Development of a Bridge Deck Management System for the Washington State Department of Transportation

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16. ABSTRACT

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.

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DEVELOPMENT OF A BRIDGE DECK MANAGEMENT SYSTEM FOR THE WASHINGTON STATE DEPARTMENT OF TRANSPORTATION

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SUMMARY

BACKGROUND

The deterioration of concrete bridge decks and their maintenance management is a concern to the Washington State Department of Transportation (WSDOT), since deterioration can affect the serviceability of its bridges. Bridge deck deterioration is caused by many environmental and construction factors, but primarily by moisture and the application of de-icing chlorides in the winter, which result in corrosion and expansion of the embedded reinforcing steel. That expansion can deteriorate the concrete internally. Bridge decks are also exposed to moisture and large changes in temperature and are subjected to direct impact and repeated loading by traffic. Freeze-thaw, stress reversals, physical damage and concrete quality also cause deterioration of bridge deck surfaces.

In general, bridge decks owned by WSDOT can be divided into three categories based on their construction. The first group comprises bridge decks that were designed and constructed in accordance with older specifications that did not produce bridge decks with sufficient protection against salt infiltration. Consequently, some of the bridge decks in this category have already developed corrosion-induced deterioration and/or have been contaminated by salt. The second group comprises bridge decks from the first category that have been rehabilitated and protected since the mid-1970s. This second category of bridge decks has been protected primarily by either latex-modified concrete (LMC) overlays or asphalt concrete/membrane (ACM) overlays. The third group includes bridge decks designed and constructed in accordance with current specifications, which offer improved protection against rebar corrosion. This group is primarily protected by epoxy-coated rebar (ECR); however, also included in the latter group are decks that were overlaid when they were constructed. As of April 1986, the number of bridge decks in the first group was 1,681, in the second group, 655, and in the third group, 224 (1).

At present, the first group has attracted the most attention for rehabilitation and/or protection. WSDOT's present policy is to protect these bridge decks with overlays to prevent further salt infiltration to mitigate the continued corrosion of the rebar. The Department has concentrated its efforts on the initial application of protective systems to all bridge decks. It has determined the conditions of the decks through a comprehensive testing program and has prioritized rehabilitation and/or protection of these decks based on factors such as traffic volumes and deck conditions. The WSDOT's bridge deck protective system priority and selection matrix is given in Table 1.

As for decks in the second group, no fully developed management system exists to deal with their reconstruction. Presently, reconstruction of this class mainly consists of removing aged ACM overlays after 10 to 15 years of service, rehabilitating the base deck if corrosion-induced deterioration has continued, and installing an LMC protective overlay. LMC overlay protective systems, on the other hand, are relatively new and have not shown major problems, although cases of their wearing, debonding, and continued underlying rebar corrosion have been documented through WSDOT inspections and WSDOT research (2). However, since under the present WSDOT bridge deck protection program decks in the first group are being protected with overlays at a rate of about 120 bridges a year, the program's efforts will be primarily directed at rehabilitation and reconstruction of overlays by the mid-1990s. Most of the decks in the first group will have received protective overlays in about 10 years. Thus, WSDOT's next concern will be the durability of protective overlays as well as the substrate deterioration of overlaid contaminated decks. Consequently, reconstruction may involve removal and replacement (or rebonding and resurfacing) of the aged overlays and rehabilitation of the underlying decks if rebar corrosion has continued.

The majority of the bridge decks in the third group (i.e., bare decks with ECR) do not pose an immediate problem, since corrosion of rebar should not be a concern. However, some of these decks may also need overlaying in the long run because of wear in the wheelpaths or other types of deck surface distress caused by environmental factors.

Table 1. WSDOT's Bridge Deck Protection System Priority and 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)
		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.

This discussion shows that the maintenance and rehabilitation of protected decks will in turn become a major effort for the Department. On the other hand, limitations in maintenance and rehabilitation funds pose a problem to the Department. Because of this, WSDOT initiated this project to develop a bridge deck management system that will provide a systematic method to predict future bridge deck conditions, that will estimate overlay service lives and life-cycle reconstruction costs, and that will provide guidelines to optimize available funding to provide continued deck overlay service and protection against substrate deterioration.

This report documents development of such a system. The bridge deck management system developed is comprehensive in nature and is the result of experience gained from WSDOT's bridge deck inspection and protection program and research. The system is designed with flexibility, so that as knowledge in the field of bridge deck performance is improved, it can be modified accordingly.

