	
9 to 8	1	2.96/2.00	2.62/2.41	1
			3.30/1.72	2
			2.89/2.30	3
			2.73/1.59	4
			3.05/2.28	5
8 to 7	18	10.26/6.54	9.79/5.55	1
			11.39/6.45	2
			10.41/7.18	3
			9.94/6.90	4
			8.31/5.60	5
7 to 6	20	12.62/7.50	11.86/8.26	1
			11.26/5.94	2
			13.43/7.99	3
			12.96/8.07	4
			13.82/7.99	5
6 to 5	20	11.68/8.15	13.09/8.89	1
		(51 data points)	12.44/7.71	2
			9.91/7.88	3
			13.97/8.29	4
			12.10/9.81	5
5 to 4	12	6.33/4.18	N/A*	1
		(6 data points)	N/A*	2
			6.62/4.13	3
			N/A*	4
			N/A*	5
4 to 3	8	N/A*	N/A*	1
		(1 data point)	N/A*	2
			N/A*	3
			N/A*	4
			N/A*	5
3 to 2	5.8	N/A*	N/A*	1
		(1 data point)	N/A*	2
			N/A*	3
			N/A*	4
			N/A*	5

*N/A = Inadequate data

Table 13. Total Transition Time Comparison between Models and Histories for Culvert with Fill Equal or Greater than 2 Feet

Model	**State Data**	**Regional Data**	
	Mean	Mean	Region
(yrs)	(yrs)	(yrs)	
71	43.85	37.36*	1
		38.39*	2
		43.26	3
		39.6*	4
		37.28*	5

*CR 5 to 4 has inadequate data, not contributing to this sum.

Deck Beam

This case refers to the superstructure of beams also acting as a deck, which is also known as adjacent box beams. Table 14 compares the current model with the results of the state and regional histories for the deck beam. When comparing the deterministic models with the state means for various CR levels, the former is seen to sometimes overestimate but other times underestimate. Both over- and underestimates are by a large amount, highlighting the involved uncertainty. For example, for CR 7 to 6, the current model's 3.25 years underestimate the state mean's 8.67 years by 63%. For CR 6 to 5, the model's 10 years overestimates the state mean's 5.96 years by 68%. These large differences indicate that not only are the current models unreliable for forecasting, but the deterministic approach also needs to be enhanced to a probabilistic approach to adequately cover the observed uncertainty.

Table 15 compares the total transition time for the deck beam case with the current model, state history, and regional history statistics. The total transition time by the current IDOT deterministic model underestimates the observed state mean. The deck beam case is an exception among the components / structures cases, because the other cases overestimate. The regional variations are seen in Table 15 and should be accounted for in new models for Illinois.

Table 14. Transition Time Comparison between Models and Histories for Deck Beam

CR	**Model**	**State Data**	**Regional Data**	
		Mean/Stdev	Mean/Stdev	Region
	(yrs)	(yrs/yrs)	(yrs/yrs)	
9 to 8	1	4.08/3.07	1.67/1.26	1
			4.20/4.14	2
			2.81/2.03	3
			6.28/2.86	4
			4.38/3.46	5
8 to 7	3.5	7.60/5.23	10.11/7.10	1
			11.51/5.28	2
			6.37/5.09	3
			6.00/3.53	4
			7.78/6.00	5
7 to 6	3.25	8.67/6.44	6.20/4.70	1
			8.64/5.51	2
			10.80/7.95	3
			10.02/6.81	4
			7.24/6.54	5
6 to 5	10	5.96/3.47	5.84/3.93	1
		30 data points	7.89/4.38	2
			6.09/3.41	3
			4.99/1.45	4
			4.89/3.27	5
5 to 4	6.4	5.84/3.22	N/A*	1
		11 data points	5.55/4.05	2
			6.79/3.71	3
			N/A*	4
			5.51/2.18	5
4 to 3	4.5	4.21/4.17	N/A*	1
		4 data points	5.57/3.88	2
			N/A*	3
			N/A*	4
			N/A*	5
3 to 2	1.5	4.68/6.54	N/A*	1
		3 data points	6.61/7.95	2
			N/A*	3
			N/A*	4
			N/A*	5

*N/A = Inadequate data

Table 15. Total Transition Time Comparison between Models and Histories for Deck Beam

Model	State Data	Regional Data	
	Mean	Mean	Region
(yrs)	(yrs)	(yrs)	
24.15	32.15	23.82*	1
		37.79	2
		32.86	3
		27.29*	4
		29.8	5

*CR 5 to 4 has inadequate data, not contributing to this sum.

DETERIORATION CURVES

This section presents graphic comparisons of the current IDOT models with the historical data analysis results to shed light on their trends, overall behaviors, and effectiveness to forecast. In particular, these graphs will help develop intuitive understanding on the forecast reliability of the current models, the variation in the CR histories missed by the deterministic modeling / prediction, and deviation of regional behaviors in the histories from the state and regional statistics.

Deck

For the deck, Figure 3 compares the current deterministic model with IDOT's Region 1 statistics and the state's statistics. The state and regional statistics include the mean and a band with boundaries defined by the mean minus one Stdev and the mean plus one Stdev. This band contains about 60% to 75% of the values, depending on the underlying probability distribution. For example, if the random variable (transition time here) follows a normal distribution, then this band covers about 68% of the samples. In other words, most values of the random variable are expected to be within this band (referring to the horizontal axis, i.e., transition time in years).

As seen in Figure 3, the current deterministic models are approximately within the band of the state histories. However, the model underestimates for Region 1 and state means at early ages; both are below the cumulative means of Region 1 and the state. The model also significantly underestimates the state histories, going below the band's lower boundary. However, the model still stays within the band for Region 1. At later ages below CR 6 to 5, the model overestimates; however, it still stays within the upper band boundaries of the mean plus one Stdev of both Region 1 and the state.

If the objective of the model is to forecast reliably for each transition between two CR levels, then the current model needs to be enhanced for a large number of such transitions. If the model is intended to forecast the total life, then the model would be considered more acceptable, being off by about 8% at CR 3.

Furthermore, the deterministic model is apparently unable to cover the wide variation or bandwidths of the state and Region 1 histories. This needs to be addressed in developing more reliable models for Illinois and its regions using a probabilistic representation, such as the Weibull distribution approach.

In addition, Figure 3 also shows that the state band is off the Region 1 band to the right, i.e., overestimating transition times in high CR levels (to CR 6 to 5). This range is the deck's major service period, beyond which more significant rehabilitations and possibly replacement will likely need to take place. This highlights the need for more reliable models for deck forecasts.

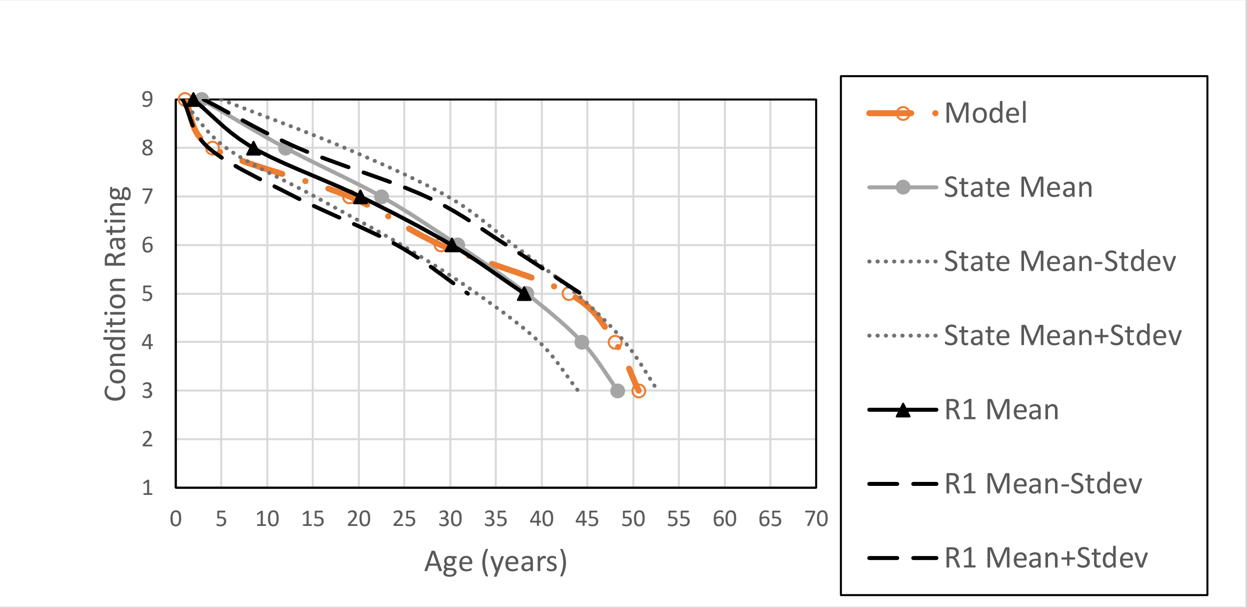

Figure 3. Chart. Deck deterioration curves: model vs state vs Region 1.

Figures 4 to 7 exhibit the same comparison as Figure 3 for Regions 2 to 5, respectively. The figures indicate the same need for region-specific models because the regional statistics are not always consistent with the state statistics extracted from respective histories.

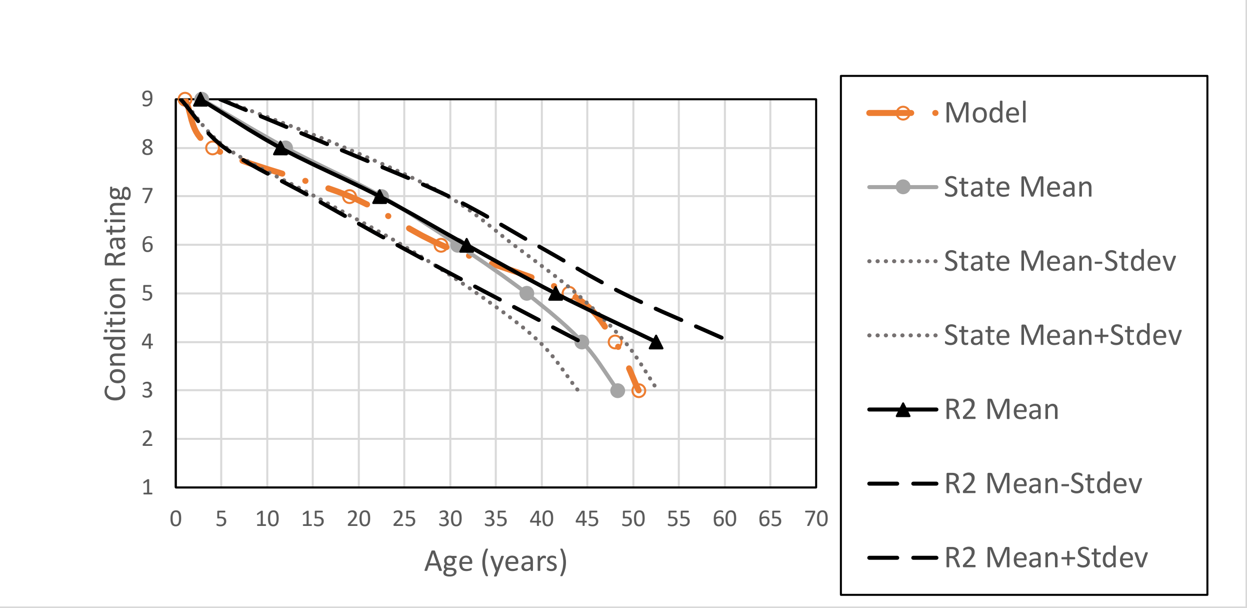

Figure 4. Chart. Deck deterioration curves: model vs state vs Region 2.

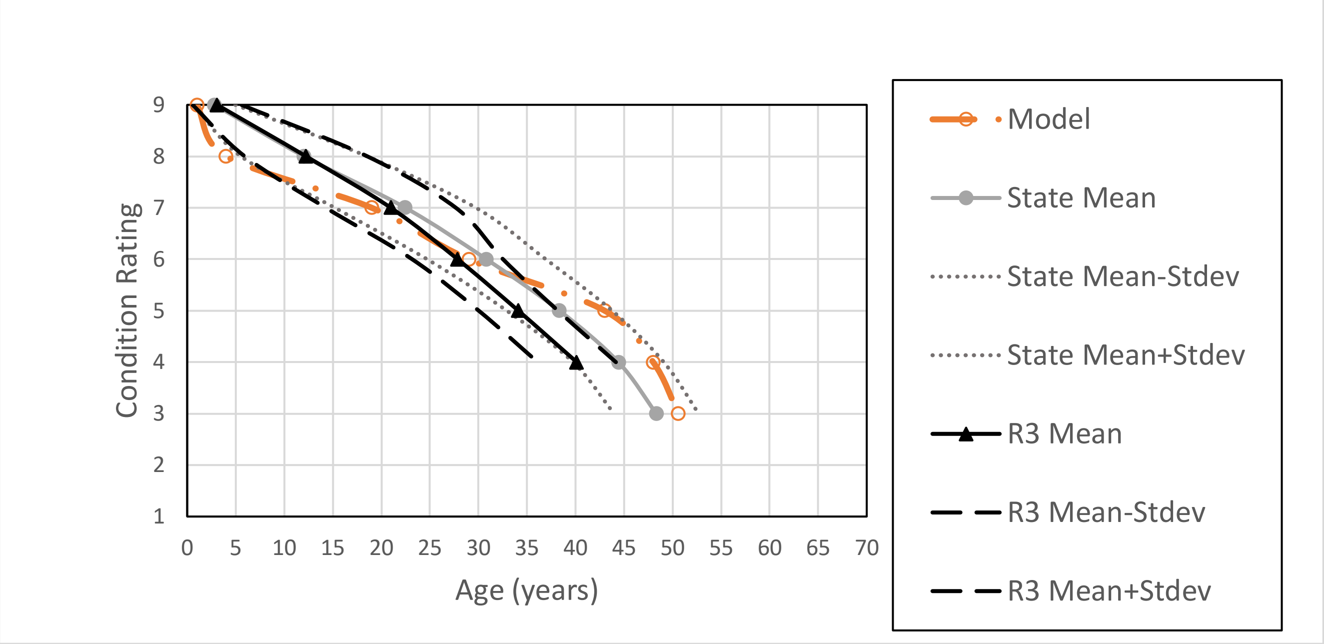

Figure 5. Chart. Deck deterioration curves: model vs state vs Region 3.

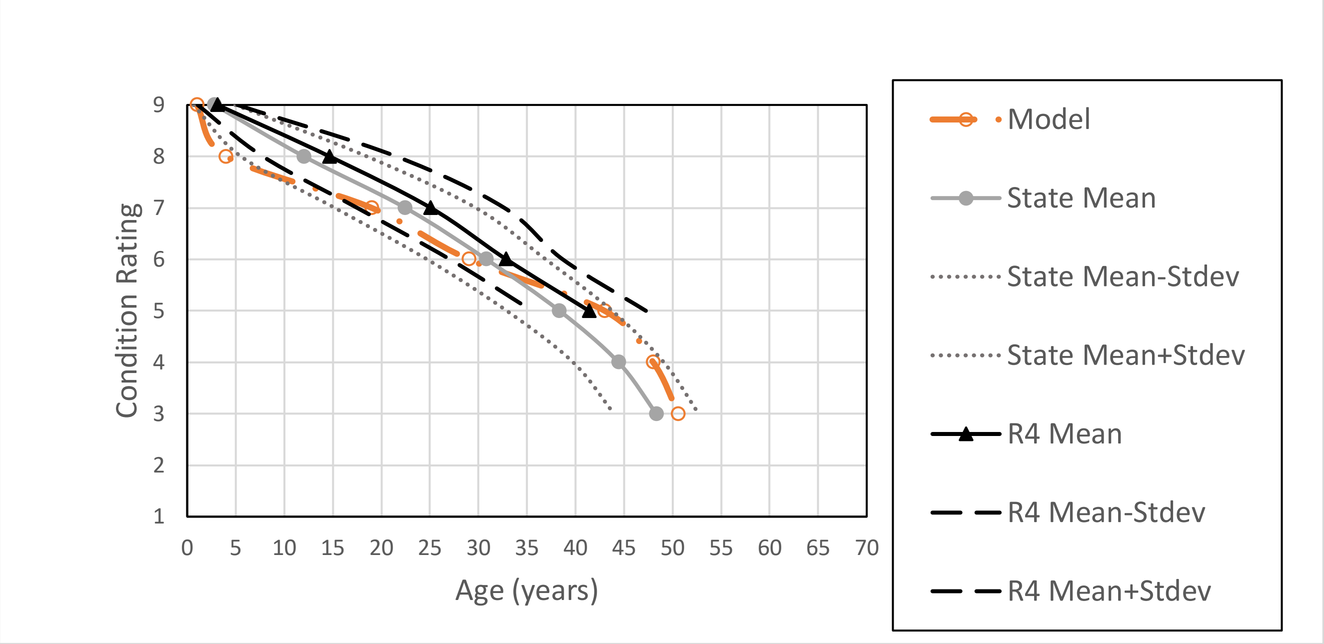

Figure 6. Chart. Deck deterioration curves: model vs state vs Region 4.

