6-29-2016

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Recommended Citation

Tabatabai, Habib; Lee, Chin-Wei; and Tabatabai, Mohammad A., "Survival Analyses for Bridge Decks in Northern United States" (2016). *Civil and Environmental Engineering Faculty Articles*. 7.
https://dc.uwm.edu/cee_facart/7

Survival Analyses for Bridge Decks in Northern United States

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Abstract: The use of deicing salts in northern regions of the United States is a major contributor to the long-term deterioration of bridge decks. In this study, the 2008 U.S. National Bridge Inventory (NBI) records were used to develop survival models for non-reconstructed bridge decks in six northern states of Minnesota, Wisconsin, Michigan, Ohio, Pennsylvania, and New York. The hypertabastic accelerated failure model was used to develop survival (reliability) and hazard (failure rate) functions for all six states. The NBI parameters included were the deck rating, type of superstructure (concrete or steel), deck surface area, age, and average daily traffic (ADT). A recorded NBI deck rating of 5 was considered to be the end of service life. Results show that ADT and deck surface area are both important factors affecting reliability and failure rates in all six states studied. In general, deck reliability and failure rates correspond reasonably well with qualitative measure of the harshness of each state's winters. The type of superstructure has a varied influence in different states. It is recommended that deck area and ADT be considered as important factors when planning maintenance operations.

Keywords: Bridge decks; reliability; service life; bridge maintenance; durability

1.0 Introduction

The use of deicing salts in northern regions of the United States is a major contributor to the corrosion of reinforcing steel in bridge decks. Diffusion of chloride ions through the concrete deck slab can lead to the initiation and progression of corrosion in the embedded reinforcing steel bars. Expansive pressures due to continuing corrosion will eventually lead to cracking, delamination and spalling of concrete.

Numerous researchers have proposed physical and computational models and relationships to predict timing for different bridge deck deterioration stages including corrosion initiation, cracking, and end of service life. Examples include works by Cady and Weyers (1984 and 1992), Liu and Weyers (1998), Lee (2011), and Tabatabai and Lee (2006). In such models, a number of assumptions are typically made regarding chloride diffusion, threshold chloride levels, corrosion rates, bar expansion due to corrosion, cover depth, strength of concrete, etc.

Conventional reliability models have been widely used in structural and bridge engineering applications. Such models (whether time-dependent or not) are generally focused on reliability approaches that compare load versus resistance based on strength limit states (e.g., works by Nowak and Eamon, 2008, Akgul and Frangopol, 2004, Estes and Frangopol, 2005, and Morcous and Akhnoukh, 2007). However, the end of service life in bridge decks is primarily related to serviceability issues (typically chloride-induced corrosion damage in the northern states) and is not directly associated with reaching a strength limit state. It is indeed very rare for a conventional bridge deck slab to reach the end of its service life through structural failure. Cheung and Li (2001) considered a serviceability criterion (deflection) when evaluating bridge deck reliability. However, the deflection criterion was based on response to loading. Madanat, Mishalani, and Ibrahim (1995) used Markov chains to assess transition probabilities using condition ratings.

Time-dependent survival models (also known as “time-to-event” models) are widely used in biomedical and other applications. In this approach, relevant data (such as survival of cancer patients at various times under different treatments and contributing factors) are analyzed to develop models that consider the influences of those treatments/factors with time. These survival models are typically data- and outcome-driven, and not based on theoretical understanding of how various treatments may or may not work. This approach is considered suitable in this study because the reliability of bridge decks are primarily based on age and serviceability issues such as corrosion, and not based on loads exceeding a certain strength limit state. Such an approach requires availability of significant time-dependent bridge deck performance data. The National Bridge Inventory (NBI) is a comprehensive database of bridge information that can provide the necessary data for such an effort.

Development of such survival models could provide valuable information for planning and prioritizing of bridge deck management and maintenance tasks. These models could also help better understand and quantify the impact of different variables on survival outcomes.

Tabatabai, Tabatabai, and Lee (2011) developed a survival model for Wisconsin bridge decks using the deck ratings and other information provided in the 2005 NBI data. In that work, a recorded deck rating of 5 was considered to be the end of service life for a bridge deck. NBI parameters such as age of bridge, Average Daily Traffic (ADT), deck surface area, and type of superstructure (steel or concrete) were used to perform survival analyses using four different models: Weibull, log-logistic, lognormal, and hypertabastic (Tabatabai et al., 2011). Reconstructed bridges and bridges with unconventional decks and superstructures were excluded from the analyses. The Akaike Information Criterion (AIC) (Akaike, 1974) was used to determine the best-fit model, which was determined to be the hypertabastic accelerated failure time model. Reliability and failure rate functions were then developed for Wisconsin bridge decks.

Other researchers have used the survival analysis approach in bridge engineering applications. Examples include works by Yang et al. (2013) and Beng and Matsumoto (2012).

2.0 Study Approach and Data

2.1 Study Approach

In this study, the same approach used by Tabatabai et al. (2011) for Wisconsin bridge decks was used to assess and compare bridge deck reliability and failure rates for bridge decks in six northern states of Minnesota, Wisconsin, Michigan, Ohio, Pennsylvania, and New York. These six states are located within the northern or northeastern regions of the U.S., in which deicing salts are routinely and extensively used on bridge decks in winter. However, there are differences among these six states including varying climates, design and construction practices, maintenance practices, etc. Therefore, a comparison of reliability parameters among these states would be of interest.

The 2008 NBI bridge data were used to accomplish this work. The factors considered were bridge age, ADT, deck surface area, and superstructure type. ADT values are typically estimated by bridge inspectors visiting the site of the bridge based on sample counting of traffic.

The ADT and deck area parameters were selected because they were considered to be potentially relevant to long-term deck performance. It is anticipated that higher traffic volumes (including truck traffic) would affect the long-term “wear-and tear” on bridge decks. Higher traffic volumes may also prompt more extensive applications of deicing salts in winter, which in turn affects the potential for chloride-induced corrosion damage.

The authors had a choice of using either ADT or ADTT (Average Daily Truck Traffic) in the analyses. These two NBI parameters are considered correlated, and therefore both parameters could not be used together in the analyses. In fact, the AASHTO LRFD Standard Specifications for Highway Bridges (2010) provides factors relating ADT and ADTT on rural and interstate highways. ADT was chosen because the end of service life is typically not due to load-induced structural failure. Although trucks cause the most “wear-and-tear” on bridges, deicing salt applications (that lead to corrosion) may occur regardless of the percentage of trucks on the road.

The deck surface area was included in the analyses because the likelihood that defects may exist in localized areas is expected to be higher on larger deck surfaces. Therefore, the size of the deck area was considered to be potentially relevant to deck reliability, and was included as a parameter in this study.

The type of superstructure (structural steel or concrete) was included as a parameter even though a clear and strong basis for its influence on deck performance is lacking. However, a difference in superstructure type is nonetheless an obvious distinction, and its effect, if any, should be understood. Therefore, this parameter was added to the study as well.

Other parameters in the NBI database were not considered (such as location within the state, features intersected, bridge clearances, structure length…) as they were either not related (directly or indirectly) to deck performance, or they were considered to be correlated with one of the parameters that were included.

The data from various states were analyzed separately (not combined). Thus comparisons of results among various states would include the effects of their differing climatic and environmental conditions, maintenance practices, deicing procedures, etc.

Since the earlier work by Tabatabai et al. (2011) indicated (based on the Akaike Information Criterion) that the hypertabastic accelerated failure time model was the best fit model for the Wisconsin data, this model was also used for the analysis of data from all six states in this study.

