Determination of End of Functional Service Life for Concrete Bridge Decks

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The end of functional service life for concrete bridge decks was estimated by quantifying the terminal levels of physical damage that warrant deck overlay. The study focused specifically on decks in snowbelt states, which can suffer accelerated deterioration as a result of expansive reinforcing steel corrosion that is initiated by chloride deicing salts. The terminal damage levels were determined from an opinion survey of state department of transportation bridge engineers, who evaluated plan-view maps of existing decks showing areas affected by cracks, delaminations, spalls, asphalt patches, and concrete patches and recommended when each deck should have been or should be rehabilitated. Linear regression models were developed to relate the engineers' responses to the level of physical damage. The terminal damage levels determined from the recommended model define the end of functional service life as a range of percent damage in the worst traffic lane.

The transportation engineering community of the United States faces a tremendous problem: the gradual deterioration of the nation's bridges. Reinforced concrete bridge components that are exposed to chloride salt solutions, such as coastal seawater or water containing dissolved winter deicing salts, can suffer accelerated deterioration as a result of chloride-induced corrosion of the reinforcing steel. The progression of events resulting from the formation of expansive corrosion products (*1*) can include cracking, delamination, spalling, and patching of the surface concrete. Manning (*2*) stated in 1986 that "the unfunded liability to correct corrosion-induced distress in bridges is approximately $20 billion and the amount is increasing at almost $500 million annually."

Concrete bridge components that are commonly affected by corrosion-induced deterioration are decks, beams, piers, and abutments. In snowbelt states decks are generally more susceptible to corrosion-induced damage than are other bridge components, because winter deicing salts are applied directly to deck riding surfaces. A concrete bridge component reaches the end of its functional service life when the level of physical damage warrants not just repair but rehabilitation of the component. For example, a concrete bridge deck can be considered to have reached the end of its functional service life when the level of damage warrants overlay of the entire deck surface following the removal of unsound concrete and the patching of excavated areas. The level of physical damage that warrants rehabilitation can be called the terminal damage level.

This paper describes a research study that was conducted to determine the end of functional service life (EOFSL) for reinforced concrete bridge decks. The study focused specifically on bare concrete decks that deteriorate as a result of reinforcing steel corrosion that is initiated by chloride deicing salts (i.e., decks in snowbelt states). Consideration was given only to decks having an original bare concrete surface not overlaid with asphalt. The EOFSL was to be determined by quantifying the terminal damage level for decks as the percentage of the deck surface area affected by cracks, delaminations, spalls, and patches. It was expected that the terminal damage level would be a range of percent damage rather than a single percent damage value.

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SIGNIFICANCE OF EOFSL FOR DECKS

In 1984 Cady and Weyers (*3,4*) proposed a corrosion-deterioration model for concrete bridges (Figure 1). The model presents a qualitative relationship between the cumulative percentage of concrete surface area damaged and time and is believed to be applicable to any reinforced concrete bridge component exposed to chloride salt solutions. The model is defined by four critical points on the time axis:

1. Time at which chloride ion diffusion through the cover concrete begins.
2. Time at which corrosion of the reinforcing steel begins.
3. Time at which cracking of the concrete surrounding the reinforcing steel begins.
4. Time at which the bridge component reaches the end of functional service life because of an accumulation of physical damage.

Each of the four time points corresponds to a level of physical damage.

By 1990, the year that the present study was initiated, the diffusion, corrosion, and damage accumulation time periods of the model had been studied and estimated (*3,4*). However, the time point and damage level defining the end of functional service life had not been determined conclusively, and thus there was no consensus within the bridge engineering community regarding the level of physical damage that justifies rehabilitation. Since it is defined as the point at which rehabilitation is warranted, EOFSL is ultimately based on decisions that are made by bridge engineers who work for the various state departments of transportation (DOTs). Because bridge rehabilitation decisions are currently made by individuals or small groups within each state, the terminal damage level for bridge decks varies considerably from one locality to another. For example, the present study included examination of 18 existing bridge decks that had been designated for rehabilitation within the previous year (i.e., had been determined by local engineers to have reached the EOFSL). For these 18 decks from five different states, the terminal damage level was found to range from 1.0 to 29.8 percent of the deck surface area.

