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A Literature Review of Time-Deterioration Prediction Techniques

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Contents

Abstract

The high incidence of corrosion of reinforced concrete decks and substructure units have changed the way the nation uses deicing chemicals for highway maintenance. As part of the SHRP Contract C-104, which seeks to develop techniques for increasing the service life of existing reinforced concrete bridges, this report is a literature review of existing deterioration models used to predict corrosion-related deterioration on reinforced concrete bridges.

Most models in this review are based on the performance of all bridges in a system. In addition, the model information was developed using condition ratings provided by technician-inspectors performing visual surveys in accordance with the National Bridge Inspection Standards (NBIS). Discussion of the models illuminates equation definitions, research parameters and life-cycle cost analyses. Included in the report is an annotated bibliography.

1. Executive Summary

Before the introduction of deicing chemicals (salt), reinforced concrete (RC) bridges were viewed by most highway custodians as virtually maintenance free and as having a service life limited only by functional obsolescence. However, since the mid-1960's, the high incidence of corrosion of RC decks and substructure units have changed this perception in areas of the nation that use deicing chemicals.

The mission of Strategic Highway Research Program (SHRP) is, in part, to increase the durability and to develop techniques for increasing the service lives of existing RC bridges. The objective of this project, C104, is to produce a computerized methodology and user's handbook for making cost-effective protection or repair decisions for RC bridges that are exposed to deicing chemicals, or suffer from salt-induced corrosion damage. The C104 methodology will unify the previous SHRP C-100 series projects within a decision-model framework.

This document presents the findings of the C104 literature review. The SHRP Problem Statement and C104 Workplan defines the topic of this review as "existing deterioration models." A model is the numerical simulation of a group of data. It may be expressed as a mathematical formula or the solution to the formula over a certain range can be shown as a graph. We are interested in deterioration models that can be used to predict corrosion-related deterioration on reinforced concrete bridges.

Most models identified during this literature review were developed based on the performance of all the bridges in a system. These models are of more value in management decisions involving many bridges (system level decisions) than in making "what to do" and "when to do it" decisions for a specific structure (project level decisions). It should also be emphasized that most of the existing models included in this report were not developed with the type of condition data that is considered by our research team as appropriate for the project level decisions required by C104. In most cases, the deterioration models were developed using condition ratings provided by technician- inspectors while performing a routine visual condition survey in accordance with the National Bridge Inspection Standards (NBIS). It is known that a visual inspection alone is inadequate to plan timely protection or repair procedures for a concrete bridge subjected to salt-induced corrosion damage. Deterioration models based on NBIS condition ratings may be useful in predicting service life, however to accomplish the purpose of this project, more precise project level models are needed to decide the optimum time for remedial action. Since most of the deterioration models identified by our literature review are system level, they may be the best predictive tool available at this time in the initial development of the C104 decision model.

The C104 literature review identified limited information on project level modeling of corrosion related deterioration. A sampling of bridges must be monitored over a long time period for chloride penetration, corrosion and delamination propagation to provide the type of condition data necessary to develop project level models. Only a limited number of condition surveys of this type are performed and it is difficult to access the findings since they are not input into the National Bridge Inventory (NBI).

Another method of studying the corrosion mechanism in reinforced concrete is by accelerating the chloride contamination under laboratory conditions. This is helpful in relating corrosion initiation and corrosion rate with the amount and depth of chloride contamination. It can also be used to study the expansion of the iron oxide corrosion material as it causes the concrete to delaminate. This type of knowledge is helpful in selecting protection and repair actions for a specific bridge (project level).

Findings related to corrosion mechanisms on the project level are discussed in Section 2.1 of this report. This is followed by findings on deterioration rates on the system level which includes a series of deterioration curves based on the models discussed in Section 2.2. Section 2.3 includes pertinent information on costs and service life of initial construction and repair/rehabilitation procedures for use in life cycle cost analyses. Section 2.4 contains flowcharts and brief descriptions of rehabilitation selection criteria developed by others. While the cost and rehabilitation selection material contained in Sections 2.3 and 2.4 are not specifically identified as part of the original focus of the literature review as described in the Work Statement, this information is relevant to the project and was, therefore, collected while researching deterioration rates.

2. Findings and Discussion

This section reports the findings of the literature review and discusses the research team's evaluation of the findings.

Project Level Deterioration

The two stages of reinforced concrete deterioration that are of particular interest in making protection and repair decisions are corrosion initiation and concrete delamination. Past research indicates that after the concrete around the reinforcing bar is contaminated with chloride beyond a certain threshold value and corrosion has initiated, most protection procedures (other than cathodic protection and possibly chloride removal) are likely to be less effective. After concrete disruption has started, repairs are inevitable and should be included with any protection procedure. The time required for each stage is governed by different factors and therefore will be discussed separately.

Time to Corrosion Initiation

Browne assumed that the corrosion-free (durability) life of a structure is the time for chlorides to reach the critical concentration at the steel surface.[1] He developed the chart shown in Exhibit 1. This chart is a family of curves of chloride concentration with distance from the surface of the concrete for different ages, for different surface chloride levels (C_e), and for different chloride diffusion coefficients. The chart predicts maintenance free service life to the onset of corrosion. The procedure for using this chart is given in Exhibit 2.

In the above chart, the diffusion coefficient must be determined. West & Hime developed a method to estimate the effective diffusion coefficient of chlorides using the plots of chloride concentration versus depth.[2] They used Fick's second law of diffusion to model the migration of chlorides through the concrete,

$$\frac{\partial(Cl^-)}{\partial t} = D_c \frac{\partial^2[Cl^-]}{\partial x^2} \tag{1}$$

Where Cl^- is the chloride concentration at some depth "x" below the concrete surface at time "t" and D_c is the effective diffusion coefficient. The exact solution to the above equation is

$$\frac{C_{max} - C_d}{C_{max} - C_{min}} = erf\left(\frac{x}{\sqrt{4 D_c t}}\right) = u \qquad (2)$$

Where u = the concentration ratio, for each depth, d, below the maximum concentration, C_{max} at or near the concrete surface. C_{min} = the background level of evenly distributed chloride ions and erf ( ) is the error function described by the argument.

The method proposed by the authors to estimate the effective diffusion coefficient is given in Exhibit 3. The authors, using chloride profiles from different structures, estimated the effective diffusion coefficients as follows:

1) The interior of a large tank which had contained a brackish effluent for 7 years with about half the salinity of seawater has a diffusion coefficient of about 4×10^{-8} cm^2/s and
2) The wall of another tank which contained a brine for 7 years with about twice the salinity of seawater has a diffusion coefficient of about 12×10^{-8} cm^2/s.

Cady and Weyers presented a predictive model in 1983 for chloride intrusion based on time and concrete depth as follows:[3]

$$d = 1.426\sqrt{t} + 1.27 \qquad (3)$$

where
d = depth of cover, cm
t = time, years

Beaton and Stratfull in 1963, published what has become the Stratfull formula:[4]

$$R = \frac{1.107^{c}\, C^{0.717}\, Si^{1.22}\, 1011}{K^{0.42}\, W^{1.17}} \qquad (4)$$

Where:
R = Time to cracking of a substructure pile, years
C = Sacks of cement per cubic yard of concrete
Si = Depth of concrete cover over reinforcing steel, inches
K = Chloride concentration of water (moisture) in contact with concrete, ppm
W = Total water content of mix as percent of concrete volume

This empirical equation is based on laboratory and field studies extending over a period of 2 1/2 years and was developed primarily from bridge substructure studies. A constant surface chloride concentration is required to use this equation. A chart was developed by the Florida Department of Transportation for Stratfull's formula. This chart, shown in Exhibit 4, represents a graphical solution of Stratfull's equation.

In 1976, Clear modified Stratfull's formula to:[5]

$$R = \frac{129\ Si^{1.22}}{K^{0.42}(W/C)} \tag{5}$$

Where W/C = Water-to-cement ratio by weight.

Clear showed that the results of the modified formula agree well with the findings of time-to-corrosion studies.[5] The modified Stratfull formula has the advantage of combining the cement factor and the total water content of the mix into a single factor.

The corrosion rate is an important determinant of the time to chloride induced corrosion of reinforced concrete members (high corrosion rates result in less time to deterioration). Clear provided the following guidelines based on laboratory, outdoor exposure and field experiences over more than 5 years with the KCC INC 3 electrode linear polarization rate of corrosion device (assuming constant corrosion rates with time):

Corrosion rate (ICORR) in milliamps (mA) per sq. ft. of steel surface.

- "ICORR less than 0.20 mA per sq. ft. - no corrosion damage expected
- ICORR between 0.20 and 1.0 mA per sq. ft. - corrosion damage possible in the range of 10 to 15 years
- ICORR between 1.0 and 10 mA per sq. ft. - corrosion damage expected in 29 to 10 years
- ICORR in excess of 10 mA per sq. ft. - corrosion damage expected in 2 years or less

Deterioration rates are, of course, dependent on many other factors as well, including reinforcing steel concentration and cover. thus, engineering judgement is required."[6]

The above is really saying that deterioration advances based on corrosion rate and time, and that significant deterioration has occurred when the corrosion rate-time is in the range of 10 to 20 mA-yr.

Other research articles that directly or indirectly discuss the time to corrosion initiation or to concrete damage were identified and are listed in the reference.[7-18]

Cady and Weyers (3) simplified Clear's equation to:[3]

$$d = 0.644t^{0.82} + 1.27 \tag{6}$$

The chart in Exhibit 5 is a plot of Equation 3 (Eq3), Clear's original data for Equation 5 (Eq.5) and Equation 6 (Eq6). This chart shows a fair agreement between the three. The authors used values appropriate to a bridge deck for the following variables in deriving the above equation:

1) Critical chloride concentration at steel level = 0.03% by weight of concrete
2) Water-to-cement ratio for typical bridge decks = 0.45
3) Chloride diffusion coefficient for w/c of 0.45 = 3×10^{-8} cm^2/s
4) Mortar phase in typical bridge deck concrete = 50% by weight

T. Oshiro and S. Tanigawa also used Fick's diffusion equation to calculate the chloride diffusion coefficient.[19]

Laylor predicted the progress of the chloride front in concrete using Fick's second law of diffusion.[20] He selected the following solution to the equation:

$$C_{(x,t)} = C_o \left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_c t}}\right)\right] \tag{7}$$

where

erf() = the error function described by the argument ().
x = Depth of rebar, inches
t = Age, years
D_c = Diffusion coefficient of chlorides, $in^2/year$
C_o = Surface chloride concentration at the depth "x" and at time "t"

The calculated value of surface chloride concentration at 15 and 20 years of life were 1.75 and 2.05 lb/yd^3.

The models discussed above assume that the chloride content at the concrete surface is constant over time. This could be considered true for structures submerged in seawater. For structures on land the chloride content at the concrete surface varies with time and hence must be modelled appropriately.

Uji, Matsuoka, and Maruga assumed that the surface chloride concentration is proportional to the square root of the time in service.[21] The constant of proportionality is assumed according to the environment of the structure; e.g., submerged, splash and atmospheric zones in a coastal structure would have different constants of proportionality. The author showed that the chloride diffusion coefficient obtained by this method is about 70% greater than the models described previously.

Though this model accounts for the variation of the surface chloride content with time, it assumes that the diffusion coefficient does not vary with time. Lin proposed a diffusion model with time dependent diffusion coefficient and surface concentration variables.[22] The author verified this model by comparing the theoretical predictions with the experimental data. The author obtained the following expressions for chloride diffusion coefficient as a function of time, D(t) and water to cement ratio D(w):

$$D(t) = [10.54 - 0.0168t - (1.181 \times 10^{-5})t^2 + (2.418 \times 10^{-8})t^3] \times 10^{-8} \quad (8)$$

for ordinary portland cement concrete and

$$D(t) = [2.81 + 7.0\exp(-0.005t)] \times 10^{-8} \quad (9)$$

for ordinary portland cement concrete with fly ash, where t = time in days, and

$$D(W) = [0.587 - 4.168W + 9.288W^2] \times 10^{-8} \quad (10)$$

for concrete at 6 months of age and

$$D(W) = [1.249 - 5.051W + 8.941W^2] \times 10^{-8} \quad (11)$$

for concrete at 6 years of age where W = water to cement ratio. The author represented the diffusion coefficient and the surface chloride concentration as follows:

$$D(t) = D_o\, f(t) \text{ and} \quad (12)$$
$$C(t) = C_o\, [1 - \exp(-at)], \quad (13)$$

where:

D_o = initial chloride diffusion coefficient
F(t) = a function of time and
a = constant dependent on concrete properties

Other researchers have presented experimental data relating: 1) chloride diffusion coefficient and the coulombs of charge passed and 2) coulombs of charge passed and the water-to-cement ratio. Berke, Pfeifer, and Weil showed that concrete with about 3600 coulombs had an effective diffusion coefficient ranging from 2×10^{-8} cm^2/s to 11×10^{-8} cm^2/s, and concrete with about 200 coulombs had an effective diffusion coefficient ranging from 0.3×10^{-8} cm^2/s to 0.7×10^{-8} cm^2/s.[23] Whiting obtained the following relationship shown in Exhibit 6 between water-to-cement ratio and the coulombs passed for a given mix design.[24]

Hutter and Donnelly of the Colorado Division of Highways studied the deterioration rates of their bare concrete decks.[25] The State's climate ranges from mountainous to desert. Their model predicts the average chloride content, Cl_{avg}, at the level of the reinforcement as follows:

$$CL_{avg} = .058 \text{ total salt} + .0019 \text{ heavy trucks} \quad (14)$$

where

$$\text{total salt} = \text{salt(in tons/mi/yr)} \times \text{age} \quad (15)$$

and

$$\text{heavy trucks} = \text{present ADT} \times \% \text{ heavy trucks} \quad (16)$$

It is assumed that the term "heavy trucks" means trucks at or near the legal weight limit.

The chart in Exhibit 7 was developed to facilitate use of the equation. The chart can also be used to estimate the service life based on a set of existing conditions. For example, a deck with a future chloride content of 2.0 lbs/CY, 500 ADTT (heavy trucks), and receiving salt at a rate of 1.5 tons per lane mile per year has a corrosion-free life of 13 years according to the chart.

Time to Concrete Disruption

Browne stated that deterioration of concrete is a two stage process, namely corrosion initiation and concrete damage.[1] The initiation stage (durability life) is primarily controlled by diffusion of chlorides to the level of the reinforcing steel. The damage stage (steel expansion to damage occurrence) is controlled by less predictable parameters involving two main factors: (1) rate of diffusion of oxygen to steel and (2) bursting forces from buildup of corrosion products. The duration of the second stage, namely the time between corrosion initiation and concrete damage, in practice appears to range anywhere from 6 months to 5 years. These factors depend on the relative amount of chloride exposure, the moisture content of the concrete, its quality, its tensile strength, the size and distribution of the reinforcement, the concrete cover thickness over reinforcement, the temperature and the shape of the concrete surface (corners are very vulnerable). Hotter climates shorten the time (if there is no drying out).

Leslie examined 1,940 spans in New York between 1972 and 1977.[26] Exhibit 8 shows the percent of spans spalled versus age where any amount of spalling greater than 1 sq. ft. existed.

Exhibit 9 gives the same information where any amount of spalling greater than 3 sq. ft. existed. Equations were developed to describe the empirical data as a function of time (t) as given below.

Spalls $\geq$ 1 sq ft

$$\% \text{ of spans} = 5.05e^{0.19t}, \text{ for } 1\tfrac{1}{2}\text{" cover} \quad (17)$$

$$\% \text{ of spans} = 2.54e^{0.20t}, \text{ for } 2\text{" cover} \quad (18)$$

Spans $\geq$ 3 sq ft

% of spans = $2.20e^{0.24t}$, for 1½ cover (19)

% of spans = $0.77e^{0.20t}$, for 2" cover (20)

An analysis of Leslie's data by Geikie shows that the average deterioration of bare concrete decks in winter climates can be described by the plots in Exhibit 10.[27] Equations were developed to describe the relationship as provided below.

$$\text{Average spalled area per span} = 0.14e^{0.39t} \quad (21)$$

$$\text{Average spalled area per span} = 0.43e^{0.41t} \quad (22)$$

It should be noted that Leslie's findings are somewhat dated.

Although not in published literature, Clear suggests a rule of thumb to describe the rate of deterioration. The rate of increase is equal to 33% of the previous year's value up to 70%. Rehabilitation would normally take place before 70% delamination. This relationship is shown in Exhibit 11.

Summary

The literature review identified two stages of project level deterioration and the corresponding models developed by the researchers. Of these models discussed, Clear's modified Stratfull Formula is often referenced because of its practicality and simplicity. Its limitation, however, is that it requires the chloride concentration at the surface to be treated as a constant. The Hutter and Donnelly model allows highway salt and ADT to be variables. So far, this only determines the time until threshold chloride concentration is attained at the steel and corrosion begins. For the concrete disruption (delamination) stage, Clear's 33% offers simplicity.

System Level Deterioration

Various performance and deterioration models were identified as part of the literature review. These models represent a numerical simulation of data collected on populations of bridges. The models were developed using NBI numerical condition ratings. Since NBI condition ratings are generally based on a visual inspection, they would not identify a reinforced concrete corrosion problem until significant surface spalling can be seen.

Performance Curves

As an introduction, a performance curve is provided in Exhibit 12. This curve is a plot of the average NBI deck condition ratings versus age for 4864 Pennsylvania bridge decks, studied by West & McClure.[28] The spline curve was produced by a computer program.

The curve shows that ratings drop quickly for bridge decks with ages 0 through 20 years. After this age, the curve flattens showing that the average bridge deck condition rating remains at approximately "6". The absence of deterioration beyond 20 years of age is attributable to the fact that agencies normally perform repairs and rehabilitation to keep bridge decks at a level of serviceability appropriate to the highway system. The researcher refers to this as the "healing effects of maintenance".

A second example of performance curves was produced by Sinha at Purdue University for the Indiana Department of Transportation.[29] Exhibit 13 provides separate performance curves for deck, superstructure and substructure units. These curves are for concrete bridge components on non-interstate highways in all states other than Indiana. Again, it can be seen that there is an initial rapid drop for the first 20 years and a flattening of the curve from 20 to 40 years at a rating of approximately "5". The curve also indicates a third stage of bridge performance after 40 years of age characterized by a rapid decline in ratings.

Performance Models

Mathematical formulae (models) have been developed to simulate the bridge condition data. If the effects of repairs and rehabilitation are not identified and removed from the data base, the model is considered a performance model. If the effects of repairs and rehabilitation are identified and removed from in the model, it is a deterioration model.

As part of the Federal Highway Administration's (FHWA) Bridge Management System (BMS) demonstration project No. 71, O'Connor examined the NBI data of the nation's bridges.[30] Exhibit 14 shows the model for all bridge deck performance and Exhibit 15 shows the model for all bridge performance. Again, a rapid initial decline is followed by a flattening of the curve. The models have a break point of approximately 16 years at a rating of approximately "6". The rating after this point remains approximately "6".

Fitzpatrick analyzed New York State Department of Transportation inspection data from 1977 to 1980.[31] The resulting performance model is shown in Exhibit 16. The double model reflects two complete inspection cycles and is explained as being the result of an accelerating rate of deterioration. Fitzpatrick found that the trends in the data point to the reduction of maintenance per bridge caused by an increasing number of structures, inflation, and budgetary restrictions.

Wisconsin Department of Transportation (WISDOT) developed performance models through the use of piece-wise linear regression.[32] The WISDOT study is based on 4463 bridge condition appraisal ratings. Various models are presented: All bridges, Exhibit 17; RC deck girders, Exhibit 18; RC slab, Exhibit 19; and prestressed concrete (P/S) spans, Exhibit 20. These performance models show an initial rapid decrease between ages 1 and 25, a flattening of the curve between ages 26 and 45, and a rapid decrease beyond age 46. P/S spans actually increase in ratings from ages 26 to 45, visibly showing the "healing effects of rehabilitation".

Chen at North Carolina State University analyzed North Carolina Department of Transportation inventory data and interviewed bridge inspectors and maintenance supervisors.[33] The analysis of the inventory data produced the generalized model shown in Exhibits 21 & 22 and the supporting tables for concrete elements. The interviews identified three factors:

1. Decks with higher ADT have higher deterioration rates.
2. Superstructures on interstate and primary roads have higher deterioration rates.
3. Substructures in coastal areas have higher deterioration rates.

Plots are shown in Exhibits 23 & 24. An analysis of the model by the C104 research team shows that ADT has a significant impact on deck ratings. For example, a 40 year old deck with an ADT less than 200 VPD will have a rating, according to the model, of 4 while a deck with an ADT of over 4000 VPD will have a rating of "2". This analysis also shows that substructure units located in Piedmont areas deteriorate slower than those located in either coastal or mountainous regions due to marine salts and deicing salts respectively. For example, a 40 year old substructure unit located in the Piedmont area would have a rating, as predicted by the model, of "5" while a unit located in a mountainous area would have a rating of "4" and a unit located in a coastal area would have a rating of "2".

Little difference was observed between prestressed concrete and reinforced concrete substructure units until the third stage of deterioration. In that stage performance was better in coastal areas but worse in mountainous regions.

Deterioration Models

Deterioration models attempt to separate and remove the effects of maintenance, repair and rehabilitation. These models are better suited for this study which attempts to quantify service lives for use in life cycle cost analyses.

Busa of the Economic Analysis Division of the Transportation System Center in Cambridge, Massachusetts, developed a deterioration model in 1985 using the NBI data as a basis.[34] Out of 648,399 bridges which were screened, 151,933 bridges were selected for use in the study. It is significant to note that only bridges less than 25 years old were chosen for use. This was done to eliminate the "healing effect of maintenance". The model which was developed is shown in Exhibit 25. The model considers age and average daily traffic (ADT) as factors. The researchers of that study also considered other factors in their linear regression analysis. These factors included:

- State
- Main structure type
- Skew vs. non-skew
- Number of main spans

- Wearing surface (unprotected asphaltic concrete, unprotected concrete, and asphaltic concrete with known membrane)
- Custodian

This model has some significant limitations.

- The model assumes linear deterioration rates.
- Ratings beyond 25 years are obtained by linear extrapolation.
- The vertical intercept is assumed to be "9".
- Timber, steel and concrete bridges were not segregated.

The researchers of this project analyzed the model by performing a sensitivity analysis. The model is graphically displayed in Exhibits 26, 27, and 28. It can be seen that deck ratings decline at a faster rate that either superstructure or substructure ratings. It can also be seen that ADT contributes to the decline of deck ratings marginally and to superstructure and substructure ratings insignificantly.

O'Connor proposed a very simple deterioration model in the FHWA demonstration project No. 71.[30,p.V-26] The model is shown in Exhibit 29 and can be stated as a rule of thumb that ratings decline at a rate of 1 point in every 10 years. This is also expressed in the table below:

Age	Rating
0	9
10	8
20	7
30	6
40	5
50	4
60	3
70	2

Deterioration models can also be very complex. West & McClure developed a series exponential deterioration models.[28 p.65] These models are shown in Exhibits 30, 31 & 32.

The first model is referred to as the two-parameter model since two quantities, β_1 and β_2 are needed to define the equation. If a rehabilitation is to be considered the four-parameter model is to be used. Likewise, if two rehabilitations are considered the six-parameter model should be used.

The Beta factors are used in Exhibits 33, 34 & 35 to model the rate of deterioration. Unfortunately β_5 and β_6 factors were not developed for PC bridges and, worse; β_3, β_4, β_5, and β_6 factors were not developed for RC bridges.

In these models the vertical intercept was not constrained to be set at "9". Setting the intercept at "9" tends to rotate the graph and distort the valves at ages other than zero. Since non-zero ages are of interest in this study, this is a valid approach. The model also shows that deterioration after a rehabilitation is accomplished, can be greater than before. This phenomenon can be exemplified by the case in which a patch is placed on a salt contaminated bridge deck. The corrosion cell, which is inadvertently established, drives corrosion in the existing deck, accelerating deterioration.

The two-parameter model is plotted in Exhibit 36 for RC bridges. For prestressed concrete bridges, the two-parameter model is shown in Exhibit 37 and the four-parameter model is shown in Exhibit 38. It can be seen that traffic has a very minor influence on bridge deterioration. It can also be seen that the deterioration rate is less for higher traffic volumes. The authors of that report concluded that this reflects the many types of RC bridges and the diverse ADT environments. It can also be seen that deterioration rates decelerate with advancing age.

The Rehabilitation Spike

As mentioned previously, a rehabilitation procedure can be considered in a deterioration model. West, McClure, et al established β_3 and β_5 factors which represent average repair and rehabilitation improvements in ratings respectively.

O'Connor conceptualized a rating updating model which tied unit cost of the repair (dollars per sq. ft.) to the rating change and considers the existing condition as well.[30 p. V.17] This model is presented in Exhibit 39. This model, unfortunately, does not assign dollar values to the vertical ordinate. This model is apparently a generalized concept.

Chen of North Carolina State University proposed a similar concept.[33,p. 112] Tables for deck, superstructure, and substructure units are presented in Exhibits 40, 41 & 42. The research team of this project plotted Chen's table to compare the concept with that of O'Connor. The plot is shown in Exhibits 43 & 44. The concepts are very similar.

Note in these tables, Exhibits 40, 41 & 42, that a minimum amount of spending is necessary to maintain the existing rating. This is referred to as routine maintenance funding. Also note that the maintenance funding level increases as the condition rating decreases.

Due to the limited sample size, North Carolina derived costs from other data. For example, the results of the regression analysis for timber substructures were proportioned to describe RC substructures and steel deck results were used to describe costs for RC decks. It should also be noted that 1981-85 data was used in the analysis.

Rehabilitation Options

How much rehabilitation and when is a question that deserves some brief comment in this report. Effective life cycle cost analyses of various rehabilitation options requires an understanding of an overall strategy.

Butler recognizes that various rehabilitation options can restore the condition to various degrees and that the performance of each rehabilitation can also vary.[35] These concerns are shown in Exhibits 45 & 46.

Chen further recognizes in Exhibit 47 that the custodian has the option of either spending a lesser degree of funds on a short schedule, Policy I, or spending greater funds on a longer schedule, Policy II.[33, p.32] In the extreme this is similar to regular preventive maintenance activities versus reactive rehabilitation.

Babaei has proposed a set of curves for various deck types, i.e. bare decks and decks with overlays.[36] As an example, Exhibit 48 shows a reconstruction strategy for a chloride contaminated deck with an overlay. Babaei has defined condition as an index, I, rather than using the FHWA rating point system. The index combines the effects of several distress categories as shown in Exhibits 49. Reconstruction is performed at some point based on "should" and "must" condition definitions. In the model, $I = 100 - Ma^b$, deterioration is described as a function of age (A), an exponent (b) and a slope coefficient (m). The shape of the graph is controlled by b. The graph is linear for $b=1$. Values greater than 1 cause the graph to be convex. Values less than 1 cause the graph to be concave. The coefficient m controls the rate of deterioration. Both b and m are established for each project based on historical data.

Summary

Factors used in the deterioration models studied include the following:

- Age
- ADT
- Bridge Type
- Location (coastal/piedmont/mountain areas)

Age was used in the models as either a multiplier or, as in one case, an exponent to the natural base e. The researchers on this project feel that age is a surrogate for other factors that constitute "cumulative damage".

ADT appears to be a factor in deterioration although the mechanism is not clearly established. At best truck traffic acts as a catalyst to break up an already deteriorating deck. Beyond this however, the cause and effect relationship for non-fatigue prone members is not clear.

The research team would add "salt usage" to the above list. This factor could be quantified as a combination of kind of highway (I, US, State, NFA) times a salt usage factor (tons/lane mile per year.)

Dr. Weyer, Principal Investigator of the SHRP C-103 project, is developing a methodology using mean annual snowfall as a surrogate to predict chloride content in bridge decks.

Cost and Service Life

Much of the literature on concrete bridge deterioration rates was included in documents that also contained information of value to the C104 project on the topic of developing life cycle cost comparisons. A review of the information is included in this section.

Types of Cost Analyses

Three types of cost analysis for evaluating repair/rehabilitation/replacement alternatives were identified in the literature search; (1) first cost analysis, (2) life-cycle cost analysis and (3) incremental benefit cost analysis. They are discussed in increasing level of complexity. A concise discussion is given by O'Connor. [30,p.VI-3]

First Cost Analysis

A first-cost analysis considers the initial capital cost only of the various economic alternatives. It does not include maintenance costs, service life, or level of service. A first-cost analysis would be suitable to evaluate the most economical design between, for example, bridges using two different beam spacings or between beam versus floorbeam-girder spans. In these examples, the maintenance costs and service lives of the various alternatives are assumed to be equal or near equal.

Life Cycle Cost Analysis

A life cycle cost analysis considers the initial capital cost, maintenance costs, the service life, and the level of service of the alternatives. The level of service is equated to a dollar value of benefit, usually user and agency cost reductions. A life cycle cost analysis is capable of evaluating alternatives, such as, reducing a load posting on removing a bottleneck by widening a bridge. In this study, we are comparing various repair options which have differing initial costs, maintenance costs, and service lives. An example is provided in Exhibit 50 in which costs are given as factors of the present replacement cost.

Incremental Benefit-Cost Analysis

A benefit-cost analysis considers initial cost, maintenance costs, service life, and level of service. Either first costs or life cycle costs can be used in the analysis. An incremental benefit-cost analysis indicates the added incremental benefit from the added incremental cost.[30 p VI-17] The costs of each alternative is first ranked in ascending order. The cost and benefit of each alternative is then plotted as shown in Exhibit 51. The optimum alternative is that which provides an incremental benefit equal to the incremental cost. This can be identified on the graph as the increment where the slope of the benefit curve equals the slope of the cost curve. At funding levels beyond this point the net costs outweigh the net benefits.

Unit Costs

A comprehensive bridge management system should include a program for collecting appropriate unit cost data as it is received from construction contracts and maintenance operations. The bridge management work group of Pennsylvania DOT established unit costs of various repair systems during the development of its BMS.[37] The categories and 1985 costs are shown in Exhibit 52.

Chen developed a similar list of unit costs for North Carolina.[33, p. 60] These costs developed in 1987 are given in Exhibit 53. Chen analyzed the cost data and developed annual maintenance cost factors for deck and substructure condition of the element. This is shown in Exhibits 54 and 55.

Sprinkel et al. developed initial costs of rapid repair systems based on questionnaire responses.[38] These are 1990 costs from SHRP C103 project and are shown in Exhibit 56.

Regional indexes are often used to convert a unit cost from one part of the country to another. Kreugler used this method for estimating maintenance costs anywhere in the USA.[39] That report lists the unit cost of maintenance in Pennsylvania as presented in Exhibit 57. These are 1985 prices. The user then prorates that cost based on the ratio of his or her state bridge construction cost per square foot to that of Pennsylvania base on the map reproduced in Exhibit 58. It should be remembered, however, that regional differences within a state can have an effect on unit costs that the methodology does not include. An example is provided in Exhibit 59.

Life-Cycle Costs

The following researchers combined unit costs with service life estimates to develop life-cycle costs.

Sprinkel et al. gathered additional unit costs from the literature review.[38] These are listed along with service lives in Exhibit 60. Additional service lives and maintenance cycles were gathered from the questionnaire and shown in Exhibit 61. The information in Exhibits 61 and 56 were used to estimate the life-cycle costs shown in Exhibit 62. The initial costs from 60 were used to estimate life-cycle costs shown in 63.

In this study, it should be noted that a 10% interest rate and a 5% inflation rate were used. In addition, the cost of maintenance was incorporated in the life-cycle analysis by increasing the initial costs by 10%

Rissel developed equivalent uniform annual costs based on expert opinions provided at a research conference.[40] A 5% discount rate was employed. The cost of traffic control was included in these 1987 cost figures shown in Exhibit 64.

Cady developed cost and service life estimates shown in Exhibits 65 and 66.[41] This was further used to develop life cycle costs incorporating the present level of damage to the deck, as shown in Exhibits 67 and 68.

Jack Bennett offered the unpublished cost figures for chloride removal shown in Exhibit 69. He suggests a unit cost of $6.60 to $7.70 depending on size and a service life of 8 years. This research is still in progress, however. More exact data may be available at the conclusion of SHRP project C-102A.

Service Life

A few researchers have developed service life information without associated costs.

Chamberland and Weyers report the results of a survey questionnaire and correlate the results with a previous TRB study from 1977 and a similar New Mexico SHD study.[42,43,44] The Questionnaire was mailed February 1989. The methods concern deck, Exhibit 70, and non deck, Exhibit 71, treatments.

Sinha developed a list of sample improvement activities for bridge decks through a delphi process.[29 vol. 1, p.17)] The table shows the improvement in rating and the increase in service life of each activity based on existing condition. This is shown in Exhibit 72.

Kruegler developed the service life extension of the total bridge shown in Exhibit 73 based on a nominal group technique.[39, p. 130] The information was collected in 1986.

Summary

The preceding section was reported as a supplement to the literature review since it includes methods of comparing repair and rehabilitation alternatives that are of interest in the development of the C104 decision logic.

Rehabilitation Selection Process

Much of the literature related to deterioration rates is included in documents that included information on various concrete bridge rehabilitation decision logic flowcharts and guidelines. Since this is also of interest in the development of the C104 methodology, it is included in this report. Our interest is the selection process rather than the individual rehabilitation alternatives which are part of other SHRP concrete research that is to be provided.

Manning developed guidelines to govern the use of concrete overlay, waterproofing membrane with paving, and cathodic protection (CP).[45] The decision matrix is presented in Exhibit 74. This process uses an exclusion method of elimination based on selection criteria. In some cases all methods are excluded, in which case some of the criteria must be violated. Various types of concrete overlays are not distinguished.

Stratfull presented a repair replace decision guideline based on the graph presented in Exhibit 75.[46] The graph uses semi-log to plot half-cell potentials versus frequency on the log scale.

Babaei presented Washington State DOT deck repair priority and protection system selection matrix as shown in Exhibit 76.[36, p.3] After some study Babaei suggests improvements to the matrix based on the research findings as shown in Exhibit 77.

Babaei presented a bridge deck reconstruction methodology as shown in Exhibit 78. [47] LMC stands for Latex Modified Concrete, ACM means Asphaltic Concrete with Membrane, and ECR refers to Epoxy Coated Rebar.

Cady developed the flowchart in Exhibit 79.[41, p.9] The chart covers a spectrum of repair/rehabilitation/replacement alternatives.

Exhibit 80 presents a flow chart of the procedure to develop a bridge condition and deterioration rate assessment report. This is from task E of SHRP C101.

Summary and Conclusions

The C104 concrete bridge protection/rehabilitation model should include rates of deterioration and costs for each alternative repair method on each part of the structure. This report contains a review of existing resource material related to these topics. The available information on deterioration rates is based primarily on NBI data collected from routine visual inspections. These findings will be combined with the judgement of the research team and information provided by other SHRP C series projects, to develop the initial model. The decision model will be adjusted for regional differences and refined over time as unit cost and service life data is collected.

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Number

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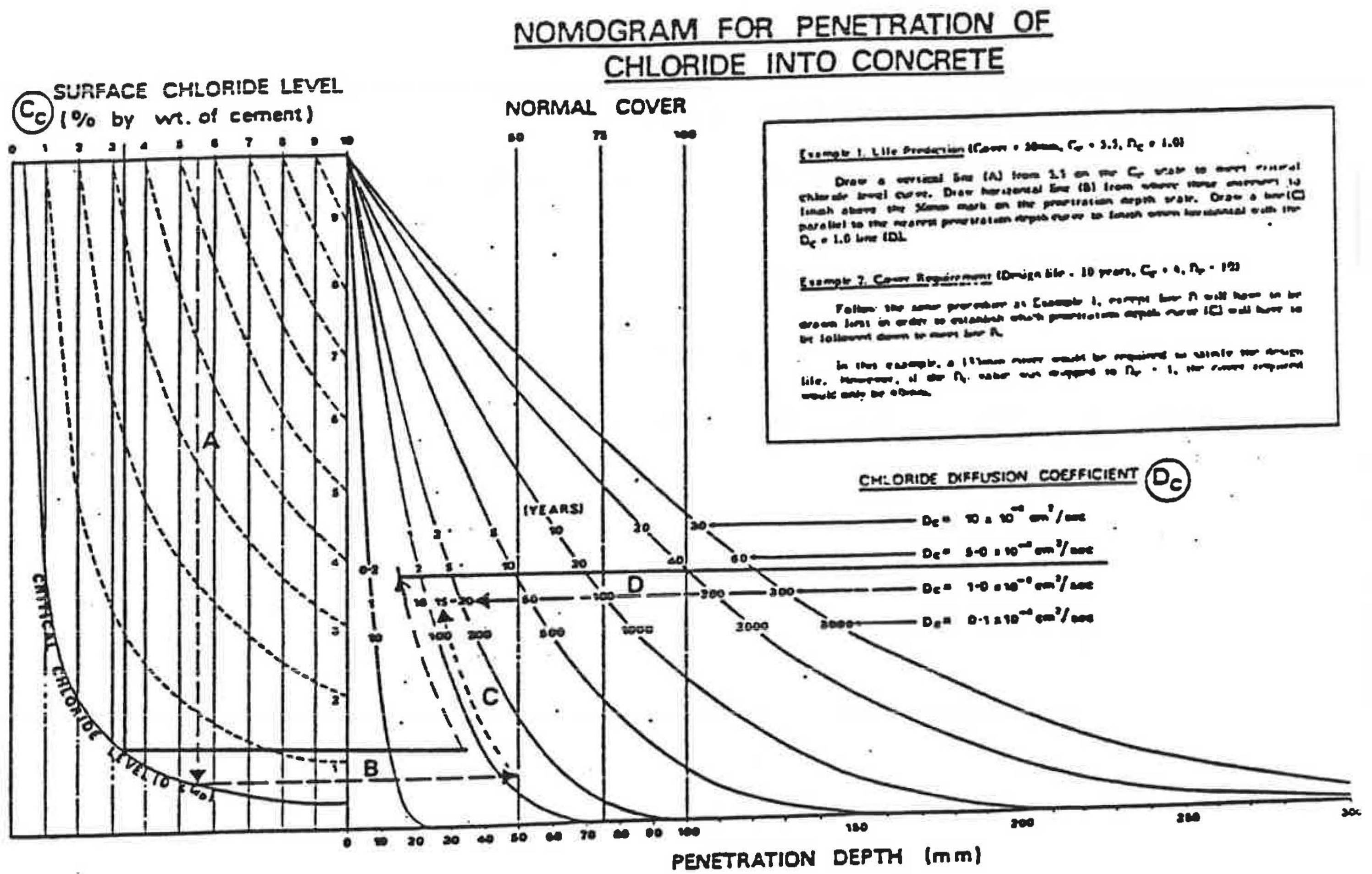
4. Figures

List of Figures

EXHIBIT 1
TIME FOR PENETRATION OF CHLORIDES



Nomogram illustrating life prediction estimations for structures.

