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SERVICE LIFE AND COST COMPARISONS FOR FOUR TYPES OF CDOT BRIDGE DECKS

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16. Abstract

This study examines costs and performance of four types of reinforced concrete bridge decks currently in service on Colorado DOT (CDOT) highway bridges. These four types allow a comparison between bare decks and decks with waterproofing membranes, and between decks with uncoated steel reinforcement and decks with epoxy-coated steel reinforcement.

Histories of deck condition ratings are used to estimate deck service life and to generate population models of service life. Decks with waterproofing membrane have longer service life than bare decks. Condition data indicate longer service life for decks with uncoated reinforcing steel, but this outcome may be due to the limited extent of condition data for decks having epoxy-coated reinforcement.

Costs for bridge decks are evaluated as initial costs, present values, and annualized costs. By all present value and annualized cost measures, decks with waterproofing membrane are least expensive. This outcome is not sensitive to the value of the discount factor.

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The research team also wishes to thank the Study Panel members including Jeff Anderson, Ali Harajli, Glen Frieler, Matt Greer, and Aziz Khan for their review and valuable comments.

EXECUTIVE SUMMARY

This study, performed by the University of Colorado at Boulder for the Research Branch of the Colorado Department of Transportation (CDOT), evaluates the relative costs of four types of reinforced concrete bridge decks. *Type*, here, indicates the type of protection of reinforcing steel against corrosion. A basic comparison among decks is annualized cost: total costs incurred by a deck divided by the number of years of service. Annualized costs are computed both with and without discount factor. Costs are computed both as costs of deck materials and costs of deck construction projects. On the basis of annualized cost, it is found that decks protected with waterproofing membrane and bituminous overlay offer the least project cost.

This finding is for Colorado bridge decks, specifically. Costs are taken from CDOT Market Analysis publications. Service life durations are estimated from CDOT bridge inspection data. Reliance on in-state data is necessary; there is no common finding on deck protection systems among US DOTs. Other state DOTs report poor performance for waterproofing membranes. Indeed, every type of deck protection is reported to have poor performance by at least some state DOTs.

A main reference on this point is the 2004 synthesis [**12**] on bridge deck performance published by the National Cooperative Highway Research Program. The synthesis presents results of a survey of US DOTs on their experience with protection systems such as epoxy-coated reinforcing steel, galvanized reinforcing steel, stainless steel reinforcement, waterproofing members, low-permeability concretes, sealers, corrosion inhibitors, etc. The synthesis shows that performance of every protection system is good at some DOTs and poor at others. It is not clear in the synthesis whether DOT evaluations of performance are quantitative or anecdotal.

These two points, the lack of consensus on performance and the uncertain basis of DOTs' evaluations, prompted CDOT to develop its own findings on bridge deck performance, and at the same time to establish methods of quantitative evaluation of performance.

Some basic information on this study:

<u>Bridge Decks</u>

A set of 82 bridge decks of four types are studied. These decks include:

- → Twenty-five decks built between 1969 and 1975 having uncoated reinforcing steel. Twenty-two decks in this group were rehabilitated with rigid overlay between 1989 and 1999.
- → Twenty-three decks built in 1993 having epoxy-coated reinforcing steel and treated with surface-applied concrete sealer.
- → Nineteen decks built in 1980 having uncoated reinforcing steel and protected with waterproofing membrane and bituminous overlay.
- → Fifteen decks built in 1991 having epoxy-coated reinforcing steel and protected with waterproofing membrane and bituminous overlay.

<u>Costs</u>

Costs for construction, maintenance and rehabilitation are collected from CDOT project data and CDOT average costs published by the CDOT Market Analysis Branch [**2**, **3**]. Costs are adjusted to a common base year (2003) using the US Army Corps of Engineers *Civil Works Construction Cost Index System* [**19**].

Service Life

Values for bridge deck service life are extrapolated from trends in deck condition ratings. Condition ratings are assigned every two years during bridge inspections. CDOT bridge files have records of condition rating for all bridge decks. Service life is taken as the time in years for a bridge deck to deteriorate from new condition to condition rating '5'. This is consistent with current CDOT practice for deck rehabilitation. Service life extrapolations are first made for individual decks. Individual values are aggregated into cumulative probability distributions. Distributions express the increasing probability of the need for deck rehabilitation with increasing years in service. Deck types in this study have median service life values that range from 31 years for decks having epoxy-coated reinforcing steel protected by sealers to 56 years for decks protected with waterproofing membrane and bituminous overlay.

Cost Analysis

Deck costs are computed using methods presented in NCHRP Report 483 *Bridge Life Cycle Cost Analysis,* and in Governmental Accounting Standards Board (GASB) Publication 34 [**4**]. Costs are computed as present value, as discounted annualized cost and as annualized cost without discount factor (this is GASB 34 Alternative method). Costs are analyzed for median service life and as integrations using service life cumulative probability distributions.

Costs are computed for:

1. Deck materials plus maintenance in service, and
2. Deck construction projects plus maintenance in service.

Costs based on deck materials offer the clearest comparison of performance of deck types. Costs based on construction projects offer a better indication of actual costs to CDOT. Project costs are larger than material costs, of course. Project costs depend in significant part on the number of decks in a contract, on the traffic volume on affected roads, on project-specific restrictions to construction operations, and in general on a variety of factors not related to deck type.

Sensitivity

Costs of deck types are examined for discount factors ranging from 2% to 10%. Over all of this range, waterproofing membranes offer the least project cost. Service life extrapolations are sensitive to the extent of condition data. Early-life condition data yield low estimates of service life duration. Longer-term condition data yield higher estimates of service life. In this study, condition data span more than 20 years for decks with uncoated reinforcing steel type, but not more than 12 years for decks with epoxy-coated reinforcing steel.

Significance

The methods employed in study 80.075 can be extended to additional types of bridge decks, to other components of bridges and to other asset classes.

The steps in evaluations/comparisons of cost are straightforward. Cost evaluations are mostly a matter of collection of available data from CDOT sources. Service life extrapolations and distributions are generated, not collected, but the computation for these employ standard linear regression and standard forms of probability distributions.

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Service Life and Cost Comparisons for Four Types of Colorado DOT Bridge Decks

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September, 2007

CHAPTER 1 SUMMARY

This study evaluates costs and performance of four types of reinforced concrete bridge decks used by the Colorado DOT (CDOT). It examines a population of 82 CDOT bridge decks; computes average service life, average material costs for construction, and average maintenance costs; and uses these to compute a set of cost evaluations, including present value unit cost and annualized unit cost. The study notes differing service life and differing costs among the four types of decks.

STUDY DECKS

The 82 study decks are selected from a larger set of 172 decks identified by CDOT. Included among these are

- → Nineteen decks built in 1980 that are protected with waterproofing membrane and asphalt overlay. These decks have uncoated steel reinforcement.
- → Twenty five decks built between 1969 and 1975. These decks have uncoated reinforcing steel. Twenty–two of these decks have been rehabilitated with rigid overlay. Eleven of these decks were rehabilitated in 1999, ten in 1995 and one in 1989.
- → Twenty-three decks built in 1993 that are protected with penetrating sealers. These decks have epoxy-coated reinforcing steel.
- → Fifteen decks built in 1991 that are protected with waterproofing membrane and asphalt overlay. These decks have epoxy-coated reinforcing steel.

The study decks are selected to obtain groups of decks of nearly equal age. For three types of decks (elements 14, 23 and 26) all decks of the same type have the same age. For element 22 decks, the group of oldest decks in the study, there is a range of 6 years for construction of decks, and a range of 10 years for rehabilitation projects. Decks in the study are presented in Chapter 2.

DECK DESIGNS AND COSTS

For the purpose of cost evaluation and comparison, deck designs conform to the CDOT Bridge Design Manual [1]. That is, deck thickness, steel reinforcement size and spacing, the use of epoxy-coating at one or both mats of reinforcement, and the thickness of HMA overlays are all taken from the design manual and relevant design memoranda. Effective spans for decks are taken at median values for each group of study decks. Costs for materials for deck construction are collected from CDOT published unit cost data for construction projects [**2**] and for maintenance projects [**3**]. Cost data are from 2003. Basic design and cost data are shown in Table 1. Chapter 4 provides detailed information on deck material quantities and costs.

Table 1 - Bridge Deck Data and Unit Costs

Deck Type	Deck Span	Thickness	Steel Qty	Concrete Protection	Epoxy Coating	Material Cost	Project Cost
Element 14	7'-8"	8"	58.5 lbs/SY	Membrane + Asphalt	None	$ 119 / SY	$ 714 / SY
Element 22 No rehab	8'-6"	8.25"	59.05 lbs/SY	None	None	$ 104 / SY	$ 624 / SY
Element 22 Rehab'd	8'-6"	8.25"	59.05 lbs/SY	Rigid Overlay	None	$ 139 / SY	$ 834 / SY
Element 23	8'-6"	8.25"	59.05 lbs/SY	Penetrating Sealer	Both mats	$ 115 / SY	$ 690 / SY
Element 26	8'-0"	8"	59.53 lbs/SY	Membrane + Asphalt	Top mat	$ 121 / SY	$ 726 / SY

DECK SERVICE LIFE

Estimates of service life for individual bridge decks in the study are obtained by extrapolation of time-domain trend lines for National Bridge Inventory (NBI) deck condition ratings. For this study, the time to reach NBI rating 5 is taken as the time to first rehabilitation of the deck, and also the initial service life of the deck. Continued service after rehabilitation is examined for element 22 decks. Condition ratings are available from 1972 onwards. For most decks, initial condition ratings are reported one year after construction. For decks constructed in 1969, the initial deck ratings are reported three years after construction. Service life estimates are summarized in Table 2.

Table 2 - Estimates of Deck Service Life

Deck Type	Service Life Estimate (years)		
	Minimum	Average	Median
Element 14	31	78	56
Element 22 No rehab	19	34	31
Element 22 Rehab'd	27	39	35
Element 23	15	29	31
Element 26	27	44	35

For each group of bridge decks, a population model for deck service life is generated. Each population model indicates the probability, as a function of time in years, that a deck will reach NBI condition rating 5. Population models are used to include variability in service life during computation of deck costs. The time required to reach condition rating 5 for 10^{th}, 50^{th}, and 90^{th} percentiles of deck populations are shown in Table 3.

Service life estimates and population models are presented in Chapter 3.

Table 3 - Deck Population Models: Deck Service Life

Deck Type	Years to Service Life Percentile		
	10th	**50th**	**90th**
Element 14	33	56	110
Element 22 No rehab	25	31	41
Element 22 Rehab'd	28	35	52
Element 23	20	31	40
Element 26	28	35	55

COST COMPARISONS

Average unit costs for the four types of bridge deck are computed as

- → Initial material cost
- → Initial construction project cost
- → Present value costs discounted over the service life of the deck
- → Annualized costs over the service life, without a discount factor (conforming to GASB 34 alternative method [**4**])
- → Annualized costs over the service life, using a discount factor.

For annualized costs and for present value costs, results are obtained both using median service life values and using service-life population models. The annual discount rate is 3.2%, as specified in circular A094 of the US Office of Management and Budget [**5**]. A summary of cost comparisons is shown in Table 4 and Table 5. Details on cost computations are presented in Chapter 4.

Table 4 – Material Cost Comparisons for CDOT Bridge Decks

	Bridge Deck Cost, $ / SY				
	Element 14	Element 22 No rehab	Element 22 Rehab'd	Element 23	Element 26
Initial Cost	119	104	139	115	121
PV1 Present Value Median Service Life	45.35	39.17	46.16	72.30	65.14
PV2 Present Value, Population Service Life	51.71	37.46	40.45	74.20	61.63
AC1 Annualized Cost, Median Service Life	3.25	3.35	3.97	5.28	4.58
AC2 Annualized Cost Population Service Life	3.59	3.25	3.60	5.82	4.50
AC3 Discounted Annualized Cost Median Service Life	1.80	2.00	2.21	3.74	2.95
AC4 Discounted Annualized Cost Population Service Life	2.14	1.92	1.89	4.28	2.89

Table 5 – Project Cost Comparisons for CDOT Bridge Decks

	Bridge Deck Cost, $ / SY				
	Element 14	Element 22 No rehab	Element 22 Rehab'd	Element 23	Element 26
Initial Cost	714	624	834	690	726
PV1 Present Value Median Service Life	147	235	277	289	266
PV2 Present Value, Population Service Life	167	225	243	311	252
AC1 Annualized Cost, Median Service Life	13.87	20.13	23.83	23.83	21.86
AC2 Annualized Cost Population Service Life	15.14	19.50	21.62	27.09	21.36
AC3 Discounted Annualized Cost Median Service Life	5.74	12.06	13.27	14.86	12.57
AC4 Discounted Annualized Cost Population Service Life	7.21	11.52	11.36	18.06	12.24

Tasks in the Study

The study has two phases and four tasks. Phase I was performed in 2004. Phase II began in the second half of 2005 and ended in the second half of 2006. Phase I includes a limited literature review, the identification of study decks, and collection of information on these decks. Phase II includes the evaluation of deck service life, computation and comparison of deck costs, and preparation of the final report for the study.

TASK 1 – LITERATURE REVIEW

Task 1 reviews literature on performance of bridge decks published in 2004, and summarizes points from a larger literature review completed by Xi et al. [**6**]. Eighteen sources from 2004 are identified in a search of TRIS, ASCE, and CompenDex databases. Complete notes on 2004 sources appear in Appendix 5.

Points directly related to the four types of bridge deck in this study are summarized below.

Xi et al [**6**] completed a study of deck protection systems for CDOT in 2004. Among the findings in the literature reported by Xi:

- → Virmani and Clemena 1998 [**7**] report that bridge decks with epoxy-coated reinforcement require no maintenance for the first 20 years of service life. Evidence of corrosion of epoxy-coated rebar among these decks is observed in 19% of rebar segments collected from concrete cores.
- → Brown et al. 2003 [**8**] report that epoxy-coated reinforcement offers a 5-year increase in deck service life compared to uncoated reinforcement.
- → Manning [**9**] reports that epoxy-coated reinforcement is no longer used in Florida for concrete substructures that are continuously wet.
- → Kansas DOT [**10**] installed waterproofing membranes between 1967 and 1974 as a retrofit on salt-contaminated bridge decks. Since then, these decks have continued in service with little maintenance.
- → Nash et al. [**11**] report on use of impressed-current cathodic protection for bridge decks in Texas, and conclude that the method is not cost-effective.

Xi further reports that:

- → Galvanized steel reinforcement may extend deck service life by 5 years compared to non-galvanized, uncoated reinforcement

A 2004 NCHRP synthesis addresses the performance of bridge decks [**12**]. Performance is measured through DOTs' responses to a questionnaire, expressing DOT perception of performance of various concrete, reinforcing steel, and deck protection products. The synthesis compares products within each category, finding that:

- → Epoxy-coated reinforcement is the most effective type of reinforcement for reducing the potential for deterioration.
- → Liquid-applied membranes and preformed membranes have about the same performance.
- → Silane and siloxane sealers are rated slightly higher (better) by DOTS than epoxy sealers, linseed oil and other sealing products.

The synthesis does not offer a comparison among deck protection types, nor does it compare the performance of reinforcement products to concrete products or to protection products. The synthesis does not provide estimates of service life for any reinforcement, concrete or sealing product.

Babaei [**13**] reports that epoxy-coated steel provides a 10-year extension of the initial period of no corrosion in bridge decks.

Brown and Weyer [**14**] report an approximate 5-year extension to service for decks using epoxy-coated reinforcement. The authors also estimate that only 1 in 4 bridge decks in Virginia will suffer corrosion of reinforcement that is sufficient require deck rehabilitation within the first 100 years of service life. For the most severe exposures, epoxy-coated reinforcement offers no improved performance relative to uncoated reinforcement.

Further note on relative performance of uncoated versus epoxy-coated reinforcing steel

Literature sources report that epoxy coating sometimes does not protect reinforcing steel from corrosion. NCHRP Synthesis 333 [**12**] summarizes literature on performance of epoxy-coated reinforcing steel in bridge decks. While performance is generally good, the synthesis notes that:

→ Manning [**9**] reports corrosion due to debonding of epoxy coating at bridge decks in the Florida keys.

→ Pyc [**15**] reports debonding for epoxy coatings for reinforcing steel collected from bridge decks in Virginia.

→ Keplar [**16**] reports corrosion of epoxy-coated reinforcing steel in the vicinity of cracks in concrete.

→ Smith and Virmani [**17**] and Samples and Ramirez [**18**] both report corrosion in about 20% of cores collected from bridge decks having epoxy-coated reinforcing steel.

Uncoated reinforcing steel can perform well when protected by waterproofing membrane. Such performance is found in this current study, and in Kansas DOT experience with rehabilitated bridge decks [**10**].

TASK 2 – CDOT DECKS IN THE STUDY

Task 2 identifies decks for the study and collects data on these decks. Task 2 also collects information needed for evaluation of relative costs of decks. The four types of decks for the study were selected through consultation with the study panel (in May 2004). For these four types, CDOT provided information on a set of 172 candidate decks. From this population, 82 decks for study were identified. A tabulation of study decks appears in Appendix 1. Information on study decks is presented in Chapter 2.

TASK 3 – DECK SERVICE LIFE. DECK COSTS.

Work under this task estimates average service life, and forms models of service life for populations of decks. Service life estimates and models are presented in Chapter 3. Initial costs for deck are computed from average unit cost data published by Colorado DOT. Cost evaluations combine initial cost, service life duration, and discount factors to obtain comparative costs among decks. Cost computations and comparisons are presented in Chapter 4.

TASK 4 – FINAL REPORT

The final report compiles all information on literature sources for performance of four deck protection systems, all information gathered for the select population of CDOT bridge decks, and all evaluations of service life, and costs.

CHAPTER 2 CDOT DECKS IN THE STUDY

The 82 study decks are selected from a larger set of 172 decks identified by CDOT. Included among these decks are:

→ Nineteen decks built in 1980 that are protected with waterproofing membrane and asphalt overlay. These decks have uncoated steel reinforcement. These are the *Element 14* decks.

→ Twenty-five decks built between 1969 and 1975. These decks have uncoated reinforcing steel. Twenty–two of these decks have been rehabilitated with rigid overlay. Eleven of these decks were rehabilitated in 1999, ten in 1995 and one in 1989. These are the *Element 22* decks.

→ Twenty-three decks built in 1993 that are protected with penetrating sealers. These decks have epoxy-coated reinforcing steel. These are the *Element 23* decks.

→ Fifteen decks built in 1991 that are protected with waterproofing membrane and asphalt overlay. These decks have epoxy-coated reinforcing steel. These are the *Element 26* decks.

The study decks are selected to obtain groups of decks of nearly equal age. For three groups of decks (elements 14, 23 and 26) all decks within a group were constructed in the same year. For element 22 decks, the group of oldest decks in the study, there is a range of 6 years for construction of decks and a range of 10 years for rehabilitation projects.

The four groups populate a matrix of deck types for comparison (Table 6).

Table 6 - Matrix of Types of Bridge Decks

	Bare Deck	Waterproofing Membrane
Uncoated Reinforcing Steel	Element 22 Decks	Element 14 Decks
Epoxy-Coated Reinforcing Steel	Element 23 Decks	Element 26 Decks

Element 22 decks are the only rehabilitated decks in the study. These decks were built between 1969 and 1975, and had bare steel reinforcement. Most of these decks saw service as bare concrete decks for ~25 years. Twenty-two decks were rehabilitated with rigid overlays, and are bare decks today. The earliest rehabilitation among these decks was in 1989, and the last was in 1999. Projects in 1995 and 1999 installed rigid overlays on twenty-one decks. Seven decks in Element 22 group were sampled for Cl- content in the 1970s. Additional sampling for Cl- at two bridge decks is performed in Phase II of this study.

Among the bridges represented in this study, bridge lengths range from 90ft to more than 1000ft, bridge widths range from 27ft to 154ft, and bridge inventory ratings range from HS-25 to HS-50. Information on bridge types and lengths are shown in Table 7 to Table 14. In all tables, *count* is the number of decks.

Table 7 - Element 14 Decks – Bridge Types

Count	Type	
6	CPGC	Concrete girder, Continuous, Prestressed
4	CSGC	Concrete slab and girder, Continuous
3	CICK	Concrete on I-Beam, Continuous, Composite
2	CBGCP	Concrete box girder, Continuous, Prestressed
2	WGCK	Welded girder, Continuous, Composite
1	CBGC	Concrete box girder, Continuous
1	CPG	Concrete girder, Prestressed

Table 8 - Element 14 Decks – Bridge Length

Bridge Length	Count
to 100 ft	1
101 ft to 150 ft	5
151 ft to 200 ft	5
201 ft to 400 ft	5
Over 400 ft	3

Table 9 - Element 22 Decks – Bridge Types

Count	Type	
8	CSGC	Concrete slab and girder, Continuous
7	WGCK	Welded girder, Continuous, Composite
3	CPG	Concrete girder, Prestressed
3	CSG	Concrete slab and girder
2	CPGC	Concrete girder, Continuous, Prestressed
1	CBGC	Concrete box girder, Continuous
1	CICK	Concrete on I-beam, Continuous, Composite

Table 10 - Element 22 Decks – Bridge Length

Length	Count
To 100 ft	11
101 to 150 ft	4
151 to 200 ft	5
Over 200 ft	5

Table 11 - Element 23 Decks – Bridge Type

Count	Type	
6	CBGCP	Concrete box girder, Continuous, Prestressed
5	CSGCP	Concrete slab and girder, Continuous, Prestressed
5	SBGC	Steel box girder, Continuous
3	CPGC	Concrete Girder, Continuous, Prestressed
2	WGK	Welded girder, Composite
1	CBGP	Concrete box girder, Prestressed
1	WGCK	Welded girder, Continuous, Composite

Table 12 - Element 23 Decks – Bridge Length

Bridge Length	Count
151 ft to 200 ft	7
201 ft to 400 ft	9
Over 400 ft	7

Table 13 - Element 26 Decks – Bridge Type

Count	Type	
4	CBGCP	Concrete box girder, Continuous, Prestressed
3	CPGC	Concrete girder, Continuous, Prestressed
3	SBGC	Steel box girder, Continuous
2	SBGCP	Steel box girder, Prestressed, Continuous
1	CBGP	Concrete box girder, Prestressed
1	CPG	Concrete girder, Prestressed
1	WGCK	Welded girder, Continuous, Composite

Table 14 - Element 26 Decks – Bridge Length

Bridge Length	Count
To 100 ft	1
101 ft to 150 ft	2
151 ft to 200 ft	2
200 ft to 400 ft	2
Over 400 ft	8

Data on bridges and decks are collected from:

- *CDOT spreadsheets*: Mr. Steve White provided Excel files containing summaries of basic data on bridges, and data on projects for bridges. These spreadsheets contain 172 bridges, and from these the set of 82 bridges for the study were identified. Data on 82 study decks taken from CDOT spreadsheets are shown in Appendix 1.
- *Bridge inspection reports*. Inspection reports list the CoRe elements for each bridge, current conditions of elements, smart flags, and inspectors' notes. Summaries include SI&A data.
- *Cardex files*. Cardex files are reviewed to verify bridge type, obtain deck thickness, stringer depth, and stringer spacing. Information collected in Cardex review is shown in Appendix 2.
- *Bridge folders*. Folders were reviewed to verify deck surface condition, and note special projects or repairs at bridges.
- *Bridge inspection summaries* (photocopied from bridge folders). These are the basic information on condition history reported as NBI ratings for deck, superstructure and substructure. NBI condition histories for study decks are listed in Appendix 3.
- *Cost data*. Average unit costs are collected from CDOT 2003 Cost Data (Construction) [**2**], and CDOT 2003 Cost Data Maintenance Projects [**3**].
- *Design data* for standard CDOT decks are obtained from the CDOT Bridge Design Manual, Section 8.1 [1].

CORING AND CL- ANALYSIS

Concrete cores are collected from bridges G-22-BJ and G-22-BL. Sampling and evaluation in 1976 indicated that Cl- contents at the level of the top mat of reinforcing steel were 0.011% and 0.005% by weight of concrete. Sampling and evaluation in this study are reported in Appendix 5.

CHAPTER 3 SERVICE LIFE OF BRIDGE DECKS

The length of service is a basic quantity in bridge deck performance for this study. Bridge deck service life is central to comparisons among types of bridge decks. The length of service is part of all computations of discounted present values of decks, and annualized costs of decks.

NCHRP Project 12-43 [**20**] defines service life as the period of time from the end of construction until a bridge's condition declines to an unacceptable level. Using this definition, deck service life may extend: 1) from initial construction to replacement of a deck, or; 2) from initial construction to a major rehabilitation of a deck, or; 3) from one major rehabilitation to the next.

In the present study, element 22 decks are the oldest decks, and 88% of these have had a deck rehabilitation project. Other decks in the study (elements 14, 23 and 26) are younger and have not (up to 2004) been rehabilitated. Among the rehabilitated element 22 decks, most (17 of 22) had rehabilitation projects after reaching condition rating 6 in the NBI scale. Four decks were rehabilitated at condition rating 5 and one at condition rating 4. Decks were rehabilitated eight years (median) after first reaching condition rating 6. For the element 22 decks, it appears that condition rating 5 is unacceptable since only 16% of decks are permitted to reach this value and only 4% of decks go below condition rating 5. CDOT's functional policy for deck rehabilitation is:

- → About eight years after a deck first reaches NBI condition rating 6, but
- → Before a deck reaches NBI condition rating 5.

For the purpose of the present study of CDOT bridge decks, the service life of a deck will be examined as both

- → The time from initial construction to first occurrence of NBI deck condition rating 5
- → The time from initial construction to (re)occurrence of deck condition rating 5 after rehabilitation (element 22 decks only).

NBI Condition Data for Bridge Decks

Raw data for NBI condition ratings for CDOT bridge decks are listed in Appendix 3. Available data are summarized in Table 15.

Table 15 - NBI Deck Condition Ratings

Deck Element	Median Age (years)	Range of Condition Ratings	Most Recent Condition Rating (median)	Median Extent of Condition Data (years)
14	22	9 to 5	7	21
22	28	9 to 4	7	27
23	10	9 to 6	7	9
26	12	9 to 7	7	12

Length of Service Life

Service life is taken as the time required, in years, for a new bridge deck to reach NBI condition rating 5. The starting time is the initial construction of the bridge deck. The ending time is the first occurrence of condition rating 5 for decks without rehabilitation, or the re-occurrence of condition rating 5 after deck rehabilitation. For all decks, estimates of the time from initial construction to the occurrence of deck condition rating 5 are made. For the rehabilitated element 22 decks, two service life estimates are made: One from initial construction to an occurrence of condition rating 5 before rehabilitation, and one from initial construction to a second occurrence of condition rating 5. The second estimate includes the effect of the rehabilitation project to extend deck service life.

Among the element 14 decks (none rehabilitated) one deck has a lowest condition rating equal to 5. All other element 14 decks have 6 has the lowest deck condition rating. Among the three element 22 decks that are not rehabilitated, one has a lowest deck condition rating equal to 5 and two have a lowest deck rating equal to 6. Among the twenty-two rehabilitated decks, seventeen had a lowest condition rating equal to 6 before repair, four had a lowest rating equal to 5 before repair and one deck had a lowest rating equal to 4 before repair. Among the element 23 decks, none are rehabilitated and the lowest deck condition rating is 6. Among the element 26 decks, none are rehabilitated and the lowest deck condition rating is 7.

Estimates of time to condition rating 5 are extrapolated from linear regression trend lines fitted to condition data histories. An example of the process is given here. Results for all decks are listed in Appendix 4.

EXAMPLE OF SERVICE LIFE ESTIMATE

The set of deck condition ratings for bridge G-04-AA is shown in Figure 1a. This is an element 14 deck built in 1980. The deck's set of condition ratings span the years 1982 to 2002. The lowest rating, a 6, occurred early in service, but may be aberrant. No rehabilitation project is reported for this deck up to 2004 and the most recent condition ratings are 7.

Trend lines for deck condition ratings are established and extended until condition rating 5 is reached. A first line is computed using no constraint on the initial (new construction) value of the condition rating. The result is plotted in Figure 1b. The trend line's equation is shown below.

$$\text{Rating} = 7.87 - 0.0497(\text{Year} - 1980) \qquad \text{Eq 1}$$

Where Rating is the NBI deck condition rating, and (Year-1980) is the number of years since initial construction. Using Eq 1, the deck will reach condition rating 5 after 58 years in service.