OVERVIEW OF THE BRIDGE DECK MANAGEMENT SYSTEM

The research team decided to pattern the overall structure of the bridge deck management system (BDMS) after WSDOT's pavement management system (PMS) developed by Nelson and LeClerc (3). There were two major reasons for this decision. First, the WSDOT PMS had been implemented and employed effectively by the Department and other highway agencies. Second, the automated data processing system developed for the PMS could be modified and used for the BDMS, thus minimizing the effort required to implement the BDMS.

Figure 1 shows the conceptual flow chart for the BDMS. The BDMS comprises four major elements: (1) inventory of data, (2) interpretation of condition data, (3) optimization at the project level, and (4) network-level programming. These four elements were obtained from WSDOT's PMS. However, they had to be adapted to meet the characteristics inherent in bridge decks.

The first element, inventory of data, is the database for the system. It includes design data, construction history, and traffic data for each bridge deck. It also includes historical condition

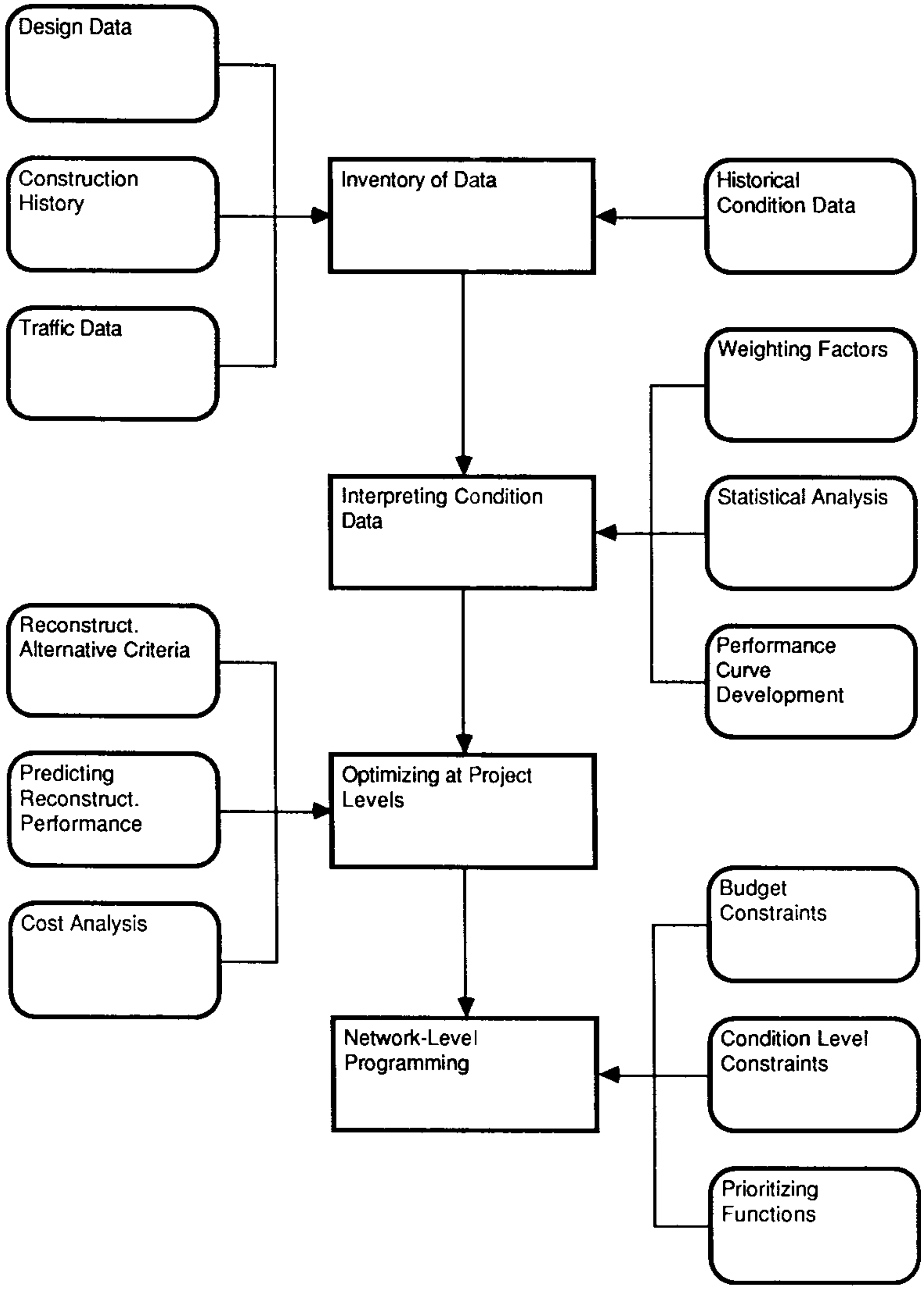


Figure 1. Bridge Deck Management System Conceptual Flow Chart

data. The latter is obtained when the bridge decks are tested from time to time; these data document actual distress and parameters that measure the potential for distress to occur.

The second element in the system, interpretation, gives meaning to the raw condition data in the database. Interpretation is accomplished by using weighting factors for each distress category to determine a combined index representing the overall condition of the bridge decks. Subsequently, a statistical analysis is performed on the indices to find performance trends for the bridge decks.

With the performance trends for each bridge deck, the third element of the BDMS, optimization, determines the optimum date for reconstruction as well as an optimum reconstruction alternative and the associated cost. It also predicts the performance of the reconstructed deck in order to forecast further reconstruction.

The fourth and last element in the system, network-level programming, determines the bridge decks' condition, reconstruction, and the associated costs at the present and in the future for the bridge network. This is done by aggregating the information on the optimized strategies for the individual bridge decks obtained in the third step. Naturally, network-level programing deals with either budget constraints or bridge deck condition level constraints. In either case, the fourth element prioritizes selected bridge decks for reconstruction so that either constraint will be satisfied.

As discussed earlier, the availability of historical bridge deck condition data is a necessity for the application of the BDMS. A chapter in the report discusses acquisition of condition data.

CHAPTER 2
INVENTORYING THE DATA