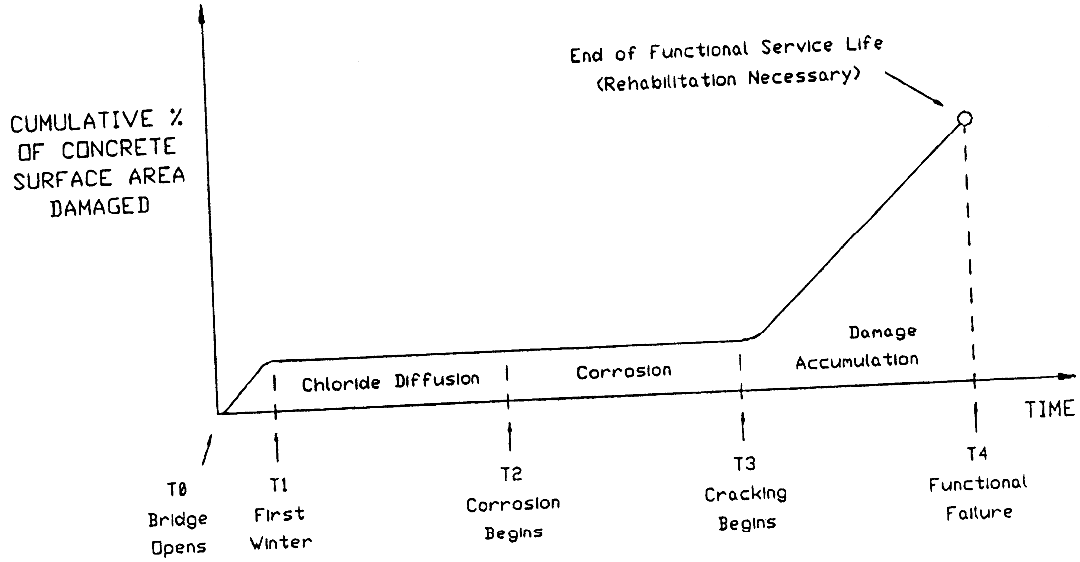

FIGURE 1 Corrosion-deterioration model for concrete bridges (*3,4*).

The lack of a quantitative definition of EOFSL is a problem for two reasons. First, it prevents any objective means of prioritizing bridge rehabilitation needs within each state and nationwide. Second, it hinders engineers' ability to evaluate bridge treatments based on life-cycle cost. The service life of a bridge component cannot be determined accurately unless the end of service life is clearly defined.

Several previous efforts to define bridge deck service life have been made. A draft report on Bridge Management Systems (*5*) summarizes five studies (*5–9*) that related bridge deck inspection condition ratings to deck age for large samples of existing bridge decks; however, no terminal damage levels were developed in those studies. In 1985 Chamberlin and colleagues (*10,11*) surveyed 30 bridge and materials engineers regarding maintenance treatments for decks. According to Weyers et al. (*11*) the survey responses "indicated that overlay of the entire surface is appropriate when spalling attains a level somewhere between 2.0 and 4.0 percent of the deck area"; however, this terminal damage level based on a single deterioration indicator (i.e., spalls) may have limited applicability, since additional deterioration indicators (i.e., cracks, delaminations, and patches) can be present on a deck. Mean age-at-overlay values that were estimated by Cady and Weyers for four sets of existing decks varied considerably, from 16 to 39 years. Mean damage-at-overlay values that were estimated by Cady and Weyers for two sets of existing decks varied considerably, from 22.0 to 38.1 percent. Although those studies provided preliminary data regarding deck service life, a need to further define the end of service life for concrete bridge decks was indicated.

