Timing for Bridge Replacement, Rehabilitation, and Maintenance

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Throughout its useful life, a bridge requires both routine and periodic maintenance and major rehabilitation work before being entirely replaced. Therefore, economic decisions on bridge replacement and rehabilitation need to be made with the future expenses in mind. For a life cycle cost (LCC) analysis to be realistic, three types of information must be supplied: timing, cost, and effect of bridge work. A reasonable estimate of the timing for future bridge repair work is especially critical because it strongly affects the results of LCC analysis. A statistical analysis examined the timing of various bridge activities performed by the Indiana Department of Transportation. The analysis indicates that bridges have been replaced for various reasons when bridge life is between 40 and 70 years, with 53 years being the average. Deck replacement has been done when bridges are about 45 years old, with no previous major rehabilitation work. Deck reconstruction and overlay, the most frequently recorded rehabilitation group, has been performed when bridges are about 22 years old. Timings of occasional routine maintenance works were not determined because the maintenance records available at the time of study did not contain specific locations of the bridges. Maintenance costs need to be included as an annual expenditure in an LCC analysis until more complete information is available.

Bridges last much longer than paved highways. Throughout its useful life, a bridge requires both routine and periodic maintenance and rehabilitation work before being entirely replaced. For a highway agency, bridges are a long-term, multiyear investment. A life cycle activity profile of a bridge includes a series of future improvements laid out in a cash flow diagram. Therefore, economic decisions on bridge replacement and rehabilitation must be made with these future expenses in mind (*1*). Comparisons of only initial investments in projects fail to reflect future funding needs.

For a life cycle cost (LCC) analysis to be realistic, three types of information must be supplied: timing, cost, and effect of bridge work. A reasonable estimate of the timing for future bridge repair activity is especially critical because it controls the outcome of an LCC analysis. A network-level analysis examined the timing of various bridge activities using data collected from bridge rehabilitation records (*2*) and bridge structural inventory and appraisal (SIA) records (*3*) maintained by the Indiana Department of Transportation (IDOT). Activities were divided into three groups: replacement, rehabilitation, and maintenance. Discussions for the costs and the effect of bridge work can be found elsewhere (*4–6*).

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TIMING FOR BRIDGE REPLACEMENT

Bridges that were replaced by IDOT between 1981 and 1985 were examined for this analysis. The bridge rehabilitation records (*2*) provided information on (a) the year of construction, (b) bridge age at replacement, (c) bridge type (concrete and steel), (d) average daily traffic (ADT), and (e) rehabilitation types. Condition ratings of deck, superstructure, and substructure at the time of replacement or rehabilitation were extracted from the bridge SIA data file (*3*). In this analysis, replacement meant the replacement of the entire bridge structure. Timing for replacement was measured by the number of years passed before the entire replacement. For all statistical analysis, the SPSS statistical analysis package (*7*) was used.

Number of Years Passed Before Replacement

From the bridges replaced during this period, 105 were selected for subsequent analyses. All of these bridges were located on non-Interstate (other) highways; none of the Interstate bridges in Indiana were replaced during the given analysis period. Three management factors were used to assess their possible impact on bridge life: climatic region (north or south), bridge type (steel or concrete), and traffic level (average daily traffic—ADT). The state of Indiana was geographically divided into north and south regions approximately at the center of the state. Bridge type was determined by the material used for bridge superstructure. Because of the few repaired bridges, the number of groupings was kept small to maintain the reliability of the results.

Table 1 presents the average life of a bridge for the two climatic regions; Table 2 presents the two bridge types defined for this analysis. Only a small difference was seen in the average life of a bridge between the two groups. The average bridge life in the southern region was 52.96 years, and 52.53 years in the northern region (see Table 1). The difference was not statistically significant, implying that the regional difference would not be a factor in determining the timing of bridge replacement.

Similar results were found for the bridge-type grouping. Bridge life did not differ significantly between the concrete and steel bridge groups. Both groups had about 53 years of mean bridge life (see Table 2).