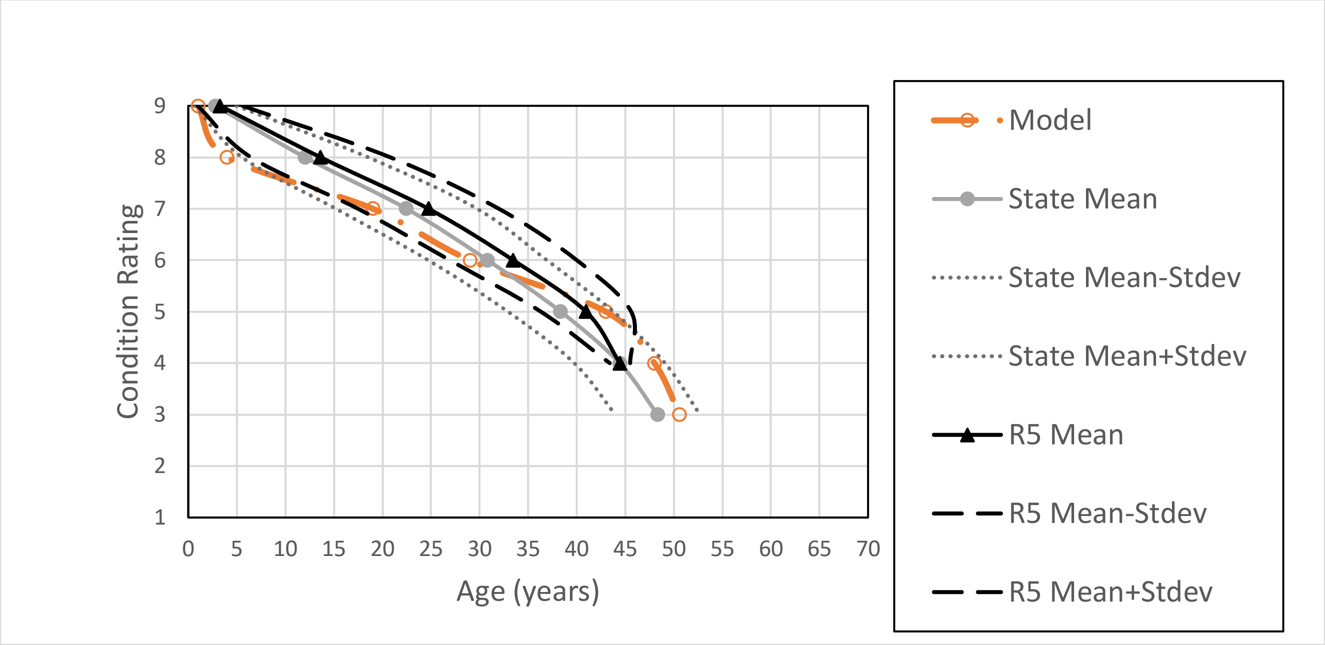

Figure 7. Chart. Deck deterioration curves: model vs state vs Region 5.

Figure 7 also shows much smaller variation at CR 4 to 3 for Region 5 at the end of the curves. This small Stdev is due to lack of data and does not appear to have recorded the real behavior. Including that last data point was to maximize the use of available data. The mean age of Region 5 at CR 4 happens to coincide with the state mean age, which likely does not reflect the reality but was, again, due to lack of data points there. Note that at all other CR levels, the Region 5 mean age is seen apart from the state mean age. Thus, the coincidental identical mean ages at CR 4 should not be taken as part of the trend.

Superstructure

For the bridge superstructure, Figures 8 to 12 compare the current models with the state and regional statistics. The following observations can be made:

- The current deterministic model does not function as well as that for the deck, at both the state and regional levels. Its forecast is far off the state and regional means, and out of their bands near CR 6 or so and then further lower CRs. The bands are defined between mean minus one Stdev and mean plus one Stdev.

- The regional bands are not fully covered by the state band, indicating the need for regional models.

- The highest consistency between the state and regional statistics occurred in Region 2, from the highest CR to about CR 5 to 4. Beyond that point, there is inconsistency between the two statistics. For other regions, this inconsistency is much more profound. This behavior again highlights the need for regional models.

- For two cases (CR 3 to 2 in Figure 8 and CR 4 to 3 in Figure 10), the Stdev becomes suddenly smaller due to lack of adequate data points near the end of these curves (near the low CR levels).

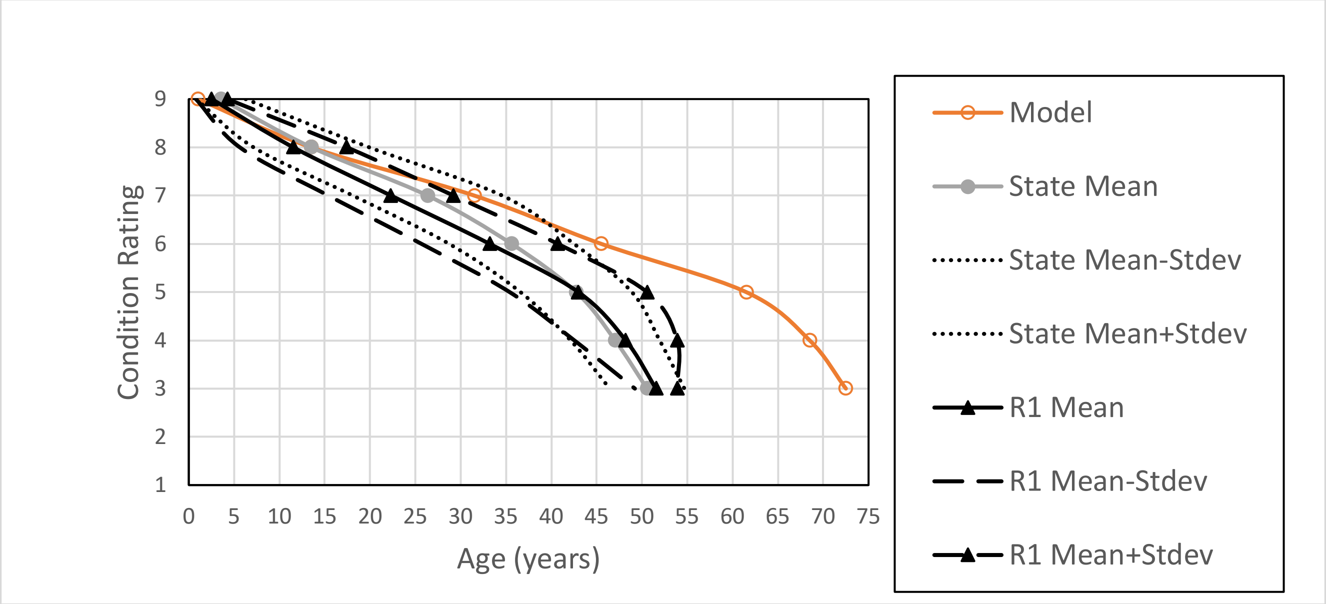

Figure 8. Chart. Superstructure deterioration curves: model vs state vs Region 1.

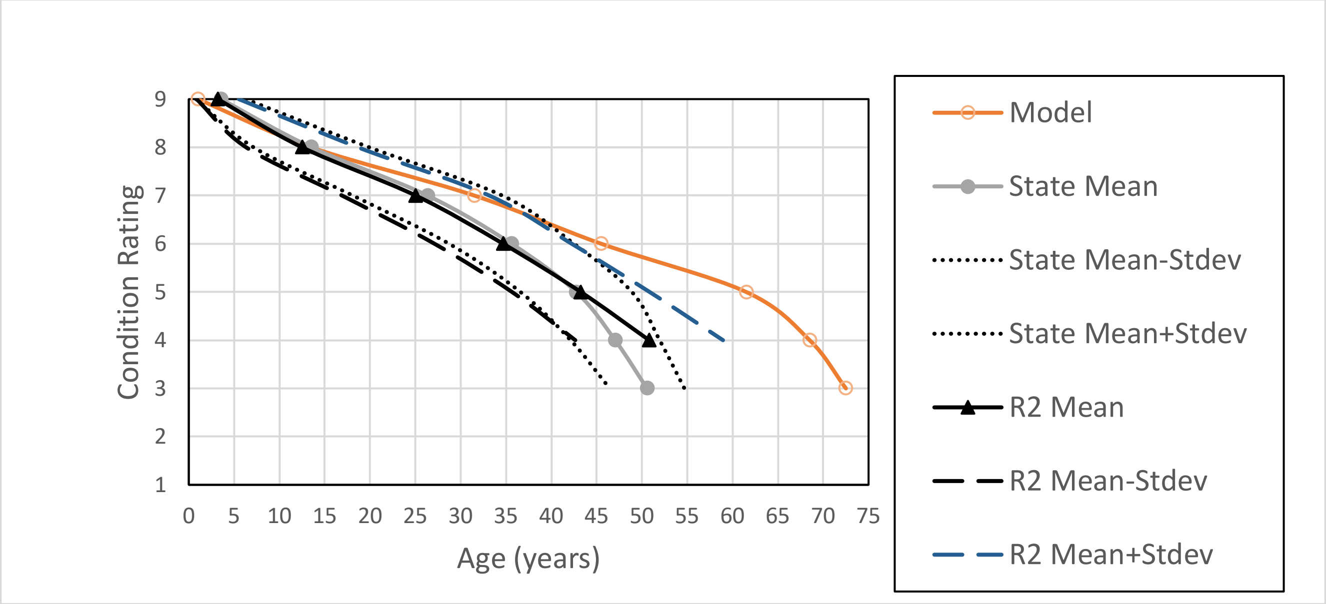

Figure 9. Chart. Superstructure deterioration curves: model vs state vs Region 2.

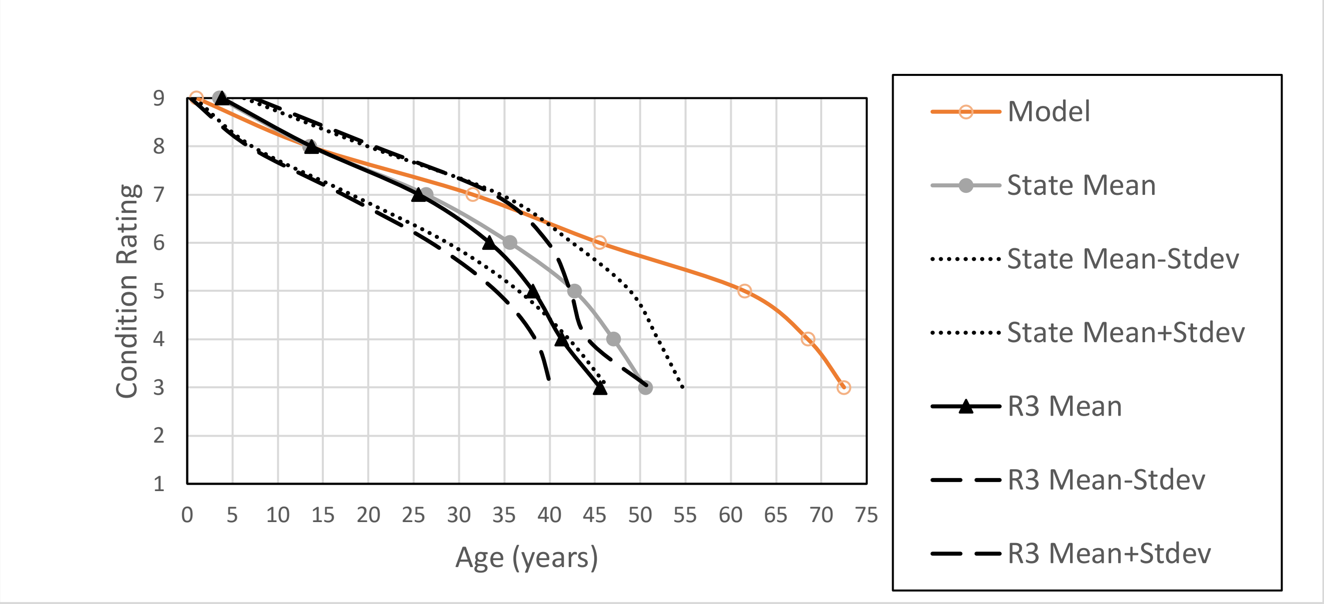

Figure 10. Chart. Superstructure deterioration curves: model vs state vs Region 3.

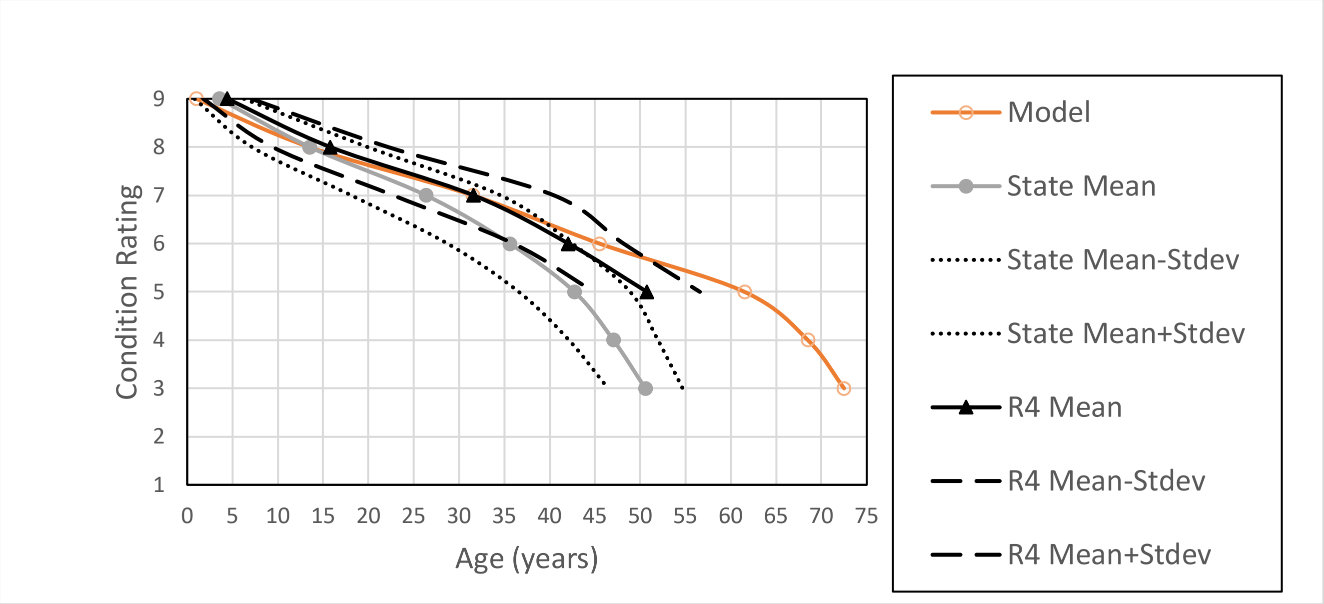

Figure 11. Chart. Superstructure deterioration curves: model vs state vs Region 4.