RESEARCH APPROACH

In the present study terminal damage levels for concrete bridge decks were determined from an opinion survey of state DOT bridge engineers who make bridge rehabilitation decisions. A field study of 18 existing deteriorated concrete bridge decks that had been designated for rehabilitation within the past year was conducted to develop plan-view deck maps showing areas affected by cracks, delaminations, spalls, and patches. Survey kits based on the damage maps were distributed to bridge engineers in 25 states that use deicing salts. The engineers evaluated the damage maps and recommended when each deck should be or should have been rehabilitated. Based on the engineers' responses, linear regression models were developed to relate the recommended deck rehabilitation time point to the physical damage level. Ranges of percent damage were then determined from the models to define the terminal damage levels corresponding to the EOFSL for concrete bridge decks.

The 18 decks that were mapped for damage were selected from Michigan, Ohio, Pennsylvania, Virginia, and Wisconsin. To ensure that the resultant damage maps would represent a realistic sample of the deteriorated decks that exist in the United States, the decks were chosen to represent ranges of geographical location, snowfall exposure, and traffic volume (Figure 2). All 18 decks carried two lanes of traffic, were less than 91m (300 ft) long, and had total surface areas not greater than approximately 2,834m^2 (9300 ft^2).

Each deck was surveyed in two longitudinal halves by blocking one lane of traffic at a time. On each longitudinal deck half drag chains and hammers were used to locate delaminations of the surface concrete. Then, all cracks, delaminations, spalls, and patches were outlined on the deck surface with different colors of temporary water-based paint. The paint was applied with roller-type paint handles with 5-cm (2-in.) roller heads. Finally, photographs of the deck surface were taken at 6-m (20-ft) intervals along the length of the deck by using a 35-mm camera pointed toward the deck at a fixed oblique tilt angle (*12,13*) from a height of 4-m (12 ft). Later, the resultant oblique photographs were digitized to create computer coordinate files to represent the outlined areas of damage. The oblique damage area images were then rectified (FORTRAN rectification program by Steven D. Johnson; unpublished) to form plan-view damage area images, which were linked together by using ERDAS software and which were plotted by using a color ink-jet printer to produce a composite plan-view map of the deck showing the areas of damage.

Snowfall (In./Yr.)	0 - 8000	> 8000 - 16000	> 16000
> 50	PA-1 MI-3	OH-5 OH-6	OH-4
> 20 - 50	PA-2 WI-2 MI-2 WI-3 WI-1 WI-4	MI-1 OH-3	
0 - 20	VA-3	VA-1 OH-1 VA-2 OH-2	

Average Annual Daily Traffic (Vehicles/Day)

FIGURE 2 Field study matrix for 18 concrete bridges mapped for damage (*11*).

The plotted damage maps showed cracks, delaminations, spalls, asphalt patches, and concrete patches in different colors. The map colors were carefully selected to be distinguishable by brightness, to not confuse survey respondents with color-defective vision, and to minimize the use of certain overpowering colors that might bias the respondents' evaluations of the damage areas (*14,15*).

OPINION SURVEY OF BRIDGE ENGINEERS

A survey kit was developed on the basis of the deck damage maps. The purpose of the survey kit was to present the damage maps to bridge engineers so that the engineers could evaluate the maps and make responses that could be used to develop terminal damage levels for concrete bridge decks. Each kit contained three damage maps to be evaluated by the respondent.