SOURCE(1)

EXHIBIT 2
PROCEDURE FOR USING BROWN'S NOMOGRAPH

Browne's nomogram is used in predicting the life of a structure. It takes into account the following variables:

1) Surface chloride level of concrete as a percentage by weight of cement.

2) Critical chloride level at the steel surface as a percentage of weight of cement.

3) Depth of penetration of chlorides in millimeters.

4) Chloride diffusion coefficient in cm^2/sec.

It is possible to guesstimate the life of a structure by defining these four variables for a given structure and the environment.

For example:

a) surface chloride level = 5.5 **Percent of Cl by weight of cement**

b) critical chloride level = 0.4%

c) cover to reinforcement = 50 mm

d) chloride diffusion coefficient = 1×10^{-8} cm^2/sec

(1) Mark a point corresponding to a value of 5.5 on C_e scale.

(2) Draw a vertical line (A) to intersect the curve marked critical chloride level (0.4%).

(3) From this intersection point, draw a horizontal line (B) to intersect a vertical line at 50 mm on the penetration depth scale.

(4) From this intersection point, draw a line (C) parallel to the nearest penetration depth curve to finish when in line with the horizontal line for Dc = 1×10^{-8} cm^2/sec.

(5) Calculate the life of the structure by interpolating with the life shown on the depth of penetration curve from either side of line C.

<u>Note</u>: For corners, the life may be approximately halved, or conversely, the cover has to be doubled to give the same life because of the two-directional diffusion path from the two sides.

-- It is evidenced that the use of cement replacement materials (e.g., pulverized fuel ash or blast furnace slag) can reduce the Dc values by significantly reducing the size of the interconnected pores in the hardened cement.

EXHIBIT 3 – PAGE 1
PROCEDURE FOR CALCULATING EFFECTIVE DIFFUSION COEFFICIENT

Step 1: Get the chloride profile data. List the chloride content at each depth (see column 1 and column 2 of Table A).

Step 2: Identify the maximum chloride concentration, C_{max} and minimum chloride concentration, C_{min}.

Step 3: Calculate

$$U = \frac{C_{max} - C_d}{C_{max} - C_{min}} = erf(p)$$

e.g. for d = 1.25, C_d = 0.1433%

C_{max} = 0.1658% C_{min} = 0.0051%

$$U = \frac{0.1658 - 0.1433}{0.1658 - 0.0051} = 0.1400 = erf(p)$$

Calculate erf(p) for all other entries and fill in column 3.

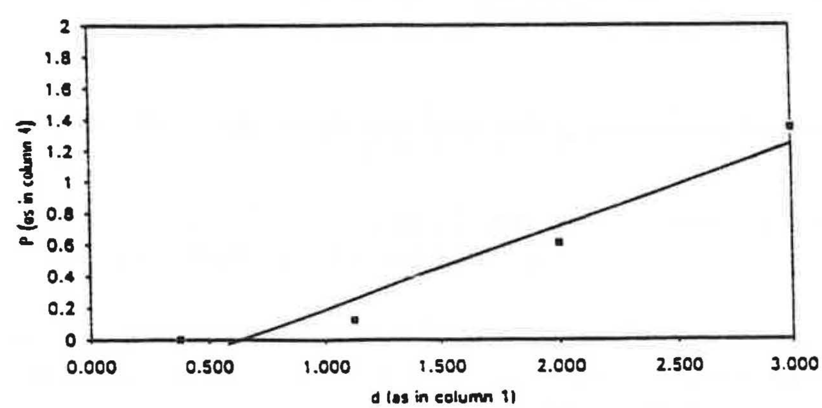
Step 4: Determine the argument "p" from the erf(p) values using the error function tables.

e.g., for erf(p) = 0.1400, the corresponding value of "p" is 0.1247

Get the value of "p" for other entries and fill in column 4.

Step 5: Plot column 1 (i.e., d) along x-axis and column 4 (i.e., p) along y-axis and obtain a best straight line fit. Give more weighage to the points on the bent of the chloride profile curve (i.e., more weighage to the points not in the evenly distributed background minimum chloride range). Extend this best fit line to intercept the x-axis. Determine the x-intercept when "p" is zero. This value of x-intercept defines the interface between the "near-surface" zone and the diffusion zone.

Plot of d vs P to determine the near surface depth



From the above plot x-intercept = 0.6337 inches

EXHIBIT 3 – PAGE 2
PROCEDURE FOR CALCULATING EFFECTIVE DIFFUSION COEFFICIENT

Step 6: Adjust "d" values by this depth to obtain "x" as in column 5 (= column 1 - intercept)

e.g., 1.25 - 0.6337 = 0.4913

Step 7: Divide "x" (column 5) by "p" (column 4) to obtain $\sqrt{4D_e t}$ and enter these values in column 6.

e.g., (0.491)/(0.1247) = 3.9399

Step 8: Calculate the average of the entries in column 6.

For this example average of $\sqrt{4D_e t}$ = 2.2904

Step 9: Determine the age of the structure when the chloride profile sample was extracted.

In this case it was 10 years. So t = 10 years = 10 x 365.25 x 24 x 60 x 60
= 3.16×10^8 sec.

Step 10: Calculate diffusion coefficient as follows:

$$\frac{(\text{Average of } \sqrt{4D_e t})^2}{4 \times t}$$

e.g. $(2.2904)^2/4 \times 3.16 \times 10^8$

$= 0.415 \times 10^{-8}$ in^2/sec

$= 2.68 \times 10^{-8}$ cm^2/sec

Table A

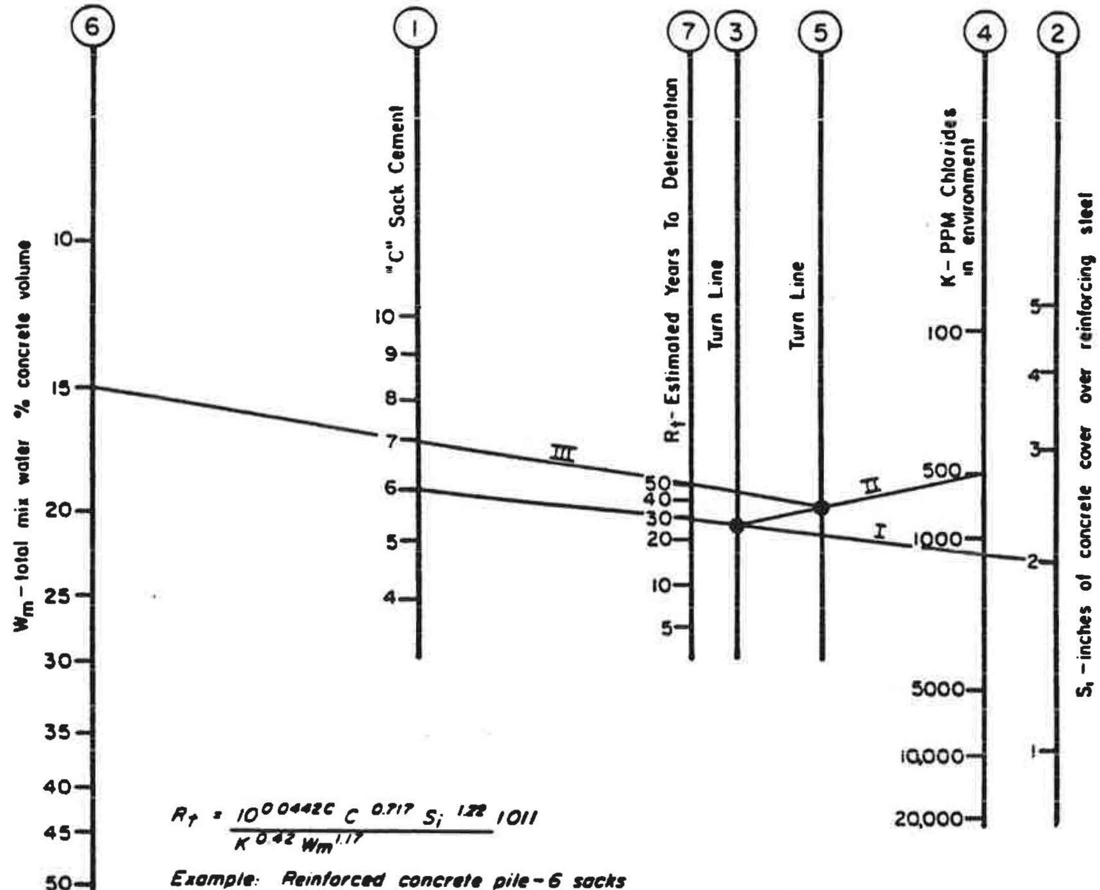
Calculation of Diffusion Coefficient

Column 1 Depth, in.	Column 2 Cl %	Column 3 erf (P)	Column 4 P	Column 5 X	Column 6 Sq(4Det)
0.375	0.1658	0.0000	0		
1.125	0.1433	0.1400	0.1247	0.491	3.9399
2.000	0.0676	0.6111	0.6095	1.366	2.2417
3.000	0.0143	0.9428	1.3449	2.366	1.7595
4.000	0.0051	1.0000	2.7577	3.366	1.2207
				Average =	2.2904

Age t = 10 years = 3.16E+08

Diffusion Coefficient = 4.16E-09 sq. in/sec
= 2.68E-08 sq. cm/sec

DETERIORATION TIME FOR REINFORCED CONCRETE PILES



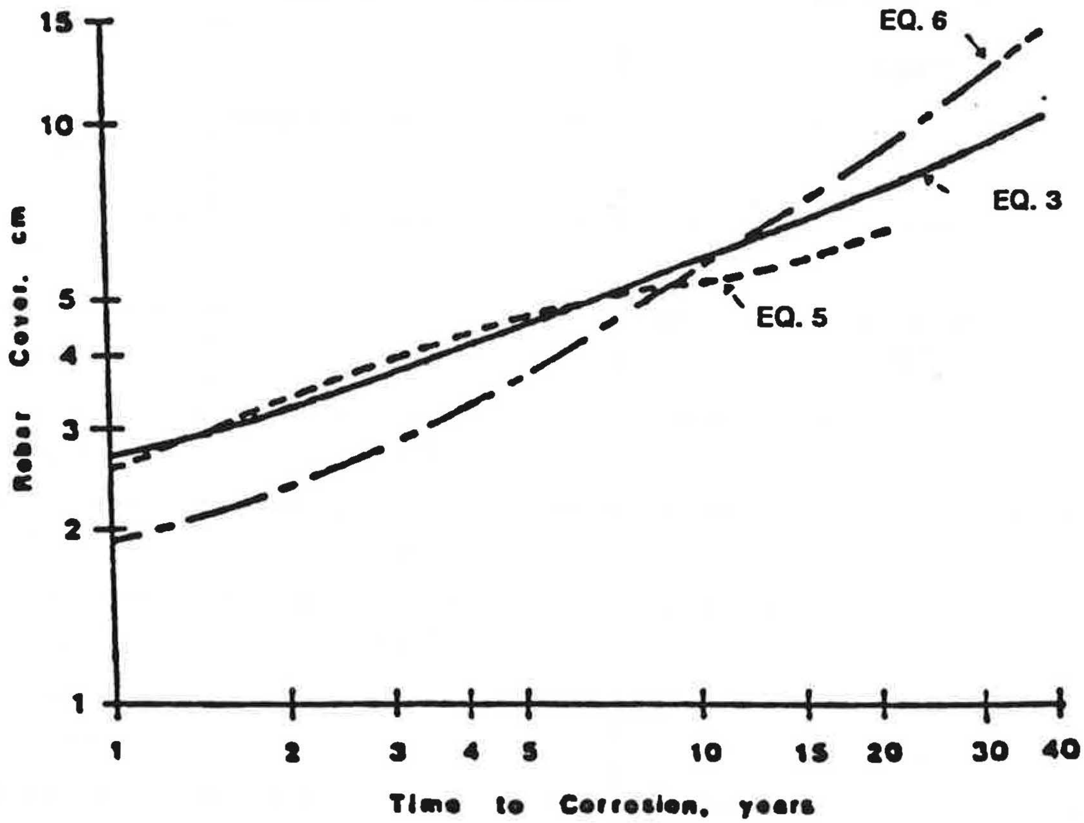
$$R_t = \frac{10^{0.0442C}\, C^{0.717}\, S_i^{1.22}\, 1011}{K^{0.42}\, W_m^{1.17}}$$

Example: *Reinforced concrete pile - 6 sacks of cement per cubic yard, 2 inches concrete cover over steel, 500 ppm chlorides in the environment, 15% by volume of total mixing water including that contained in the aggregate. Follow nomograph in sequence indicated by lines I, II and III. Answer is approximately 50 years.*

Chart for estimating deterioration time for reinforced concrete pile.

SOURCE(4)

EXHIBIT 5
COMPARISON OF CORROSION TIMES



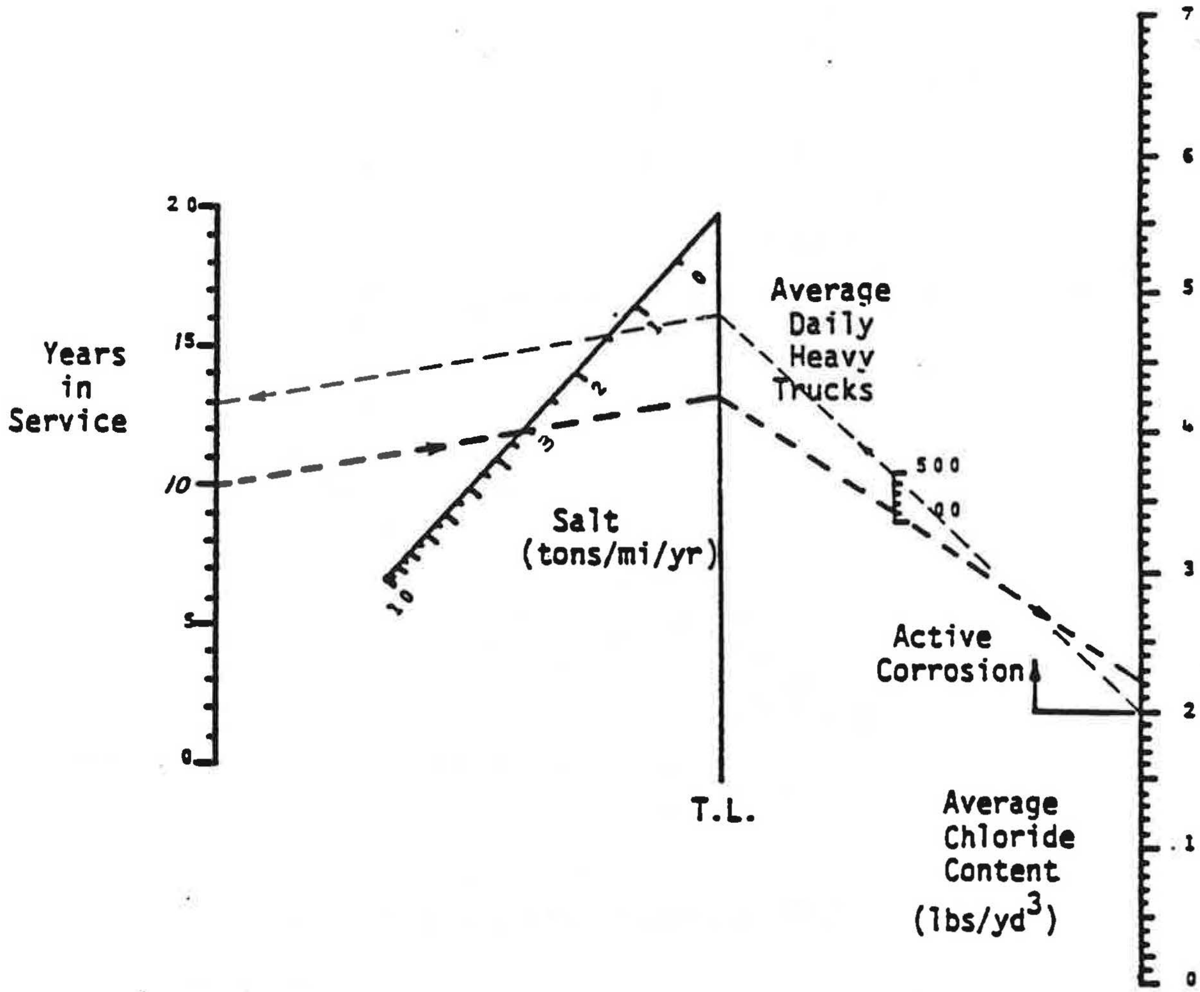
—Comparison among relationships for rebar cover versus time.

SOURCE(3)

EXHIBIT 6
WATER CEMENT RATIO AND COULOMBS PASSED

Water-to-Cement Ratio	Coulombs Passed	Cure Time
0.26	44	1 day
	65	7 days
0.28	942	1 day
	852	7 days
0.40	3897	1 day
	3242	7 days
0.50	5703	1 day
	4315	7 days
0.60	5911	1 day
	4526	7 days
0.75	7065	1 day
	5915	7 days

EXHIBIT 7
AVERAGE SALT CONTENT



Example:

Age of structure = 10 years
Deicing salt = 3 tons/mile/year
Average daily heavy trucks = 100
Resulting Chloride Content = 2.2 lbs/yd^3

Note: For new structures, or if no deicing salt is used, enter zero heavy trucks.

Figure 3.40

SOURCE(23)

EXHIBIT 8

PERCENT SPANS SPALLED IN NY >1 SQ. FT.

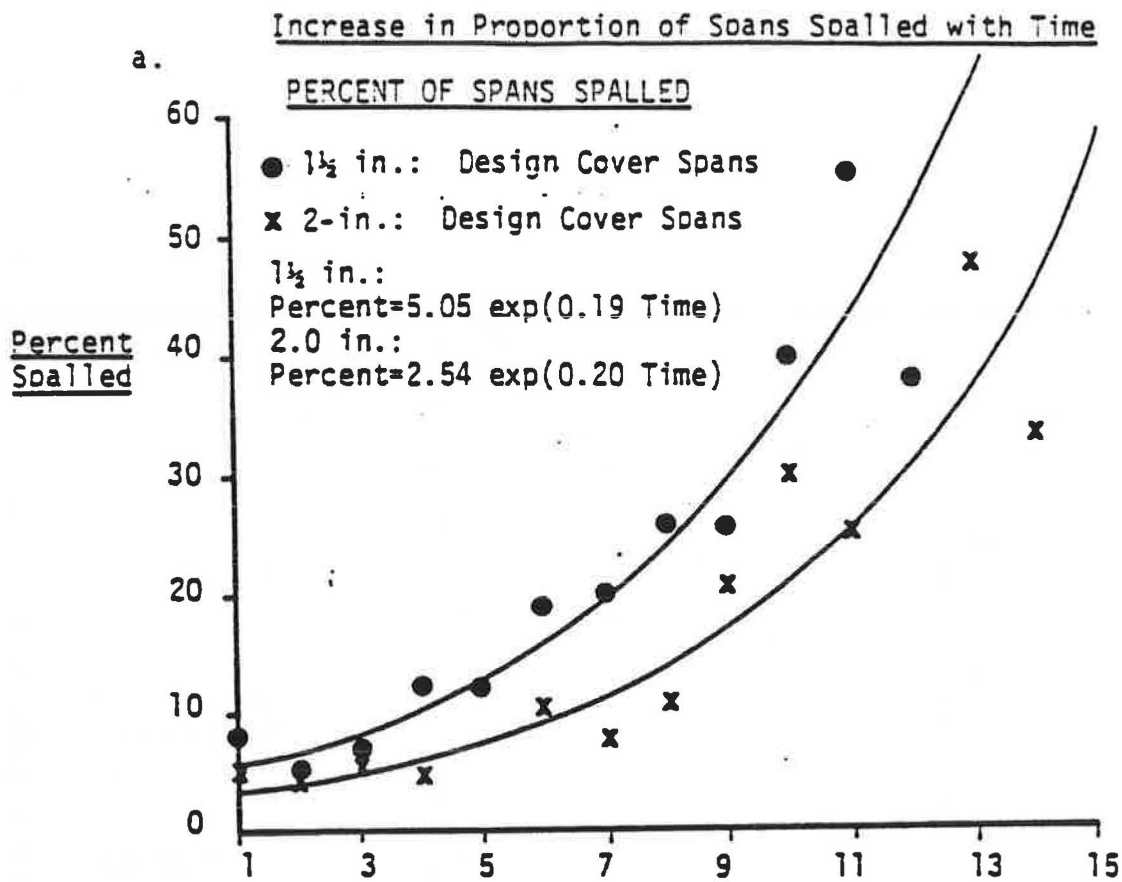


EXHIBIT 9
PERCENT SPANS SPALLED IN NY >3 SQ. FT.

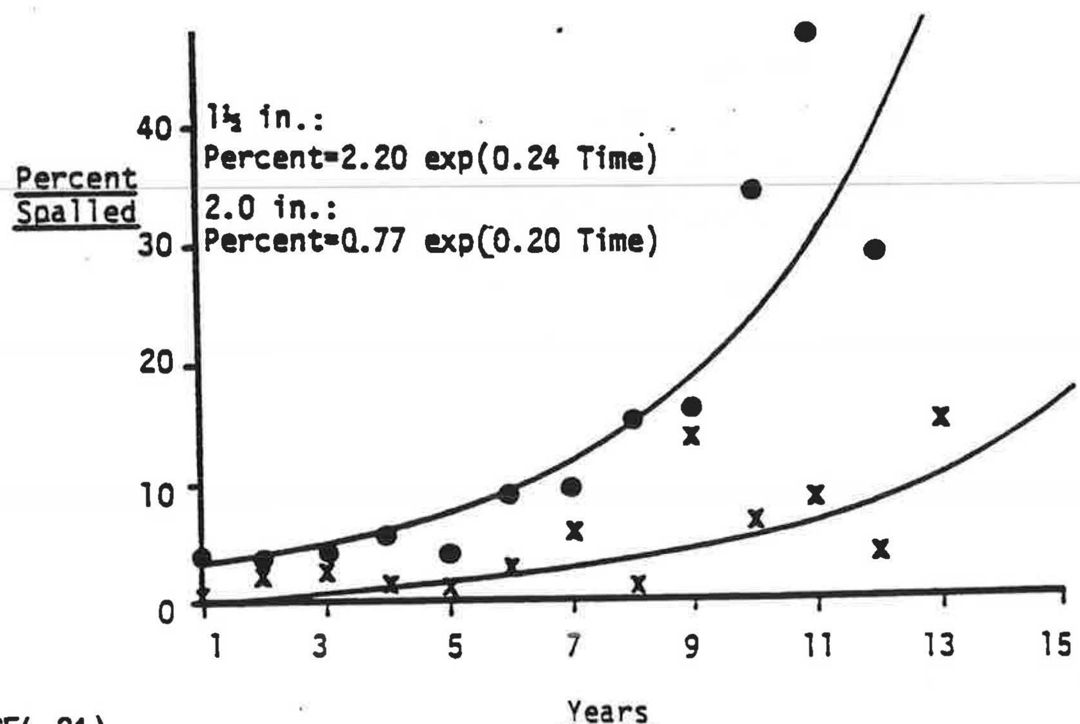


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EXHIBIT 10

AVERAGE SPALLED AREA PER SPAN

Average Deterioration of Bare Concrete Decks in Winter Climate

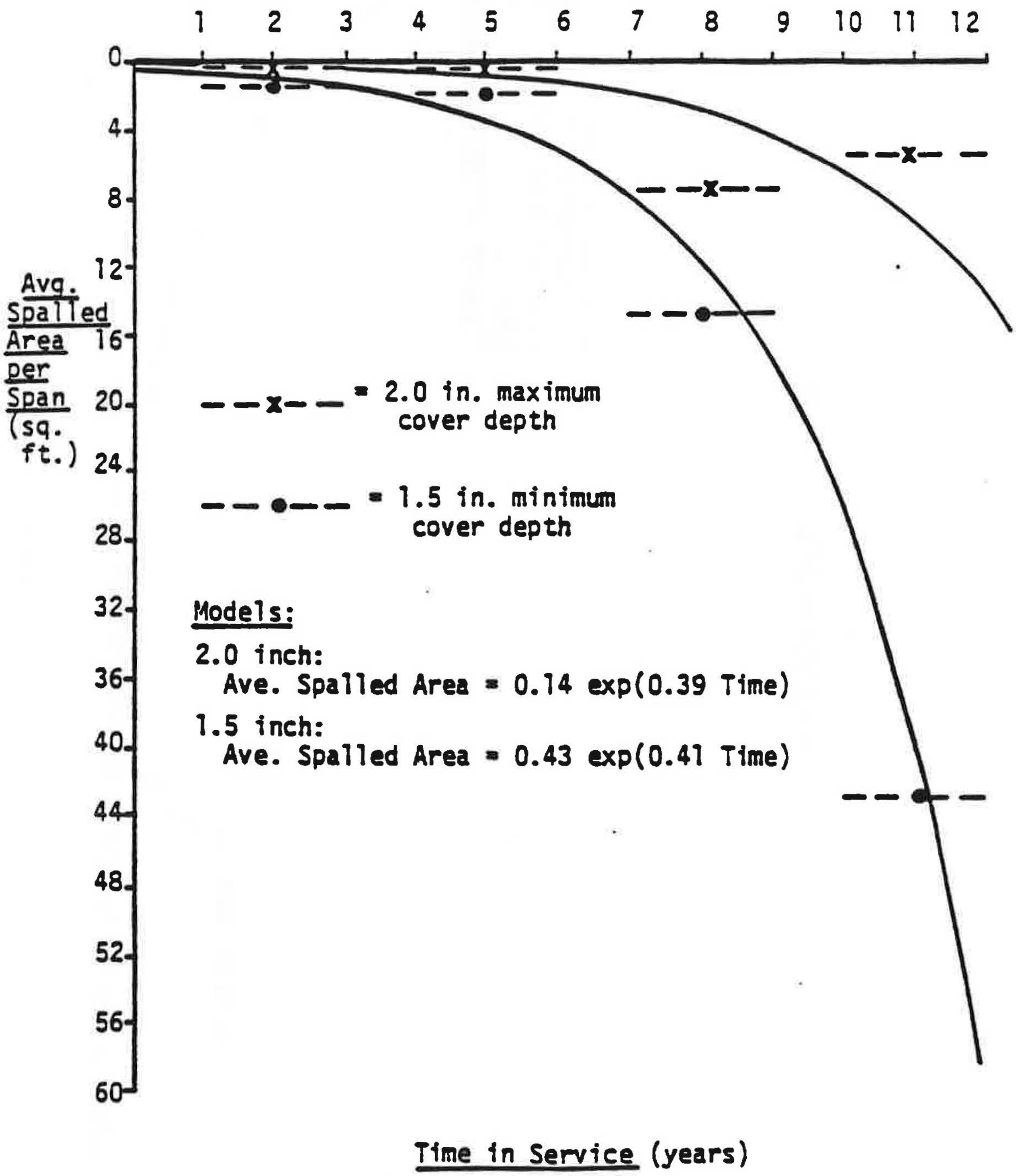

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EXHIBIT 11
DELAMINATION VS. TIME

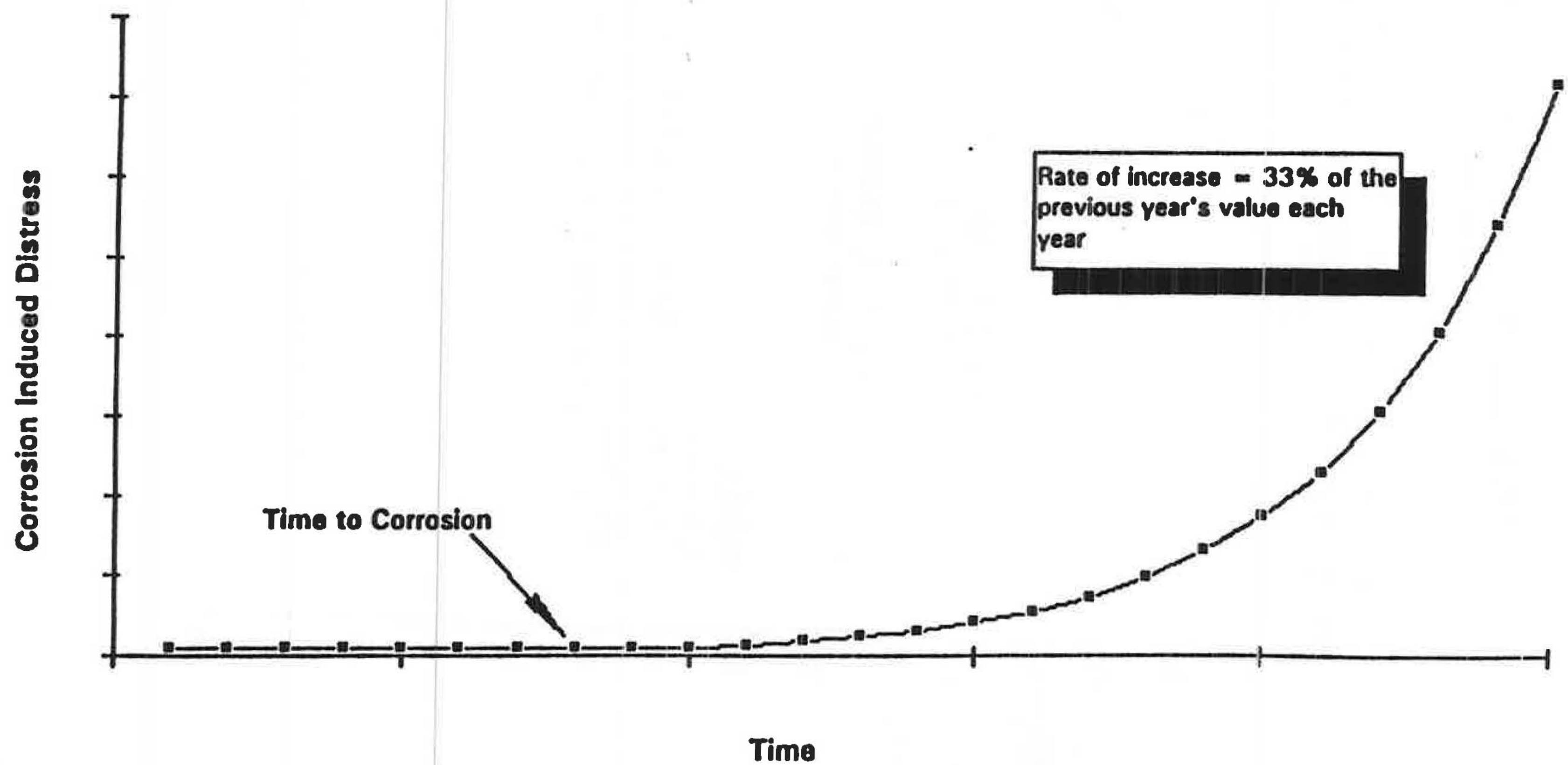
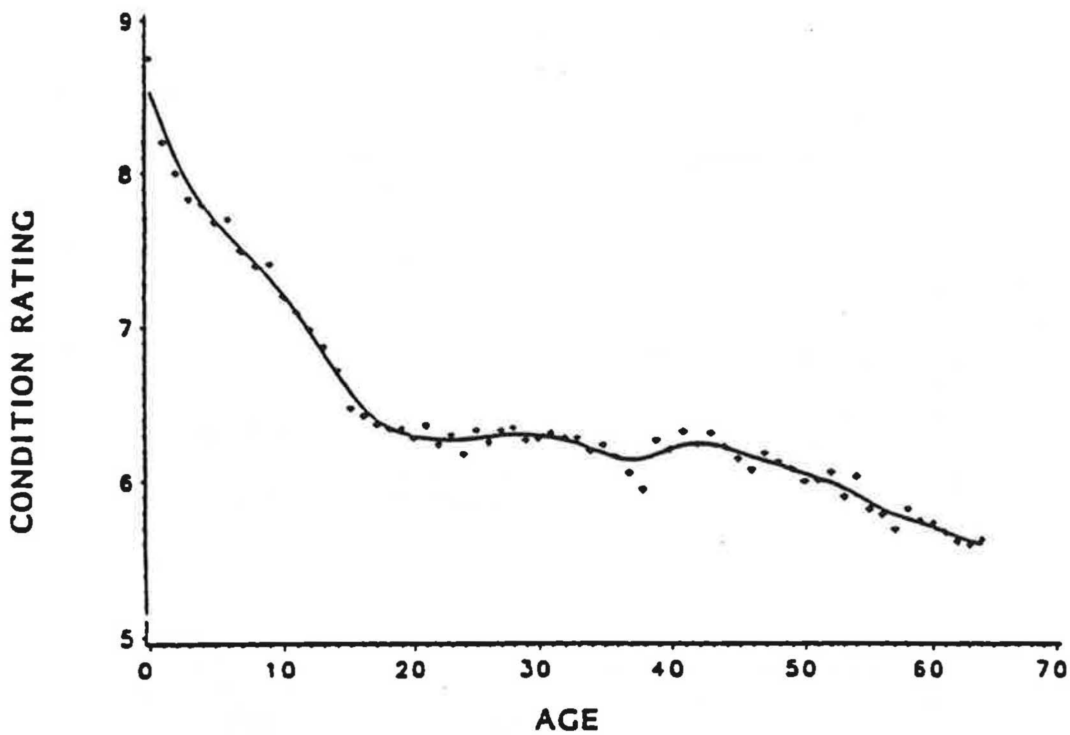


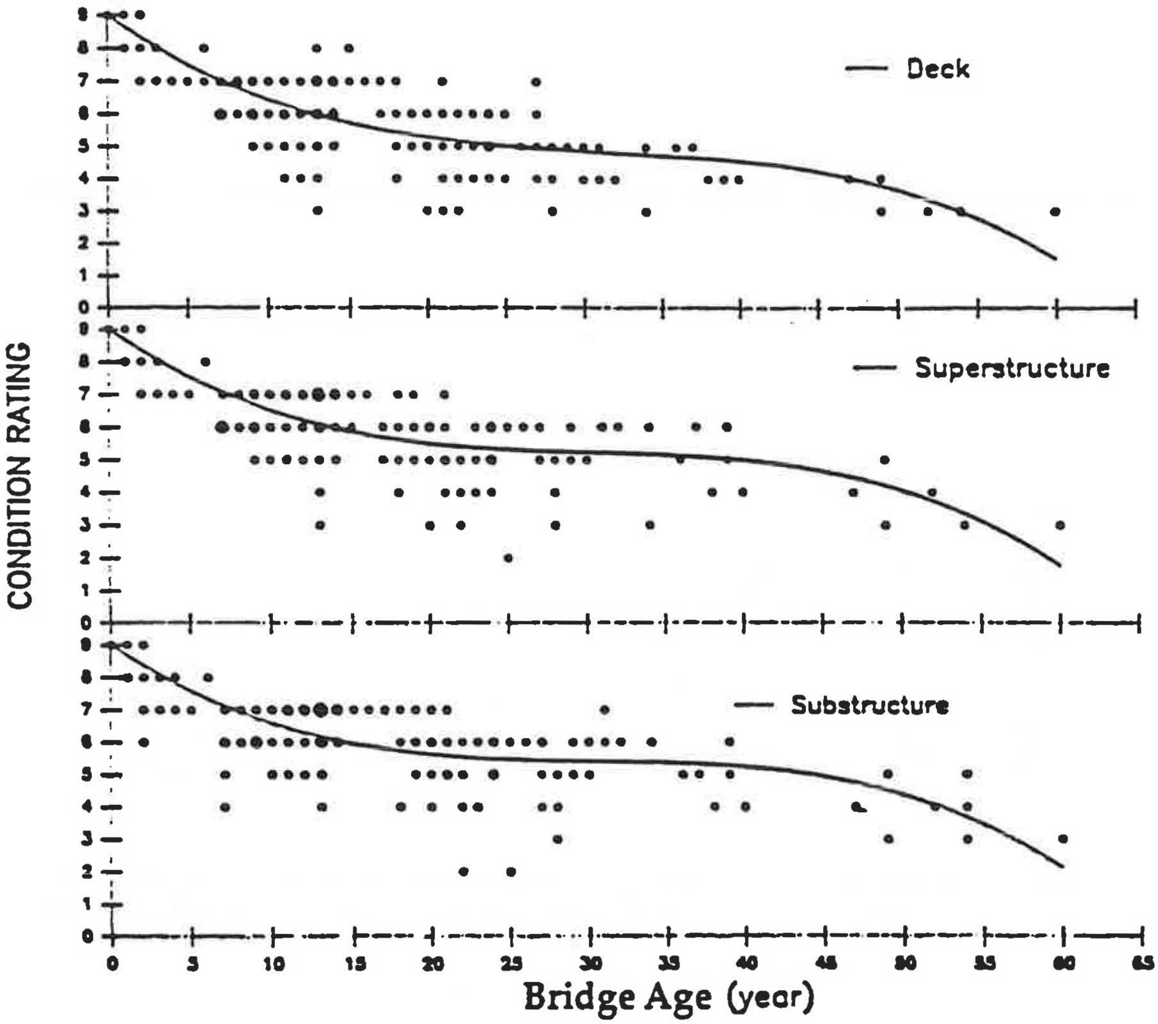
EXHIBIT 12
AVERAGE PA BRIDGE DECK RATING VS. AGE



Average bridge deck condition rating versus age.