The main component of the Inventory of Data, or the database, includes the historical condition data representing the magnitude of distresses that affect the serviceability and integrity of the bridge decks. Table 2 categorizes the types of distress for which the BDMS requires measurements. One characteristic of those distresses is that they are accumulative in their effect on deck performance. Below, the nature of those distresses and the methods of their measurement are described.

SPALLS AND DELAMS

Delams (or delamination) are internal cracks in the concrete caused by the expansion of corroding bars. The cracking is generally horizontal, is detected by chain dragging of the bridge deck surface, and is recorded on a grid. However, chain dragging collectively identifies delams and debonding of overlays. Delams can be distinguished from debonded areas with a half-cell corrosion detection device (see below). Spalls are potholes in the bridge deck surface and are the result of delamination cracks propagating and reaching the surface. Spalls are detected by visually surveying the deck and are recorded on a grid.

STRIPPING AND DEBONDING OF OVERLAYS

Debonding is the separation of the overlay from the base deck at the bonded interface while the overlay is still in place. It is detected by chain dragging of the bridge deck surface and is recorded on a grid. On decks overlaid with LMC, debonded areas can be distinguished from delaminated areas by using a half-cell corrosion detection device (2). When more negative half-cell potentials are obtained on the deteriorated areas than on the adjacent sound areas, delaminations are present. When debonding occurs on decks overlaid with ACM, the half-cell potential test cannot be conducted because of the dielectric nature of the membrane. On decks of this nature, debonding can be distinguished from delaminations by coring at a few randomly chosen locations in the areas designated as distressed by chain dragging. The exposed concrete surface under the asphalt and

Table 2. Distress Categories for Historical Condition Data Collection

Distress Categories	Type of Test
Spalls & Delams caused by bar corrosion	Visual survey and Chain dragging (1,2)
Stripping and Debonding of Overlays	Visual survey, Chain dragging, & Coring (1,2)
Patching	Visual survey (2)
Scaling of Concrete	Visual survey (2)
Wear & Rutting	Straight edge (3)
Surface Cracking	Visual survey (2)

(1) Delams are distinguished from debonding by using half-cell test

(2) Recorded on a grid (preferably 5' x 5' grid)

(3) Average rut depth along the bridge

membrane is then sounded with a hammer to verify delamination or debonding. Four-inch diameter cores are suitable for this purpose. The ratio of core locations that verify debonding to those that verify delaminations may represent the ratio of the bridge deck debonded areas to the bridge deck delaminated areas. If coring is not feasible, then that ratio may be roughly found from data on the chloride content of the base deck. In this case, the ratio of debonded areas to the total distressed areas may be assumed equal to the ratio of the number of concrete samples with a chloride content less than 2 lb/c.y. to the total number of chloride samples, when the latter ratio is more than 0.5. The evidence so far indicates that these ratios may be valid, but further refinement will be necessary as new field data are collected.