Concept of Time to Rehabilitate

Since the Cady-Weyers deterioration model is based on physical damage as a function of time, the survey kit items were written such that the engineers' responses were based on a time continuum. For each deck damage map that they evaluated the respondents were asked to recommend the time to rehabilitate (TTR), which was defined in the survey kit as follows:

> Assume that every concrete bridge component exposed to deicing salts eventually deteriorates to a physical condition that justifies rehabilitation. Define this physical condition as the *rehabilitation condition*. The true rehabilitation condition is reached when the component has reached the end of its functional service life, and *significant correction* is necessary to return it to an acceptable level of service. The *time to rehabilitate* is the time when a concrete bridge component reaches its rehabilitation condition. It may be in the past, present, or future. For example, the time to rehabilitate was in the past if the component should have been rehabilitated about 5 years ago. The time to rehabilitate is in the present if the component should be rehabilitated now. The time to rehabilitate is in the future if the component should be rehabilitated in about 5 years. The rehabilitation condition (a measure of physical damage) is a point on the y-axis of the Cady-Weyers model, whereas the time to rehabilitate is a point on the x-axis.

The engineers were asked to recommend the TTR by choosing a response from a time scale; for example, two of the possible choices from this scale were the following: "this component should be rehabilitated in about 10 years" and "this component should have been rehabilitated about 10 years ago." The time scale ranged from 20 years before the rehabilitation condition to 20 years beyond the rehabilitation condition, in increments of 2 years.

The engineers were given the age of each deck that they evaluated so that they could estimate the rate of physical deterioration to assist in estimating the TTR. The traffic volume (expressed as the average annual daily traffic (AADT)) and the typical speed of traffic (expressed as greater than 72 kph (45 mph) or less than 72 kph (45 mph)) were also provided so that the respondents could estimate a deck usage factor.

Concepts of Local Standards and Snowbelt Standards

It was reasoned that since the rehabilitation condition is a subjective estimate it may vary considerably from one engineering district to another. Thus, it was considered unlikely that the engineers' TTR responses using local standards would form a strong consensus about the rehabilitation condition. Accordingly, the engineers were asked to estimate the rehabilitation condition using two hypothetical sets of criteria: local standards and snowbelt standards. The difference between local standards and snowbelt standards could be described as the difference between current practices and recommended practices, respectively.

Opinion Survey Results

A total of 90 survey kits were sent to bridge engineers in the following 25 states identified as using deicing salts (*11,16*):

Connecticut	Massachusetts	Ohio
Delaware	Michigan	Pennsylvania
Illinois	Minnesota	Rhode Island
Indiana	Missouri	Tennessee
Iowa	Nebraska	Vermont
Kansas	New Hampshire	Virginia
Kentucky	New Jersey	West Virginia
Maine	New York	Wisconsin
Maryland		

Sixty qualified respondents returned survey kits with responses, representing a 67 percent response rate. At least one survey kit with responses was received from every targeted state except Delaware and Massachusetts.

Four of the 60 qualified respondents were found to have made outlier TTR responses. Outlier responses were identified by internal inconsistencies within an engineer's responses and included mistakes such as recommending the time to repair for a deck rather than the time to rehabilitate. In total 6 of 162 deck TTR responses (3.7 percent) were discarded as outliers.

Linear regression techniques and Minitab statistical software were used to develop regression model equations relating the engineers' TTR responses to the level of damage on the deck. The regression equations were developed by using a data-splitting approach (*17*) for cross-validation purposes (*18*), in which half of the engineers' responses were used to develop the equation and the other half were used to cross-validate it. Twenty variables were identified as potential predictors of the engineers' TTR responses, including the following:

- Surface area of deck [m^2 (ft^2)];
- Percentage of whole deck spalled;
- Percentage of whole deck delaminated;
- Percentage of whole deck patched with asphalt;
- Percentage of whole deck patched with concrete;
- Lineal feet of cracks/surface area of deck [m/m^2 (ft/ft^2)];
- Age of deck;
- AADT;
- Typical speed of traffic on deck;
- Percentage of whole deck delaminated, spalled, patched with asphalt, and patched with concrete;
- Percentage of worst traffic lane delaminated, spalled, patched with asphalt, and patched with concrete; and
- Percentage of both traffic lanes delaminated, spalled, patched with asphalt, and patched with concrete.

The Minitab command BREGRESS was used in the evaluation of the variables and selection of the optimum models.