SOURCE(26)

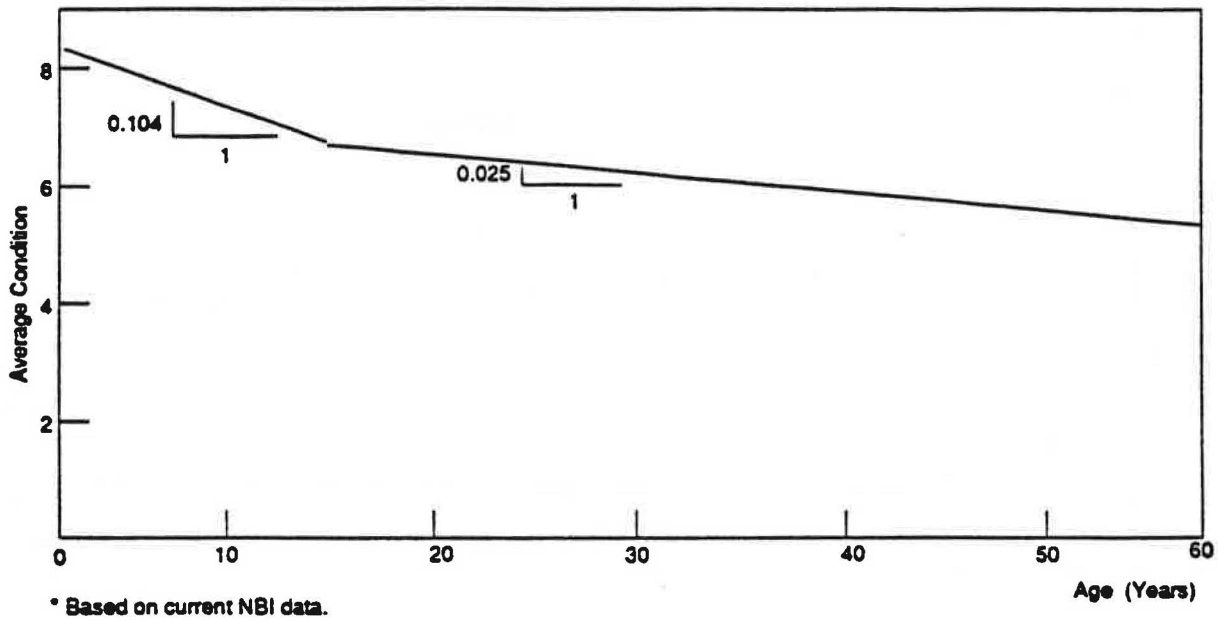
EXHIBIT 13
CONDITION VS. AGE FOR STATES OTHER THAN INDIANA



Performance Curves of Concrete Bridge Components on Other State Highways

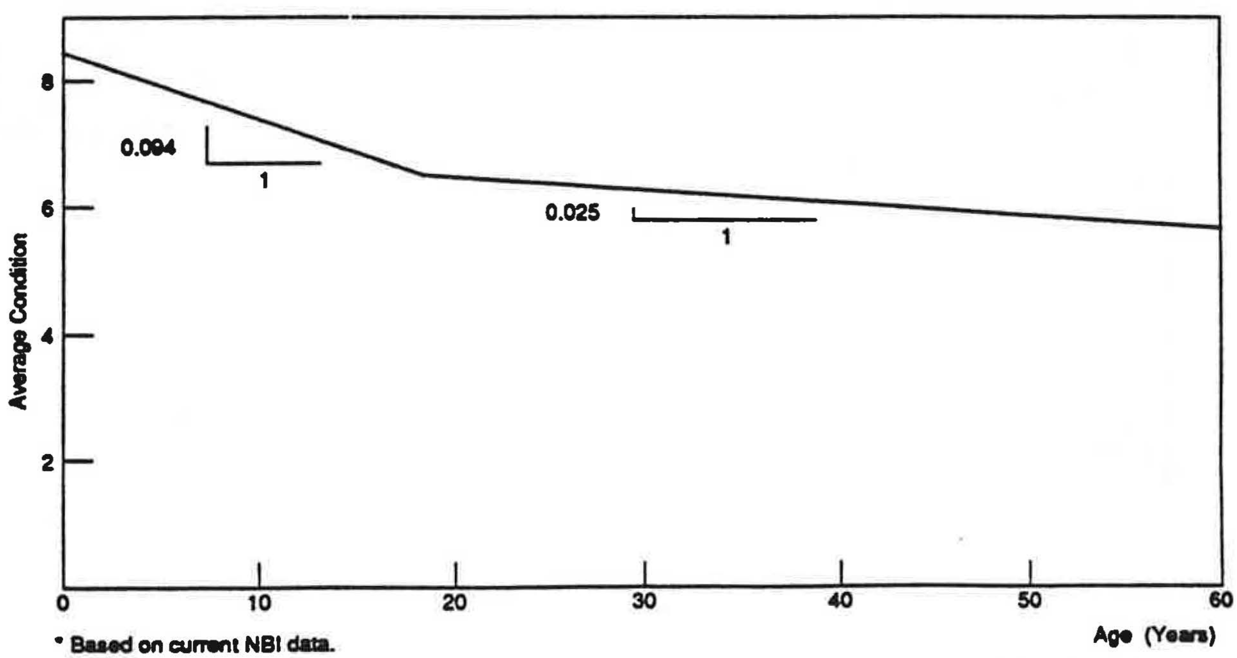
SOURCE(27)

EXHIBIT 14
NBI DECK CONDITION VS. AGE



* Based on current NBI data.

EXHIBIT 15
NBI BRIDGE CONDITION VS. AGE



* Based on current NBI data.

SOURCE(28)

EXHIBIT 16
NYSDOT PERFORMANCE MODEL – ALL BRIDGES

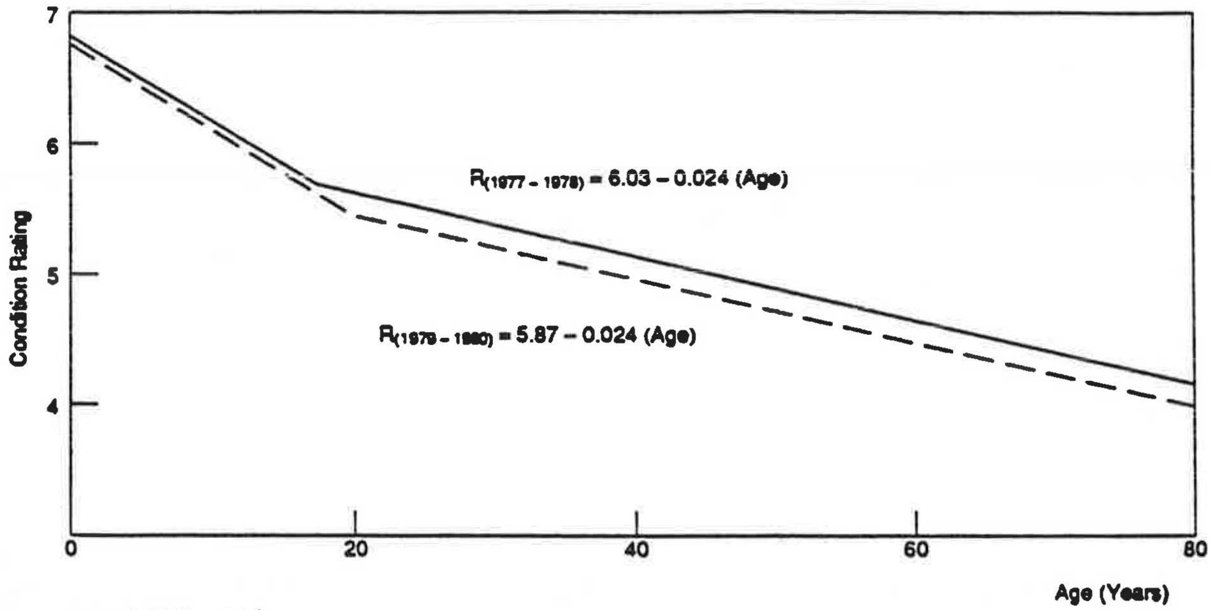


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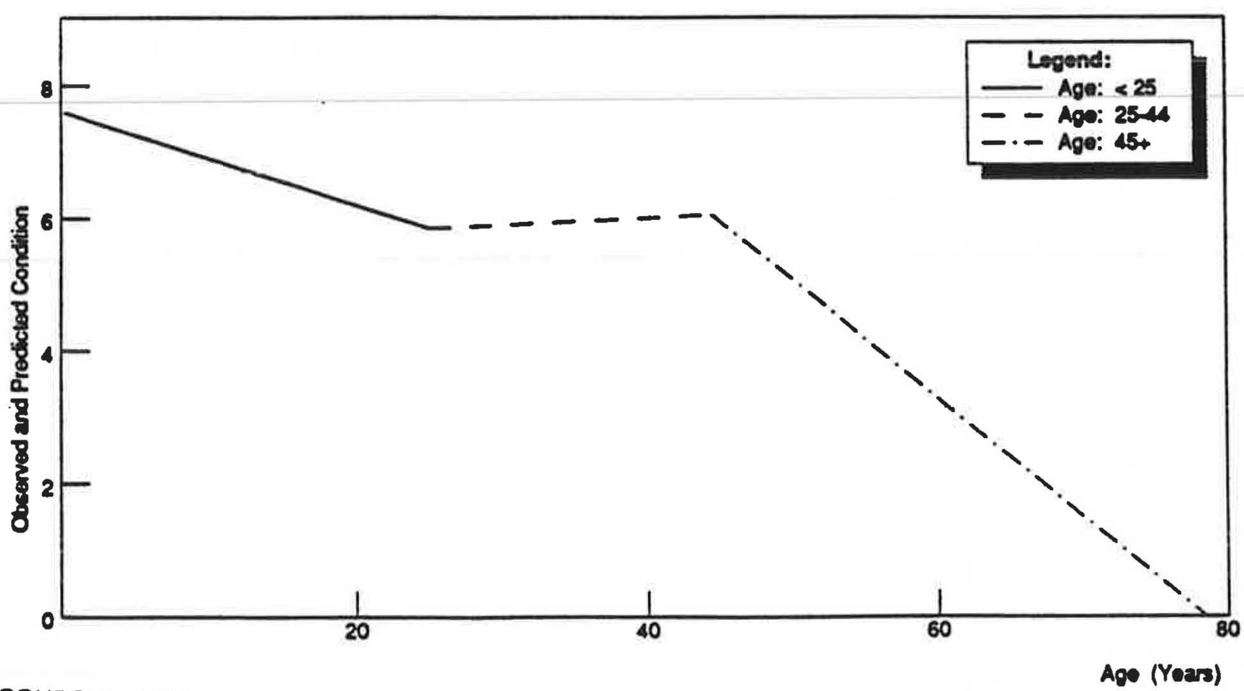
EXHIBIT 17
WisDOT PERFORMANCE MODEL – ALL BRIDGES



SOURCE(30)

EXHIBIT 18
WisDOT PERFORMANCE MODEL – R.C. DECKS

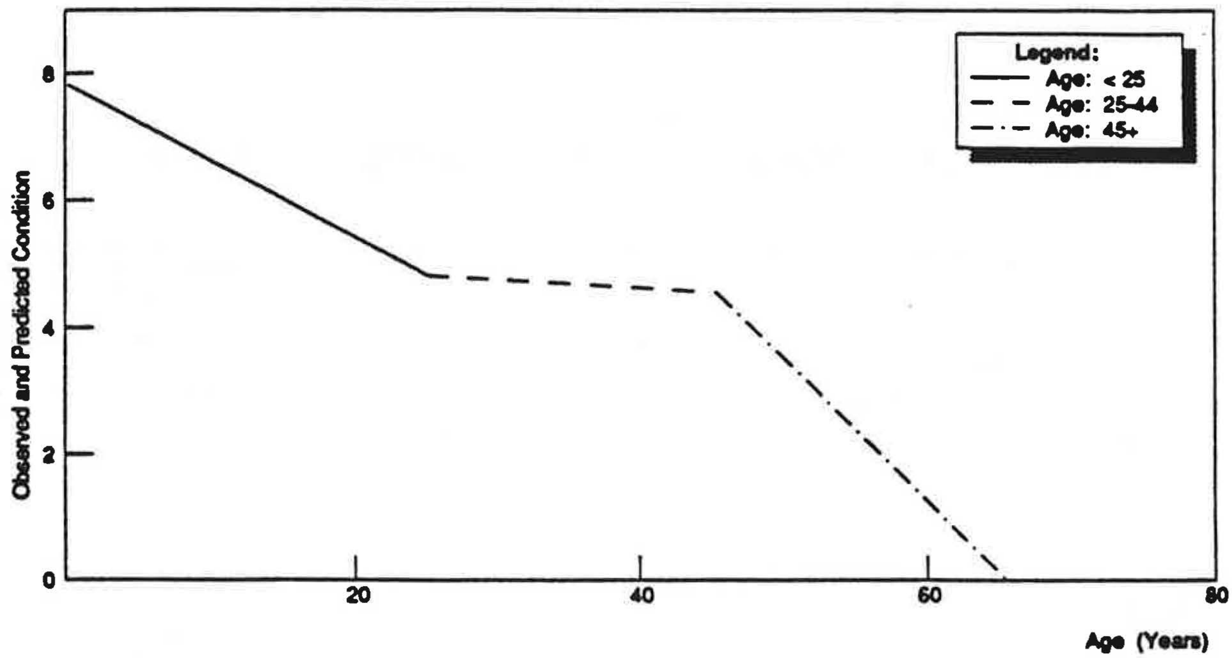
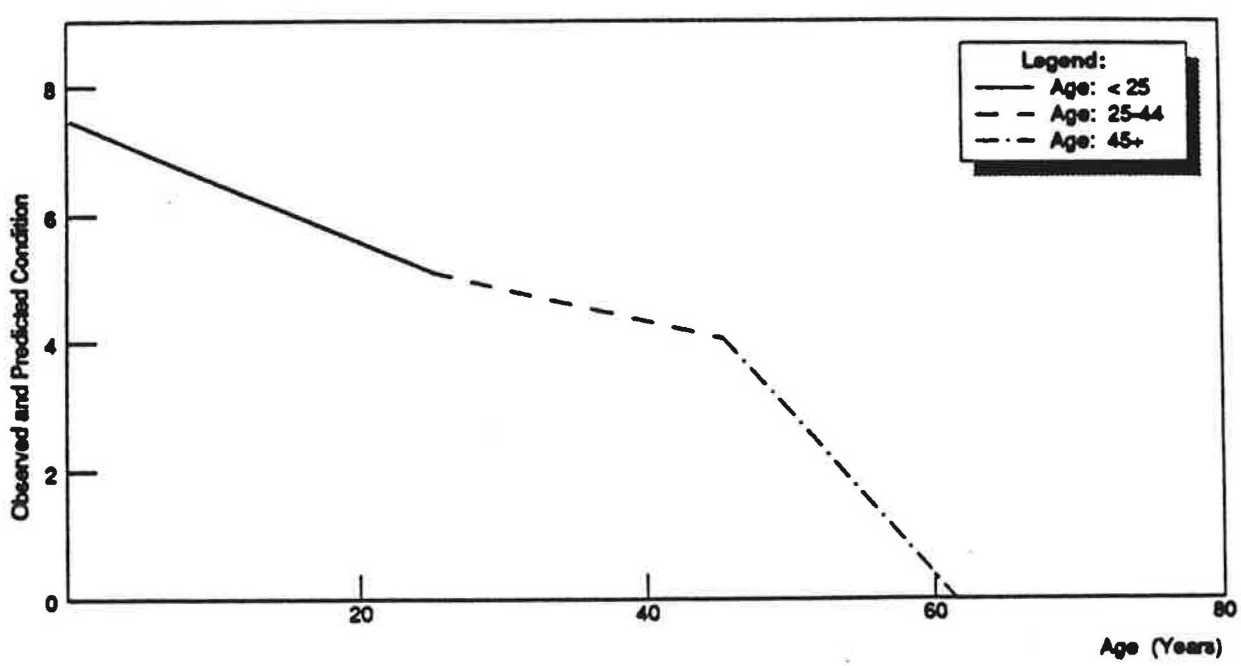
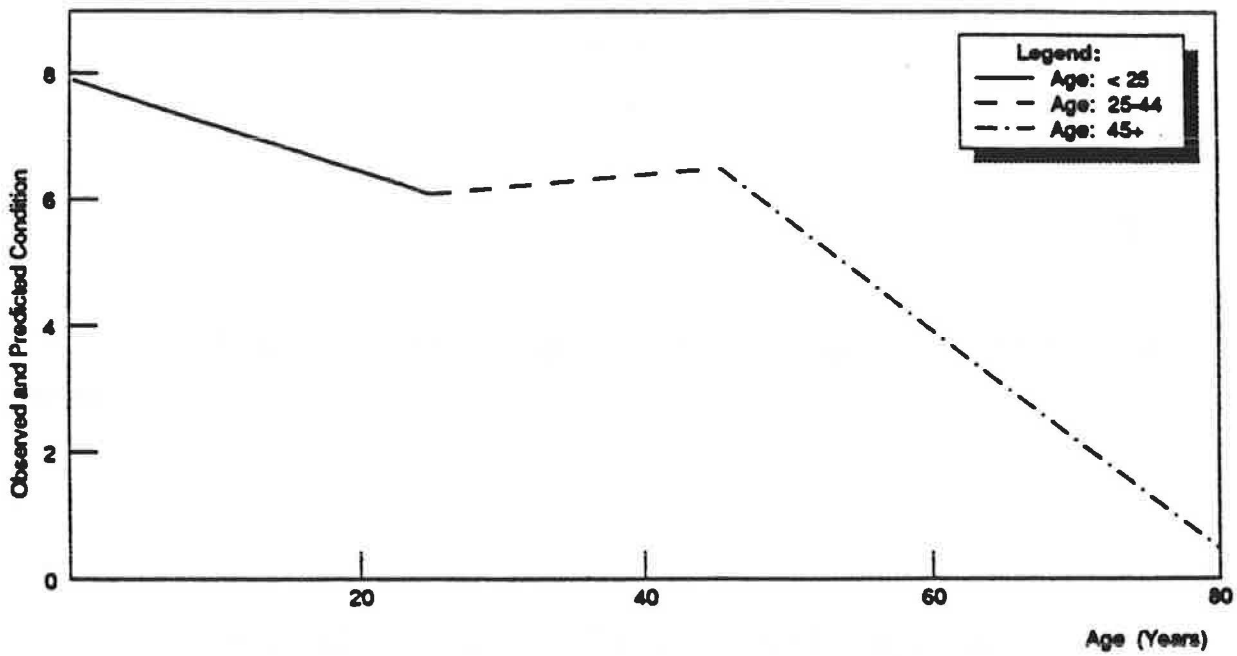


EXHIBIT 19
WisDOT PERFORMANCE MODEL – SLAB SPANS



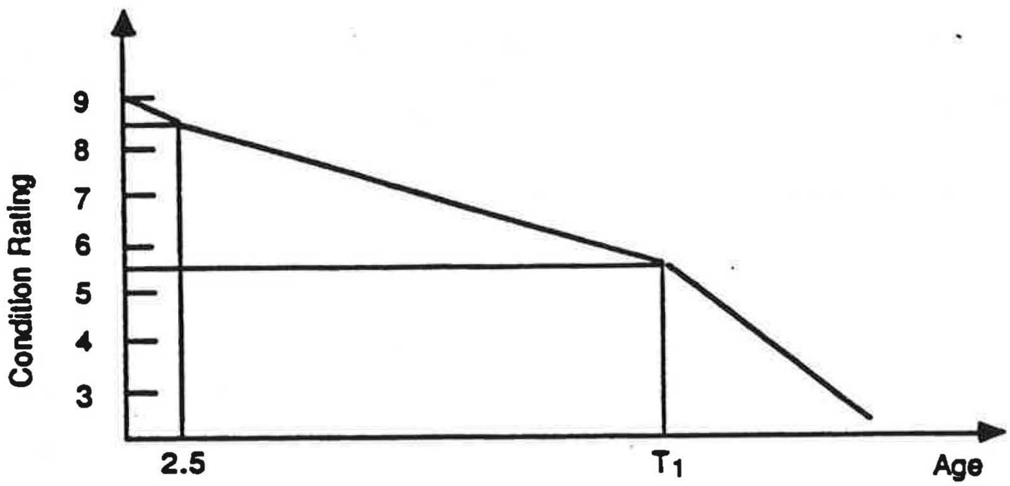
SOURCE(30)

EXHIBIT 20
WisDOT PERFORMANCE MODEL – PRESTRESSED SPANS



SOURCE(30)

EXHIBIT 21
NCDOT PERFORMANCE MODEL – PAGE 1



T_1 : Survey average age for condition rating 5.5

Deck Deterioration Rates.

Material	ADT	Deterioration Rate (Years/Point) Rating 9	Ratings 8-6	Ratings 5-4
	<= 200	5	9.7	6.5
	201-800	5	9.0	6.3
Reinforced	801-2000	5	8.0	5.6
Concrete	2001-4000	5	7.4	5.5
	> 4000	5	6.4	5.2

SOURCE(31)

NCDOT PERFORMANCE MODEL – PAGE 2

Superstructure Deterioration Rates.

Material & Structure Type	System	Deterioration Rate (Years/Point) Rating 9	Ratings 8-6	Ratings 5-4
Reinforced Concrete				
Slab	I&P*	5	8.7	6.0
	S**	5	10.6	6.7
Tee-Beam	I&P	5	9.2	4.9
	S	5	9.5	6.1
Prestressed Concrete				
Multi-Meam	I&P	5	7.9	5.1
	S	5	8.5	5.1

* Interstate and primary systems.
** Secondary system.

Substructure Deterioration Rates.

Material	Location	Deterioration Rate (Years/Point) Rating 9	Ratings 8-6	Ratings 5-4
Reinforced Concrete	Coastal Area	5	7.8	4.9
	Piedmont Area	5	11.3	6.9
	Mountain Area	5	8.8	6.7
Prestressed	Coastal Area	5	7.5	5.6
	Piedmont Area	5	11.7	7.0
	Mountain Area	5	8.2	4.9

EXHIBIT 23
NCDOT PERFORMANCE CURVE – DECK

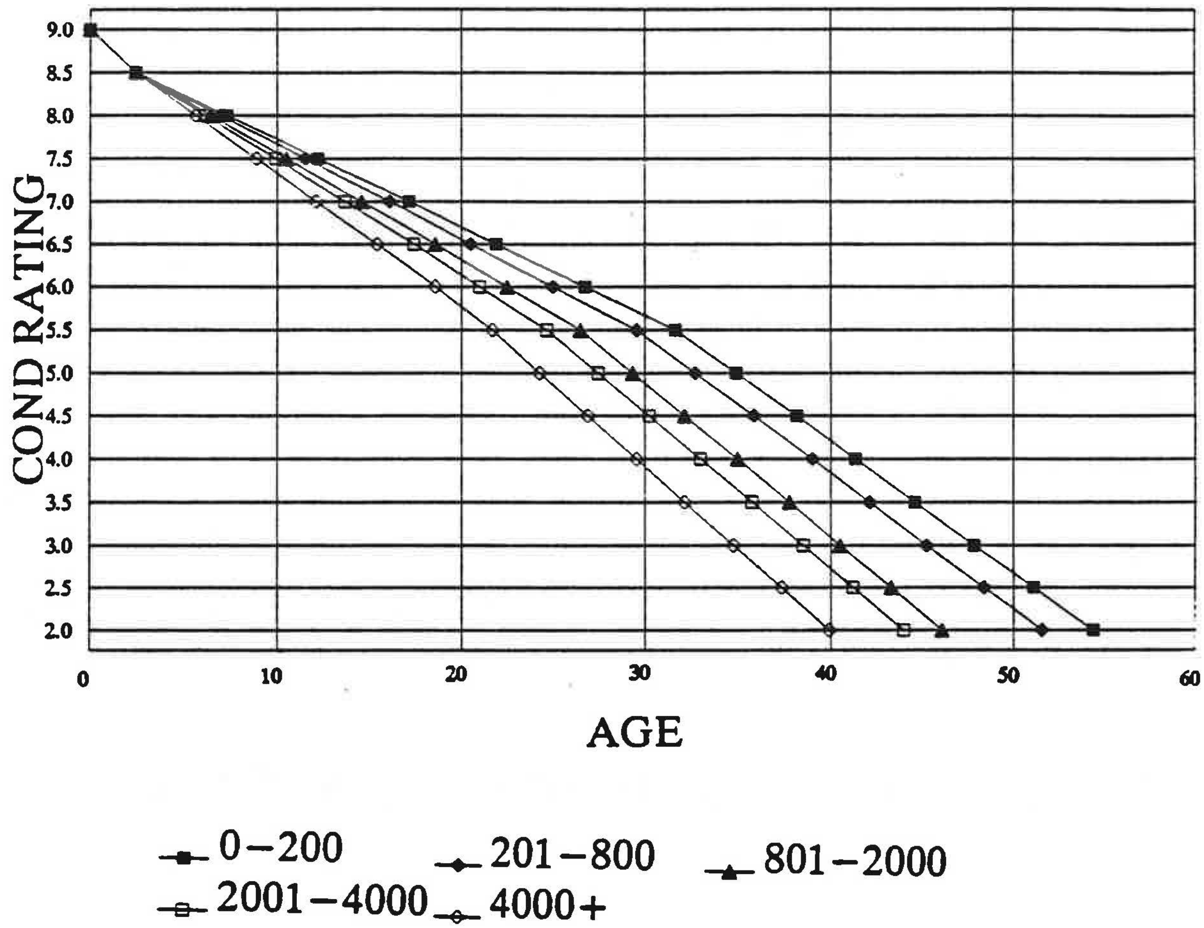
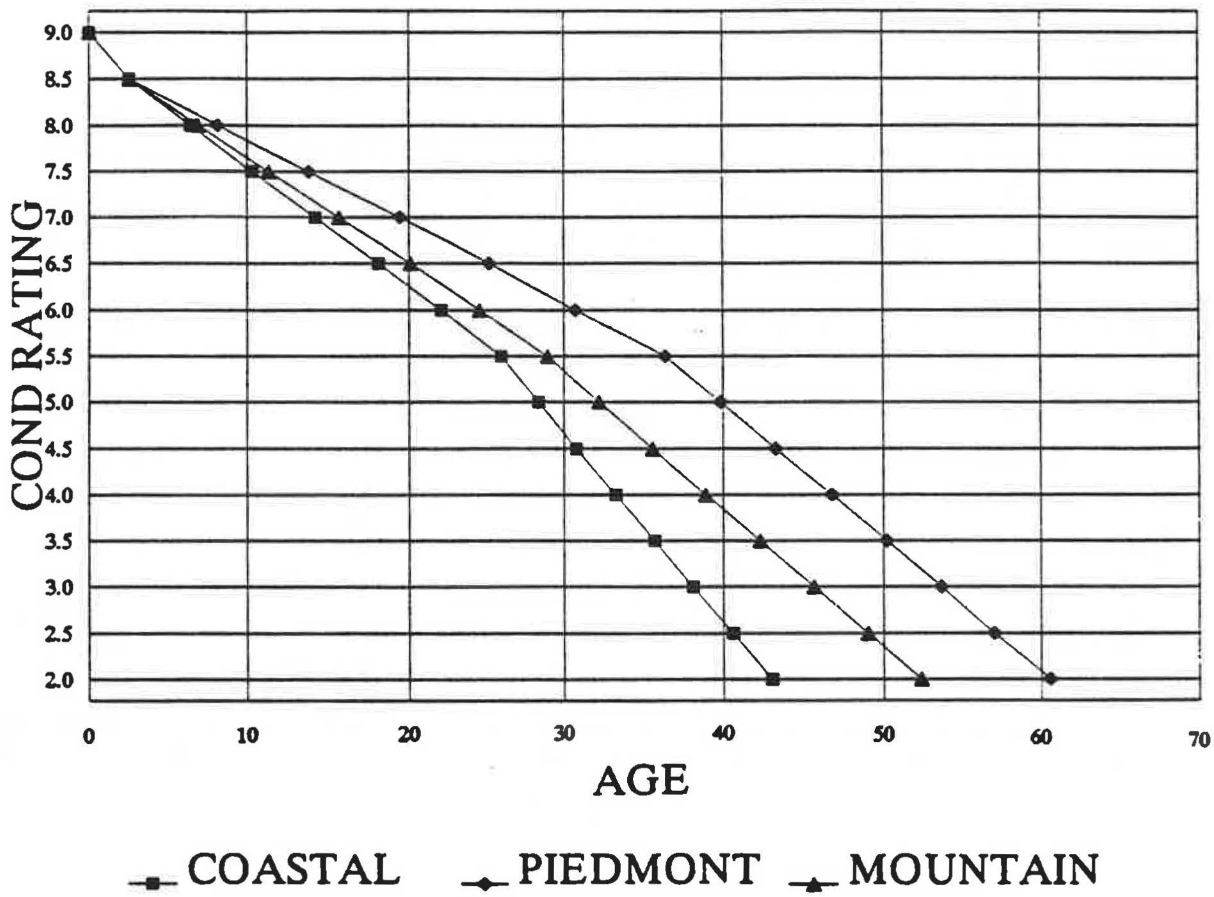


EXHIBIT 24
NCDOT PERFORMANCE CURVE – SUBSTRUCTURE



$$DECK = 9 - 0.119 \times (AGE) - 2.158 \times 10^{-6} \times (ADTAGE)$$

$$SUPER = 9 - 0.103 \times (AGE) - 1.982 \times 10^{-6} \times (ADT)$$

$$SUB = 9 - 0.105 \times (AGE) - 2.051 \times 10^{-6} \times (ADT)$$

$$ADTAGE = \frac{(ADT) \times (AGE)}{10}$$

BASED ON 150,000+ BRIDGES, < 25 YEARS OLD

INVESTIGATED & DISMISSED

SKEW
MULTISPANS
WEARING SURFACE
CUSTODIAN
STRUCTURE TYPE

SOURCE(32)