An analysis was performed to establish that the selected parameters of age, deck area, superstructure type, and deck area were not correlated. This analysis was done for each state's data. Correlation results show that the selected parameters were not correlated (Appendix Table A1).

2.2 National Bridge Inventory (NBI) Data

The NBI database contains over 100 data items for each bridge in the database. All bridges are inspected at a maximum interval of two years, and various components of each bridge, including bridge decks, receive numerical ratings by inspectors.

The numerical NBI Ratings are defined as follows: Failed condition (0), imminent failure condition (1), critical condition (2), serious condition (3), poor condition (4), fair condition (5), satisfactory condition (6), good condition (7), very good condition (8), and excellent condition (9).

A bridge is rated structurally deficient if its deck receives a condition rating of less than 5. The actual rating for a bridge deck with a recorded rating of 5 (recorded at the time of last inspection) is between 4 and 5. Such a rating is considered by many to be the end of service life of a bridge deck when rehabilitation or replacement should take place (Hearn, 1999).

A complete explanation of the process of data extraction is presented by Tabatabai et al. (2011), a summary of which is presented below. First, for each of the six states, NBI records that were missing the deck rating, construction date, or ADT were removed from the dataset. All bridges that had previously undergone reconstruction or rehabilitation of the deck (reconstructed) were also removed. The reconstructed bridges were not considered here because the detailed history of repair works are not recorded in the NBI data and such repairs alter the subsequent deck reliability.

Parameters included in the analysis were deck rating (NBI Item 58), age (NBI Item No. 90, year of last inspection minus Item No. 27, year built), deck area (Item No. 49, structure length times Item No. 51, curb-to-curb width), and ADT (Item No. 29).

The less common types of decks and structural systems were excluded. Only concrete, prestressed concrete and steel superstructures (Item 43) were considered. Systems such as trusses, arches, and cable-stayed bridges were excluded since their numbers are relatively small. Deck systems (Item No. 107) other than cast-in-place or precast concrete were also excluded. Decks other than reinforced concrete decks are a small fraction of all decks, and their deterioration modes would be different. Finally, only bridges with a recorded deck rating (Item No. 58) of 5, considered to be the end of service life, were retained.

3.0 Survival Model

The probability of failure is defined here as the probability of reaching the end of service life at a given age (time). Reliability or survival (S), is the probability of not reaching the end of service life at a given age (1 minus the probability of failure). Hazard (h) is the instantaneous failure rate (probability of failure per unit time) at any given age assuming that failure has not occurred up to that age.

3.1 Hypertabastic Distribution

The hypertabastic distribution is a statistical distribution that was first introduced by Tabatabai, Zoran, Williams, and Singh (2007). There have been several applications of this distribution in biomedical sciences including the analysis of the effects of covariates on the survival time of cancer patients (Tabatabai, Eby, Nimeh, Singh, 2012a and 2012b).

Unlike other distributions (e.g. Weibull, log-logistic, lognormal…), an important feature of the hypertabastic hazard function is its ability to model different patterns of failure rate (Tabatabai et al., 2007 and 2011). The hypertabastic failure rates can take many different shapes such as: monotonically decreasing with time; increasing and then decreasing (unimodal); increasing towards an asymptote; increasing with upward concavity followed by increase with downward concavity; increasing with upward concavity followed by a linear increase; and increasing with upward concavity (Tabatabai et al., 2007 and 2011).

Tabatabai et al. (2011) determined that the hypertabastic accelerated failure model was the most suitable model for the Wisconsin NBI deck data based on the Akaike Information Criterion and the non-proportionality of hazards.

The hypertabastic distribution function, F(t), probability density function, f(t), the failure rate function, h(t), and the survival function, S(t), are described below as: (Tabatabai et al., 2011)

$$F(t) = \begin{cases} 1 - \operatorname{sech}\{\alpha[1 - t^{\beta}\coth(t^{\beta})]/\beta\}, & for\ t > 0 \\ 0 & , for\ t \leq 0 \end{cases} \qquad (1)$$

$$f(t) = \begin{cases} \operatorname{sech}[W(t)]\,[\alpha t^{2\beta-1}\operatorname{csch}^2(t^{\beta}) - \alpha t^{\beta-1}\coth(t^{\beta})]\tanh[W(t)], & for\ t > 0 \\ 0 & , for\ t \leq 0 \end{cases}$$

(2)

$$h(t) = \alpha[t^{2\beta-1}\operatorname{csch}^2(t^{\beta}) - t^{\beta-1}\coth(t^{\beta})]\tanh[W(t)] \qquad (3)$$

$$S(t) = \operatorname{sech}\{\alpha[1 - t^{\beta}\coth(t^{\beta})]/\beta\} \qquad (4)$$

$$W(t) = \alpha[1 - t^{\beta}\coth(t^{\beta})]/\beta \qquad (5)$$

The parameters α and β (defined later for each of the six states) are positive. Functions sech( ) and coth( ) are hyperbolic secant and hyperbolic cotangent, respectively.

3.2 Hypertabastic Survival and Hazard Equations

Three main parameters were considered in the model: Average Daily Traffic (ADT), deck area (AREA) and superstructure type (TYPE). The TYPE parameter is binary, assuming a value of 0 when the superstructure is concrete and 1 when it is steel. The AREA covariate is the surface area of the deck in square meters, and ADT is directly extracted from the NBI data.

Equations 1 through 4 above do not include the influence of the bridge parameters of interest. To consider the effects of such parameters, an exponential function of these parameters is used in either the “proportional hazard” or “accelerated failure time” forms of the hypertabastic model. The hypertabastic accelerated failure model was maximized using the method of maximum likelihood[12]. The resulting Wald test statistics for the parameters in each of the six states are shown in the Appendix Table A2. Wald test results indicate that all three variables are statistically significant in all six states.

Tabatabai et al. (2011) noted that the Kaplan-Meier hazard graphs (Kaplan and Meier, 1958) for steel and concrete superstructures crossed each other at multiple points. Therefore, the proportional hazards model would not be valid. The same is true for the data analyzed in this paper. Therefore, the accelerated failure time model was used.

Using the hypertabastic accelerated failure time model and neglecting small terms, the following equations were proposed for $h(t_g)$ and $S(t_g)$: (Tabatabai et al., 2011)

$$S(t_g) = \operatorname{sech}\{\alpha[1 - {t_g}^{\beta} \coth({t_g}^{\beta})]/\beta\} \tag{6}$$

$$h(t_g) = \alpha[-{t_g}^{\beta-1} \coth({t_g}^{\beta})] \tanh[W(t_g)]\, e^{[c.AREA+d.ADT+e.TYPE]} \tag{7}$$

$$t_g = (AGE)e^{[c.AREA+d.ADT+e.TYPE]} \tag{8}$$

$$W(t_g) = \alpha[1 - {t_g}^{\beta} \coth({t_g}^{\beta})]/\beta \tag{9}$$

In Eq. 8 above, parameter t_g is defined as a mathematical function of AGE (age of bridge in years), AREA, ADT, and TYPE. Parameters α, β, c, d, and e are all determined for each group of data analyzed (i.e. for each of the 6 states) using the procedures proposed by Tabatabai et al. (2011). For the cases in which TYPE is not a consideration (i.e. steel and concrete superstructures are not distinguished), a different set of α, β, c, and e parameters are used with the e parameter being equal to zero.