Notice in Figure 1b that the trend line yields a rating equal to 7.87 for the newly constructed deck. The rating for the new deck was reported as 9, the expected value. It may reasonably be required that the trend line include the correct rating value for the new deck. A second trend line is computed; this time constraining the line to include a rating equal to 9 at zero years of service. The result is plotted in Figure 1c and its equation is shown below.

$$\text{Rating} = 9 - 0.13(\text{Year} - 1980) \qquad \text{Eq 2}$$

Eq 2 yields an estimate of 31 years in service to reach condition rating 5. The deck condition data are scattered. Eq 2 offers a higher correlation coefficient than Eq 1 (0.74 versus 0.16).

Similar trend lines are formed for every deck. The results are listed in Appendix 4. All trend lines are constrained to pass through rating 9 or rating 8 at zero years of service. Rating 8 is used as the intercept for decks that have no rating 9 in their condition history.

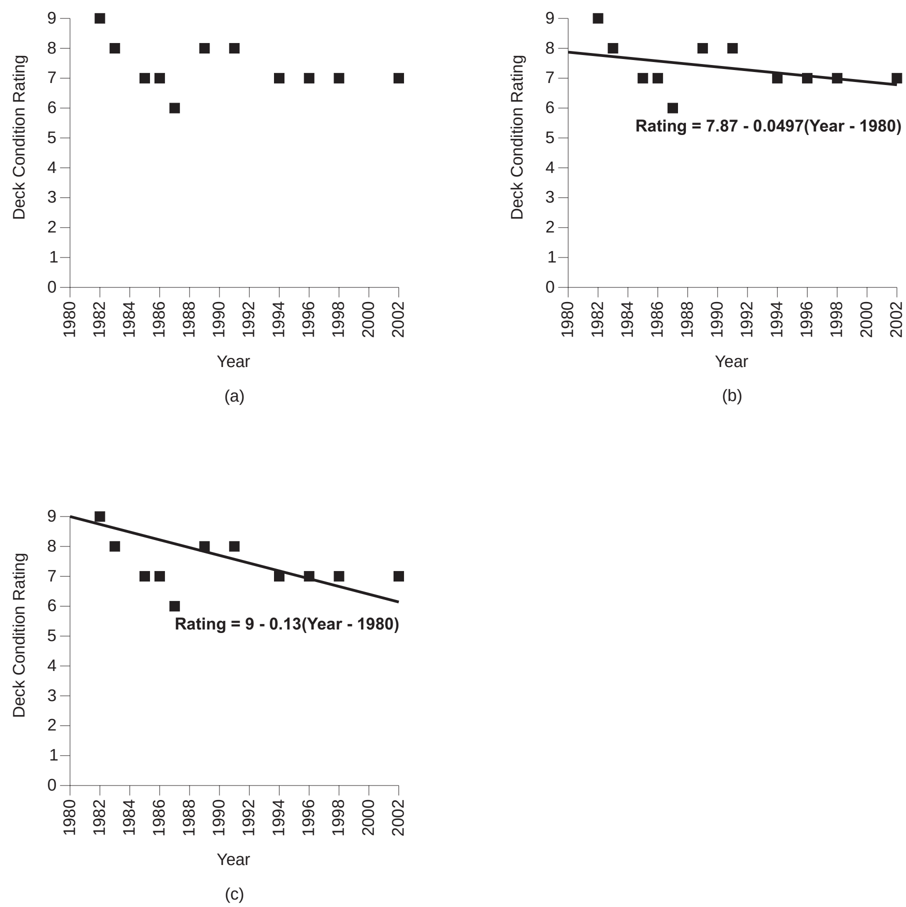


Figure 1 - Example of Trend Line for Deck Condition Ratings

Population Probability Distributions of Service Life of Decks

Estimates of service life for individual bridge decks are used to form models of service lives for populations of similar decks. These are called deck population models. Four probability distributions are considered for use. Selection of individual models is based on success in fitting available data. The four probability distributions are:

- → Rayleigh distribution
- → Rayleigh distribution using a time-shifted origin; called an xo-Rayleigh distribution
- → Exponential distribution
- → Exponential distribution using a time-shifted origin; called an xo-Exponential distribution

For all distributions, deck service life in years is the independent variable. Each distribution indicates the probability that decks reach condition state 5 as a function of years in service. All four distributions operate with positive values of service life only. The xo- distributions operate only with service life values greater than xo. The distributions are presented below.

RAYLEIGH DISTRIBUTION

The Rayleigh distribution has the probability density function $f(x)$ and the cumulative density function $F(x)$, as follows

$$f(x) = \frac{x}{s^2} e^{-\frac{x^2}{2s^2}}$$

$$F(x) = 1 - e^{-\frac{x^2}{2s^2}} \qquad \textbf{Eq 3}$$

'x' is deck service life in years. Only positive values of service life are admissible. The distribution parameter, s, is related to mean service life and median service life as

$$s = (\text{mean})\sqrt{\frac{2}{\pi}}$$

$$s = \sqrt{\frac{(\text{median})^2}{\ln(4)}} \qquad \textbf{Eq 4}$$

XO- RAYLEIGH DISTRIBUTION

A Rayleigh distribution is formed with a time-origin shifted to a shortest service life value, xo. This form of the Rayleigh distribution indicates zero probability for service life shorter than xo. Let

$$\xi = x - x_o \qquad \text{Eq 5}$$

And define the Rayleigh distribution as

$$f(x) = \frac{1}{s^2}\xi e^{-\frac{\xi^2}{2s^2}}$$
$$F(x) = 1 - e^{-\frac{\xi^2}{2s^2}} \quad \text{Eq 6}$$

The modeling parameter 's' is computed from the median service life as

$$s = \sqrt{\frac{(median - x_o)^2}{\ln(4)}} \quad \text{Eq 7}$$

Or from the mean service life as

$$s = (mean - x_o)\sqrt{\frac{2}{\pi}} \quad \text{Eq 8}$$

The model now has two parameters, s and x_o, allowing a fit to both mean and median service life values.

EXPONENTIAL DISTRIBUTION

The exponential distribution has a probability density function, $f(x)$ and a cumulative density function $F(x)$ as follows:

$$f(x) = \frac{1}{s} e^{-x/s}$$
$$F(x) = 1 - e^{-x/s} \quad \text{Eq 9}$$

The distribution is valid for positive values of x and s. Here too, x is deck service life in years.

The model parameter, s, is obtained from the mean (average) service life as

$$s = (mean) \quad \text{Eq 10}$$

The model parameter is obtained from the median service life as

$$s = \frac{(median)}{\ln(2)} \quad \text{Eq 11}$$

xo- EXPONENTIAL DISTRIBUTION

An exponential distribution is formed with a time-origin shifted to a shortest service life value, xo. This form of the exponential distribution indicates zero probability for service life shorter than xo. Let

$$\xi = x - x_o \qquad \text{Eq 12}$$

The distribution is

$$f(x) = \frac{1}{s} e^{-\xi/s}$$
$$F(x) = 1 - e^{-\xi/s} \qquad \text{Eq 13}$$

The model parameter s is obtained from the mean (average) service life as

$$s = (mean - x_o) \qquad \text{Eq 14}$$

The model parameter is obtained from the median service life as

$$s = \frac{(median - x_o)}{\ln(2)} \qquad \text{Eq 15}$$

Fitting Population Models to Estimates of Deck Service Life

Model parameters s and xo are selected to obtain the best agreement between population models and individual estimates of deck service life. The comparison is made in terms of cumulative probability of years to reach condition rating five.

Individual estimates of deck service life are used to compute discrete, cumulative probability of reaching condition rating five.

$$D(x_i) = \frac{n_i}{N} \qquad \textbf{Eq 16}$$

Where N is the total number of decks in a population, xi is a sorted list of service life values running from least time to greatest time, ni are index values ($1, 2, 3, \ldots, N$) corresponding to the service life values xi, and $D(xi)$ are discrete fractional values of probability. Discrete probabilities for deck service life are shown in Figure 2 for elements 14, 23 and 26, and in Figure 3 for element 22.

The error between discrete probability values and the population models is computed as

$$Err = \sum (D(x_i) - F(x_i))^2 \qquad \textbf{Eq 17}$$

Error is evaluated at every data point, and summed for overall error between discrete data and each population model.

Error is minimized by adjusting model parameters s and xo. To do this, partial derivatives of error with respect to the two parameters are evaluated. Values of s and xo are sought such that the partial derivatives are simultaneously equal to zero.

$$\begin{aligned} \frac{\partial Err}{\partial s} &= \sum -2(D(x_i) - F(x_i))\frac{\partial F(x_i)}{\partial s} \\ \frac{\partial Err}{\partial x_o} &= \sum -2(D(x_i) - F(x_i))\frac{\partial F(x_i)}{\partial x_o} \end{aligned} \qquad \textbf{Eq 18}$$

Particular forms of these partial derivatives are presented below.

MINIMIZE ERROR FOR RAYLEIGH DISTRIBUTION

The Rayleigh distribution has a single parameter, s. The distribution and its partial derivative of error with respect to s are

$$F(x) = 1 - e^{-\frac{x^2}{2s^2}}$$

$$\frac{\partial Err}{\partial s} = \sum -2(D(x) - F(x))\left(-\frac{x^2}{s^3}e^{-\frac{x^2}{2s^2}}\right) \qquad \textbf{Eq 19}$$

$$\frac{\partial Err}{\partial s} = \sum 2(D(x) - F(x))\left(\frac{x^2}{s^3}\right)(1 - F(x))$$

MINIMIZE ERROR FOR XO-RAYLEIGH DISTRIBUTION

The xo-Rayleigh distribution has two parameters, s and xo. The distribution is expanded as

$$F(x) = 1 - e^{-\frac{x^2}{2s^2}} e^{\frac{xx_o}{s^2}} e^{-\frac{x_o^2}{2s^2}} \qquad \textbf{Eq 20}$$

The partial derivative with respect to s is

$$\frac{\partial Err}{\partial s} = \sum -2(D(x) - F(x))\left(-\frac{x^2}{s^3}e^{-\frac{x^2}{2s^2}} e^{\frac{xx_o}{s^2}} e^{-\frac{x_o^2}{2s^2}} + \frac{2xx_o}{s^3}e^{-\frac{x^2}{2s^2}} e^{\frac{xx_o}{s^2}} e^{-\frac{x_o^2}{2s^2}} - \frac{x_o^2}{s^3}e^{-\frac{x^2}{2s^2}} e^{\frac{xx_o}{s^2}} e^{-\frac{x_o^2}{2s^2}}\right)$$

$$\frac{\partial Err}{\partial s} = \sum 2(D(x) - F(x))\left(\frac{x^2}{s^3} - \frac{2xx_o}{s^3} + \frac{x_o{}^2}{s^3}\right)(1 - F(x)) \qquad \textbf{Eq 21}$$

The partial derivative with respect to xo is

$$\frac{\partial Err}{\partial x_o} = \sum -2(D(x) - F(x))\left(-\frac{x}{s^2}e^{-\frac{x^2}{2s^2}}e^{\frac{xx_o}{s^2}}e^{-\frac{x_o{}^2}{2s^2}} + \frac{x_o}{s^2}e^{-\frac{x^2}{2s^2}}e^{\frac{xx_o}{s^2}}e^{-\frac{x_o{}^2}{2s^2}}\right)$$

$$\frac{\partial Err}{\partial x_o} = \sum 2(D(x) - F(x))\left(\frac{x}{s^2} - \frac{x_o}{s^2}\right)(1 - F(x)) \qquad \textbf{Eq 22}$$

MINIMIZE ERROR FOR EXPONENTIAL DISTRIBUTION

The exponential distribution has a single parameter, s. The distribution and its derivative with respect to s are

$$F(x) = 1 - e^{-\frac{x}{s}}$$

$$\frac{\partial Err}{\partial s} = \sum -2(D(x) - F(x))\left(-\frac{x}{s^2}e^{-\frac{x}{s}}\right) \qquad \textbf{Eq 23}$$

$$\frac{\partial Err}{\partial s} = \sum 2(DT(x) - F(x))\left(\frac{x}{s^2}\right)(1 - F(x))$$

MINIMIZE ERROR FOR XO-EXPONENTIAL DISTRIBUTION

The xo-exponential distribution has two parameters, s and xo. The distribution is expanded as

$$F(x) = 1 - e^{-\frac{x}{s}}e^{\frac{x_o}{s}} \qquad \textbf{Eq 24}$$

The partial derivative of error with respect to s is

$$\frac{\partial Err}{\partial s} = \sum -2\left(D(x)-F(x)\right)\left(-\frac{x}{s^2}e^{-\frac{x}{s}}e^{\frac{x_o}{s}}+\frac{x_0}{s^2}e^{-\frac{x}{s}}e^{\frac{x_o}{s}}\right)$$

$$\frac{\partial Err}{\partial s} = \sum 2\left(D(x)-F(x)\right)\left(\frac{x}{s^2}-\frac{x_o}{s^2}\right)\left(1-F(x)\right) \qquad \textbf{Eq 25}$$

The partial derivative of error with respect to x_o is

$$\frac{\partial Err}{\partial x_o} = \sum -2\left(D(x)-F(x)\right)\left(-\frac{1}{s}e^{-\frac{x}{s}}e^{\frac{x_o}{s}}\right)$$

$$\frac{\partial Err}{\partial x_o} = \sum 2\left(D(x)-F(x)\right)\left(\frac{1}{s}\right)\left(1-F(x)\right) \qquad \textbf{Eq 26}$$

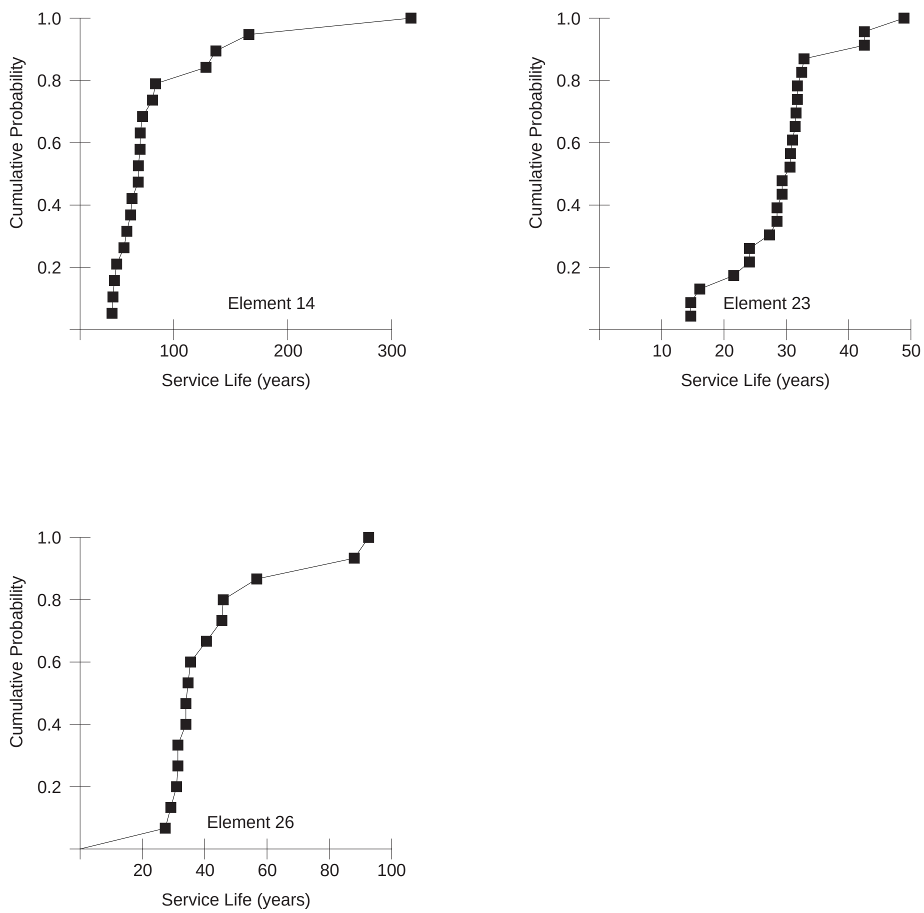


Figure 2 – Discrete Cumulative Probability of Deck Service Life – Elements 14, 23 and 26

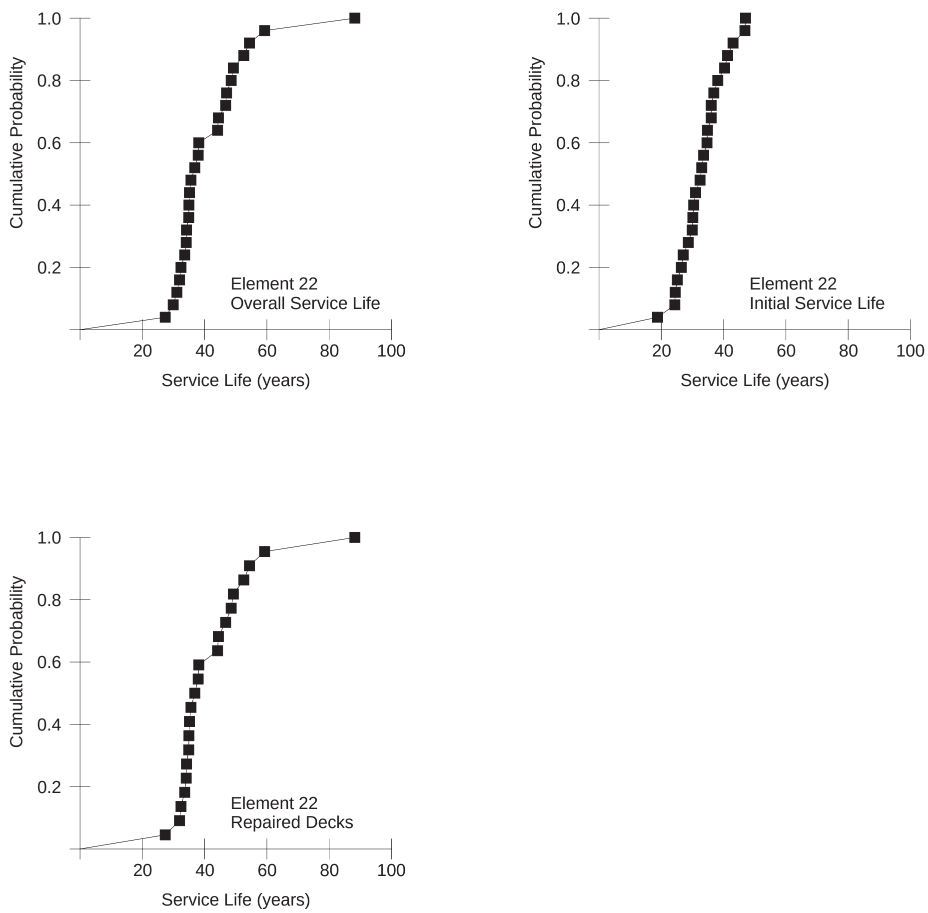


Figure 3 – Discrete Cumulative Probability of Deck Service Life – Element 22

Results: Service Life of CDOT Decks

ELEMENT 14 – DECKS WITH BARE STEEL, WATERPROOFING MEMBRANE AND ASPHALT WEARING SURFACE

A summary of discrete estimates of deck service life is shown in Table 16. Population model parameters are listed in Table 17. Values of mean and median service life computed from population models are listed in Table 18. Plots of discrete data and distributions are shown in Figure 4. Based on these, the xo-exponential distribution is selected as the model for deck service life for element 14 decks.

Table 16 - Discrete Estimates of Service Life - Element 14

Element 14	
Decks (N)	19
Mean Service Life (years)	78
Median Service Life (years)	56
Least Service Life (years)	31

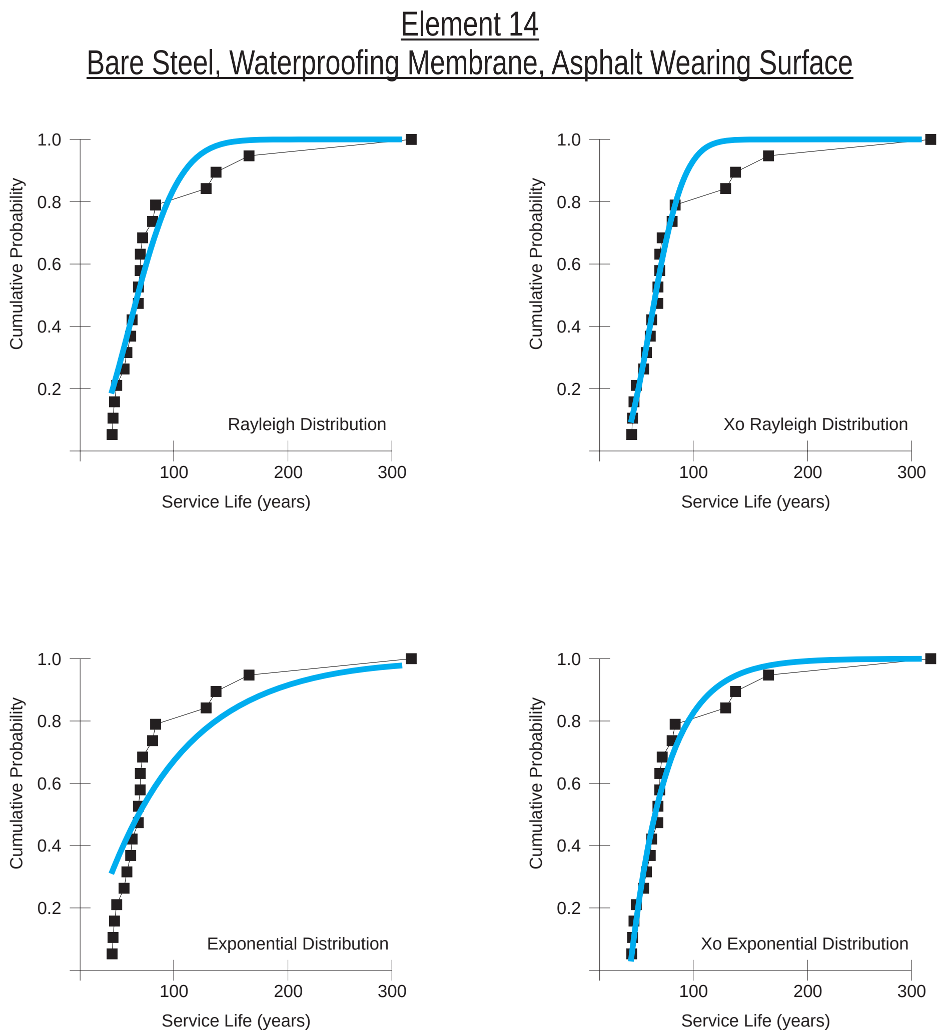
Table 17 – Parameters of Service Life Distributions - Element 14

Distribution	**s (years)**	**xo (years)**	**Err / N, %**
Rayleigh	47	-	0.58
xo-Rayleigh	32	16	0.31
Exponential	81	-	1.80
xo-Exponential	35	29	0.28

Table 18 – Mean and Median Service Life Using Population Models - Element 14

Distribution	**Mean**	**Median**
Rayleigh (years)	59	55
xo-Rayleigh (years)	56	54
Exponential (years)	81	56
xo-Exponential (years)	64	53

Figure 4 - Element 14 Service Life Distributions



ELEMENT 22 – DECKS WITH BARE STEEL. SOME REHABILITATED WITH RIGID OVERLAY

A summary of discrete estimates of mean service life and median service life is shown in Table 19. Population model parameters are listed in Table 20. Values of mean and median service life computed from population models are listed in Table 21. Plots of discrete data and distributions are shown in Figure 5 for all element 22 condition data, in Figure 6 for element 22 condition data with no rehabilitation, and in Figure 7 for element 22 condition data with rehabilitation. Based on these, the xo-Rayleigh distributions are selected as population models for initial service of element 22 decks, and for service life of rehabilitated element 22 decks.

Table 19 - Discrete Estimates of Service Life - Element 22

Element 22 – All Decks, Overall Service Life	
Decks (N)	25
Mean Service Life (years)	42
Median Service Life (years)	37
Least Service Life (years)	27
Element 22 – All Decks, Initial Service Life (up to Rehab)	
Decks (N)	25
Mean Service Life (years)	34
Median Service Life (years)	31
Least Service Life (years)	19
Element 22 – Rehab Decks, Overall Service Life	
Decks (N)	22
Mean Service Life (years)	39
Median Service Life (years)	35
Least Service Life (years)	27

Table 20 – Parameters of Service Life Distributions - Element 22

Distribution	**s (years)**	**xo (years)**	**Err / N, %**
All Decks, Overall Service			
Rayleigh	33	-	2.0
xo-Rayleigh	14	22	0.34
Exponential	54	-	4.3
xo-Exponential	15	27	0.46
All Decks, Initial Service			
Rayleigh	27	-	2.3
xo-Rayleigh	10	20	0.11
Exponential	43	-	4.7
xo-Exponential	15	21	1.1
Rehab Decks, Overall Service			
Rayleigh	34	-	1.8
xo-Rayleigh	14	22	0.45

Distribution	s (years)	xo (years)	Err / N, %
Exponential	55	-	4.3
xo-Exponential	17	27	0.60

Table 21 – Mean and Median Service Life Using Distributions - Element 22

Distribution	Mean	Median
All Decks, Overall Service		
Rayleigh (years)	41	39
xo-Rayleigh (years)	40	38
Exponential (years)	54	37
xo-Exponential (years)	42	37
All Decks, Initial Service		
Rayleigh (years)	34	32
xo-Rayleigh (years)	33	32
Exponential (years)	43	30
xo-Exponential (years)	36	31
Rehab Decks, Overall Service		
Rayleigh (years)	43	40
xo-Rayleigh (years)	40	38
Exponential (years)	55	38
xo-Exponential (years)	44	39