EXHIBIT 26
DECK MODEL AS A GRAPH

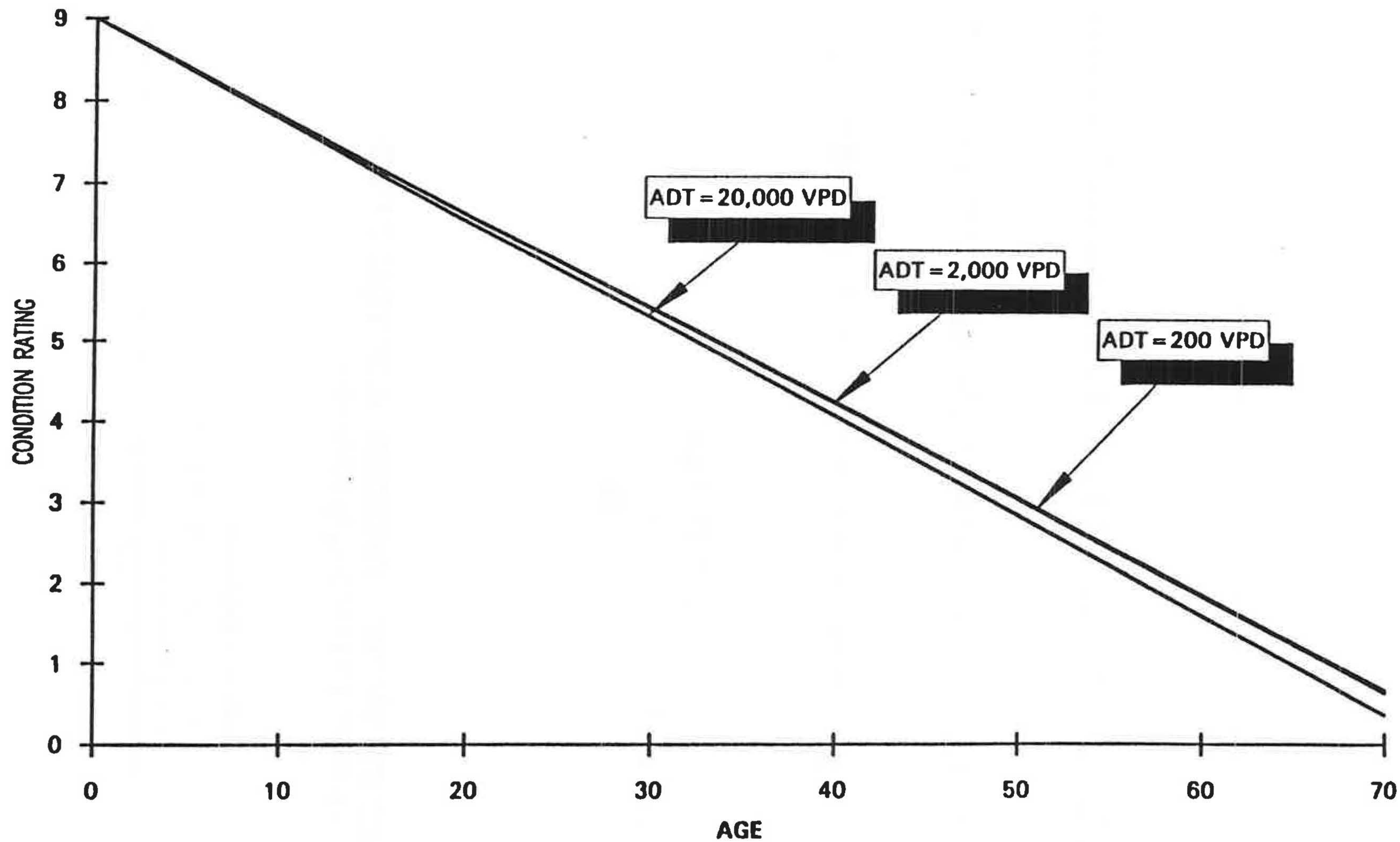


EXHIBIT 27
SUPERSTRUCTURE MODEL AS A GRAPH

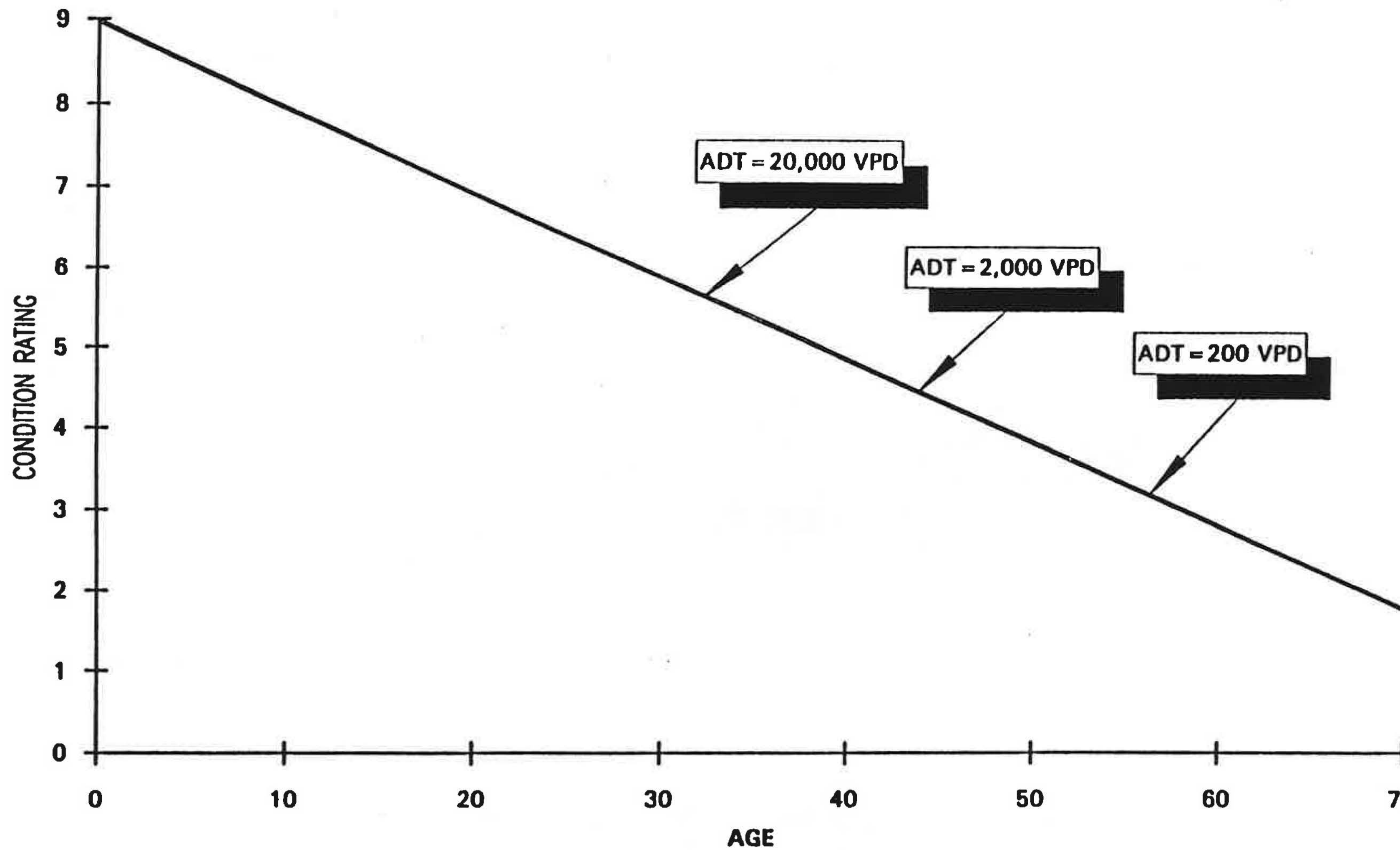


EXHIBIT 28
SUBSTRUCTURE MODEL AS A GRAPH

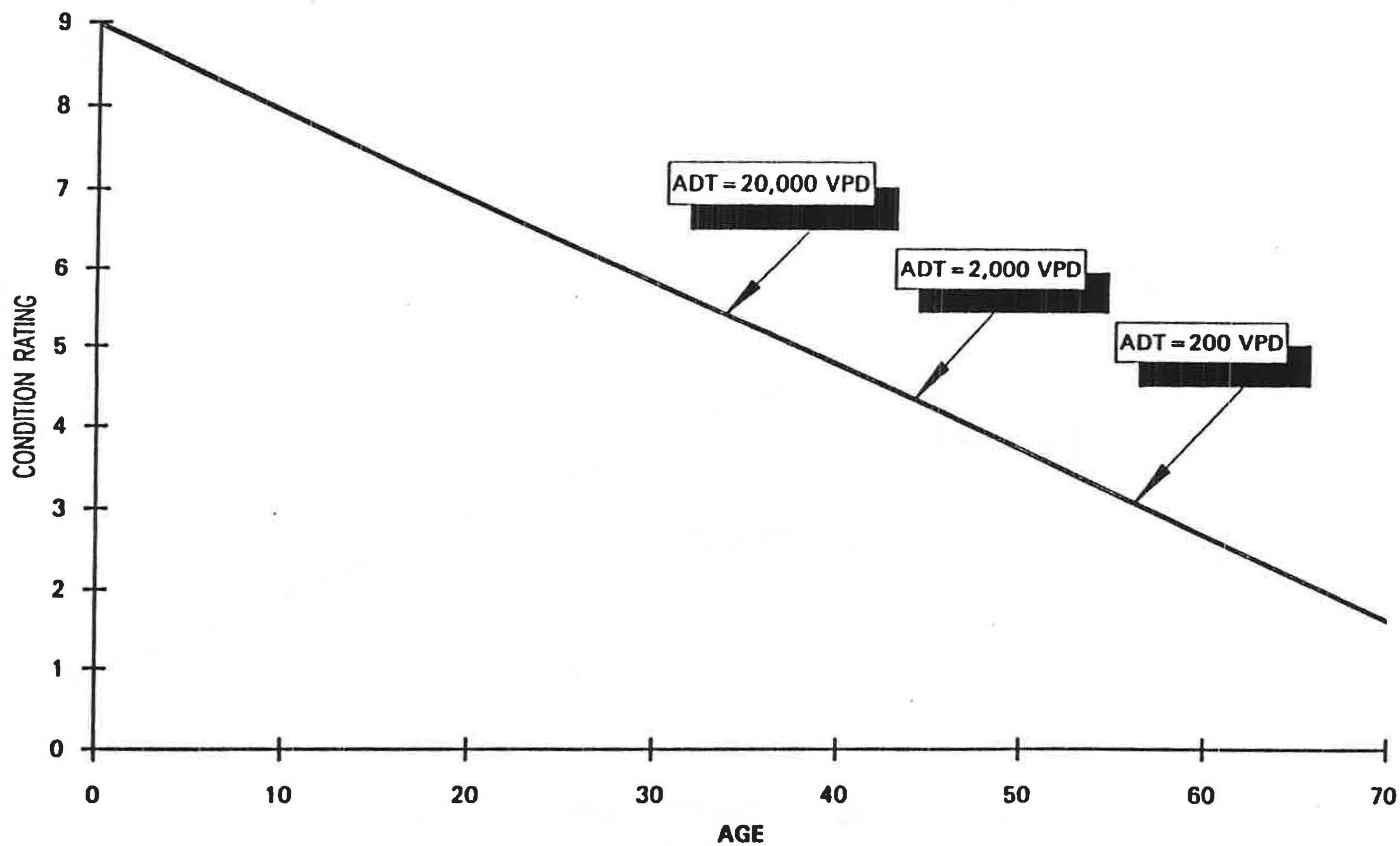
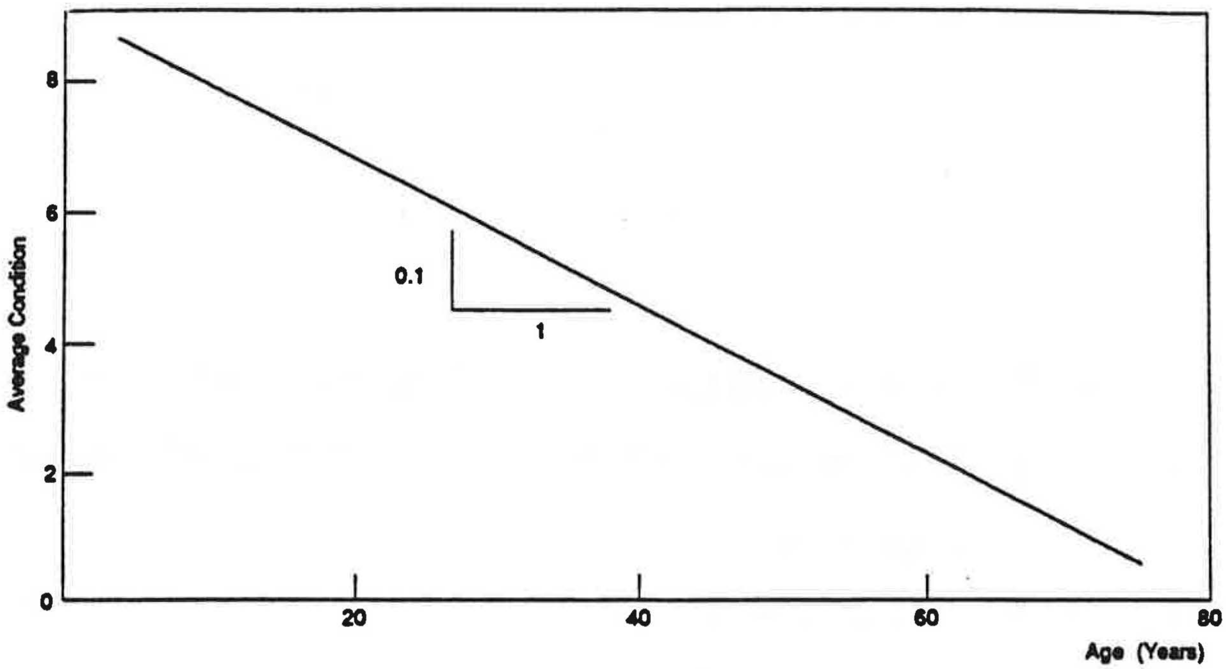


EXHIBIT 29
SIMPLE LINEAR DETERIORATION CURVE



SOURCE(28)

EXHIBIT 30

NON–LINEAR MODEL – TWO PARAMETER

$$Y(t) = \beta_1 \, e^{-t/\beta_2}$$

where

$Y(t)$ = Bridge condition as a function of age

e = 2.7183 = Base of natural system of logarithms

t = Bridge age

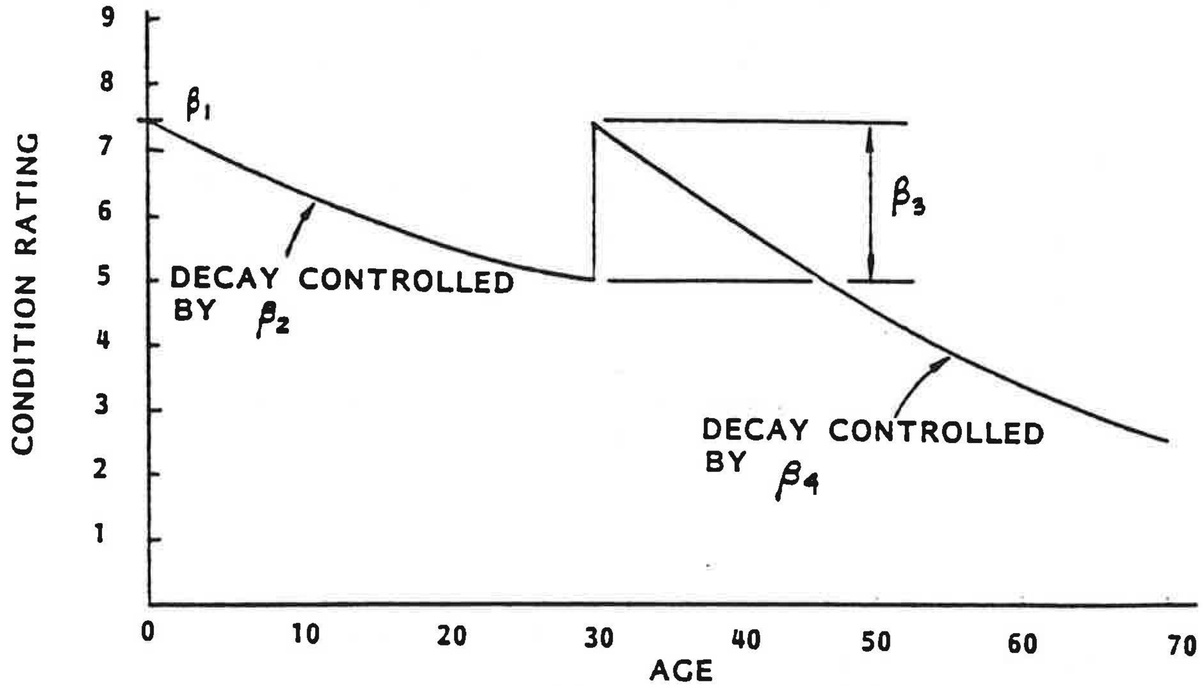
β_1 = $Y(t)$ at $t = 0$

β_2 = Exponential decay coefficient

SOURCE(26)

EXHIBIT 31

NON-LINEAR MODEL – FOUR PARAMETER



Four-parameter model.

$$Y(t) = (1-x)\beta_1 e^{-t/\beta_2} + x(\beta_1 e^{-t_r/\beta_2} + \beta_3) e^{-(t-t_r)/\beta_4}$$

where

$Y(t)$ = Bridge condition as a function of age

e = 2.7183 = Base of natural system of logarithms

t = Bridge age

t_r = Bridge age when a major rehabilitation is performed on the bridge

β_1 = $Y(t)$ for $t = 0$

β_2 and β_4 = Exponential decay coefficients

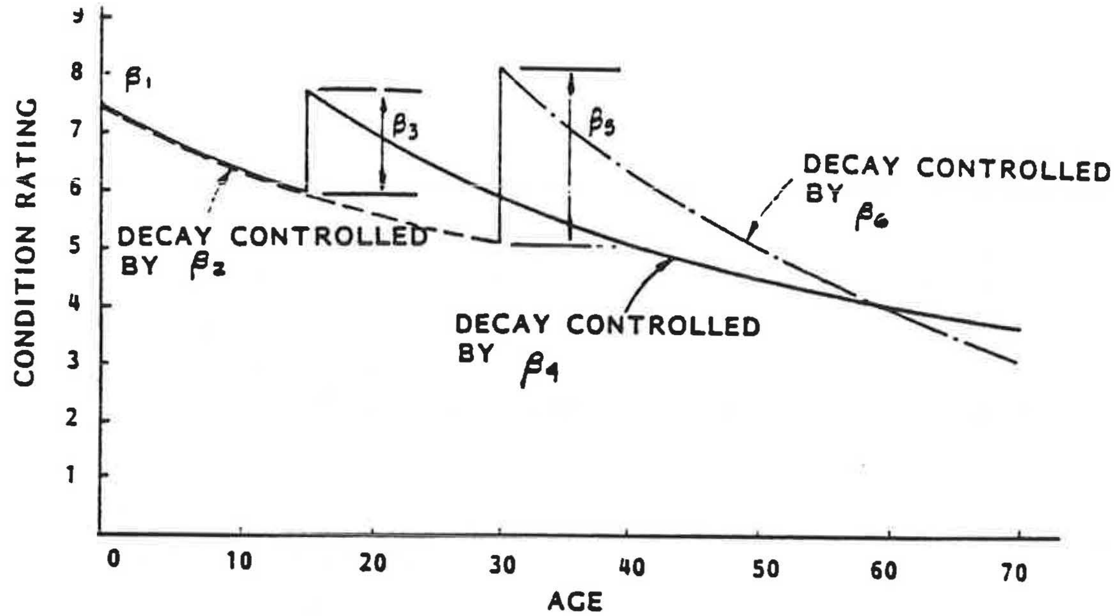
β_3 = The "spike" introduced to the curve due to a rehabilitation

x = 1.0 for rehabilitated structure; otherwise, $x = 0$

SOURCE(26)

EXHIBIT 32

NON-LINEAR MODEL – SIX PARAMETER



$$Y(t) = (1-x)\,(1-y)\,\beta_1 e^{-t/\beta_2} + x(\beta_1 e^{-t_r/\beta_2} + \beta_3)e^{-(t-t_r)/\beta_4} + y\,(\beta_1 e^{-t_r/\beta_2} + \beta_5)e^{-(t-t_r)/\beta_6}$$

where

- $Y(t)$ – Bridge condition as a function of age
- e – 2.7183 – Base of natural system of logarithms
- t – Bridge age
- t_r – Bridge age when a major reconstruction is performed on the bridge
- x – 1.0 if t_r less than or equal to 25; otherwise, x – 0.0
- y – 1.0 if t_r is greater than 25; otherwise, y – 0.0
- β_1 – $Y(t)$ for $t = 0$
- β_2 – Exponential decay coefficient before a rehabilitation takes place
- β_3 – The rating "spike" introduced due to a reconstruction occurring at an age equal to or less than 25 years
- β_4 – Expontial decay coefficient after rehabilitation; this coefficient is used in conjunction with β_3
- β_5 – The rating "spike" introduced due to a reconstruction occurring at an age of more than 25 years
- β_6 – Exponential decay coefficient after rehabilitation; this coefficient is used in conjunction with β_5

EXHIBIT 33
TWO PARAMETER MODEL COEFFICIENTS FOR R.C. BRIDGES

Table 26. Two-parameter model coefficients for reinforced concrete bridges.

	Bridge Component					
	Deck		Superstructure		Substructure	
ADT	β_1	β_2	β_1	β_2	β_1	β_2
0 - 1,000	7.93	181.7	8.78	126.9	8.48	148.0
1,001 - 10,000	7.44	248.2	8.82	126.0	8.04	178.4
Over 10,000	6.99	332.8	8.69	132.8	8.12	156.9

EXHIBIT 34
TWO PARAMETER MODEL COEFFICIENTS FOR P/S BRIDGES

	Bridge Component					
	Deck		Superstructure		Substructure	
ADT	β_1	β_2	β_1	β_2	β_1	β_2
0 - 1,000	7.69	177.0	8.52	121.2	8.01	191.2
1,001 - 10,000	7.67	108.7	8.44	111.2	7.90	134.8
Over 10,000	7.86	81.5	8.48	100.2	8.40	77.7

EXHIBIT 35
FOUR PARAMETER MODEL COEFFICIENTS FOR P/S BRIDGES

	Bridge Component							
	Deck				Superstructure			
ADT	β_1	β_2	β_3	β_4	β_1	β_2	β_3	β_4
Over 10,000	8.10	57.9	1.77	40.4	8.55	85.5	0.65	84.0

EXHIBIT 36
TWO PARAMETER MODEL CURVE FOR R.C. BRIDGES

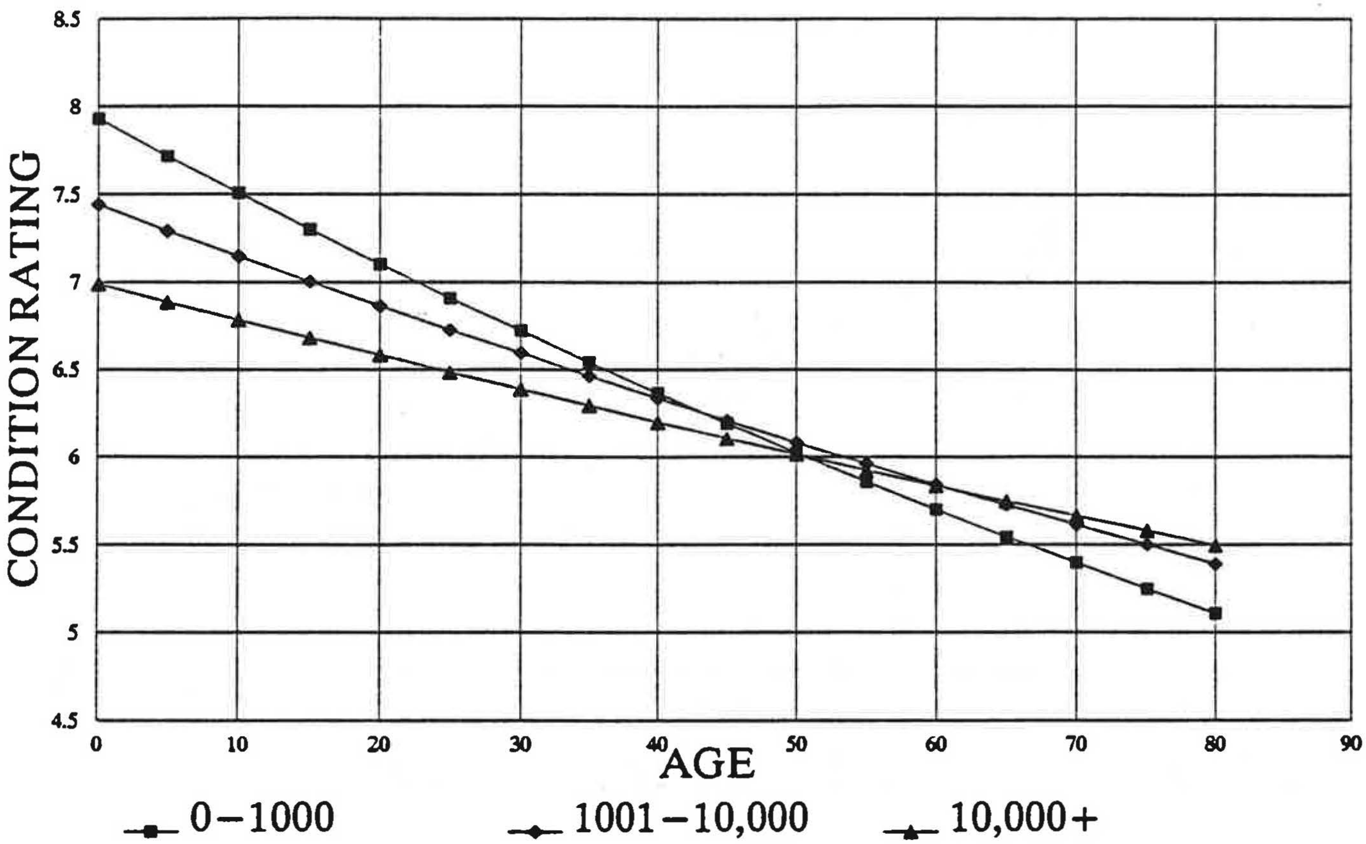


EXHIBIT 37
TWO PARAMETER MODEL CURVE FOR P/S CONCRETE BRIDGES

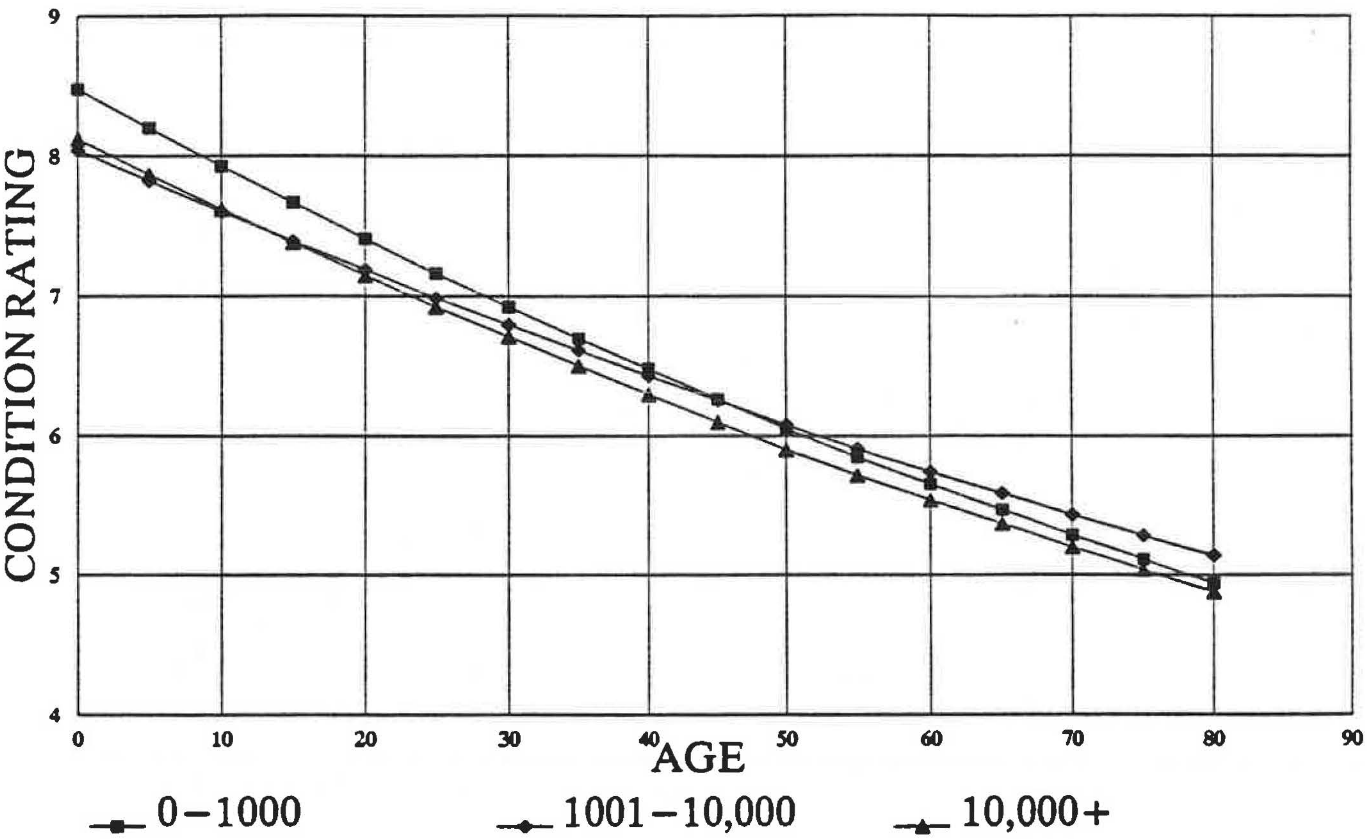


EXHIBIT 38
FOUR PARAMETER MODEL CURVE FOR P/S CONCRETE BRIDGES

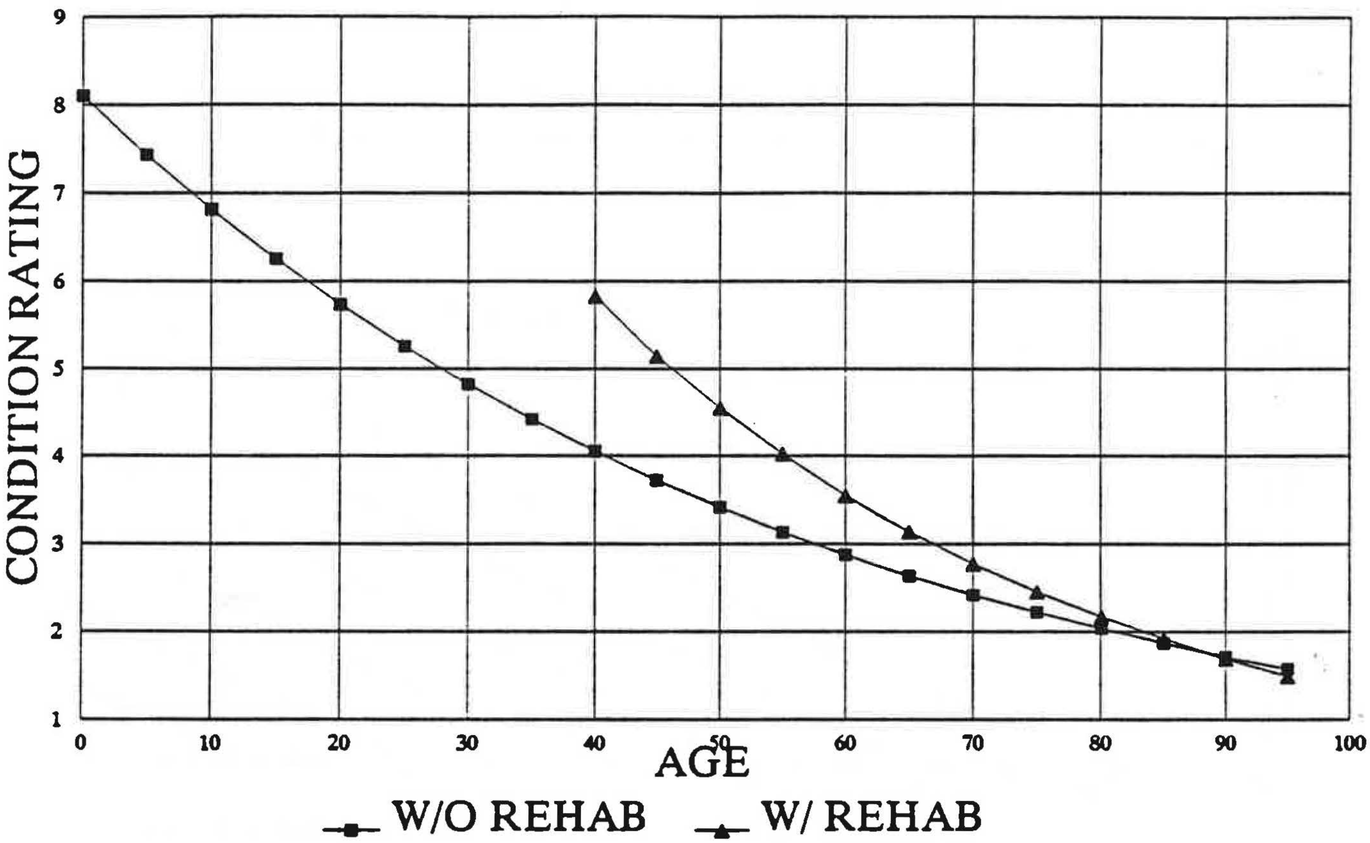
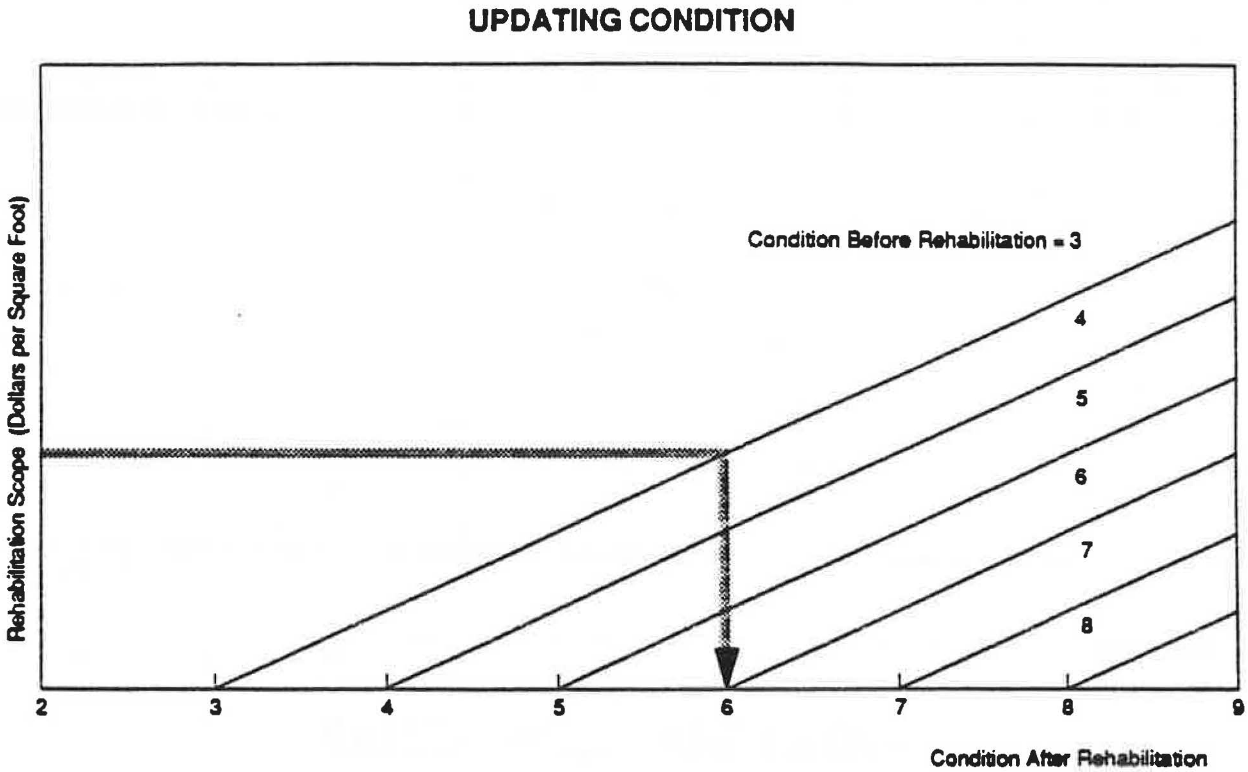


EXHIBIT 39
CONDITION IMPROVEMENT DUE TO REHABILITATION



SOURCE(28)

EXHIBIT 40
REHABILITATION COSTS FOR R.C. DECKS

Deck Condition Rating After Rehabilitation

Unit: $ / Square Foot Deck Area

Deck Condition Rating Before Rehabilitation	9	8	7	6	5	4	3	2
9								
8		1.081						
7		2.907	1.987					
6		4.733	3.813	2.894				
5		6.559	5.639	4.720	3.801			
4		8.385	7.465	6.546	5.627	4.708		
3		10.211	9.292	8.372	7.453	6.534	5.614	
2								

SOURCE(31)

EXHIBIT 41
REHABILITATION COSTS FOR R.C. SUPERSTRUCTURES

Unit: $ / Square Foot of Deck Area

Superstructure Condition Rating Before Rehabilitation \ Superstructure Condition Rating After Rehabilitation	9	8	7	6	5	4	3	2
9								
8		4.426						
7		6.012	5.036					
6		7.598	6.621	5.645				
5		9.184	8.207	7.231	6.254			
4		10.770	9.793	8.817	7.840	6.863		
3		12.355	11.379	10.400	9.426	8.449	7.473	
2								

EXHIBIT 42
REHABILITATION COSTS FOR R.C. SUBSTRUCTURES

Substructure Condition Rating After Rehabilitation

Unit: $ / Square Foot of Deck Area

Substructure Condition Rating Before Rehabilitation	9	8	7	6	5	4	3	2
9								
8		0.728						
7		2.500	1.147					
6		4.269	2.918	1.566				
5		6.040	4.689	3.337	1.986			
4		7.811	6.459	5.108	3.757	2.405		
3		9.582	8.230	6.879	5.527	4.176	2.824	
2								

EXHIBIT 43
CONDITION IMPROVEMENT DUE TO REHABILITATION – DECK

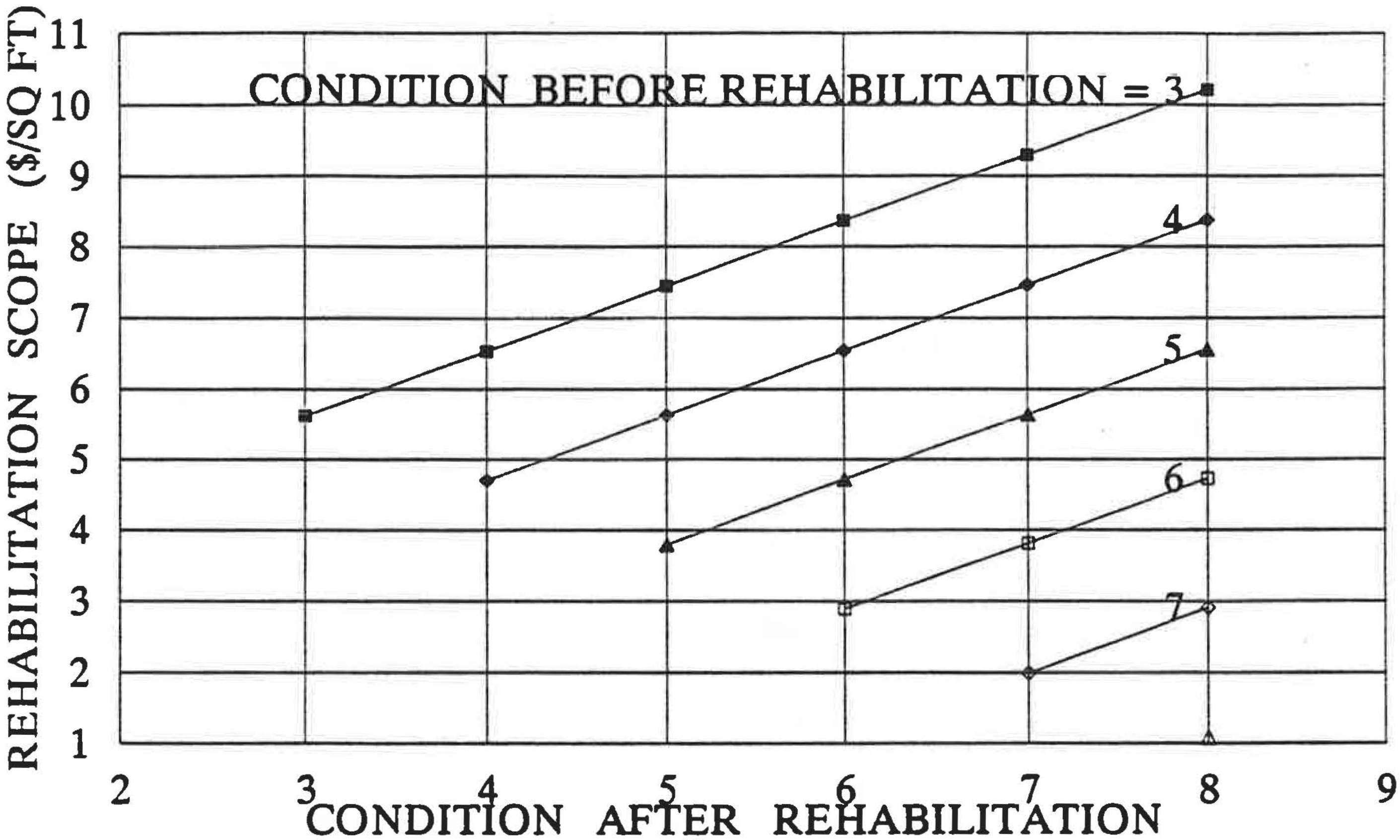


EXHIBIT 44
CONDITION IMPROVEMENT DUE TO REHABILITATION OF SUBSTRUCTURE

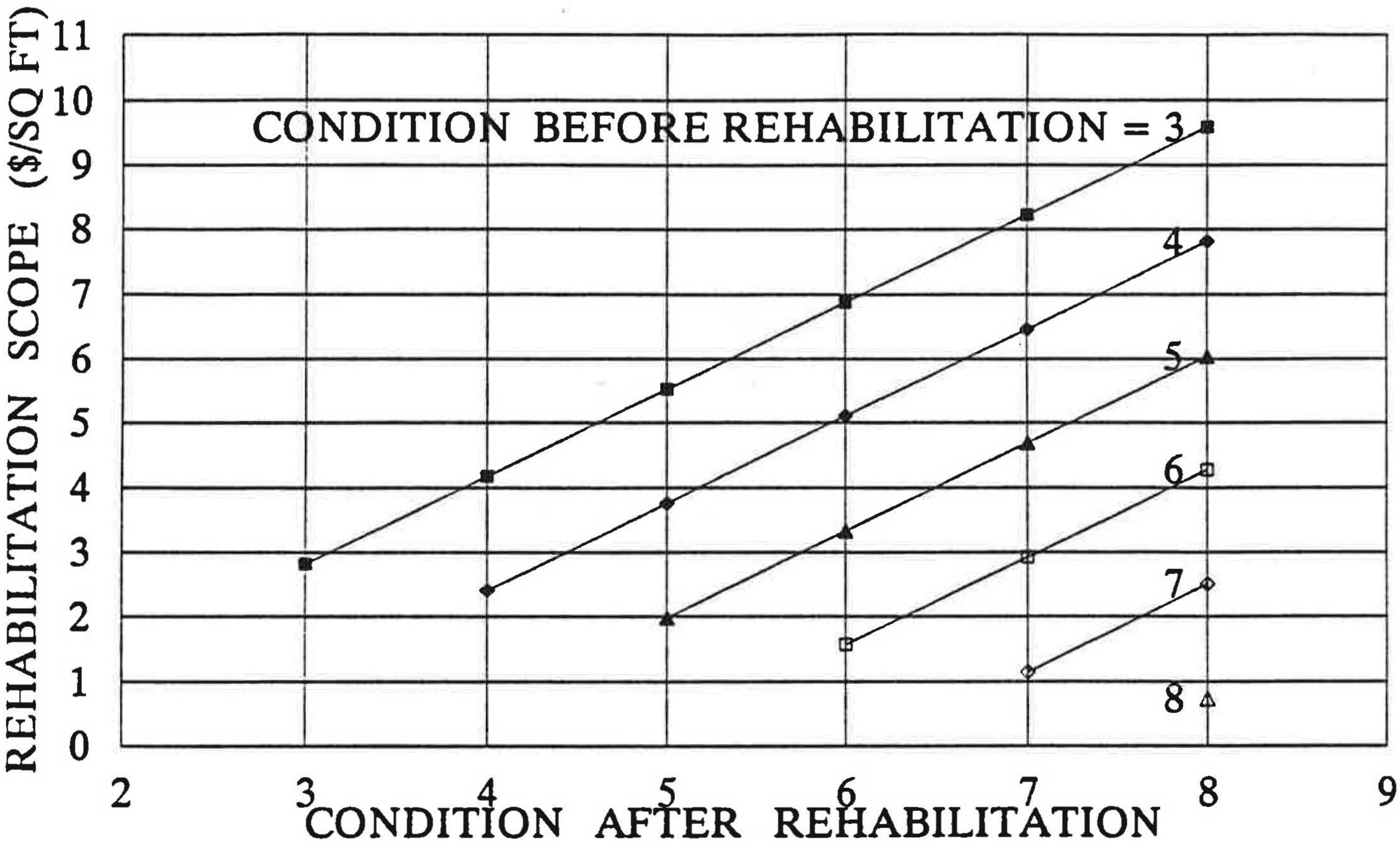


EXHIBIT 45
EFFECT OF REHAB SCOPE

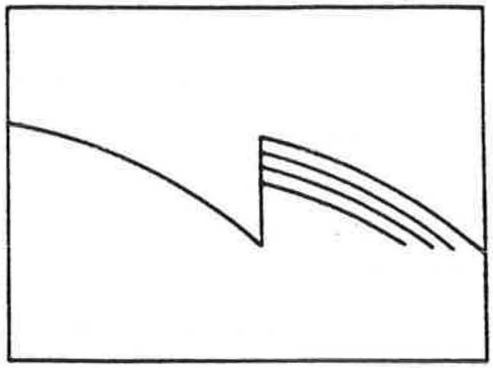


Figure 3. The condition is corrected to different degrees.