Prevailing traffic, especially truck traffic, was believed to affect bridge life. The life span of the sampled bridges was plotted against the 1985 ADT at the bridge sites. Figure 1 shows a scatter plot of these bridges. The data points were

TABLE 1 COMPARISON OF BRIDGE LIFE BY CLIMATIC REGION

Group	Count	Mean (yrs)	Standard Deviation (yrs)	Standard Error (yrs)	Min. (yrs)	Max. (yrs)	95%C.I.* (yrs)
North	53	52.53	5.81	0.798	39	65	50.92-54.13
South	52	52.96	5.74	0.796	41	71	51.36-54.56
All	105	52.74	5.75	0.562	39	71	51.63-53.86

Note: * 95%C.I. = 95% confidence interval of the mean

TABLE 2 COMPARISON OF BRIDGE LIFE BY BRIDGE TYPE

Group	Count	Mean (yrs)	Standard Deviation (yrs)	Standard Error (yrs)	Min. (yrs)	Max. (yrs)	95%C.I.* (yrs)
Conc.	75	52.91	5.84	0.674	39	65	51.56-54.25
Steel	30	52.33	5.61	1.024	45	71	50.24-54.43
All	105	52.74	5.75	0.562	39	71	51.63-53.86

Note: * 95%C.I. = 95% confidence interval of the mean

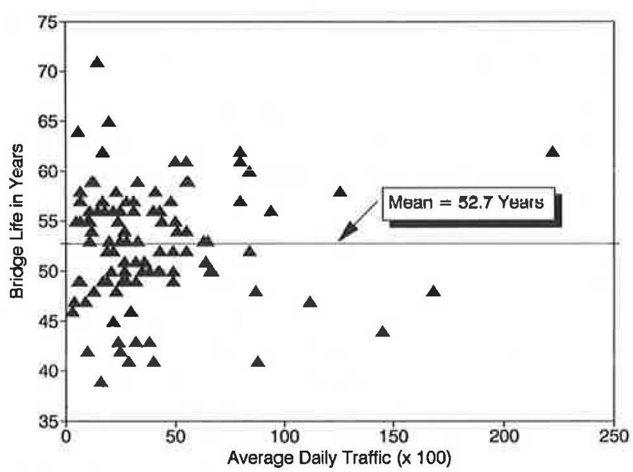


FIGURE 1 Bridge life versus ADT.

normally distributed around the overall mean value of approximately 52.74 years. A linear regression analysis on bridge life with ADT as a predictor variable showed that the slope of the regression was not statistically significant at a 5 percent significance level for this data set. This test implied that the level of traffic volume would not have a strong effect in the determination for bridge replacement. One probable reason for this outcome is that bridges are designed primarily for heavy trucks.

The existence of previous major rehabilitation or widening work or both was believed to affect the decision of bridge replacement. A one-way analysis of variance (ANOVA) was performed to assess the difference between the mean bridge ages of the two groups: (a) a group of bridges that were rehabilitated only once, and (b) a group of bridges that had never been rehabilitated before their replacement.

For a statistical inference derived from the ANOVA to be correct, the assumption of homogeneity of variance in sample data must be met. The Cochran's *C*-statistic provided by the SPSS package (*7*) was used to test this assumption. The resultant *C*-statistic was 0.639 and its significance probability was 0.042. Therefore, this assumption was met at the significance level of 0.001, the significance level used for testing the homogeneity of variance (*8*).

The ANOVA presented in Table 3 indicates that the difference in the mean life of a bridge between the two groups was significant at the 5 percent significance level ($\alpha = 0.05$) with a significance probability of 0.0003; therefore, intermediate rehabilitation work did affect the bridge service life (see Table 4). Bridges that were rehabilitated once had a mean life of about 51 years, and bridges that had no history of major rehabilitation had a mean life of about 55 years. Although the difference was statistically significant, it was only 4 years,

TABLE 3 ANOVA TABLE

Source	d.f.	SS	MS	F-Ratio	Significance Probability
Between Groups	1	415.92	415.92	14.15	0.0003
Within Groups	103	3028.13	29.4		
Total	104	3444.05			

Cochran's C-Statistic = 0.6392 (Probability = 0.042 > α = 0.01)