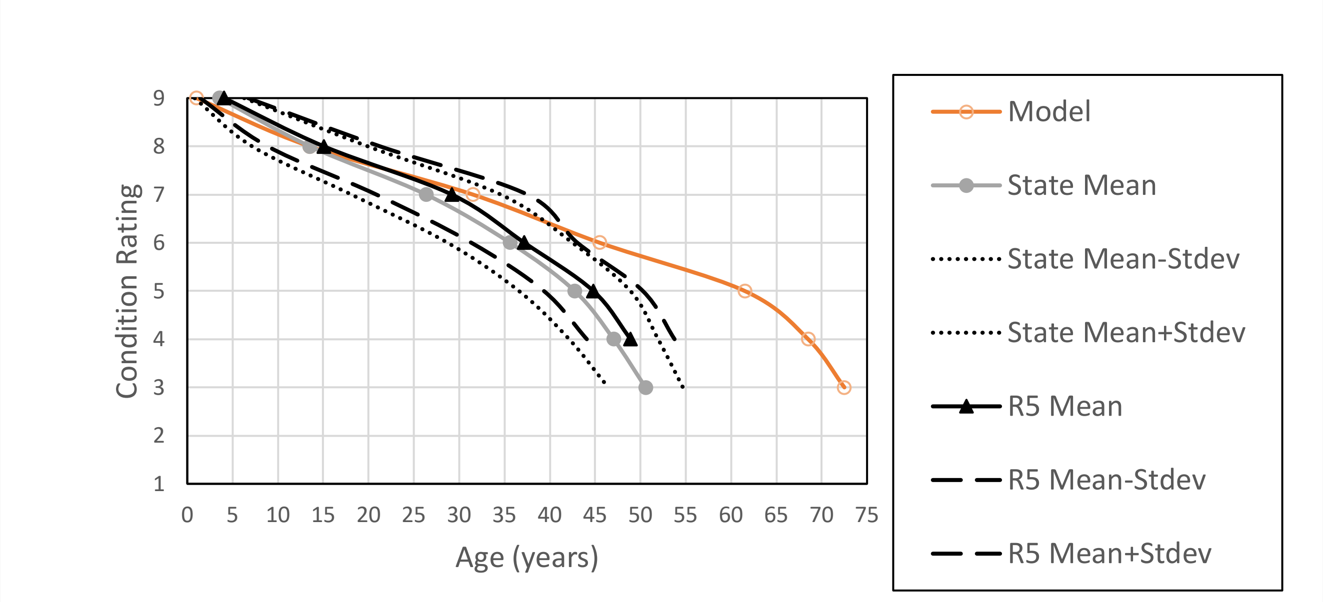

Figure 12. Chart. Superstructure deterioration curves: model vs state vs Region 5.

Substructure

Figures 13 to 17 compare the current models with the state and regional statistics for the bridge substructure in Illinois. Like the superstructure case, the current deterministic model has performed inadequately for the substructure performance forecasts. It has overestimated the transition times and the total time (i.e., age and life span) by large amounts at various CR levels, compared to both the state and regional statistics.

The deviation of the current model from the bands between mean minus one Stdev and mean plus one Stdev is evident in Figures 13 to 17 for all five regions. The regional statistics also appear to be off from the state statistics for most cases of regional and CR level, which, again, demonstrates the need for regional models for a more reliable forecast.

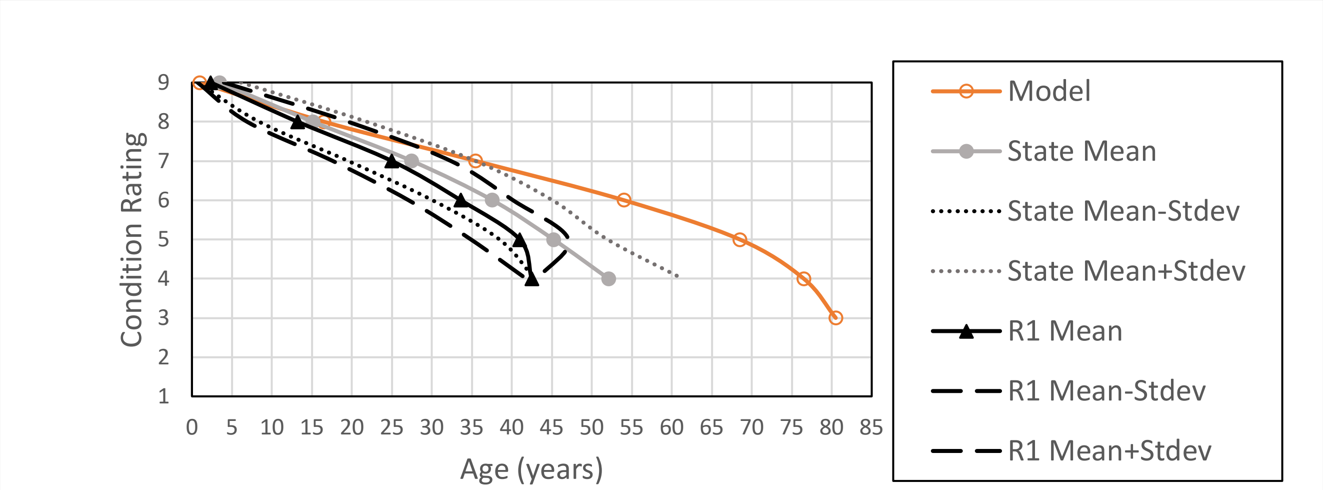

Figure 13. Chart. Substructure deterioration curves: model vs state vs Region 1.

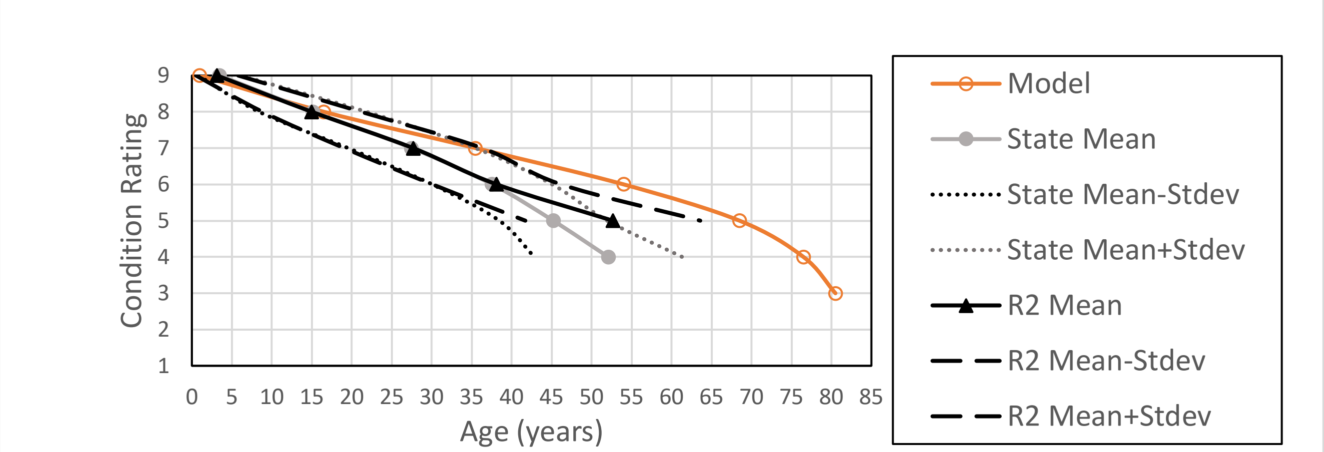

Figure 14. Chart. Substructure deterioration curves: model vs state vs Region 2.

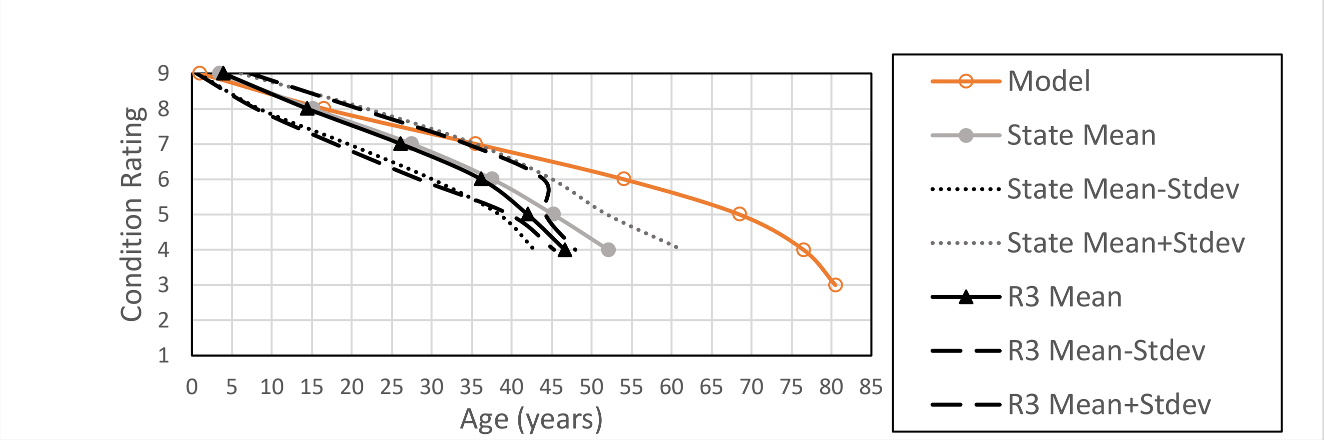

Figure 15. Chart. Substructure deterioration curves: model vs state vs Region 3.

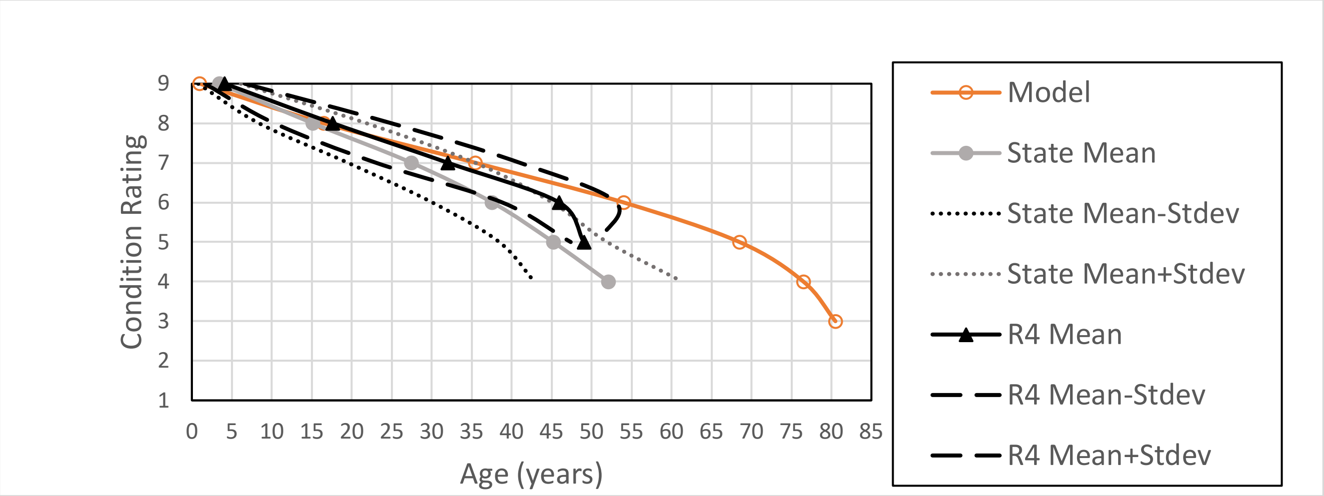

Figure 16. Chart. Substructure deterioration curves: model vs state vs Region 4.

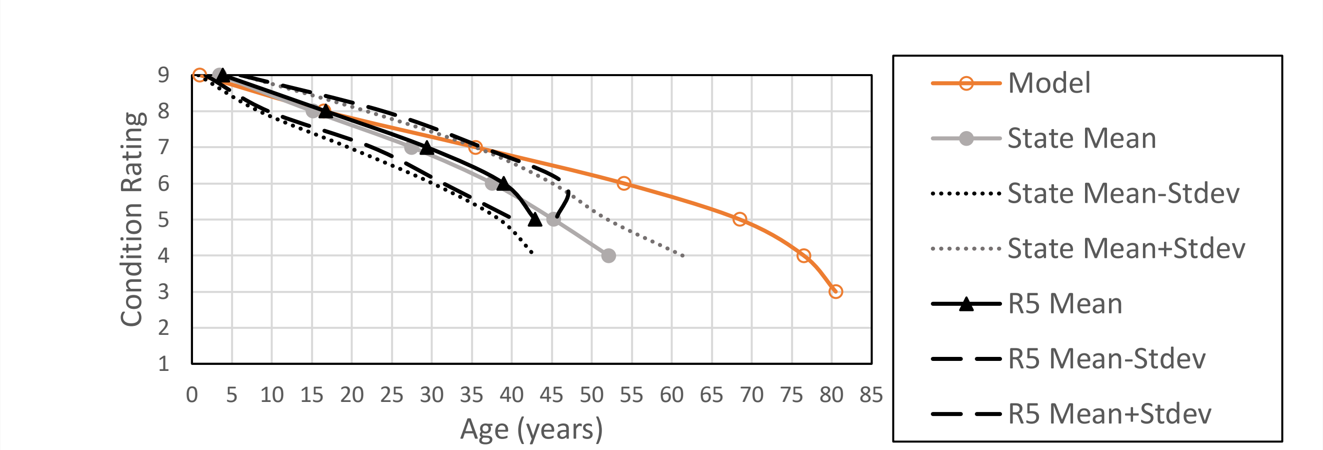

Figure 17. Chart. Substructure deterioration curves: model vs state vs Region 5.

Culvert with Fill Less than 2 Feet

Figures 18 through 22 compare the current models with the state and regional statistics for culverts with fill less than 2 feet in Illinois. Similar observations can be made for this case as those for the superstructure and substructure cases, namely:

- The current deterministic model is unable to function adequately at both the state and regional levels. Its forecast is off from the state and regional means, and out of their bands near CR 6 or so and then further lower CRs. The bands are defined between mean minus one Stdev and mean plus one Stdev. Nevertheless, the severity of the off forecast is not as excessive as that for the substructure in the low CR end.

- The regional bands are not fully covered by the state band, indicating the need for regional models.

- The highest consistency between the state and regional statistics occurred in Regions 3 and 5, from the highest CR to about CR 7 to 6 or CR 6 to 5. Beyond that point, there is inconsistency between the two statistics. For other regions, this inconsistency is much more profound. This behavior again highlights the need for regional models.

- For two cases (CR 5 to 4 or the last transition in Figure 20 for Region 3 and in Figure 22 for Region 5), the Stdev becomes suddenly smaller due to lack of adequate data points near the end of these curves (near the low CR levels).

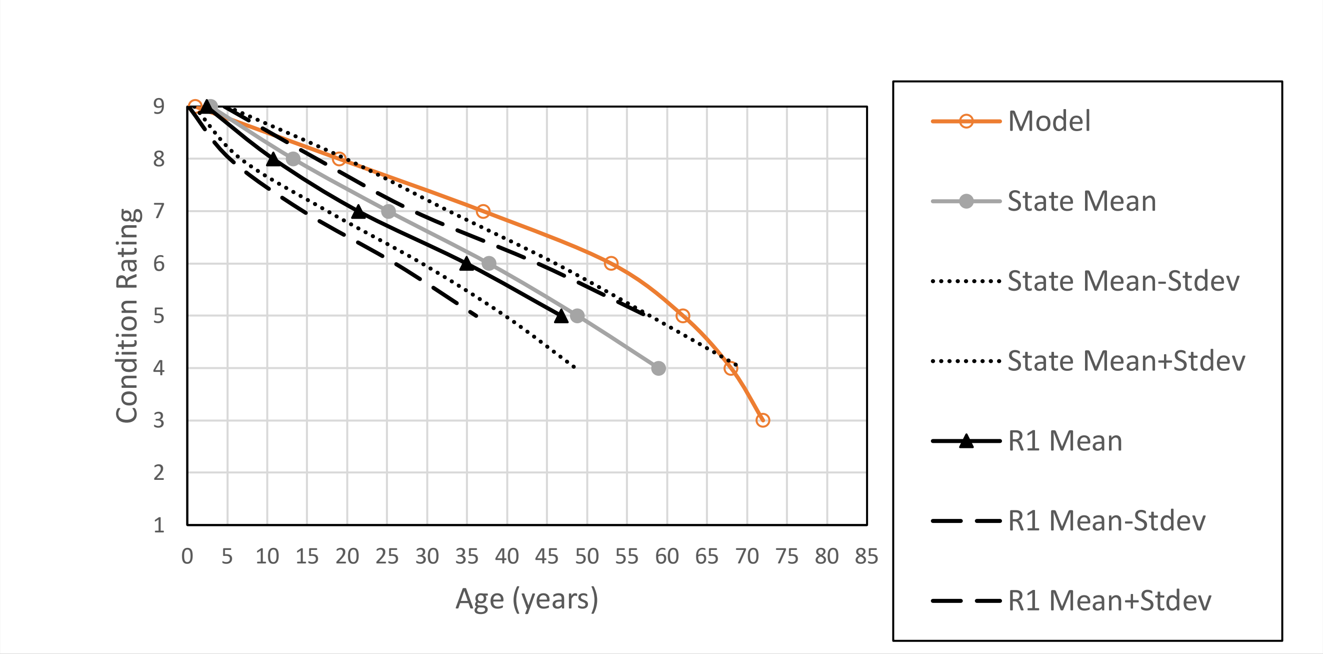

Figure 18. Chart. Culvert with fill less than 2 feet deterioration curves: model vs state vs Region 1.