EXHIBIT 46
EFFECT OF REHAB PERFORMANCE

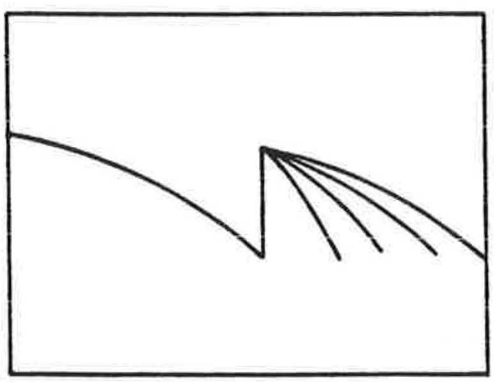
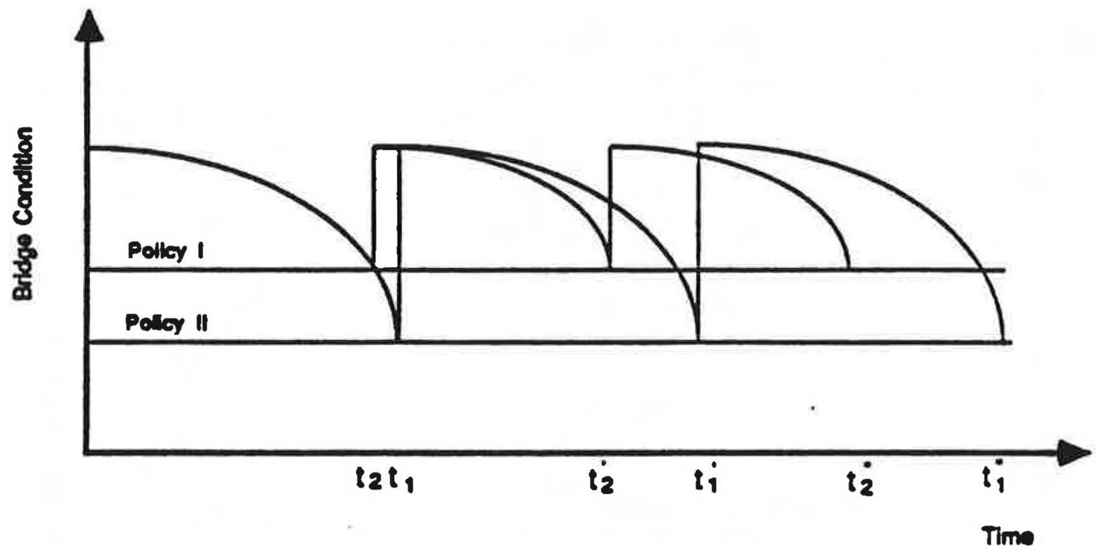


Figure 4. The performance following a treatment may vary.

SOURCE(33)

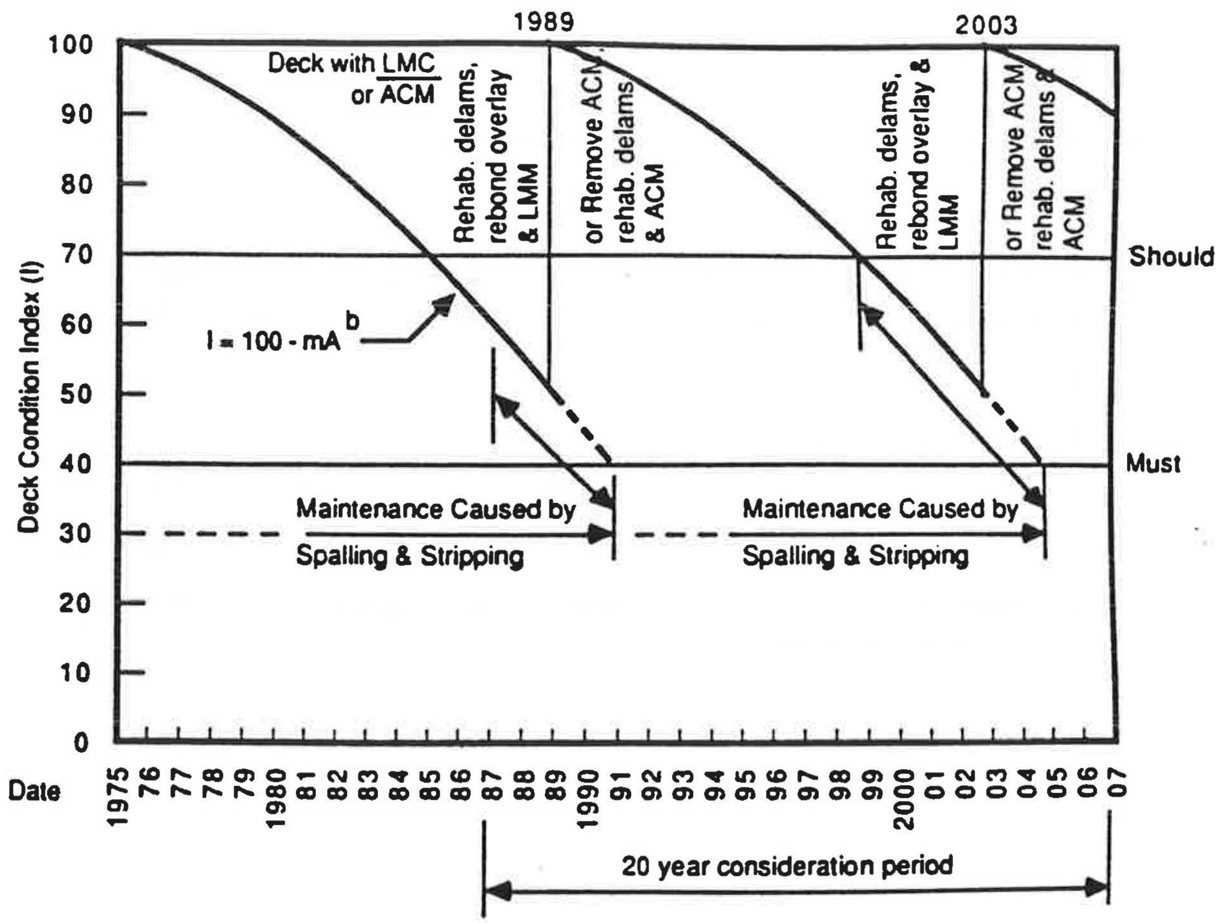
EXHIBIT 47
EFFECT OF REHAB FREQUENCY



(b) Rehabilitating the bridge element from different condition levels.

SOURCE(31)

EXHIBIT 48
REHAB STRATEGY FOR A CONTAMINATED DECK WITH OVERLAY



SOURCE(34)

EXHIBIT 49
CONDITION INDEX FOR BARE DECKS

Type of Deck	BARE DECKS CONTAINING EPOXY-COATED REBAR				
Type of Distress	Spalls (1) & Delams	Patching	Scaling	Wear & Rutting	Cracking
Further Classification of Distress	X	X	Depth (in.) d	Depth (in.) d	X
Weighting Factor, Fi	6	4	5x (d)	2.5x (d)	1/10

Deck Deficiency Points, $D = \Sigma F_iA_i$

Where Ai is the affected area (% of deck area) (2)

Deck Condition Index, I = 100 - D and I> 0

(1) Corrosion-induced deterioration is not expected, however data is needed to support the effectiveness of the protective system

(2) Ai for rutting is assumed 25% of deck area which is approximately the area of wheel tracks

Category Classification	Condition Index, I
None or light deterioration	100 - 70
Moderate deterioration	70 - 40
Severe Deterioration	40 - 0

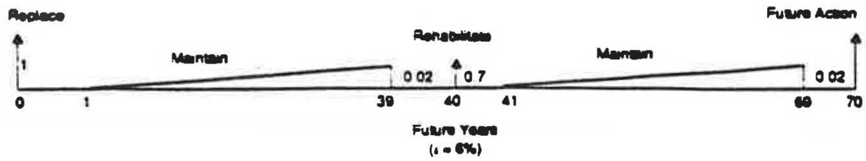
When: I => 70, should rehabilitate

When: I => 40, must rehabilitate

SOURCE(34)

LIFE CYCLE COST ANALYSIS

CONVERTING A GRADIENT SERIES TO SINGLE PAYMENTS

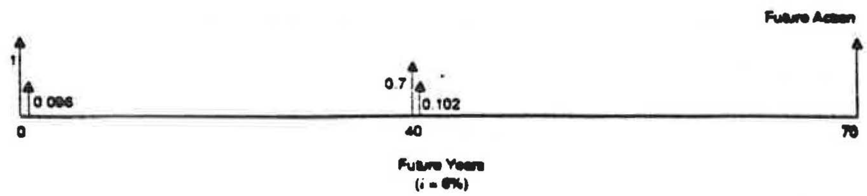


General Formula: $\frac{G}{i}\left[\frac{1-(1+i)^{-n}}{i} - \frac{n}{(1+i)^{n}}\right]$

For years 1 through 39: $\left[\frac{0.02/38}{0.06}\right]\left[\frac{1-(1.06)^{-39}}{0.06} - \frac{39}{(1.06)^{39}}\right] = 0.096$

For years 41 through 69: $\left[\frac{0.02/28}{0.06}\right]\left[\frac{1-(1.06)^{-29}}{0.06} - \frac{29}{(1.06)^{29}}\right] = 0.102$

CONVERTING FUTURE SINGLE PAYMENTS TO PRESENT WORTH

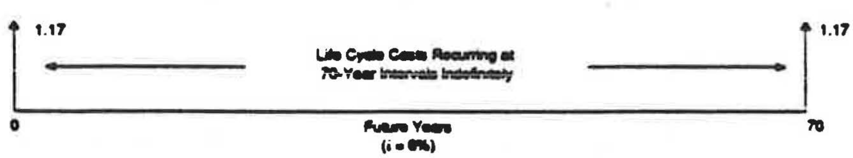


$LCC = 1 + 0.096 + (0.7 + 0.102)\,(pwf'_{40})$

$LCC = 1.096 + 0.802\,(1.06^{-40})$

$LCC = 1.17$

PRESENT WORTH OF A PERPETUAL SERIES



$LCC_p = 1.17\,(pwf''_{70})$

$LCC_p = 1.17\left[\frac{1.06^{70}}{1.06^{70}-1}\right]$

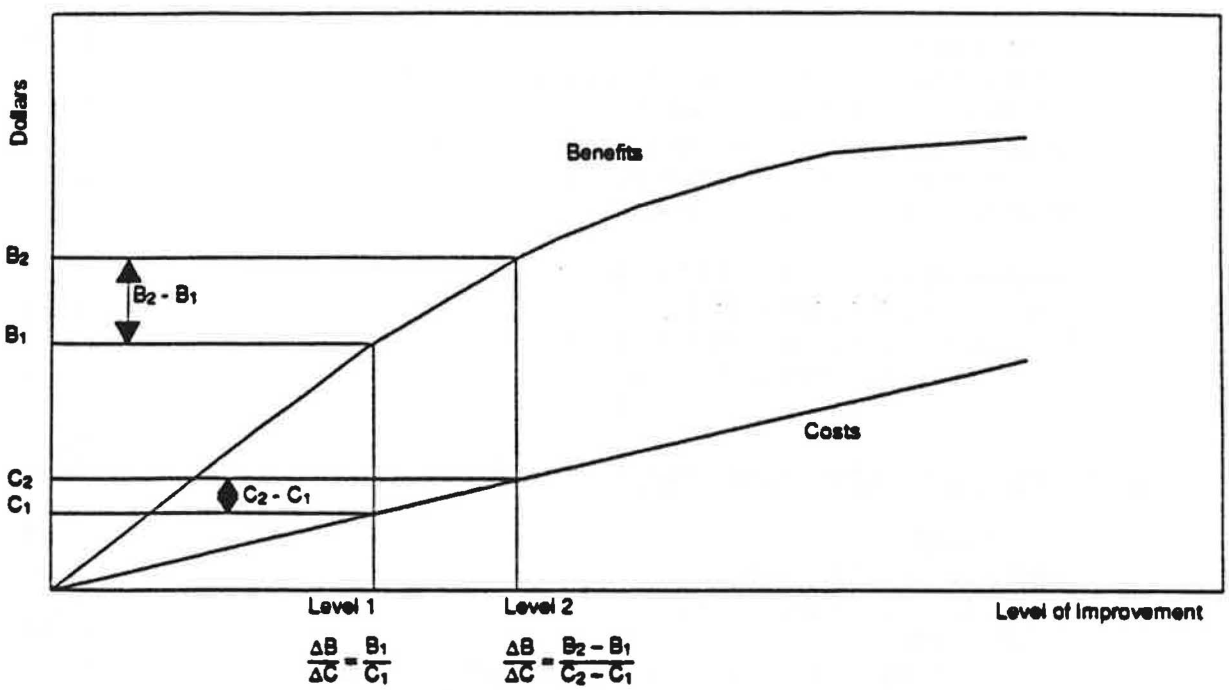
$LCC_p = 1.17\,(1.02)$

$LCC_p = 1.19$

SOURCE(28)

EXHIBIT 51
INCREMENTAL COST–BENEFIT ANALYSIS

COMPARING ALTERNATIVES



SOURCE(28)

EXHIBIT 52
UNIT COSTS FOR REHAB – PADOT

Deck - First Digit	Unit Cost
0 - Do Nothing	0.00
1 - Rehabilitate concrete deck (patch membrane, bituminous wearing surface)	5.00
2 - Rehabilitate concrete deck (patch & latex, concrete or other wearing surface)	12.00
3 - Replace with concrete deck	18.00
4 - Replace with steel grid deck	18.00
5 - Replace with timber deck	12.00
6 - Replace deck (as a component of superstructure replacement)	15.00

Superstructure Other Than Deck - Second Digit	Unit Cost
0 - Do Nothing	0.00
1 - Rehabilitate (minor)	7.00
2 - Rehabilitate (extensive)	16.00
3 - Widen bridge	27.00
4 - Widen bridge & superstructure rehabilitation	33.00
5 - Widen bridge & extensive superstructure rehabilitation	40.00
6 - Replace	32.00

Substructure - Third Digit	Unit Cost
0 - Do Nothing	0.00
1 - Rehabilitate (minor)	7.00
2 - Rehabilitate (extensive)	15.00
3 - Replace portion	13.00
4 - Replace major portion	20.00
6 - Replace	33.00
8 - Rehabilitate culvert	30.00
9 - Replace culvert	75.00

Note:
- All costs are per square foot of the out to out deck surface (top slab or plan view outline of culvert barrel).
- Initial values used by the BMS System are shown.

SOURCE(35)

EXHIBIT 53
UNIT COSTS FOR REHAB – NCDOT

Funct. Code	Unit Cost	Units	Function Code Descriptions (Until June 30, 1985)*
47A	1.83	$/SF	Spot painting of structural steel.
47B	0.96	$/SF	Complete painting of structural steel.
478	1.71	$/SF	Maintenance and repairs to concrete bridge floors.
479	6.03	$/SF	Repairs to timber bridge floors.
480	4.96	$/SF	Repairs to steel plank floors.
481	2.74	$/LF	Maintenance or repairs to timber bridge handrails.
482	29.14	$/LF	Maintenance or repairs to concrete bridge handrails.
483	3.40	$/LF	Repairs to aluminum handrails and concrete parapets.
487	2.06	$/LF	Maintenance or repairs to steel bridge handrails.
488	24.38	$/LF	Maintenance of steel expansion joint devices.
490	6.15	$/LF	Maintenance of standard deck expansion joints.
491	8.86	$/LF	Maint. of misc. expansion joints.
492	27.52	$/MANHOUR	General maintenance or replacement of superstructure.
493	23.67	$/MANHOUR	Maintenance or replacement of timber substructure.
494	17.51	$/MANHOUR	Maintenance or replacement of P/S concrete pile substructure.
495	13.83	$/MANHOUR	Maintenance or replacement of precast concrete pile substructure.
496	17.92	$/MANHOUR	Maintenance or replacement of steel pile substructure.
497	17.62	$/MANHOUR	Maint. of RC piers and abutments.

* The above codes were used until June, 1985 when a revised set of codes were adapted (see Appendix 10.4). Since more than two years of inspection and work reporting are necessary for transition, the original codes were used in this study.

SOURCE(31)

EXHIBIT 54
ANNUAL MAINTENANCE COST FACTORS – NCDOT – PAGE 1

Unit: $ / Square Foot of Deck Area.

Type of Materials and ADT Range	Deck Condition Ratings						
	9	8	7	6	5	4	3
Timber Deck							
ADT <= 200	0	0.035	0.065	0.093	0.246	0.464	0.860
201-800	0	0.040	0.076	0.108	0.246	0.464	0.860
801-2000	0	0.051	0.095	0.135	0.277	0.522	0.967
2001-4000	0	0.066	0.124	0.176	0.296	0.557	1.032
> 4000	0	0.076	0.143	0.203	0.341	0.642	1.191
RC Deck							
ADT <= 200	0	0.008	0.011	0.015	0.040	0.133	0.319
201-800	0	0.009	0.012	0.016	0.041	0.137	0.329
801-2000	0	0.010	0.014	0.018	0.046	0.155	0.370
2001-4000	0	0.011	0.015	0.019	0.047	0.157	0.376
> 4000	0	0.013	0.017	0.022	0.050	0.166	0.398
Steel Deck							
ADT <= 200	0	0.094	0.111	0.128	0.231	0.258	0.286
201-800	0	0.102	0.121	0.140	0.231	0.258	0.286
801-2000	0	0.117	0.138	0.159	0.231	0.258	0.286
2001-4000	0	0.131	0.155	0.179	0.241	0.269	0.300
> 4000	0	0.144	0.170	0.196	0.276	0.309	0.341

Note: Includes reallocation of Function Code 492.

SOURCE(31)

EXHIBIT 55

ANNUAL MAINTENANCE COST FACTORS – NCDOT – PAGE 2

Unit: $ / Square Foot of Deck Area.

Type of Materials and Region	Substructure Condition Ratings						
	9	8	7	6	5	4	3
Timber Substructure							
Coastal	0	0.121	0.123	0.126	0.205	0.209	0.214
Piedmont	0	0.104	0.107	0.109	0.156	0.159	0.163
Mountain	0	0.112	0.114	0.117	0.187	0.191	0.195
RC Substructure							
Coastal	0	0.000	0.022	0.066	0.174	0.244	0.314
Piedmont	0	0.000	0.015	0.045	0.124	0.174	0.223
Mountain	0	0.000	0.019	0.058	0.128	0.179	0.230
Steel Substructure							
Coastal	0	0.000	0.024	0.058	0.125	0.171	0.217
Piedmont	0	0.000	0.016	0.038	0.103	0.141	0.178
Mountain	0	0.000	0.021	0.051	0.099	0.136	0.172
P/S Concrete Substructure							
Coastal	0	0.000	0.006	0.024	0.057	0.081	0.105
Piedmont	0	0.000	0.004	0.016	0.046	0.065	0.084
Mountain	0	0.000	0.006	0.022	0.065	0.093	0.147

Note: Costs include all the five possible maintenance needs of a particular material type's main span.

EXHIBIT 56
INITIAL COSTS – C104 QUESTIONNAIRE

Initial Cost of Rapid Repair Systems Based on Questionnaire Response ($/yd^2)

System	Traffic Control	Surface Prepar-ation	Placing and Curing	Other	Average Total	Low Total	High Total
Bituminous Concrete Overlay on Membrane	3.73	3.09	15.28	2.52	24.62	1.95	44.00
Coating	0.11	4.39	11.95	0.00	16.45	6.95	24.41
Portland Cement Concrete Overlay	19.31	21.39	38.02	8.73	87.45	77.28	95.60
Penetrating Sealer	0.67	0.46	1.57	0.07	2.77	1.36	4.55
Polymer Overlay	0.73	5.68	31.35	0.64	38.40	4.00	92.99
Other Hydraulic Concrete Overlay	0.36	46.80	53.30	0.00	100.46	—	—
Crack Repair and Sealing	0.15	5.28	4.05	0.00	9.48	6.95	12.00
Bituminous Concrete Patch	63.42	7.54	39.57	0.63	111.16	7.00	250.00
Portland Cement Concrete Patch	30.93	108.34	119.74	7.12	266.13	15.00	611.43
Polymer Concrete Patch	0.11	18.00	48.75	0.00	66.86	—	—
Other Hydraulic Concrete Patch	32.84	31.26	102.92	14.30	181.32	3.96	527.47
Steel Plate over Concrete	9.00	6.00	9.00	60.00	84.00	—	—
Precast Concrete Deck Panel	149.37	176.29	288.55	162.44	776.65	741.94	800.00
Site-Cast Portland Cement Concrete	33.14	33.77	74.65	0.00	141.56	34.32	249.00
Other Site-Cast Hydraulic Concrete	271.67	94.33	297.33	0.00	663.33	249.00	980.00

[a]($/linear foot).

SOURCE(36)

EXHIBIT 57
SERVICE LIFE & UNIT COSTS – PADOT

		ITEM NO.	UNIT	PRICE
	APPROACH SLAB (REPLACE)		S.Y.	43.00
FLUSH/CLEAN	DECK		E.B.	200.00
FLUSH/CLEAN	SCUPPER/DOWNSPOUTING		E.B.	130.00
FLUSH/CLEAN	BEARING/BEARING SEAT		E.B.	100.00
FLUSH/CLEAN	STEEL-HORIZONTAL SURFACE		E.B.	100.00
DECK	BITUM. DECK W. SURFACE(*)		S.Y.	35.00
DECK	TIMBER DECK (*)		S.Y.	40.00
DECK	OPEN STEEL GRID (*)		S.Y.	360.00
DECK	CONCRETE DECK (REPAIR)		S.Y.	120.00
DECK	CONCRETE SIDEWALK (REPAIR)		S.Y.	140.00
DECK	CONCRETE CURB/PARAPET (REPAIR)		S.Y.	140.00
DECK JOINTS	LIQUIDSEALANTJT(REPAIR/RESEAL)		L.F.	20.00
DECK JOINTS	COMPRESSION SEAL (*)		L.F.	28.00
DECK JOINTS	MODULAR DAM (*)		L.F.	63.00
DECK JOINTS	STEEL TOOTH OR PLATE DAM ( )		L.F.	46.00
DECK JOINTS	OTHER TYPES (*)		L.F.	64.00
RAILING	BRIDGE/PARAPET (*)		L.F.	40.00
RAILING	STRUCTUREMOUNTEDGUIDERAIL( )		L.F.	84.00
RAILING	PEDESTRIAN (*)		L.F.	62.00
RAILING	MEDIAN BARRIER (*)		L.F.	60.00
DECK DRAINAGE	SCUPPER GRATE (REPLACE)		EA.	100.00
DECK DRAINAGE	DRAIN/SCUPPER (INSTALL)		EA.	400.00
DECK DRAINAGE	DOWNSPOUTING (*)		EA.	13.00
DECK DRAINAGE				
BEARINGS	STEEL (REHABILITATE)		EA.	645.00
BEARINGS	STEEL (REPLACE)		EA.	1,500.00
BEARINGS	EXPANSION (RESET)		EA.	1,100.00
BEARINGS	PEDESTAL/SEAT (RECONSTRUCT)		EA.	5,400.00
TIMBER	STRINGER (*)		EA.	600.00
TIMBER	OTHER MEMBERS (*)		EA.	600.00
STEEL	STRINGER (*)		EA.	10,000.00
STEEL	FLOORBEAM (*)		EA.	10,000.00
STEEL	GIRDER (*)		EA.	10,000.00
STEEL	DIAPHRAGM/LATERAL BRACING (*)		EA.	1,000.00
RC/PS	STRINGER (*)		EA.	6,200.00
RC/PS	DIAPHRAGM (*)		EA.	200.00
RC/PS	OTHER MEMBERS (*)		EA.	6,200.00
TRUSS	MBR. (STRENGTHEN/REPAIR/REPL.)		EA.	6,000.00
TRUSS	PORTAL (MODIFY)		EA.	500.00
TRUSS	MEMBER (TIGHTEN/FLAMESHORTEN)		EA.	500.00

		ITEM NO.	UNIT	PRICE
PAINTING	SUPERSTRUCTURE - SPOT		E.B.	3,000.00
PAINTING	SUBSTRUCTURE - SPOT		E.B.	1,000.00
PAINTING	SUPERSTRUCTURE - FULL		E.B.	7,500.00
PAINTING	SUBSTRUCTURE - FULL		E.B.	2,500.00
	BACKWALL (*)		C.Y.	600.00
	ABUTMENTS (REPAIR)		C.Y.	600.00
	WING (*)		C.Y.	400.00
	PIERS (REPAIR)		C.Y.	600.00
	FOOTING (UNDERPIN)		C.Y.	300.00
	MASONRY (REPOINT)		C.Y.	
	ABUTMENT SLOPEWALL (*)		S.Y.	44.00
	ABUT. SLOPEWALL (CONSTRUCT NEW)		S.Y.	60.00
	PILE REPAIR		EA.	1,000.00
EROSION CONTROL	STREAMBEDPAVING(REPR./CONSTR.)		C.Y.	50.00
EROSION CONTROL	ROCK PROTECTION		C.Y.	60.00
EROSION CONTROL	SCOUR HOLE (BACKFILL)		C.Y.	65.00
EROSION CONTROL	STREAM DEFLECTOR(REPR./CONSTR.)		C.Y.	82.00
EROSION CONTROL	VEGETATION/DEBRIS (REMOVE)		C.Y.	10.00
EROSION CONTROL	DEPOSITION (REMOVE)		C.Y.	11.00
CULVERT	HEADWALL/WINGS (*)		S.Y.	135.00
CULVERT	APRON/CUTOFF WALL (*)		S.Y.	100.00
CULVERT	BARREL (REPAIR)		S.Y.	200.00
APPLY PROTECTIVE COATING	DECK/PARAPETS/SIDEWALK		S.Y.	1.50
APPLY PROTECTIVE COATING	SUBSTRUCTURE		S.Y.	2.00
CONSTRUCTION TEMPORARY	SUPPORT BENT		EA.	3,000.00
CONSTRUCTION TEMPORARY	PIPES		EA.	10,000.00
CONSTRUCTION TEMPORARY	BRIDGE		EA.	20,000.00

(*) REPAIR/REPLACE AS APPLICABLE

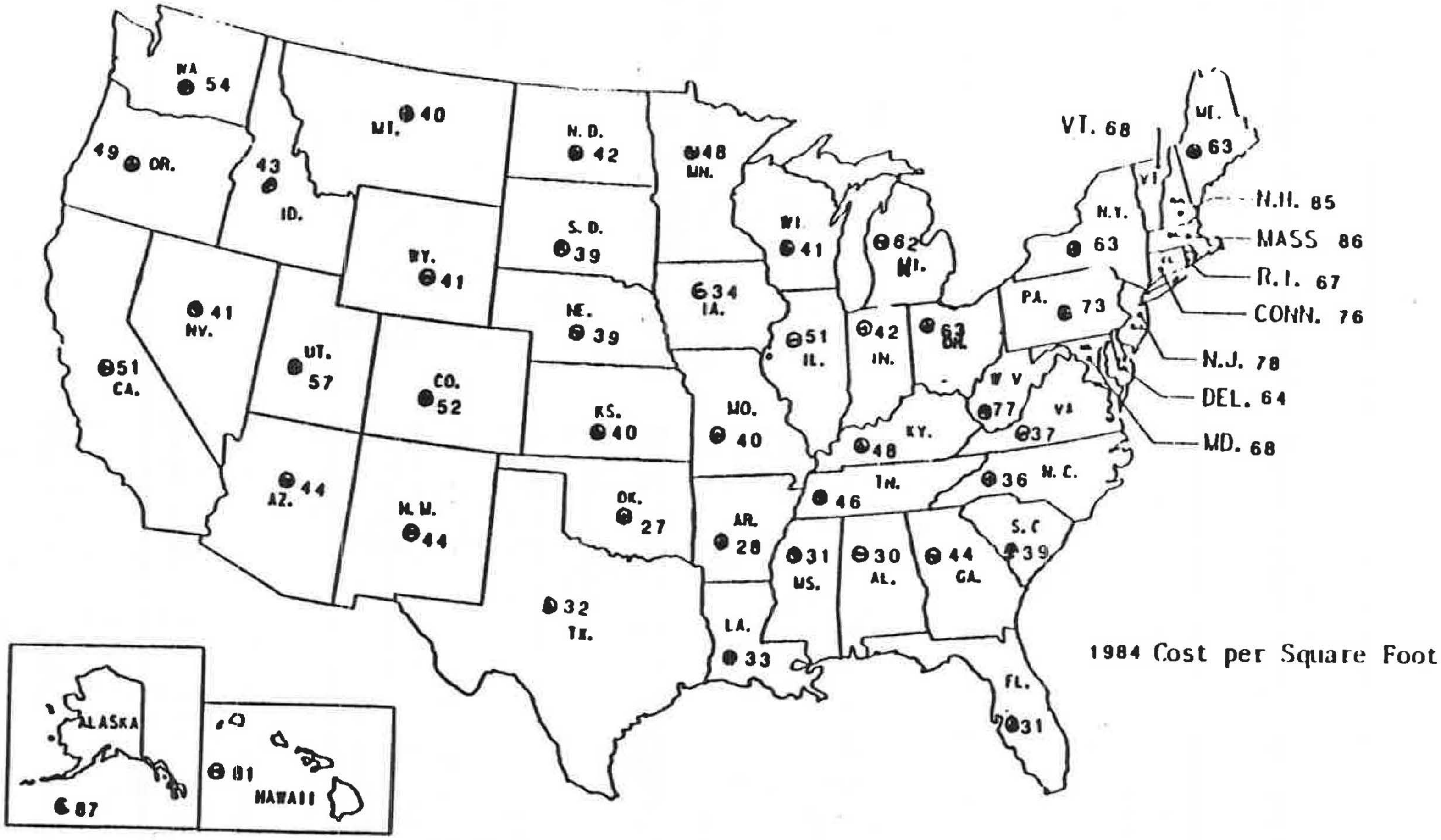
E.B. = EACH BRIDGE

* Prices as per May 30, 1986

Source: Pennsylvania Department of Transportation

SOURCE(37)

EXHIBIT 58
UNIT CONSTRUCTION COSTS – NATIONALLY



Source: U.S. Department of Transportation, Federal Highway Administration

Figure 7. Isoprice map showing bridge construction cost.

SOURCE(37)

EXHIBIT 59
COST INDEXING EXAMPLE

Maintenance activity on concrete deck repair unit of measurement is square yards (yd^2).

Base unit cost developed in the State of Pennsylvania is \$120/yd^2.

Develop a unit cost for concrete deck repair in the State of Arizona.

From figure 7, "Isoprice Map bridge construction costs (1984)."

Bridge construction costs in Pennsylvania	\$73.00
Bridge construction costs in Arizona	\$44.00

For this example, it is assumed that inflation in Pennsylvania and Arizona was the same between 1984 and present.

Index: 44.00/73.00 = 0.603

Unit cost for concrete = base unit cost deck in Pennsylvania x index = \$120/yd^2 x 0.603 = \$72.36/yd^2

SOURCE(37)

EXHIBIT 60
SERVICE LIFE & INITIAL COSTS – C104 LITERATURE REVIEW

Service Life and Initial Cost of Rapid Repair Systems Based on Literature Review

System	Service Life (yrs.)			Initial Cost ($/yd²)			References
	Average	Low	High	Average	Low	High	High
Bituminous Concrete Overlay on Membrane	9.7	3.7	15.0	50.84	15.53	135.44	7, 20, 21, 22, 23
Coating	—	—	—	—	—	—	—
Portland Cement Concrete Overlay	17.9	13.6	25.0	83.21	11.19	287.75	20, 21, 22, 23, 24, 25, 26
Penetrating Sealer	5.0	—	—	5.45	2.58	9.84	7, 23, 27, 28, 29
Polymer Overlay	10.0	—	—	43.55	7.03	100.08	7, 14, 23, 24, 25, 30, 31, 32
Other Hydraulic Concrete Overlay	—	—	—	6.08	—	—	24
Crack Repair and Sealing[a]	10.0	—	—	—	—	—	23
Joint Repair[a]	3.7	3.5	3.9	78.23	77.73	78.72	21
Bituminous Concrete Patch	0.6	0.1	1.0	40.57	20.01	72.24	21, 23, 33, 34
Portland Cement Concrete Patch	14.8	4.3	35.0	202.17	164.71	239.63	20, 21, 23
Polymer Concrete Patch	5.5	—	—	247.07	—	—	21
Other Hydraulic Concrete Patch	3.8	—	—	235.16	—	—	21
Steel Plate over Concrete	—	—	—	—	—	—	—
Precast Concrete Box Beam	44.1	—	—	967.44	—	—	21
Precast Concrete Channel and Tee Beam	—	—	—	—	—	—	—
Precast Concrete Deck Panel	25.3	24.5	26.1	852.35	822.58	882.11	21
Site Cast Portland Cement Concrete	34.8	29.6	40.0	482.39	468.84	495.93	20, 21
Other Site Cast Hydraulic Concrete	12.5	—	—	686.64	—	—	21

[a]($/linear foot).

SOURCE(36)

EXHIBIT 61
SERVICE LIFE – C104 QUESTIONNAIRE

System	Time until Maintenance			Service Life		
	Average	Low	High	Average	Low	High
Bituminous Concrete Overlay on Membrane	5.1	1.0	10.0	11.8	4.5	20.0
Coating	5.2	2.8	10.3	10.3	5.5	20.0
Portland Cement Concrete Overlay	8.3	5.3	11.9	15.5	10.0	22.5
Penetrating Sealer	6.8	4.0	10.1	16.5	10.0	25.0
Polymer Overlay	6.4	3.0	10.0	12.7	6.0	25.0
Crack Repair and Sealing[a]	7.5	5.0	10.0	15.0	10.0	20.0
Bituminous Concrete Patch	0.3	0.1	0.8	1.7	1.0	3.0
Portland Cement Concrete Patch	2.8	0.3	7.0	5.9	1.8	10.0
Polymer Concrete Patch	10.0	—	—	20.0	15.0	25.0
Other Hydraulic Concrete Patch	6.3	1.0	10.0	11.9	2.0	20.0
Steel Plate over Concrete	10.0	—	—	15.0	—	—
Precast Concrete Deck Panel	20.0	12.5	30.0	38.8	30.0	50.0
Site-Cast Portland Cement Concrete	6.2	4.0	8.0	11.7	7.5	15.0
Other Site-Cast Hydraulic Concrete	2.0	—	—	5.5	5.0	6.0

[a]($/linear foot).

SOURCE(36)

EXHIBIT 62
INITIAL COSTS & LIFE CYCLE COSTS – C104 QUESTIONNAIRE

Code Number	System	Initial Cost	Present Value Total Cost* 25-Yr Evaluation Period	50-Yr Evaluation Period
IA	Bituminous Concrete Overlay on Membrane	24.62	42.84	55.40
IB	Coating	16.45	31.69	41.03
IC	High-Early-Strength Portland Cement Concrete Overlay	87.45	127.08	160.77
ID	Penetrating Sealer	2.77	3.90	4.90
IE	Polymer Overlay	38.40	63.03	81.53
IF	Other Hydraulic Cement Concrete Overlay	100.46	—	—
IIA	Crack Repair and Sealing**	9.48	14.08	17.86
IIC	Patching with Bituminous Concrete	111.16	1,453.69	1,884.92
IID	Patching with High-Early-Strength Portland Cement Concrete	266.13	815.22	1,057.85
IIE	Patching with Polymer Concrete	66.86	81.36	104.88
IIF	Patching with Other Hydraulic Concrete	181.32	312.20	403.78
IIG	Temporary Steel Plate over Conventional Concrete Patch	84.00	123.77	157.14
IIID	Replacement with Precast Concrete Deck Panel	776.65	724.35	874.72
IIIF	Replacement with Site-Cast High Early Strength Portland Cement Concrete	141.56	247.03	319.35
IIIH	Replacement with Other Site-Cast Hydraulic Concrete	663.33	2,334.08	3,017.19

* Parameters: 10% interest rate; 5% inflation rate; maintenance cost 10% of initial cost.
** ($/linear foot).