Note: d.f. = Degree of freedom
SS = Sum of squares
MS = Mean squares

Groups: 1. Bridges without major improvement
2. Bridges with major improvement

TABLE 4 DESCRIPTIVE STATISTICS ON SERVICE LIFE

Group	Count	Mean (yrs)	Standard Deviation (yrs)	Standard Error (yrs)	Min. (yrs)	Max. (yrs)	95%C.I.* (yrs)
Without Improvement	47	50.53	4.54	0.662	41	62	49.20-51.86
With Improvement	58	54.53	6.04	0.793	39	71	52.95-56.12
All	105	52.74	5.75	0.562	39	71	51.63-53.86

Note: * 95%C.I. = 95% confidence interval of the mean

implying that the existence of previous major rehabilitation work may not strongly affect the decision making of bridge inspectors in recommending bridge replacements. This result, however, does not necessarily mean that rehabilitation would not strengthen the bridge structure.

Condition Ratings at the Time of Replacement

Along with bridge life, condition ratings of the bridge deck, superstructure, and substructure at the time of replacement were examined separately for all the sampled bridges in both the concrete and steel types. Numerical ratings used in Indiana follow the definitions found in the structural inventory and appraisal guidelines prepared by FHWA (*9*). Figure 2 shows the ratings of the three bridge components within each bridge group. Not much difference was found. Nearly two-thirds of the bridges had condition ratings less than or equal to 5 at the time of replacement. The remaining third of the bridges were rated as 6 or higher.

However, caution is needed in interpreting these condition-rating distributions, because the plots shown in Figure 2 include the effects of rehabilitation and maintenance work. Decisions for replacing bridges may not only be affected by the condition rating but by some other factors, such as bridge age and realignment of the approach road. It was difficult to establish a conclusive relationship between the condition rating and timing of replacement. Nevertheless, this analysis indicated that the current practice of assuming 50 years as the bridge service life may be appropriate for network-level bridge management to ensure the structural safety of bridges in the system. The mean life span of all the bridges in the data set was found to be approximately 53 years with 95 percent confidence interval between 52 and 54 years.