Figure 5 - Element 22 – All Decks, Overall Service Life

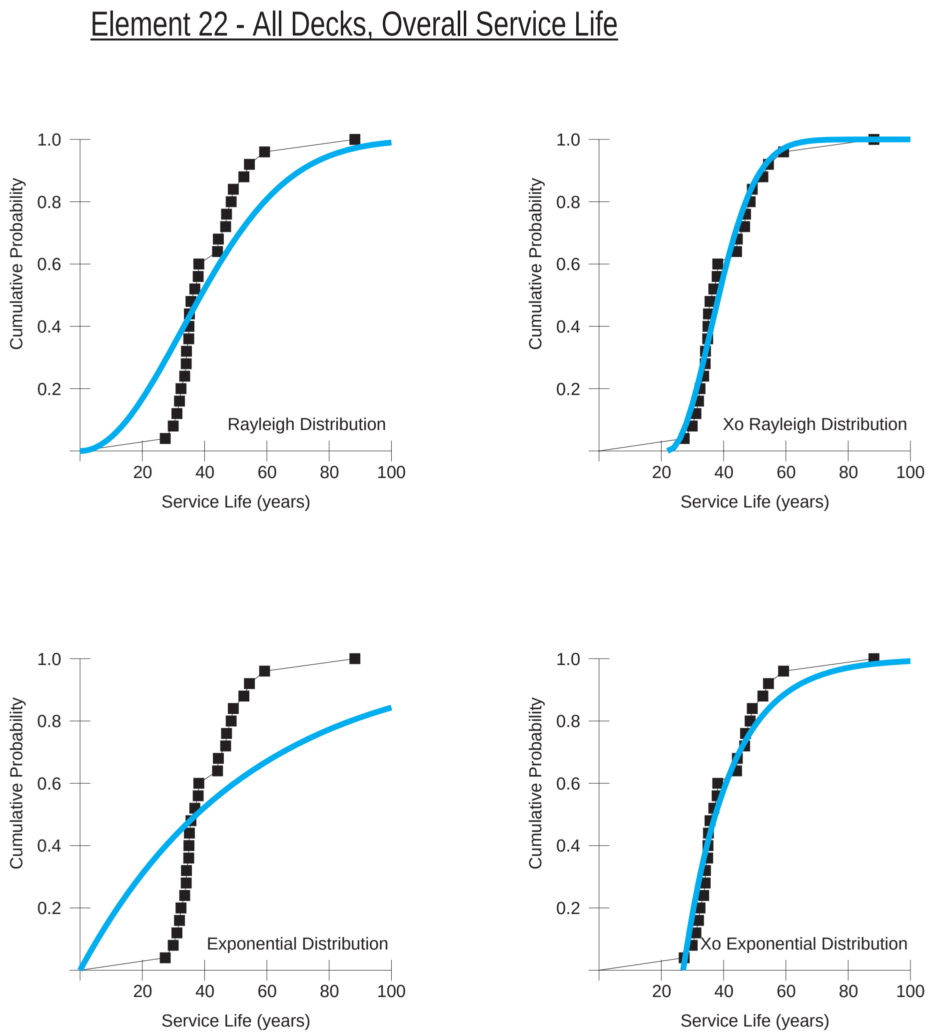


Figure 6 - Element 22 – All Decks, Initial Service Life

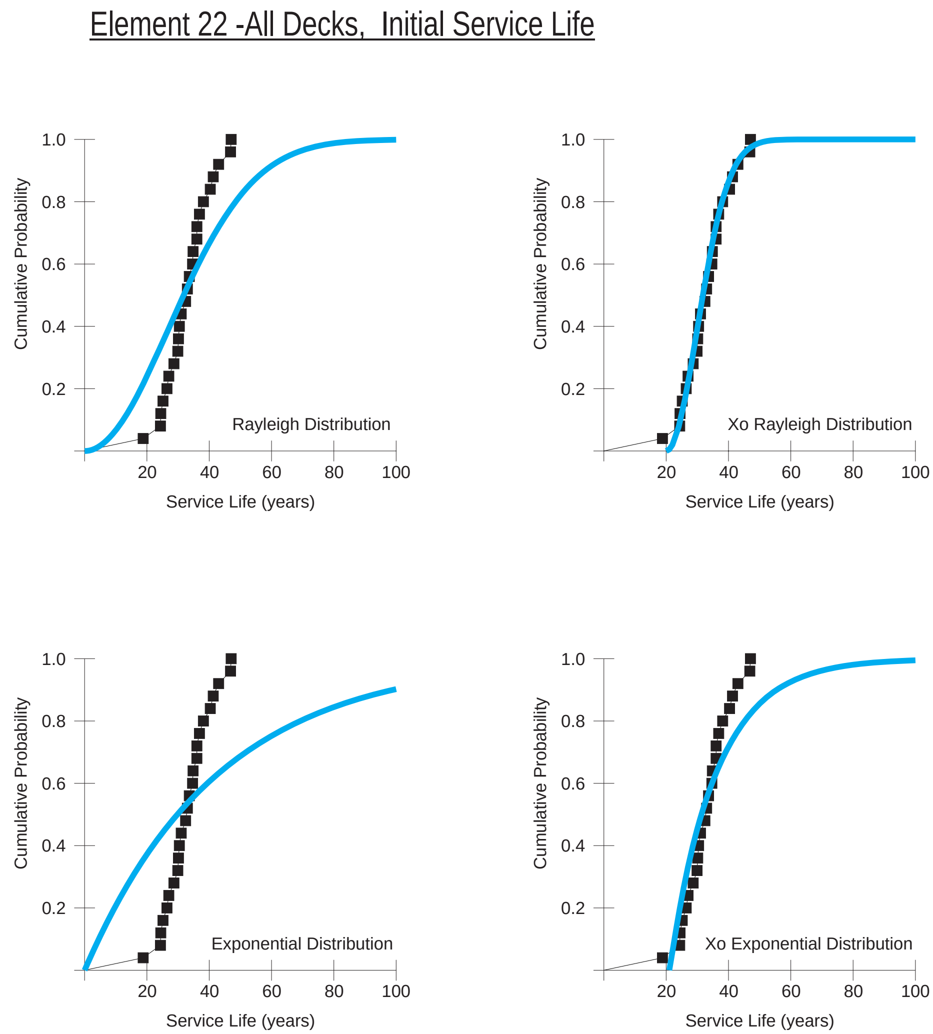
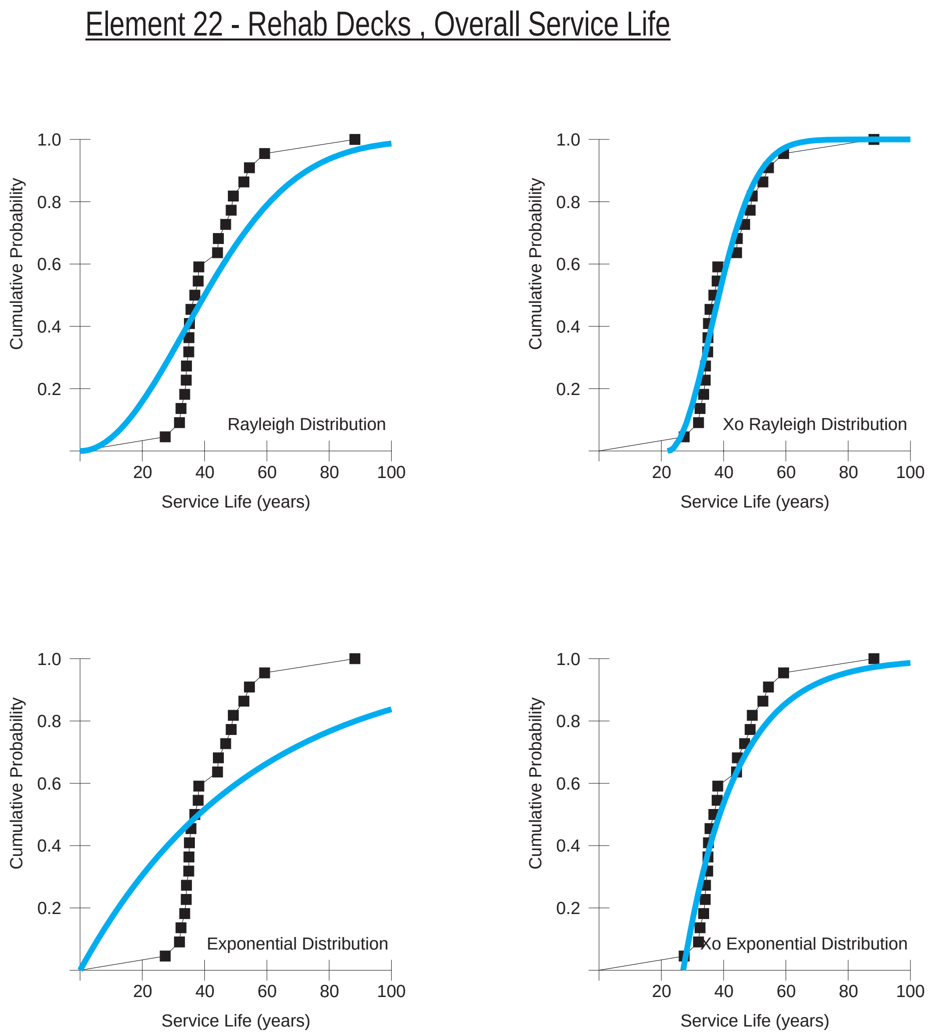


Figure 7 - Element 22 – Rehab Decks, Overall Service Life



ELEMENT 23 – DECKS WITH EPOXY-COATED STEEL AND PENETRATING SEALERS

A summary of discrete estimates of mean service life and median service life are shown in Table 22. Population model parameters are listed in Table 23. Values of mean and median service life computed from population models are listed in Table 24. Plots of discrete data and distributions are shown in Figure 8. Based on these, the xo-Rayleigh distribution is selected as the model for deck service life for element 23 decks.

Table 22 - Discrete Estimates of Service Life - Element 23

Element 23	
Decks (N)	23
Mean Service Life (years)	29
Median Service Life (years)	31
Least Service Life (years)	15

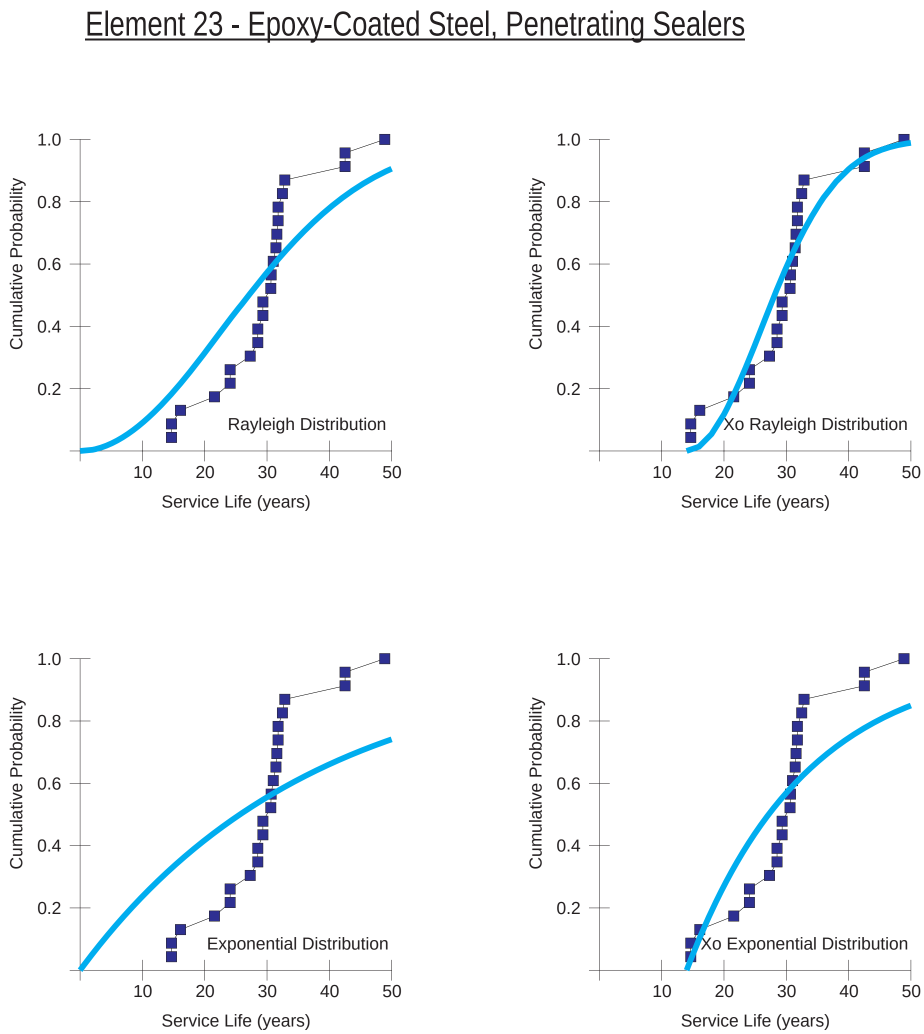
Table 23 – Parameters of Service Life Distributions - Element 23

Distribution	**s (years)**	**xo (years)**	**Err / N, %**
Rayleigh	23	-	1.9
xo-Rayleigh	12	14	0.86
Exponential	37	-	4.0
xo-Exponential	19	14	1.9

Table 24 – Mean and Median Service Life Using Distributions - Element 23

Distribution	**Mean**	**Median**
Rayleigh (years)	29	27
xo-Rayleigh (years)	29	28
Exponential (years)	37	26
xo-Exponential (years)	33	27

Figure 8 - Element 23 Service Life Distributions



ELEMENT 26 – DECKS WITH EPOXY-COATED STEEL, WATERPROOFING MEMBRANE AND ASPHALT WEARING SURFACE

A summary of discrete estimates of mean service life and median service life are shown in Table 25. Population model parameters are listed in Table 26. Values of mean and median service life computed from population models are listed in Table 27. Plots of discrete data and distributions are shown in Figure 9. Based on these, the xo-Exponential distribution is selected as the model for deck service life for element 26 decks.

Table 25 - Discrete Estimates of Service Life - Element 26

Element 26	
Decks (N)	15
Mean Service Life (years)	44
Median Service Life (years)	35
Least Service Life (years)	27

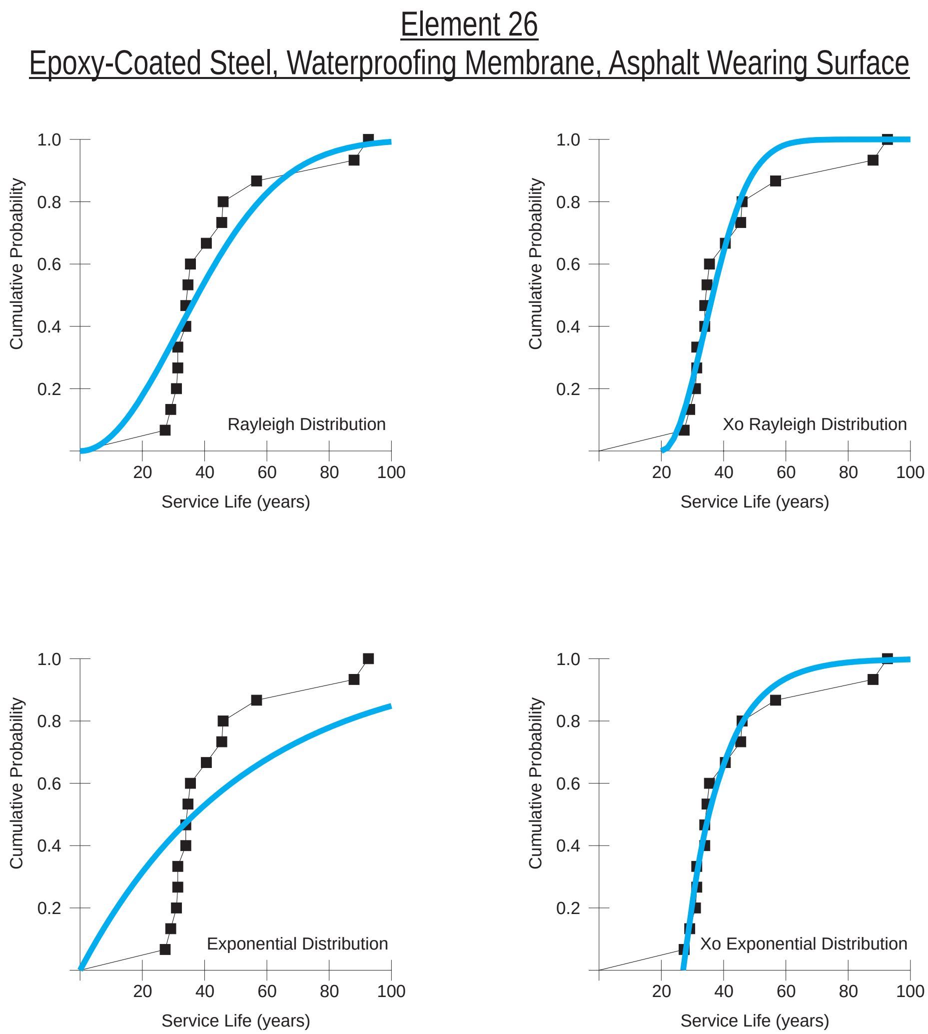
Table 26 – Parameters of Service Life Distributions - Element 26

Distribution	s (years)	xo (years)	Err / N, %
Rayleigh	32	-	1.6
xo-Rayleigh	14	20	0.53
Exponential	53	-	3.6
xo-Exponential	12	27	0.25

Table 27 – Mean and Median Service Life Using Distributions - Element 26

Distribution	Mean	Median
Rayleigh (years)	40	38
xo-Rayleigh (years)	38	36
Exponential (years)	53	37
xo-Exponential (years)	39	35

Figure 9 - Element 26 Service Life Distributions



Sensitivity of Estimates to Extent of Condition History

Estimates of service life of bridge decks are sensitive to the extent of histories of condition data. There are two causes: the initial rate of decrease of condition ratings can be greater than the long term rate, and the (usually) long duration of decks in fair condition at ratings 7 or 6 is absent from condition histories of relatively young decks.

Bridge G-04-AA is used as an example. Trend lines for deck condition ratings are computed for condition histories that are truncated variously to the first 5 years of service, the first 10 years of service, and the first 15 years of service. Trend lines for truncated condition histories indicate the estimates of service life that would have been obtained if the computations were executed for this bridge in 1985, in 1990 and in 1995 using only the condition data available up to each of those years. These trend lines are compared to each other and to the trend line for the full 22 years of service of G-04-AA. All trend lines are constrained to pass through condition rating 9 at zero years of service. Results are listed in Table 28 and plotted in Figure 10.

Table 28 - Trend Lines for Truncated Condition History

Extent of Condition History	Rating Trend (/year)	Regression Coefficient	Years to Condition Rating 5
5 years	-0.342	0.89	12
10 years	-0.270	0.78	15
15 years	-0.180	0.71	22
22 years	-0.130	0.74	31

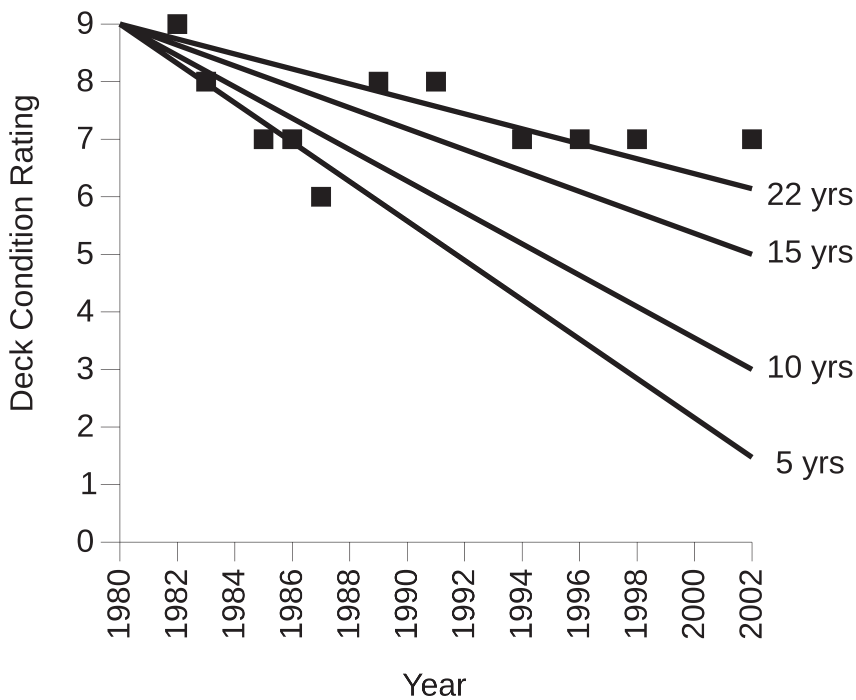


Figure 10 - Trend Lines and Extent of Condition History

Extrapolations for service life range from twelve years to thirty-one years, with an increase in estimated service life for each increase in extent of condition history. For the present study, there is a concern that service life may be underestimated for the younger decks in the study. These include all decks having epoxy-coated reinforcing steel.

Service Life Estimates Using ACI *Life-365*

Service life estimates are also obtained from *Life-365*, a Windows-based software application prepared by ACI committee 365 that estimates time to initial corrosion, time to first repair and life-cycle costs for reinforced concrete structures [**21**]. A copy of the software was provided to the study team by Mr. Gregg Lowery of Colorado DOT.

Life-365 accepts input data on concrete properties, reinforcement type, protection system, geographic location and exposure. For this study, *Life-365* was executed with default values for concrete properties. Geographic location was set to Denver, Colorado and exposure was urban highway. The reinforcement type (uncoated or epoxy-coated), concrete protection (bare, membrane, or sealer), deck thickness and clear concrete cover were input for each deck type. Outputs from *Life-365* are shown in Table 29.

Table 29 - Service Life Estimates Using Life-365

	Reinforcing Steel	Concrete Protection	Corrosion Initiation (years)	Time to Repair (years)
Element 14	uncoated	membrane	17.9	23.9
Element 22	uncoated	bare	16.0	22.0
Element 23	epoxy-coated	sealer	19.1	39.1
Element 26	epoxy-coated	membrane	17.9	37.9

Life-365 indicates that the time to repair, which is similar to the measure of service life used in this study, is about 15 years longer for epoxy-coated reinforcing steel compared to bare reinforcing steel. *Life-365* also indicates that membranes extend service life by 2 years for deck with bare reinforcing steel, and shorten service life by 1 year for decks with epoxy-coated reinforcing steel.

Results from *Life-365* depend on concrete cover and on deck thickness. The software is used again with a single value of cover (3") and a single deck thickness (8.25"). The outcomes are shown in Table 31.

Table 30 – Comparison of Life-365 Results for Identical Cover and Thickness

	Reinforcing Steel	Concrete Protection	Corrosion Initiation (years)	Time to Repair (years)
Element 14	bare	membrane	25.0	31.0
Element 22	bare	bare	16.0	22.0
Element 23	epoxy-coated	sealer	19.1	39.1
Element 26	epoxy-coated	membrane	25.0	45.0

These results indicate that service life for decks with epoxy-coated reinforcement is longer by 15 years or more compared to decks with bare reinforcing steel. Waterproofing membranes increase service life by 6 or more years.

SUMMARY FOR SERVICE LIFE OF DECKS

Values of median service life of bridge decks obtained from discrete data are shown in Table 31. The longest service life values occur for decks having waterproofing membrane. Epoxy-coated reinforcing steel does not offer longer service life than uncoated reinforcing steel.

Table 31 – Bridge Deck Median Service Life

	Waterproofing Membrane	Bare Deck
Uncoated Reinforcing Steel	56 years	35 years
Epoxy-Coated Reinforcing Steel	35 years	31 years

Service life estimates are sensitive to the extent of condition histories. For decks with uncoated reinforcing steel, histories are 21 years (membrane) and 27 years (bare deck). For decks with epoxy-coated reinforcing steel, condition histories are shorter; 12 years for decks with membranes and 9 years for bare decks. For decks with epoxy-coated steel, values in Table 31 may be underestimates of service life. However, two findings can be put forward:

→ For decks with uncoated reinforcing steel, waterproofing membranes provide much longer service life.

→ For decks with epoxy-coated reinforcing steel, waterproofing membranes provide somewhat longer service life.

Comparisons of performance of bare reinforcing steel to epoxy-coated reinforcing steel might not be valid due to the limited extent of condition histories for decks with epoxy-coated reinforcing steel.

CHAPTER 4 COSTS AND COST COMPARISONS FOR CDOT DECKS

Costs for Bridge Decks

Costs for decks are computed as costs of materials and as costs of construction projects. Unit costs of materials for decks are collected from CDOT published unit cost data for construction projects [**2**] and for maintenance projects [**3**]. Cost data are from 2003. Quantities of materials are based on deck designs that conform to the CDOT Bridge Design Manual [1]. Exhibit 1 through Exhibit 5 show quantities and costs for decks. Element 22 decks are shown separately for decks with and without rehabilitation.

Project data are shown, where available, and are listed as unit cost per deck area. All project costs are adjusted to 2003 using the tables of the US Army Corps Civil Works Construction Cost Index system [**19**]. Yearly cost indices for Feature 08 – Roads, Railroads and Bridges are listed in Table 79. Deck unit costs are summarized in Table 32. Unit costs for deck construction projects average 6 times the costs of deck materials.

Exhibit 1 - Quantities and Costs for Element 14 Decks

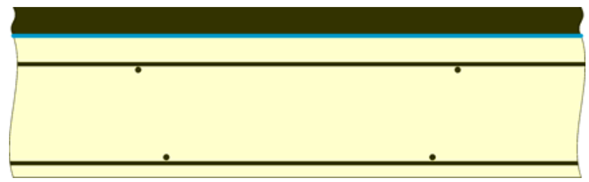
Bare (uncoated) steel reinforcement with waterproofing membrane and asphalt overlay. Constructed in 1980. No rehabilitation projects.

<u>Reinforcing Steel</u>

- ■ Bare
- ☐ Epoxy-Coated Top Mat
- ☐ Epoxy-Coated Both Mats

<u>Deck Surface</u>

- ☐ Bare
- ■ Membrane + Asphalt
- ☐ Concrete Sealer
- ☐ Rigid Overlay



DESIGN VARIABLES

	min	max	median
Deck thickness	6.25"	8.5	7.5"
Deck transverse span	7'-2.5"	13'-8"	7'-8"

CDOT BRIDGE DESIGN MANUAL – WORKING STRESS DESIGN:

Deck transverse span	7'-8"		Concrete	0.025 CY / SF
Deck thickness	8"		Rebars	6.25 LF / SF
Transverse Top Steel	#5 @ 5"		Rebars	6.52 lbs / SF
Transverse Bottom Steel	#5 @ 5"			
Top Longitudinal	#5 @ 18"		Concrete	0.222 CY / SY
'D' longitudinal bars	6 - #5		Rebars	56.2 LF / SY
			Rebars	58.7 lbs / SY

CDOT COST DATA

Membrane	2003 CDOT Construction Cost data	$ 9 / SY
HBP – 3" Overlay	2003 CDOT Construction Cost data ($ 48 / ton)	$ 7.83 / SY
8" Thick Concrete for Deck	2003 CDOT Construction Cost data ($ 312.90 / CY)	$ 69.53 / SY
Rebar	2003 CDOT Construction Cost data ($ 0.55 / lb)	$ 32.29 / SY
Total cost	2003	$ 119 / SY

PROJECT DATA – CONSTRUCTION COST

	Actual	2003 Equivalent
Min Cost	$222 / SY	$429 / SY
Max Cost	$1,342 / SY	$2,375 / SY
Median Cost	$410 / SY	$746 / SY

Exhibit 2 - Quantities and Costs for Element 22 Decks, No Rehabilitation

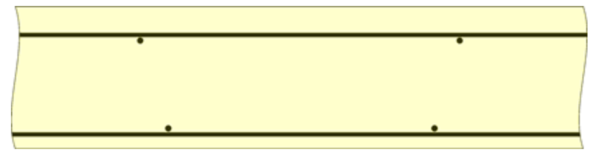
Bare (uncoated steel & (rehab) rigid overlay). Not rehabilitated. Constructed between 1969 and 1975.

Reinforcing Steel

- ■ Bare
- □ Epoxy-Coated Top Mat
- □ Epoxy-Coated Both Mats

Deck Surface

- ■ Bare
- □ Membrane + Asphalt
- □ Concrete Sealer
- □ Rigid Overlay



DESIGN VARIABLES

	min	max	median
Deck thickness	7.0"	7.5"	7.5"
Deck transverse span	6'-6"	9'-3"	8'-6"

CDOT BRIDGE DESIGN MANUAL – WORKING STRESS DESIGN:

Deck transverse span	8'-6"		Concrete	0.026 CY / SF
Deck thickness	8.25"		Rebars	6.29 LF / SF
Transverse Top Steel	#5 @ 5"		Rebars	6.56 lbs / SF
Transverse Bottom Steel	#5 @ 5"			
Top Longitudinal	#5 @ 18"		Concrete	0.229 CY / SY
'D' longitudinal bars	7 - #5		Rebars	56.6 LF / SY
			Rebars	59.05 lbs / SY

CDOT COST DATA

8.25" Thick Concrete for Deck	2003 CDOT Construction Cost data ($ 312.90 / CY)	$ 71.71 / SY
Rebar	2003 CDOT Construction Cost data ($ 0.55 / lb)	$ 32.47 / SY
Total cost		$ 104 / SY

PROJECT DATA – CONSTRUCTION COST

	Actual	2003 Equivalent
Min Cost	$85.91 / SY	$346 / SY
Max Cost	$279 / SY	$784 / SY
Median Cost	$131 / SY	$535 / SY

Exhibit 3 - Quantities and Costs for Element 22 Decks, Rehabilitated Decks

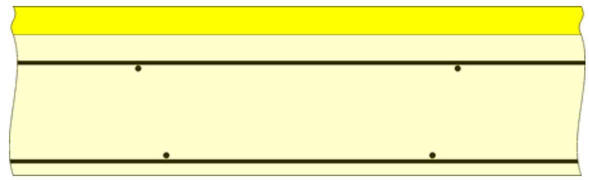
Rehabilitated decks. Bare (uncoated steel & (rehab) rigid overlay). Rehabilitation projects between 1989 and 1999.