SOURCE(36)

EXHIBIT 63
INITIAL COSTS & LIFE CYCLE COSTS – C104 LITERATURE REVIEW

Code Number	System	Initial Cost	Present Value Total Cost* 25-Yr Evaluation Period	Present Value Total Cost* 50-Yr Evaluation Period
IA	Bituminous Concrete Overlay on Membrane	50.84	95.90	123.21
IB	Coating	—	—	—
IC	High-Early-Strength Portland Cement Concrete Overlay	83.21	103.13	130.96
ID	Penetrating Sealer	5.34	17.74	22.98
IE	Polymer Overlay	43.55	80.27	102.96
IF	Other Hydraulic Cement Concrete Overlay	—	—	—
IIA	Crack Repair and Sealing**	—	—	—
IIB	Joint Repair**	78.23	334.16	432.49
IIC	Patching with Bituminous Concrete	40.57	991.02	1,283.63
IID	Patching with High-Early-Strength Portland Cement Concrete	202.17	281.82	360.28
IIE	Patching with Polymer Concrete	247.07	742.20	958.46
IIF	Patching with Other Hydraulic Concrete	235.16	980.81	1,268.66
IIG	Temporary Steel Plate over Conventional Concrete Patch	—	—	—
IIIB	Replacement with Precast Concrete Box Beam	967.44	843.71	1,006.87
IIID	Replacement with Precast Concrete Deck Panel	852.35	849.37	1,096.63
IIIF	Replacement with Site-Cast High Early Strength Portland Cement Concrete	482.39	442.27	547.01
IIIH	Replacement with Other Site-Cast Hydraulic Concrete	686.64	1,059.77	1,372.73

* Parameters: 10% interest rate; 5% inflation rate; maintenance cost 10%of initial cost.
** ($/linear foot).

SOURCE(36)

EXHIBIT 64
EQUIVALENT UNIFORM ANNUAL COSTS – PADOT

DESCRIPTION	PROCEDURE NUMBER	MEAN LIFE	MEAN UNIT COST	EST QUAN	TRAFFIC CONTROL (HOURS)	EQUIVALENT UNIFORM ANNUAL COST
REHAB SLOPE WALLS (PARTIAL REPAIR WITH STONE)	8	18.30	148.60 CY	12		150.99
SOIL SLOPE WALL PARTIAL PROTECTION USING STONE	10	20.10	173.50 CY	20		277.62
PIER AND CAP PATCHING - DEPTH OF 1 INCH	1	9.80	39.50 SF	60		311.79
REMOVE AND REPLACE DECK DRAIN PIPE	44	22.55	37.27 LF	90	40	431.30
BACKWALL REPAIR	7	22.70	702.50 CY	4	80	568.23
REHAB SLOPE WALLS (REPLACEMENT WITH STONE)	9	28.50	138.00 CY	66		579.98
PAVEMENT RELIEF JOINTS, INSTALL	49	19.727	118.64 LF	60	20	672.93
SOIL SLOPE WALL FULL PROTECTION USING STONE	11	27.67	164.50 CY	66		732.86
DRAINAGE SCUPPERS, REPLACE WITH NEW SQUARE BOX DESIGN	42	32.73	1562.64 EA	6	40	738.72
REPAIR OF CRACKED PRESTRESSED BOX BEAMS	14	16.46	65.73 LF	70	160	1286.44
PIER AND CAP PATCHING - DEPTH OF 1 TO 3 INCHES	2	13.00	39.20 SF	350		1460.57
PRESTRESSED I-BEAMS, PATCH AND RESTORE PRESTRESSING	16	22.00	14845.00 EA	1	80	1492.44
PIER ENCASEMENT	4	25.50	532.00 CY	46		1718.99
POST TENSIONING OF CRACKED HAMMER HEAD PIERS	12	25.20	28530.00 EA	1		2016.07
PARAPETS, REPLACE EXISTING WITH CAST-IN-PLACE UNITS	47	34.55	103.64 LF	280	80	2075.65
PARAPETS, REPLACE EXISTING WITH PRECAST UNITS — TYPE VI	46	24.55	96.82 LF	280	80	2285.58
APPROACH SLAB REPLACEMENT, REMOVE AND REPLACE	48	23.09	19.14 SF	1500	40	2301.03
EXPANSION JOINT REPLACEMENT WITH UNARMORED COMPRESSION SEAL	30	15.73	198.64 LF	90	120	2340.40
PARAPETS, MODIFY EXISTING — TYPES IA, IB, II, III, IV, V	45	30.27	114.80 LF	280	80	2393.73
REPLACEMENT OF LONGITUDINALLY CRACKED BOX BEAMS	15	44.09	536.36 LF	70	80	2396.04
EXPANSION JOINT REPLACEMENT WITH ARMORED COMPRESSION SEAL	31	24.55	299.55 LF	90	120	2446.68
EPOXY GROUTED REINFORCEMENT FOR HAMMER HEAD PIERS	13	20.80	31005.00 EA	1	8	2469.26
EXPANSION JOINT REPLACEMENT WITH ARMORED NEOPRENE STRIP SEAL	32	22.73	328.64 LF	90	120	2744.31
PRESTRESSED I-BEAMS, REPLACE	17	43.18	727.91 LF	70	160	3446.89
REPAIR OF EXPANSION JOINTS (SLIDING PLATE)	29	5.12	158.00 LF	90	80	4240.43
REPAIR OF EXPANSION JOINTS (OPEN ARMORED)	28	3.91	114.30 LF	90	80	4344.48
PIER AND CAP PATCHING - DEPTH OF GREATER THAN 3 INCHES	3	18.00	51.50 SF	1000		4408.63
PIER AND PIER CAP REPLACEMENT	5	42.00	1155.00 CY	73		4839.84
DECK TYPE 2 REMOVAL PATCHING WITH HIGH EARLY STRENGTH PCC	22	8.46	86.71 SF	1050	80	4857.73
EXPANSION JOINT REPLACEMENT WITH TOOTH JOINT (WITH TROUGH)	34	28.64	770.91 LF	90	120	5087.14
EXPANSION JOINT REPLACEMENT WITH TOOTH JOINT (WITHOUT TROUGH)	33	27.73	767.73 LF	90	120	5144.77
DECK TYPE 3 REMOVAL PATCHING WITH HIGH EARLY STRENGTH PCC	24	16.09	58.18 SF	1050	80	5477.98
DECK TYPE 1 REMOVAL PATCHING WITH HIGH EARLY STRENGTH PCC	19	4.32	16.57 SF	1050	80	5842.28
BRIDGE DECK OVERLAYS - ASPHALT CONCRETE	26	3.91	4.76 SF	4200	8	5893.86
PIER REPLACEMENT	6	36.00	1244.44 CY	73	160	6070.89
DECK TYPE 2 REMOVAL PATCHING WITH MAGNESIUM PHOSPHATE CONCRETE	23	8.00	33.86 SF	1050	80	6244.14
BRIDGE DECK PATCHING - ASPHALTIC CONCRETE (TEMPORARY)	18	1.00	14.34 SF	420	8	6428.38
DECK TYPE 1 REMOVAL PATCHING WITH MAGNESIUM PHOSPHATE CONCRETE	20	4.91	23.71 SF	1050	80	6969.96
DRAINAGE SCUPPERS, REPLACE WITH STRAIGHT DROP PIPE	43	27.91	430.91 LF	280	40	8272.34
DECK TYPE 1 REMOVAL PATCHING WITH POLYMER CONCRETE	21	5.46	32.61 SF	1050	80	8354.48
DECK TYPE 3 REMOVAL PATCHING WITH MAGNESIUM PHOSPHATE CONCRETE	25	12.55	69.18 SF	1050	80	8458.44
REPLACEMENT OF DECK ON STEEL SUPERSTRUCTURE, CIP	35	35.00	42.00 SF	4200	160	11359.34
BRIDGE DECK OVERLAYS - LATEX-MODIFIED CONCRETE	27	17.00	29.05 SF	4200	160	11671.83
DECK REPLACEMENT ON ADJACENT BOX BEAMS, FULL REMOVAL, CIP	40	30.46	48.05 SF	4200	160	13660.87
DECK REPLACEMENT, PRESTRESSED I-BEAM SUPERSTRUCTURE, CIP	37	36.36	52.09 SF	4200	160	13731.64
DECK REPLACEMENT ON ADJACENT BOX BEAMS, PARTIAL REMOVAL, CIP	39	21.46	40.86 SF	4200	160	13963.49
DECK REPLACEMENT ON SPREAD BOX BEAMS, FULL REMOVAL, CIP	41	30.46	53.09 SF	4200	40	14565.17
REPLACEMENT OF DECK ON STEEL SUPERSTRUCTURE, PRECAST	36	26.09	82.91 SF	4200	160	24848.28
DECK REPLACEMENT, PRESTRESSED I-BEAM SUPERSTRUCTURE, PRECAST	38	26.36	88.91 SF	4200	160	26462.11

SOURCE(38)

SOURCE(39)

EXHIBIT 65
1980 SERVICE LIFE & UNIT COSTS – PADOT – PAGE 1

Item, Material, or Activity	Estimated Cost ($/ft²)	Estimated Maintenance-Free Service Life (yr)	Information Sources (See List)
I. Concrete removal (preparation for overlays, rehabilitation or replacement)			
A. Scarification (1/4 in.)	0.61		2
B. To top of upper rebar mat (Type 1)	8.10		2,29
C. To 1 in. below top rebar mat (Type 2)	14.75		2,29
D. Below type 2 to full depth (partial)(Type 3)	15.16		1,27
E. Complete deck removal	11.56		1-3,28
F. Deck modifications (raising expansion dams, scuppers, and backwalls)	1.00		28
II. Conventional (unprotected) new concrete bridge deck	12.94	5	1-3,28
III. New deck with coated rebars			
A. Epoxy-coated bars in top rebar mat	14.29	25	1,4,5,15,28,35,48
B. Galvanized bars (all)	14.82	23	34,35,48
IV. Concrete-filled steel grid deck	19.98	50	4,39,40
V. Precast deck sections	19.17		25-27
VI. Cathodic protection system (conductive-layer type)	5.26	10	4,6,7,15

EXHIBIT 66
1980 SERVICE LIFE & UNIT COSTS – PADOT – PAGE 2

Item, Material, or Activity	Estimated Cost ($/ft²)	Estimated Maintenance-Free Service Life (yr)	Information Sources (See List)
VII. Overlays (not including cost of scarifying or concrete removal)			
A. Latex-modified concrete or mortar (2 in. thick)	4.09	15[a] 20[b]	1,2,4,5,11-14,27 28,30-33,35,48
B. Low slump dense concrete (2 in. thick)	4.77	15[a] 20[b]	2,4,13,15,35 48,49
C. Internally sealed ("wax bead")(2 in. thick)	2.00		43
D. Polymer concrete (1/2 in. thick in 1/8-in. layers)	3.12		17
E. Preformed membrane and bituminous concrete wearing course	2.11	8	1,4,7-10,35
F. Mastic membrane and bituminous concrete wearing course	1.68	8	4
VIII. Polymer impregnation (methyl methacrylate)			
A. 1/4 in. deep	0.80		5,8,15,16,18-24,48
B. 1 in. deep	2.30		5,8,15,16,18-24,48
C. 2 in. deep	5.17		5,8,15,16,18-24,48
D. 3 in. deep	8.70		5,8,15,16,18-24,48
E. 4 in. deep	12.94		5,8,15,16,18-24,48
IX. Repair, patching and surfacing for rideability			
A. Bituminous concrete patching (2 in. thick, average)	1.23	0.67	34,42,44-46
B. Bituminous concrete wearing surface (1-1/2 in. thick)	0.44	8	15,28,29,35,48
C. Portland cement concrete patching (Type 2 concrete removal)	18.96		4,13,14
D. Epoxy patching (2 in. thick)	42.08		5,8,21,47
E. Delamination rebonding with epoxy	5.02		36,37

[a]Only deteriorated concrete removed. [b]All deteriorated and chloride-contaminated concrete removed.

EXHIBIT 67
COST EFFECTIVE SOUND DECK REPAIRS

Alternative	Funding Type[a]	Funding Share	Present Worth of Life-Cycle Costs ($/ft²): Non-chloride-Contaminated Deck (48-year Planning Horizon)	Present Worth of Life-Cycle Costs ($/ft²): Chloride-Contaminated Deck (45-year Planning Horizon)
Patch with bituminous concrete until percent spalls and fracture planes = 20%. Then, patch and provide bituminous concrete wearing surface until percent spalls and fracture planes = 40%. Then, rehabilitate with latex-modified concrete overlay.	ECER	Total	1.30	1.42
		State	0.84	0.90
	PR	Total	1.63	1.76
		State	0.78	0.83
Scarify and provide latex-modified concrete overlay. Replace every 20 years.	ECER	Total	b	7.70
		State		1.93
	PR	Total	6.31	23.06
		State	0.63	2.31
Patch with bituminous concrete until percent spalls and fracture planes = 20%. Then, and every 20 years thereafter rehabilitate with latex-modified concrete overlay.	ECER	Total	2.89	3.16
		State	0.80	1.02
	PR	Total	5.23	5.73
		State	0.95	0.85
Install cathodic protection system. Replace every 10 years.	ECER	Total	b	c
		State		
	PR	Total	9.48	9.49
		State	0.95	0.95
Install waterproof membrane and bituminous concrete wearing course. Replace every 8 years.	ECER	Total	b	7.29
		State		1.82
	PR	Total	4.12	18.87
		State	0.41	1.89

[a]ECER = Experimental Cost-Effective Reconstruction (federal participation 75 percent).
PR = Permanent Reconstruction (federal participation 90 percent).

[b]Not applicable (concrete not chloride-contaminated at time of application of protective measures).

[c]Not applicable (cathodic protection does not require removal of sound chloride-contaminated concrete).

EXHIBIT 68
COST EFFECTIVE DETERIORATED DECK REPAIRS

			Present Worth of Life-Cycle Costs ($/ft²)[a]						
	Funding		Percent Fracture Planes and Spalls at Present Time						
Alternative	Type[b]	Share	1	3	5	10	15	20	25
Patch with bituminous concrete until percent spalls and fracture planes = 20%. Then install bituminous concrete wearing courses until percent spalls and fracture planes = 40%. Then install latex-modified concrete overlay.	ECER	Total	2.75	4.44	4.90	5.93	7.49	8.86	9.27
		State	1.31	1.85	2.01	2.39	2.92	3.35	3.45
	PR	Total	4.09	5.91	6.47	7.77	10.12	12.07	12.06
		State	1.15	1.47	1.59	1.87	2.26	2.57	2.57
Patch with bituminous concrete until percent spalls and fracture planes = 20%. Then install latex-modified concrete overlay.	ECER	Total	4.57	5.90	6.51	7.93	10.95	Not Applicable (initial deterioration > action criterion)	
		State	1.35	1.69	1.84	2.19	2.85		
	PR	Total	8.22	10.84	11.90	14.34	18.86		
		State	1.08	1.34	1.44	1.68	2.02		
Install latex-modified concrete overlay.	ECER	Total	8.36	9.11	9.65	10.88	12.06	13.18	14.30
		State	2.09	2.28	2.41	2.72	3.02	3.30	3.58
	PR	Total	22.64	22.64	22.64	22.64	22.64	22.64	22.64
		State	2.26	2.26	2.26	2.26	2.26	2.26	2.26
Install cathodic protection	ECER	Total	Not Applicable (cathodic protection does not require removal of sound chloride-contaminated concrete).						
		State							
	PR	Total	9.56	9.94	10.32	11.27	12.21	13.16	14.11
		State	0.96	0.99	1.03	1.13	1.22	1.32	1.41
Replace deck	HBRR	Total	25.86						
		State	5.17						

[a]Forty-year planning horizon.

[b]ECER = Experimental Cost-Effective Reconstruction (federal participation 75 percent).
PR = Permanent Reconstruction (federal participation 90 percent).
HBRR = Highway Bridge Replacement and Rehabilitation (federal participation 80 percent).

SOURCE(39)

EXHIBIT 69
CHLORIDE REMOVAL COSTS

Job Size	1000 sq.ft.	5000 sq ft.	10000 sq.ft.
2 men			
Core Sampling			
Pretreatment	2	5	10
Post-treatment	5	10	20
.25 man-hr/sample	$70.00	$150.00	$300.00
Laboratory Charges			
chloride analysis	$140.00	$300.00	$600.00
Installation Labor			
Set Up Equipment			
3 man-hr/day	$60.00	$300.00	$600.00
Mount Battens			
4 man-hr/1000 ft2	$80.00	$400.00	$800.00
Apply Fiber			
4 man-hr/1000 ft2	$80.00	$400.00	$800.00
Install Mesh & Wiring			
7 man-hr/1000 ft2	$140.00	$700.00	$1400.00
Overhead; Travel, Living			
$200./day/man	$400.00	$2000.00	$4000.00
Scaffolding; $25/day	$25.00	$125.00	$250.00
Sandblasting; $300/1000 ft2	$300.00	$500.00	$1000.00
System Removal			
8 man-hr/1000 ft2	$160.00	$800.00	$1600.00
Disposal @ $50/1000 ft2	$50.00	$250.00	$500.00
Raw Materials			
wooden battens	20	100	200
one 1x2x10'/50 ft2	$20.00	$100.00	$200.00
steel anode			
5' widths	$75.00	$375.00	$750.00
fasteners			
batten anchors; 3/50 ft2	$6.00	$30.00	$60.00
cellulose fiber			
20 bags/1000 ft2	$264.20	$1188.90	$2452.00
calcium hydroxide			
3.6 kg/1000ft2	$32.00	$160.00	$320.00
water			
480 gal/1000 ft2	$13.44	$67.20	$134.40
Engineering - Plan Job			
8 man-hr/installation	$320.00	$320.00	$320.00
Electricity			
5 kilowatts/1000 ft2	$420.00	$1200.00	$4200.00
Maintenance Labor			
daily wetting			
1 man-hr/1000 ft2/day	$1400.00	$7000.00	$14000.00
Maintenance Water			
120 gal/1000 ft2/day			
$2.80/100 gal	$235.20	$1176.00	$2352.00
Royalties	$0.00	$0.00	$0.00
Insurance	$0.00	$0.00	$0.00
Taxes	$0.00	$0.00	$0.00
Depreciation	$95.00	$475.00	$950.00
Contingiency	$438.58	$1801.71	$3758.84
Total Cost	$4824.42	$19818.81	$41347.24

SOURCE: SHRP C-102A

EXHIBIT 70
SERVICE LIVES OF DECK TREATMENTS

		Average*		Scatter*		
Treatments	N	Median	Mode	Min.	Max.	Inter-Quartil Range
Topical						
AC Patching	30	1	1	0	25	1-2
Mortar/Concrete Patching	45	5	5	1/2	35	4-10
Epoxy Injection	28	10	10	4-5	50	10-20
Conventional Areal						
Sealers	32	4-5	5	1	25	2-10
Membranes + AC Overlay	39	15	15	5	60	10-15
LMC Overlay	40	15-20	20	0	60	10-20
LSDC Overlay	36	20	20	0	50	10-20
Experimental Areal						
Thin Polymer Overlay	29	10	10	2	25+	6-12
Polymer Impregnation	7	15	NA	1-10	30+	NA
FRC Overlay	7	15	NA	0	25	NA
Cathodic Protection	28	20	20	1	Indef.	15-30
MSC Overlay	13	20+	NA	10	60	20-25

* Where "NA" appears in the "Mode" column, it indicates either that number of responses is too few for the mode to have meaning or that distribution of responses is multimodal. Where it appears in "Interquartile Range" column, it indicates that the number of resp is too few to identify a meaningful interquartile range.

SOURCE(40)

EXHIBIT 71
SERVICE LIVES OF NON-DECK TREATMENTS

Treatments	Element	N	Average* Median	Mode	Scatter* Min.	Max.	Inter-Quartile Range
Sealers	R	30	5-10	10	2	25+	3-10
Sealers	S/S	29	5-10	10	2	35	3-10
Concrete Patching	R	36	10	10	2	35	5-10
Concrete Patching	S/S	37	10	10	2	35	5-10
Coatings	R	29	10	10	4	25	7-15
Coatings	S/S	31	10	10	2-3	25	5-10
PCC Patch & Encase	R	29	10	10	5	40	10-20
PCC Patch & Encase	S/S	33	10	10	2	40	10-20
Shotcrete	R	33	10+	10	0	40	10-15
Shotcrete	S/S	31	10+	10	0	40	10-15
Epoxy Injection	R	29	15	NA	4-5	50	10-25
Epoxy Injection	S/S	25	15	10	0-1	50	10-20
Cathodic Protection	R	10	15-20	NA	10	50	NA
Cathodic Protection	S/S	11	20	NA	5	50	NA

* Where "NA" appears in the "Mode" column, it indicates either that the number of responses is too few for the mode to have meaning or that the distribution of responses is multimodal. Where it appears in the "Interquartile Range" column, it indicates that the number of responses is too few to identify a meaningful interquartile range.

SOURCE(40)

EXHIBIT 72
EFFECTIVENESS OF DECK REHAB ON RATING & SERVICE LIFE

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation (%)
		Before	After	Change	Minimum	Average	Maximum	
Deck Replacement	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair		N.A.			N.A.		0
	Poor	4	8	4	16	21	27	100
	V. Poor	3	8	5	16	21	27	100
Deck Reconstruction	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	7	3	7	12	17	60
	Poor	4	7	3	7	11	16	100
	V. Poor	3	7	4	7	10	15	90
Deck Patching	V. Good		N.A.			N.A.		0
	Good	6	7	1	5	7	8	60
	Fair	5	6	1	4	5	7	90
	Poor	4	6	2	3	5	7	100
	V. Poor	3 (4)	6	3	3	4	6	90

Notes: * N.A. - Not applicable, meaning that inspector would rarely recommend this activity when condition rating is in the given level.
* Percentage of the chance of recommendation was rounded to the nearest 10s.

SOURCE(37)

EXHIBIT 73
SERVICE LIVES OF REHABS

PROBLEM NUMBER	BRIDGE NEED	MAINTENANCE TECHNIQUE OR SOLUTION	LIFE OF REPAIR OR SYSTEM	DECK LIFE	EXTENDED LIFE OF TOTAL BRIDGE	ALTERNATIVE LIFE OF REPAIR	ALTERNATIVE LIFE OF BRIDGE
I.	Loss of Paint—isolated truss areas	spot painting—localized sandblasting—3 coats of paint	7.1		11.8		
II.	Spalled deck	Patch spalls—liquid epoxy bonding agent—quick set cement mortar	6.4	5.2	0.8		
III.	Loss of steel section to corrosion	Add steel plate reinforcement by welding—sandblast and paint	20.0		20.0		
IV.	Truss diagonal buckled by truck	Replace diagonal	46.6		30.4		
V.	Stone arch—loss of mortar	Pointing of masonry	31.1		33.3		
VI.	P.C. stringer damaged by truck	Repair of lost concrete section, followed by external post—tensioning	37.1		28.8		
VII.	R.C. piles—deterioration at waterline	Place reinforcement via plastic sacks filled with mortar	20.6		22.8		
VIII.	Frozen, corroded bearings	Alt (1) replace w/new steel bearing Alt (2) replace w/new neoprene bearing	40.5	31.0		29.5	27.5
IX.	Timber stringers rotted out	Replace 4 timber stringers	23.5		15.5		
X.	Armored floor joints loose, nonfunctional	Replace old armored joint w/new angle iron armor and neoprene seal	19.5	11.0	11.5		
XI.	Scour hole under abutment	Construct concrete jacket and fill scour hole with concrete	33.5		29.5		
				EXT. LIFE SUBSTRUCTURE			
XII.	Salt penetration seats, caps	Apply liquid epoxy resin coating to pier caps and abutment bridge seats	10.5	7.0	6.0		
XIII.	Major cracks—full height abuts.	Epoxy injection	12.0		12.0		
XIV.	Backwall cracking—concrete broken	New R.C. backwall	37.0	26.0	25.0		
XV.	Low approach pavement—bump	Fill (low area) with plant mix bituminous concrete to grade	8.0		N/A		

EXHIBIT 74
DECK REHAB DECISION MATRIX

Table 2/ Decision Matrix for Selection of Deck Rehabilitation Method

Criterion	Concrete overlay	Waterproofing membrane and paving	Cathodic protection	Rationale
Delamination and spalls exceeding 10% of the deck area.		No	No	Where extensive patching is required it becomes more economical and more durable to construct a concrete overlay.
Corrosion potential more negative than −0.35 V over more than 20% of the deck area.		No		Patch repairs and waterproofing rarely reduce corrosion activity and may accelerate it.
Moderate or heavy scaling exceeding 10% of the deck area		No	No	The amount of patching becomes too expensive and consequently uneconomical.
Active cracks in deck slab.	No			Cracks active under live load or temperature change are reflected in a concrete overlay.
Remaining life of structure less than 10 years.	No		No	Additional cost of a concrete overlay or cathodic protection is not justified.
Concrete not properly air entrained.			No	Application of a bituminous surfacing (without waterproofing) may accelerate deterioration of the concrete.
Complex deck geometry. Skew exceeding 45°, curvature exceeding 10°, or changing super-elevation.	No			Concrete finishing machines (especially those used for low-slump concrete) have difficulty accommodating complex geometry.
Limited load capacity of structure*		No	No	Bituminous overlay is a non-structural component. Concrete overlay can be especially useful where the span/thickness ratio of deck slab exceeds 15.**
Electrical power unavailable.			No	Power required for rectifier (unless mains, solar, wind or battery power can be provided economically.
Epoxy injection repairs previously performed and will not be removed.			No	Epoxy insulates underlying reinforcement from cathodic protection.

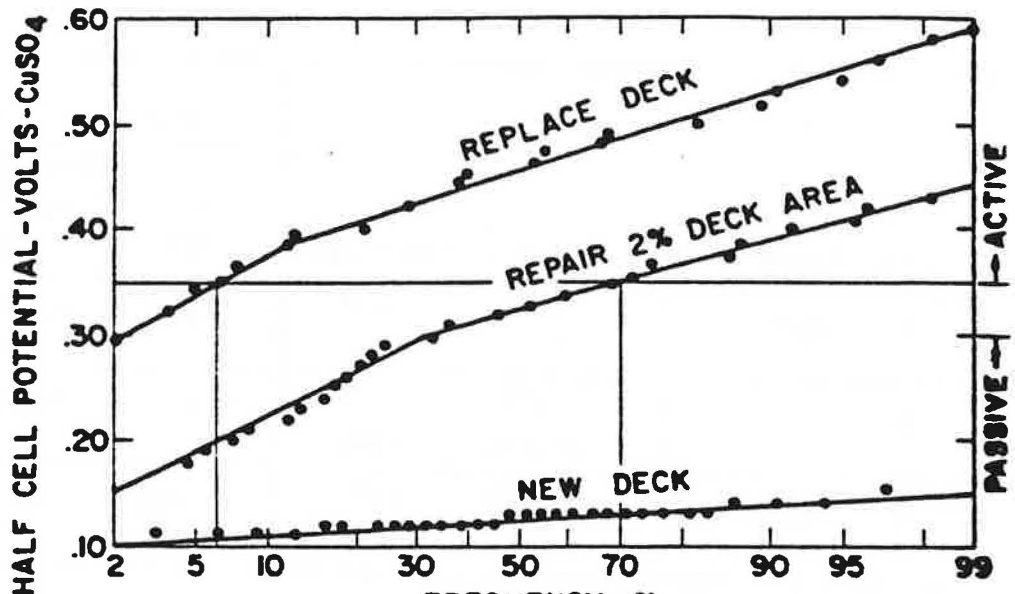
* Capacity after rehabilitation must be verified. Additional strengthening may be necessary.

** See OHBDC Section 7.

SOURCE(43)

EXHIBIT 75
DECK REHAB DECISION, HALF-CELL PLOT

Distribution of half-cell potentials.



SOURCE(44)

EXHIBIT 76
WSDOT DECK DECISION MATRIX

Table 1. WSDOT's Bridge Deck Repair Priority and Protection System Selection Matrix

					Priority No. – Protection System		
						Traffic Category	
Group	Rating	Code	cl>2#/cy [a]	Deterioration [b]	>10,000 ADT	2,000 - 10,000 ADT	<2,000 ADT
1	slight	8	none	None	3(LMC)[c]	4(LMC-AC)[d]	8(LMC-AC)
		7	none	None			
2	moderate	6	<20%	<2%	6(LMC)	7(LMC-AC)	9(LMC-AC)
		5	20-40%	2-5%			
3	severe	4	40-60%	>5%	1(LMC)	2(LMC)	5(LMC)
		3	>60%	>5%			

a. Percent of chloride samples exceeding 2#/c.y.

b. Deterioration is defined as the percent of the total deck area that has spalls and/or delaminations.

c. Protection method: latex-modified concrete overlay.

d. Protection method: latex-modified concrete overlay or asphalt concrete and waterproofing membrane.

SOURCE(34)

EXHIBIT 77
WSDOT DECK DECISION MATRIX – AFTER ADJUSTMENTS

Table 14. Suggested Bridge Deck Protection System Selection Matrix

Group	Rating	Code	cl>2#/cy [a]	Deterioration [b]	Priority No. – Protection System (Traffic Category) >10,000 ADT	2,000 - 10,000 ADT	<2,000 ADT
1	slight	8	none	None	3(LMC)[c]	4(LMC-AC)[d]	8(LMC-AC)[d]
		7	none	None			
2	moderate	6	<20%	<2%	6(LMC)[e]	7(LMC-AC)[f]	9(LMC-AC)[f]
		5	20-40%	2-5%			
3	severe	4	40-60%	>5%	1(LMC)[e]	2(LMC)[e]	5(LMC-AC)[f]
		3	>60%	>5%			

a. Percent of chloride samples exceeding 2#/c.y.

b. Deterioration is defined as the percent of the total deck area that has spalls and/or delaminations.

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c. Protection method: latex-modified concrete overlay.

d. Protection method: latex-modified concrete overlay or asphalt concrete and waterproofing membrane.

e. Protection method: latex-modified concrete overlay with cracks sealed.

f. Protection method: latex-modified concrete overlay with cracks seale or asphalt concrete and waterproofing membrane applied on a deck patched with conventional concrete or fast setting material with equal properties.

SOURCE(34)

EXHIBIT 78
FLOWCHART FOR DECK REHABILITATION

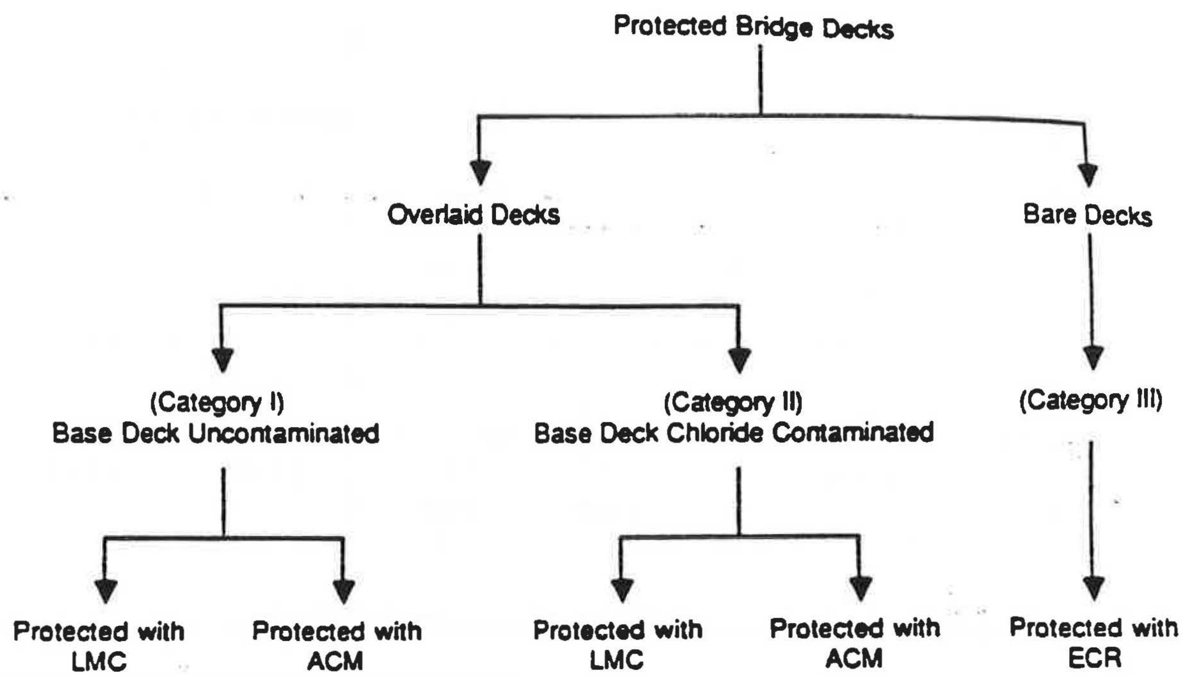


Figure 4. Classification of Protected Bridge Decks for Reconstruction Strategies

SOURCE(45)

EXHIBIT 79
FLOWCHART FOR DECK RECONSTRUCTION

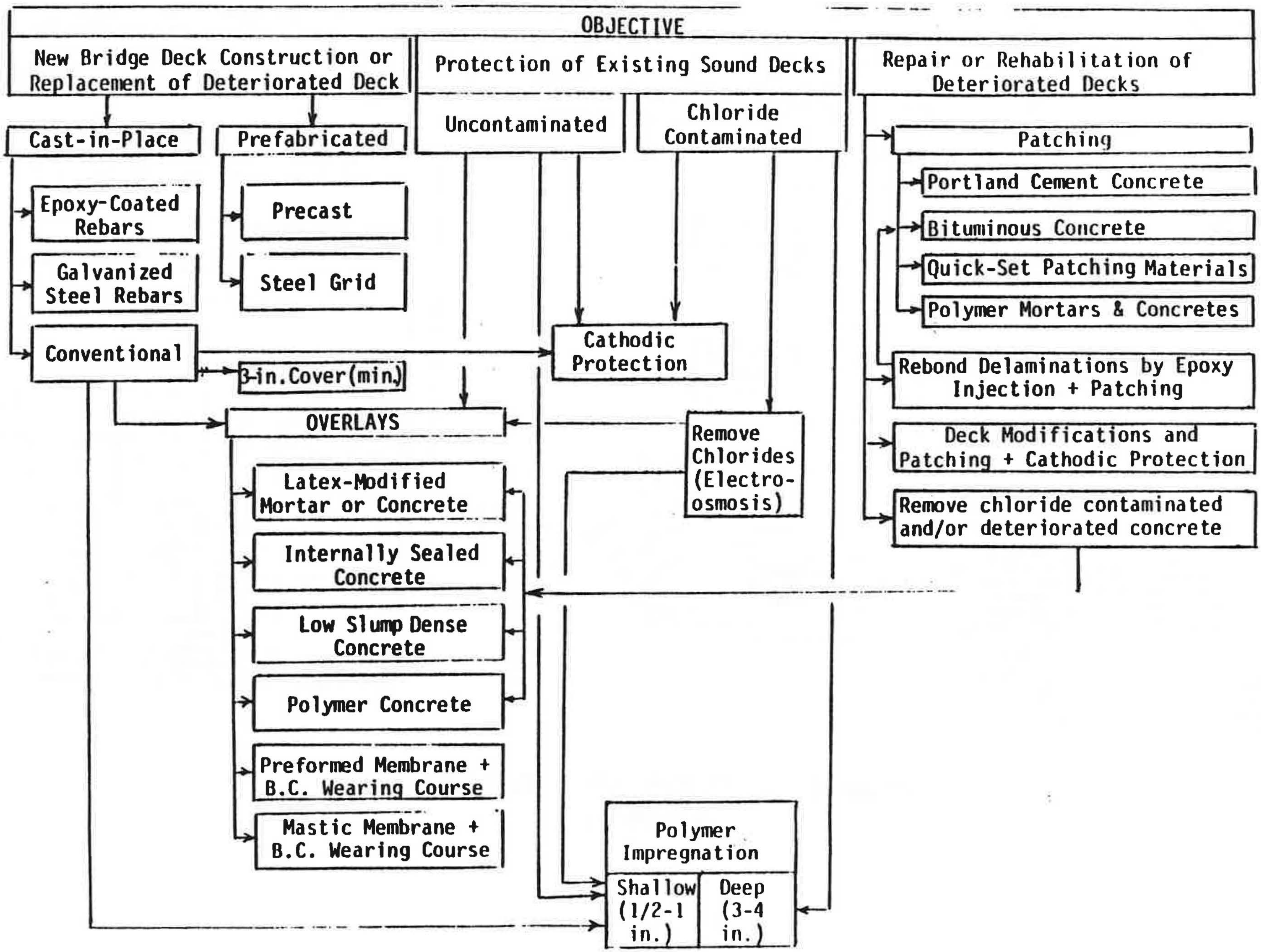
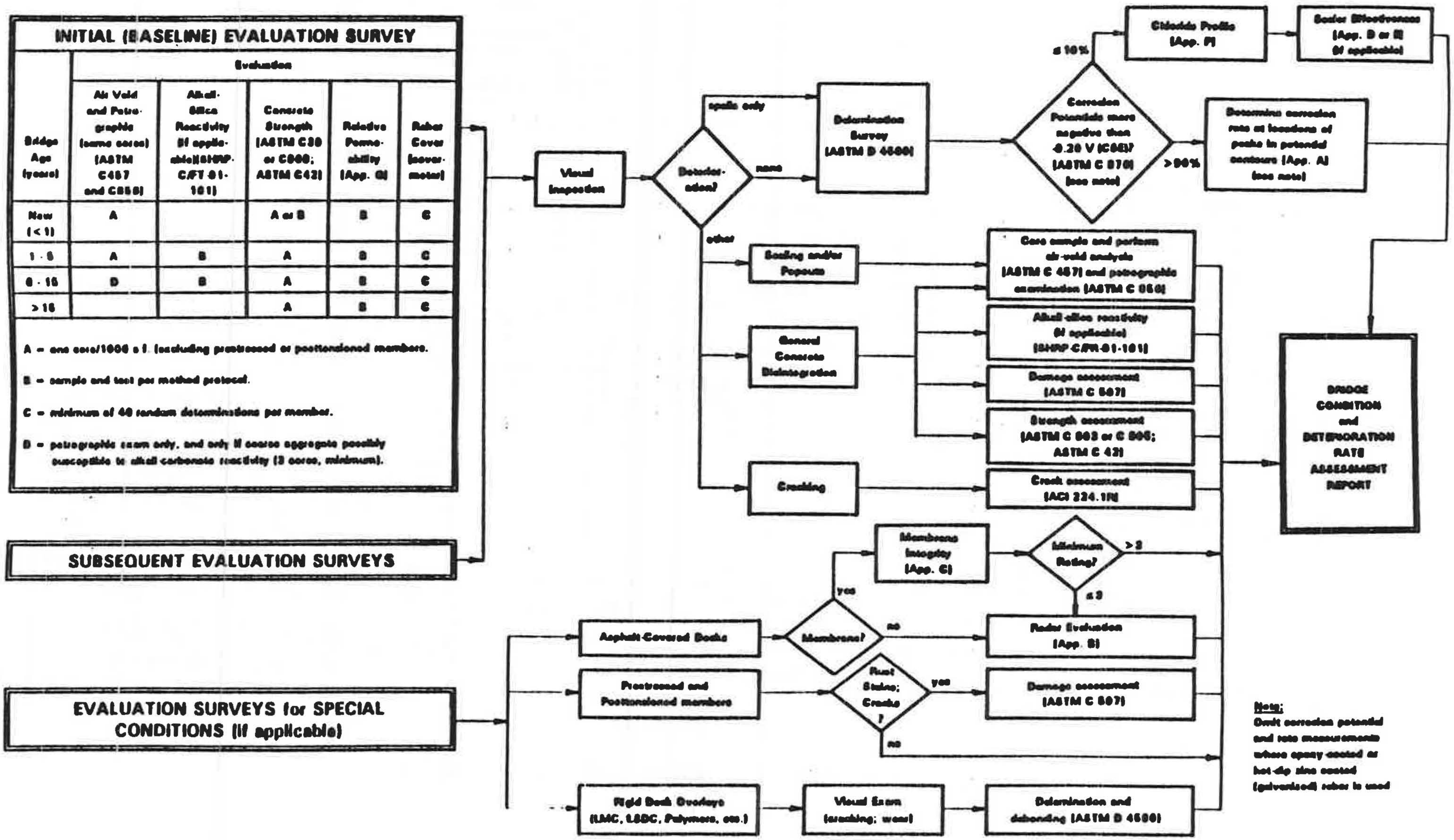


EXHIBIT 80
FLOWCHART FOR PROCEDURE MANUAL



5. Annotated Bibliography

TOPIC CODES

Code	Topic
1	Project Level Deterioration
2	System Level Deterioration
3	Cost Analysis
4	Cost and Service Life
5	Decision Logic
6	Condition Assessment
7	Remedial Procedures

Topic
Codes

7 AASHTO Guide for Bridge Maintenance Management 1980. American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 1980.