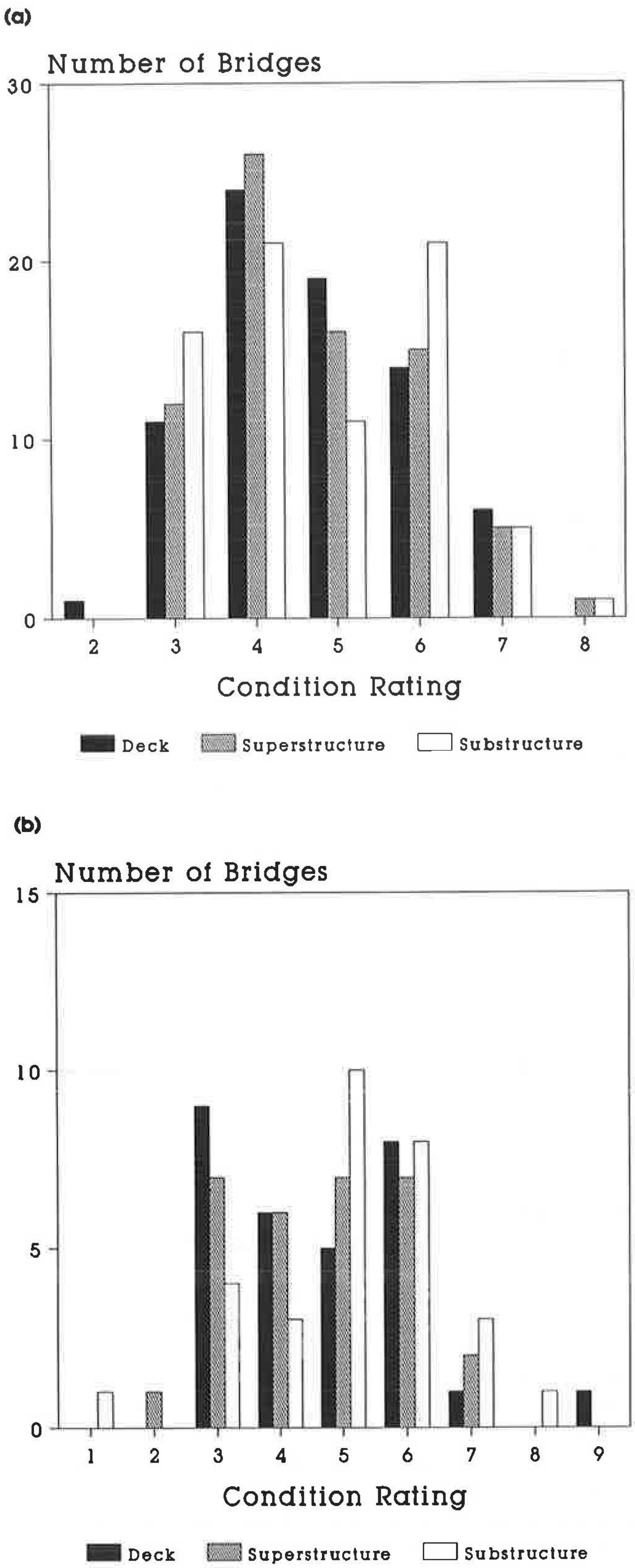


FIGURE 2 Distribution of condition ratings at the time of bridge replacement: a, concrete bridges; b, steel bridges.

TIMING FOR MAJOR REHABILITATION WORK

Two major rehabilitation groups (deck reconstruction and deck replacement) were used for the analysis because they were the groups most frequently used to identify rehabilitation work by the state bridge inspectors. Under the deck reconstruction group, part of the deck is repaired by shallow or deep patching, or both, and the surface is overlaid. Other items, such as expansion joints and railings, may be repaired as well. However, the entire deck is not replaced under this group. The deck replacement group, on the other hand, consists of the replacement of the entire deck with a completely new one. This work may be accompanied by some superstructure rehabilitation, partial or whole, and widening of the deck or superstructure, or both.

Deck Reconstruction

Two management parameters—the number of years passed before the time of the first deck reconstruction and the percentage of deck area in need of patching—were selected in this analysis because of their importance in recommending deck reconstruction. Classification factors, such as highway type, traffic volume, and climatic conditions, were tested for their effects on the inspector's decision to recommend deck reconstruction work. Bridges that had only one deck reconstruction since their initial construction were selected for the analysis; 237 bridges met this criterion.

Number of Years Passed Before Deck Reconstruction

One-way ANOVA tests on the three classification factors showed that only the regional classification had a significant effect on the number of years passed before the first deck reconstruction. Table 5 presents the result of this analysis. The resulting significance probability was 0.0004 (0.4 percent) and the regional effect was significant at the 5 percent significance level. This result indicated that there were statistically significant differences between the mean number of years passed by the time of the first deck reconstruction in the northern region (20.3 years) and that of the southern region (23.5 years). Therefore, on the average, state bridge inspectors were recommending the deck reconstruction activity about 3 years earlier for bridges in the northern region than for those in the southern region. This difference was primarily caused by the severe weather and the frequent use of deicing materials in northern Indiana.

Percentage of Deck Area Needing Patching

The extent of needed patching is considered to be an indicator of deck deterioration that is most obvious to the inspectors in evaluating deck conditions. Needed patching can be measured at the site and is, in fact, reported in the rehabilitation design plans. Using one-way and two-way ANOVAs, the effects of classification factors on the selection of the deck reconstruction and overlay alternative were examined for the percentage of deck area in need of patching. The three classification factors used in the preceding analysis were again used.

TABLE 5 COMPARISON OF THE NUMBER OF YEARS PASSED BEFORE FIRST DECK RECONSTRUCTION, BY CLIMATIC REGION

North	South	Total
N = 121 Mean = 20.3 yrs. SE = 0.64 95%CI = 19.0-21.6	N = 116 Mean = 23.5 yrs. SE = 0.65 95%CI = 22.2-24.8	N = 237 Mean = 21.9 yrs. SE = 0.45 95%CI = 21.0-22.8

Homogeneity test significance level = 0.335 > α = 0.001

Significance probability of two groups (North & South) = 0.0004 < α = 0.05

Notes: N = Number of samples in the group
Mean = Mean number of years passed from initial construction
SE = Standard error of the mean (in years)
95%CI = 95% confidence interval of the mean (in years)

The ANOVA indicated that the climatic region factor was not significant at the 5 percent significance level. Therefore, this factor may not be a statistically significant component when the percentage of deck area in need of patching is used as a decision factor. Thus, the state bridge inspectors are more concerned with factors other than the regional difference when they decide on deck reconstruction.