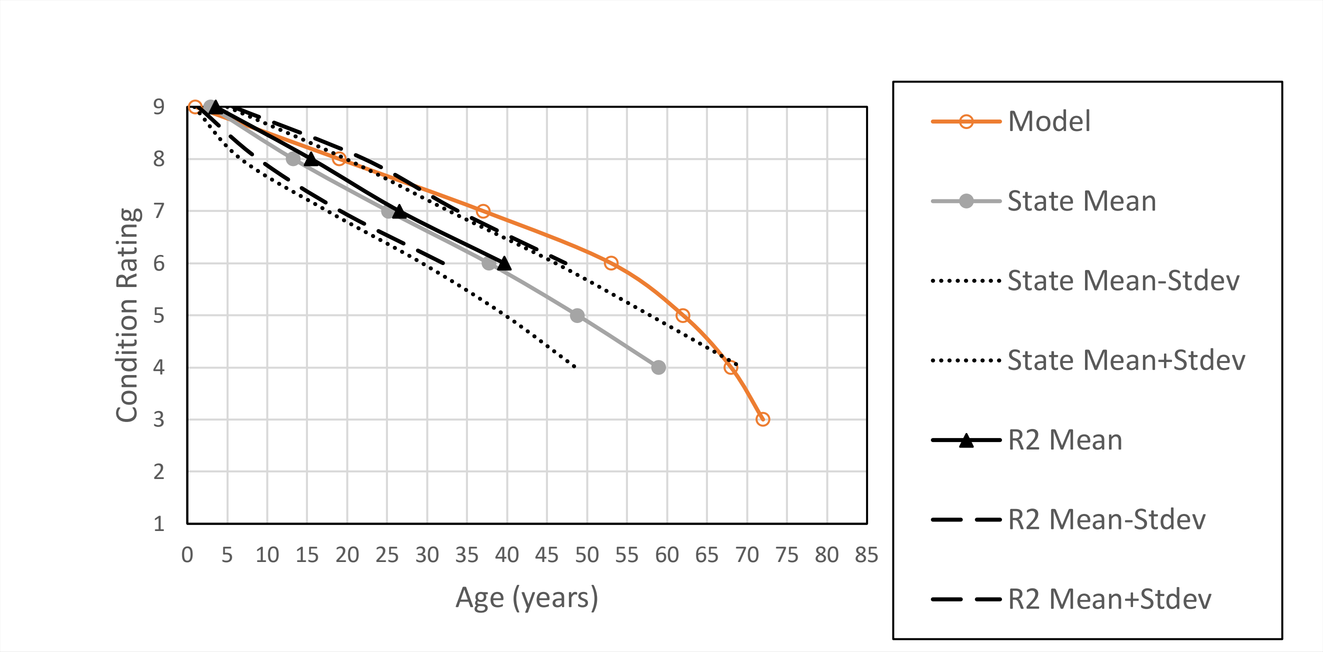

Figure 19. Chart. Culvert with fill less than 2 feet deterioration curves: model vs state vs Region 2.

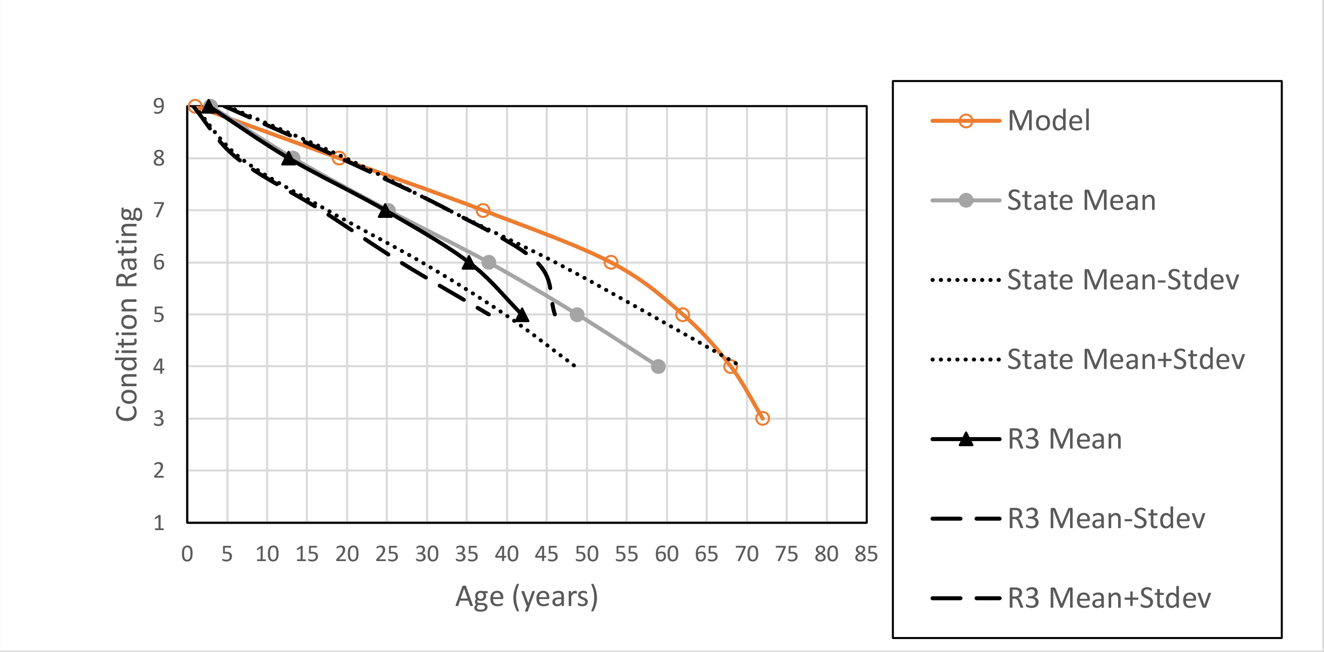

Figure 20. Chart. Culvert with fill less than 2 feet deterioration curves: model vs state vs Region 3.

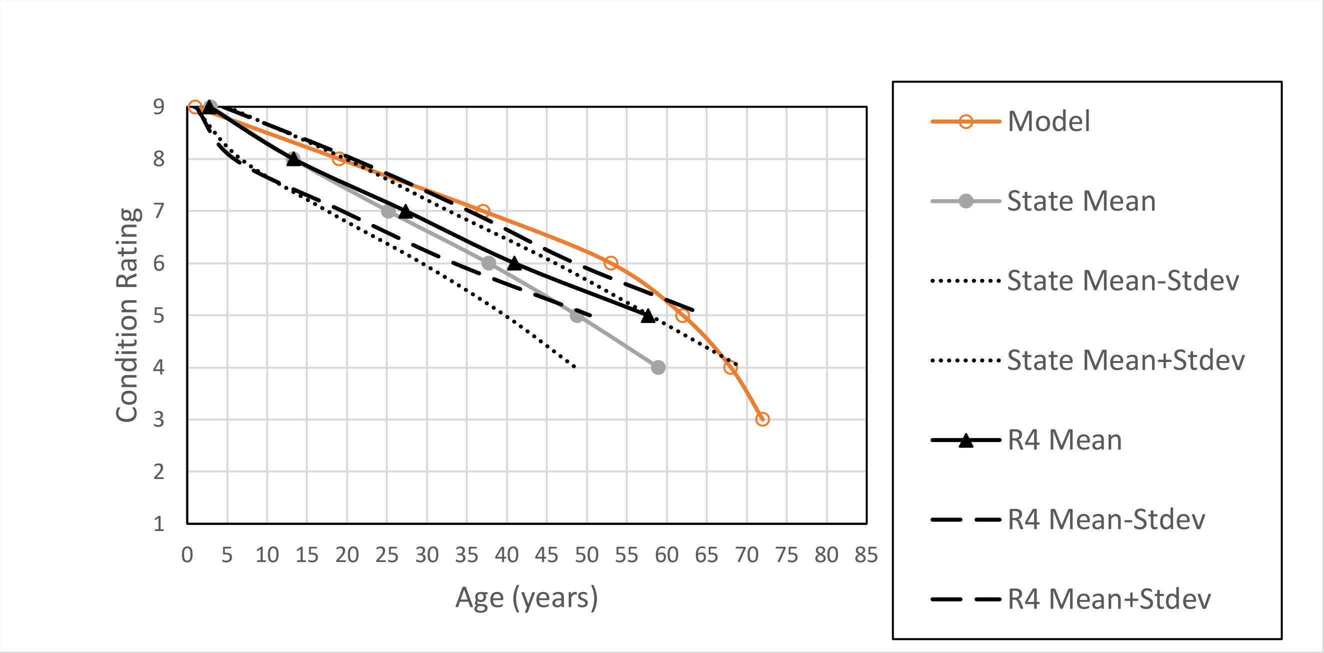

Figure 21. Chart. Culvert with fill less than 2 feet deterioration curves: model vs state vs Region 4.

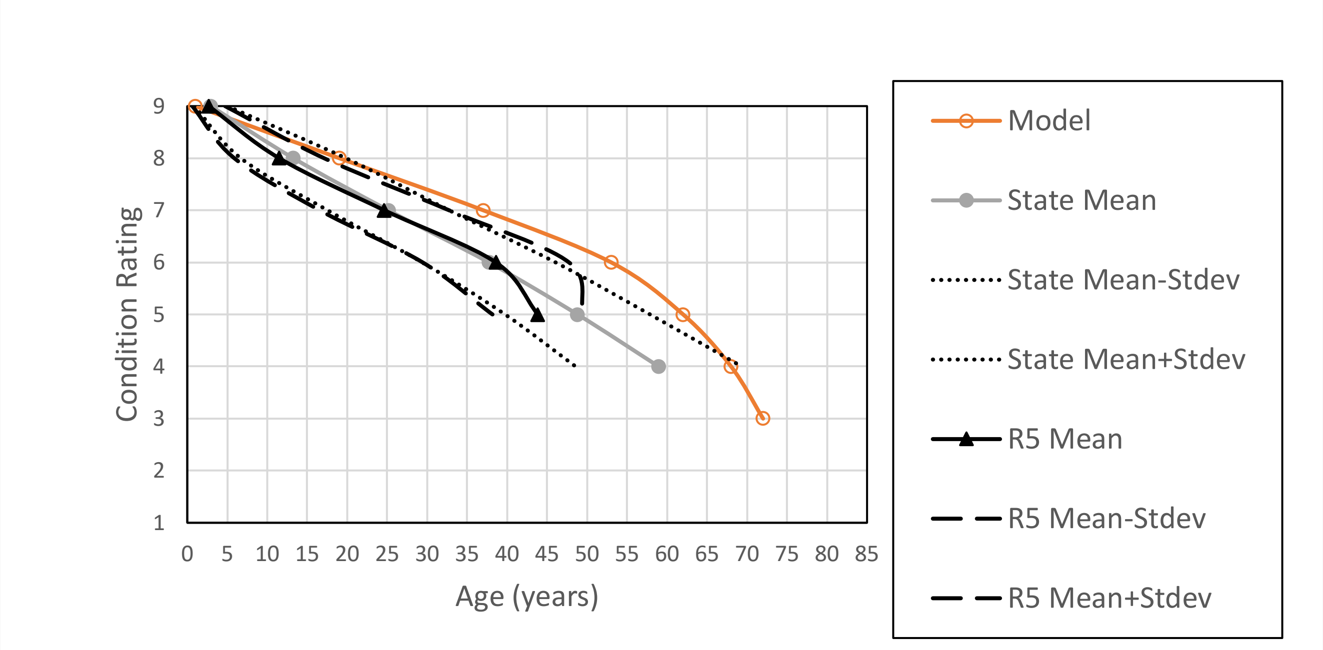

Figure 22. Chart. Culvert with fill less than 2 feet deterioration curves: model vs state vs Region 5.

Culvert with Fill Equal to or Greater than 2 Feet

Figures 23 to 27 present graphic comparisons for culverts with fill equal to or greater than 2 feet in Illinois. Less data are available, so the state and regional statistics curves stop at CR 5 to 4 or CR 6 to 5, earlier than those for the other culvert group as well as the other components or subsystems (deck, superstructure, and substructure).

The following observations are made for culverts with deeper fill:

- The current deterministic models are still inadequate for forecasting at both the state and regional levels. This inadequacy is more severe than the earlier group of culverts and the other bridge components. Its forecast is off the state and region means, and out of their bands near CR 7 or so and then further lower CRs. The bands are defined between mean minus one Stdev and mean plus one Stdev.

- The regional bands are closer to the state bands, which is better than the other bridge component cases as well as the other culvert system.

- Region 3 shows the Stdev becoming smaller at CR 5 at the end of the curves. This also happens for the state statistics. Both are due to lack of adequate data points near the end of these curves.

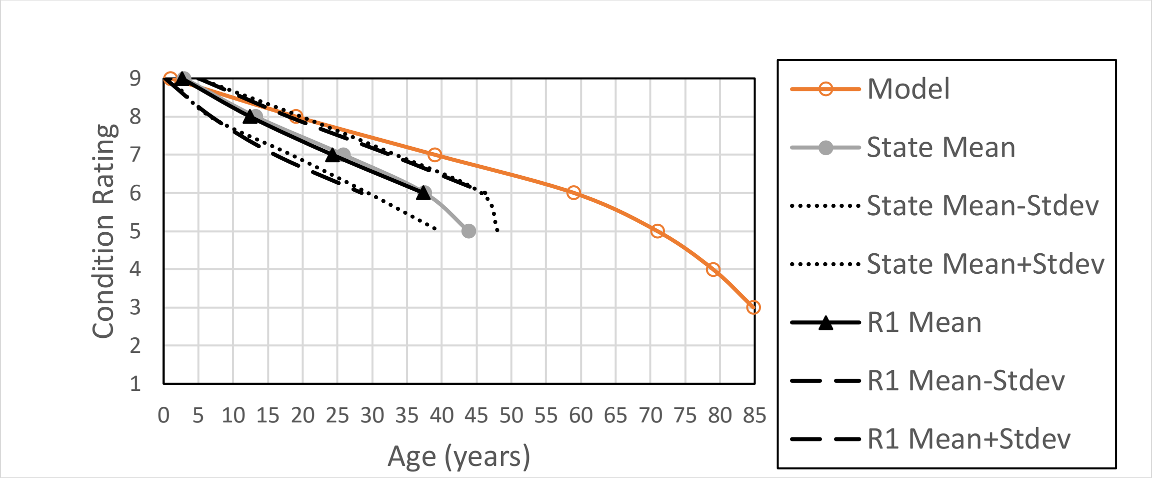

Figure 23. Chart. Culvert with fill equal to or greater than 2 feet deterioration curves: model vs state vs Region 1.

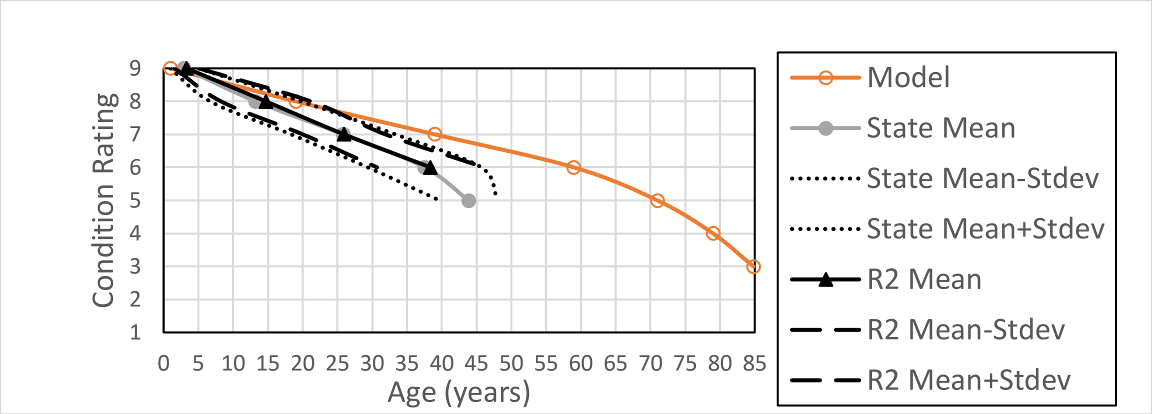

Figure 24. Chart. Culvert with fill equal to or greater than 2 feet deterioration curves: model vs state vs Region 2.