4.0 Results and Discussion

Figure 1 shows Kaplan-Meier non-parametric estimates of bridge deck reliability in all six states. This non-parametric estimate does not include the influences of deck area, ADT or superstructure type.

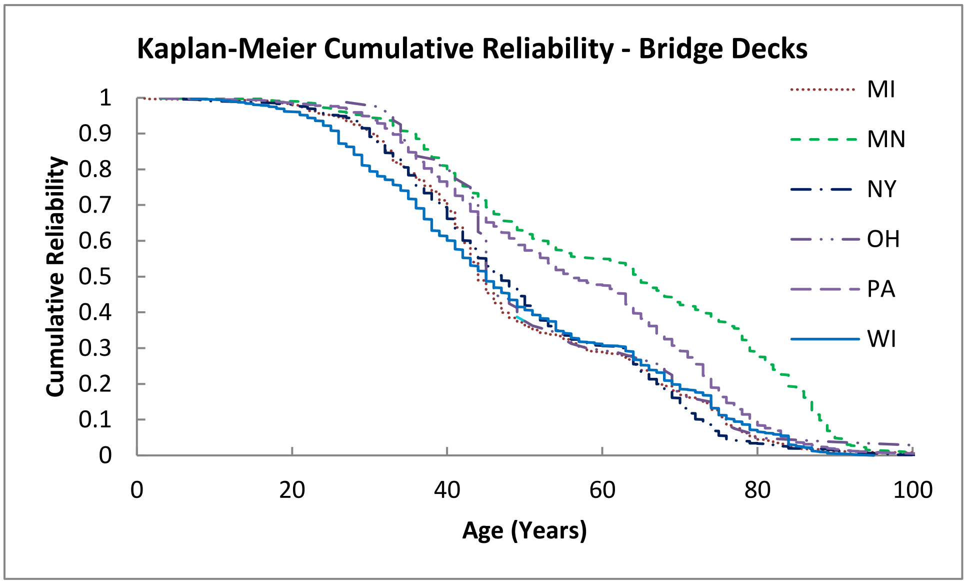

Figure 1. Kaplan-Meier reliability for bridge decks in six states.

Tables 1 through 3 show basic statistical information on the six-state NBI data obtained for concrete, steel, and combined (steel and concrete) superstructures, respectively. The total number of bridges included in the analyses was 7208. The mean age (corresponding to a recorded deck rating of 5) is 57 years for concrete superstructures, 51 years for steel superstructures, and 53 years for both superstructures combined. The corresponding median ages are slightly lower. The median deck areas and ADT values are substantially lower than the corresponding mean values for all six states. This indicates that the mean values are influenced by a relatively small number of bridges with very large ADT and deck surface areas.

The various model parameters obtained for the six states are shown in Tables 4 and 5. In Table 4, the parameter TYPE is not considered as a factor in the analysis (i.e. e=0). Values in Table 5 are used when the type of superstructure is a consideration. TYPE is equal to 0 for a bridge with a concrete superstructure and 1 for a steel superstructure. Values of parameters in Tables 4 and 5 can be used in conjunction with Equations 6 through 9 to determine reliability (survival) and failure rates (hazard).

Table 1. Statistical Information on NBI Data from Six States (Concrete Superstructures)

		WI	**MI**	**MN**	**NY**	**OH**	**PA**	**ALL**
ADT	**Mean**	6456	7299	4482	5830	4115	5992	5672
	Median	1100	3100	580	2518	991	1840	1520
Age (years)	**Mean**	44	51	60	51	61	59	57
	Median	38	45	55	55	61	64	56
Area (m^2)	**Mean**	369	376	279	600	184	335	316
	Median	247	252	146	177	102	124	141
No. of Bridges		418	315	275	90	660	1566	3324

Table 2. Statistical Information on NBI Data from Six States (Steel Superstructures)

		WI	**MI**	**MN**	**NY**	**OH**	**PA**	**ALL**
ADT	**Mean**	3621	9906	3275	11800	13878	7828	9440
	Median	378	3882	118	3186	6094	2238	2273
Age (years)	**Mean**	53	49	64	50	46	51	51
	Median	52	43	66	47	42	49	47
Area (m^2)	**Mean**	434	727	344	798	1096	637	722
	Median	115	486	72	357	646	290	359
No. of Bridges		478	616	304	1244	568	674	3884

Table 3. Statistical Information on NBI Data from Six States (Both Concrete and Steel Superstructures Considered)

		WI	**MI**	**MN**	**NY**	**OH**	**PA**	**ALL**
ADT	**Mean**	4944	9024	3848	11397	8631	6545	7703
	Median	590	3600	275	3014	1890	1949	1830
	Standard Deviation	9707	15624	13887	23522	17458	13819	16664
	Kurtosis	13	34	72	22	26	66.85	39.7
	Skewness	3	5	8	4	4.4	6.9	5.43
Age (years)	**Mean**	49	50	62	50	54	56	53
	Median	45	44	65	47	47	56	49
	Standard Deviation	19.7	17.9	21.4	17.1	20.4	18.6	19.4
	Kurtosis	-1	-0.2	-1	-0.3	0.3	66.9	-0.6
	Skewness	0.3	0.5	-0.1	0.3	0.9	0	0.4
Deck Area (m^2)	**Mean**	404	608	314	785	606	426	535
	Median	170	403	92	338	288	151	211
	Standard Deviation	665	1149	792	2764	1666	1280	1641
	Kurtosis	49	234	170	302	215	473	560
	Skewness	5	12	12	15	13	19	19.8
No. of Bridges		896	931	579	1334	1228	2240	7208

Table 4. Parameters for the Hypertabastic Accelerated Failure Time Models (Type of Superstructure Not a Concern)

	WI	**MI**	**MN**	**NY**	**OH**	**PA**
α	0.0011872	0.0009377	0.0005163	0.0008729	0.0008353	0.0004564
β	1.9408993	2.0235278	2.0721226	2.0572905	2.011958	2.1593075
c	0.0001866	2.067E-05	8.436E-05	7.771E-06	2.118E-05	2.698E-05
d	7.519E-06	5.903E-06	3.291E-06	2.361E-06	5.929E-06	4.355E-06
e	0	0	0	0	0	0

Table 5. Parameters for the Hypertabastic Accelerated Failure Time Models (Type of Superstructure is a Concern – TYPE=0 for Concrete; 1 for Steel)

	WI	**MI**	**MN**	**NY**	**OH**	**PA**
α	0.0013627	0.0009057	0.000548	0.0007573	0.0004779	0.0003147
β	1.95443	2.0251421	2.0724131	2.0623495	2.1164233	2.2332711
c	0.0002005	2.021E-05	8.686E-05	7.737E-06	1.406E-05	2.686E-05
d	5.769E-06	5.86E-06	3.214E-06	2.326E-06	4.648E-06	4.123E-06
e	-0.160159	0.0226917	-0.054284	0.0647562	0.2246436	0.1528821

It should be noted that the equations provided can be used to calculate and display results for any values assigned to covariates. Figure 2 shows the determined Probability Density Functions (PDF) for all six states assuming that the two covariates (AREA, ADT) are equal to each state's corresponding mean values (shown in Table 3). The mean values of covariates are used as example. Figures for other covariate values such as median values or means across all states are not shown for brevity.