The highway type and the amount of traffic were, on the other hand, both significant (see Tables 6 and 7). The 95 percent confidence interval of the expected mean percent patching area for Interstate bridges was between 6.20 and 8.00 percent, when the first deck reconstruction and overlay were undertaken. The confidence interval of the mean for bridges on other state highways was between 10.56 and 13.41 percent. The state bridge inspectors tolerated less deterioration for bridges on Interstate highways than for bridges on other state highways.

For ADT, two factor levels were defined for this analysis: low (ADT < 10,000) and high (ADT ≥ 10,000). The mean percentage of deck area in need of patching was significantly different between the two factor levels, as presented in Table 7. Bridges with high traffic volumes were more likely than bridges with low traffic volumes to have the deck reconstruction work performed when the percentage of deck area in need of patching was low.

As highway type and traffic volume factors were found to be significant, a two-way ANOVA was performed to examine the interaction effect of these two factors on percent patching areas. Table 8 presents the model and results of this analysis. Both main effects and the interaction effect became significant at the 5 percent significance level. This result implies that when the percentage of deck area in need of patching is used as a decision variable, the combination of highway type and traffic volume should be considered in deciding on the timing of the deck reconstruction and overlay alternative. For instance, the mean percentage of the deck area in need of patching would be 7.35 percent for bridges on Interstate highways with ADT > 10,000, as presented in Table 8. The mean values

TABLE 6 PERCENTAGE OF DECK AREA IN NEED OF PATCHING AT TIME OF FIRST DECK RECONSTRUCTION, BY HIGHWAY TYPE

Interstates	Other State Highways
N = 111 Mean = 7.04% 95%CI = 6.20-8.00	N = 126 Mean = 11.90% 95%CI = 10.56-13.41

Homogeneity test significance level = 0.002 > α = 0.001

Significance probability of two groups = 0.000 < α = 0.05

TABLE 7 PERCENTAGE OF DECK AREA IN NEED OF PATCHING AT TIME OF FIRST DECK RECONSTRUCTION, BY ADT

ADT < 10,000	10,000 ≤ ADT
N = 144 Mean = 10.31% 95%CI = 9.16-11.60	N = 93 Mean = 7.95% 95%CI = 6.86-9.21

Homogeneity test significance level = 0.110 > α = 0.001

Significance probability of two groups = 0.007 < α = 0.05

Notes: N = Number of samples in the group
M = Mean percent of deck area needing patching at the time of the first deck reconstruction
95%CI = 95% confidence interval of the mean

TABLE 8 COMBINED EFFECTS OF HIGHWAY TYPE AND TRAFFIC VOLUME LEVEL ON THE SECTION OF DECK RECONSTRUCTION BY PERCENTAGE OF DECK AREA IN NEED OF PATCHING

		Traffic Volume (ADT)	
		Low ADT < 10,000	High 10,000 ≤ ADT
Highway	Interstate	N = 33 Mean = 6.36% 95%CI = 5.03-8.04	N = 78 Mean = 7.35% 95%CI = 6.31-8.56
	Other State Highway	N = 111 Mean = 11.90% 95%CI =10.47-13.52	N = 15 Mean = 11.94% 95%CI = 8.44-16.90

Homogeneity test significance level = 0.002 > α = 0.001

Notes: N = Number of samples in the group
Mean = Mean percent of deck needing patching at the time of the first deck reconstruction
95%CI = 95% confidence interval of the mean

obtained from this analysis can be used in a bridge management system to automatically select bridges that may need deck reconstruction.