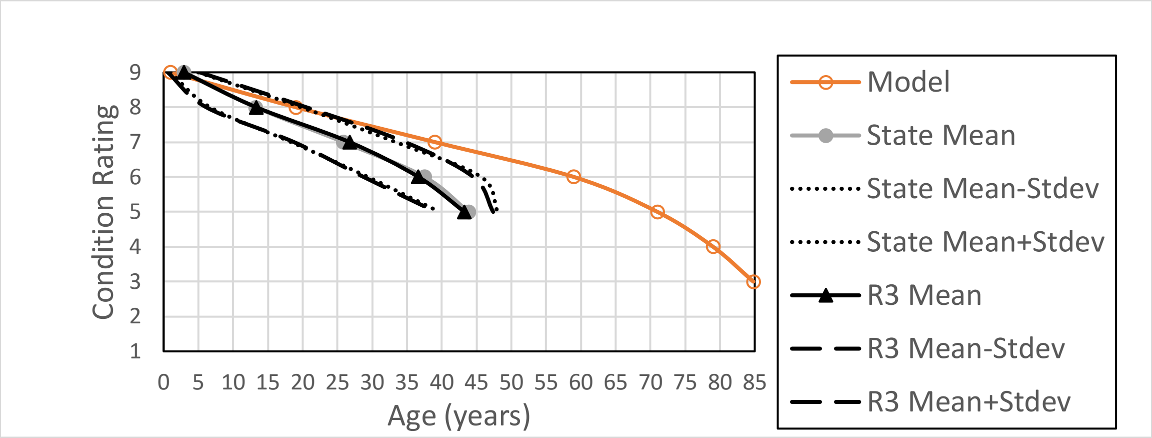

Figure 25. Chart. Culvert with fill equal to or greater than 2 feet deterioration curves: model vs state vs Region 3.

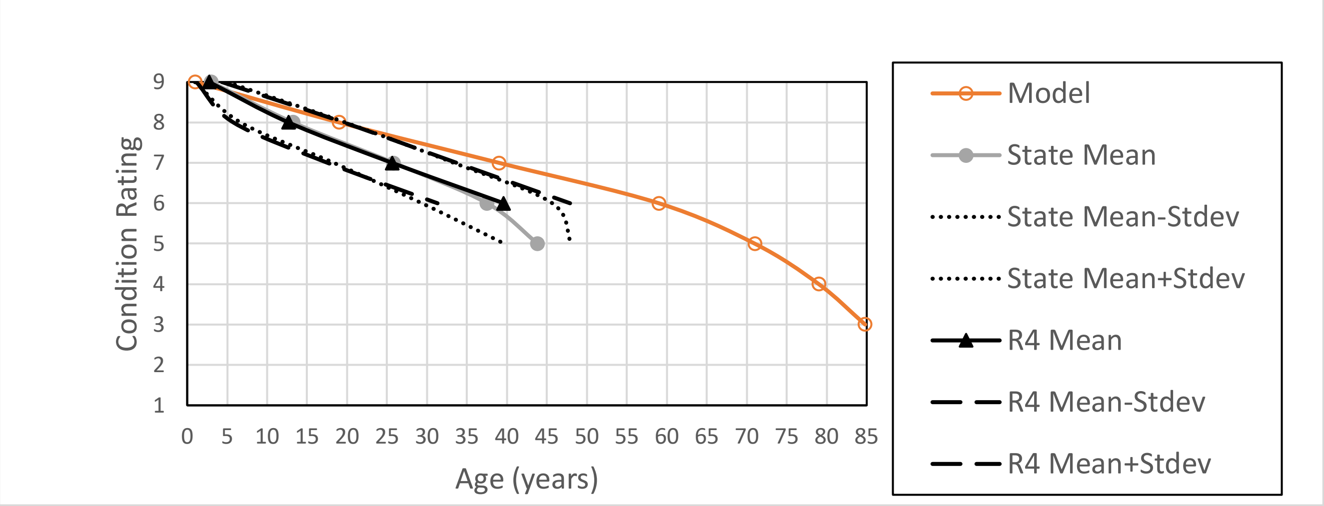

Figure 26. Chart. Culvert with fill equal to or greater than 2 feet deterioration curves: model vs state vs Region 4.

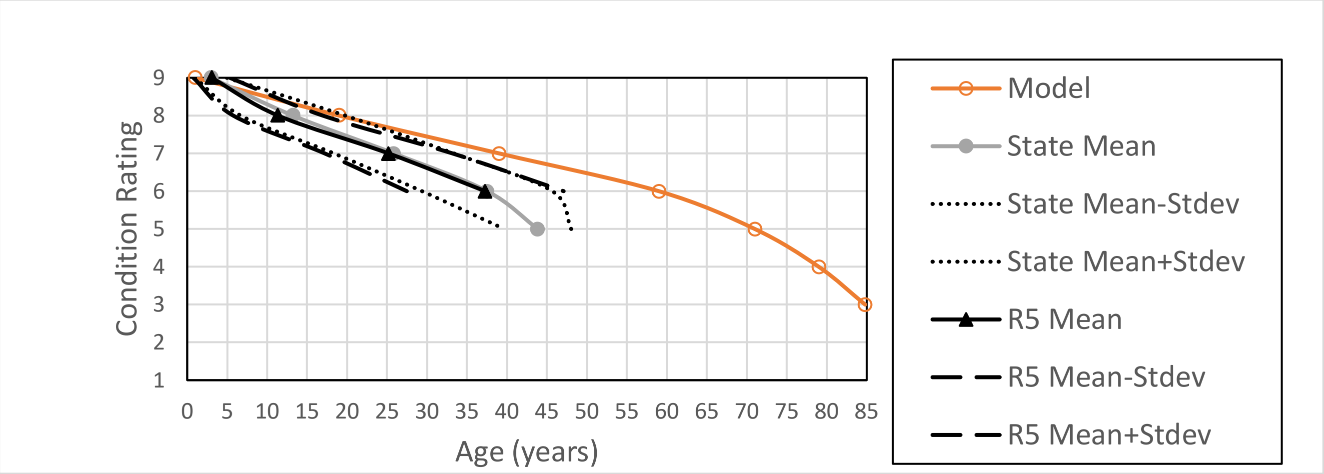

Figure 27. Chart. Culvert with fill equal to or greater than 2 feet deterioration curves: model vs state vs Region 5.

Deck Beam

Figures 28 to 32 display the comparison for the deck beam. This is the only case where the current deterministic model underestimates or underforecasts the transition times and total life, among all bridge components and culvert systems. The deterministic deterioration curves in Figures 28 to 32 appear to the left of the state and regional bands, defined by mean minus one Stdev and mean plus Stdev. This underforecast is shown to be significant, so that the deterministic deterioration curves are out of the bands by about at least five years.

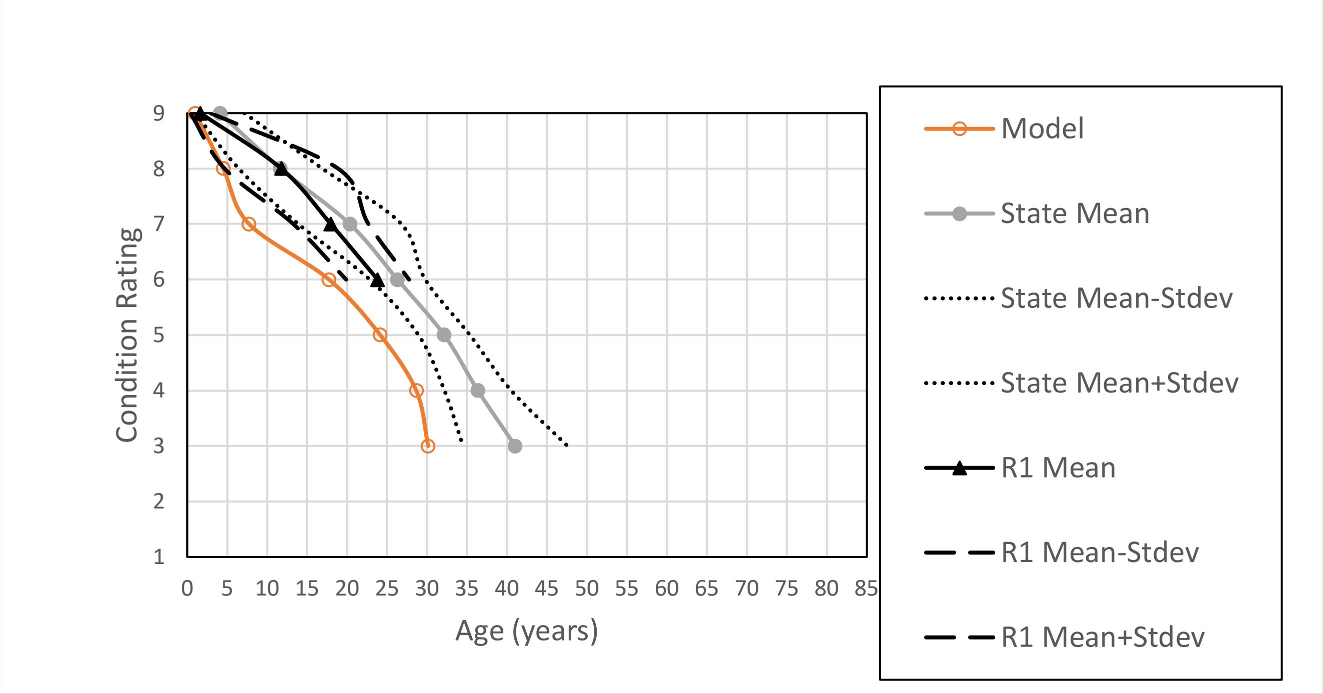

Figure 28. Chart. Deck beam deterioration curves: model vs state vs Region 1.

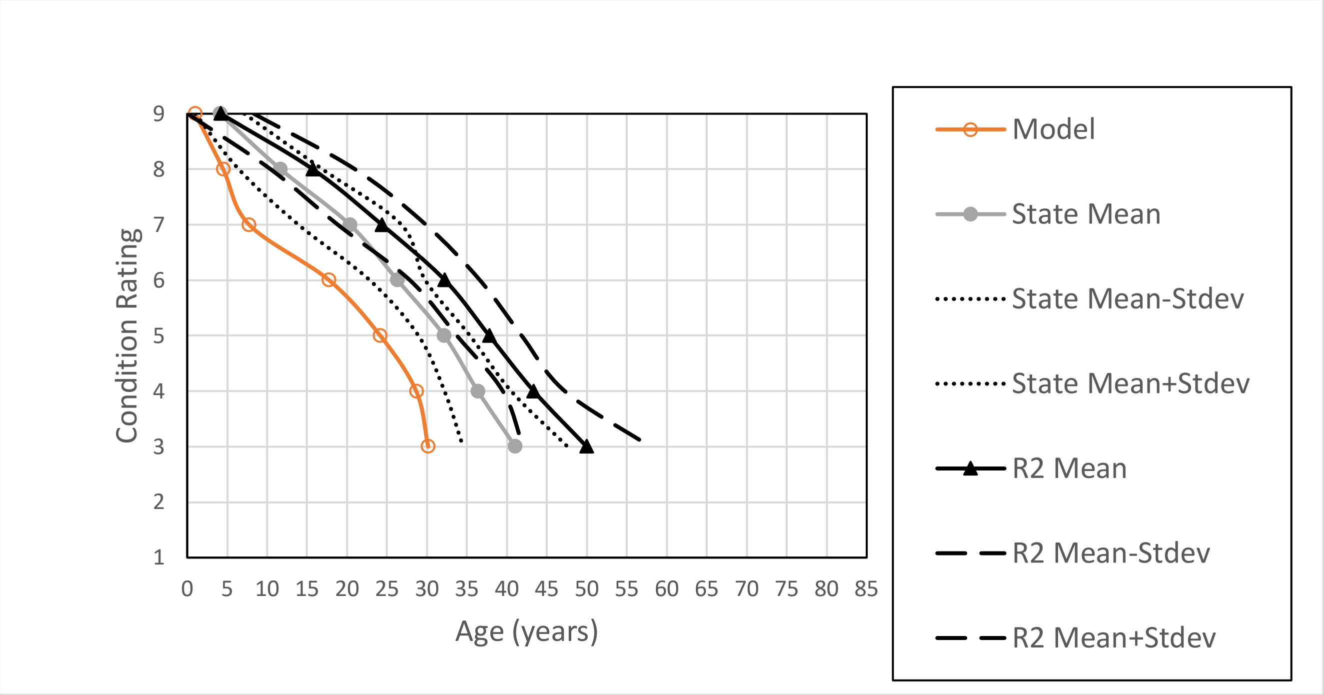

Figure 29. Chart. Deck beam deterioration curves: model vs state vs Region 2.

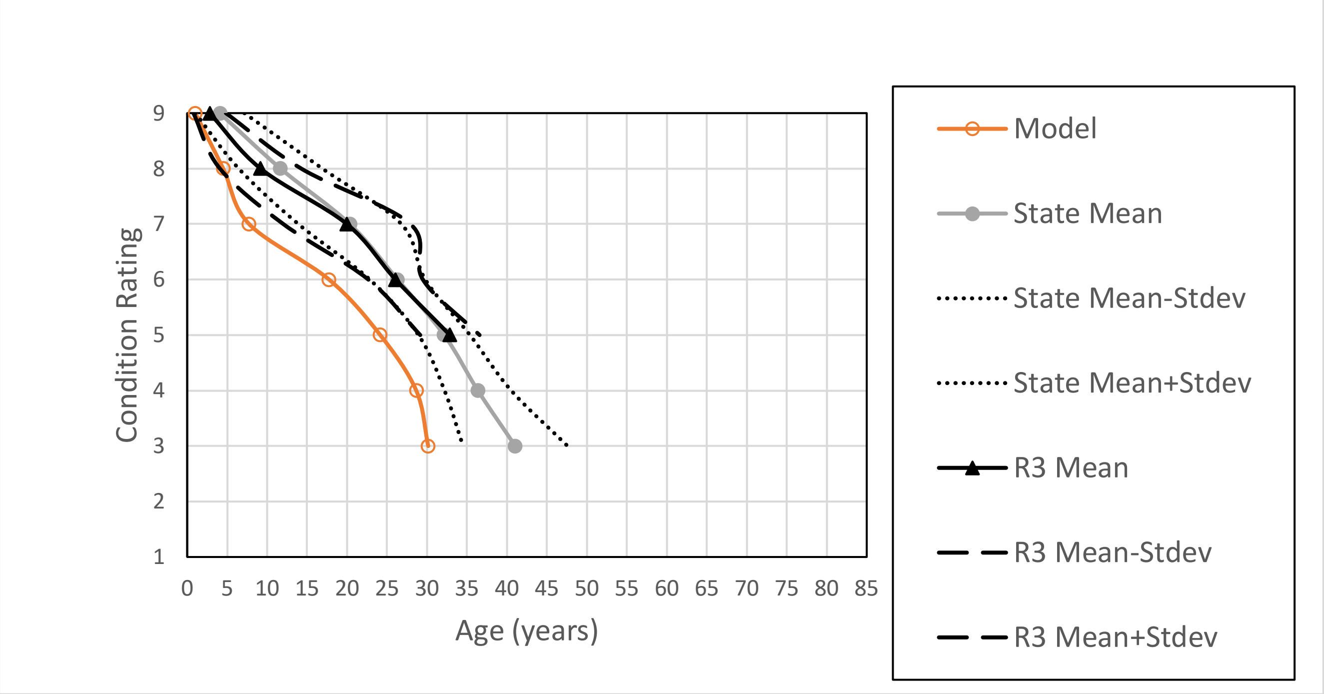

Figure 30. Chart. Deck beam deterioration curves: model vs state vs Region 3.