Reinforcing Steel

- ■ Bare
- ☐ Epoxy-Coated Top Mat
- ☐ Epoxy-Coated Both Mats

Deck Surface

- ☐ Bare
- ☐ Membrane + Asphalt
- ☐ Concrete Sealer
- ■ Rigid Overlay



DESIGN VARIABLES

	min	max	median
Deck thickness	7.0"	7.5"	7.5"
Deck transverse span	6'-6"	9'-3"	8'-6"

CDOT BRIDGE DESIGN MANUAL – WORKING STRESS DESIGN:

Deck transverse span	8'-6"		Concrete	0.026 CY / SF
Deck thickness	8.25"		Rebars	6.29 LF / SF
Transverse Top Steel	#5 @ 5"		Rebars	6.56 lbs / SF
Transverse Bottom Steel	#5 @ 5"			
Top Longitudinal	#5 @ 18"		Concrete	0.229 CY / SY
'D' longitudinal bars	7 - #5		Rebars	56.6 LF / SY
			Rebars	59.05 lbs / SY

CDOT COST DATA

8.25" Thick Concrete for Deck	2003 CDOT Construction Cost data ($ 312.90 / CY)	$ 71.71 / SY
Rebar	2003 CDOT Construction Cost data ($ 0.55 / lb)	$ 32.47 / SY
Rehabilitation	Element 22 Project Data	$ 34.41 / SY
Total cost		$ 139 / SY

PROJECT DATA – CONSTRUCTION

	Actual	2003
Min Cost	$85.91 / SY	$346 / SY
Max Cost	$279 / SY	$784 / SY
Median Cost	$131 / SY	$535 / SY

REHABILITATION

	Actual	2003
Min Cost	$130.36 / SY	$ 140.92 / SY
Max Cost	$375 / SY	$ 405 / SY
Median Cost	$149 / SY	$ 177 / SY

Exhibit 4 - Quantities and Costs for Element 23 Decks

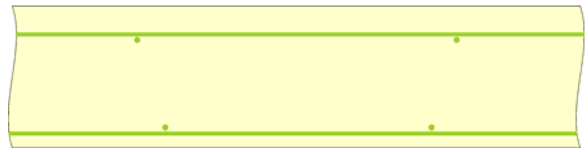
Decks having penetrating sealers & epoxy-coated reinforcing steel. Constructed in 1993.

Reinforcing Steel

- ☐ Bare
- ☐ Epoxy-Coated Top Mat
- ■ Epoxy-Coated Both Mats

Deck Surface

- ☐ Bare
- ☐ Membrane + Asphalt
- ■ Concrete Sealer
- ☐ Rigid Overlay



DESIGN VARIABLES

	min	max	median
Deck thickness	7.5"	9.5"	8.25"
Deck transverse span	6'-11"	12'-1"	8'-6"

CDOT BRIDGE DESIGN MANUAL – WORKING STRESS DESIGN:

Deck transverse span	8'-6"		Concrete	0.026 CY / SF	
Deck thickness	8.25"		Rebars	6.29 LF / SF	
Transverse Top Steel	#5 @ 5"		Rebars	6.56 lbs / SF	
Transverse Bottom Steel	#5 @ 5"				
Top Longitudinal	#5 @ 18"		Concrete	0.229 CY / SY	
'D' longitudinal bars	7 - #5		Rebars	56.6 LF / SY	
			Rebars	59.05 lbs / SY	

CDOT COST DATA

Penetrating Sealer	2003 CDOT Construction cost data ($ 4.70 / SY)	$ 4.70 / SY
8.25" Thick Concrete for Deck	2003 CDOT Construction cost data ($ 312.90 / CY)	$ 71.71 / SY
Epoxy Coated Rebar	2003 CDOT Construction cost data ($ 0.66 / lb)	$ 38.97 / SY
Total cost		$ 115 / SY

PROJECT DATA – CONSTRUCTION COST

	Actual	2003 Equivalent
Min Cost	$ 283/ SY	$ 349/ SY
Max Cost	$ 2383/ SY	$ 2842 / SY
Median Cost	$ 575/ SY	$ 690/ SY

Exhibit 5 - Quantities and Costs for Element 26 Decks

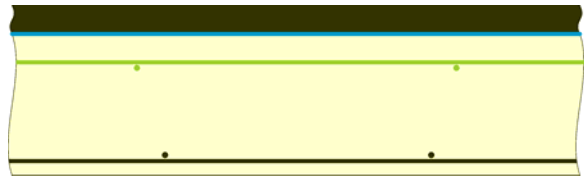
Decks having epoxy-coated reinforcing steel and waterproofing membrane with asphalt wearing surface. Constructed in 1991.

Reinforcing Steel

- ☐ Bare
- ■ Epoxy-Coated Top Mat
- ☐ Epoxy-Coated Both Mats

Deck Surface

- ☐ Bare
- ■ Membrane + Asphalt
- ☐ Concrete Sealer
- ☐ Rigid Overlay



DESIGN VARIABLES

	min	max	median
Deck thickness	7.0"	8.5"	7.79"
Deck transverse span	5'-3"	11'-11"	8'-0"

CDOT BRIDGE DESIGN MANUAL – WORKING STRESS DESIGN:

Deck transverse span	8'-0"		Concrete	0.025 CY / SF	
Deck thickness	8.0"		Epoxy Rebars	3.28 LF / SF	
Transverse Top Steel	#5 @ 5"		Bare Rebars	2.4 LF / SF	
Transverse Bottom Steel	#5 @ 5"		Epoxy Rebars	3.42 lbs / SF	
Top Longi	#5 @ 18"		Bare Rebars	2.5 lbs / SF	
D longi bars	7 - #5				
			Concrete	0.222 CY / SY	
			Epoxy Rebars	27.6 LF / SY	
			Bare Rebars	29.48 LF / SY	
			Epoxy Rebars	28.79 lbs / SY	
			Bare Rebars	30.74 lbs / SY	

CDOT COST DATA

Membrane	2003 CDOT Construction Cost data ($9 / SY)	$ 9 / SY
HBP – 3" Overlay	2003 CDOT Construction Cost data ($ 48 / ton)	$ 7.83 / SY
8.0" Thick Concrete for Deck	2003 CDOT Construction cost data ($ 312.90 / CY)	$ 69.53 / SY
Epoxy Coated Rebar	2003 CDOT Construction cost data ($ 0.66 / lb)	$ 19.00 / SY
Rebar	2003 CDOT Construction Cost data ($ 0.55 / lb)	$ 15.83 / SY
Total cost		$ 121 / SY

PROJECT DATA – CONSTRUCTION COST

	Actual	2003 Equivalent
Min Cost	$ 199.22 / SY	$ 255.52 / SY
Max Cost	$ 1,684.80 / SY	$ 2,160.91 / SY
Median Cost	$ 643.25 / SY	$ 816.36 / SY

Cost Comparisons Based on Deck Materials

In this section, costs of types of bridge decks are compared as unit costs for materials and maintenance over the service life of decks. Five sets of costs are compared. These include the four types of deck plus the set of rehabilitated decks in the group of element 22 decks.

To paraphrase the OMB Circular 94 [**5**], a type of bridge deck is cost-effective if it has the lowest cost among alternative types of deck. The cost must be considered for the service life of the bridge deck. The cost of the deck is expressed both as an annualized cost and as present value of replacement cost.

Deck costs are compared with and without use of a discount factor. Both approaches have presence in US federal guidelines for analysis of public agency capital programs. The government accounting standards board in their GASB 34 Primer [**4**] defines a basis for accounting and reporting maintenance programs for highway networks. GASB's Alternative method directs DOTs to report actual expenditures on highway and structures. For bridges, expenditures will include both maintenance projects and replacement projects. Along with expenditures, DOTs establish public goals for conditions of structures, and examine actual conditions to determine whether goals are being met and, by inference, whether expenditures are adequate. No discount rate is used. Viewed from the network perspective, a bridge deck replacement is a maintenance project. Deck replacements allow continued service of an existing route.

Comparisons using discount rates conform to Circular A-94 [**5**] of the US government Office of Management and Budget.

Initial Costs for Deck Materials

Initial material costs of bridge decks are listed in Table 32.

Table 32 – Initial Unit Material Costs (IC) for Bridge Decks

Element 14	Element 22 No Rehab	Element 22 Rehab	Element 23	Element 26
Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
$ 119 / SY	$ 104 / SY	$ 139 / SY	$ 115 / SY	$ 121 / SY

Maintenance Costs

Periodic maintenance costs are incurred for decks with waterproofing membrane and decks with surface-applied sealers. Based on information from CDOT[1], HMA overlays for deck elements 14 and 26 are re-applied every 7 years. Sealers for deck element 23 are re-applied every 3 years.

Maintenance unit costs are shown in Table 33. Total maintenance costs are accumulated as unit costs times the number of applications of maintenance during service life.

Table 33 – Maintenance Unit Costs (MC) for Bridge Decks

Element 14	Element 22 No Rehab	Element 22 Rehab	Element 23	Element 26
Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
$ 7.83 / SY	$ 0 / SY	$ 0 / SY	$ 4.70 / SY	$ 7.83 / SY

For application interval, A, the number of applications of maintenance within service life, L is

[1] Email communication from Aziz Khan, Feb. 15, 2007

$$\sum_{j=1}^{\infty}\left\{1 \quad : (jA) < L\right\} \qquad \textbf{Eq 27}$$

Total unit cost for a deck is the sum of initial cost and accumulated maintenance costs.

PRESENT VALUE OF MATERIALS REPLACEMENT COST (PV1)

The cost of future replacement of each deck type is computed as unit cost in 2003 dollars occurring at x years in the future, where x is the service life. The present value is the discounted value of the cost to construct the same type of deck at x years into the future. The OMB circular specifies a discount rate equal to 3.2% for the 2003 base year and for analysis of projects extending 30 or more years into the future.

For initial costs, x is the service life, L. Present value of initial cost is

$$PV_{IC} = \frac{IC}{(1+i)^{L}} \qquad \textbf{Eq 28}$$

For maintenance costs, each in the series of applications of maintenance is discounted individually from its time of future application to the present day. Present value of maintenance costs is the sum of the individual discounted maintenance applications.

$$PV_{MC} = \sum_{j=1}^{\infty}\left\{\frac{MC}{(1+i)^{(jA)}} \quad : (jA) < L\right\} \qquad \textbf{Eq 29}$$

Present value of a bridge deck is the sum of present value of initial cost and present value of maintenance cost. Present value is first computed using median service life.

$$PV1 = PV_{IC} + PV_{MC} \qquad \textbf{Eq 30}$$

The results for CDOT decks are listed in Table 34.

Table 34 – PV1: Present Value of Deck Material Replacement Using Median Service Life

	Element 14	Element 22 No Rehab	Element 22 Rehab	Element 23	Element 26
	Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
IC	\$ 258 \$ 119 / SY	\$ 248 \$ 104 / SY	\$ 336 \$ 139 / SY	\$ 259 \$ 115 / SY	\$ 260 \$ 121 / SY
L	56 years	31 years	35 years	31 years	35 years
MC	\$ 7.83 / SY	\$ 0 / SY	\$ 0 / SY	\$ 4.70 / SY	\$ 7.83 / SY
A	7 years	-	-	3 years	7 years
PV_{IC}	\$ 20.39 / SY	\$ 39.17 / SY	\$ 46.16 / SY	\$ 43.31 / SY	\$ 40.18 / SY
PV_{MC}	\$ 24.96 / SY	0	0	\$ 28.99 / SY	\$ 24.96 / SY
PV1	\$ 45.35 / SY	\$ 39.17 / SY	\$ 46.16 / SY	\$ 72.30 / SY	\$ 65.14 / SY

A second computation of present value recognizes variability in deck service life. The population models of deck service life are used here. Initial costs are discounted continuously over probable service life (Eq 31). Maintenance costs are discounted for discrete applications for probable surviving populations of decks (Eq 32).

$$PV_{IC} = \int_{xo}^{\infty} f(x) \frac{IC}{(1+i)^{x}} dx \qquad \textbf{Eq 31}$$

Where

PV_{IC} = Present value of initial cost computed with population model of deck service life

$f(x)$ = Probability density function for deck service life

$$PV_{MC} = \sum_{j=1}^{\infty} \left\{ \frac{MC}{(1+i)^{(jA)}} (1 - F(jA)) \right\} \qquad \textbf{Eq 32}$$

Where

PV_{MC} = Present value of probable maintenance costs

$F(x)$ = Cumulative probability function for deck service life

Table 35 – PV2: Present Value of Deck Material Replacement Using Service Life Probability

	Element 14	**Element 22 No Rehab**	**Element 22 Rehab**	**Element 23**	**Element 26**
	Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
Model	xo-Exponential	xo-Rayleigh	xo-Rayleigh	xo-Rayleigh	xo-Exponential
s	35 years	10 years	14 years	12 years	12 years
xo	29 years	20 years	22 years	14 years	27 years
PV_{IC}	$ 24.57 / SY	$ 37.46 / SY	$ 40.45 / SY	$ 47.42 / SY	$ 38.10 / SY
PV_{MC}	$ 27.14 / SY	0.00	0.00	$ 26.78 / SY	$ 23.53 / SY
PV2	$ 51.71 / SY	$ 37.46 / SY	$ 40.45 / SY	$ 74.20 / SY	$ 61.63 / SY

Annualized Cost

AC1: Annualized Material Costs at Median Service Life

Simple annualized cost is deck unit cost divided by service life in years. The first result does not use a discount factor, consistent with GASB 34. Initial costs are annualized at median service life (Eq 33). Maintenance costs are annualized at the application interval (Eq 34).

$$AC_{IC} = \frac{IC}{x} \quad \textbf{Eq 33}$$

Where

$$AC_{MC} = \frac{MC}{A} \quad \textbf{Eq 34}$$

Table 36 – AC1: Annualized Cost of Deck Materials Using Median Service Life. No Discount Factor.

	Element 14	**Element 22 No Rehab**	**Element 22 Rehab**	**Element 23**	**Element 26**
	Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
IC	$ 258 $ 119 / SY	$ 248 $ 104 / SY	$ 336 $ 139 / SY	$ 259 $ 115 / SY	$ 260 $ 121 / SY
x	56 years	31 years	35 years	31 years	35 years
AC_{IC}	$ 2.13 / SY	$ 3.35 / SY	$ 3.97 / SY	$ 3.71 / SY	$ 3.46 / SY
MC	$ 7.83 / SY	$ 0 / SY	$ 0 / SY	$ 4.70 / SY	$ 7.83 / SY
A	7 years	-	-	3 years	7 years
AC_{MC}	$ 1.12 / SY	-	-	$ 1.57 / SY	$ 1.12 / SY
AC1	$ 3.25 / SY	$ 3.35 / SY	$ 3.97 / SY	$ 5.28 / SY	$ 4.58 / SY

AC2: Annualized Material Costs at Probable Service Life

Uncertainty in service life is recognized, and annualized unit cost is computed with population models of service life. Here too, no discount factor is used. Initial costs are annualized using probability density functions for bridge deck service life. Maintenance applications are annualized over their application interval.

$$AC2 = \int_0^{\infty} \frac{IC}{x} f(x)dx + \frac{MC}{A} \quad \textbf{Eq 35}$$

Table 37 – AC2: Annualized Cost of Deck Materials Using Service Life Probability Density. No Discount Factor.

	Element 14	Element 22 No Rehab	Element 22 Rehab	Element 23	Element 26
	Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
UC	$ 119 / SY	$ 104 / SY	$ 139 / SY	$ 115 / SY	$ 121 / SY
Model	xo-Rayleigh	xo-Rayleigh	xo-Rayleigh	xo-Rayleigh	xo-Exponential
s	32 years	10 years	14 years	12 years	12 years
xo	16 years	20 years	22 years	14 years	27 years
AC_{MC}	$ 1.12 / SY	-	-	$ 1.57 / SY	$ 1.12 / SY
AC2	$ 3.59 / SY	$ 3.25 / SY	$ 3.60 / SY	$ 5.82 / SY	$ 4.50 / SY

AC3: Annualized Material Costs Discounted at Median Service Life

Annualized cost using a discount rate is computed for deck unit cost at median service life. Initial costs are discounted at median service life. Maintenance costs are discounted over the application interval

$$AC_{IC} = IC\frac{i}{(1+i)^L - 1} \quad \textbf{Eq 36}$$

$$AC_{MC} = MC\frac{i}{(1+i)^A - 1} \quad \textbf{Eq 37}$$

Table 38 – AC3: Annualized Cost of Deck Materials Using Median Service Life and Discount Factor.

	Element 14	Element 22 No Rehab	Element 22 Rehab	Element 23	Element 26
	Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
IC	$ 119 / SY	$ 104 / SY	$ 139 / SY	$ 115 / SY	$ 121 / SY
x	56 years	31 years	35 years	31 years	35 years

AC_{IC}	\$ 1.70 \$ 0.78 / SY	\$ 4.78 \$ 2.00 / SY	\$ 5.35 \$ 2.21 / SY	\$ 5.01 \$ 2.22 / SY	\$ 4.14 / SY
AC_{MC}	\$ 1.02 / SY	0	0	\$ 1.52 / SY	\$ 1.02 / SY
AC3	\$ 1.80 / SY	\$ 2.00 / SY	\$ 2.21 / SY	\$ 3.74 / SY	\$ 2.95 / SY

AC4: Annualized Material Costs Discounted at Probable Service Life

Uncertainty in service life is brought into the computation of annualized initial cost as

$$AC_{IC} = \int_0^{\infty} IC \frac{i\,f(x)}{(1+i)^x - 1} dx \qquad \textbf{Eq 38}$$

Table 39 – AC4: Annualized Cost of Deck Materials Using Service Life Probability Density and Discount Factor

	Element 14	Element 22 No Rehab	Element 22 Rehab	Element 23	Element 26
	Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
IC	\$ 119 / SY	\$ 104 / SY	\$ 139 / SY	\$ 115 / SY	\$ 121 / SY
Model	xo-Exponential	xo-Rayleigh	xo-Rayleigh	xo-Rayleigh	xo-Exponential
s	32 years	10 years	14 years	12 years	12 years
xo	16 years	20 years	22 years	14 years	27 years
AC_{IC}	\$ 1.12 / SY	\$ 1.92 / SY	\$ 1.89 / SY	\$ 2.76 / SY	\$ 1.87 / SY
AC_{MC}	\$ 1.02 / SY	0	0	\$ 1.52 / SY	\$ 1.02 / SY
AC4	\$ 2.14 / SY	\$ 1.92 / SY	\$ 1.89 / SY	\$ 4.28 / SY	\$ 2.89 / SY

Comparison of Deck Material Costs

The summary of deck types by the various cost evaluations is shown in Table 40.

Table 40 - Deck Material Cost Evaluations

	Element 14	Element 22N	Element 22R	Element 23	Element 26
IC	\$ 119 / SY	\$ 104 / SY	\$ 139 / SY	\$ 115 / SY	\$ 121 / SY
PV1	\$ 45.35 / SY	\$ 39.17 / SY	\$ 46.16 / SY	\$ 72.30 / SY	\$ 65.14 / SY
PV2	\$ 51.71 / SY	\$ 37.46 / SY	\$ 40.45 / SY	\$ 74.20 / SY	\$ 61.63 / SY
AC1	\$ 3.25 / SY	\$ 3.35 / SY	\$ 3.97 / SY	\$ 5.28 / SY	\$ 4.58 / SY
AC2	\$ 3.59 / SY	\$ 3.25 / SY	\$ 3.60 / SY	\$ 5.82 / SY	\$ 4.50 / SY
AC3	\$ 1.80 / SY	\$ 2.00 / SY	\$ 2.21 / SY	\$ 3.74 / SY	\$ 2.95 / SY
AC4	\$ 2.14 / SY	\$ 1.92 / SY	\$ 1.89 / SY	\$ 4.28 / SY	\$ 2.89 / SY

Ranks of deck types by cost ('1' is least expensive) are shown in Table 41.

Table 41 - Deck Material Cost Ranks (1 = lowest cost)

	Element 14	Element 22N	Element 22R	Element 23	Element 26
IC	3	1	5	2	4
PV1	2	1	3	5	4
PV2	3	1	2	5	4
AC1	1	2	3	5	4
AC2	2	1	3	5	4
AC3	1	2	3	5	4
AC4	3	2	1	5	4

Element 22 decks, using uncoated reinforcing steel without protective sealers or membranes, are least costly in four of six evaluations. These decks are not rehabilitated. Element 22 decks, having uncoated steel protected by waterproofing membrane, are least costly in two evaluations. Decks with epoxy-coated reinforcing steel are more expensive in most evaluations.

Sensitivity to Discount Factor

Four cost evaluations (PV1, PV2, AC3 and AC4) employ a discount factor. The previous section computed deck costs using the OMB-specified annual discount factor equal to 3.2%. This section considers a range of discount factors, from 2% to 10%, to examine the sensitivity of deck costs to discount factor.

Summaries of deterministic present value, PV1, both as cost and rank are shown in Table 42.

Table 42 - Deck Material Costs PV1 and Ranks for Various Discount Rates

Discount Factor	Element 14 $/SY		Element 22N $/SY		Element 22R $/SY		Element 23 $/SY		Element 26 $/SY	
2 %	72	3	56	1	70	2	97	5	93	4
3.2 %	45	2	39	1	46	3	72	5	65	4
4 %	34	2	31	1	35	3	60	5	52	4
6 %	19	3	17	1	18	2	39	5	30	4
8 %	12	3	10	2	9.40	1	27	5	19	4
10 %	8.75	3	5.42	2	4.95	1	19	5	12	4

Summaries of probabilistic present value, PV2, both as cost and rank are shown in Table 43.

Table 43 – Deck Material Costs PV2 and Ranks for Various Discount Rates

Discount Factor	Element 14 $/SY		Element 22N $/SY		Element 22R $/SY		Element 23 $/SY		Element 26 $/SY	
2 %	79	3	55	1	63	2	97	5	88	4
3.2 %	50	3	37	1	40	2	74	5	61	4
4 %	39	3	29	1	30	2	63	5	49	4
6 %	22	3	16	2	15	1	42	5	29	4
8 %	14	3	9.04	2	7.57	1	30	5	19	4
10 %	10	3	5.16	2	3.96	1	22	5	12	4

Summaries for deterministic annualized cost, AC3, both as cost and rank are shown in Table 44.

Table 44 – Deck Material Costs AC3 and Ranks for Various Discount Rates

Discount Factor	Element 14 $/SY		Element 22N $/SY		Element 22R $/SY		Element 23 $/SY		Element 26 $/SY	
2 %	2.22	1	2.45	2	2.78	3	4.25	5	3.47	4
3.2 %	1.80	1	2.01	2	2.21	3	3.74	5	2.94	4
4 %	1.59	1	1.75	2	1.89	3	3.44	5	2.63	4
6 %	1.22	1	1.23	2	1.25	3	2.83	5	2.02	4
8 %	1.01	3	0.84	2	0.81	1	2.38	5	1.58	4
10 %	0.88	3	0.57	2	0.51	1	2.05	5	1.27	4

Summaries for probabilistic annualized cost, AC4, both as cost and rank are shown in Table 45.

Table 45 - Deck Material Costs AC4 and Ranks for Various Discount Rates

Discount Factor	Element 14 $/SY		Element 22N $/SY		Element 22R $/SY		Element 23 $/SY		Element 26 $/SY	
2 %	2.46	3	2.36	1	2.43	2	4.79	5	3.40	4
3.2 %	2.05	3	1.92	2	1.89	1	4.27	5	2.89	4
4 %	1.83	3	1.67	2	1.60	1	3.97	5	2.59	4
6 %	1.44	3	1.16	2	1.03	1	3.33	5	2.01	4
8 %	1.19	3	0.80	2	0.65	1	2.83	5	1.60	4
10 %	1.02	3	0.55	2	0.41	1	2.46	5	1.30	4

The value of the discount rate has significant effect on deck costs and some effect on rankings among decks. Element 22 decks are least costly by most evaluations and at most values of discount rates. Higher discount rates make rehabilitation of Element 22 decks more cost effective.

General conclusion on material costs: Decks with uncoated reinforcing steel are least expensive by all measures of present value and annualized costs, and at most values of discount rate.

Cost Comparisons Based on Deck Projects

This section compares decks based on project costs. CDOT data show that costs for deck construction projects range from 5 to 7 times the costs of deck materials alone. To compare costs among deck types, project costs are estimated at 6 times material costs. Here too, maintenance costs for membranes and sealers are included. Five deck types are compared. These include the four types of deck plus the set of rehabilitated decks in the group of element 22 decks. The set of initial costs, present value costs are annualized costs defined in the previous section are used here.

INITIAL PROJECT COSTS FOR DECKS

Initial project costs of bridge decks are listed in Table 46.

Table 46 – Initial Unit Project Costs (IC) for Bridge Decks

Element 14	Element 22 No Rehab	Element 22 Rehab	Element 23	Element 26
Bare Steel	Bare Steel	Bare Steel	Epoxy-Coated Steel	Epoxy-Coated Steel

+ Membrane	+ Bare Deck	+ Rigid Overlay	+ Concrete Sealer	+ Membrane
$ 714 / SY	$ 624 / SY	$ 834 / SY	$ 690 / SY	$ 726 / SY

MAINTENANCE COSTS

Maintenance costs are shown in Table 33.

PRESENT VALUE OF REPLACEMENT PROJECT COST (PV1)

The cost of future replacement project for each deck type is computed as unit cost in 2003 dollars for deck replacement projects occurring at x years in the future, where x is the service life.

The results for CDOT decks are listed in Table 47.

Table 47 – PV1: Present Value of Deck Replacement Project Using Median Service Life

	Element 14	Element 22 No Rehab	Element 22 Rehab	Element 23	Element 26
	Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
IC	$ 714 / SY	$ 624 / SY	$ 834 / SY	$ 690 / SY	$ 726 / SY
L	56 years	31 years	35 years	31 years	35 years
MC	$ 7.83 / SY	$ 0 / SY	$ 0 / SY	$ 4.70 / SY	$ 7.83 / SY
A	7 years	-	-	3 years	7 years
PV_{IC}	$ 122 / SY	$ 235 / SY	$ 277 / SY	$ 260 / SY	$ 241 / SY
PV_{MC}	$ 24.96 / SY	0	0	$ 28.99 / SY	$ 24.96 / SY
PV1	$ 147 / SY	$ 235 / SY	$ 277 / SY	$ 289 / SY	$ 266 / SY

A second computation of present value recognizes variability in deck service life.

Table 48 – PV2: Present Value of Deck Replacement Project Using Service Life Probability

	Element 14	Element 22 No Rehab	Element 22 Rehab	Element 23	Element 26
	Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
Model	xo-Exponential	xo-Rayleigh	xo-Rayleigh	xo-Rayleigh	xo-Exponential
s	35 years	10 years	14 years	12 years	12 years
xo	29 years	20 years	22 years	14 years	27 years
PV_{IC}	$ 139 / SY	$ 225 / SY	$ 243 / SY	$ 285 / SY	$ 229 / SY
PV_{MC}	$ 27.14 / SY	0.00	0.00	$ 26.78 / SY	$ 23.53 / SY
PV2	$ 167 / SY	$ 225 / SY	$ 243 / SY	$ 311 / SY	$ 252 / SY

ANNUALIZED COST

AC1: Annualized Project Costs at Median Service Life

Simple annualized project cost is deck unit cost divided by service life in years.

Table 49 – AC1: Annualized Cost of Deck Project Using Median Service Life. No Discount Factor.

	Element 14	Element 22 No Rehab	Element 22 Rehab	Element 23	Element 26
	Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
IC	$ 714 / SY	$ 624 / SY	$ 834 / SY	$ 690 / SY	$ 726 / SY
x	56 years	31 years	35 years	31 years	35 years
AC_{IC}	$ 12.75 / SY	$ 20.13 / SY	$ 23.83 / SY	$ 22.26 / SY	$ 20.74 / SY
MC	$ 7.83 / SY	$ 0 / SY	$ 0 / SY	$ 4.70 / SY	$ 7.83 / SY
A	7 years	-	-	3 years	7 years
AC_{MC}	$ 1.12 / SY	-	-	$ 1.57 / SY	$ 1.12 / SY
AC1	$ 13.87 / SY	$ 20.13 / SY	$ 23.83 / SY	$ 23.83 / SY	$ 21.86 / SY

AC2: Annualized Project Costs At Probable Service Life

Uncertainty in service life is recognized, and annualized unit cost is computed with population models of service life.

Table 50 – AC2: Annualized Cost of Deck Project Using Service Life Probability Density. No Discount Factor

	Element 14	Element 22 No Rehab	Element 22 Rehab	Element 23	Element 26
	Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
UC	$ 714 / SY	$ 624 / SY	$ 834 / SY	$ 690 / SY	$ 726 / SY
Model	xo-Rayleigh	xo-Rayleigh	xo-Rayleigh	xo-Rayleigh	xo-Exponential
s	32 years	10 years	14 years	12 years	12 years
xo	16 years	20 years	22 years	14 years	27 years
AC_{MC}	$ 1.12 / SY	-	-	$ 1.57 / SY	$ 1.12 / SY
AC2	$ 15.14 / SY	$ 19.50 / SY	$ 21.62 / SY	$ 27.09 / SY	$ 21.36 / SY

AC3: Annualized Project Costs Discounted at Median Service Life

Annualized project cost using a discount rate is computed for deck unit cost at median service life.

Table 51 – AC3: Annualized Cost of Deck Project Using Median Service Life and Discount Factor.