Local Standards TTR Model

The best model developed from the engineers' TTR responses based on local standards was as follows:

$$\hat{y} = -10.3 + 14.0x - 11.4\,x^{1.05} \tag{1}$$

where $\hat{y}$ is equal to the fitted time to rehabilitate for decks, based on local standards, and x is the percentage of the whole deck delaminated, spalled, and patched with asphalt. Minitab computed the following statistics that describe the model:

Predictor	*Coefficient*	*Standard Deviation*	*t-ratio*	*p*
Constant	−10.303	1.939	−5.31	0.000
x	14.014	5.795	2.42	0.017
$x^{1.05}$	−11.438	4.979	−2.30	0.023

$s = 6.906$ $R^2 = 22.0\%$ $R^2(\text{adj}) = 21.0\%$
Regression: F computed $= 21.59, p = .000$

The p-values are close to zero, which means the probability that the linear relationship indicated by the sample of TTR responses does not actually exist for the population of all TTR responses is sufficiently low. The cross-validation percentage for the model was determined to be 97.4 percent, indicating that the model works well for other data samples within the population of TTR responses.

The deficiency of the model is the low value of the coefficient of multiple determination, R^2, which indicates that the regression equation explains only 22.0 percent of the variability in the engineers' TTR responses. Since R^2 is low there is too much unexplained variability to conclude that the model equation is a good predictor of future individual TTR responses. However, since the model cross-validates well, 95 percent confidence intervals based on the model equation can be used to predict future mean TTR responses with 95 percent certainty (*19*).

The model equation line and 95 percent confidence interval (CI) lines are presented in Figure 3, which shows that the confidence interval lines intersect the horizontal line of TTR equal to zero at x values of 5.8 percent and 10.0 percent. For deck damage values of 5.8 percent or less there is at least 95 percent certainty that the mean TTR response will not be a TTR equal to zero. Similarly, for deck damage values of 10.0 percent or greater there is at least 95 percent certainty that the mean TTR response will not be a TTR equal to

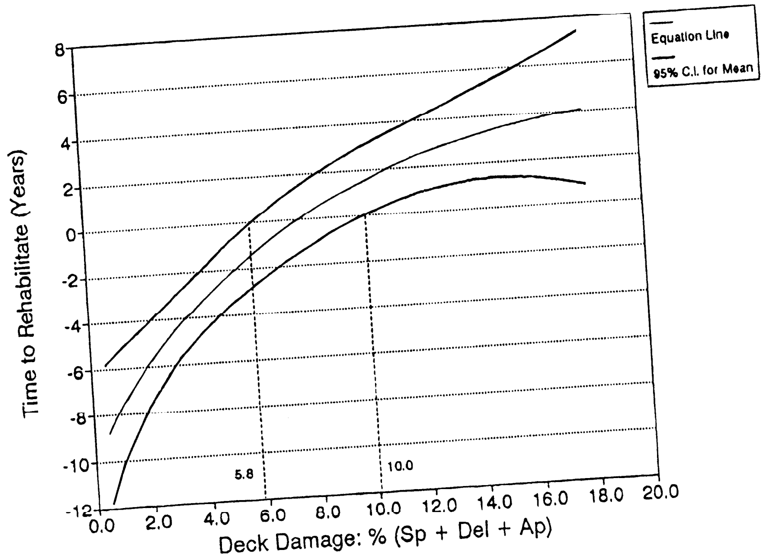

FIGURE 3 **Local standards TTR model for concrete bridge decks.**

zero. A mean recommendation by bridge engineers to rehabilitate the deck now is probable only for deck damage values between 5.8 and 10.0 percent. Thus, the indicated local standards terminal damage level for decks is 5.8 percent $< x <$ 10.0 percent.