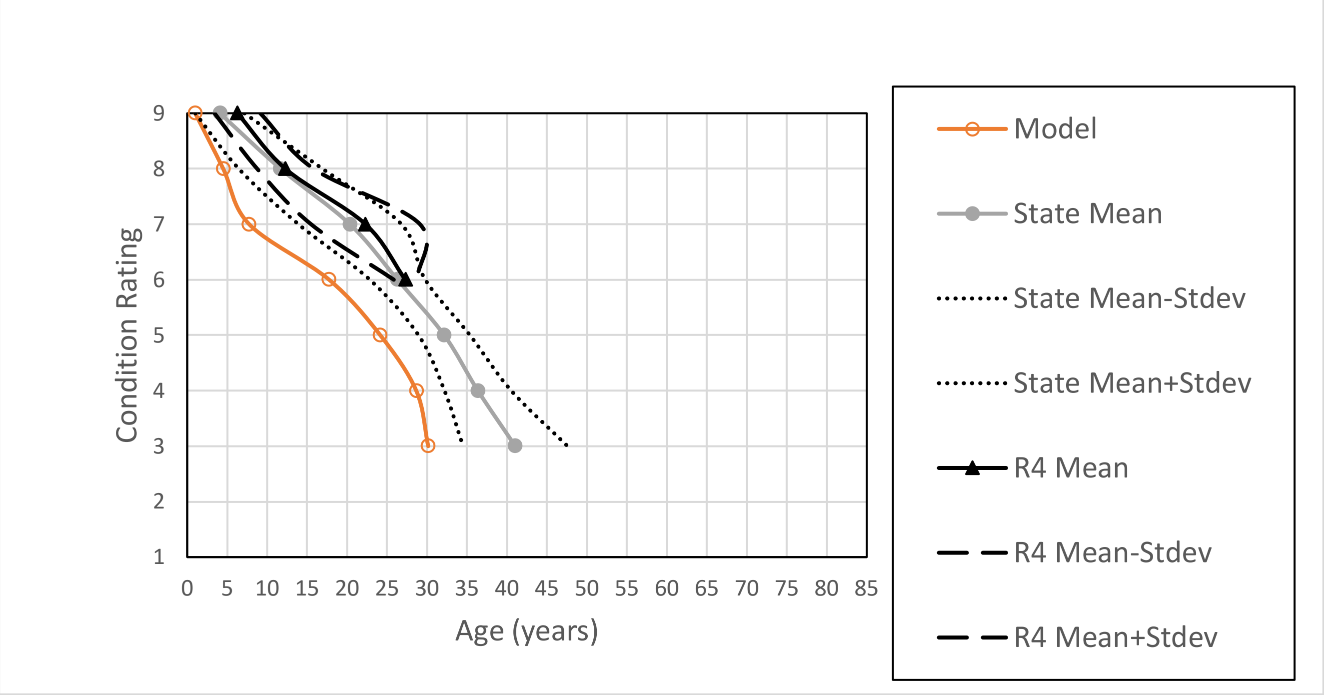

Figure 31. Chart. Deck beam deterioration curves: model vs state vs Region 4.

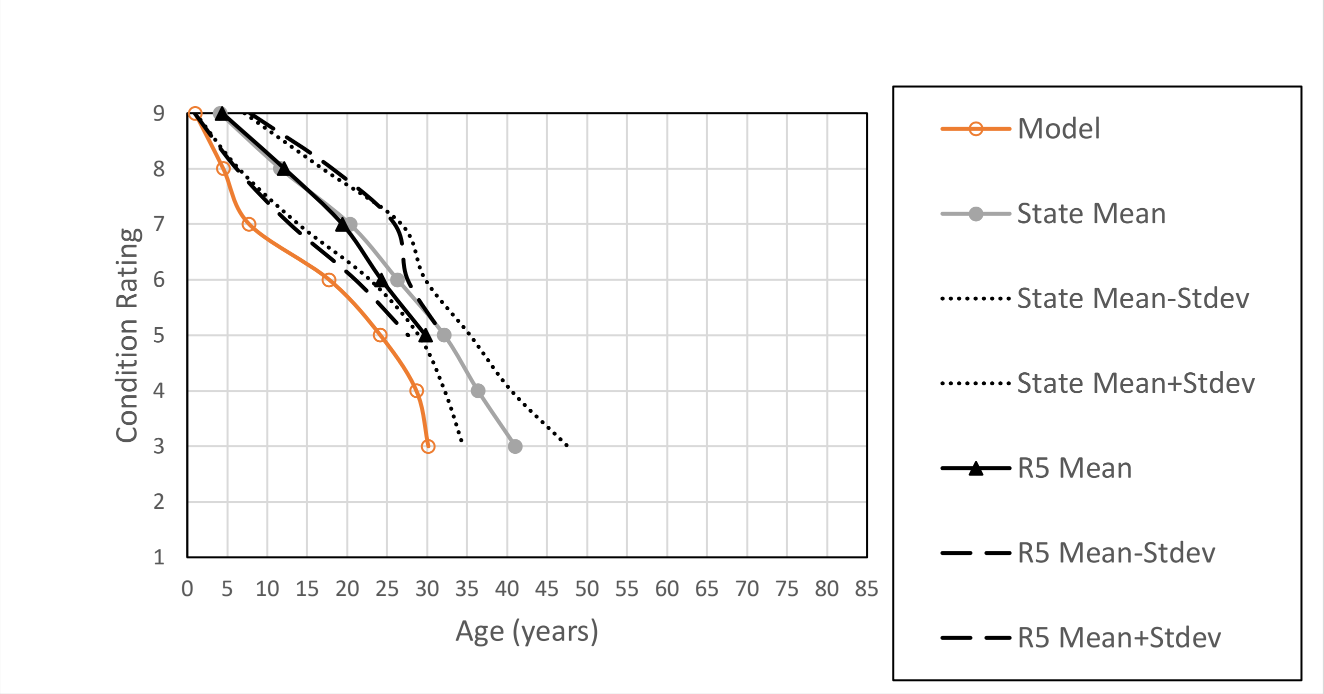

Figure 32. Chart. Deck beam deterioration curves: model vs state vs Region 5.

The regional bands in Figures 18 to 32 deviate from the state bands, though the differences are not uniform among the five regions, indicating a need for regional models. Smaller Stdev values are seen near CR 5 or 6, i.e., near the end of the regional deterioration curves, due to lack of adequate data. An exception is Region 2, which fortunately has more data points than the other regions. Nevertheless, these additional data points do not necessarily provide statistically significant information on the trend, but some information is better than nothing for further understanding.

COMPARISON WITH INDIANA DETERIORATION CURVES

Among the states that responded to the questionnaire, Indiana is the only one that has developed region-based bridge component deterioration models. Indiana’s deterioration curves were based on CR histories available for all of the state’s 19,800 structures. It is worthwhile to have a comparison between the histories of Illinois and Indiana for benchmarking and further understanding. This comparison is presented below pertaining to the deck, superstructure, substructure, and culvert. Note that Indiana does not have separate deterioration models for the deck beam. It also does not group culverts by fill depth, either. Three regions are defined in Indiana: north, central, and south. The following comparison is organized according to geography or climate, using Indiana North vs. Illinois Region 1, Indiana Central vs. Illinois Region 3, and Indiana South vs. Illinois Region 5.

The Indiana deterioration curves also do not offer information on variation in CR or transition time. Therefore, the following comparison is performed using the mean values of the Illinois results without the Stdev.

Deck

Figures 33 to 35 provide a comparison between Illinois and Indiana for the bridge deck. The figures present the following behaviors among the current Illinois state models, CR histories of Illinois regions, and CR histories of Indiana regions:

- The current Illinois models behave differently from the histories of Illinois Region 1 and the Indiana North region at almost all CR levels.
- The means of the Illinois Region 1 histories are much closer to the Indiana North histories than the current Illinois models. This is especially true for central and southern Indiana and the corresponding Illinois regions, 3 and 5, respectively.
- Apparent differences are seen between Illinois Region 1 and Indiana North. This may be attributable to Region 1 being further north than the Indiana North region. Region 1 is also a much smaller geographic area (covering the metropolitan Chicago, as seen in Figure 2) than Indiana North. These factors may have contributed to the observed differences between Illinois Region 1 and Indiana North. However, the differences between Illinois and Indiana are insignificant between Illinois Region 3 vs. Indiana Central and Illinois Region 5 vs. Indiana South (as shown in Figures 34 and 35, respectively). In other words, the differences in the central and south areas between Illinois and Indiana are much less significant and hardly noticeable for some CR levels.
- Figure 35, for comparison, still demonstrates differences between the current Illinois models and CR histories, whether Illinois or Indiana. In contrast, the total life prediction by the current Illinois models is close to the averages of the histories of Illinois and Indiana, much closer than the other two regions, Indiana North and Central.

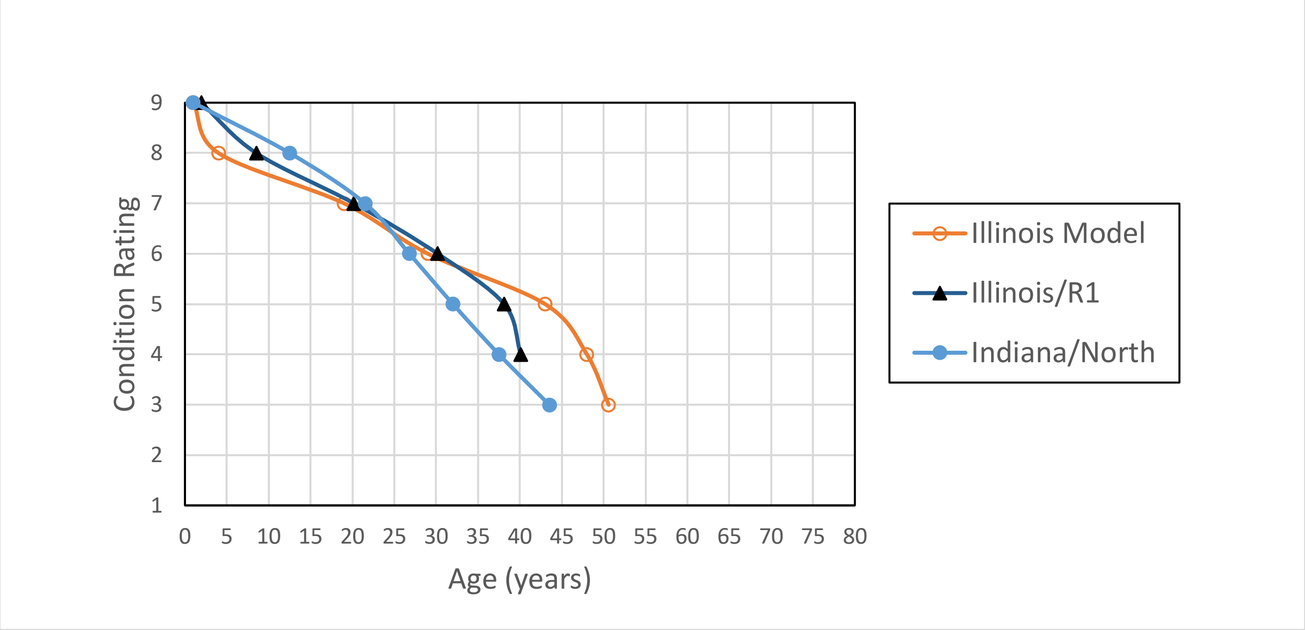

Figure 33. Chart. Illinois Region 1 vs Indiana North: Deck.

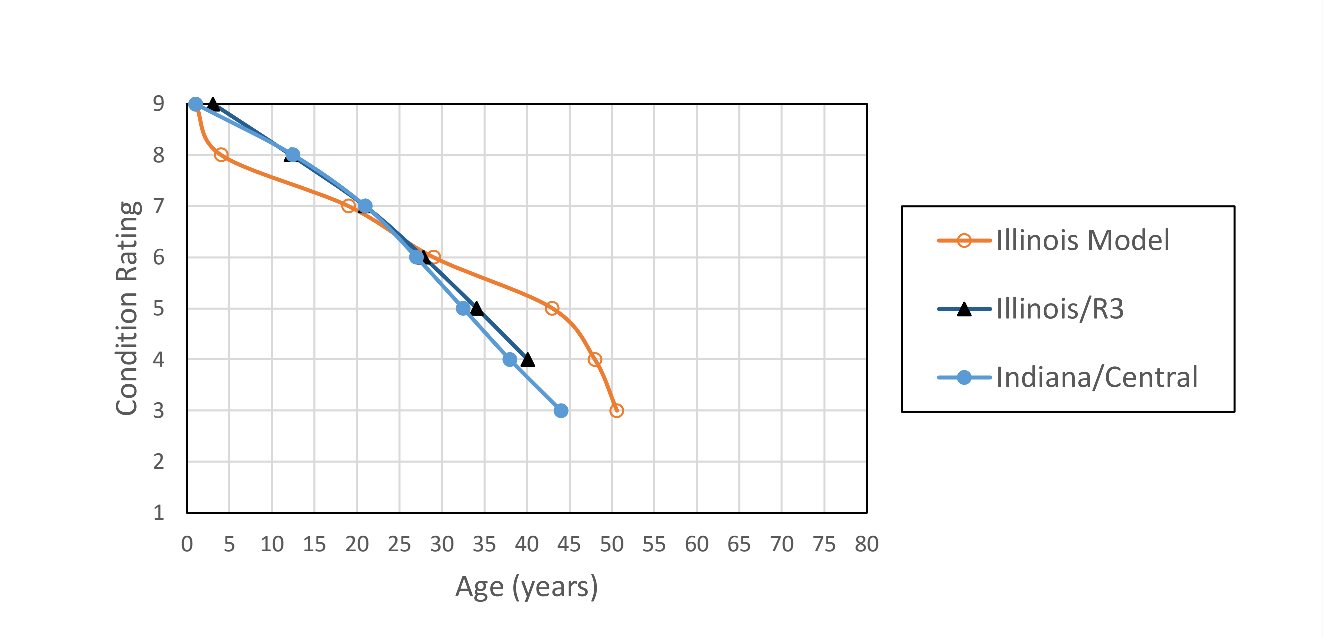

Figure 34. Chart. Illinois Region 3 vs Indiana Central: Deck.

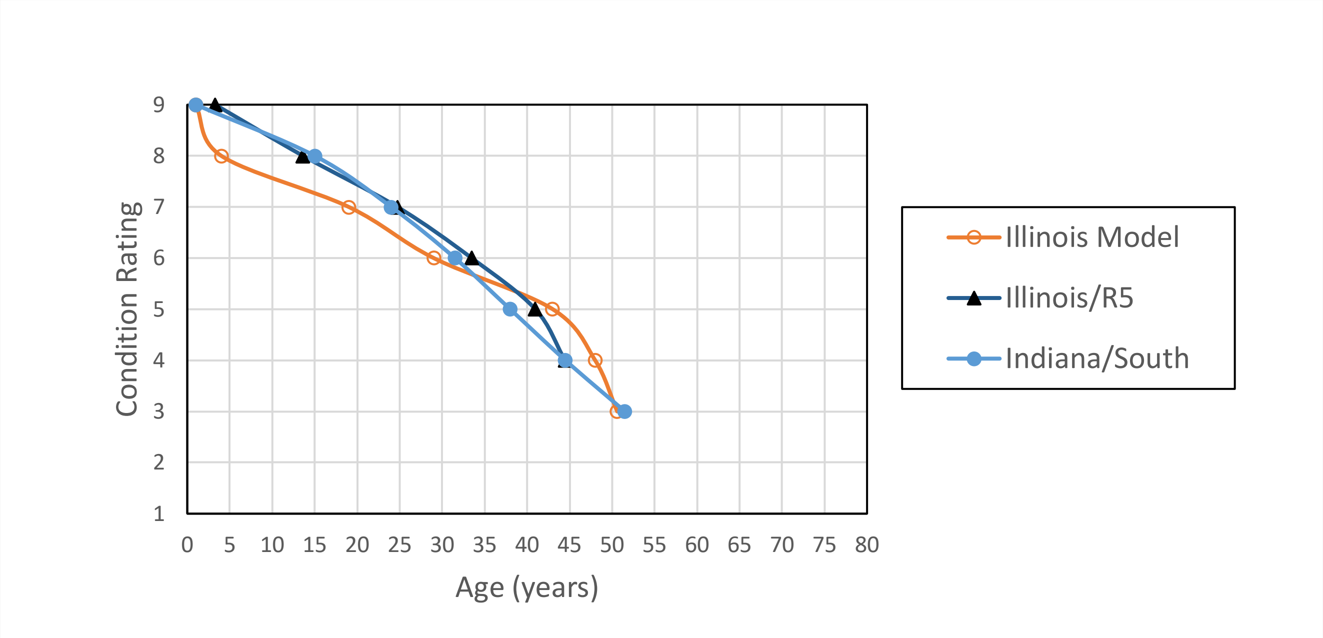

Figure 35. Chart. Illinois Region 5 vs Indiana South: Deck.