	Element 14	Element 22 No Rehab	Element 22 Rehab	Element 23	Element 26
	Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
IC	$ 714 / SY	$ 624 / SY	$ 834 / SY	$ 690 / SY	$ 726 / SY
x	56 years	31 years	35 years	31 years	35 years
AC_{IC}	$ 4.73 / SY	$ 12.06 / SY	$ 13.27 / SY	$ 13.34 / SY	$ 11.55 / SY
AC_{MC}	$ 1.02 / SY	0	0	$ 1.52 / SY	$ 1.02 / SY
AC3	$ 5.74 / SY	$ 12.06 / SY	$ 13.27 / SY	$ 14.86 / SY	$ 12.57 / SY

AC4: Annualized Project Costs Discounted at Probable Service Life

Table 52 – AC4: Annualized Cost of Deck Project Using Service Life Probability Density and Discount Factor

	Element 14	**Element 22 No Rehab**	**Element 22 Rehab**	**Element 23**	**Element 26**
	Bare Steel + Membrane	Bare Steel + Bare Deck	Bare Steel + Rigid Overlay	Epoxy-Coated Steel + Concrete Sealer	Epoxy-Coated Steel + Membrane
IC	$ 714 / SY	$ 624 / SY	$ 834 / SY	$ 690 / SY	$ 726 / SY
Model	xo-Exponential	xo-Rayleigh	xo-Rayleigh	xo-Rayleigh	xo-Exponential
s	32 years	10 years	14 years	12 years	12 years
xo	16 years	20 years	22 years	14 years	27 years
AC_{IC}	$ 6.19 / SY	$ 11.52 / SY	$ 11.36 / SY	$ 16.54 / SY	$ 11.22 / SY
AC_{MC}	$ 1.02 / SY	0	0	$ 1.52 / SY	$ 1.02 / SY
AC4	$ 7.21 / SY	$ 11.52 / SY	$ 11.36 / SY	$ 18.06 / SY	$ 12.24 / SY

Comparison of Deck Project Costs

The summary of deck types by the various project cost evaluations is shown in Table 53.

Table 53 - Deck Project Cost Evaluations

	Element 14	**Element 22N**	**Element 22R**	**Element 23**	**Element 26**
IC	$ 714 / SY	$ 624 / SY	$ 834 / SY	$ 690 / SY	$ 726 / SY
PV1	$ 147 / SY	$ 235 / SY	$ 277 / SY	$ 289 / SY	$ 266 / SY
PV2	$ 167 / SY	$ 225 / SY	$ 243 / SY	$ 311 / SY	$ 252 / SY
AC1	$ 13.87 / SY	$ 20.13 / SY	$ 23.83 / SY	$ 23.83 / SY	$ 21.86 / SY
AC2	$ 15.14 / SY	$ 19.50 / SY	$ 21.62 / SY	$ 27.09 / SY	$ 21.36 / SY
AC3	$ 5.74 / SY	$ 12.06 / SY	$ 13.27 / SY	$ 14.86 / SY	$ 12.57 / SY
AC4	$ 7.21 / SY	$ 11.52 / SY	$ 11.36 / SY	$ 18.06 / SY	$ 12.24 / SY

Ranks of deck types by project cost ('1' is least expensive) are shown in Table 54.

Table 54 - Deck Project Cost Ranks (1 = lowest cost)

	Element 14	Element 22N	Element 22R	Element 23	Element 26
IC	3	1	5	2	4
PV1	1	2	4	5	3
PV2	1	2	3	5	4
AC1	1	2	4,5	4,5	3
AC2	1	2	4	5	3
AC3	1	2	4	5	3
AC4	1	3	2	5	4

Element 14 decks, using bare steel and waterproofing membrane, are the least costly by all measures except initial cost. Element 22 decks, without rehabilitation are next in cost by most measures. Rehabilitated decks or decks protected by concrete sealers are most costly by most measures.

Sensitivity to Discount Factor

Four project cost evaluations (PV1, PV2, AC3 and AC4) employ a discount factor. The previous section computed deck project costs using the OMB-specified annual discount factor equal to 3.2%. This section considers a range of discount factors, from 2% to 10%, to examine the sensitivity of deck project costs to discount factor.

Summaries of deterministic present value, PV1, both as cost and rank are shown in Table 55.

Table 55 - Deck Project Costs PV1 and Ranks for Various Discount Rates

Discount Factor	Element 14 $/SY		Element 22N $/SY		Element 22R $/SY		Element 23 $/SY		Element 26 $/SY	
2 %	268	1	338	2	417	5	408	4	396	3
3.2 %	147	1	235	2	277	4	289	5	266	3
4 %	101	1	185	2	211	4	231	5	205	3
6 %	42	1	102	2	109	3,4	134	5	109	3,4
8 %	20	1	57	3	56	2	80	5	60	4
10 %	12	1	33	3	30	2	49	5	34	4

Summaries of probabilistic present value, PV2, both as cost and rank are shown in Table 56.

Table 56 - Deck Project Costs PV2 and Ranks for Various Discount Rates

Discount Factor	Element 14 $/SY		Element 22N $/SY		Element 22R $/SY		Element 23 $/SY		Element 26 $/SY	
2 %	280	1	327	2	381	4	424	5	377	3
3.2 %	167	1	225	2	243	3	311	5	252	4
4 %	121	1	176	2	181	3	255	5	194	4
6 %	60	1	97	3	89	2	159	5	105	4
8 %	32	1	54	3	45	2	102	5	59	4
10 %	19	1	31	3	24	2	68	5	35	4

Summaries for deterministic annualized cost, AC3, both as cost and rank are shown in Table 57.

Table 57 - Deck Project Costs AC3 and Ranks for Various Discount Rates

Discount Factor	Element 14 $/SY		Element 22N $/SY		Element 22R $/SY		Element 23 $/SY		Element 26 $/SY	
2 %	8.08	1	14.72	2	16.68	4	17.82	5	15.57	3
3.2 %	5.74	1	12.06	2	13.27	4	14.86	5	12.57	3
4 %	4.56	1	10.52	2	11.32	4	13.14	5	10.85	3
6 %	2.64	1	7.36	2	7.48	4	9.61	5	7.45	3
8 %	1.66	1	5.06	3	4.84	2	7.04	5	5.09	4
10 %	1.17	1	3.43	3	3.08	2	5.21	5	3.50	4

Summaries for probabilistic annualized cost, AC4, both as cost and rank are shown in Table 58.

Table 58 - Deck Project Costs AC4 and Ranks for Various Discount Rates

Discount Factor	Element 14 $/SY		Element 22N $/SY		Element 22R $/SY		Element 23 $/SY		Element 26 $/SY	
2 %	9.47	1	14.13	2	14.59	3	21.07	5	15.15	4
3.2 %	7.21	1	11.52	3	11.36	2	18.06	5	12.24	4
4 %	6.04	1	10.02	3	9.57	2	16.29	5	10.60	4
6 %	3.99	1	6.99	3	6.16	2	12.59	5	7.40	4
8 %	2.74	1	4.81	3	3.92	2	9.77	5	5.19	4
10 %	1.96	1	3.29	3	2.48	2	7.65	5	3.68	4

The value of the discount rate has significant effect on deck costs and some effect on rankings among decks. Element 14 decks are least expensive at all values of discount rate. Decks with epoxy-coated reinforcing steel, Elements 23 and 26 are relatively more expensive at all values of discount rate.

General conclusion on costs: Decks with waterproofing membrane are least expensive by all measures of present value and annualized costs.

CHAPTER 5 CONCLUSION

This study examines costs and performance of four types of reinforced concrete bridge decks currently in service on CDOT highway bridges. These four types allow comparisons between bare decks and decks with waterproofing membranes, and between decks with uncoated steel and decks with epoxy-coated reinforcement.

Histories of deck condition ratings are used to estimate deck service life and to generate population models of service life. Decks with waterproofing membrane have longer service life than bare decks. Condition data indicate longer service life for decks with uncoated reinforcing steel, but this outcome may be due to the limited extent of condition data for decks having epoxy-coated reinforcement.

Costs for bridge decks are evaluated as initial costs, present values, and annualized costs. Considering the cost of materials only, decks with uncoated reinforcing steel and without protection against corrosion offer least cost. Considering project costs, decks with uncoated reinforcing steel protected by waterproofing membrane offer least cost.

Appendix 1 - Tabulation of CDOT Decks in Study

ELEMENT 14 DECKS

Bridge decks having bare steel, waterproofing membrane, and asphalt wearing surface.

All decks built in 1980.

Table 59 - Element 14 Decks – Basic Information

Bridge	Highway	Deck Condition Rating (item 58)	Spans	Type	Len (ft)	Width (ft)	Inv Rate (ton)	Reg	Sect
B-13-D	14	8	1	CPG	95	40	33	4	1
C-16-DI	34	8	2	CBGC	149	36	35	4	1
E-16-KB	121	7	3	CICK	178	36	34	6	8
E-16-KD	70	8	2	WGCK	176	44	33	6	8
F-08-O	70	7	3	CSGC	122	42	33	3	2
F-08-P	70	7	3	CSGC	122	42	33	3	2
F-08-Q	70	7	4	WGCK	441	42	35	3	2
F-08-U	70	7	3	CSGC	122	42	34	3	2
F-08-V	70	8	3	CSGC	122	48	34	3	2
F-16-JV	88	7	2	CICK	173	36	36	6	8
G-04-AA	70	7	4	CPGC	403	42	34	3	2
G-04-AB	70	7	4	CPGC	403	42	34	3	2
G-04-AC	70	7	2	CPGC	181	42	34	3	2
G-04-AD	70	8	2	CPGC	181	42	34	3	2
G-04-AE	70	7	2	CBGCP	244	38	34	3	2
G-04-AF	70	7	3	CPGC	205	38	33	3	2
G-04-AG	70	8	3	CPGC	208	38	33	3	2
G-04-AH	70	7	4	CBGCP	365	32	34	3	2
H-17-CQ	25	7	3	CICK	203	120	34	1	5

Table 60 - Projects for Element 14 Bridges

Bridge	Project	Year	Amount	Notes
B-13-D	RS0014(11)	1980	$194,700	Original construction
	STR0142-029	1997	$1,624	Overlay
C-16-DI	ERFO108(10)	1980	$409,000	Original construction
E-16-KB	I76-1(56)	1980	$508,000	New, experimental exp jt.
	I76-1[67]0	1981	$14,800	HBP
E-16-KD	I76-1(56)+IR76-1[61]	1980	$284,400	Original construction
	I76-1[68]	1983	-0-	HBP,wtrprfg memb
F-08-O	I70-2(79)131	1980	$131,100	Original construction
	I70-2[81]	1980	$3,700	Overlay,wtrprfg memb
	NH0702-216	1999	$2,359	Overlay/chain link fence
F-08-P	I70-2(79)131	1980	$139,500	Original construction
	I70-2[81]	1980	$3,700	Overlay,wtrprfg memb
	NH0702-216	1999	$2,359	Overlay/chain link fence
F-08-Q	I70-2(79)131	1980	$873,700	Original construction
	I70-2[81]	1980	$13,500	Overlay,wtrprfg memb
	NH0702-216	1999	$23,587	Overlay
F-08-U	I70-2(76)134	1980	$124,100	Original construction
	I70-2[81]	1980	$3,700	Overlay,wtrprfg memb

Bridge	Project	Year	Amount	Notes
	NH0702-216	1999	$2,359	Overlay/chain link fence
F-08-V	I70-2(76)134	1980	$140,000	Original construction
	I70-2[81]	1980	$4,100	Overlay,wtrprfg memb
	NH0702-216	1999	$23,587	Overlay/chain link fence
F-16-JV	RRS0088(1)	1980	$278,100	Original construction
G-04-AA	I70-1(64)63	1980	$617,100	Original construction
	I70-1[54]60	1981	$22,600	Overlay,wtrprfg memb
G-04-AB	I70-1(64)63	1980	$586,800	Original construction
	I70-1[54]60	1981	$22,600	Overlay,wtrprfg memb
G-04-AC	I70-1(64)63	1980	$297,200	Original construction
	I70-1[54]60	1981	$5,800	Overlay,wtrprfg memb
G-04-AD	I70-1(64)63	1980	$302,100	Original construction
	I70-1[54]60	1981	$5,800	Overlay,wtrprfg memb
G-04-AE	I70-1(68)60	1980	$379,200	Original construction
	I70-1[54]60	1981	$7,100	Overlay,wtrprfg memb
G-04-AF	I70-1(67)64	1980	$430,000	Original construction
	I70-1[54]	1981	$5,900	Overlay,wtrprfg memb
G-04-AG	I70-1(67)64	1980	$433,300	Original construction
	I70-1[54]60	1981	$6,100	Overlay,wtrprfg memb
G-04-AH	I70-1(67)64	1980	$616,800	Original construction
	I70-1[82]	1984	$13,000	Overlay,wtrprfg memb
H-17-CQ	I25-2(128)	1980	$923,700	Original construction
	IM-0252-278	1996	-0-	Expansion device

ELEMENT 22 DECKS

Decks built with black steel, and since rehabilitated with rigid overlay. All bridges are in region 1.

Table 61 - Element 22 Decks – Basic Information

Bridge	Highway	Year Built	Deck Condition Rating (Item 58)	Spans	Type	Len (ft)	Width (ft)	Inv Rate (ton)
G-21-H	70	1971	7	3	CSG	109	42	34
G-21-K	70	1972	7	3	CSG	94	42	30
G-21-O	70	1972	7	1	CPG	90	42	29
G-22-BA	24	1975	7	2	CBGC	219	44	30
G-22-BC	70	1975	7	2	WGCK	244	42	33
G-22-BD	70	1975	7	3	WGCK	178	42	34
G-22-BE	70	1975	6	3	WGCK	159	42	34
G-22-BF	70	1975	7	3	CICK	129	29	33
G-22-BG	70	1975	7	2	CPGC	139	42	27
G-22-BH	70	1975	6	2	CPGC	125	42	32
G-22-BJ	70	1972	7	3	CSG	95	42	30
G-22-BL	70	1975	7	2	WGCK	234	42	33
G-22-BN	70	1975	7	3	WGCK	187	29	33
G-22-BT	70	1975	7	2	WGCK	226	42	33
G-22-BU	70	1975	6	2	WGCK	216	42	33
G-24-J	70	1975	8	2	CPG	199	42	38
G-24-U	70	1975	7	2	CPG	199	42	38
G-28-H	70	1969	6	3	CSGC	94	38.5	32
G-28-I	70	1969	7	3	CSGC	94	38.5	32
G-28-J	70	1969	7	3	CSGC	94	38.5	32
G-28-K	70	1969	7	3	CSGC	94	38.5	32
G-28-L	70	1969	6	3	CSGC	94	38.5	32
G-28-M	70	1969	7	3	CSGC	93	38.5	31
G-28-N	70	1969	5	3	CSGC	94	38.5	32
G-28-O	70	1969	6	3	CSGC	95	38.5	31

Table 62 – Rehabilitation Information for Element 22 Decks

Bridge	Year built	Year rehab	Service of original deck (years)
G-21-H	1971	1989	18
G-21-K	1972		32
G-21-O	1972		32
G-22-BA	1975	1999	24
G-22-BC	1975	1999	24
G-22-BD	1975	1999	24
G-22-BE	1975	1999	24
G-22-BF	1975	1999	24
G-22-BG	1975	1999	24
G-22-BH	1975	1999	24
G-22-BJ	1972		32
G-22-BL	1975	1999	24
G-22-BN	1975	1999	24

Bridge	Year built	Year rehab	Service of original deck (years)
G-22-BT	1975	1999	24
G-22-BU	1975	1999	24
G-24-J	1975	1995	20
G-24-U	1975	1995	20
G-28-H	1969	1995	26
G-28-I	1969	1995	26
G-28-J	1969	1995	26
G-28-K	1969	1995	26
G-28-L	1969	1995	26
G-28-M	1969	1995	26
G-28-N	1969	1995	26
G-28-O	1969	1995	26

Table 63 - Projects for Element 22 Bridges

Bridge	Project	Year	Amount	Notes
G-21-H	I70-4(53)350	1971	$43,700.00	ORIGINAL CONSTRUCTION
	CXIR34-0070-03	1989	$3,700.00	OVERLAY
	IM0704-065	1998		RAIL/APP/BEARINGS/JNTS
G-21-K	I70-4(57)360	1972	$50,000.00	ORIGINAL CONSTRUCTION
	I70-4[60]360	1972	-0-	HBP,WTRPRFG MEMB
	IM-IR[CX]070-4[141]	1996	$90,400.00	BRIDGERAIL/APP SLAB
G-21-O	I70-4(57)360	1972	$52,500.00	ORIGINAL CONSTRUCTION
	I70-4[60]360	1972	-0-	WTRPRFG MEMB
	IM-IR[CX]070-4[141]	1996	$71,400.00	BRIDGERAIL/APP SLAB
G-22-BA	I70-4(59)369	1975	$192,000.00	ORIGINAL CONSTRUCTION
	IR70-5[37]][42]	1985	$37,300.00	BRIDGERAIL
	IM0704-185	1999	$139,571.82	MAJOR REHAB
G-22-BC	I70-4(67)370	1975	$318,100.00	ORIGINAL CONSTRUCTION
	I70-4[68]370	1976	$43,400.00	BRIDGERAIL
	IR70-5[37][42]	1985	$43,300.00	BRIDGERAIL
	IM0704-185	1999	$356,464.33	MAJOR REHAB
G-22-BD	I70-4(67)370	1975	$196,900.00	ORIGINAL CONSTRUCTION
	I70-4[68]370	1976	-0-	-0-
	IR70-5[37][42]	1985	$30,300.00	BRIDGERAIL
	IM0704-185	1999	$275,659.31	MAJOR REHAB
G-22-BE	I70-4(67)370	1975	$179,700.00	ORIGINAL CONSTRUCTION
	I70-4[68]370	1976	-0-	BRIDGERAIL
	IR70-5[37][42]	1985	$27,500.00	BRIDGERAIL
	IM0704-185	1999	$275,659.31	MAJOR REHAB
G-22-BF	I70-4(67)370	1975	$106,200.00	ORIGINAL CONSTRUCTION
	IR70-5[37][42]	1985	$23,400.00	BRIDGERAIL
	IM0704-185	1999	$82,721.20	MAJOR REHAB
G-22-BG	I70-4(67)370	1975	$122,200.00	ORIGINAL CONSTRUCTION
	I70-4[67]370	1976	$134,473.02	ORIGINAL CONSTRUCTION
	I70-2[68]370	1986	$24,400.00	BRIDGERAIL
	IM0704-185	1999	$218,698.16	MAJOR REHAB
G-22-BH	I70-4(67)370	1975	$111,400.00	ORIGINAL CONSTRUCTION
	I70-4[68]370	1976	$22,400.00	BRIDGERAIL
	IM0704-185	1999	$218,698.16	DECK REHAB/BRIDGERAIL

Bridge	Project	Year	Amount	Notes
G-22-BJ	I70-4(57)360	1972	$51,600.00	ORIGINAL CONSTRUCTION
	I70-4[60]360	1972	-0-	WTRPRFG MEMB
	IM-IR[CX]070-4[141]	1996	$94,500.00	BRIDGERAIL/APP SLAB
G-22-BL	I70-4(67)370	1975	$304,300.00	ORIGINAL CONSTRUCTION
	I70-4[68]370	1976	$42,000.00	BRIDGERAIL
	IR70-5[37][42]	1985	$41,900.00	BRIDGERAIL
	IM0704-185	1999	$356,464.33	MAJOR REHAB
G-22-BN	I70-4(67)370	1975	$138,400.00	ORIGINAL CONSTRUCTION
	IR70-5[37][42]	1985	$33,400.00	BRIDGERAIL
	IM0704-185	1999	$109,282.95	MAJOR REHAB
G-22-BT	I70-4(67)370	1975	$287,800.00	ORIGINAL CONSTRUCTION
	I70-4[68]370	1976	-0-	BRIDGERAIL
	MISCELLANEOUS	1986	$37,400.00	-0-
	IM0704-185	1999	$333,737.52	MAJOR REHAB
G-22-BU	I70-4(67)370	1975	$275,700.00	ORIGINAL CONSTRUCTION
	I70-4[68]370	1976	$36,200.00	BRIDGERAIL
	IM0704-185	1999	$333,737.52	MAJOR REHAB
G-24-J	I70-5(22)406	1975	$121,800.00	ORIGINAL CONSTRUCTION
		1995		Rigid Overlay
G-24-U	I70-5(22)406	1975	$122,000.00	ORIGINAL CONSTRUCTION
		1995		Rigid Overlay
G-28-H	I70-5(15)450	1969	$45,200.00	ORIGINAL CONSTRUCTION
		1995		Rigid Overlay
G-28-I	I70-5(15)450	1969	$45,200.00	ORIGINAL CONSTRUCTION
		1995		Rigid Overlay
G-28-J	I70-5(15)450	1969	$44,300.00	ORIGINAL CONSTRUCTION
		1995		Rigid Overlay
G-28-K	I70-5(15)450	1969	$45,800.00	ORIGINAL CONSTRUCTION
		1995		Rigid Overlay
G-28-L	I70-5(15)450	1969	$44,800.00	ORIGINAL CONSTRUCTION
		1995		Rigid Overlay
G-28-M	I70-5(15)450	1969	$44,100.00	ORIGINAL CONSTRUCTION
		1995		Rigid Overlay
G-28-N	I70-5(15)450	1969	$44,300.00	ORIGINAL CONSTRUCTION
		1995		Rigid Overlay
G-28-O	I70-5(15)450	1969	$44,400.00	ORIGINAL CONSTRUCTION
		1995		Rigid Overlay

ELEMENT 23 DECKS

Decks with epoxy-coated reinforcing steel, and penetrating sealers.

All decks built in 1993.

Table 64 - Element 23 Decks – Basic Information

Bridge	Highway	Deck Condition Rating (Item58)	Spans	Type	Len (ft)	Width (ft)	Inv Rate (ton)	Reg	Sect
E-16-NX	25	6	2	CBGCP	183	36	45	6	8
E-16-OP	25	7	3	CBGCP	620	28	47	6	8
E-16-PJ	70	7	3	SBGC	548	34	39	6	8
E-17-OK	25	7	3	CSGCP	195	29	52	6	8
E-17-OL	76	7	3	CSGCP	202	38	43	6	8
E-17-OM	76	7	3	CSGCP	202	38	43	6	8
E-17-ON	76	7	3	CSGCP	226	45	46	6	8
E-17-OP	25	7	4	CSGCP	279	29	46	6	8
E-17-OZ	25	7	3	CBGCP	278	96	45	6	8
E-17-PA	25	7	3	CBGCP	275	154	42	6	8
E-17-PB	70	7	3	SBGC	231	33.3	37	6	8
E-17-PC	70	7	3	SBGC	231	32	37	6	8
E-17-PD	70	7	5	SBGC	843	65	39	6	8
E-17-PO	70	7	3	SBGC	250	32	50	6	8
E-17-PU	25	8	1	CBGP	156	28	38	6	8
E-17-PY	224	7	4	CPGC	420	40	35	6	8
E-17-RR	70	7	1	WGK	190	37.9	31	6	8
E-17-RS	70	8	1	WGK	159	33	38	6	8
E-17-RT	70	7	4	WGCK	630	56	43	6	8
E-17-RV	70	7	3	CBGCP	179	40	44	6	8
E-17-RW	70	7	3	CBGCP	200	40	44	6	8
F-20-BW	70	6	5	CPGC	644	46	43	1	5
F-20-BX	70	6	5	CPGC	644	46	43	1	5

Table 65 - Projects for Element 23 Bridges

Bridge	Project	Year	Amount	Notes
E-16-NX	IRD[E]025-2[242]	1993	$328,274.19	ORIGINAL CONSTRUCTION
E-16-OP	CC-01-0025-51	1992	-0-	NEW CONSTRUCTION RTD
E-16-PJ	IRD-CX[A]025-2[242]	1992	$1,847,528.22	ORIGINAL CONSTRUCTION
E-17-OK	ID[A]-I[CX]076-1[122	1992	$359,856.97	ORIGINAL CONSTRUCTION
E-17-OL	ID[A]-I[CX]076-1[122	1992	$428,163.19	ORIGINAL CONSTRUCTION
E-17-OM	ID[A]-I[CX]076-1[122	1992	$426,403.70	ORIGINAL CONSTRUCTION
E-17-ON	ID[A]-I[CX]076-1[122	1992	$572,812.12	ORIGINAL CONSTRUCTION
E-17-OP	ID[A]-I[CX]076-1[122	1992	$460,312.71	ORIGINAL CONSTRUCTION
E-17-OZ	IRICX25-3[108]	1993	$1,389,700.00	ORIGINAL CONSTRUCTION
	MTCE 06-015	2003	-0-	EXP.JNT.REPAIR
E-17-PA	IRICX25-3[108]	1993	$2,257,400.00	ORIGINAL CONSTRUCTION
	MTCE 06-015	2003	-0-	EXP.JNT.REPAIR
E-17-PB	IRD[C]070-4[146]	1993	$1,309,400.00	ORIGINAL CONSTRUCTION
E-17-PC	IRD[C]070-4[146]	1993	$1,245,900.00	ORIGINAL CONSTRUCTION
E-17-PD	IRD[C]070-4[146]	1993	$1,726,000.00	ORIGINAL CONSTRUCTION
E-17-PO	IRD[C]070-4[146]	1993	$968,000.00	ORIGINAL CONSTRUCTION

Bridge	**Project**	**Year**	**Amount**	**Notes**
E-17-PU	IRICX25-3[108]	1993	$614,300.00	ORIGINAL CONSTRUCTION
E-17-PY	BRS0224[001]	1992	$1,041,100.00	ORIGINAL CONSTRUCTION
E-17-RR	CC12-0070-06	1992	$885,900.00	ORIGINAL CONSTRUCTION
	IM0704-176	1997	$25,800.00	DRAIN/REPAIR CONCRETE
E-17-RS	CC12-0070-06	1992	$719,300.00	ORIGINAL CONSTRUCTION
	IM0704-176	1997	$27,000.00	EMBMKMT PROT/CURBS
E-17-RT	CC12-0070-06	1992	$2,673,600.00	ORIGINAL CONSTRUCTION
	IM0704-176	1997	$18,400.00	DRAINS/EMBMKMT PROT/CURBS
	MTCE 06-028	2003	-0-	SLABJACKING
E-17-RV	CC12-0070-06	1992	$426,000.00	ORIGINAL CONSTRUCTION
	IM0704-176	1997	$11,000.00	EMBMKMT PROT/CURBS
E-17-RW	CC12-0070-06	1992	$474,400.00	ORIGINAL CONSTRUCTION
	IM0704-176	1997	$7,900.00	EMBMKMT PROT/CURBS
F-20-BW	IM-IR[CX]070-4[135]	1992	$1,180,219.92	ORIGINAL CONSTRUCTION
F-20-BX	IM-IR[CX]070-4[135]	1992	$1,185,554.92	ORIGINAL CONSTRUCTION

ELEMENT 26 DECKS

Decks with epoxy-coated reinforcing steel, waterproofing membrane and asphalt wearing surface.

All decks built in 1991.