Condition Ratings at the Time of Deck Reconstruction

This analysis was performed to examine the timing of deck reconstruction work in relation to condition rating. Condition ratings are seen as a reflection of the severity and extent of distresses that exist on bridge structures. Because deck reconstruction is closely related to the condition ratings of the deck and superstructure, these two condition ratings were checked. Figure 3 shows the difference in condition-rating distributions of the deck and the superstructure. Condition ratings of decks were mostly 5 and 6 when the deck was reconstructed. However, condition ratings of the superstructure were mostly 6 and 7 at the time of deck reconstruction, implying that the speed of deterioration of a superstructure would be slower than that of a bridge deck.

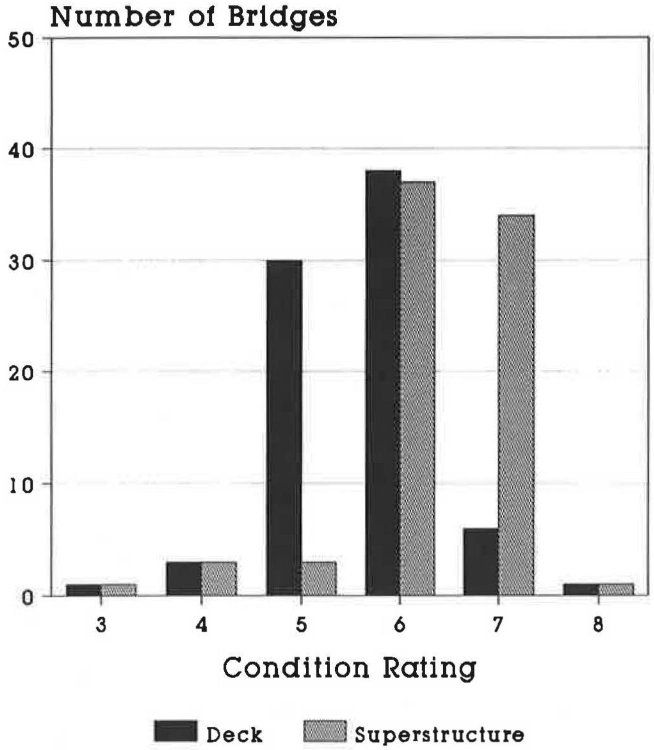


FIGURE 3 Condition ratings at the time of first deck reconstruction.

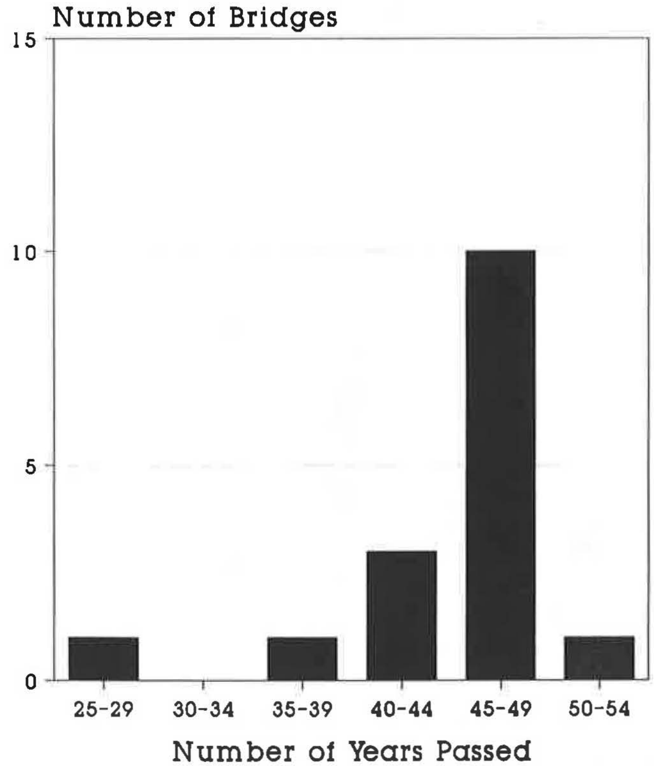
Deck Replacement

There were only a few bridges found in the deck replacement category. Within the 3-year period 1984–1986, only 16 bridges fit the description of this rehabilitation alternative. These bridges had only one deck replacement during their entire life and no other major rehabilitation work was performed.

Number of Years Passed Before Deck Replacement

Figure 4 shows the frequency of deck replacement for each 5-year range. Although there was one extreme case (deck replacement at the 26th year), this process seems to have been undertaken when bridge age was greater than about 40 years.