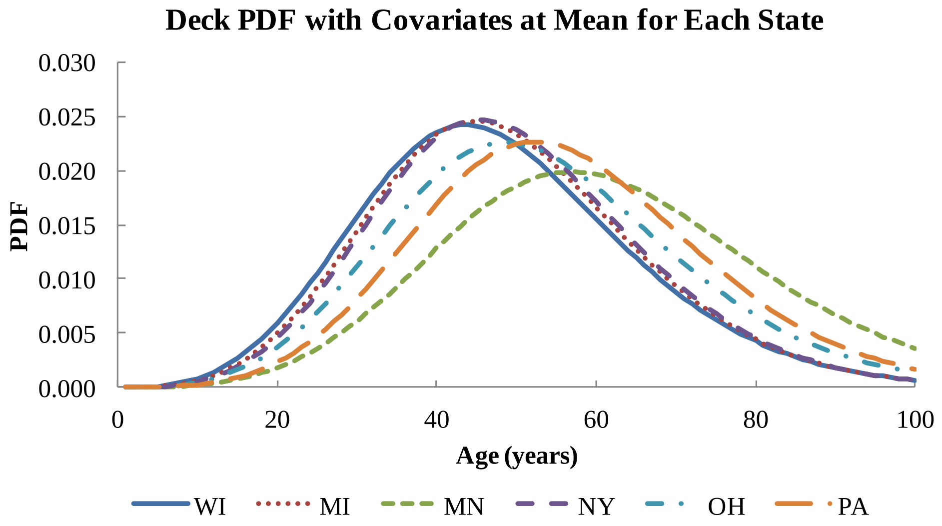

Figure 2. Hypertabastic PDF curves for six states (Type of superstructure not considered)

In Figure 2, the curves appearing to the right indicate better bridge deck performance as they take longer to reach a particular probability of failure in both the ascending and descending branches. Figures 3 and 4 show deck reliability and failure rate curves for all six states, respectively. These reliabilities were calculated assuming that the covariates are at the mean values for each state (shown in Table 3). The six states, in decreasing order of deck reliability, are Minnesota, Pennsylvania, Ohio, New York, Michigan, and Wisconsin. Three states of New York, Michigan and Wisconsin are in a close cluster. In general, this placement order follows an approximate measure of winters' harshness in those states, expect for one anomaly – Minnesota.

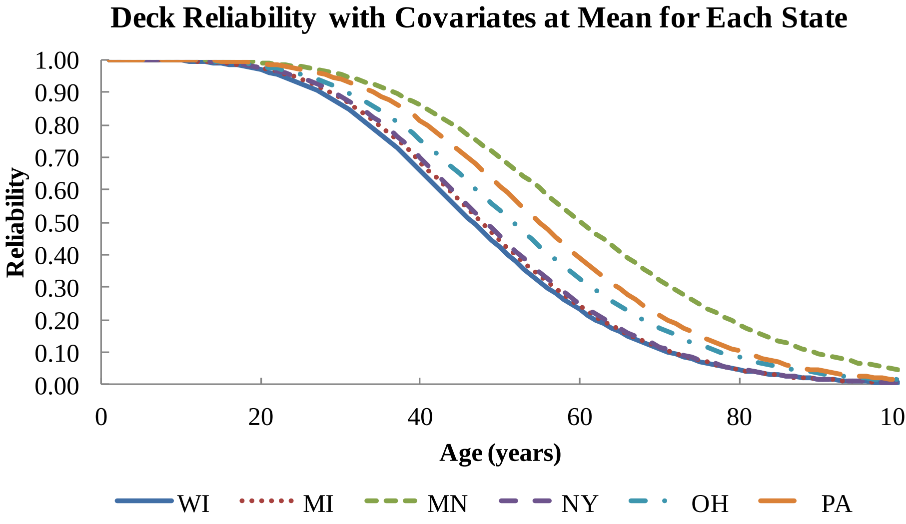

Figure 3. Hypertabastic reliability (survival) curves for six states (Type of superstructure not considered)

The research team was initially puzzled by the lack of conformance of reliability data from Minnesota with its other regional neighbors. So, the team rechecked data and reanalyzed results to rule out mistakes. Bridge engineers from the Minnesota Department of Transportation (MnDOT) were contacted by telephone to inquire about this apparent anomaly. From these discussions, it appears that the MnDOT may decide to place an overlay on the bridge deck when the deck rating is approaching 5. At least in some cases, the NBI records may not be revised to reflect this rehabilitation action. So, the rating of 5 is reached later compared to the other neighboring states.

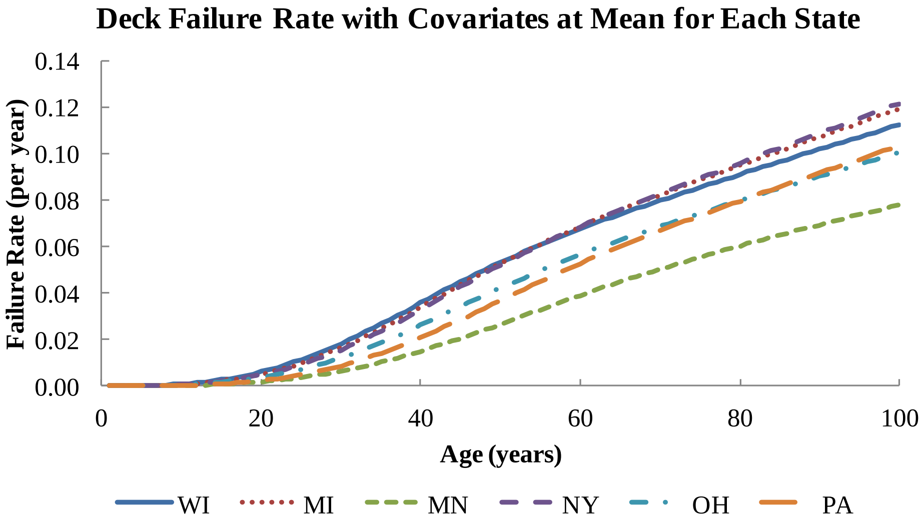

Figure 4. Hypertabastic failure rate curves for six states (Type of superstructure not considered)

The deck reliability and failure rate curves were also calculated assuming that the covariates are at the overall mean values (mean of all six states as opposed to mean for each individual state). The results are similar to Figures 3 and 4, but are not shown here for brevity.

Next, we consider the effect of the type of superstructure on reliability and failure rate. Figure 5 compares reliability curves as a function of age for steel, concrete and combined superstructures. These reliabilities are calculated assuming the covariates are at mean values for each state. In Wisconsin and Minnesota, the reliabilities are somewhat higher for concrete superstructures; while in Ohio, Pennsylvania, and New York, bridge decks with steel superstructures show higher reliability. For Michigan, the reliability estimations for steel and concrete superstructures are very close. It should be noted that the lowest value of Wald statistic was indicated for the TYPE parameter in Michigan (see Appendix Table A2)