Snowbelt Standards TTR Model

The best model developed from the engineers' TTR responses based on snowbelt standards was as follows:

$$\hat{y} = -11.2 + 5.34\,x - 3.41\,x^{1.1} \tag{2}$$

where $\hat{y}$ is equal to the fitted time to rehabilitate for decks, based on snowbelt standards, and x is equal to the percentage of worst traffic lane delaminated, spalled, and patched with asphalt. Minitab computed the following statistics that describe the model:

Predictor	*Coefficient*	*Standard Deviation*	*t-ratio*	*p*
Constant	−11.229	1.586	−7.08	0.000
x	5.345	1.318	4.06	0.000
$x^{1.1}$	−3.4073	0.9123	−3.73	0.000

$s = 6.021$ $R^2 = 31.7\%$ R^2 (adj) = 30.9%
Regression: F computed = 35.59, p = .000

The p-values and cross-validation percentage (94.6 percent) for the model were considered to be acceptable. Figure 4 presents the model equation line and 95 percent confidence interval lines. The confidence interval lines intersect the horizontal line of TTR equal

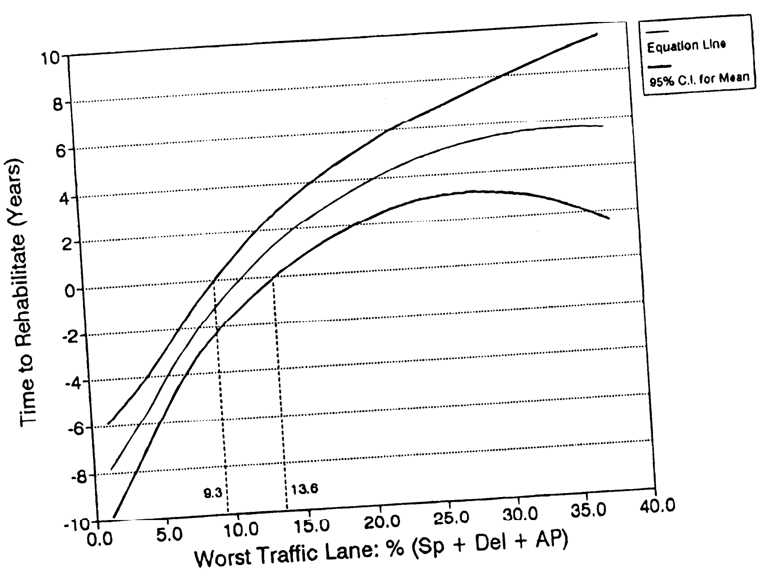

FIGURE 4 **Snowbelt standards TTR model for concrete bridge decks.**

to zero at x-values of 9.3 and 13.6 percent; thus, the indicated snowbelt standards terminal damage level for decks is 9.3 percent $< x$ $<$ 13.6 percent.

Comparison of TTR Models

For the snowbelt standards TTR model the independent variable is the percentage of the worst traffic lane area that is delaminated, spalled, and patched with asphalt. For the local standards TTR model the independent variable is the percentage of the whole deck area that is delaminated, spalled, and patched with asphalt. Essentially, the snowbelt standards TTR model shows a lower level of data variability and a more specific independent variable than the local standards TTR model.

Despite this difference the independent variables for both models are based on the same aggregate of damage, namely, delaminations, spalls, and asphalt patches. It is realistic for these models to indicate that cracks and concrete patches, which are generally less likely to affect the present or future riding quality of a deck than are delaminations, spalls, and asphalt patches, do not have a quantifiable impact on deck rehabilitation decisions relative to the other deterioration indicators.

Limitations of TTR Models

Both models are based on engineers' evaluations of damage maps for bridge decks that carry two lanes of traffic and that have surface areas not greater than approximately 2,835 m^2 (9,300 ft^2). The deck models may be less applicable to decks having other than two lanes of traffic or having surface areas greater than approximately 2,835 m^2 (9,300 ft^2). Rehabilitation of single-lane decks may require bridge closure and traffic detours, whereas rehabilitation of decks with more than two lanes may require additional lane changes. The rehabilitation labor and materials costs are likely to be greater for decks with surface areas exceeding the surface areas of the decks in the present study. Thus, for decks outside the scope of the study potentially greater rehabilitation costs may correspond to elevated terminal damage levels.