This report outlines maintenance objectives and presents specifications for many maintenance activities.

6 AASHTO Manual for Maintenance Inspection of Bridges 1983. American Association of State Highway and Transportation Officials (AASHTO), Highway Subcommittee on Bridges and Structures, Washington, D.C., 1984.

This manual was prepared to serve as a standard to provide uniformity in the procedures and policies of determining the physical condition and maintenance needs of highway bridges. The procedures for correcting known deficiencies are outside the scope of the manual. However, it is pointed out that the protection of the investment in the structure facility through well programmed repairs and preventive maintenance is second only to the safety of traffic and to the structure itself.

7 AASHTO Manual for Bridge Maintenance. American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 1976.

This manual is a guide for bridge engineers to help identify problem areas and make recommendations that are considered effective. Efficient management methods concerning the problems of bridge maintenance are also discussed.

7 ACI "Routine Maintenance of Concrete Bridges." Structural Repair Corrosion Damage and Control, American Concrete Institute, Committee 345, ASCI, SCM-1985, Detroit, Michigan, pp. 45-46.

Standard maintenance activities are discussed for the deck, superstructure, and substructure.

7 ACI "Routine Maintenance of Concrete Bridges." Report No. ACI 345.1R-83, American Concrete Institute, Detroit, Michigan, pp. 35-46.

Various potential sources of distress are described in the superstructure, substructure, approaches, slopes, and channel. Guidance for avoiding or correcting such troubles is also provided in the form of a day-to-day maintenance and preventive maintenance guide. Experience in highway operation has shown that continuous and systematic maintenance of a bridge will extend its service life and reduce its operating expense.

1 AASHTO. Manual for Maintenance Inspection of Bridges in 1983. American Association of State Highway and Transportation Officials , Washington, D.C., 1984, 50 pp.

Concrete bridges for which no plans are available and show no signs of deterioration need not be posted for live load.

1 AASHTO. Standard Specification for Highway Bridges. American Association of State Highway and Transportation Officials, Washington, D.C.

Reinforced concrete design specifications are detailed for slabs, substructures, etc.

4 AASHTO. A Manual on User Benefit Analysis of Highway and Bus Transit Improvements. American Association of State Highway and Transportation Officials, Washington, D.C., 1987, 189 pp.

Cost data is provided on user costs.

4 Arner, R. C., J. M. Kruegler, and K. R. Patel. Pennsylvania's Bridge Maintenance Management System. Pennsylvania Department of Transportation, Harrisburg, Pennsylvania, January 1986.

Report conceptualizes the bridge maintenance management subsystem for the overall BMS. A bridge maintenance prioritization procedure was developed to rank activities, the severity of the deficiency, the bridge

criticality, and the bridge adequacy. Estimated remaining life is based on SI&A condition ratings.

1 Babaei, K., and N. M. Hawkins. "Performance of Rehabilitated/Protected Concrete Bridge Decks." Draft paper for ASTM symposium on Corrosion Forms and Controlled Infrastructures, November 3-4, 1991, San Diego, 19 pp.

The paper documents results of testing 5 latex-modified concrete overlays, 5 low slump dense concrete overlays, and 2 cathodically protected bridge decks. The study showed that latex-modified concrete decks have an average deterioration rate of 0.4% of the deck area per year and that low slump dense concrete decks deteriorate at a rate of 0.5% of the bridge deck area per year. After about 5 years of service, both cathodically protected bridge decks showed satisfactory performance with regard to corrosion. The slotted cathodic system had problems with spalling in the concrete adjacent to the slot, internal which originated from the bottom of the slots, and acid deterioration at the slot-deck interface. The first two problems related to traffic impact; the second problem was related to humidity. In summary, concrete overlay strategies seem more cost effective than cathodic protection systems unless no continued corrosion is tolerable.

2,5 Babaei, K. "Development of a Bridge Deck Management System for Washington State Department of Transportation." (Contract/Grant Y 3399, Task 19). Washington State Department of Transportation, March 1988, 77 pp.

This report documents development of a systematic bridge deck management system for the Washington State Department of Transportation. This system determines present and future bridge deck condition, estimates required reconstruction and its associated costs, and prioritizes and selects reconstruction while considering either budget constraints or condition level constraints.

1 Babaei, K. "Evaluation of Concrete Overlays for Bridge Applications." Washington State DOT, Research Project Y-3399, June 1987, Olympia, 53 pp.

This report documents performance of 12 concrete bridge decks that were rehabilitated with latex-modified concrete (LMC) and low-slump dense concrete (LSDC) overlays. The research team visited 47 concrete overlayed bridge decks. The WS protective system selection criteria are given in a table. Because LMC had a potential for better durability and promised to retard corrosion in existing salt-contaminated more efficiently, it became the primary system in Washington. The use of LSDC was discontinued in 1984 due to concerns about chloride permeability. Few crack-free overlays of both LMC and LSDC were found. The pattern of cracking suggests initial plastic shrinkage lengthened as a result of structural flexing, thermal cycling, and wetting and drying. One-third of the decks overlayed with LMC and two-thirds of the decks overlayed with

LSDC were delaminated. Table 12 compares the average annual pre-imposed overlaying concrete deterioration rates for the delaminated LMC and LSDC. The pre-overlayed deterioration rates were obtained by dividing the percent rehabilitated area by the age of the bridge at the time of overlay. The post-overlay delamination rates were determined by dividing the percent of the delaminated area of the deck by the age at the time of testing. Over long term, originally contaminated decks may still delaminate in the absence of overlay cracking. Table 14, which is based on the research findings, suggests a modification of the WSDOT bridge deck protective system selection criteria.

7 Baker, H. H., and R. G. Posgay. "The Relationship between Concrete Cure and Surface Preparation." Journal of Protective Coatings and Linings, Vol. VIII, No. 8, August 1991, pp. 50-56.

Several concrete panels were tested to determine factors affecting coating adhesion. It was found that sweep (brush) blasting will remove various curing membranes while acid etching is not completely effective. Curing membranes act as a surface contamination. The concrete surface needs to be completely cured before a coating can be applied. Sweep blasting a portion of the concrete surface will provide a quick indication of extent of curing.

1 Beaton, J. L. and Stratfull, R. F., "Environmental Influence of Corrosion of reinforcing in Concrete Bridge Substructures". Concrete Bridge Decks and Pavement Surfaces, HRR 14 HRB Washington, D.C., 1963, pp 60-78.

Time to corrosion is described by the Stratfull Formulas.

1 Berke, N., Pfeifer, D., and Weil, T; "Protection against Chloride-Induced Corrosion".

Presents relationships, based on experimental data, between Coulombs passed versus effective chloride diffusion coefficient.

4,5 Blackburn, R. R., and W. B. Glauz. Economic Evaluation of the Effects of Ice and Frost on Bridge Decks. American Association of State Highway Transportation Officials (AASHTO), 57th Meeting, Washington, D.C., 1971.

The objective was to develop a comprehensive cost-benefit methodology, complete with the set of realistic parameter values, that can be used by a highway administrator to determine the added design or extra maintenance cost justified to prevent or remedy ice or frost on bridge decks.

7 "Bridge Maintenance Products and Methods Used by the States for Deck Repairs, Structural Painting, and Various Other Activities." Maintenance Aid Digest, Report No. MAD16, February 1978.

A report on the findings of a survey conducted among the States to discover methods and products found to be either successful or unsuccessful in deck repairing, deck sealing, and bridge painting.

7 Brown, R.P. and Tinnea, J.S., Cathodic Protection Design Problems for Reinforced Concrete". Materials Performance, Vol. 30, No. 1, National Association of Corrosion Engineers, Houston, August 1991, pp. 28-31.

Many cathodic protection systems have failed or showed premature deterioration. Corrosion engineering are finding that CP materials are failing because systems were improperly designed or operated. In marine environments, daily tidal changes greatly affect CP current distribution. Splash zone areas and areas immediately above (approximately 3 feet) require additional CP current and should be powered through a separate circuit to allow proper control.

1 Browne, R. D. "Design Prediction of the Life for Reinforced Concrete in Marine and Other Chloride Environments." Durability of Building Materials, Vol. I, 1982, Amsterdam, pp. 113-125.

Concrete structures in marine environments can exhibit damage due to reinforcement corrosion after 15 years in the UK and as little as 5 years in hotter climates. A family of curves of chloride concentration with distance from the surface with time for different surface chloride levels and chloride diffusion coefficients can be represented as shown in the nomograph in figure 8. The nomograph considers (1) surface chloride level, (2) critical chloride level, (3) concrete cover depth, (4) chloride diffusion coefficient to arrive at years of life (design life).

7 Burke, N. D., and J. B. Bushman. "Corrosion and Cathodic Protection of Steel Reinforced Concrete Bridge Decks." FHWA-IP-88-007, FHWA, Washington, D.C., 1988, 94 pp.

This report is a textbook on corrosion; cathodic protection; how to evaluate systems; and how to design, install, operate, inspect, and maintain systems. Chapter 5 discusses various systems. The first system, developed for California DOT in 1973, was applied on the Sly Park Road bridge on U.S. 50 near Sacramento. This system was effective but required 4-inch overlay modifications to approaches, drains, expansion joints, etc. The second generation anode system, first used in 1979, provided thin-wire anodes in saw-cut slots in the bridge deck. Conductive polymer mounds were first tried in 1983 in Minneapolis. Flexible conductive polymer mesh with a concrete overlay was first tried on a deck in the Washington, D.C., area in 1985. Mixed precious metal oxide mesh uses titanium wire in a tight diamond pattern.

4 Burns, E. N., C. L. Dudek, and O. J. Pendleton. "Construction Costs and Safety Impacts of Work Zone Traffic Control Strategies, Volume I: Final Report." Report FHWA-RD-89-209, Federal Highway Administration, 1989.

Research was performed to determine total costs (construction and road user costs) and safety impacts associated with traffic control through work zones on rural four-lane, divided highways using single lane closure (SLC) versus two-lane traffic operations (TLTWO). Construction data were collected from 51 construction projects in 11 States, and traffic capacity delay studies were conducted at 25 projects in 10 States. This (Volume I) is the main report, which provides detailed information on each of the projects and the results of the individual studies. The Volume II report provides an informational guide and a simplified procedure to estimate road user costs for SLC and TLTWO traffic control strategies.

2 Busa, G.,; Cassella, M.; Gazda, W.; and Horn, R. "A National Bridge Deterioration Model. Report No. SS-42-U5-26, USDOT, Transportation Systems Center, Cambridge, Sept. 1985.

A deterioration model based on over 150,000 bridges is developed.

3 Butler, B. C., Jr.; R. F. Carmichael III; P. Flanagan; and F. N. Finn. "Evaluating Alternative Maintenance Strategy." National Cooperative Highway Research Program Report No. 285, Transportation Research Board, Washington, D.C., June 1986, 86 pp.

This report describes the use of a computer program (BLCCA) developed to provide an economic analysis of agency bridge maintenance options. The use of a record program (IMPACT) that calculates the impact of surface roughness, road closures, accidents, and other factors on a bridge user is also described. Deferred maintenance is not a quantifiable term. Little information could be found that quantifies the effectiveness of different maintenance treatments in slowing the deterioration of maintenance elements. Life cycle costs were identified as being an effective method to use in evaluating agency costs and public impact. Various deterioration curve scenarios are discussed on page 8. Bridge deck condition (roughness) is expressed in present serviceability index (PSI) units. Life cycle cost analysis is explained in Appendix C which discusses a computer program called the Bridge Life Cycle Cost Analyzer (BLCCA). A total cost of building and maintaining a structure is a sum of two cost functions. The amortized construction cost and the accumulated total maintenance cost. The optimal life of a bridge from the standpoint of minimizing costs corresponds to the low point on the U-shaped total cost curve.

3,4 Cady, P. D., and R. E. Weyers. "Chloride Penetration and Deterioration of Concrete Bridge Decks." Cement Concrete and Aggregates, CCAGDP Vol. 5, No. 2, Winter 1983, pp. 81-87.

Report discusses current practice, life cycle cost factors, cost effectiveness models, cost and service life data, and evaluation of alternatives. Estimated maintenance-free service life of various types of new construction, overlays, and repairs are presented. Planning horizons are given. The uncertainty relative to service life is also discussed in Appendix A. The paper synthesizes empirical data to formulate a predictive model for chloride intrusion in bridge decks. Subsidence cracking is important because of the position of the cracks immediately above the parallel to the reinforcing bars. Working cracks, on the other hand, are aligned perpendicular to the main reinforcement and provide little access to the bars. Subsidence cracking is a function of rebar cover, bar diameter, and slump of the concrete. This type of cracking provides very rapid means of transferring chloride ion from the concrete surface to the reinforcement. Diffusion, following Fick's Law, is simplified in the report. The time to corrosion is found to vary with the square of the depth of the steel. Time to corrosion is approximately 7 years for 1 inches of cover and 17 years for 2½ inches of cover.

3,4 Cady, P. D. "Bridge Deck Rehabilitation Decision Making." Transportation Research Record 1035, Transportation Research Board, National Research Council, Washington, D.C., 1985.

Policies for the protection, repair, rehabilitation , and replacement of concrete bridge decks were investigated, with the goal of providing recommendations based on minimum life-cycle costs. Present policies in most states consist of decision matrices or flow diagrams based on a few parameters related to deck condition and, sometimes, to service. Few appear to possess the capacity to reflect the cost-effectiveness of feasible alternative strategies. The development of a mathematical model for evaluating alternative strategies for bridge deck protection, repair, rehabilitation, and replacement, which forms the basis for current policy of the Pennsylvania Department of Transportation is described. Detailed procedures for data acquisition are presented, and a typical calculation is illustrated.

3,4 Cady, P. D. "Policies for the Protection, Repair, Rehabilitation, and Replacement of Concrete Bridge Decks." Report PTI 8103, Pennsylvania Department of Transportation, April 1981, 83 pp.

This study investigated policies for the protection, repair, rehabilitation, and replacement of concrete bridge decks, with the goal of providing recommended policies based on minimizing life-cycle costs. The primary recommendation presented in this report is that life-cycle costs should be

determined for the feasible alternatives in each individual case, at least for major bridges. A mathematical model was developed to facilitate such an evaluation. Using generalized conditions, it was determined with the cost-effectiveness model that the least costly approach is to maintain rideability with bituminous concrete patching and wearing courses until structural considerations necessitate rehabilitation with rigid overlays. The effects on life-cycle costs of funding policies, inflation, interest rate, uncertainty relative to service life, and deck deterioration rates were also studied. Recommendations include the following. New decks should be constructed with epoxy-coated reinforcing in the top mat. Existing bridge decks which are uncovered should have the average rebar cover determined from at least 40 random measurements. Petrographic analysis of cores should be used to determine the nature of deterioration which is suspected to be other than corrosion induced. Corrosion-induced damage should be repaired by a strategy based on minimum life cycle cost. Covered, existing decks should be visually inspected and repaired by either new wearing course, rehabilitated with a rigid, low permeability overlay, or scheduled for replacement. Concrete removal should be limited to deteriorated concrete. Deck replacement should be avoided until necessitated by serviceability requirements.

4 Chamberlin, W.P. and Weyers, R.E., "Protection and Rehabilitation Treatments for Concrete Bridges Components: Status and Service Life Options of Highway Agencies." SHRP C-103, Task 1 Report, Unpublished, 31 pp.

Service lives are listed.

7 Chambron, E., and J. Thomas. Bridge and Tunnel Maintenance Methods. Revue General Des Chemins De Fer, Vol. 97, French, January 1978.

A report on the different maintenance methods used and the planning involved.

3,4 Chen, C. J., and D. W. Johnston. "Bridge Management Under a Level of Service Concept Providing Optimum Improvement Action, Time, and Budget Prediction." Report FHWA/NC/88-004, North Carolina Department of Transportation, September 1987, 383 pp.

A bridge management analysis program considering owner costs and user costs was developed to determine the optimum improvement action and time for each individual bridge in a system under various level of service goals. Bridge ownership costs due to maintenance, rehabilitation , and replacement and bridge user costs due to level of service deficiency were evaluated. Bridge maintenance needs were determined based on bridge element condition. Bridge rehabilitation needs were determined as a function of bridge element conditions before and after rehabilitation and

desired user level of service goals. Bridge replacement costs were determined based on the desirable level of service goals for various roadway functional classifications. User costs were determined for vehicular accidents and detours due to bridge load capacity, deck width, vertical clearance, and approach roadway alignment level of service deficiencies.
A computer program incorporating parameters and relationships of bridge ownership and user costs was created to analyze North Carolina bridges. Based on the optimum improvement alternative selected for each individual bridge, the future funding needs, bridge conditions, load capacity, and bridge level of service deficiencies were predicted under different combinations of condition and user level of service goals.

4,7 Chou, K. G. "Bridge Boasts Newest Wave of Cathodic Protection." Roads and Bridges, March 1986, pp. 74-80.

Prefabricated polymer anode mesh was installed on a bridge in Washington State. Deicing salts and traffic had damaged the deck. Deck length is estimated to have been extended by 30 years. The system was used in connection with a latex-modified concrete overlay. The mesh arrives at the job site ready to rolled out, tacked down, and then covered with the overlay. The job was completed in 3 weeks. The first cathodic protection system was installed in 1973 by the California DOT on the Sly Park bridge near Sacramento. The first generation system, devised by California corrosion engineer, Richard Stratful, consisted of anodes spaced 10 feet apart, covered with 2 inches of asphaltic concrete modified with coke breeze and another 2 inches of regular asphaltic concrete to provide durability. The system added weight and elevated the bridge level and trapped water at the overlay-deck interface. The slotted system appeared in the second generation system according to this article. Slots are cut at 12-inch spaces. Platinum-clad niobium wires or graphite strands are laid in the slots and covered with a conductive mix of epoxy and coke breeze. The system did not add weight or affect bridge geometry; however, cutting the slots was time consuming and labor intensive. The third generation systems consisted of mounds in lines 12 to 18 inches apart.

1 Clear, K. C. " Time-To-Corrosion of Reinforcing Steel in Concrete Slabs". FHWA-RD-76-70, FHWA, Washington, D.C., April 1976, 64 pp.

The modified Stratfull Formula is presented.

1 Clear, K. C. "Evaluation of Portland Cement Concrete for Permanent Bridge Deck Repair." FHWA-RD-74-5, FHWA, Washington, D.C., February 1974, 48 pp.

The effects of chloride in reinforced concrete and the chloride content corrosion thresholds are discussed. Concrete tests include delamination detector, electrical potential corrosion detection device, pachometer, and chloride analyses are discussed.

6 Clemeña, G. G. "Nondestructive Inspection of Overlayed Bridge Decks with Ground-Penetrating Radar." Transportation Research Record 899, Transportation Research Board, Washington, D.C., 1983, pp. 21-32.

Ground-penetrating radar can be used with reasonable reliability to survey overlayed bridge decks. The distinction between reflection patterns for sound and deteriorated concrete is very fine. Minor and small deterioration is hard to distinguish. Deterioration on the surface of the concrete slab due to freeze-thaw damage by moisture trapped between the overlay and the slab is currently difficult to differentiate from dispondents.

7 Department of the Army "Maintenance and Repair of Surface Areas." Maintenance and Repair of Bridge, TM 5-624, Office of the Chief Engineer, Department of the Army, Washington, D.C., March 1977.

This section of the manual deals mainly with the maintenance of various types of common bridge structures predominant on military installations.

4,7 Division of Materials and Research. "Investigation of Bridge Deck Protective Systems." Missouri Highway and Transportation Department, Missouri Cooperative Highway Research Program Final Report 76-2, Missouri Highway and Transportation Department, December 1988, 140 pp.

This study evaluated effectiveness of various repair systems. Systems included cathodic protection, low-slump concrete, latex-modified concrete, and membranes. All protected systems were overlayed with asphaltic concrete except for low-slump and latex-modified concretes. Each of the protective systems provided a relatively maintenance-free overlay for an 8-year period. Rutting and shoving of the asphalt concrete was minor but the predominant problem with membranes and cathodic protection systems Low-slump and latex-modified concrete overlays provided the smoothest riding surfaces. Membrane systems protected the decks from ingress of chloride ions. Concrete overlays did not prevent ingress of chloride ions but did slow the amount and the depth of penetration with time.

7 "Epoxies Restore Cracked Concrete". Railway Track and Structures Vol. 70, No. 9, Ann Arbor, Michigan, 1974.

Epoxies offer a method for restoration. The repairs can be carried out without the need for reducing train speeds or disrupting train traffic. Structural integrity is achieved at a fraction of the cost of alternative repair methods.

5,7 FHWA. "Value Engineering Study of Bridge Deck Maintenance, Repair, and Protection." Report DTFH61-88-C-00074, Federal Highway Administration, 1989.

This report presents the results, conclusions and recommendations of a Value Engineering Task Team assigned to study "Bridge Deck Maintenance, Repair and Protection." The objective of the study was to develop recommendations for optimizing maintenance resource expenditures for; methods, materials, work crew loading and equipment used in the repair of cracking, scaling and spalling of concrete bridge decks. This also included an in-depth analysis of new, innovative, and state-of-the-art methods, materials and equipment used for bridge deck maintenance (routine, preventative and corrective), repair (rehabilitation) and protective systems for bridge decks.

6 FHWA. Bridge Inspectors Training Manual 70. USDOT, FHWA, Washington, D.C., 1979.

Deterioration assessment of concrete is discussed.

6 FHWA. "Field Inspection Guide for Bridge Deck Cathodic Protection." FHWA-DP-34-3, Federal Highway Administration, Washington, D.C., December 1988, 55 pp.

The report is a guide for inspectors who are unfamiliar with the construction of cathodic protection systems. The report covers anode slotted systems with platinum wire anodes primary with carbon strand anode secondary wires with conductive backfill. Also, platinum and carbon strand anodes. Titanium mesh anodes.

2 FHWA. Recording and Coding Guide for the Structure Inventory in Appraisal of the Nation's Bridges. Federal Highway Administration, Washington, D.C., January 1979, 38 pp.

Item 58 of the Coding Guide specifies the table for condition rating of concrete bridge decks based on area percent spalled, corrosion potentials, and chloride content. This table has been deleted in the 1988 edition.

2 FHWA. Recording and Coding Guide for the Structure Inventory in Appraisal of the Nation's Bridges. Federal Highway Administration, Washington, D.C., December 1988, 38 pp.

Items 58 through 62 require condition ratings which are defined in the table on page 36. These condition ratings are used in most deterioration models cited in this literature review.

4 FHWA "Unit Costs and Productivity Standards for Various Highway and Bridge Maintenance Activities." Federal Highway Administration, June 1977.

Unit costs for various activities are provided in tables.

2 FHWA Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1979.

This guide, endorsed by the AASHTO Subcommittee for Bridges and Structures, has been prepared by the states in recording and coding the elements that will form a bridge inventory data base.

2 Fitzpatrick, M. W., D. A. Law, and W. C. Dixon. "Deterioration of New York State Highway Structures." Bridge and Pavement Maintenance, TRR 800, Transportation Research Board, Washington, D.C., 1981, pp. 1-8.

New York analyzed its inspection data. It was found that bridges are deteriorating at a rate of 0.15 rating points per year since the year 1965. Before this date, bridges deteriorated at a rate of 0.023 rating points per year.

2 Fitzpatrick, M. W., D. A. Law, and W. C. Dixon. "The Deterioration of New York State Highway Structures." Report No. FHWA/NY/SR-80/70, Federal Highway Administration, Washington, D.C., December 1980.

Project determines the optimum statewide work program size for bridge maintenance. Rating versus age is plotted. Average cost per structure as a function of condition rating is delineated.

2 Fitzpatrick, M. W., D. A. Law, and W. C. Dixon. "The Deterioration of New York State Highway Structures." Special Report 70, Engineering Research and Development Bureau, New York State Department of Transportation, Albany, New York, 1981.

This is a status report and a forecast of New York State bridge maintenance requirements.

6 Florida Department of Transportation. Field Test Manual for On Site Corrosion Evaluation. Florida Department of Transportation, October 1984

Manual provides information and procedures to be used for on-site evaluation of bridge deck cracking and corrosion.

6 Florida Department of Transportation. "Bridge Management Inventory System (BMIS) Manual."

Manual provides background and the bridge inventory procedures used by the State of Florida.

7 Fontana, J. J., W. Reams, and D. Elling. "Sprayable, Electrically Conductive, Polymer Concrete Coatings." FHWA/RD-85/102, FHWA, Washington, D.C., July 1987, 27 pp.

A sprayable, electrically conductive, polymer concrete coating was developed for overhead applications. It uses impressed current cathodic protection for girders, piers, columns, and beams. The system was estimated to cost $1.00 per square foot excluding installation of the anode, spray equipment, air compressor, or scaffolding.

7 Fontana, J. J., W. Reams, and D. Elling. "Conductive Overlay in Conjunction with an Active Cathodic Protection System." FHWA-RD-88-145, FHWA, Washington, D.C., January 1989, 71 pp.

Report describes development of premixed, electrically conductive, polymer concrete overlay applied on a bridge in Virginia. Unit cost including traffic control was $17.79 per square foot.

2 GADOT Georgia Bridge Priority Rating System. George Department of Transportation, Atlanta, Georgia, January 8, 1982.

Georgia's bridge repair/replacement system is discussed.

1 Geikie, R. I, "The Development of Quality Standards and Impace Model for use in Highway Maintenance Management". His Master's Thesis at Mass. Inst. of Tech., Sept. 1991.

Concrete disruption is studied in New Mexico, Colorado, Pennsylvania, and New York.

1 Graber, D. R. "Inspection of the Substructure of the Chesapeake Bay Bridge-Tunnel Above and Below the Waterline." Highway Maintenance Operation and Research, 1990, Transportation Research Record No. 1268, Material Construction and Maintenance, Transportation Research Board, Washington, D.C., 1990, pp. 130-137.

Inspection and in-depth testing of hollow, prestressed piles was conducted. Deterioration curves for remaining steel area, corrosion potential, and chlorides are provided.

4 Graham, J. L., and J. Migletz. "Design Considerations for Two-Lane, Two-Way Work Zone Operations." Report FHWA/RD-83/112, Federal Highway Administration, October 1983.

This report presents the results of operational and accident studies of 36 construction sites employing either two-lane, two-way operations or lane closure traffic control. Project cost information for four TLTWO and ten

lane closure sites was also analyzed. Results of the study were divided into four areas: evaluation of centerline treatments on the two-way roadway segment; design of temporary median crossover roadways; comparison of TLTWO and lane closure operations; and general results. The study of centerline treatments revealed that zones with double yellow centerline only had higher accident rates and the vehicle encroachment rate into opposing lanes is much higher than for any other type of centerline treatment studied. Accident rates with other centerline treatments do not support a requirement for portable concrete barriers in all TLTWO zones. Results of the study of median crossover design revealed lower accident rates and smoother speed transitions for crossovers with a flat diagonal design compared to those with reverse curve design. Comparisons of TLTWO and land closure sites revealed that the lane closure alternative will be more cost effective than TLTWO traffic control unless substantial construction cost reduction could be realized with TLTWO.

7 Guidelines for Developing a Bridge Management Program. Indiana University, Indianapolis, September 1974.

Specifications and commentary are provided for common types of bridge repair.

7 Hagenbuch, J. D. "Protection for Concrete Bridge Decks by Membrane Waterproofing." Highway Research Record No. 254, Highway Research Board, Washington, D.C., 1967.

Report discusses procedures, cost, and effectiveness of membrane waterproofing on concrete bridge decks. Report concludes that this is the most reliable method at a reasonable cost.'

7 "High Pressure Water Pulverizes Bad Concrete." Better Roads, Vol. 55, No. 11, November 1985, pp. 28 & 29.

Article describes far tractor-sized device which uses hydrodemolition to shatter delaminated concrete bridge decks.

2,5 Hudson, S. W., W. J. Wilkes, et al. "Bridge Management Systems." NCHRP Report 300, Transportation Research Board, Washington, D.C., December 1987, 74 pp.

A decision tree is provided which aids in the selection of specific maintenance rehabilitation and replacement methods. This is better than a ranking level method. With this method, trees can be as simple or as complicated as desired. The Transportation Systems Center (TSC), U.S. Department of Transportation, Cambridge, Massachusetts, recommends default deterioration models as listed below.

$C\ (Deck) = (9 - 0.119 \times age) - (2.158 \times 10^{-6} \times ADTAGE)$
$C\ (Super) = (9 - 0.103 \times age) - (1.982 \times 10^{-6})(ADT)$
$C\ (Sub) = (9 - 0.105 \times age) - (2.051 \times 10^{-6})(ADT)$
where: $ADTAGE = ADT \times age \div 10$

These equations were developed using more than 150,000 bridges with an age of 1 to 25 years to discount the healing effects of rehabilitation measures performed after than point. On average, as pointed out in the FHWA BMS demonstration project, bridges deteriorate at approximately 0.1 condition points per year.

2,7 Hughes, R. D., and J. H. Havens. "Construction, Protection, and Maintenance of Concrete Bridge Decks." Report No. 335, Kentucky Department of Highways/Division of Research, August 1972.

This report presents a historical account of deterioration of reinforced concrete bridge decks. Preventive maintenance treatments to both new and in-service decks are discussed.

1 Hutter, Werner, and Donnelly, "Rate of Deterioration of Concrete Bridge Decks in Colorado." Colorado DOH, FHWA-CO-RD-77-6, Denver, Sept, 1977.

Established deterioration of bare concrete decks in various climates as a function of salt usage.

2 Hyman, W. A., and D. J. Hughes. "Computer Model for Life Cycle Cost Analysis of Statewide Bridge Repair and Replacement Needs." Bridge Inspection and Rehabilitation, Transportation Research Record 899, Transportation Research Board, Washington, D.C., 1983, pp. 52-61.

Wisconsin DOT developed a computer simulation model that uses useful life analysis to determine the least cost mix of bridge repair and replacement work for up to 25,000 bridges and up to 20 program periods. The model considers condition, life expectancy, maintenance records, and subjective judgment to input critical maintenance activities and costs. Model supplements information on the structural adequacy and functional obsolescence of structures with life-cycle cost analysis to determine the number of bridges in Wisconsin that will require replacement in specific time periods. The model estimates the number of bridges that will require repairs, calculates the cost of replacement, determines the type of repair work in each period, and forecasts bridge condition.

2 Johnston, D. W., and P. Zia. "Level-of-Service System for Bridge Evaluation." Bridge Maintenance Management, Corrosion Control, Heating, and Deicing Chemicals, Transportation Research Record 968, Transportation Research Board, Washington, D.C., 1984, pp. 1-8.

Acceptable levels of service related to public needs can be established according to functional class of the highway system being carried. Deciding priorities for rehabilitation can be based on the magnitude of the bridge deficiency calculated in a manner that parallels the magnitude of the user cost incurred.

2 Johnston, D. W., and P. Zia. A Level of Service System for Bridge Evaluation. North Carolina State University, Raleigh, North Carolina, August 1983

Inspection data was used to develop concepts. Sufficiency rating does not adequately emphasize traffic, detour length, or level of service. A level of service system has been developed for evaluation and prioritization of bridges on the basis of level of service deficiency.

7 Kato, T., and Y. Goto. "Effect on Water Infiltration of Penetrating Cracks on Deterioration of Bridge Deck Slabs." Second Bridge Engineers Conference Vol. 1, Transportation Research Record No. 950, Transportation Research Board, Washington, D.C., 1984, pp. 202-209.

Laboratory specimens are tested and countermeasures to deterioration are discussed.

6 Knorr, R. E., J. M. Buba, and G. P. Kogut. "Bridge Rehabilitation Programming by Using Infrared Techniques." Transportation Research Record 899, Transportation Research Board, Washington, D.C., 1983, pp. 32-34.

Infrared is useful for relatively rapid evaluation of large numbers of bridge decks for use in programming maintenance. Limitations of the technology are apparent in observing overlayed surfaces because of the distinction between delaminated areas versus debonded, bituminous overlay were not reliable.

5 Koretzky, H. P. The Pennsylvania Bridge Management System Draft Final Report. Pennsylvania Department of Transportation, Harrisburg, Pennsylvania, February 1987.

Report conceptualizes the bridge management system for implementation in Pennsylvania. A system for estimating remaining life of a structure based on SI&A condition ratings is presented.

4 Kruegler, J. M., G. M. Briggs, C. C. McMullen, and G. A. Earnhart. "Cost-Effective Bridge Maintenance Strategies, Volume II: Guidelines and Recommendations." Report FHWA/RD-86/110, Federal Highway Administration, 1986, 211 pp.

This document provides guidelines and recommendations on developing a systematic approach for managers of bridge maintenance. It also includes a summary synthesis on the state of practice of bridge maintenance programs in the United States. The elements of cost-effective strategies for bridge maintenance are defined as: the identification of needs, the selection of strategies, the prioritization of strategies and the implementation of the maintenance program. Guidelines are presented to assist the bridge maintenance manager in: bridge maintenance inspections, strategy selection, estimating cost of maintenance strategies, estimating service life for maintenance activities and prioritization.

7 KRW "Synthesis of Current Bridge Maintenance Practices." FHWA Contract No. DTFH61-84-C-00045, unpublished, KRW, Inc., and Byrd Tallamy MacDonald and Lewis, Burke, Virginia, 1985.

Cost-effective bridge maintenance strategies are discussed. Most information concerns what to repair or how to repair and very little on when to repair.

4 Kulkami, R., et al. "Maintenance Levels-of-Service Guidelines." NCHRP Report No. 223, Transportation Research Board, Washington, D.C., 1980.

This report describes an approach to determine optimum maintenance levels of service for elements of the highway system.

3 Kulkarni, R. B. "Life Cycle Costing of Paved Alaskan Highways." Pavement Management Activities, Transportation Research Record No. 997, Transportation Research Board, Washington, D.C., 1984, pp. 19-27.