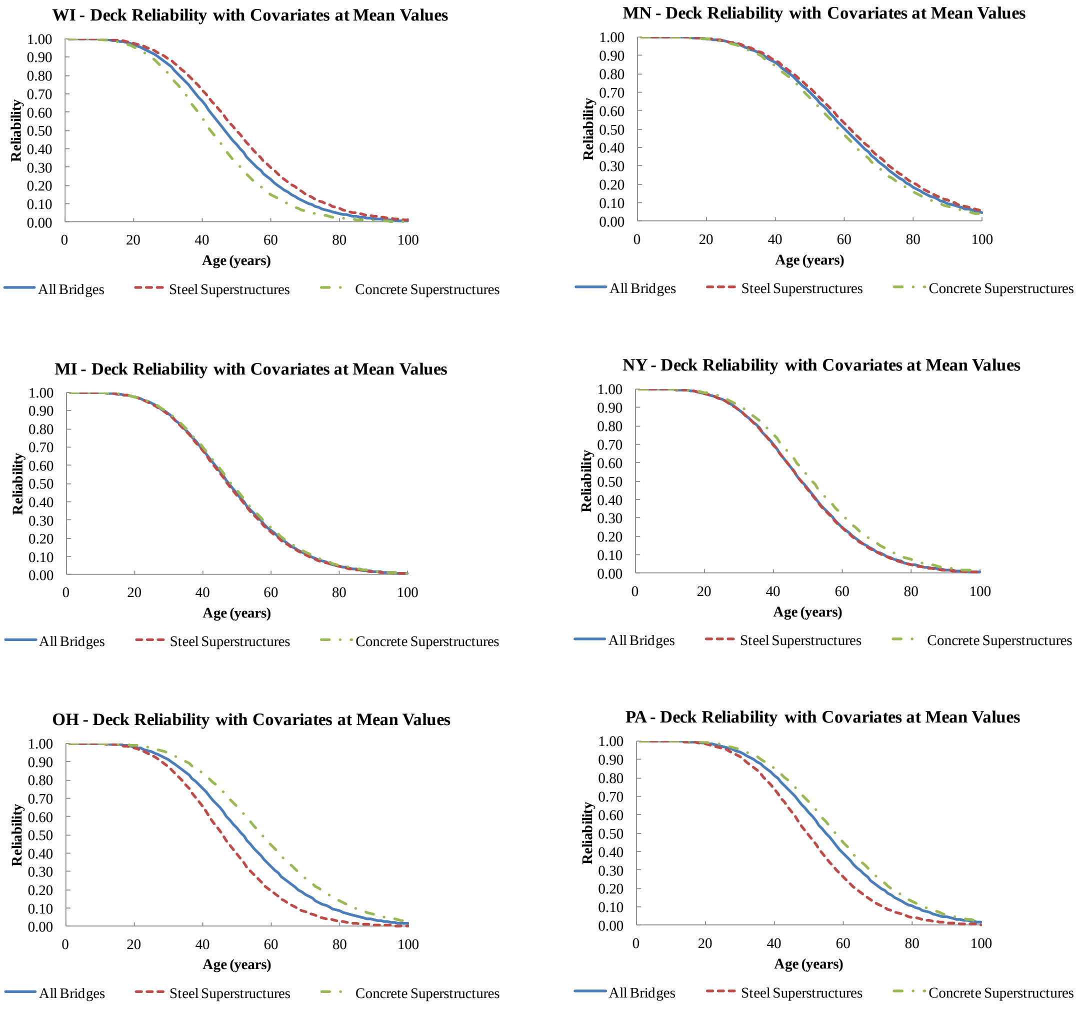

Figure 5. Reliability of bridge decks on steel and concrete superstructures - covariates at each state's mean values

The above figures compared reliability estimated at different ages. In Figures 6 through 11, reliability changes as a function of deck area are shown when the age of deck is 50 years and the ADT is at 125, 600, 5000, 27000, and 50000 vehicles. As was similarly indicated by the Wald test results in Table A2, these figures clearly show that both ADT and deck area have significant influence on reliability. The reduction in reliability with deck area at age 50 can be generally approximated by a straight line with a negative slope.

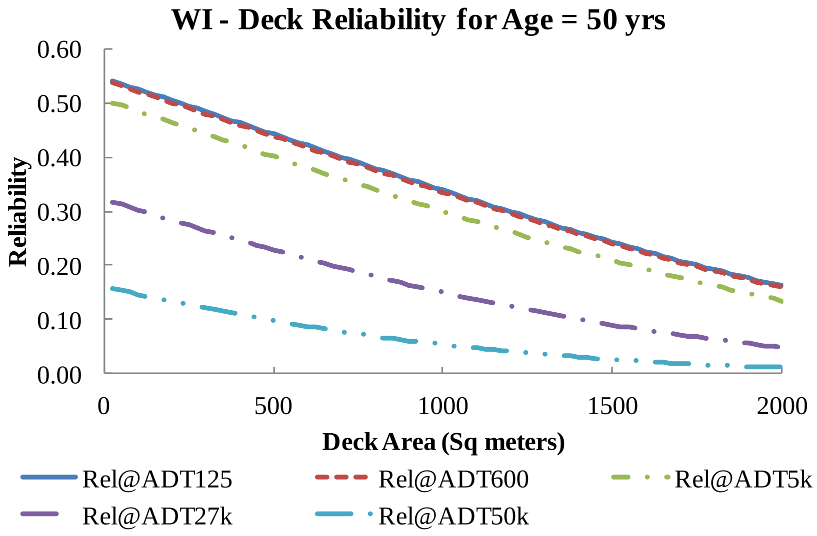

Figure 6. Variation in reliability of Wisconsin decks as a function of deck area at age 50 with various ADT values.

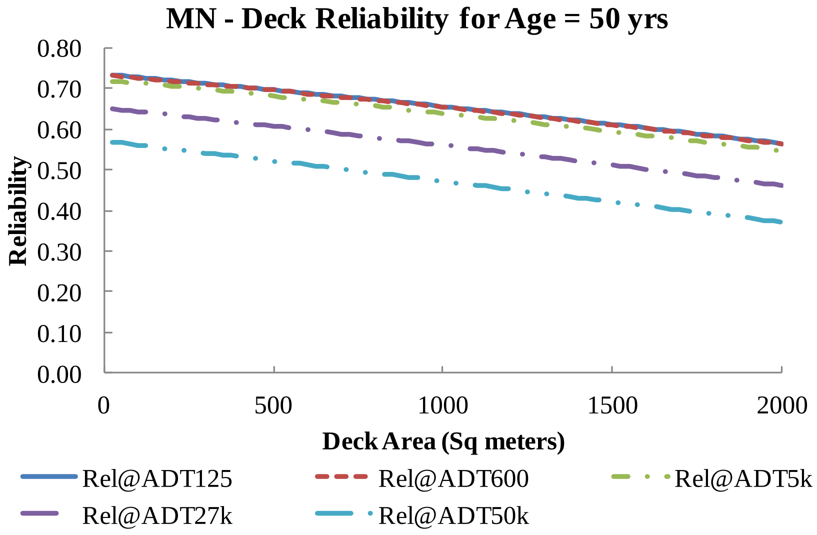

Figure 7. Variation in reliability of Minnesota decks as a function of deck area at age 50 with various ADT values.

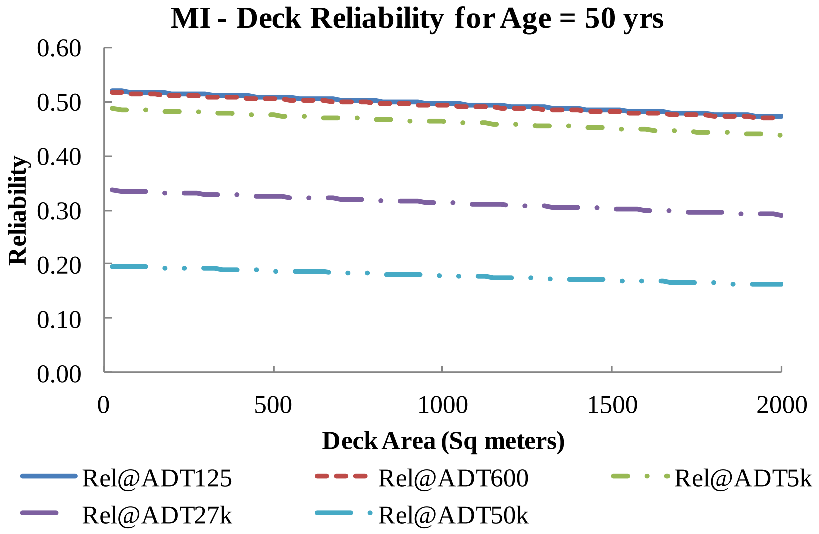

Figure 8. Variation in reliability of Michigan decks as a function of deck area at age 50 with various ADT values.