Findings from Other Survey Kit Items

The survey kits contained several items in addition to those that asked the respondent to recommend the time to rehabilitate for bridge decks. The findings from these other survey kit items are summarized as follows.

1. A majority of bridge engineers indicated that their ratings of the overall physical condition of a deteriorated concrete bridge deck are influenced more by the physical condition of traffic-lane areas than by the physical condition of shoulder areas.
2. The five deck rehabilitation decision factors most frequently selected by bridge engineers as being influential are as follows, listed in the order of selection frequency:
   - Amount of physical deterioration,
   - Availability of funds/labor,
   - Condition of the superstructure,
   - Volume of traffic (AADT), and
   - Rate of physical deterioration.
3. A majority of bridge engineers indicated that their ratings of the overall physical condition of a concrete bridge are influenced more by the physical condition of the superstructure than by the physical condition of either the deck or the substructure.
4. A majority of bridge engineers indicated that their decisions to repair or rehabilitate concrete bridge substructure components are often significantly affected by whether a decision has been made to repair or rehabilitate the deck. Thus, it may be impractical to quantify terminal damage levels to define the end of functional service life for concrete bridge substructure components.

CONCLUSIONS

Because the survey respondents evaluated damage maps representing particular types of bridge decks, these conclusions are applicable only to two-lane bridge decks with surface areas not greater than approximately 2,835 m^2 (9,300 ft^2).

1. Based on snowbelt standards (i.e., recommended practices) it is likely that the end of functional service life for concrete bridge decks is reached when the percentage of the worst traffic lane surface area that is delaminated, spalled, and patched with asphalt ranges from 9.3 to 13.6 percent.
2. Based on local standards (i.e., current practices) it is likely that the end of functional service life for concrete bridge decks is reached when the percentage of the whole deck surface area that is delaminated, spalled, and patched with asphalt ranges from 5.8 to 10.0 percent.

It is the researchers' opinion that the snowbelt standards TTR model is more useful than the local standards TTR model, because it describes recommended practices rather than the highly variable current practices. The snowbelt standards TTR model is also considered to be more valid statistically, because the R^2 values indicate a greater consensus among the respondents for this model than for the local standards TTR model. In addition, the independent variable for the snowbelt standards TTR model, which is based on the damage level in the worst traffic lane, is consistent with the responses from the majority of bridge engineers who indicated that their ratings of the overall physical condition of a deteriorated concrete bridge deck are influenced more by the physical condition of the traffic-lane areas than by the physical condition of the shoulder areas.

Either model can be used as a tool for prioritizing bridge deck rehabilitation needs. For example, by using the snowbelt standards TTR model as shown in Figure 4, the recommended TTR ranges for decks at various damage levels in the worst traffic lane can be determined graphically from the upper and lower boundaries of the 95 percent confidence interval:

Damage Level (%) in Worst Lane	*Recommended TTR*
2.5	5.2 to 8.4 years from now
7.3	1.5 to 3.7 years from now
12.8	2.4 years ago to 0.4 years from now
17.4	4.4 to 1.5 years ago

Unlike the end of structural service life, which often can be objectively defined on the basis of a readily observable failure, the EDFSL is ultimately a matter of opinion. The findings from the present study indicate that the decision to rehabilitate a bridge deck may be based in part on factors other than the extent of physical deterioration, such as the availability of funds or labor, the condition of the superstructure, the volume of traffic (AADT), or the rate of physical deterioration. Nonetheless, the terminal damage levels that were determined in the study represent a general estimate of EDFSL for concrete bridge decks and may provide a basis for discussion within the bridge engineering community to further define EDFSL.

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