Table 66 - Element 26 Decks – Basic Information

	Bridge	Highway	Deck Condition Rating (Item58)	Spans	Type	Len (ft)	Width (ft)	Inv Rate (ton)	Reg	Sect
E-17-NZ	E-17-NZ	76	7	3	SBGCP	546	65	41	6	8
E-17-OH	E-17-OH	76	8	3	SBGCP	508	37.5	46	6	8
E-17-OO	E-17-OO	224	8	5	SBGC	695	92	39	6	8
F-07-AZ	F-07-AZ	70	8	1	CBGP	90	30	25	3	2
F-08-AU	F-08-AU	70	7	8	CBGCP	776	33.5	45	3	2
F-11-BE	F-11-BE	24	8	2	CPGC	205	40	41	3	2
F-11-BF	F-11-BF	24	8	1	CPG	124	40	40	3	2
F-16-RI	F-16-RI	40	7	4	CBGCP	443	50	47	6	8
F-16-RP	F-16-RP	285	8	2	CBGCP	212	112	41	6	8
F-16-RQ	F-16-RQ	285	7	3	CBGCP	124	112	37	6	8
F-17-JW	F-17-JW	25	8	5	SBGC	638	27	46	6	8
F-17-JX	F-17-JX	470	7	7	SBGC	1196	38	38	6	8
F-17-JY	F-17-JY	25	8	2	CPGC	181	27	45	6	8
F-17-JZ	F-17-JZ	25	7	2	CPGC	181	27	45	6	8
I-07-S	I-07-S	133	7	4	WGCK	524	40	46	3	2

Table 67 - Projects for Element 26 Bridges

Bridge	Project	Year	Amount	Notes
E-17-NZ	I[CX]76-1[129][133]	1991	$2,961,600.00	ORIGINAL CONSTRUCTION
E-17-OH	I[CX]76-1[129][143]	1991	$1,571,200.00	ORIGINAL CONSTRUCTION
E-17-OO	I[CX]76-1[130]	1991	$2,751,700.00	ORIGINAL CONSTRUCTION
	SP0253-150	1998	-0-	SIGNAL LIGHT POLE & FENCE
F-07-AZ	I[CX]70-2[147]	1991	$269,300.00	ORIGINAL CONSTRUCTION
F-08-AU	I[CX]70-2[141]	1991	$2,762,000.00	ORIGINAL CONSTRUCTION
F-11-BE	BRF024-1(24)	1991	$566,300.00	ORIGINAL CONSTRUCTION
F-11-BF	BRF024-1(24)	1991	$583,300.00	ORIGINAL CONSTRUCTION
F-16-RI	IR(CX)25-2(213)	1991	$1,154,200.00	ORIGINAL CONSTRUCTION
F-16-RP	BRF285-4[041]	1991	$1,477,600.00	ORIGINAL CONSTRUCTION
	MTCE 06-010	2002	-0-	RESURFACING
F-16-RQ	BRF285-4[041]	1991	$774,800.00	ORIGINAL CONSTRUCTION
	MTCE 06-010	2002	-0-	RESURFACING
F-17-JW	1A06/1B02[E470 AUTHO	1991	-0-	ORIGINAL CONSTRUCTION
F-17-JX	1A06/1B02[E470 AUTHO	1991	-0-	ORIGINAL CONSTRUCTION
F-17-JY	1A06/1B02[E470 AUTHO	1991	-0-	ORIGINAL CONSTRUCTION
F-17-JZ	1A06/1B02[E470 AUTHO	1991	-0-	ORIGINAL CONSTRUCTION
	C0252-290	1996	$67,300.00	GIRDER REPLACEMENT
I-07-S	RS0133[20]	1991	$1,439,200.00	ORIGINAL CONSTRUCTION

Appendix 2 - Information from CDOT Cardex Files

Table 68 - Cardex File Information

Bridge	Region	Hwy	Mile post	Element	Built	Type	Span Type	Deck Thick (in)	Stringer Spacing (ft)	Stringer Depth	Notes
B-13-D	4	14	74.178	14	1980	CPG	Simple	7.5	8.58	4.5	
C-16-DI	4	34	81.897	14	1980	CBGC	Contin	7.5	7.5	4.25	
E-16-KB	6	121	16.7	14	1980	CICK	Contin	6.25	4 @ 7'10"	W36x170	
E-16-KD	6	70	269.47	14	1980	WGCK	Contin	8.25	5@ 8'	WS `46"	
E-16-NM	6	36	50.36	26	1991	CPGC	Contin		8.34	5.67	Membrane
E-16-NX	6	25	213.99	23	1993	CBGCP	Contin		8	3.67	Spread Box
E-16-OP	6	25	212.14	23	1993	CBGCP	Contin	8.25		9.5	Micro Silica Overlay
E-16-PJ	6	70	274.07	23	1993	SBGC	Contin	8.25	9.8	Stl Bx 6'	
E-17-NZ	6	76	5.781	26	1991	SBGCP	Contin		11.9	8'5"	
E-17-OH	6	76	5.78	26	1991	SBGCP	Contin		9	W box 8'4"	
E-17-OK	6	25	216.25	23	1993	CSGCP	Contin		12.1	4.25	Sealer
E-17-OL	6	76	5.48	23	1993	CSGCP	Contin		10.75	4'3"	
E-17-OM	6	76	5.49	23	1993	CSGCP	Contin		10.75	4'3"	
E-17-ON	6	76	5.5	23	1993	CSGCP	Contin		10	4'3"	
E-17-OO	6	224	0.474	26	1991	SBGC	Contin	8	8.5	9.5	
E-17-OP	6	25	216.2	23	1993	CSGCP	Contin		11.1	4.25	Sealer
E-17-OW	6	25	215.77	35	1993	CBGCP	Contin	8.5	9.23	1.22	
E-17-OX	6	25	215.53	35	1993	CBGCP	Contin	7.75	10	2.92	Spread Box
E-17-OZ	6	25	216.579	23	1993	CBGCP	Contin	7.5	7.41	3.83	
E-17-PA	6	25	216.58	23	1993	CBGCP	Contin	8	10.667	3.83	
E-17-PB	6	70	274	23	1993	SBGC	Contin	8.5	8'6" to 10'	3'6" & 5'6"	
E-17-PC	6	70	274.07	23	1993	SBGC	Contin	8.5	10', 8'6"	Stl Bx 3'6" to 5'6"	
E-17-PD	6	70	274.072	23	1993	SBGC	Contin	9.5	8.5	Stl Bx 6'4"	
E-17-PO	6	70	274.062	23	1993	SBGC	Contin	8.5	7.3	Stl Bx 5.6'	
E-17-PU	6	25	216.76	23	1993	CBGP	Simple	8	8.11	6.5	
E-17-PV	6	25	216.5	52	1993	CS	Simple	24			
E-17-PY	6	224	2.39	23	1993	CPGC	Contin		8	G54	

Bridge	Region	Hwy	Mile post	Element	Built	Type	Span Type	Deck Thick (in)	Stringer Spacing (ft)	Stringer Depth	Notes
E-17-RR	6	70	283.642	23	1993	WGK	Simple		5 @ 6’11”	7’8”	
E-17-RS	6	70	283.888	23	1993	WGK	Simple		4 @ 7’6”	7’2”	
E-17-RT	6	70	284.251	23	1993	WGCK	Contin		7 @ 7’6”	6’	
E-17-RU	6	70	284.62	35	1993	CPGC	Contin		6’ + 6@11’	PB 5’8”	G68
E-17-RV	6	70	284.41	23	1993	CBGCP	Contin	7.75	3 @ 10’8”	Mono Bx 4’0”	
E-17-RW	6	70	284.4	23	1993	CBGCP	Contin	7.75”	3 @ 10’8”	Mono Bx 4’4”	
F-07-AZ	3	70	121.25	26	1991	CBGP	Simple		5.4’	P Box 3’2”	Membrane
F-08-AR	3	70	125.91	26	1991	CBGS	Simple		16.7’	Single Box 10’	Membrane
F-08-AU	3	70	127.61	26	1991	CBGCP	Contin		7.7’	Mono Box 4’	Membrane
F-08-O	3	70	133.384	14	1980	CSGC	Contin	7.5	5 @ 7’5”	3’7.5”	
F-08-P	3	70	133.385	14	1980	CSGC	Contin	7.5	5 @ 7’5”	3’7.5”	
F-08-Q	3	70	133.483	14	1980	WGCK	Contin	8.5	4 @ 9’6”	7’1”	
F-08-S	3	70	133.772	14	1980	CICK	Contin	7.75	5 @ 7’8”	W33x118	
F-08-T	3	70	133.773	14	1980	CICK	Contin	7.75	5 @ 7’8”	W33x118	
F-08-U	3	70	134.053	14	1980	CSGC	Contin	7.5	5 @ 7’5”	3’7.5”	
F-08-V	3	70	134.054	14	1980	CSGC	Contin	7.5	6 @ 7’2.5”	3’7.5”	
F-11-BE	3	24	148.263	26	1991	CPGC	Contin		8	45	Membrane
F-11-BF	3	24	148.403	26	1991	CPG	Simple		6	5.67	Membrane
F-16-JV	6	88	8.873	14	1980	CICK	Contin	8.5	5 @ 7’9”	W36x186	
F-16-RI	6	40	296.37	26	1991	CBGCP	Contin	8.25	4 @ 9’	Mono box 5’6”	
F-16-RP	6	285	253.487	26	1991	CBGCP	Contin	7	5.25	4’7”	Sprd Bx
F-16-RQ	6	285	254.266	26	1991	CBGCP	Contin	7	7.9	3’10”	Sprd Bx
F-17-JW	6	25	194.36	26	1991	SBGC	Contin	7.58	7.5	5	Stl Bx
F-17-JW	6	25	194.36	26	1991	SBGC	Contin				
F-17-JX	6	470	25.748	26	1991	SBGC	Contin	8.5	10.5	W Bx 6’6”	
F-17-JY	6	25	195.4	26	1991	CPGC	Contin		8	G54	Membrane
F-17-JZ	6	25	195.6	26	1991	CPGC	Contin		8	G54	Membrane
F-20-BW	1	70	315.39	23	1993	CPGC	Contin		7.1	PB 5’8”	G68 Sealer
F-20-BX	1	70	315.389	23	1993	CPGC	Contin		7.3	PB 5.5’	
G-04-AA	3	70	62.886	14	1980	CPGC	Contin	7.25	5 @ 7’6”	PB 5’3.25”	G-54?

Bridge	Region	Hwy	Mile post	Element	Built	Type	Span Type	Deck Thick (in)	Stringer Spacing (ft)	Stringer Depth	Notes
G-04-AB	3	70	62.887	14	1980	CPGC	Contin	7.25	5 @ 7’6”	PB G-54	Membrane
G-04-AC	3	70	63.133	14	1980	CPGC	Contin	7.25	5 @ 7’6”	PB G-54	Membrane
G-04-AD	3	70	63.134	14	1980	CPGC	Contin	7.25	5 @ 7’6”	PB G-54	Membrane
G-04-AE	3	70	61.648	14	1980	CBGCP	Contin		10’	Mono box 5’6”	
G-04-AF	3	70	64.604	14	1980	CPGC	Contin	8.5	3 @ 13’4”	PB G-54	Membrane
G-04-AG	3	70	64.605	14	1980	CPGC	Contin	8.5	3 @ 13’8”	PB G-54	Membrane
G-04-AH	3	70	64.87	14	1980	CBGCP	Contin	8.5	8.9’	Mono Box 5’3”	Membrane
G-21-H	1	70	341.073	22	1971	CSG	Simple	7.5	4 @ 9’1”	2’9”	
G-21-K	1	70	350.904	22	1972	CSG	Simple	7	5 @ 7’6”	2’2”	
G-21-O	1	70	355.542	22	1972	CPG	Simple	7	5 @ 7’6”	4’0”	Membrane
G-22-BA	1	24	0.477	22	1975	CBGC	Contin				
G-22-BC	1	70	361.744	22	1975	WGCK	Contin	7.5	5 @ 7’7”	WS 80”	
G-22-BD	1	70	361.885	22	1975	WGCK	Contin		4@9’3”	WS 38”	HBP
G-22-BE	1	70	361.886	22	1975	WGCK	Contin		9’3”	WS 38”	
G-22-BF	1	70	361.93	22	1975	CICK	Contin	7.25	3 @ 8’0”	W27 X 84	
G-22-BG	1	70	362.3	22	1975	CPGC	Contin	7.25	4 @ 9’2”	PB 5’4”	G54
G-22-BH	1	70	362.301	22	1975	CPGC	Contin	7.25	4 @ 9’2”	PB 4’6”	G54
G-22-BJ	1	70	357.77	22	1972	CSG	Simple	7	5 @ 7’6”	2’2”	
G-22-BL	1	70	361.743	22	1975	WGCK	Contin	7.5	5 @ 7’7”	WS 80”	
G-22-BN	1	70	361.92	22	1975	WGCK	Contin	7.25	3 @ 8’0”	WS 38”	
G-22-BT	1	70	363.026	22	1975	WGCK	Contin	7.5	7’7”	WS 74”	
G-22-BU	1	70	363.025	22	1975	WGCK	Contin	7.5	5 @ 7’7”	WS 71”	
G-24-J	1	70	397.622	22	1975	CPG	Simple	7	6 @ 6’6”	4’6”	AASHTO IV
G-24-U	1	70	397.623	22	1975	CPG	Simple	7	6 @ 6’6”	4’6”	AASHTO IV
G-28-H	1	70	448.298	22	1969	CSGC	Contin	7.5	4 @ 8’6”	2’7.5”	
G-28-I	1	70	448.297	22	1969	CSGC	Contin	7.5	4 @ 8’6”	2’7.5”	
G-28-J	1	70	446.219	22	1969	CSGC	Contin	7.5	4 @ 8’6”	2’7.5”	
G-28-K	1	70	442.172	22	1969	CSGC	Contin	7.5	4 @ 8’6”	2’7.5”	
G-28-L	1	70	442.173	22	1969	CSGC	Contin	7.5	4 @ 8’6”	2’7.5”	
G-28-M	1	70	444.196	22	1969	CSGC	Contin	7.5	4 @ 8’6”	2’7.5”	

Bridge	Region	Hwy	Mile post	Element	Built	Type	Span Type	Deck Thick (in)	Stringer Spacing (ft)	Stringer Depth	Notes
G-28-N	1	70	446.22	22	1969	CSGC	Contin	7.5	4 @ 8’6”	2’7.5”	
G-28-O	1	70	444.197	22	1969	CSGC	Contin	7.5	4 @ 8’6”	2’7.5”	
H-17-CQ	1	25	172.018	14	1980	CICK	Contin	8.5	7.75	2.75	HBP 2”
I-06-O	3	133	12.45	26	1991	WGCK	Contin		5.6	24”	
I-06-V	3	133	13.99	26	1991	WGCK	Contin		11.3	5’3”	
I-07-S	3	133	15.95	26	1991	WGCK	Contin		11.2	5’8”	

Appendix 3 - NBI Deck Condition Ratings

Element 14 Decks

Table 69 - Element 14 Condition Summary

Bridge	Maximum Age (years)	Minimum Condition Rating	Most Recent Condition Rating	Condition Record Extent (years)
B-13-D	23	6	8	22
C-16-DI	23	7	8	23
E-16-KB	21	6	7	19
E-16-KD	24	6	8	22
F-08-O	24	7	7	24
F-08-P	24	7	7	24
F-08-Q	24	7	7	23
F-08-U	22	6	7	21
F-08-V	22	7	8	21
F-16-JV	22	6	7	20
G-04-AA	22	6	7	20
G-04-AB	22	5	7	20
G-04-AC	22	7	7	21
G-04-AD	22	6	8	21
G-04-AE	24	6	7	23
G-04-AF	22	6	7	21
G-04-AG	22	6	8	21
G-04-AH	24	6	7	23
H-17-CQ	23	6	7	22
Medians	22	6	7	21

Table 70 - NBI Condition Ratings – Element 14 Decks

B-13-D

Inspection Year	Deck	Super.	Sub.
1981	9	9	9
1984	7	7	7
1986	6	7	7
1988	6	8	8
1990	8	9	8
1992	8	8	8
1993	8	8	8
1995	8	8	8
1997	8	8	8
1999	8	8	8
2003	8	8	8

C-16-DI

Inspection Year	Deck	Super.	Sub.
1980	9	9	9
1981	8	8	8
1984	7	7	7
1986	7	7	7
1988	7	7	8
1990	7	8	8
1992	8	8	8
1993	8	8	8
1995	8	8	8
1997	8	8	8
1999	8	8	8
2001	8	8	7
2003	8	8	7

E-16-KB

Inspection Year	Deck	Super.	Sub.
1982	8	8	8
1984	8	8	8
1985	7	8	8
1986	8	8	8
1988	6	8	8
1990	7	8	8
1992	7	8	7
1995	7	8	7
1999	7	8	7
2001	7	8	7

E-16-KD

Inspection Year	Deck	Super.	Sub.
1982	8	8	8
1984	8	8	9
1985	8	8	8
1987	6	7	6
1989	6	8	7
1991	7	8	8
1993	7	8	8
1996	8	8	7
2000	8	7	7
2004	8	7	7

F-08-O

Inspection Year	Deck	Super.	Sub.
1980	8	8	8
1981	8	8	8
1983	8	8	8
1985	8	7	8
1986	8	8	8
1988	7	6	7
1990	7	7	7
1992	7	7	7
1994	7	7	7
1996	7	7	7
1998	7	8	8
2000	7	8	8
2002	7	8	8
2004	7	8	8

F-08-P

Inspection Year	Deck	Super.	Sub.
1980	8	8	8
1981	8	8	8
1983	8	8	8
1985	8	7	8
1986	8	8	8
1988	7	7	7
1990	8	8	7
1992	7	6	7
1994	7	7	7
1996	8	8	8
1998	8	8	8
2000	8	7	8
2002	7	7	7
2004	7	7	7

F-08-Q

Inspection Year	Deck	Super.	Sub.
1981	8	8	8
1983	8	8	8
1985	8	8	6
1986	7	8	6
1988	7	8	6
1990	7	8	7
1992	7	8	6
1994	7	8	8
1996	7	8	8
1998	7	8	8
2000	7	8	8
2002	7	8	8
2004	7	6	8

F-08-U

Inspection Year	Deck	Super.	Sub.
1981	8	8	8
1982	8	8	8
1984	7	8	8
1986	8	8	8
1988	7	8	8
1990	7	7	7
1992	6	7	7
1994	6	7	7
1996	7	8	8
1998	7	8	8
2002	7	8	7

F-08-V

Inspection Year	Deck	Super.	Sub.
1981	8	8	8
1982	8	8	8
1984	7	8	8
1986	8	8	8
1988	8	7	7
1990	7	8	7
1992	7	8	7
1994	7	7	7
1996	8	8	8
1998	8	8	8
2002	8	8	8

F-16-JV

Inspection Year	Deck	Super.	Sub.
1982	8	8	9
1983	7	8	8
1984	8	8	8
1986	8	8	8
1988	6	8	7
1990	7	8	7
1994	7	8	7
1996	7	8	8
1998	7	7	8
2002	7	7	8

G-04-AA

Inspection Year	Deck	Super.	Sub.
1982	9	9	9
1983	8	8	7
1985	7	8	7
1986	7	8	7
1987	6	8	6
1989	8	8	6
1991	8	8	7
1994	7	8	6
1996	7	8	6
1998	7	8	6
2002	7	8	6

G-04-AB

Inspection Year	Deck	Super.	Sub.
1982	8	8	8
1983	8	8	7
1985	7	8	7
1986	7	8	6
1987	5	7	5
1989	8	7	6
1991	7	8	6
1994	7	8	6
1996	7	8	6
1998	7	8	6
2002	7	8	6

G-04-AC

Inspection Year	Deck	Super.	Sub.
1981	9	9	9
1982	8	8	8
1983	8	8	8
1985	7	8	7
1986	7	8	8
1987	7	7	7
1989	9	8	7
1991	8	8	8
1994	7	8	8
1996	7	8	8
1998	7	8	8
2002	7	8	8

G-04-AD

Inspection Year	Deck	Super.	Sub.
1981	9	9	9
1982	8	8	8
1983	7	8	8
1985	7	8	7
1986	7	8	8
1987	6	7	7
1989	8	8	7
1991	8	8	7
1994	8	8	8
1996	8	8	8
1998	8	8	8
2002	8	8	8

G-04-AE

Inspection Year	Deck	Super.	Sub.
1981	9	9	9
1982	8	8	8
1983	8	8	8
1985	8	8	7
1986	7	8	7
1987	6	6	6
1989	8	6	6
1991	8	7	7
1994	7	7	7
1996	7	7	7
1998	7	7	7
2000	7	7	7
2002	7	7	7
2004	7	7	7

G-04-AF

Inspection Year	Deck	Super.	Sub.
1981	8	8	8
1982	8	9	8
1984	7	8	8
1985	7	8	7
1986	7	8	7
1987	6	7	6
1989	8	8	7
1991	7	8	7
1994	7	8	7
1996	7	8	7
1998	7	8	7
2002	7	8	7

G-04-AG

Inspection Year	Deck	Super.	Sub.
1981	8	8	8
1982	8	9	8
1984	7	8	8
1985	7	8	8
1986	7	8	7
1987	6	7	7
1989	9	9	7
1991	8	8	8
1994	8	9	8
1996	8	9	8
1998	8	8	8
2002	8	8	8

G-04-AH

Inspection Year	Deck	Super.	Sub.
1981	7	6	8
1982	8	8	7
1983	7	6	8
1985	6	6	6
1986	6	6	5
1987	6	6	5
1989	6	7	5
1991	7	7	5
1994	7	7	5
1996	7	8	6
1998	7	8	6
2000	7	8	7
2002	7	8	7
2004	7	8	7

H-17-CQ

Inspection Year	Deck	Super.	Sub.
1981	7	8	8
1982	9	9	9
1983	9	9	9
1985	8	8	8
1986	7	8	7
1987	6	8	8
1989	7	8	7
1991	7	8	7
1993	7	8	8
1995	7	8	7
1997	7	8	7
1999	7	7	7
2001	7	7	7
2003	7	7	7

Element 22 Decks

Table 71 - Element 22 Condition Summary

Bridge	Maximum Age (years)	Minimum Condition Rating	Most Recent Condition Rating	Condition Record Extent (years)
G-21-H	32	6	7	31
G-21-K	31	6	7	29
G-21-O	31	5	7	29
G-22-BA	28	6	7	25
G-22-BC	26	6	7	25
G-22-BD	26	6	7	25
G-22-BE	26	5	6	25
G-22-BF	26	6	7	25
G-22-BG	28	6	7	26
G-22-BH	28	6	6	26
G-22-BJ	31	6	7	30
G-22-BL	26	6	7	25
G-22-BN	28	6	7	27
G-22-BT	28	5	7	27
G-22-BU	28	5	6	27
G-24-J	28	6	8	26
G-24-U	28	6	7	26
G-28-H	34	6	6	31
G-28-I	34	6	7	31
G-28-J	34	6	7	31
G-28-K	34	6	7	31
G-28-L	34	4	6	31
G-28-M	34	6	7	31
G-28-N	34	5	5	31
G-28-O	34	6	6	31
Median	28	6	7	27

NBI Condition Ratings – Element 22 Decks

G-21-H (Project 1989)

Inspection Year	Deck	Super.	Sub.
1972	8	8	8
1974	8	8	8
1975	7	7	8
1978	9	9	9
1979	9	9	9
1980	6	7	6
1982	9	9	9
1984	8	9	9
1985	8	8	8
1986	6	7	6
1988	6	7	6
1990	7	7	6
1991	7	7	6
1993	7	7	6
1995	7	7	6
1997	7	7	6
2001	7	7	6
2003	7	7	6

G-21-K

Inspection Year	Deck	Super.	Sub.
1974	9	9	9
1975	8	8	8
1978	9	9	9
1979	9	9	9
1980	8	8	8
1982	9	9	9
1984	9	9	9
1985	8	8	8
1986	6	7	6
1988	6	7	7
1990	7	7	7
1992	7	7	7
1993	7	7	7
1995	7	7	7
1995	7	7	7
1997	7	7	7
1999	7	7	7
2001	7	7	7
2003	7	7	7

G-21-O

Inspection Year	Deck	Super.	Sub.
1974	8	8	8
1975	8	8	8
1978	9	9	9
1979	9	9	9
1980	8	8	8
1982	9	9	9
1983	8	8	8
1984	9	9	9
1985	7	8	7
1986	8	8	8
1987	5	7	6
1988	7	7	6
1990	7	8	7
1992	7	8	7
1993	7	8	7
1995	7	8	7
1997	8	8	8
1999	8	8	8
2001	7	8	7
2003	7	8	7

G-22-BA (Project 1999)

Inspection Year	Deck	Super.	Sub.
1978	9	9	9
1979	9	9	9
1980	8	7	8
1982	9	9	9
1984	9	9	9
1985	7	7	7
1986	7	7	7
1988	6	6	6
1990	6	6	6
1992	6	6	7
1993	6	6	7
1995	6	6	6
1997	6	6	6
1999	6	5	6
2001	7	5	6
2003	7	6	6

G-22-BC (Project 1999)

Inspection Year	Deck	Super.	Sub.
1976	8	8	8
1977	9	9	9
1978	7	8	8
1979	9	9	9
1982	9	9	9
1983	6	8	7
1984	9	9	9
1986	8	8	8
1988	6	6	7
1990	6	7	7
1992	6	7	7
1993	7	7	7
1995	7	7	7
1997	6	7	7
2000	7	7	7
2001	7	7	7

G-22-BD (Project 1999)

Inspection Year	Deck	Super.	Sub.
1976	8	8	8
1977	9	9	9
1978	7	8	8
1979	9	9	9
1982	9	9	9
1984	7	8	7
1985	8	8	8
1986	7	8	8
1988	6	8	7
1990	6	8	7
1992	7	8	7
1993	7	8	7
1995	7	8	7
1999	6	8	7
2001	7	8	7

G-22-BE (Project 19999)

Inspection Year	Deck	Super.	Sub.
1976	8	8	7
1977	9	9	7
1978	8	8	7
1979	9	9	9
1982	9	9	9
1984	7	8	7
1985	8	8	8
1986	6	8	7
1988	5	7	6
1990	7	8	7
1992	7	8	7
1993	7	7	7
1995	7	7	7
1997	7	7	7
2001	6	7	7

G-22-BF (Project 1999)

Inspection Year	Deck	Super.	Sub.
1976	8	8	8
1977	9	9	9
1978	7	8	7
1979	9	9	9
1982	9	9	9
1984	7	8	7
1985	8	8	8
1986	6	8	6
1988	7	8	7
1990	6	8	7
1992	7	8	7
1993	7	8	7
1995	7	8	7
1997	7	7	7
2001	7	7	7

G-22-BG (Project 1999)

Inspection Year	Deck	Super.	Sub.
1977	8	9	9
1978	9	9	9
1979	9	9	8
1980	9	9	9
1982	9	9	9
1984	7	8	7
1985	8	8	8
1986	6	8	7
1988	6	8	7
1990	7	8	7
1992	7	8	7
1993	7	8	7
1995	7	8	7
1997	7	8	7
2001	7	8	7
2003	7	8	7

G-22-BH (Project 1999)

Inspection Year	Deck	Super.	Sub.
1977	9	9	9
1978	9	9	9
1979	7	8	7
1980	9	9	9
1982	9	9	9
1984	7	8	7
1985	7	8	8
1986	6	8	8
1988	6	8	8
1990	7	8	7
1992	7	8	7
1993	7	8	7
1995	7	8	7
1997	7	8	7
2000	7	8	7
2001	6	8	7
2003	6	8	7

G-22-BJ

Inspection Year	Deck	Super.	Sub.
1973	9	9	9
1974	7	7	7
1978	9	9	9
1979	8	8	8
1980	9	9	9
1982	9	9	9
1984	8	8	8
1985	6	6	6
1986	6	6	7
1988	7	7	7
1990	7	7	7
1992	7	7	7
1993	7	7	7
1995	7	7	7
1997	8	7	8
1999	7	7	7
2001	7	7	7
2003	7	7	7

G-22-BL (Project 1999)

Inspection Year	Deck	Super.	Sub.
1976	8	8	8
1977	9	9	9
1978	6	8	8
1979	9	9	9
1979	9	9	9
1982	7	8	7
1984	9	9	9
1985	9	9	9
1986	7	7	7
1988	7	7	7
1990	7	7	7
1992	7	7	7
1993	7	7	7
1995	7	7	7
1997	6	7	7
1999	6	7	7
2000	7	7	7
2001	7	7	7

G-22-BN (Project 1999)

Inspection Year	Deck	Super.	Sub.
1976	8	8	8
1977	9	9	9
1978	8	8	8
1979	9	9	9
1982	9	9	9
1984	7	7	7
1985	8	8	8
1986	6	8	6
1988	7	8	7
1990	7	8	7
1992	7	8	7
1993	7	8	7
1995	6	8	7
1997	6	8	7
2001	7	8	7
2003	7	7	7

G-22-BT (Project 1999)

Inspection Year	Deck	Super.	Sub.
1976	8	7	7
1977	9	9	9
1978	7	7	7
1979	9	9	9
1982	9	9	9
1984	7	8	7
1985	8	8	8
1986	6	8	7
1988	5	7	6
1990	6	7	7
1992	6	7	7
1993	6	7	7
1995	6	7	7
1997	6	7	7
1999	6	7	7
2001	7	7	7
2003	7	7	7

G-22-BU (Project 1999)

Inspection Year	Deck	Super.	Sub.
1976	8	8	7
1977	9	9	9
1978	7	8	7
1979	9	9	9
1982	9	9	9
1984	7	8	7
1985	8	8	8
1986	6	8	7
1988	5	7	6
1990	6	7	7
1992	6	7	7
1993	6	7	7
1995	6	7	7
1997	6	7	6
1999	6	7	6
2001	6	7	7
2003	6	6	7