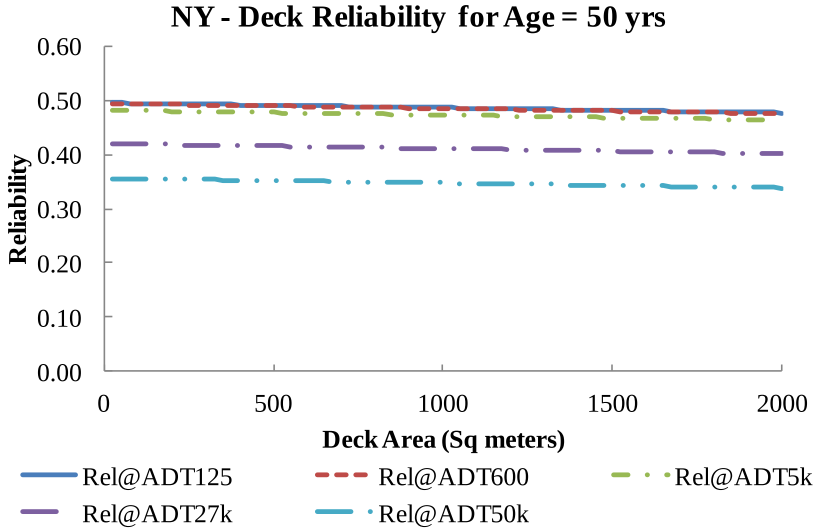

Figure 9. Variation in reliability of New York decks as a function of deck area at age 50 with various ADT values.

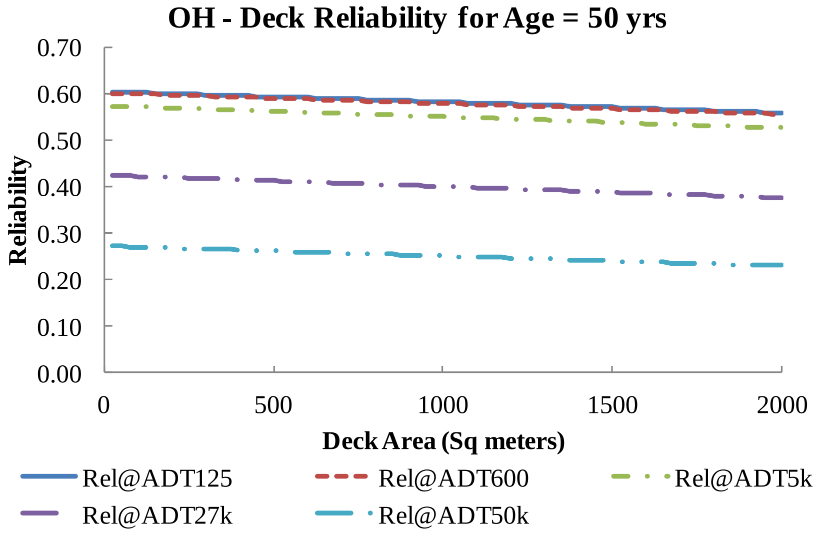

Figure 10. Variation in reliability of Ohio decks as a function of deck area at age 50 with various ADT values.

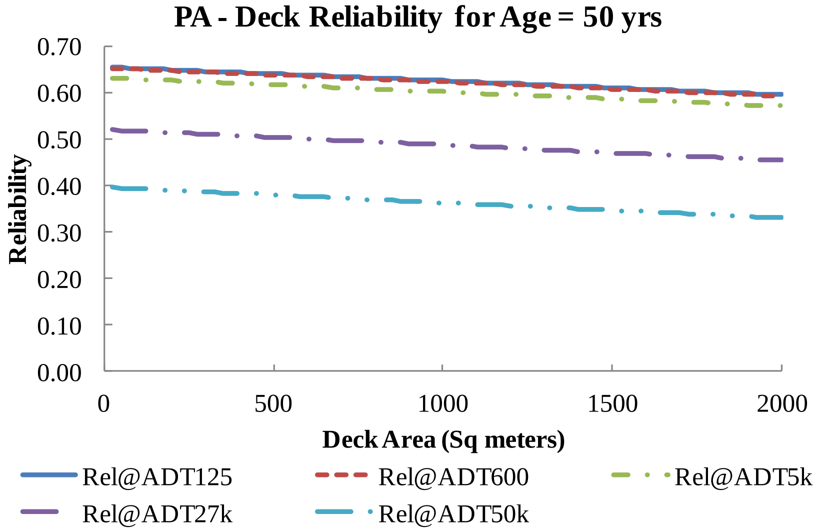

Figure 11. Variation in reliability of Pennsylvania decks as a function of deck area at age 50 with various ADT values.

In Figures 12 through 17, changes in failure rate as a function of deck area are considered when the age of deck is 50 years and the ADT is at 125, 600, 5000, 27000, or 50000 vehicles. These figures also clearly show that ADT has significant influence on reliability in all six states. Deck area is also an important factor in failure rate (at age 50) for three of the six states (except New York, Pennsylvania and Ohio). Both ADT and deck area affect reliability and failure rates at different ages. However, the extent of influence varies.

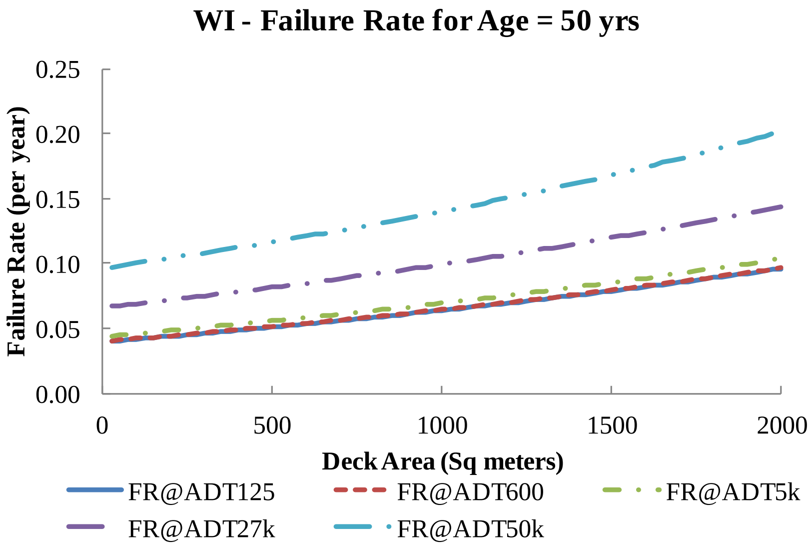

Figure 12. Variation in failure rate of Wisconsin decks as a function of deck area at age 50 with various ADT values.