Figure 4 also shows the summary statistics of these bridges. The mean number of years passed before deck replacement was 44.6 years, and the 95 percent confidence interval level was 41.4 to 47.8 years. When the extreme case of 26 years was excluded from the data set, the mean value became 45.9 years with the 95 percent confidence interval being 44.2 to 47.7 years. This finding is important because deck reconstruction is recommended about 20 to 22 years after bridge construction. Clearly, there will be a trade-off between the deck reconstruction at an early stage of bridge life and the deck replacement at a later stage, because the unit costs of these two rehabilitation alternatives are substantially different. Unit costs of deck replacement were found to be about twice as much as the units costs of deck reconstruction (*6*).



Summary Statistics for Deck Replacement:

Number of samples = 16
Mean = 44.6 years
Standard deviation = 6.0 years
Standard error = 1.5 years
95% Confidence interval = 41.4 years to 47.8 years

FIGURE 4 Number of years passed before the first deck replacement.

Condition Ratings at the Time of Deck Replacement

Condition ratings at the time of deck replacement were plotted for the three components of the bridge structure (deck, superstructure, and substructure), as shown in Figure 5. Substructure condition ratings were plotted to compare with the ratings of the deck and superstructure. Deck replacement is recommended when the deck condition rating reaches a value of 6 or less. The superstructure may be at a similar condition level. However, the substructure may not be as deteriorated as the deck and superstructure, when the replacement work is recommended. By the time the substructure condition rating declines to Condition Rating 6 or lower, other parts of the bridge may become so deteriorated that the replacement of the entire structure may be warranted (see Figure 2 for comparison).

TIMING FOR MAINTENANCE WORK

Bridge routine maintenance activities are performed to maintain the structural integrity of a bridge structure, decrease the speed of its deterioration, and ensure the safe passage of traffic. Each maintenance activity may have a minimal effect

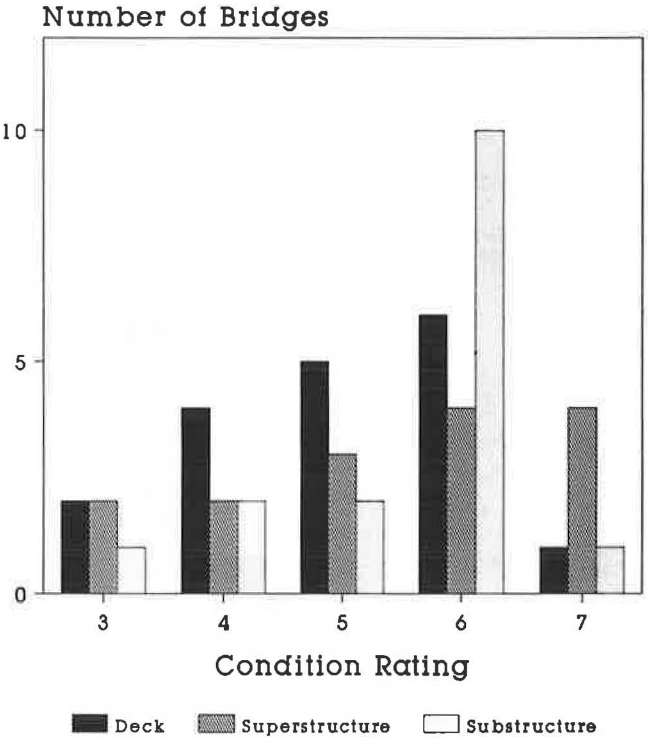


FIGURE 5 Condition ratings at the time of first deck replacement.

by itself but a group of well-planned maintenance activities may be able to achieve these goals. Maintenance work is conducted at any condition-rating level as long as it is needed.

The analysis of timing of maintenance activities became difficult because of the nature of routine maintenance and the lack of information in the maintenance activity records of IDOT available at the time of this study. Some works, such as deck cleaning and flushing, are annual events and need not be analyzed for timing. These tasks are performed, especially in the northern region of Indiana, to decrease salt contamination and possible future damages of the deck induced by debris collected in spots such as drainage pans and expansion joints. Records of other occasional maintenance activities, e.g., bridge repair and patching, were difficult to trace to individual bridges. The maintenance activity recording procedure available did not require the maintenance crew to include specific locations of bridges for which maintenance work has been performed.