Superstructure

Figures 36 to 38 compare the superstructure models of Illinois Regions 1, 3, and 5 to Indiana North, Central, and South, respectively. For this case, the current Illinois models are apparently off from the CR histories of Illinois and Indiana. In contrast, these histories exhibit a much more consistent relation, similar to the deck case above. Nevertheless, this consistency is better for the central and southern regions. Again, the apparent disagreement in the north between Illinois and Indiana may be because Illinois Region 1 is not very compatible with Indiana North in terms of latitude, geographic area, and economic activity or traffic and truck traffic volumes. These factors can influence required MR&R, scatter in statistics, and load-related deterioration.

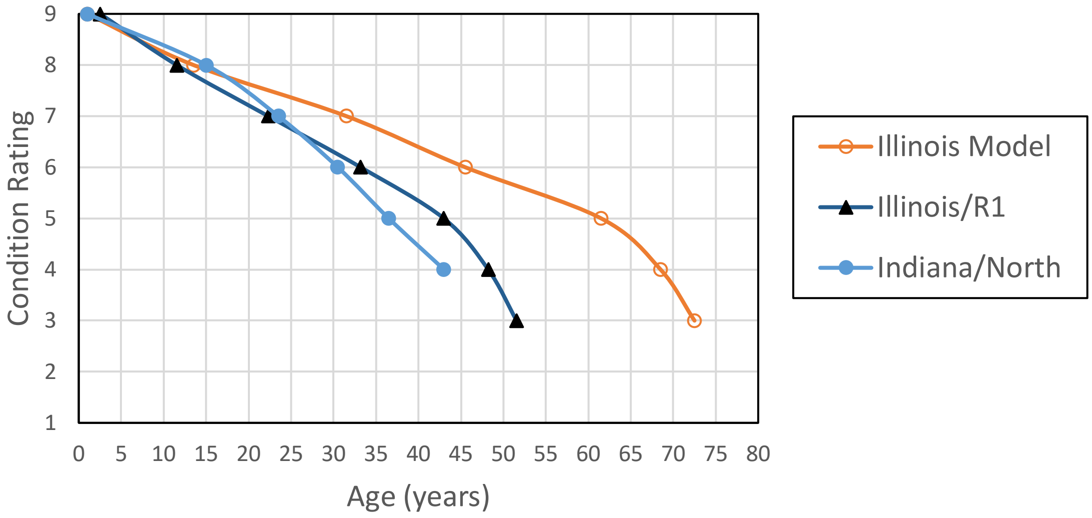

Figure 36. Chart. Illinois Region 1 vs Indiana North: Superstructure.

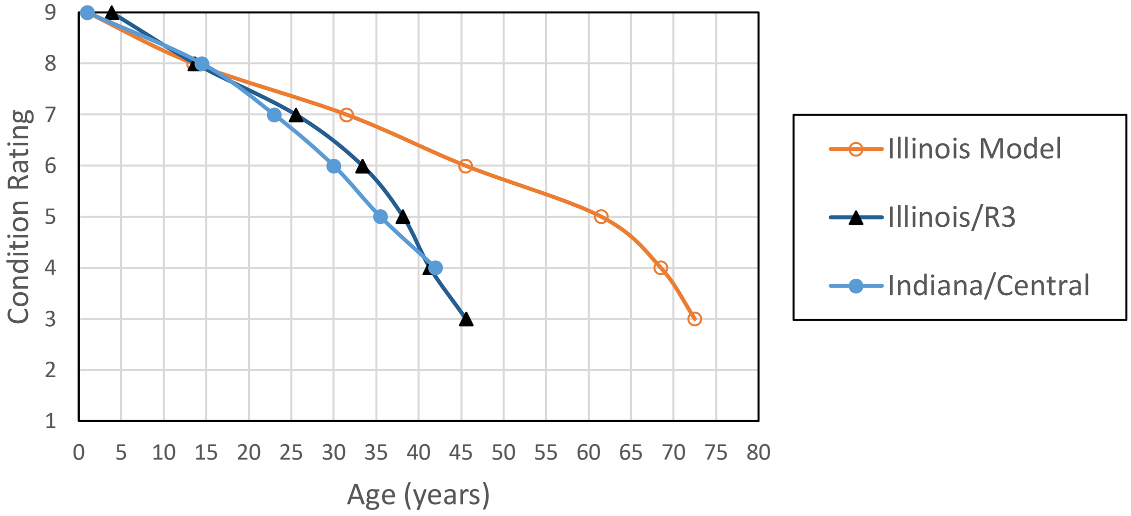

Figure 37. Chart. Illinois Region 3 vs Indiana Central: Superstructure.

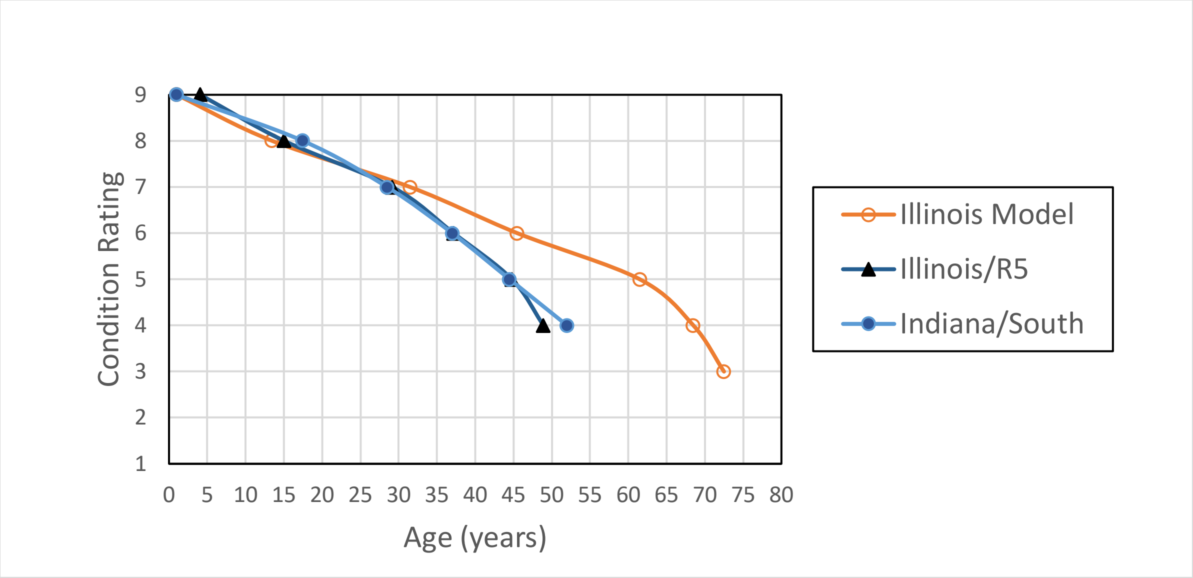

Figure 38. Chart. Illinois Region 5 vs Indiana South: Superstructure.

Substructure

Figures 39 to 41 are for the bridge substructure case. The Illinois regional histories show closer behaviors to the Indiana regional histories than with the current Illinois models meant for all three regions of Illinois. This regional consistency is best for Illinois Region 5 vs Indiana South compared with the other regions.

Note that the inconsistency between the CR histories and the current Illinois models is further outstanding for the bridge substructure than for the superstructure. The worst case is in Illinois Region 1 and Indiana North. The total life difference is as large as approximately 30 years, when the transition of CR 3 to 2 is taken to the practical end of the bridge substructure's life, where historical data are sparse or practically nonexisistent.

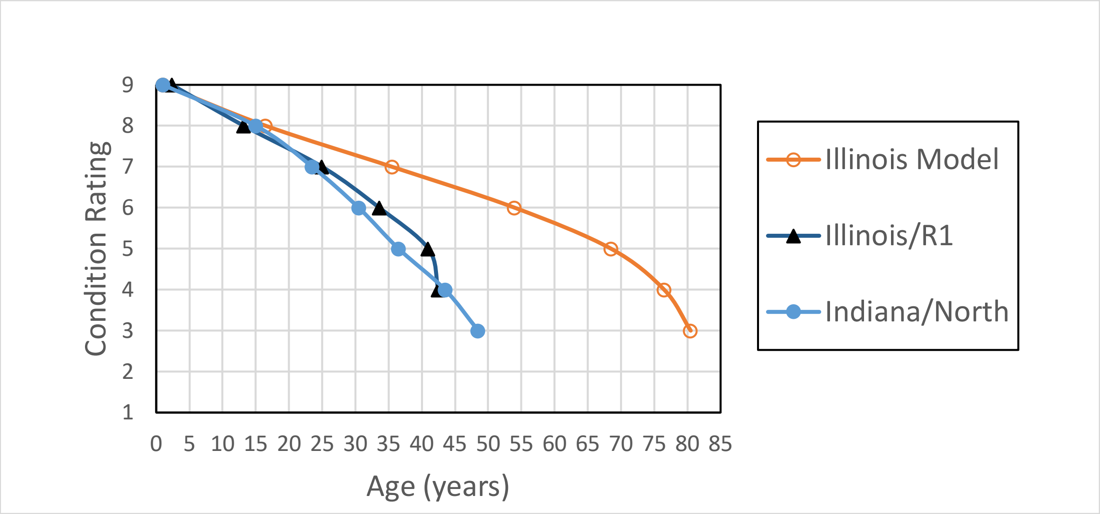

Figure 39. Chart. Illinois Region 1 vs Indiana North: Substructure.

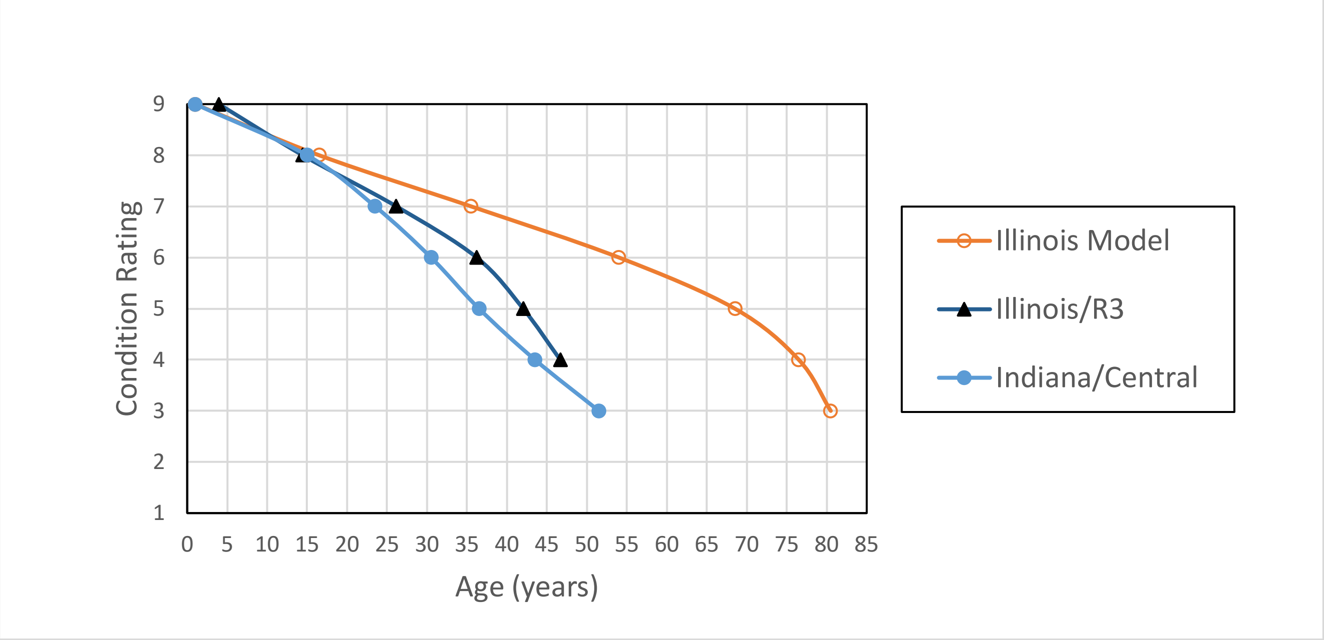

Figure 40. Chart. Illinois Region 3 vs Indiana Central: Substructure.

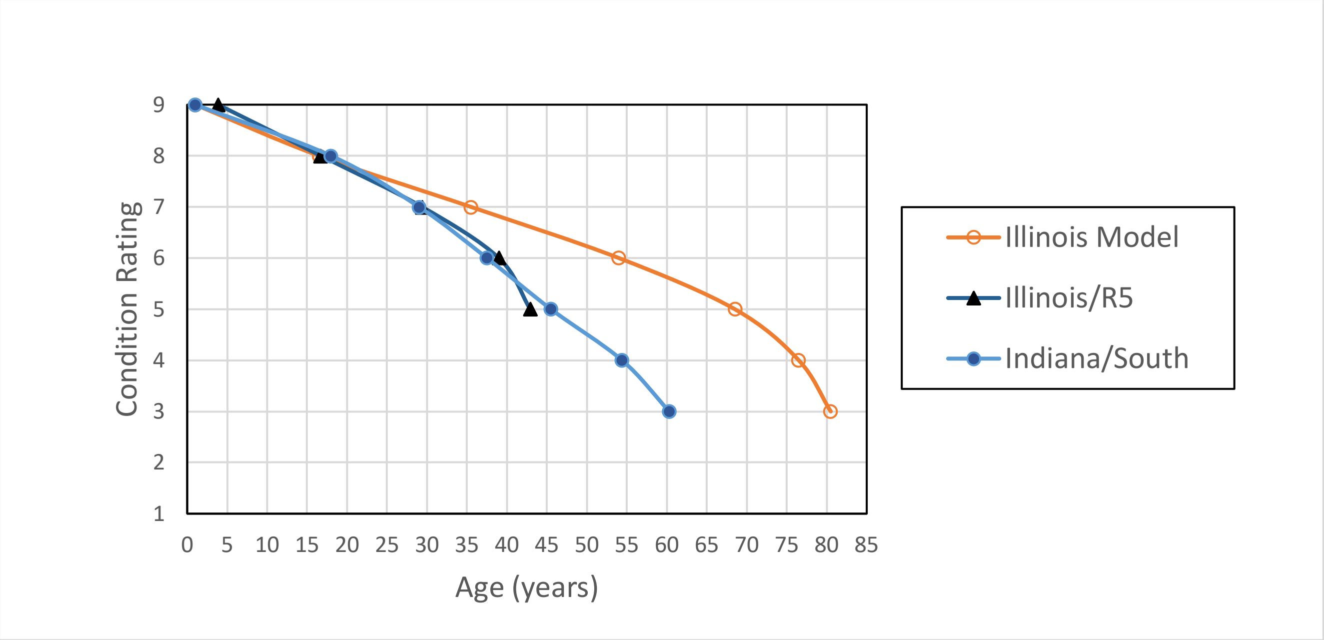

Figure 41. Chart. Illinois Region 5 vs Indiana South: Substructure.

Culvert

Illinois divides culverts into two groups (shallow fill [< 2 feet] and deep fill [≥ 2 feet]), while Indiana uses only one group. As such, Figures 42 to 44 present the two Illinois culvert groups together in the graphs for comparison with Indiana.