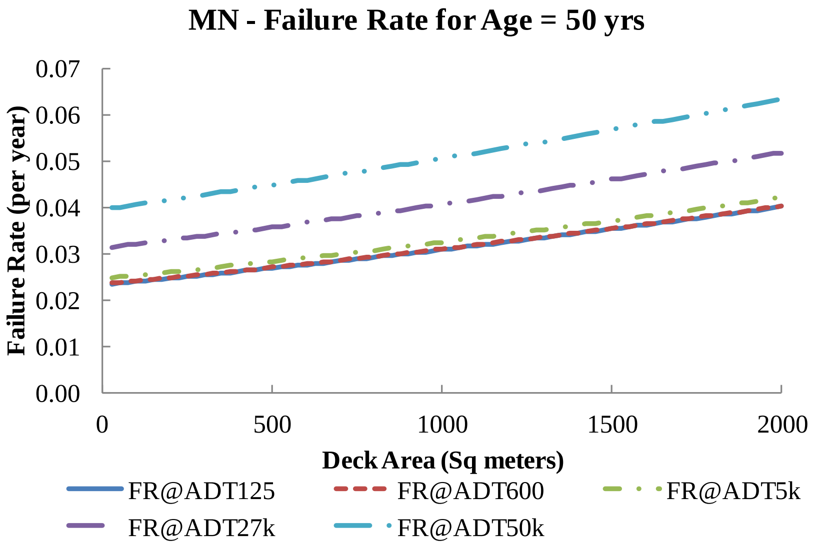

Figure 13. Variation in failure rate of Minnesota decks as a function of deck area at age 50 with various ADT values.

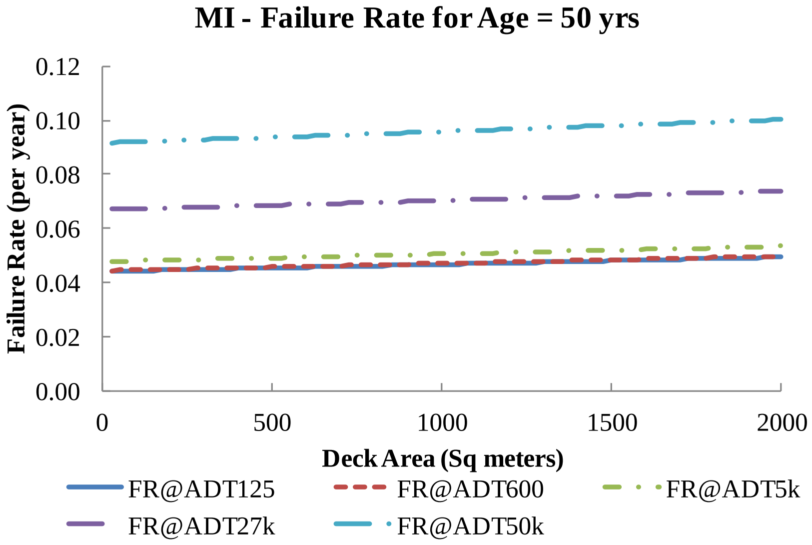

Figure 14. Variation in failure rate of Michigan decks as a function of deck area at age 50 with various ADT values.

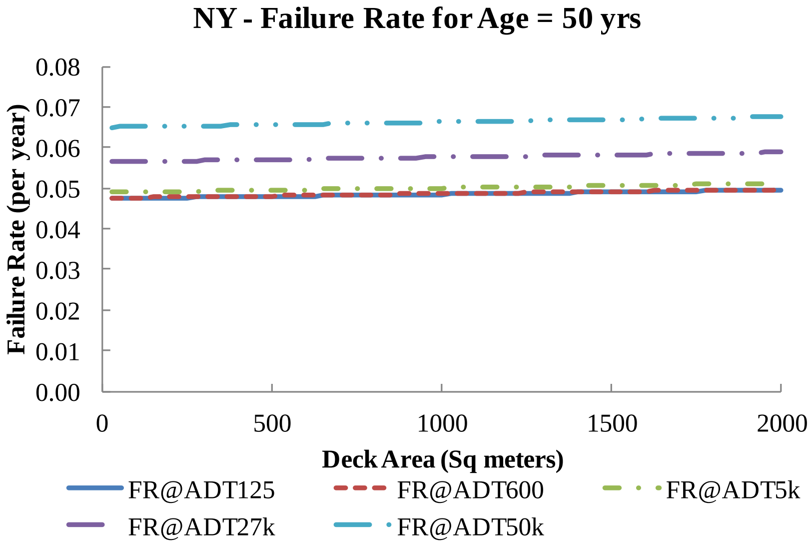

Figure 15. Variation in failure rate of New York decks as a function of deck area at age 50 with various ADT values.

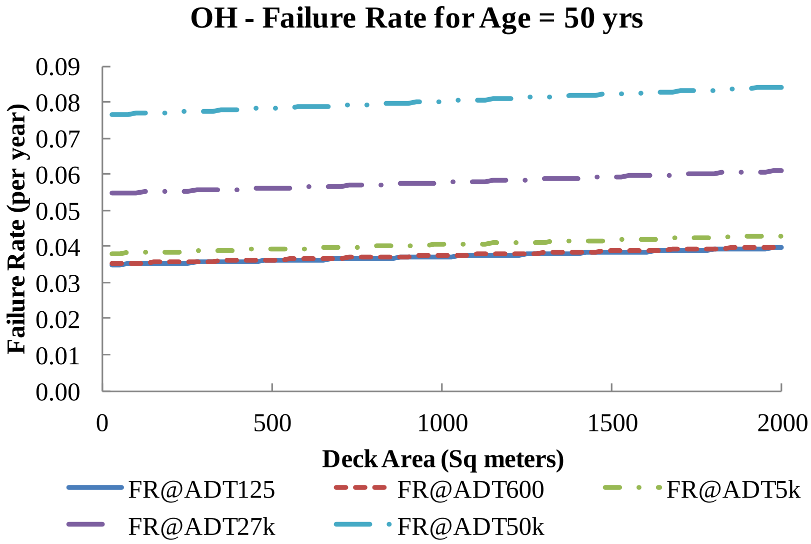

Figure 16. Variation in failure rate of Ohio decks as a function of deck area at age 50 with various ADT values.

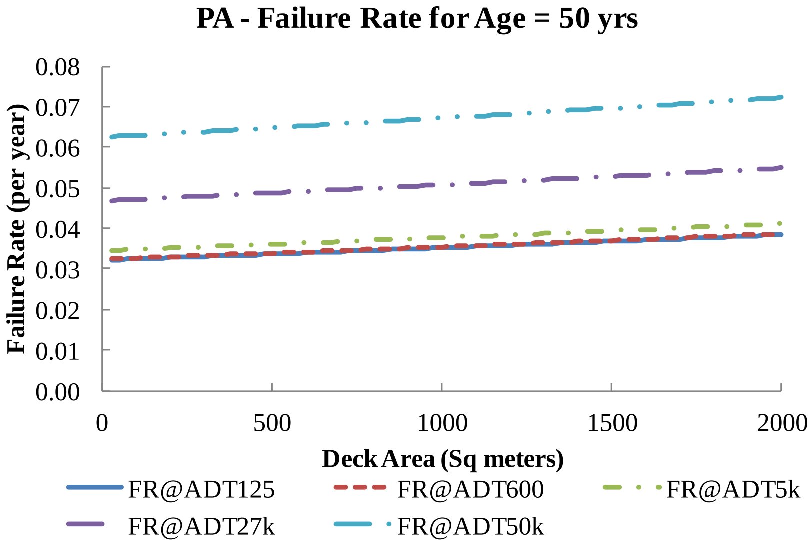

Figure 17. Variation in failure rate of Pennsylvania decks as a function of deck area at age 50 with various ADT values.