For a life cycle cost analysis, the timing for occasional maintenance activities needs to be input based on engineering judgment at the moment. Expenditures for maintenance and repair work are often assumed to increase as the bridge age increases. However, the data showed no evidence for substantiating this assumption. Identifying maintenance activities with specific bridge structures so a data base can be developed is essential. A lack of data for the timing of maintenance activities may cause some difficulty in conducting a realistic LCC analysis. However, the use of the annual maintenance cost concept may not seriously jeopardize the validity of the LCC analysis. The outcome of LCC analysis was more sensitive to large capital expenditures such as rehabilitation and replacement than to small expenditures for maintenance (*10*).

SUMMARY AND CONCLUSIONS

Estimates of the timing for future bridge improvement activities were made on the basis of historical records, and the relationship between condition ratings and recommended actions was examined. Consequently, the results indicate what was done, not what could be done. The timing used by bridge engineers may not have been optimal, and the results do not represent service lives that can be theoretically achieved. Nevertheless, findings from this study can be helpful in performing a realistic LCC analysis. However, the results apply primarily to bridges in Indiana, and analyses on bridges in other states may provide different results. In this analysis, changes in design, rehabilitation, and maintenance policies, if any, were assumed to be reflected in the data collected.

The average bridge service life of about 50 years used by the state is a reasonable assumption on which to conduct an LCC analysis. The state-wide average was found to be about 53 years. Climatic region, bridge type, and traffic volume factors did not significantly affect the decisions recommending bridge replacement. Such a decision is based on the overall structural safety of a bridge, as perceived by state bridge inspectors. The age of a bridge is one of their primary decision factors. A clear relationship between the condition rating at the time of replacement and the bridge life could not be established because condition ratings were affected by rehabilitation and maintenance activities performed during the life span of the bridge.

On the other hand, differences of service life of bridges with or without rehabilitation were found to be statistically significant. However, the average difference observed was only 4 years. The existence of previous rehabilitation work may have a small impact on current replacement decision making. Rehabilitation work done on bridges is often related to bridge deck and superstructure, and the life spans of these bridge components are shorter than the life span of the entire bridge structure. Deck and superstructure conditions seem to be the key element that causes bridge inspectors to recommend bridge replacement.

As for rehabilitation alternatives, two major activity categories, deck reconstruction and deck replacement, were evaluated. The first deck reconstruction took place approximately 22 years, on the average, after the initial construction of the bridge. The effect of climatic conditions was found to be present and the mean values were 20.3 years for the northern region and 23.5 years for the southern region. The frequent use of deicing materials in the northern region of Indiana may be the primary cause for this difference. Some bridges received second deck reconstruction work in their lifetime, but they rarely received third and fourth deck reconstruction work.

The deteriorated area in need of patching is often a sign of the need for deck reconstruction. The percentage of deck area in need of patching at the time of deck reconstruction was used as a parameter to express the level of deck deterioration. The amount of deck area in need of patching at the time of deck reconstruction varies by highway type and traffic volume. On the average, bridges on Interstates had smaller percentages of deteriorated deck areas when deck reconstruction was recommended, implying that bridge inspectors tend to place higher priority on bridges on Interstate highways when appraising them for the reconstruction.

The average life of a bridge before it received the first deck replacement was found to be approximately 45 years. Few bridges received deck replacement as compared with deck reconstruction. Those bridges that had their decks replaced did not receive any major deck rehabilitation before their replacement. Because the difference between the unit costs of deck reconstruction and replacement was large, a careful tradeoff analysis would be necessary to select a rehabilitation alternative.

No detailed analysis of timing of maintenance work was undertaken in the present study because the existing maintenance record-keeping procedure did not provide information on maintenance work for specific bridges. Record keeping of maintenance work needs to include information related to specific bridge locations in a data base for future statistical analyses. At the moment, engineering judgment needs to be used to enter future maintenance activities as annual expenditures in an LCC analysis.

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