G-24-J (Project 1995)

Inspection Year	Deck	Super.	Sub.
1977	7	8	8
1978	9	9	9
1979	6	8	8
1980	9	9	9
1982	9	9	9
1984	7	8	8
1985	8	8	8
1986	8	8	8
1988	6	7	7
1990	6	8	7
1992	7	8	7
1993	7	8	7
1995	8	8	7
1997	8	8	7
2003	8	8	7

G-24-U (Project 1995)

Inspection Year	Deck	Super.	Sub.
1977	7	8	8
1978	9	9	9
1979	6	8	7
1980	9	9	9
1982	9	9	9
1984	7	8	8
1985	8	8	8
1986	6	8	7
1988	6	8	7
1990	6	8	6
1992	7	8	7
1993	7	8	7
1995	7	8	7
1997	7	8	7
1999	7	8	7
2003	7	8	7

G-28-H (Project 1995)

Inspection Year	Deck	Super.	Sub.
1972	8	8	8
1973	9	9	9
1976	8	9	9
1978	9	9	9
1979	9	9	9
1982	8	8	7
1983	9	9	9
1984	8	8	8
1987	6	7	7
1988	6	7	6
1990	6	8	7
1992	6	7	7
1993	6	7	7
1995	6	8	8
1997	6	8	8
1999	6	8	8
2001	6	8	8
2003	6	8	8

G-28-I (Project 1995)

Inspection Year	Deck	Super.	Sub.
1972	8	8	8
1973	9	9	9
1976	8	8	8
1978	9	9	9
1979	9	9	9
1982	7	8	8
1983	9	9	9
1984	8	8	8
1987	6	7	6
1988	6	7	7
1990	7	8	7
1992	7	7	7
1993	7	8	7
1995	8	8	8
1997	8	8	8
1999	8	8	8
2001	7	8	8
2003	7	8	8

G-28-J (Project 1995)

Inspection Year	Deck	Super.	Sub.
1972	8	8	8
1973	9	9	9
1976	7	8	7
1978	9	9	9
1979	9	9	9
1982	7	8	8
1983	9	9	9
1984	8	8	8
1987	6	7	7
1988	6	6	7
1990	7	8	7
1992	7	8	7
1993	7	8	7
1995	8	8	8
1997	7	8	8
1999	7	8	8
2001	7	8	8
2003	7	8	8

G-28-K (Project 1995)

Inspection Year	Deck	Super.	Sub.
1972	8	8	8
1973	9	9	9
1976	7	8	7
1978	9	9	9
1979	9	9	9
1982	7	8	7
1983	9	9	9
1984	8	8	8
1987	6	7	6
1988	7	7	7
1990	7	8	8
1992	7	8	8
1993	7	8	8
1995	8	8	8
1997	7	8	8
1999	7	8	7
2001	7	8	7
2003	7	8	7

G-28-L (Project 1995)

Inspection Year	Deck	Super.	Sub.
1972	8	8	8
1973	9	9	9
1976	7	8	8
1978	9	9	9
1979	8	8	8
1982	7	8	8
1983	9	9	9
1984	8	8	8
1987	6	8	8
1988	4	7	6
1990	5	8	7
1992	5	7	7
1993	5	7	7
1995	7	7	7
1997	7	7	7
1999	7	7	7
2001	6	7	7
2003	6	7	

G-28-M (Project 1995)

Inspection Year	Deck	Super.	Sub.
1972	8	8	8
1973	9	9	9
1976	7	8	7
1978	9	9	9
1979	9	9	9
1982	7	8	7
1983	9	9	9
1984	8	8	8
1987	6	8	8
1988	6	7	7
1990	6	8	7
1992	6	7	7
1993	6	7	7
1995	8	8	8
1997	8	8	8
1999	7	8	7
2001	7	8	7
2003	7	8	7

G-28-N (Project 1995)

Inspection Year	Deck	Super.	Sub.
1972	8	8	8
1973	9	9	9
1976	8	9	8
1978	9	9	9
1979	8	8	8
1982	7	8	8
1983	9	9	9
1984	8	8	8
1987	6	7	6
1988	6	7	6
1990	7	8	7
1992	6	7	7
1993	6	7	7
1995	6	7	8
1997	6	7	8
1999	6	7	8
2001	5	6	7
2003	5	6	7

G-28-O (Project 1995)

Inspection Year	Deck	Super.	Sub.
1972	8	8	8
1973	9	9	9
1976	8	9	8
1978	9	9	9
1979	8	8	8
1982	7	8	8
1983	9	9	9
1984	8	8	8
1988	7	7	6
1990	7	8	8
1992	7	8	7
1993	7	8	7
1995	7	8	8
1997	7	8	8
1999	7	8	8
2001	6	6	7
2003	6	6	7

ELEMENT 23 DECKS

Table 72 - Element 23 Condition Summary

Bridge	Maximum Age (years)	Minimum Condition Rating	Most Recent Condition Rating	Condition Record Extent (years)
E-16-NX	11	6	6	10
E-16-OP	11	6	6	9
E-16-PJ	11	6	6	9
E-17-OK	10	7	7	8
E-17-OL	10	7	7	9
E-17-OM	10	6	6	9
E-17-ON	10	7	7	9
E-17-OP	10	7	7	8
E-17-OZ	11	7	7	11
E-17-PA	11	7	7	11
E-17-PB	11	7	7	9
E-17-PC	10	7	7	8
E-17-PD	11	7	7	9
E-17-PO	11	7	7	11
E-17-PU	10	8	8	10
E-17-PY	10	7	7	9
E-17-RR	10	7	7	9
E-17-RS	10	8	8	9
E-17-RT	10	7	7	9
E-17-RV	10	7	7	9
E-17-RW	10	7	7	9
F-20-BW	10	6	6	10
F-20-BX	10	6	6	10
Median	10	7	7	9

NBI Condition Ratings – Element 23 Decks

E-16-NX

Inspection Year	Deck	Super.	Sub.
1994	7	9	9
1996	6	9	9
1998	6	8	8
2000	6	8	8
2002	6	8	8
2004	6	8	8

E-16-OP

Inspection Year	Deck	Super.	Sub.
1995	7	7	8
1996	7	7	8
1998	7	7	8
2000	7	7	8
2002	7	7	8
2004	6	7	8

E-16-PJ

Inspection Year	Deck	Super.	Sub.
1995	7	8	8
1996	7	7	8
1998	7	7	8
2000	7	7	8
2002	7	7	8
2004	6	7	8

E-17-OK

Inspection Year	Deck	Super.	Sub.
1995	8	8	8
1997	8	8	8
1999	8	8	7
2001	7	8	8
2003	7	8	8

E-17-OL

Inspection Year	Deck	Super.	Sub.
1994	7	8	8
1995	7	8	8
1997	7	8	8
1999	7	8	8
2001	7	8	8
2003	7	8	8

E-17-OM

Inspection Year	Deck	Super.	Sub.
1994	7	8	8
1995	7	8	8
1997	7	8	8
1999	7	8	8
2001	7	8	8
2003	6	8	7

E-17-ON

Inspection Year	Deck	Super.	Sub.
1994	8	8	8
1997	7	8	8
1999	7	8	8
2003	7	8	8

E-17-OP

Inspection Year	Deck	Super.	Sub.
1995	8	8	8
1997	7	8	8
1999	7	8	7
2001	7	8	8
2003	7	8	8

E-17-OZ

Inspection Year	Deck	Super.	Sub.
1993	8	8	8
1994	7	9	8
1996	7	9	8
1998	7	8	8
2000	7	8	8
2002	7	8	8
2004	7	8	8

E-17-PA

Inspection Year	Deck	Super.	Sub.
1993	7	8	8
1994	7	9	8
1996	7	8	8
1998	7	8	8
2000	7	8	8
2002	7	8	8
2004	7	8	8

E-17-PB

Inspection Year	Deck	Super.	Sub.
1995	8	8	8
1996	7	8	8
1998	7	8	8
1999	7	8	8
2002	7	8	8
2004	7	8	8

E-17-PC

Inspection Year	Deck	Super.	Sub.
1995	7	8	7
1997	7	8	8
1999	7	8	8
2001	7	8	8
2003	7	8	8

E-17-PD

Inspection Year	Deck	Super.	Sub.
1995	7	8	8
1996	7	7	8
1998	7	7	8
1999	7	7	8
2002	7	7	8
2004	7	7	8

E-17-PO

Inspection Year	Deck	Super.	Sub.
1993	7	8	8
1995	7	8	8
1997	7	8	8
2000	7	8	8
2002	7	8	8
2004	7	8	8

E-17-PU

Inspection Year	Deck	Super.	Sub.
1993	8	8	9
1995	8	8	8
1997	8	8	8
1999	8	8	8
2001	8	8	8
2003	8	8	8

E-17-PY

Inspection Year	Deck	Super.	Sub.
1994	8	8	8
1997	7	8	8
1999	7	8	8
2001	7	8	8
2003	7	8	7

E-17-RR

Inspection Year	Deck	Super.	Sub.
1994	8	8	7
1995	8	8	7
1997	7	8	7
1999	7	8	7
2001	7	8	7
2003	7	8	7

E-17-RS

Inspection Year	Deck	Super.	Sub.
1994	8	8	8
1995	8	8	8
1997	8	8	8
1999	8	8	7
2001	8	8	7
2003	8	8	7

E-17-RT

Inspection Year	Deck	Super.	Sub.
1994	7	8	8
1995	7	8	7
1997	7	8	7
1999	7	8	7
2003	7	7	7

E-17-RV

Inspection Year	Deck	Super.	Sub.
1994	8	8	8
1995	8	8	8
1997	8	8	8
2002	7	8	8
2003	7	8	8

E-17-RW

Inspection Year	Deck	Super.	Sub.
1994	8	8	8
1995	8	8	8
1997	8	8	8
2002	7	8	8
2003	7	8	8

F-20-BW

Inspection Year	Deck	Super.	Sub.
1993	7	9	8
1995	6	8	7
1997	6	8	7
1999	6	8	7
2001	6	8	7
2003	6	8	7

F-20-BX

Inspection Year	Deck	Super.	Sub.
1993	7	8	8
1995	6	8	8
1997	6	8	8
1999	6	8	8
2001	6	8	7
2003	6	8	7

ELEMENT 26 DECKS

Table 73 - Element 26 Condition Summary

Bridge	Maximum Age (years)	Minimum Condition Rating	Most Recent Condition Rating	Condition Record Extent (years)
E-17-NZ	12	7	7	11
E-17-OH	12	8	8	11
E-17-OO	10	8	8	8
F-07-AZ	13	7	7	12
F-08-AU	13	7	7	12
F-11-BE	11	8	8	11
F-11-BF	13	8	8	13
F-16-RI	10	7	7	10
F-16-RP	12	7	8	12
F-16-RQ	12	7	7	12
F-17-JW	12	7	7	11
F-17-JX	12	7	7	11
F-17-JY	13	8	8	12
F-17-JZ	13	7	7	12
I-07-S	13	7	7	12
Median	12	7	7	12

NBI Condition Ratings – Element 26 Decks

E-17-NZ

Inspection Year	Deck	Super.	Sub.
1992	7	9	8
1993	7	8	8
1995	7	8	7
1997	7	7	7
1999	7	7	7
2001	7	7	7
2003	7	7	7

E-17-OH

Inspection Year	Deck	Super.	Sub.
1992	8	9	8
1993	8	8	8
1995	8	8	8
1997	8	8	8
1999	8	8	8
2001	8	8	8
2003	8	8	8

E-17-OO

Inspection Year	Deck	Super.	Sub.
1993	8	8	8
1997	8	8	8
1999	8	8	8
2001	8	7	8

F-07-AZ

Inspection Year	Deck	Super.	Sub.
1992	7	7	7
1994	7	7	7
1996	8	7	8
1998	8	7	8
2002	8	7	8
2004	7	7	7

F-08-AU

Inspection Year	Deck	Super.	Sub.
1992	8	8	8
1994	8	7	7
1996	8	7	7
1998	7	7	7
2000	7	7	7
2002	7	7	7
2004	7	7	7

F-11-BE

Inspection Year	Deck	Super.	Sub.
1991	9	9	8
1994	8	8	8
1996	8	8	7
1998	8	8	7
2002	8	8	7

F-11-BF

Inspection Year	Deck	Super.	Sub.
1991	8	9	8
1994	8	8	8
1996	8	8	7
1998	8	8	7
2000	8	8	7
2002	8	8	7
2004	8	8	7

F-16-RI

Inspection Year	Deck	Super.	Sub.
1991	7	8	8
1994	7	7	7
1997	7	7	7
1999	7	7	7
2001	7	7	7

F-16-RP

Inspection Year	Deck	Super.	Sub.
1991	8	9	9
1993	7	8	8
1995	8	8	8
1997	7	8	7
1999	8	8	8
2001	8	7	7
2003	8	8	8

F-16-RQ

Inspection Year	Deck	Super.	Sub.
1991	8	9	9
1993	7	8	8
1995	7	8	8
1997	7	8	8
1999	7	8	8
2001	7	8	8
2003	7	8	8

F-17-JW

Inspection Year	Deck	Super.	Sub.
1992	7	8	8
1993	8	9	8
1995	8	8	8
1997	8	8	8
2001	8	8	8
2003	7	8	8

F-17-JX

Inspection Year	Deck	Super.	Sub.
1992	8	9	9
1993	7	8	8
1995	7	8	8
1997	8	8	8
1999	7	8	8
2001	7	8	8
2003	7	8	8

F-17-JY

Inspection Year	Deck	Super.	Sub.
1992	8	8	9
1993	8	8	8
1995	8	8	8
1997	8	8	8
1999	8	8	8
2001	8	8	8
2004	8	8	8

F-17-JZ

Inspection Year	Deck	Super.	Sub.
1992	8	8	8
1993	8	8	8
1995	8	8	8
1997	8	8	8
2001	7	8	8
2004	7	8	8

I-07-S

Inspection Year	Deck	Super.	Sub.
1992	7	8	7
1994	8	8	8
1995	8	8	8
1996	8	8	8
1998	7	8	8
2000	7	8	8
2002	7	8	8
2004	7	8	8

Appendix 4 - Trend Lines for Deck Service Life

Table 74 – Trend Lines, Element 14 Decks

Bridge ID	Condition Rating at Zero Age	Condition Rating Trend (per year)	Service Life Estimate (years)	Regression Coefficient
B-13-D	9	-0.082	49	0.45
C-16-DI	9	-0.095	42	0.57
E-16-KB	8	-0.069	58	0.67
E-16-KD	8	-0.033	121	0.18
F-08-O	8	-0.055	73	0.88
F-08-P	8	-0.031	131	0.49
F-08-Q	8	-0.057	70	0.86
F-08-U	8	-0.080	50	0.74
F-08-V	8	-0.025	163	0.25
F-16-JV	8	-0.066	60	0.66
G-04-AA	9	-0.130	31	0.74
G-04-AB	8	-0.071	56	0.50
G-04-AC	9	-0.121	33	0.75
G-04-AD	9	-0.089	45	0.45
G-04-AE	9	-0.114	35	0.79
G-04-AF	8	-0.069	58	0.63
G-04-AG	8	-0.013	319	0.03
G-04-AH	8	-0.071	56	0.52
H-17-CQ	9	-0.127	32	0.75

Table 75 – Trend Lines, Element 22 Decks – Initial Service (pre-Rehab and No Rehab)

Bridge ID	Condition Rating at Zero Age	Condition Rating Trend (per year)	Service Life Estimate (years)	Regression Coefficient
G-21-H	9	-0.133	30	0.61
G-21-K	9	-0.111	36	0.60
G-21-O	9	-0.045	88	0.40
G-22-BA	9	-0.151	26	0.91
G-22-BC	9	-0.143	28	0.77
G-22-BD	9	-0.181	22	0.66
G-22-BE	9	-0.132	30	0.77
G-22-BF	9	-0.129	31	0.79
G-22-BG	9	-0.125	32	0.81
G-22-BH	9	-0.132	30	0.79
G-22-BJ	9	-0.085	47	0.74
G-22-BL	9	-0.121	33	0.72
G-22-BN	9	-0.140	29	0.88
G-22-BT	9	-0.174	23	0.86
G-22-BU	9	-0.164	24	0.86
G-24-J	9	-0.148	27	0.69
G-24-U	9	-0.164	24	0.71
G-28-H	9	-0.115	35	0.85
G-28-I	9	-0.097	41	0.78

Bridge ID	Condition Rating at Zero Age	Condition Rating Trend (per year)	Service Life Estimate (years)	Regression Coefficient
G-28-J	9	-0..099	40	0.76
G-28-K	9	-0.093	43	0.76
G-28-L	9	-0.159	25	0.84
G-28-M	9	-0.121	33	0.82
G-28-N	9	-0.115	35	0.85
G-28-O	9	-0.085	47	0.84

Table 76 – Trend Lines, Element 22 Decks – Overall for Rehabilitated Decks

Bridge ID	Condition Rating at Zero Age	Condition Rating Trend (per year)	Service Life Estimate (years)	Regression Coefficient
G-21-H	9	-0.090	44	0.73
G-22-BA	9	-0.125	32	0.85
G-22-BC	9	-0.119	34	0.75
G-22-BD	9	-0.123	32	0.81
G-22-BE	9	-0.129	31	0.80
G-22-BF	9	-0.117	34	0.78
G-22-BG	9	-0.105	38	0.79
G-22-BH	9	-0.117	34	0.84
G-22-BL	9	-0.109	37	0.77
G-22-BN	9	-0.114	35	0.83
G-22-BT	9	-0.134	30	0.79
G-22-BU	9	-0.146	27	0.86
G-24-J	9	-0.091	44	0.53
G-24-U	9	-0.115	35	0.70
G-28-H	9	-0.105	38	0.90
G-28-I	9	-0.067	59	0.72
G-28-J	9	-0.076	53	0.77
G-28-K	9	-0.074	54	0.79
G-28-L	9	-0.112	36	0.78
G-28-M	9	-0.081	49	0.73
G-28-N	9	-0.114	35	0.93
G-28-O	9	-0.082	49	0.92

Table 77 – Trend Lines, Element 23 Decks

Bridge ID	Condition Rating at Zero Age	Condition Rating Trend (per year)	Service Life Estimate (years)	Regression Coefficient
E-16-NX	8	-0.248	16	0.84
E-16-OP	8	-0.166	24	0.89
E-16-PJ	8	-0.166	24	0.89
E-17-OK	8	-0.082	49	0.74
E-17-OL	8	-0.140	29	0.72
E-17-OM	8	-0.186	22	0.85
E-17-ON	8	-0.131	31	0.87
E-17-OP	8	-0.127	31	0.89

Bridge ID	Condition Rating at Zero Age	Condition Rating Trend (per year)	Service Life Estimate (years)	Regression Coefficient
E-17-OZ	8	-0.126	32	0.76
E-17-PA	8	-0.126	32	0.65
E-17-PB	8	-0.123	32	0.84
E-17-PC	8	-0.136	29	0.82
E-17-PD	8	-0.130	31	0.78
E-17-PO	8	-0.122	33	0.67
E-17-PU	9	-0.136	29	0.68
E-17-PY	8	-0.129	31	0.90
E-17-RR	8	-0.127	32	0.89
E-17-RS	9	-0.140	29	0.72
E-17-RT	8	-0.147	27	0.67
E-17-RV	8	-0.094	43	0.89
E-17-RW	8	-0.094	43	0.89
F-20-BW	8	-0.273	15	0.78
F-20-BX	8	-0.273	15	0.78

Table 78 –Trend Lines, Element 26 Decks

Bridge ID	Condition Rating at Zero Age	Condition Rating Trend (per year)	Service Life Estimate (years)	Regression Coefficient
E-17-NZ	8	-0.118	34	0.72
E-17-OH	9	-0.118	34	0.72
E-17-OO	9	-0.127	31	0.83
F-07-AZ	8	-0.045	88	0.26
F-08-AU	8	-0.088	46	0.88
F-11-BE	9	-0.127	31	0.83
F-11-BF	9	-0.146	27	0.70
F-16-RI	8	-0.129	31	0.70
F-16-RP	9	-0.137	29	0.53
F-16-RQ	8	-0.115	35	0.81
F-17-JW	8	-0.043	93	0.28
F-17-JX	8	-0.099	41	0.71
F-17-JY	9	-0.113	35	0.71
F-17-JZ	8	-0.071	57	0.81
I-07-S	8	-0.087	46	0.71

Inflation Information

Table 79 - US Army Corps Cost Indices for Feature 08 [19]

Year	Cost Index
1969	112.79
1970	118.78
1971	134.7
1972	146.5
1973	153.85
1974	167.31
1975	193.03
1976	206.77
1977	218.7
1978	239.5
1979	260.37
1980	280.18
1981	306.16
1982	327.4
1983	340.86
1984	349.51
1985	355.43
1986	358.36

Year	Cost Index
1987	366.32
1988	380.42
1989	394.57
1990	402.95
1991	411.27
1992	422.37
1993	440.44
1994	454.26
1995	463.84
1996	473.27
1997	486.24
1998	490.26
1999	501.14
2000	507.97
2001	513.3
2002	529.95
2003	541.73

Appendix 5 - Test Results of Chloride Profiles in Concrete Cores

CORING CONCRETE SAMPLES

Two bridges were selected in the project for coring concrete samples: G-22-BJ and G-22-BL. See Figure 11 and 12.

Figure 11 - Bridge G-22-BJ Westbound and CDOT Traffic Control Team

Figure 12 - Bridge G-22-BL

The concrete samples were then tested for chloride profiles. Information on the concrete cores follows:

BRIDGE G-22-BJ ON WESTBOUND I-70, MP 357.77 (WEST OF LIMON)

Two concrete cores were taken.

One core was taken from the traffic lane, 4 ft inside of the shoulder line. The core was broken into two portions during the drilling process. The top portion was numbered as J↑1L, and the bottom portion J↑2L. The other core was taken from the shoulder, 5 ft outside of the shoulder line. The core was numbered as J↑S.

There was no steel bar found in the concrete cores. Figure 13 shows the coring site on the bridge G-22-BJ.

BRIDGE G-22-BL ON EASTBOUND I-70, MP 361.743 (EAST OF LIMON)

Two concrete cores were taken.

One core was taken from the traffic lane, 4.5 ft inside of the shoulder line. The core was broken into two portions during the drilling process. The top portion was numbered as L↑1L, and the bottom portion was numbered as L↑2L. The other core was taken from the shoulder, 4.5 ft outside of the shoulder line. The core was numbered as L↑S.

There was no steel bar found in the concrete cores. Figure 14 shows the coring site on the bridge G-22-BL.

NOTATIONS USED FOR NUMBERING THE CORES

J – G-22-BJ.

L (the first L) – G-22-BL (the first L)

↑ - Points to the top surface.

1 and 2 – top and bottom portion.

L (the last L) – Traffic lane.

S – Shoulder.

Figure 13 - Coring Concrete Samples on Bridge G-22-BJ. The Core Was Broken in the Traffic Lane

Figure 14 - Coring Concrete Samples on Bridge G-22-BL from the Shoulder

GEOMETRICAL DIMENSIONS OF CONCRETE CORES

The location and geometrical dimensions of the drilled concrete cores are shown in Table 80.

Table 80 - Location and Geometrical Dimensions of Concrete Cores

Concrete Core	Mean Diameter (in)	Mean Height (in)	Location	
J↑S	5.6932	-	West Bound	Shoulder
J↑1L	5.6937	3.3363		Traffic lane (Top)
J↑2L	5.6937	3.5575		Traffic lane (Bottom)
L↑S	5.6965	-	East Bound	Shoulder
L↑1L	5.6903	2.8820		Traffic lane (Top)
L↑2L	5.6903	2.3341		Traffic lane (Bottom)

CHLORIDE PROFILES OF CONCRETE CORES

The chloride concentrations at different depth of concrete cores obtained from the bridge decks are shown in Table 81 for all concrete cores. The chloride profiles of concrete cores from the shoulders were shown in Figure 15, and Figure 18, and the chloride profiles of broken concrete cores from traffic lanes were connected and shown in Figure 16 and Figure 18.

Table 81 - Chloride Concentrations at Different Depths of Concrete Cores

J↑S			J↑1L, J↑2L			L↑S			L↑1L, L↑2L		
No.	Depth (in)	Cl- (%)	No.	Depth (in)	Cl- (%)	No.	Depth (in)	Cl- (%)	No.	Depth (in)	Cl- (%)
J↑S1	0.15	0.219	J↑1L1	0.11	0.237	L↑S1	0.11	0.357	L↑1L1	0.12	0.332
J↑S2	0.50	0.273	J↑1L2	0.30	0.260	L↑S2	0.32	0.314	L↑1L2	0.35	0.343
J↑S3	0.95	0.252	J↑1L3	0.49	0.232	L↑S3	0.49	0.311	L↑1L3	0.56	0.276
J↑S4	1.10	0.176	J↑1L4	0.68	0.184	L↑S4	0.66	0.280	L↑1L4	0.77	0.257
J↑S5	1.25	0.137	J↑1L5	0.87	0.165	L↑S5	0.84	0.279	L↑1L5	1.00	0.240
J↑S6	1.43	0.188	J↑1L6	1.08	0.049	L↑S6	1.00	0.234	L↑1L6	1.24	0.214
J↑S7	1.58	0.173	J↑1L7	1.31	0.043	L↑S7	1.20	0.230	L↑1L7	1.50	0.153
J↑S8	1.70	0.168	J↑1L8	1.54	0.037	L↑S8	1.40	0.252	L↑1L8	1.73	0.095
J↑S9	1.93	0.125	J↑1L9	1.75	0.023	L↑S9	1.59	0.249	L↑1L9	1.91	0.047
J↑S10	2.02	0.130	J↑1L10	1.93	0.011	L↑S10	1.76	0.213	L↑1L10	2.09	0.036
J↑S11	2.18	0.115	J↑1L11	2.11	0.006	L↑S11	1.90	0.150	L↑1L11	2.29	0.014
J↑S12	2.30	0.066	J↑2L1	3.50	0	L↑S12	2.07	0.137	L↑1L12	2.49	0.008
J↑S13	2.50	0.048	J↑2L2	3.76	0	L↑S13	2.26	0.155	L↑1L13	2.71	0
J↑S14	3.00	0	J↑2L3	3.96	0	L↑S14	2.47	0.040	L↑2L1	3.07	0
J↑S15	3.25	0				L↑S15	2.69	0.035	L↑2L2	3.31	0
						L↑S16	2.87	0.028	L↑2L3	3.47	0
						L↑S17	3.09	0.022	L↑2L4	3.63	0
						L↑S18	3.38	0.001			