Components of the life cycle system include initial cost, cost of routine maintenance, possible of salvage value, and user cost. The optimization subsystem at the end of the life cycle cost analysis considered life cycle cost, rehability constraints, and ranking alternatives. Pavement performance is predicated on future fatigue cracking.

5 LeDoux, F. S., A. S. Levine, and R. N. Kamp. "New York State Department of Transportation Bridge Inspection and Rehabilitation Design Program." Bridge Inspection and Rehabilitation, Transportation Research Record No. 899, Transportation Research Board, Washington, D.C., pp. 35-43.

New York DOT establishes a formalized procedure to make effective rehabilitation/repair decisions.

1 Leslie, W.G and Chamberlin, W.P., "Effects of Concrete Cover Depth and Absorption on Bridge Deck Deterioration". NYSDOT, FHWA/NH/RR-80-75, Albany, Feb 1980.

Presents a review of deck deterioration in New York.

1 Lin, S.H., "Chloride diffusion in a porous concrete slab".

Presents a purely mathematical model for calculating the diffusion of chloride.

6 Madanat, S. M. "Evaluation of Accuracy of Measurement Technologies and Its Impacts on Infrastructure Management." MSCE Thesis, Massachusetts Institute of Technology, Department of Civil Engineering, September 1988.

6,7 Manning, D. G., and F. B. Holt. "Detecting Deterioration in Asphalt-Covered Bridge Decks." Bridge Inspection and Rehabilitation, Transportation Research Record 899, Transportation Research Board, Washington, D.C., 1983, pp. 10-21.

Information on the condition of bridge decks is required to develop a comprehensive maintenance rehabilitation and replacement strategy. Test procedures include chain drag, sonic reflection, ultrasonic transmission, micro-seismic refraction, resistivity, electrical potential, radar, thermography. Of the systems tested, radar and thermography have the greatest potential for development into routine operational procedures. Both are suited to rapid assessment of large numbers of bridge decks. Radar requires further development. Thermography requires better definition of weather conditions for its use. Chain drag identified 13% of delaminated areas with no false results. Independent of weather and inexpensive sonic reflection had very low accuracy. Ultrasonic transmission was impractical. Micro-seismic reflection identified anomalies but interpretation difficult. Resistivity results were not meaningful. Electrical potential useful indication of corrosion activity, does not identify other forms of deterioration. Radar correlation with no deterioration but also many false results. Thermography--excellent correlation of deterioration with no false results. Main disadvantages dependent on weather.

5,7 Manning, D. G., and J. Ryell. "Decision Criteria for the Rehabilitation of Concrete Bridge Decks." Transportation Research Record 762, Transportation Research Board, Washington, D.C., 1980, pp. 1-8.

Bridge-deck rehabilitation is consuming an increasing proportion of the resources of highway agencies. The nature and extent of deterioration are highly variable so that there is neither a single problem nor a single solution. The requirements for a condition survey are described. The performance of concrete overlays, water-proofing membranes, and cathodic protection applied to existing structures is assessed from field studies and

the literature. Decision criteria that can be used to identify the most appropriate method of rehabilitation for any particular structure are given. A systematic approach to bridge deck rehabilitation is presented. The relative merits of rehabilitation methods are as follows. Concrete overlays have the advantage of being a structural component of the deck slab relatively impervious with long life and well suited for badly spalled, deteriorated decks. Its disadvantage is that it is not suitable for decks with complex geometry, decks with moving cracks, and may not stop corrosive action. Waterproofing membrane with bituminous concrete wearing course has the advantage of bridging cracks with small amounts of movement relatively impervious, good riding surface, applicable to any deck geometry. The disadvantages include performance highly variable; will not stop active corrosion, limited life, non-structural component, not suitable for grades greater than 4%. Cathodic protection has the advantages that it stops corrosion, can be used on decks with moving cracks, provides a good riding surface, and can be used with any deck geometry. Disadvantages include presence of wearing course will accelerate deterioration of marginal quality concrete, non-structural component of the deck slab, periodic monitoring of performance, wearing course requires periodic replacement, specialized contractor inspection required, electrical power source required. A decision matrix is provided for selecting a repair method based on criteria. A systematic approach to bridge deck rehabilitation is presented. Performance of overlays and membranes are assessed. Decision criteria can be used to identify the most appropriate method. Factors include location, ADT, geometry, nature of deterioration, extent of deterioration, load carrying capacity, cost, future reconstruction program, and experience. Sound engineering judgment, appreciation of all the factors involved, and a systematic approach are the keys to identifying the most appropriate method.

7 Manning, D. G., and D. H. Bye. "Bridge Deck Rehabilitation Manual, Part II: Contract Preparation." Ontario Ministry of Transportation and Communication, April 1984, Ontario, 21 pp.

The advantages and disadvantages of concrete overlays, waterproofing membranes, and cathodic protection are discussed. A decision matrix for selection of deck rehabilitation methods is presented. These methods include concrete overlays, waterproofing membrane and paving, and cathodic protection.

7 Manson, J. A., R. E. Weyers, P. D. Cady, et al. "Long-Term Rehabilitation of Salt-Contaminated Bridge Decks." NCHRP Report 257, Transportation Research Board, Washington, D.C., April 1983, 32 pp.

An economic model was developed to evaluate the life cycle cost of various alternatives. This model takes into account all costs involved in rehabilitation, the cost of subsequent maintenance, the anticipated service life, and the time value of money. This report covers critical review and experimental work conducted on new methods for the rehabilitation of salt-contaminated bridge decks. Emphasis was given to improving techniques for the impregnation of concrete with methyl methacrylate and to the concept of scarification to remove the top layer of concrete followed by impregnation with a polymer or corrosion inhibitor and overlaying with a low permeability concrete. Exploratory research with the electro-chemical removal of salt was also conducted. The possibility of controlling corrosion by controlling pH or by use of a scavenger for chloride ion or oxygen was considered but promising leads were not found. Methods involving the use of methyl methacrylate were the most cost effective. A factor limiting the useful life of the various repair systems is often not always durability not corrosion resistance. On the basis of all factors considered, treatment with methyl methacrylate is recommended for further evaluation. In particular, the deep, grooving method should be examined. Further evaluation of the soaking or pressure technique would also be valuable. The electro-chemical should receive attention if coupled with polymer impregnation. It would be useful to evaluate the use of an inhibitor, especially calcium nitrate.

1 Markow, M. J., and W. S. Balta. "Optimal Rehabilitation Frequencies for Highway Pavements." Traffic Management in Highway Work Zones and Setting Optimal Maintenance Levels and Rehabilitation Frequencies, Transportation Research Record 1035, Transportation Research Board, Washington, D.C., 1985, pp. 31-43.

Controlled theory structures a problem in terms of a dynamic objective function subject to dynamic constraints. Dynamic control theory is described in this article in a number of examples are given. Several deterioration models for pavements are provided.

1,7 McDaniel, R. S. "Long-Term Evaluation of Selected Bridge Deck Protection Systems." HEEP 12, Interim Report, West Lafayette, Indiana, March 1987, 69 pp.

The report summarizes 7 years of field and laboratory data collected on 14 bridges, 7 constructed with latex-modified concrete and 7 constructed with low slump dense concrete. It was recommended that the latex-modified concrete overlays seemed to be performing better than low slump dense concrete overlays as constructed. The low slump dense concrete had problems with density control.

5 Murray, M. A. "Epoxy Modified Portland Cement Concrete Overlays." Structural Repair Corrosion Damage and Control, American Concrete Institute, SCM-8(85), Detroit, Michigan, 1985, pp. 65-76.

General review of structures and conditions that require an overlay. Types of overlays and construction techniques are reviewed. The author

concludes that polymer concrete systems will provide the lowest cost/benefit ratio in the long run compared with other systems that may provide a lower initial cost. Report identifies 21 selected maintenance and rehabilitation areas and 36 repair standards.

5 Nash, S. C., and D. W. Johnston. "Level of Service Analysis for Bridge Maintenance Activities in North Carolina." FHWA/NC/88-003, North Carolina Department of Transportation, November 1985.

This study deals with the problem of identifying optimal maintenance levels of service for bridge maintenance activities. A systematic, objective methodology and a non-linear optimization program is utilized to structure and analyze a bridge maintenance model. The non-linear program, Algorithm for the Selection of Optimal Policy (ASOP), was modified for use on the NCDOT computer system. The program was applied to bridge maintenance needs and was used to identify optimal levels of service for various amounts of available resources. Results of the study indicate: (1) the methodology is applicable to bridge maintenance activities, (2) ASOP performed consistently, identifying optimal levels of service for a wide range of available resources, and (3) Limitations of the bridge model developed from this methodology are related to available resource data and not the ASOP program or its optimization techniques.

6,7 National Cooperative Highway Research Program. "Durability of Concrete Bridge Decks." NCHRP Synthesis of Highway Practice 57, Transportation Research Board, Washington, D.C., May, 1979.

Topics discussed are: evaluating existing bridge decks; techniques for new construction; techniques for new construction and repair; techniques for repair. Techniques for repair include: concrete removal; patch repairs; injection repairs; chloride removal. Techniques for new construction and repair include: sealing impregnants; polymer overlays; concrete overlays; waterproofing membranes; and cathodic protection. The characteristics of applied in-place membranes are the following: difficult to assure the quality of two component materials; careful field inspection required to control thickness and detect pinholes; application independent of deck geometry; bonding not usually a problem; installation not affected by deck details. Characteristics of preformed membranes: quality of materials controlled under factory conditions; thickness and integrity control at the factory; labor-intensive installation; difficult to install on curved or rough decks; cured sheets may be difficult to bond to substrate, protection layer, and at ends; vulnerable to quality of workmanship at critical locations such as curved expansion joints and deck drains; tends to be more expensive. Merits of bituminous wearing course are the following: provide a smooth riding surface and reduces stress concentrations on the slab. Disadvantages include: adds dead load and is not a structural component; deterioration of the concrete cannot be detected until serious distress has occurred; must be reapplied periodically, typically 5-15 years; bituminous concrete is both permeable and porous, trapping brine on the surface of the membrane; asphalt absorbs solar radiation, increasing the number of frost cycles; asphalt is difficult to compact at curved joints and drains where it is most critical. If linkage of curves through the membrane, water is trapped on the deck and deterioration is likely to be accelerated. Bond of the membrane and the wearing course is difficult because of the different coefficients of expansion.

2,3 O'Connor, D.S., and W. A. Hyman. "Bridge Management Systems." Demonstration Project 71, FHWA-DP-71-01R, Federal Highway Administration, 1989, 197 pp.

This document is an introduction to bridge management systems. It explores the relevant engineering and economic issues and presents an overview of methodologies and concepts in bridge management.

The methods used by various State highway agencies to identify needs and prioritize projects for maintenance, rehabilitation and replacement are reviewed and compared. Included are a level of service concept for defining bridge improvement needs methods for priority ranking of bridge projects, a procedure for determining optimal maintenance strategies, and several approaches to bridge service life prediction and future need projection.
Methods for evaluating the cost and benefits of bridge improvement alternatives considering both life cycle and user costs are presented together with an analytical approach to network level priority optimization. Algorithms for estimating user cost related to functional deficiencies of bridges are suggested. The applicability of an incremental benefit/cost analysis algorithm (INCBEN) developed by the Texas Transportation Institute for priority ranking is discussed. This algorithm compares and ranges bridge improvement alternatives system-wide with the objective of maximizing net benefits.

4 OECD "Bridge Rehabilitation and Strengthening." Organization for Economic Cooperation and Development, Paris, 1983, 103 pp.

Maintenance, repair, and rehabilitation are defined. A service life of 20 years is used for surfaces, waterproofing, rails, bearings, joints, etc., and a service life of 64 years is used for bridge decks, columns, foundations, retaining walls, etc., in Denmark. In other countries, the life span of structural elements is assumed to be between 100 and 150 years. Report discusses various major activities.

7 OECD "Bridge Maintenance." Road Research, Organization for Economic Cooperation and Development, September 1981, 131 pp.

The main conclusions of this report are that the resources available as regards maintenance policy are not sufficient and that there is little technical and economic data available. From the technological and methodological standpoint, there is a need for improving existing maintenance techniques and developing new ones. The need to establish truly rational policies for bridge maintenance has recently become increasingly apparent both as a result of economic preserves and in response to the demands of users for quality traffic service and safety.

5 PADOT "Developing a Bridge Maintenance Information System." Performance Report, Transportation Press Office, Pennsylvania Department of Transportation, Fall 1984.

The bridge management information system (BMIS) interrelates inspection, design, maintenance, rehabilitation, and replacement of bridge projects. It provides a tool for systematically prioritizing projects.

4 Parekh, I. R., D. R. Graber, and A. Hedayati. "A Comprehensive Bridge Posting Policy and Its Economic and Administrative Effects." FHWA/PA-84-010, Pennsylvania Department of Transportation, Harrisburg; U.S. Department of Transportation, Washington, D.C.; October 15, 1984; 112 pp.

A bridge posting policy was developed for Pennsylvania. Average daily truck traffic was defined as a function of kind of highway carried by the facility. Interstate routes carried 33% ADT; U.S. routes carried 10% ADT; and PA routes carried 6% ADT.

4 Parekh, I. R., D. R. Graber, and R. H. Berger. "Bridge Load Posting Policy Pilot Project." FHWA-PA-85-031, Pennsylvania Department of Transportation, Harrisburg; U.S. Department of Transportation, Washington, D.C.; September 30, 1986; 164 pp.

A load posting policy was tested using Pennsylvania data. Truck traffic is only a catalyst to break up a pre-existing delaminated bridge deck. ADT, in itself, does not cause deterioration. Level of overload is defined in gross terms.

4 Pennsylvania Department of Transportation. "The Pennsylvania Bridge Management System." Pennsylvania Department of Transportation, Office of Research and Special Studies, Project 84-28A, February 1987.

Final report of Bridge Management Work Group.

1 Pfeifer, D. W., J. R. Landgren, and A. Zoob. "Protective Systems of New Prestressed and Substructure Concrete." FHWA/RD-86/193, FHWA, Washington, D.C., April 1987, 133 pp.

143 concrete sections were tested in this study. It was found that low water-cement ratios and adequate cover have been official influence in reducing corrosion and chloride penetration. Silane sealers and silica fume pozzolanic admixtures dramatically reduce chloride penetration and stop corrosion initiation. Epoxy-coated reinforcement and epoxy-coated prestressing strands did not corrode. Galvanized reinforcement and bare reinforcement with calcium nitrate corrosion inhibitors developed low levels of corrosion.

1 Pfeifer, D. W. "Steel Corrosion Damage on Vertical Concrete Surfaces." Structural Repair Corrosion Damage and Control, American Concrete Institute, SCM-8(85), Detroit, Michigan, 1985, pp. 117-124.

Causes of corrosion and repair are discussed. The corrosion process test methods and materials are also discussed.

7 Pfeifer, D. W., and W. F. Perenchio. "Coatings, Penetrants and Specialty Concrete Overlays for Concrete Surfaces." Structural Repair Corrosion Damage and Control, American Concrete Institute, SCM-8(85), Detroit, Michigan, 1985, pp. 127-146.

Twelve types of penetrants and coatings are discussed. Test methods are identified. Application specifications are also discussed.

7 Pfeifer, D. W., and W. F. Perenchio. "Cost Effective Protection of Rebars Against Chlorides: Sealers or Overlays?" Structural Repair Corrosion Damage and Control, American Concrete Institute, SCM-8(85), Detroit, Michigan, 1985, pp. 173-177.

The advantages of sealers vs. overlays are discussed.

5 Porter, J. C. "Precepts of the Evaluation of Facilities for Human Use and the Application to Bridge Replacement Priorities." Transportation Research Record 664, Bridge Engineering, Vol. 1, Transportation Research Board, Washington, D.C., pp. 14-21.

A methodology developed around the recognition that facilities subject to evaluation are directly or indirectly intended for human use is applied to a bridge replacement priority process through the use of the sufficiency rating. Author finds traditional method too subjective. Sufficiency can be evaluated in the context of current standards of technology and practice. Sufficiency provides a common denominator.

6,7 Purvis, R. L., and R. H. Berger. "Bridge Joint Maintenance." Public Works, Public Works Journal Corporation, Ridgewood, New Jersey, December 1982-January 1983.

An article in two parts. Part one describes various types of bridge joints and maintenance requirements. Part two describes routine and common joint problems. Joint leakage must be fixed because adverse effects are just as dramatic on the substructure as they are on the deck. Rehabilitation will be useless and preservation impossible if funding is not linked with a commitment to maintenance.

6 Purvis, R. L., and R. H. Berger. "Bridge Joint Maintenance." Bridge Inspection and Rehabilitation, Transportation Research Record 899, Transportation Research Board, Washington, D.C., 1982, pp. 1-10.

The attributes of the ideal deck expansion joint are listed. The opening should be adequate to accommodate movement, the joint should be accessible for inspection and maintenance, the seal should be continuous, the area for debris accumulation should be minimal, the interface bond should not rely solely on adhesive action, materials and anchors should be durable against mechanical wear.

4 Rissel, M. C., D. R. Graber, R. J. Vollmer, and M. H. Rissel. "Levels of Maintenance for Bridges Related to Service Life and Cost." Report FHWA-PA-87-024+84-02, Pennsylvania Department of Transportation, 1987, 100 pp.

This study dealt with recommendations for maintenance activities which should be performed on a bridge during the life of the structure so that the serviceability of the bridge is maintained at the least cost over its lifetime. This included arranging and comparing the levels of maintenance in terms of service life and cost that the priorities of work could be established. Recommendations are made regarding: cost of maintenance activities, longevity of maintenance work and repair procedures, and establishing priorities.

6 Rissel, M. C., D. R. Graber, M. J. Shoemaker, and T. S. Flournoy. "Assessment of Deficiencies and Preservation of Bridge Substructures Below the Waterline." National Cooperative Highway Research Program Report 251, TRR, Washington, D.C., October 1982, 80 pp.

A condition rating scale for substructures is presented based on the urgency of maintenance such that 9 new condition equals no repairs needed. The rating is further modified a second table which adjusts the rating plus or minus up to 2 points for threat to integrity of the structure.

7 Roberts, B., M. B. Scott, and C. F. Scholer. "Minor Maintenance Manual for County Bridges." Report No. H-84-10, Purdue University, Federal Highway Administration, Washington, D.C., August 1984.

This report outlines a routine program of bridge maintenance.

5 Shirole, A. M. "Management of Bridge Maintenance, Repair, and Rehabilitation: A City Perspective." City of Minneapolis, Minnesota.

Bridge management for a major metropolitan city is discussed. Objectives, data base, cost control, and effective managing are discussed.

5 Shirole, A. M. "Management of Bridge Maintenance, Repair, and Rehabilitation--A City Perspective." Bridge Maintenance Management, Corrosion Control, Heating, and Deicing Chemicals, Transportation Research Record 962, Transportation Research Board, Washington, D.C., 1984, pp. 9-12.

The city of Minneapolis has developed a rehabilitation or replacement decision process. A 5-year catho improvement process was developed. Bridges with sufficiency rating between 0 and 80 are screened annually, and possible candidates for rehabilitation/replacement are identified. Bridges that are candidates for rehabilitation are subject to an in-depth investigation by a materials engineer. A decision is then made based on recommendations resulting from the in-depth investigation.

5 Sinha, K. C., et al. "The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 1: The Elements of Indiana Bridge Management System (IBMS)." Report FHWA/IN/JHRP-88/15, Indiana Department of Transportation, 1991, 65 pp.

This is the first of a six-volume final report which presents the findings of a research study that was undertaken to develop a framework for managing bridge maintenance, rehabilitation and replacement activities in the State of Indiana. This volume provides an overview of the entire system with a particular emphasis on the organization and data management aspects of the system.

6 Sinha, K. C., et al. "The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 2: A System for Bridge Structural Condition Assessment." Report FHWA/IN/JHRP-88/15, Indiana Department of Transportation, 1990, 316 pp.

This is the second of a six-volume final report which presents the findings of a research study that was undertaken to develop a framework for managing bridge maintenance, rehabilitation and replacement activities in the State of Indiana. This volume describes the present bridge inspection practices in Indiana and their shortcomings, and documents the development and implementation of a system that can assist bridge inspectors in the assessment of bridge structural conditions. The procedure is based on fuzzy sets mathematics. A computer program is discussed that can be run on a personal computer.

5 Sinha, K. C., et al. "The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 3: Bridge

Traffic Safety Evaluation." Report FHWA/IN/JHRP-88/15, Indiana Department of Transportation, 1990, 126 pp.

This is the third of a six-volume final report which presents the findings of a research study that was undertaken to develop a framework for managing bridge maintenance, rehabilitation and replacement activities in the State of Indiana. This volume presents the findings of the part of the study which dealt with the evaluation of bridge traffic safety. A procedure was developed to determine the bridge traffic safety index on the basis of factors related to bridge, approach roadway and environmental conditions.

4 Sinha, K. C., et al. "The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 4: Cost Analysis." Report FHWA/IN/JHRP-88/15, Indiana Department of Transportation, 1990, 169 pp.

This is the fourth of a six-volume final report which presents the findings of a research study that was undertaken to develop a framework for managing bridge maintenance, rehabilitation and replacement activities in the State of Indiana. This volume presents cost analyses of maintenance, rehabilitation and replacement projects in Indiana. An analysis of timings of bridge improvement projects is discussed. The use of the information in a life cycle cost approach of project evaluation is presented. A computer program was written so that a life cycle cost analysis can be undertaken to select bridge improvement activities.

5 Sinha, K. C., et al. "The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 5: Priority Ranking Method." FHWA/IN/JHRP-88/15, Indiana Department of Transportation, 1990, 106 pp.

This is the fifth of a six-volume final report which presents the findings of a research study that was undertaken to develop a framework for managing bridge maintenance, rehabilitation and replacement activities in the State of Indiana. This volume presents a priority ranking method for bridge project selection, for the Indiana Bridge Management System. This volume also includes the results of a survey and analysis to determine the effectiveness of bridge replacement and rehabilitation projects with respect to bridge structural condition ratings and remaining service lives.

3,5 Sinha, K. C., et al. "The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 6: Performance Analysis and Optimization." Report FHWA/IN/JHRP-88/15, Indiana Department of Transportation, 1990, 88 pp.

This is the sixth of a six-volume final report which presents the findings of a research study that was undertaken to develop a framework for managing

bridge maintenance, rehabilitation and replacement activities in the State of Indiana. This volume presents the results of research on bridge performance analyses and the development of an optimization model for bridge project selection. Also included is a discussion on bridge condition deterioration curves and appropriate performance prediction models.

4 Sprinkel, M. M., R. E. Weyers, and A. R. Sellars. "Rapid Techniques for the Repair and Protection of Bridge Decks." Unpublished paper no. 910383, Transportation Research Board Annual Meeting, January 13, 1991, Washington, D.C., 31 pp.

Based on the life cycle cost analysis, the most cost-effective protection system is penetrating sealers. The most cost-effective patching system is patching with polymer concrete or patching with high, early-strength Portland cement concrete. The most cost-effective replacement system is sight-cast, high, early-strength Portland cement concrete. Service lives and unit costs are provided in period.

4 Sprinkel, M. M. "Thin Polymer Concrete Overlays for Bridge Deck Protection." Second Bridge Engineer Conference - Vol. 1, Transportation Research Record No. 950, Transportation Research Board, Washington, D.C., 1984, pp. 193-201.

Properties of new construction are discussed.

5 Stane, R. A. "Bridge Repair or Renewal." Atchison, Topeka and Santa Fe Railway, Topeka, Kansas.

A computer program is discussed which determines whether a bridge should be repaired or replaced. It also compares the economics of various new structures.

5 Stewart, C. F. "Considerations for Repairing Salt Damaged Bridge Decks." Journal of the American Concrete Institute, Vol. 72, No. 12, American Concrete Institute, Washington, D.C., December 1975.

Increased communication between researchers should be beneficial in narrowing philosophical differences and in providing the decision maker with more effective guidance. The most important factor is the initial cause of the damage and the effect that the restoration will have on this cause.

3 Stewart, C. F. "Bridge Deck Restoration - Methods and Procedures Part I: Repairs." Report No. CA-HY-80-7120-2-72-10, California Department of Transportation, November 1972.

Problems are discussed associated with restoration of deicing salt-damaged decks. It is emphasized that a restoration is a cost/benefit expediency for gaining additional deck service life.

5 Stratfull, R. F. "Half-Cell Potentials and the Corrosion of Steel in Concrete." Corrosion, Concrete, and Quality Control, Highway Research Record No. 433, Highway Research Board, Washington, D.C., 1973, pp. 12-21.

The half-cell potentials of steel embedded in concrete specimens and laboratory tests were periodically measured and related to the visual observation of concrete cracking. It was found that the half-cell potential of steel can only be correlated on the statistical basis to concrete cracking in specific conditions. The half-cell potential of steel does not measure the physical or structural condition of the concrete. The cracking of concrete due to the corrosion of steel is related to many other factors. Electrical potential measurements can indicate active or passive steel conditions. The differences in the electrical half-cell potentials are associated with the solution potential of the steel. In a voltage gradient, the measured half cell may not necessarily reflect the true half-cell potential of the most proximate steel because the volt meter can only measure the highest voltage at that point.

7 Stratfull, R. F., E. C. Noel, and K. Seyoum. "Evaluation of Cathodic Protection Criteria for the Rehabilitation of Bridge Decks." FHWA-RD-88-141, FHWA, Washington, D.C., May 1988, 74 pp.

Deck sections were salvaged from the George Washington Memorial Parkway in the Washington, D.C., area for laboratory evaluation of cathodic protection criteria. Conclusions addressed methods to measure effectiveness of cathodic protection.

5 Stratfull, R. F. "Corrosion Autopsy of a Structurally Unsound Bridge Deck." Corrosion, Concrete, and Quality Control, Highway Research Record No. 433, Highway Research Board, Washington, D.C., 1973, pp. 1-10.

An investigation was performed on a 12-year-old, salt-contaminated, reinforced concrete bridge deck that had to be replaced because of its deteriorated condition. Figure 6 in this report, titled "Distribution of Half-Cell Potentials," relates half-cell potential in volts versus cumulative frequency in percent. Three bridges pointed upon this indicate the difference in the thoughts between a new deck, a deck which needs to be replaced, and a deck where 2% of the deck area needs to be repaired.

7 Swiat, W. J., and J. B. Bushman. "Further Improvements in Cathodic Protection." FHWA-RD-88-267, FHWA, Washington, D.C., April 1989, 205 pp.

Seven cathodic protection systems are discussed: (1) conductive polymer concrete in slots anode system; (2) zinc arch-spray anode system; (3) conductive polymer spray system; (4) raychem's Ferex 100, flexible polymetric material with a latex modified concrete overlay; (5) titanium wire mesh with catalytic, Elgard 210 anode with modified HCR thorotop overlay. The study concluded that E log I test method was the most realistic in determining current requirements. Use of polarization decay o: 100 milivolt method may have resulted in underprotection in most areas oı structures tested.

7 Swiat, W. J., and J. W. Rog. "Further Improvements in Cathodic Protection." FHWA/RD-87/062, FHWA, Washington, D.C., June 1987, 124 pp.

A description from their evaluation and improvements in vision of anode systems considered for the installation phase of this research project are discussed. The first cathodically protected bridge deck was in June 1973 o: the Sly Park Road overcrossing U.S. Route 50 in California. The various systems evaluated include coke asphalt, non-overlay, slotted, conductive polymer mound with concrete overlay, Raychem Ferex 100 with concrete overlay, Eltech Elgard anode with concrete overlay, Porter DAC-85 conductive coating, Zinc metalized coating, spray-applied conductive polymer concrete. These methods were tested on 2 bridge decks--one in a marine environment and one in a northern environment. No conclusions were drawn.

1 Tachau, R.M. and McPherson, R.B., "A Study of New Mexico Bridge Deck Protective Systems". NM SHD, July 1984.

U.S. deck rehab practices were surveyed.

5 Tascione, T., W. R. Hudson, N. H. Burns, and R. Harrison. "Bridge Project Selection for Texas." Report FHWA/TX-88+439-3, Texas State Department of Highways and Public Transportation, November 1987.

The computerized bridge project selection program for Texas is a State and District level closed-loop process for the proper selection of bridge rehabilitation and replacement projects. The process described addresses need for the consistent and effective evaluation of over 47,000 disparate inventoried structures.

4,6,7 Terrel, R. L. "Deterioration, Prevention, and Reconstruction of Bridge Decks." Washington State Department of Transportation, Federal Highway Administration, Washington, D.C., 1982.

The primary objective is to determine methods of field appraisal, current deck protective systems, and solutions to bridge deck deterioration, including techniques and cost.

3 Thuesen, H. G., W. J. Fabrycky, and E. J. Thuesen. Engineering Economy. Prentiss Hall, Inc., Englewood Cliffs, New Jersey, 4th edition, 1971, 490 pp.

Basic economic decision making is discussed. Interest tables are provided in the appendix.

7 Tighe, M. R. "The Show Me State Shows Off Cathodic Protection." Public Works Magazine, Vol. 121, No. 1, January 1990, pp. 70-71.

Missouri has 126 CP systems in place or under way, almost half of all CP applications in the U.S. The Elgard anode is designed to be compatible within its surrounding concrete environment and can sustain the design current discharge for the life of the rehabilitation--25 years or longer.

5 Tracy, R. G. "Priority Assignment for Bridge Deck Repairs." State of Minnesota Department of Transportation, Research and Development Section, St. Paul, Minnesota.

A system is described for integrating traffic use with current deck condition to determine a priority for protection, rehabilitation, or replacement of bridge decks.

5 Tracy, R. G. "Priority Assignment for Bridge Deck Repairs." Maintenance, Economics, Management and Pavements, Transportation Research Record No. 77, Transportation Research Board, Washington, D.C., pp. 50-54.

Paper presents approaches used to assign priorities to bridge decks for protection, rehabilitation, and replacement.

5 TRB "Evaluation Criteria and Priority Setting for State Highway Programs." NCHRP Synthesis of Highway Practice No. 84, Transportation Research Board, Washington, D.C., November 1981.

Report outlines procedures used for establishing highway priorities. These include using the sufficiency ratings, priority planning procedures, highway investment analysis packages, priority programming systems, highway economic evaluation models, pavement management systems, pavement condition measurements, and bridge evaluations. Since bridge failures can be catastrophic, bridges deserve special attention. Current practice includes: develop a list, review and analysis by headquarters committee, prepare recommendations for secretary, and submit to the governor.

5 University of Virginia, Civil Engineering; Virginia Highway and Transportation Research Council; and Virginia Department of Highways and Transportation. "Rehabilitation and Replacement of Bridge Decks on Secondary Highways and Local Roads." National Cooperative Highway Research Program Report 243, Transportation Research Board, Washington, D.C., December 1981, 46 pp.

The table given on page 4 specifies maintenance procedures based on percent areas of deck found to be unsound, with ADT as a second qualifier. Patching, epoxy injection, cathodic protection, waterproofing membranes, and overlays are discussed.

4,7 Van Til, C. J., B. J. Carr, and B. A. Vallerga. "Waterproof Membranes for Protection of Concrete Decks Laboratory Phase." NCHRP Report No. 165, Transportation Research Board, Washington, D.C., 1979.

Benefit-cost ratio analysis for waterproofing membranes is discussed. Service life was assumed for this analysis.

4 Vesikari, E. "Service Life of Concrete Structures with Regard to Corrosion of Reinforcement." Research Report 553, Technical Research Center of Finland, 1988, 53 pp.

Figure 16 provides probability density functions calculated at intervals of 5 years and cumulative probability functions of service life of edge beams with various cover thicknesses and different types of cement (Portland blast furnace). Water-cement ratio is assumed to be 0.4 with the coefficient of variance of 0.1. Curves apply only to edge beams which are exposed to deicing salts. Maximum probability occurs at 0.15 for a cover of 30 mm at 20 years. All other probabilities are less. Fifty mm of cover have a maximum probability of 6% at 45 years.

1,6 Virmani, Y. P. "Technical Summary: Salt Penetration and Corrosion in Prestressed Concrete Members." Materials Performance, Vol. 30, No. 8, National Association of Corrosion Engineers, Houston, August 1991, pp. 62-63.

The study was conducted on the condition of prestressed concrete bridge members located in northern climates and southern areas subject to marine spray. Results indicate that, in northern areas, the primary cause of deterioration is penetration of salt solutions through the concrete cover and anchorage zones. In southern areas, the primary cause of deterioration is marine salt penetrating directly into substructure elements by wave action.

6,7 Weed, R. M. "Evaluation of Several Bridge Deck Protective Systems." Report No. FHWA/NJ-81-003-7783, Federal Highway Administration, Washington, D.C., August 1980.

This report details the installation and evaluation of ten different bridge deck protective systems. Methods of evaluation include an appraisal by construction, maintenance, and research engineers on the ease of installation.

3 Weissmann, J., R. Harrison, N. J. Burns, and W. R. Hudson. "Selecting Rehabilitation and Replacement Bridge Projects." Extending the Life of Bridges, ASTM-STP-1100, American Society of Testing Materials, Philadelphia, 1990, pp. 3-17.

Where networks are concerned, life cycle analysis can be used in determining budgetary levels and the scheduling of activities which will ensure that maximum bridge life is obtained. As part of maximizing bridge life, a procedure was developed for Texas which first determined which bridge projects met FHWA financing criteria and then prioritized those projects according to multi-attribute criteria. It is recommended that life cycle cost techniques be used to first assess the magnitude of rehabilitation needs and then determine whether specific actions to extend bridge life are economically viable.

2 West, H. H., R. M. McClure, E. H. Gannon, H. L. Riad, and B. E. Siverling. "A Nonlinear Deterioration Model for the Estimation of Bridge Design Life." Report FHWA-PA-89-016+86-07, Pennsylvania Department of Transportation, 1989, 137 pp.

A nonlinear deterioration model was developed that expresses bridge condition rating as a function of age using an exponential decay function coupled with a rehabilitation "spike" to provide the sudden increase in rating that accompanies bridge rehabilitation. Several variations of the basic model were considered with the coefficients for each model determined through a nonlinear regression analysis. The model was applied to substructures, superstructures, and decks of steel girder-type, prestressed concrete, and reinforced concrete bridges. For each component of each bridge, three separate ADT ranges were considered. The resulting deterioration models were assessed, limited conclusions were drawn regarding their applicability, and selected versions were applied to the problem of predicting bridge life.

1 West. R.E. and Hine, W.G., Corrosion/85 paper 256, National Association of Corrosion engineers, Houston, 1985, pp 256/1-256/13.

A method is presented which caculates diffusion coefficient from chloride profile data for use in predicting remaining life.

3 Weyers, R. E., P. D. Cady, and R. M. McClure. "Cost-Effective Methodology for the Rehabilitation and Replacement of Bridges." Research Project 81-4, Final Report, Pennsylvania Transportation Institute, Pennsylvania State University, FHWA/PA-84/004, PTI 8324, September 1983, 48 pp.

A cost-effective methodology was developed using models for rehabilitation and replacement which is based on cash flow diagrams. Several examples are worked through. Three replacement alternatives are available: force account rehabilitation plus replacement; contract rehabilitation plus replacement; and immediate replacement. The value management term is then calculated. If positive, structure should be rehabilitated; otherwise, replacement is indicated. Economic models are presented in terms of equivalent uniform annual cost. The true cost of long-term borrowing is generally considered to be about 4% to 6%. However, with inflation, interest rates for highway construction can be as much as 9.4%.

3 Weyers, R. E., P. D. Cady, and R. M. McClure. "Cost-Effective Decision Models for Maintenance, Rehabilitation, and Replacement of Bridges." Second Bridge Engineers Conference Vol. 1, Transportation Research Record No. 950, Transportation Research Board, Washington, D.C., 1984, pp. 28-33.

Cost analysis models are discussed.

7 Weyers, R. E., and R. M. McClure. "A Collection of Attempted Maintenance Force Remedial Bridge Work." FHWA/PA-84/003, Pennsylvania Transportation Institute, Pennsylvania State University, PTI 8315, September 1983, 196 pp.

Preventative and corrective maintenance practices for bridge systems were identified by making an extensive search of technical literature. Thirty-six repair standards and 21 selected maintenance and rehabilitation areas are presented. An excellent how-to book.

7 Weyers, R. E., and R. M. McClure. "A Collection of Attempted Maintenance Force Remedial Bridge Work." Final Report, Research Project 81-4, Pennsylvania Department of Transportation, Harrisburg, Pennsylvania, September 1983.

Preventative and corrective maintenance practices for bridge systems are identified. Thirty-six repair standards in 21 selected maintenance areas are presented. Standards are complete with drawings illustrating construction details.

3,6 Younger, C. L. "Experimental Cost-Effective Reconstruction of Bridge Decks." Report No. FHWA-NJ-82-001, Federal Highway Administration, Washington, D.C., June 1981.

This report presents the results of an evaluation of the initial period of performance of experimental reconstruction systems designed to bring about an economic extension of the life of bridge decks in which salt-contaminated concrete has been left in place.

6. Abbreviations

AASHTO	=	American Association of State Highway and Transportation Officials
ACI	=	American Concrete Institute
ACM	=	Asphaltic Concrete with Membrane
ADT	=	Average Daily Traffic
BMS	=	Bridge Management System
ECR	=	Epoxy Coated Rebar
FHWA	=	Federal Highway Administration
LMC	=	Latex Modified Concrete
NBI	=	National Bridge Inventory
NBIS	=	National Bridge Inspection Standards
NCDOT	=	North Carolina Department of Transportation
NYSDOT	=	New York State Department of Transportation
PADOT	=	Pennsylvania Department of Transportation
RC	=	Reinforced Concrete
SHRP	=	Strategic Highway Research Program
WISCOT	=	Wisconsin Department of Transportation