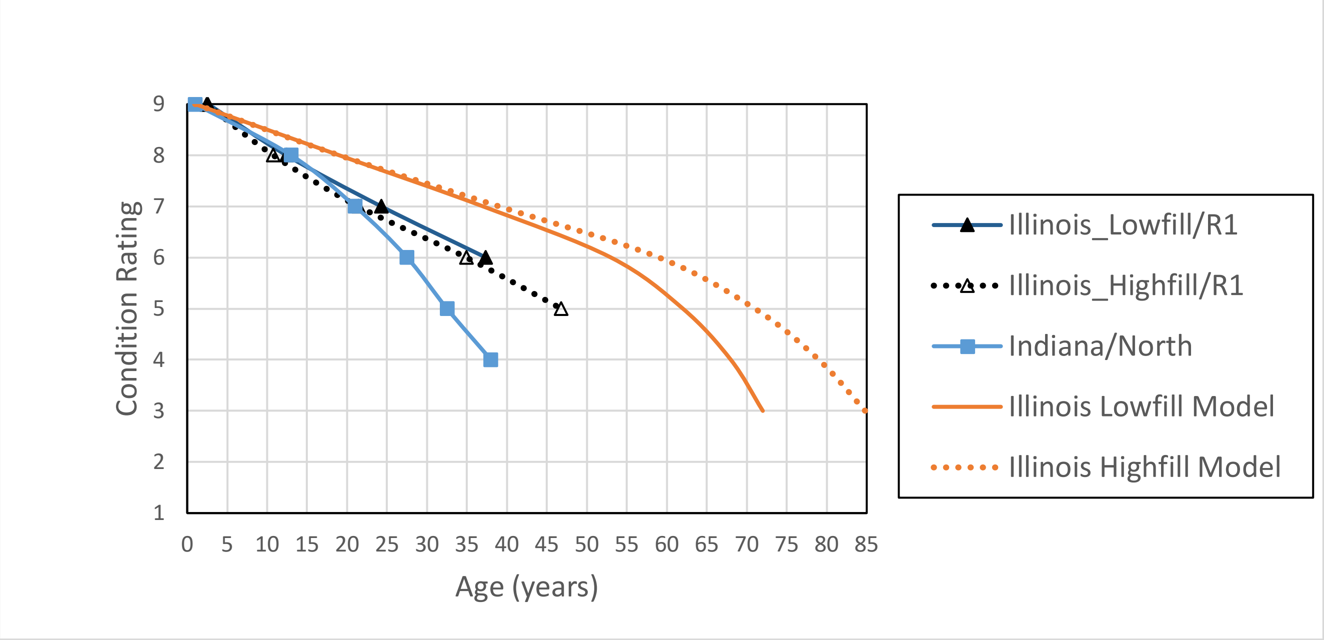

Figure 42. Chart. Illinois Region 1 vs Indiana North: Culvert.

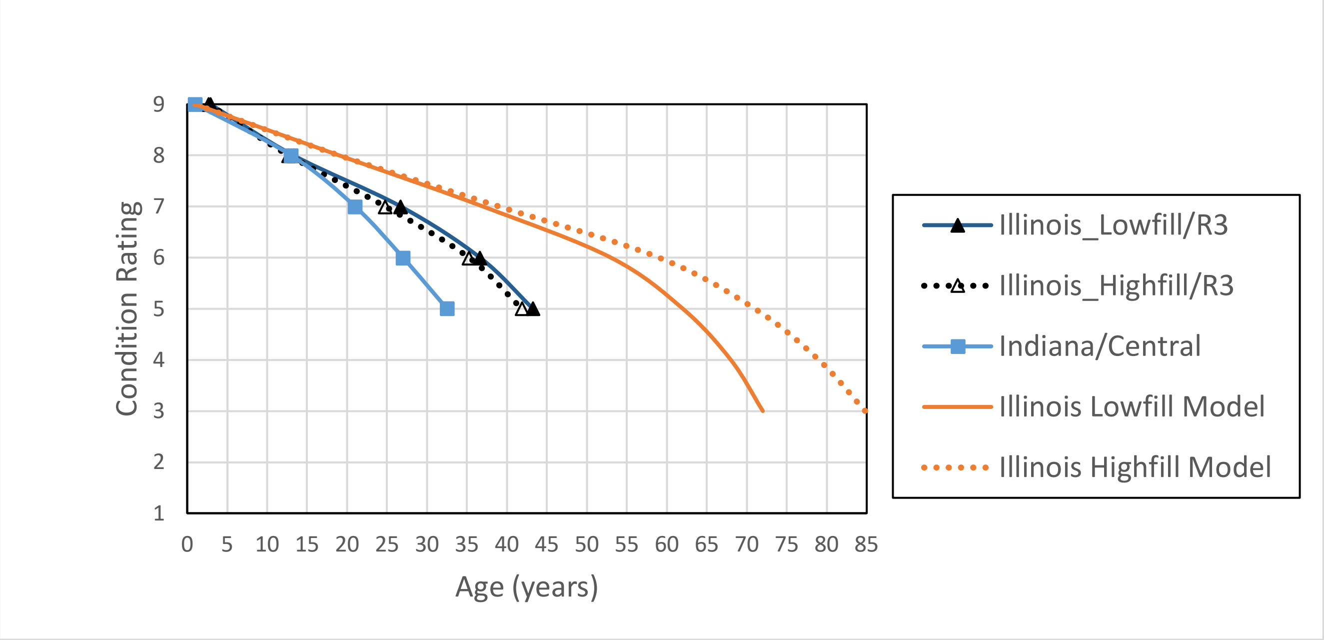

Figure 43. Chart. Illinois Region 3 vs Indiana Central: Culvert.

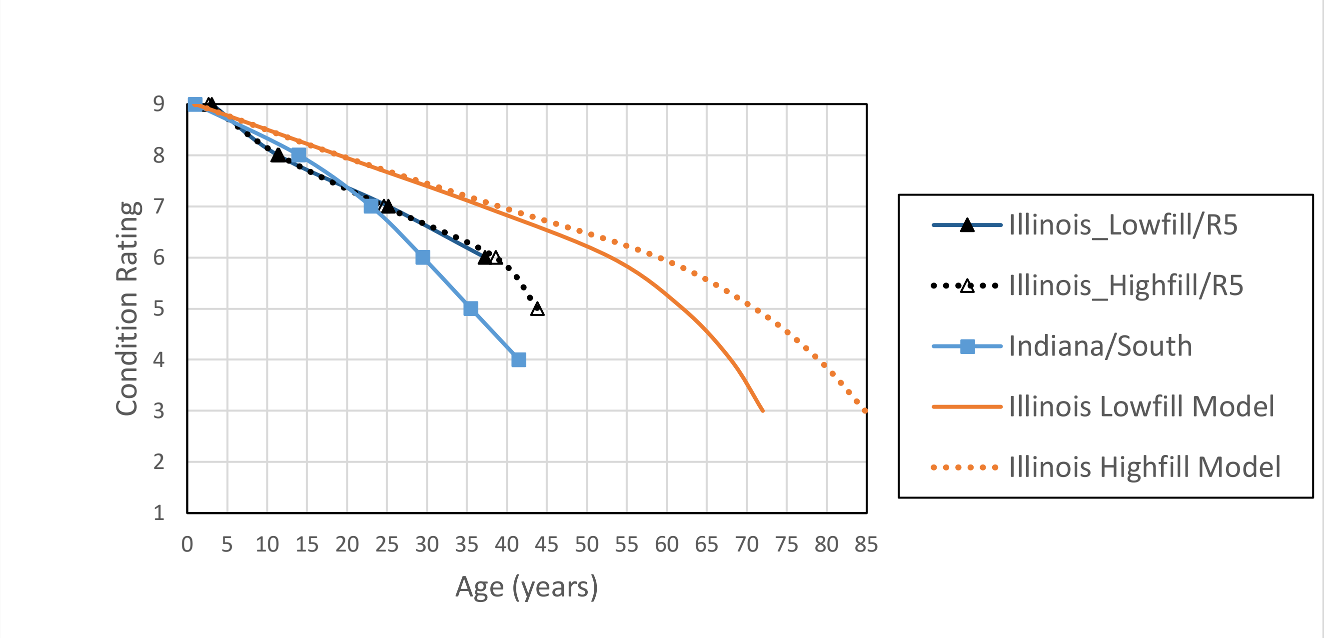

Figure 44. Chart. Illinois Region 5 vs Indiana South: Culvert.

In Figures 42 to 44, the Illinois CR histories appear to be closer to the Indiana histories than the Illinois models. However, this closer relation deteriorates when CR is below 8 or 7. This deviation is more severe for Illinois Regions 1 and 3 vs Indiana North and Central, respectively.

CHAPTER 5: PROBABILISTIC MODELING USING THE WEIBULL DISTRIBUTION

Given this project's limited duration, probabilistic approaches are preliminarily considered for Illinois bridge deterioration modeling and forecasting. A modeling example for the transition time using the Weibull distribution is presented below for illustration and discussion.

This example is important because it illustrates a feasible approach that can be extended to all components / systems and levels of CR discussed above. This Weibull distribution approach has also been adopted in BrM and fully supported by AASHTO in terms of its applicability for widespread application.

The Weibull distribution is a popular tool in various fields of science and engineering (Evans et al. 2019). It has been used to model the life of a product, facility, etc. In this study, this distribution is used to model the transition time between any two CR levels. The probability density function of the Weibull distribution for transition time *t* is commonly formulated as follows:

$$f(t)=\begin{cases}\frac{t}{\lambda}(\frac{t}{\lambda})^{k-1}e^{-(\frac{t}{\lambda})^{k}} & for\,t\geq 0.0\\ 0 \quad for\,t<0.0\end{cases} \tag{1}$$

Figure 45. Equation. Probability density function of Weibull distribution.

where λ and k are model parameters, $\lambda > 0$ is the scale factor to scale t, and $k > 0$ is the shape factor dictating the shape of the density function.

There are several methods to fit the observation data to the Weibull distribution. However, there are no advantages in the literature associated with any particular method, as long as the method includes a feature to validate the distribution type.

As such, a probability paper method is used here to determine the Weibull distribution parameters. The method's concept is simple and has been used for other probability distributions. It first derives the Weibull cumulative probability function into a probability paper, which allows the data to be plotted on it. If the data points presented on the probability paper indicate a straight-line trend, then the Weibull distribution is confirmed. The resulting straight-line's parameters (its slope and intercept) are then used to find the model parameter in Equation 1.

Figure 46 shows the results of an example application to the deck's transition time from CR 7 to 6. One of the two distributions shown is fitted using the state histories and the other using Region 3 histories. The current deterministic model for this case is also plotted in the same figure at 15 years for comparison. The probability paper plot for the state CR history data is shown in Figure 47, along with the fitted straight-line regression. The high R^2 value of 0.9486 in the figure indicates a very good fit and confirms the Weibull distribution.

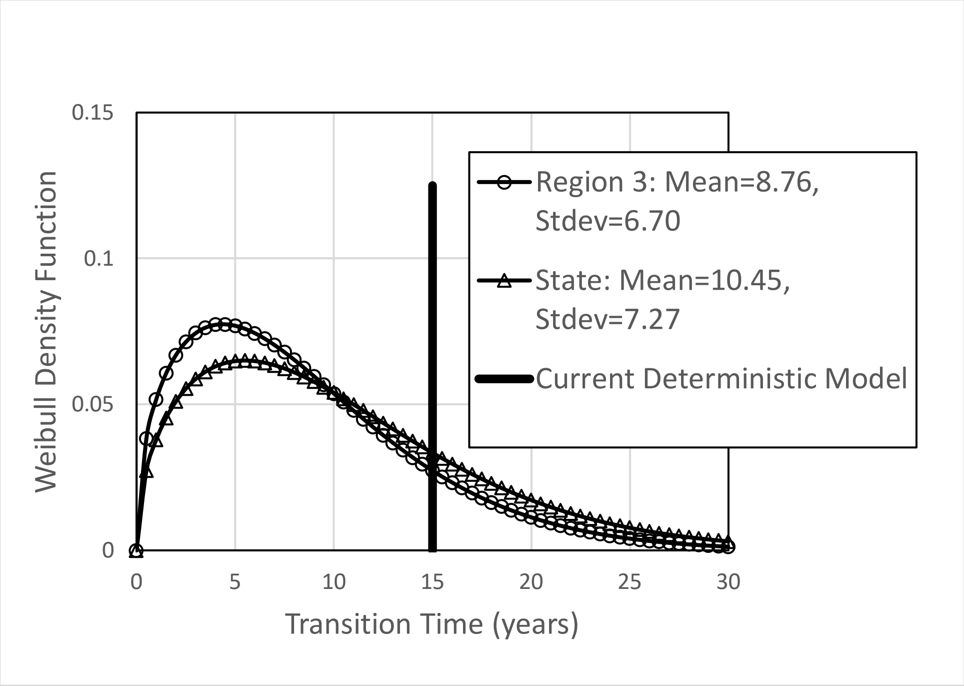

Figure 46. Chart. Fitted Weibull distribution densities for deck, CR 7 to 6.

Compared with the current Illinois model

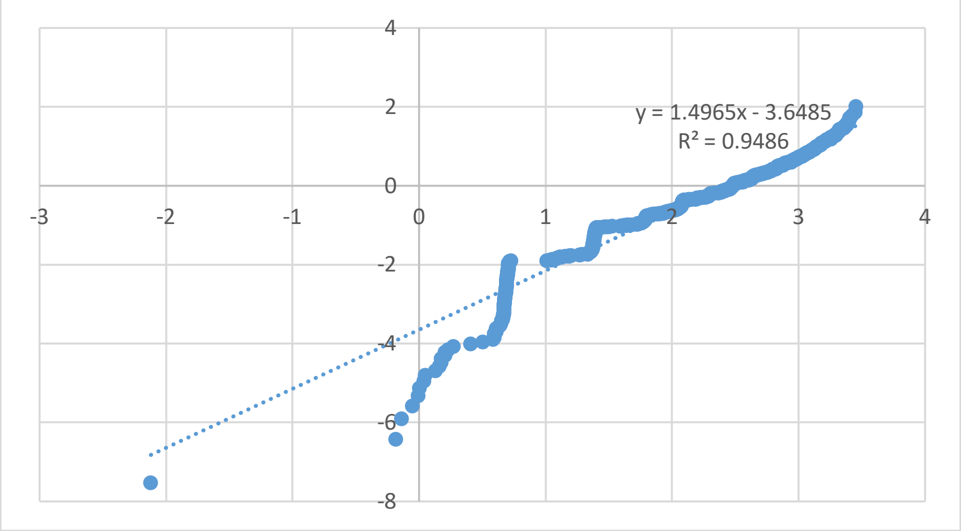

Figure 47. Chart. State data fitted on Weibull probability paper for deck, CR 7 to 6.

When such modeling is performed for all CR levels and bridge subsystems (deck, superstructure, substructure) and culvert systems, probabilistic forecasting can be carried out covering the observed variations in a systematic framework. This approach is thereby recommended to be pursued in a future study to fully enhance IDOT's capability of scientifically forecasting bridge deterioration. Note that the effects of bridge improvements such as deck overlay and rehabilitation can also be modeled using the Weibull distribution, which is a versatile probabilistic tool.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been reached from this study based on the analysis results and their comparisons as well as with the Indiana regional deterioration curves.

- Significant variations are observed in the transition times between every two CR levels of NBI. An exception is CR 9 to 8, because there is no room for variation above CR 9.

- Region 1 behavior is most often different from the statewide behavior compared with other regions. The Region 1 mean life is often shorter than the statewide mean. In addition, the Stdev of Region 1 is often smaller than that of the state, indicating reduced uncertainty in Region 1.

- The forecasts of the current deterministic deterioration models are off compared with the observed histories at the state and regional levels. The current models often overestimate or overforecast the lives of bridge components and culvert systems, except for the case of the deck beam. Note that the deck beam data set is significantly smaller than other bridge components (deck, superstructure, substructure) and the two culvert systems.

- The observed mean values for the transition times are recommended to be used for forecasting deterioration of Illinois bridges and culverts at the regional level. The observed variations (Stdev) from the mean values are also recommended to be considered when performing forecasts. However, when historical data are inadequate leading to unreliable Stdev at lower CR levels, the Stdev for the higher CR levels may be used. This is a short-term solution until more data become available to provide more reliable Stdev values for lower CR levels.

Because this is a relatively short and small study, several factors were not included in the scope and in the provided data. Accordingly, the following items are recommended for further research to investigate their effects:

- Other influential factors should be studied regarding their effects on CR. Examples include, but are not limited to, improvements (MR&R) to bridge components and culver systems, truck traffic intensity and cumulated volume over the transition time, structure component features (e.g., black bars, epoxy-coated bars, and weathering steel) and environmental factors such as the number of freeze-thaw cycles.

- Given the observed significant variation in CR and transition times, probabilistic approaches are recommended for further refinement of the Illinois deterioration models.

- The Weibull distribution approach to model transition times is viable for Illinois. It is recommended to pursue this approach further for more realistic and reliable forecasts of bridge deterioration and the associated planning for their improvement.

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