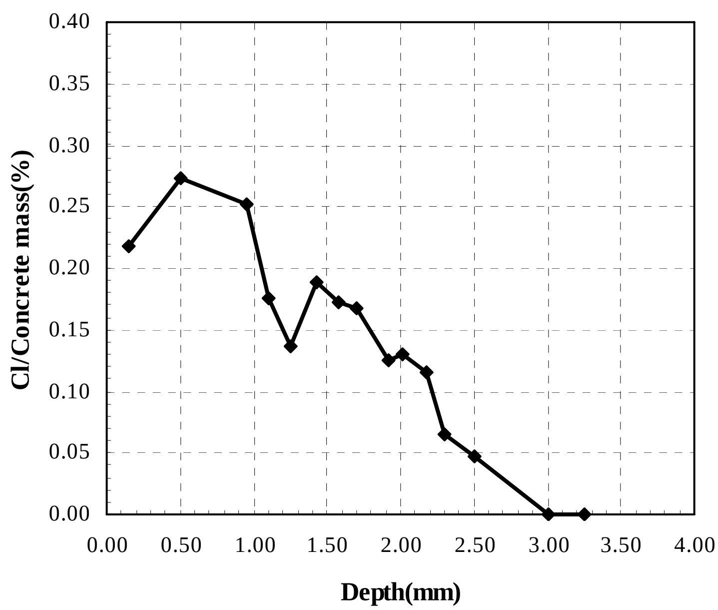


Figure 15 - Chloride Profile in Concrete Core J↑S

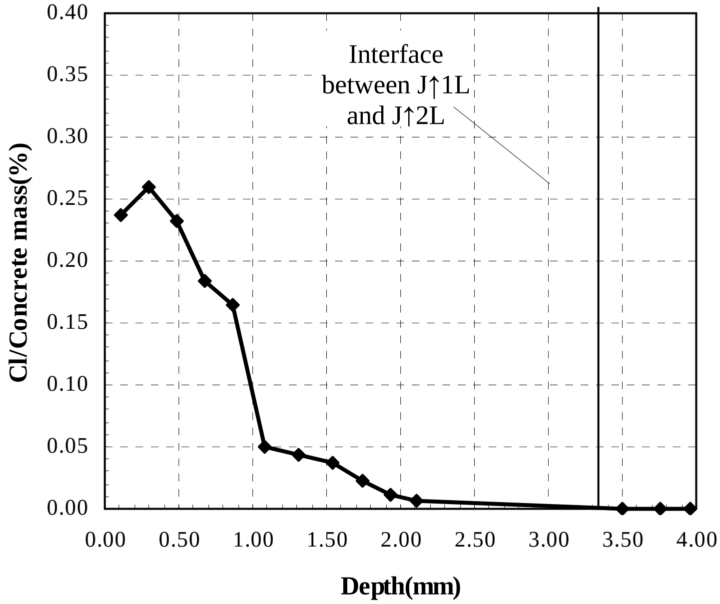


Figure 16 - Chloride Profile in Concrete Core J↑1L and J↑2L

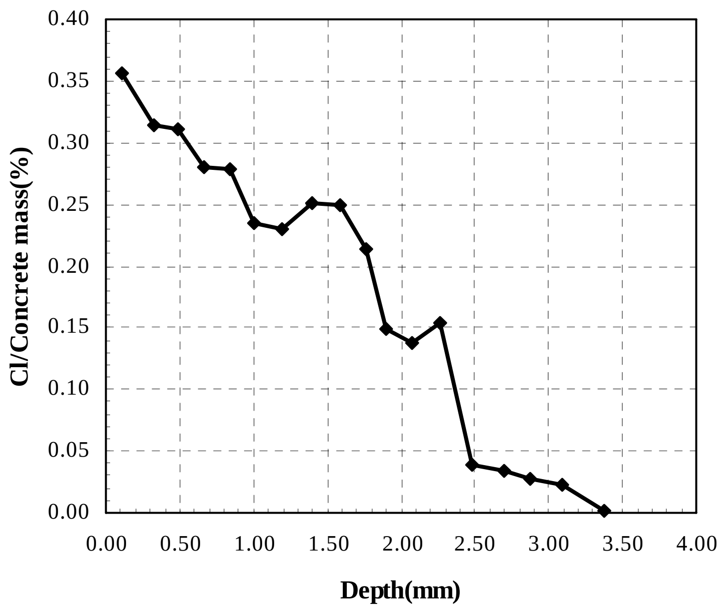


Figure 17 - Chloride Profile in Concrete Core L↑S

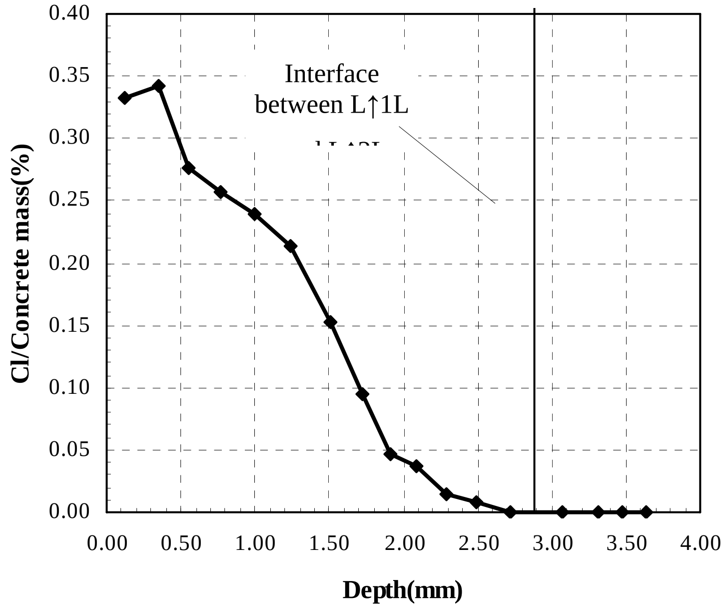


Figure 18 -Chloride Profile in Concrete Core L↑1L and L↑2L

CONCLUSIONS ON CHLORIDE TESTING

1. On the pavement surface, the chloride concentrations of the concrete in G-22-BJ (about 0.25%) are lower than the concentrations of G-22-BL (about 0.35%). This is observed for both traffic lane and shoulder of the two bridges. This may be due to the difference in the amount of salt applied in the two bridges, or due to different traffic loads on the west bound and east bound of I-70 near Limon.
2. The surface chloride concentrations in traffic lane are about the same as the concentrations from the shoulder. This is observed for both bridges. This means that the shoulders (up to 5 ft. outside of traffic lane) received same amount of salt as the traffic lane.
3. The interior chloride concentrations in traffic lane are much lower than the interior concentrations in the shoulder. For example, the chloride concentrations at 2.5 inches in the traffic lanes of the two bridges are about zero, while the chloride concentrations at the same depth in the shoulders of the two bridges are about 0.05%. This means that the chloride penetrate faster in the shoulders than in the traffic lane.
4. Usually, concrete in traffic lane exhibits more severe damage than the concrete in shoulder. As a result, the chloride penetration process in traffic lane should be faster than in the shoulder (with less damage). The opposite trend observed in the present project deserves further research.
5. Both concrete cores from traffic lanes broke at the depth about 3 inches. We initially thought that there would be an overlay placed on the bridge decks and the cores were broken along the interface between the old concrete and the overlay. From Figure 16 and Figure 18, the profiles of two pieces of concrete (top pieces and bottom pieces) connect very well, which means that there was no overlay placed on the bridge decks.

Appendix 6 - Notes on 2004 Literature Sources

Henry G. Russell (2004). "Concrete Bridge Deck Performance." NCHRP Synthesis 333, TRB, Washington, 188p.

Synthesis 333 reviews standard deck constructions used in 45 transportation agencies. Review includes concrete materials, reinforcement materials, protective systems, design practice, construction practice, specifications and costs.

All data are from a survey sent to transportation agencies.

Excerpts:

"This synthesis provides information on previous and current design and construction practices that have been used with the goal of improving the performance of concrete bridge decks.

"Post-tensioned concrete bridge decks are not included in this report.

"Information was obtained from a literature review and from the 45 responses to a survey questionnaire sent to 64 highway agencies in the United States and Canada.

TABLE 3 (Russell 2004)
USE OF WATERPROOFING MEMBRANE SYSTEMS

	No. of Respondents[a]		Performance Rating[b]	
Material	Past	Current	Range	Average
Preformed Systems				
None	10	10	—	—
Asphalt-impregnated fabric	15	9	2 to 5	3.0
Polymer	4	0	2 to 5	2.8
Elastomer	3	4	1 to 5	3.2
Asphalt-laminated board	7	3	2 to 4	3.0
Other	2	2	2 to 4	2.7
Liquid Systems				
Bituminous	11	10	1 to 5	2.8
Resinous	3	3	1 to 5	3.3
Other	4	3	1 to 4	2.6

[a]Total number of survey respondents = 45.
[b]1 = excellent, 5 = poor, — = not applicable.

Thirty-four transportation agencies use some form of membrane. Performance, for each and every product, ranges from excellent to poor. This could mean that all DOTs have poor experience with some products, or that some DOTs have poor experience with all products. The data presented here do not reveal this.

TABLE 4 (Russell 2004)

USE OF SEALERS
No. of Respondents[a] Performance Rating[b] Sealer Past Current Range Average
None 4 7 — —
Silanes, Siloxanes 17 19 1 to 5 2.8
Epoxies 10 9 1 to 4 3.0
Linseed Oil 24 7 1 to 5 3.6
Other 11 8 1 to 5 4.2 [a]Total number of survey respondents = 45. [b]1= excellent, 5 = poor, — = not applicable.

Forty-three agencies use sealers. Performance ratings for each and every product range from excellent to poor. Notice further that there is no quantitative information on performance, such as years to first pothole, years to deck rehab, years to deck replacement, years to Cl- content at level of steel, years to specific NBI rating, etc.

“In the survey for this synthesis, 15 or 33% of the 45 respondents indicated that they repair cracks in bridge decks, 9 or 20% indicated that they did not repair cracks, and 17 or 38% indicated that they repair cracks sometimes. “Sometimes” depended on the severity of the cracking. The more frequently listed crack repair methods were epoxy injection and the use of methacrylates or other sealants. Of these, epoxy injection and methacrylates were identified as the most effective in prolonging bridge deck life.

“In the survey conducted for this synthesis, the Ohio DOT was the only U.S. transportation agency that reported the use of warranties as part of their specifications. In 1999, Ohio introduced a specification requiring contractors to warrant new bridge decks constructed with HPC (Schultz 2002). The contractor is required to warrant against alligator and map cracking for 1 year and against scaling and spalling for 7 years.

It is telling that the warranty is only for 7 years for scaling and spalling. This, perhaps, is the extent of predictable/reliable performance of a reinforced concrete deck;

The questions themselves seek DOTs response as ‘least effective’ and ‘most effective’ product/material/practice in the construction of bridge decks.

Sprinkle, M. (2003) ”Twenty-five year experience with polymer concrete bridge deck overlay.” ACI SP-214, Polymers in Concrete, the First Thirty Years, A.O.Kaeding, R.C. Prusinski, eds., p51-61.

The paper reports monitoring/testing of 14 decks with polymer concrete overlays. Average age at survey ranged from 7 to 12 years. The oldest overlay was 19 years old. Primary survey done in 1995. The last survey in 2000 of the oldest overly (then 25 years old).

Tests included tensile bond strength, permeability to Cl- (AASHTO T 277), ASTM E 524 skid resistance,

Data suggest that average service life is 25 years for polymer overlays.

Oddly the paper does not report the surface condition of the decks. The presence of cracks or spalls is not reported.

Daniel M. Balmer 1 and George E. Ramey, (2003)”Effects of Bridge Deck Thickness on Properties and Behavior of Bridge Decks.” Practice Periodical On Structural Design And Construction, ASCE, p 83-93

The authors use a numerical analysis of flexural response, both as static loading and as vibratory loads to compute the probability of cracking in bridge decks. Cracking, by itself, is equated with a loss of service. The authors propose an increase to deck thickness, since the greater stiffness should mean fewer cracks. No material-, curing- or construction-related sources of deck cracking are considered. The paper presents no field data for decks.

G. C. M. Gaal, C. Van der veen, J. C. Walraven, and M. H. Djorai (2003). “Prediction of Deterioration - Start Application of Deicing Agent Taken into Account” TRB 9th International Bridge Management Conference, p407-417.

Model of Cl- diffusion is enhanced with a time-dependent diffusion coefficient. This allows age at first exposure to be recognized. The diffusion coefficient is said to decrease with time. Comparison is made between spalled area predicted by the diffusion-based model and observed spalled area in some 50 decks. Data on spalled area are very scattered. The model passes through these data, but offers little info on likely performance of individual decks.

Khossrow Babaei (2003). "Methodology for Prediction of Condition of Concrete Bridge Decks at Network Level." TRB 9th International Bridge Management Conference, p418-429

The author proposes 27 groups of bridge decks in the US leading to 27 matrices of transition probabilities. The groups arise from 3 salt exposure levels, 3 ranges of cover depth and 3 ranges of water/cement ratio. Transition probabilities correspond to Pontis condition states for bridge decks. Permeability to Cl- is correlated with water-cement ratio of concrete.

The author proposes that the effect of epoxy coating on reinforcing steel is a 10-year extension of the initial period of no corrosion Later performance of deck will match that of deck having unprotected steel.

Comparison to element-level data shows reasonable agreement for decks in either pristine or very poor condition.

Milan J. Jolley (2003). "Evaluation of Corrosion-Resistant Steel Reinforcement." Iowa State Univ., 20p.

Excerpts:

"To investigate corrosion prevention through the use of corrosion-resistant alloys, MMFX Microcomposite steel reinforcement, a high-strength, high chromium steel reinforcement, is evaluated for corrosion resistance. MMFX steel is compared to epoxy-coated and to uncoated mild steel reinforcement. Principal emphasis is placed on corrosion performance of the steel, which is evaluated using ASTM and Rapid Macrocell accelerated corrosion tests.

"Ongoing research study at Iowa State University will determine if MMFX Microcomposite steel reinforcement provides superior corrosion resistance to epoxy-coated mild steel reinforcement in bridge decks. After 12 weeks, the associated ASTM ACT corrosion potentials indicate neither MMFX Microcomposite nor epoxy-coated mild steel reinforcement steel have undergone active corrosion. However, the uncoated mild steel underwent active corrosion in the second week of the ASTM test. Within the second week, Rapid Macrocell ACT produced severe corrosion risk potentials for all reinforcement types."

"Test methods include ASTM G 109 – accelerated corrosion of steel in pre-cracked concrete, and a rapid corrosion cell test developed under SHRP. This is the *Rapid Macrocell Accelerated Corrosion Test* developed at the University of Kansas under the SHRP program *(17, 1*8) and updated under the NCHRP-IDEA program *(*3). This entails immersion of rebars in both slated and plain water, connected to for an electrochemical cell.

"Prisms were prepared with 1 inch clear cover for accelerated tests. Specimens were cured 21 days before rapid corrosion test. The ASTM test showed corrosion potential only for uncoated steel. The SHRP ACT test showed severe corrosion risk for black steel, for epoxy coated steel and for MMFX rebars.

Jason M. Blomberg, (2003). "Laboratory Testing of Bridge Deck Mixes" Missouri Dept. of Transportation, Jefferson City, Mo, 74p.

A study of early-life cracking in concrete decks. Eleven mix designs were tested for strength, for freeze-thaw durability, for permeability, and for shrinkage. The relation of concrete mix design to early-life cracking is not established. This examination is laboratory only, without field data or demonstration.

Robert J. Frosch, David T. Blackman, and Roger D. Radabaugh (2003). "Investigation of Bridge Deck Cracking in Various Bridge Superstructure Systems" FHWA/IN/JTRP-2002/25, 265p.

Cracking in bridge deck is attributed to restrained shrinkage. This phase of the study is a laboratory study of effects of restraint. Variables in restraint include formwork details, bar size and spacing, and thickness of epoxy coating on bars.

Gerardo G. Clemeña, Milton B. Pritchett, and Claude S. Napier (2003). "Application Of Cathodic Prevention In A New Concrete Bridge Deck In Virginia." Virginia Transportation Research Council, Charlottesville, 38p.

Clemena, et al. report the study of an impressed current cathodic protection (CP) system. The study finds that the system is not economically favorable compared to stainless steel rebars, and corrosion resistant stainless-clad bars.

The installation of CP in a new bridge is significantly cheaper than its use as retrofit. The electrical current demands are less on new rebars as compared to corroding ones, and the electrical charge on new rebars will repulse Cl- ions. The deck was monitored through its construction period and for sixteen months of operation of the CP system.

Maintenance of the system is a significant concern. Fuses, rectifiers and electrical connections must be inspected and maintained. A remote monitoring system for voltage and current was not reliable, indicating poor performance in one section of the CP system, while similar voltage and current measurements at the bridge showed normal conditions and performance.

The basic findings are:

"Even though using an impressed-current CP system in a new concrete bridge deck is a feasible option for preventing the initiation of corrosion on rebars, there are issues concerning its practicality and cost-effectiveness.

RECOMMENDATIONS

1. Unless there is a commitment on the part of bridge owners to maintain impressed-current CP systems regularly, the use of cathodic prevention should not be considered for a new bridge deck.

2. Other options for preventing or eliminating corrosion in new concrete bridges that are relatively trouble-free and cost-effective, such as the use of stainless steel–clad bars, should be considered."

Michael M. Sprinkel (2003) "Evaluation Of Corrosion Inhibitors For Concrete Bridge Deck Patches And Overlays." Virginia Transportation Research Council, Charlottesville, 36p.

"The study includes 156 exposure slabs, 4 bridge decks with overlays, and 1 patched bridge substructure. A total of 136 exposure slabs were constructed to simulate overlay and patch repairs, and 20 full-depth slabs were constructed to simulate new construction."

Some exposure slabs were fabricated with Cl- added to concrete to simulate the effects of contraindication in decks in service.

The findings:

"Overlays cracked and delaminated on exposure slabs that were fabricated with 15 lb/yd3 of chloride ion because of corrosion of the top mat of reinforcement. There was no difference in the performance of overlays constructed with and without inhibitors and topical treatments. Overlays and patches with and without inhibitor treatments placed on and in slabs with 3, 6, and 10 lb/yd 3 of chloride are performing satisfactorily. However, results do not show reductions in the tendency for corrosion that can be attributed to the inhibitors. Overlays and patches with and without inhibitor treatments on and in the five bridges indicate mixed results. Corrosion is occurring in the majority of the repairs done with and without inhibitor treatments. The corrosion-inhibiting treatments do not seem to be reducing corrosion in the bridges and, in fact, may be increasing corrosion.

“It is not obvious that corrosion is occurring in the full-depth slabs constructed with and without inhibitors to represent new construction. The slabs do not show signs of corrosion-induced cracking after 5 years of ponding.

“Topical applications of inhibitors did not affect the bond strength of the overlays. Overlays containing Rheocrete 222+ and 7 percent silica fume had lower bond strengths. Overlays on base concretes with the higher chloride content had lower bond strengths. In summary, this project does not show any benefit from the use of the corrosion inhibiting admixtures and the topical applications made to the chloride-contaminated concrete surfaces prior to placement of the patches and overlays. Additional years of monitoring of the exposure slabs and bridges may provide useful results.”

The products:

“Full-depth slabs, overlays, and patches were cast with concrete containing no inhibitor; an inorganic inhibitor; Derex Corrosion Inhibitor (DCI) (4 gal/yd^3 [20 L/m^3]); an organic inhibitor, Ferrogard 901 (2 gal/yd^3 [10 L/m^3]); or Rheocrete 222+ (1 gal/yd^3 [5 L/m^3]). Before being patched or overlaid, some slabs received three applications of a topical inorganic inhibitor, Postrite (P) (125ft^2/gal [3.1 m^2/L]), or two applications of an organic inhibitor, Ferrogard 903 (300 ft^2/gal [7.4 m^2/L]). The surfaces treated with Ferrogard 903 were power washed before being patched and overlaid.

“Some of these slabs were repaired with additional inhibitors that were supplied after the project started (Migrating Corrosion Inhibitor [MCI], Catexol and AXIM), and others were repaired with Rapid Set (RS), latex-modified concrete (LMC), RSLMC, and asphalt. Full-depth Slabs 133 through 136 were also prepared with additional CIAs.”

Gerardo G. Clemena, Dina N. Kukreja, and Claude S. Napier (2003) “Trial Use Of A Stainless Steel-Clad Steel Bar In A New Concrete Bridge Deck In Virginia.” Virginia Transportation Research Council, Charlottesville, 29p.

Lab studies of (solid) stainless steel bars of various alloys have shown very good performance in Cl-contaminated concrete, even when contamination is 7 to 10 times the level sufficient to induce corrosion in carbon steel bars. Costs are high, however, with an installed price for stainless bars about 5 times that of carbon steel bars.

An alternative is a steel bar clad with type 304 stainless steel. The installed cost is only 2.5 times that of carbon steel bars. A stainless steel coating works like an epoxy coating. It excludes contaminants. It does not passivate, and it does not offer sacrificial material. Unlike epoxy, stainless steel cladding is tough and abrasion resistant. Tough stainless cladding resists damage during construction of decks.

But stainless steel cladding is still a king of coating, therefore ductility at bend points, and sealing at ends of bars are important considerations.

The additional cost of stainless steel clad rebar for the deck was about 5% of total construction cost for the overpass structure built in Virginia.

Conclusions of the study:

“Stainless steel-clad bars can be used as direct substitutes for either uncoated black steel or epoxy-coated bars for effective, corrosion-resistant reinforcement of concrete bridge decks that will be exposed to deicing salts. The long-term costs of such structures will be less than those built with either black steel or epoxy-coated bars, which have lower initial costs. This advantage of clad bars becomes more attractive as the expected service life of the structures is raised.”

Amir Hanna (2003). "Fiber Reinforced Polymer Composites for Concrete Bridge Deck Reinforcement" NCHRP Research Results Digest, No 282, 3p.

Several FRP products are available for use as primary reinforcement in concrete bridge decks. There is a lack of standard testing methods to establish the strength, durability and performance of these materials. This limits the potential for immediate use of these products. Standard test procedures are needed for short term behavior including bond strength, pull-out resistance, and fiber strength, environmental durability in presence of contaminants, freeze-thaw, alkaline exposure, and fatigue resistance, Aging of FRP: tests are needed to evaluate changes in strength, stiffness or bond over time and how these are affected by environmental factors.

The general conclusion is that test procedures are not available to support routine use of fiber reinforced polymers by DOTs. Quality control and assurance are not adequately addressed.

Gerardo G. Clemeña, (2003). "Investigation Of The Resistance Of Several New Metallic Reinforcing Bars To Chloride-Induced Corrosion In Concrete." Virginia Transportation Research Council, Charlottesville, 27p.

The author reports an investigation of several kinds of corrosion-resistant reinforcing steel bars including: (1) stainless steel-clad carbon steel bars, (2) bars made of an MMFX-2 microcomposite steel, (3) bars made of a new lean duplex stainless steel called 2101 LDX, and (4) a carbon steel bar coated with a 2-mil layer of arc-sprayed zinc and epoxy (the outermost coating is epoxy). For comparison, two solid stainless steel (304 and 316LN) bars and a carbon steel bar (ASTM A615) were also included. All bars were embedded in concrete test slabs, and subject to weekly cycles of ponding in salt water followed by drying. Observations of macrocell-current, open-circuit potential and polarization resistance for 3 years.

Author notes that if coatings on steel are durable enough to withstand damaged during construction, and if concrete remains free of damaging cracks, then concrete decks may have service life of 50 to 75 years.

Cladding on some bars was deliberately damaged by drilling 3mm diameter holes. These bars cycled for 700 days without corrosion. A second set of bars with larger, slot defects in cladding were tested.

Some observations:

Carbon steel bars became depassivated after 92 days of cyclic exposure.

2101 LDX bars were passive for the first 147 days of weekly salt exposure.

MMFX-2 bars became depassivated after approximately 245 days.

Bars with zinc + epoxy coating were passive for the entire 735 days of exposure.

Bars with zinc + epoxy coatings that were damaged by slot cuts remained passive for 532 days.

Stainless steel 316LN and 304 bars, and 316L stainless-clad bars remained passive for 1082 days of cyclic exposure.

Stainless clad bars with 3mm holes remained passive throughout the test. Stainless clad bars with slot defects in cladding were depassivated after 392 days.

The cost model is interesting. Construction costs per m2 are computed. Costs equal initial construction costs and are constant until a deck repair or rehab is needed. Then aggregate costs of construction + rehab are reported.

Michael C. Brown, Richard E. Weyers (2003) "Corrosion Protection Service Life Of Epoxy-Coated Reinforcing Steel In Virginia Bridge Decks." Virginia Transportation Research Council, Charlottesville, 66p.

The authors compare current conditions among bridge decks in service in Virginia. They compare epoxy-coated rebar (ECR) decks to black steel decks for 10 decks. Some 141 cores were obtained and examined. Two decks had black steel and eight have ECR.

"Less than 25 percent of all Virginia bridge decks built under specifications in place since 1981 is projected to corrode sufficiently to require rehabilitation within 100 years, regardless of bar type. The corrosion service life extension attributable to ECR in bridge decks was found to be approximately 5 years beyond that of bare steel and, therefore, ECR is not a cost-effective method of corrosion prevention for bridge decks. Virginia would save approximately $845,000 per year in bridge deck construction costs by deleting the requirement for ECR."

The authors cite literature that equates Cl- corrosion vulnerability of ECR with damaged coatings to that of black steel: there is no protective value if the coating is damaged.

Difficulty to rehabilitate ECR decks:

"Presently no effective method exists for the rehabilitation of concrete bridge components built with ECR. The removal of chloride-contaminated cover concrete is not likely to alleviate corrosion of ECR, once initiated, because the corrosion takes place under the coating. The removal of cover concrete does not remove the chloride from beneath the coating, and does nothing to address the development of an acidic, therefore corrosive, localized environment beneath the coating. In addition, no existing corrosion condition assessment method is amenable to field survey work. Therefore, there are significant but unquantifiable risks in the continued use of ECR as the primary method of corrosion prevention."

Benefit of ECR:

"In approximately the worst 20% of cases where performance is most critical, ECR provided no significant increase in projected time to corrosion initiation over that of bare steel. For a 100-year lifespan, ECR reduced the proportion of Virginia bridge deck areas expected to corrode by less than 2.5%. Comparing the expected field propagation periods of bare steel and ECR, service life was extended by approximately 5 years using ECR."

V. W. Robbins (2003) "Design of a Steel Free Bridge Deck System." Iowa State University, 19p.

"A reduction or elimination of the internal reinforcing steel would reduce the deterioration of the deck concrete while increasing the durability and life expectancy of the bridge deck allowing the bridge owner to use their maintenance, human and financial resources more effectively. A SFD is deck slab system with no internal reinforcement; it develops its strength from the formation of a compressive arch within the deck slab between the supporting girders."

A steel free deck was proposed as a retrofit to an existing steel girder bridge. The new deck is composite with the steel girders. The deck does have steel reinforcement for negative moments at overhangs.

The deck 'arches' between stringers are tied arches. Flanges of steel girders are tied by steel straps at the bottom surface of decks.

Michael S. Linford, and Lawrence D. Reaveley (2004). "A Study Of The I-15 Reconstruction Project To Investigate Variables Affecting Bridge Deck Cracking." Utah Dept of Transportation, *UT-04.04,* Salt Lake City, 145p

A study in response to cracks observed in newly built concrete decks along I-15 through Salt Lake City, Utah.

The study focused on several design and construction aspects including:

•The use of silica fume concrete. All of the cast-in-place bridge deck concrete used in the I-15 Reconstruction Project had silica fume (5% by weight of cementitious materials) added to it. This material is added to increase the strength and density of concrete.

•The use of precast concrete deck panels. The majority of new concrete girder bridges were constructed with precast concrete deck panels. These panels serve as stay-in-place formwork and constitute the lower portion of the bridge deck. The remaining upper portion of the bridge deck consists of a traditional cast-in-place, reinforced concrete slab that becomes composite with the lower precast panels.

•The use of wide-spaced steel girders together with transversely post-tensioned concrete decks.

•The use of deep, long span, spliced, post-tensioned concrete girders. These girders were erected in three separate sections on temporary supports. Once the girders were spliced and the deck construction was complete, the girder sections were longitudinally post-tensioned and the interior temporary supports were removed.

There are 71 bridges in the study, about one half of the new bridges built for the I-15 corridor through Salt Lake City.

“There are full depth cracks on nearly all of the new bridges of I-15. These cracks resulted from placing large amounts of deck concrete in constrained environments.

“The concrete decks were restrained by composite attachment to girders, bents, diaphragms, and abutments. The rigid attachment between these elements and the deck is essential for economical girder design and seismic load resistance. However, this rigid attachment leads to transverse and diagonal cracking as the concrete cures and shrinks.

“Precast concrete deck panels have worked well on I-15 and other projects to limit the amount of through-cracking in bridge decks. In the worst case, precast panels define predictable vertical planes for full-depth cracking to take place. For future concrete girder bridges, the use of a composite bridge deck system consisting of precast concrete panels below a reinforced cast-in-place slab should be considered

Ying-Hua Huang, Teresa M. Adams, and Jose´ A. Pincheira, (2004) “Analysis of Life-Cycle Maintenance Strategies for Concrete Bridge Decks.” Journal Of Bridge Engineering, ASCE, MAY/JUNE 2004, p250-258.

“According to the year 2001 state bridge inventory, Wisconsin has over 9,700 concrete bridge decks. Of the existing concrete bridge decks, 1,580 have been provided with a concrete overlay, 713 have been given an asphaltic concrete ~AC! overlay, and 378 have been given an AC overlay with a membrane. The number of bare decks is 7,062 with an average age of 20 years. “

The authors report earlier work that estimates remaining service life based on type of maintenance treatment and time of treatment relative to time of construction of the bridge.

Estimated service life of asphalt overlay (as retrofit) is 7 years.

Estimated service life of concrete overlay (as retrofit) is 15 to 20 years.

Cost data:

Treatment	Agency unit cost dollars/m^2! Minimum	Most likely	Maximum
Patching	108	161	215
Concrete overlay	269	323	377
Asphaltic concrete overlay without membrane	43	54	65

Asphaltic concrete overlay with membrane	54	81	108
Deck replacement ~new deck with epoxy-coated bars!	377	398	431

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