Table 6 summarizes PDF, reliability, and failure rates at 30, 50, and 70 years. The covariates are assumed to be at mean values for each state, and the type of superstructure is not considered.

Table 6. Summary of reliability, failure rate and PDF at various ages 30, 50 and 70 years (covariates at mean value for each state)

		WI	**MI**	**MN**	**NY**	**OH**	**PA**
Reliability	**30 years**	0.862	0.881	0.954	0.889	0.910	0.940
	50 years	0.422	0.445	0.700	0.457	0.536	0.612
	70 years	0.110	0.113	0.322	0.117	0.174	0.214
Failure rate (per year)	**30 years**	0.029	0.027	0.012	0.026	0.021	0.017
	50 years	0.058	0.058	0.035	0.058	0.049	0.046
	70 years	0.080	0.083	0.053	0.083	0.070	0.069
PDF	**30 years**	0.017	0.017	0.010	0.017	0.015	0.013
	50 years	0.006	0.006	0.011	0.006	0.008	0.009
	70 years	0.001	0.001	0.003	0.000	0.001	0.001

The unexpected results for Minnesota may be due to application of overlays prior to reaching a deck rating of 5, while NBI records not marked as “reconstructed”. Furthermore, it is clear that reliability decreases and failure rate increases with time in all cases. Other analyses show that at the age of 20 years, reliabilities of the six states are all above 0.95 and failure rates are all below 0.01 per year. At 50 years (which is approximately the average age for deck rating 5), reliability drops to 0.371 for Wisconsin and 0.67 for Minnesota. Therefore, the probability of failure (due to serviceability issues) for bridge decks at 50 years is on the order 0.35 to 0.65. In contrast, the probability of failure inherent in AASHTO LRFD bridge design (based on strength limit states) is on the order of 2 in 10,000 (Mertz, 2008).

5.0 Summary and Conclusions

The 2008 NBI records were used in this study to develop survival models for non-reconstructed bridge decks in six northern states. The recorded deck rating of 5 (actual deck rating of between 4 and 5) was used as indicator of the end of service life. The NBI parameters considered were the type of superstructure (concrete or steel), deck surface area, age, and ADT. Reconstructed bridges were excluded from the analyses.

The order of states, from highest to lowest deck reliability, is Minnesota, Pennsylvania, Ohio, New York, Michigan, and Wisconsin. Three states - New York, Michigan and Wisconsin - are in a close cluster with regard to deck reliability and failure rates. In general, deck reliability and failure rates correspond reasonably well with qualitative measure of the harshness of the states' winters. However, results indicate that the State of Minnesota has the highest bridge deck reliability and the lowest failure rate compared to all the five other northern deicing states studied. This does not agree with the expectation and pattern observed with the other five states. Based on conversations with MinDOT engineers, it appears that the unexpectedly higher comparative reliability of Minnesota decks may be due to the application of overlays before decks reach a rating of 5. Such overlay applications are not necessarily reflected in the NBI records as "reconstructed", and were thus not excluded or excludable from the analyses.

Results also show that ADT and deck surface area are both important factors affecting reliability and failure rates in all six states studied. The type of superstructure has an inconsistent effect across the six states considered. In Wisconsin and Minnesota, the reliabilities are somewhat higher for concrete superstructures; while in Ohio, Pennsylvania, and New York, bridge decks with steel superstructures show higher reliability. For Michigan, reliability estimations for steel and concrete superstructures are close.

The results of this study can be beneficial for planning of bridge deck maintenance operations in northern deicing environments. It is recommended that deck area and ADT be considered as important factors when planning preventive maintenance operations. In the future, it is envisioned that bridge owners would assign target reliability levels to new and existing bridges, and plan the type(s) and frequency of application of protective measures to achieve the target reliability levels. To do so, research is needed on the impact of various treatments (such as penetrating sealers, overlays, and coatings) and their application frequencies on bridge deck reliability. Further studies are also needed for development of similar reliability models for bridge superstructures.

6.0 References

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7.0 Appendix

Table A1. Correlation Tables for Parameters Used in Each State.

State		**ADT**	**Type**	**Age**	**Area**
WI	**ADT**	1			
	Type	-0.146	1		
	Age	-0.303	0.237	1	
	Area	0.490	0.048	-0.403	1
MI		**ADT**	**Type**	**Age**	**Area**
	ADT	1			
	Type	0.082	1		
	Age	-0.256	-0.024	1	
	Area	0.327	0.147	-0.231	1
MN		**ADT**	**Type**	**Age**	**Area**
	ADT	1			
	Type	-0.044	1		
	Age	-0.069	0.061	1	
	Area	0.443	0.039	-0.090	1
NY		**ADT**	**Type**	**Age**	**Area**
	ADT	1			
	Type	-0.038	1		
	Age	-0.178	0.244	1	
	Area	0.380	-0.008	-0.141	1
OH		**ADT**	**Type**	**Age**	**Area**
	ADT	1			
	Type	0.278	1		
	Age	-0.298	-0.345	1	
	Area	0.494	0.273	-0.226	1
PA		**ADT**	**Type**	**Age**	**Area**
	ADT	1			
	Type	0.061	1		
	Age	-0.083	-0.080	1	
	Area	0.366	0.108	-0.090	1

Table A2. Parameter and standard error estimates for Hypertabastic Accelerated Failure Time Models

		WI	**MI**	**MN**	**NY**	**OH**	**PA**
α	Estimate	1.363E-3	9.057E-4	5.480E-4	7.573E-4	4.779E-4	3.147E-4
	Standard error	2.50E-4	1.67E-4	1.43E-4	1.34E-4	7.99E-5	4.50E-5
	Wald	29.72	29.53	14.71	32.03	35.79	48.97
	p-value	4.99E-8	5.49E-8	1.26E-4	1.52E-8	2.20E-9	2.60E-12
β	Estimate	1.954	2.025	2.072	2.062	2.116	2.233
	Standard error	5.04E-2	5.01E-2	6.79E-2	4.33E-2	4.38E-2	3.74E-2
	Wald	1503.34	1634.24	930.48	2269.23	2339.46	3559.90
	p-value	7.4E-329	2.7E-357	2.3E-204	2.9E-495	1.6E-510	1.3E-775
Deck Area	Estimate	2.005E-4	2.021E-5	8.686E-5	7.737E-6	1.406E-5	2.686E-5
	Standard error	1.34E-5	5.40E-6	1.39E-5	2.77E-6	5.36E-6	3.14E-6
	Wald	224.09	14.00	39.27	7.81	6.88	73.33
	p-value	1.16E-50	1.83E-4	3.70E-10	5.19E-3	8.73E-3	1.09E-17
ADT	Estimate	5.769E-6	5.860E-6	3.214E-0	2.326E-6	4.648E-6	4.123E-6
	Standard error	1.26E-6	5.98E-7	9.84E-7	3.87E-7	5.41E-7	4.58E-7
	Wald	21.12	96.17	10.68	36.17	73.80	81.10
	p-value	4.31E-6	1.06E-22	1.08E-3	1.81E-9	8.65E-18	2.14E-19
Type	Estimate	-0.1602	0.0227	-0.0543	0.0648	0.2246	0.1529
	Standard error	2.45E-2	2.38E-2	2.84E-2	3.82E-2	1.94E-2	1.43E-2
	Wald	42.66	0.91	3.65	2.88	134.52	114.76
	p-value	6.52E-11	3.40E-1	5.60E-2	8.99E-2	4.21E-31	8.87E-27