Debonded overlays eventually will strip off the deck under repeated traffic impact. "Stripping" means the loss of the overlay, which causes potholes on the deck. Stripped areas are visually detected and are recorded on a grid.

PATCHING

"Patching" here means temporary patching. Patches are detected by a visual survey and are recorded on a grid.

CONCRETE SCALING

Freeze/thaw action (especially in the presence of chloride de-icers) causes mortar to scale on the concrete surface. Scaled areas are detected by a visual survey and recorded on a grid. Additionally, the depth of scaling is measured with a scale at various locations and is averaged.

WEAR AND RUTTING

Wear and rutting of the surface are caused by traffic action in the wheeltracks. The depth of the rutting is measured every 20 feet along the bridge with a straight edge and is averaged.

SURFACE CRACKING

Surface cracking is quantified on a grid. Every grid square is visually inspected and designated either cracked or uncracked. The number of cracked grid squares determines the total cracked area of the surface.

CHAPTER 3
INTERPRETING THE CONDITION DATA

CONDITION INDEX

A systematic approach to determining an average combined condition index is presented in Table 3 for LMC overlaid bridge decks, in Table 4 for ACM overlaid bridge decks, and in Table 5 for bare decks containing epoxy-coated rebar. In this approach, weighting factors (F_i) are first determined for each distress category. The worse the effects of a distress category are on bridge integrity and serviceability, the higher is the magnitude of the associated weighting factor. The weighting factors introduced in Tables 3, 4 and 5 are preliminary and may be modified in the future. The BDMS is flexible enough to accept changes to the weighting factors as knowledge about bridge deck deterioration is improved.

By applying the weighting factors to the area of the bridge deck affected by each distress category (A_i), deck deficiency points (D) are calculated systematically. The deck condition index (I) is then equal to 100 minus D.

CONDITION CATEGORIES

The deck condition index needs to be categorized in order to provide significance for the indices. Table 6 presents a categorization of the deck condition index. According to Table 6, indices between 70 and 40 represent moderate deterioration. Ideally, when the index is 70, the deck should be rehabilitated and when it is 40, the deck must be rehabilitated. These two boundaries were based on the correlation between the deck condition index and the magnitude of each distress category, as shown in Table 7. Here again the BDMS is flexible enough to accept different magnitudes of condition index corresponding to "should rehabilitate" and "must rehabilitate." For example, the nature of a bridge's structure or the importance of the route may dictate different "should" and "must" levels.

Table 3. A Systematic Approach to Determine a Combined Condition Index for Concrete Overlaid Bridge Decks

Type of Deck	CONCRETE OVERLAID					
Type of Distress	Spalls & Delams	Overlay Stripping & Debonding	Patching	Scaling	Wear & Rutting	Cracking
Further Classification of Distress				Depth (in.) d	Depth (in.) d	
Weighting Factor, Fi	6	4	4	5x (d)	2.5x (d)	1/10
Deck Deficiency Points, $D = \Sigma F_i A_i$ Where A_i is the affected area (% of deck area) (1)						
Deck Condition Index, $I = 100 - D$ and $I > 0$						

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

Table 4. A Systematic Approach to Determine a Combined Condition Index for Asphalt Concrete/Membrane Overlaid Bridge Decks

Type of Deck	ASPHALT CONCRETE/MEMBRANE OVERLAID				
Type of Distress	Spalls & Delams	Overlay Stripping & Debonding	Patching	Wear & Rutting	Cracking
Further Classification of Distress				Depth (in.) d	
Weighting Factor, Fi	6	4	4	2.5x (d)	1/10
Deck Deficiency Points, $D = \sum F_i A_i$ Where Ai is the affected area (% of deck area) (1)					
Deck Condition Index, $I = 100 - D$ and $I > 0$					

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

Table 5. A Systematic Approach to Determine a Combined Condition Index for Bare Decks Containing Epoxy-Coated Rebar

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

Table 6. Bridge Deck Condition Categories Based on Condition Index

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

Table 7. Correlation between Deck Condition Indices Corresponding to the Boundaries of Moderate Deterioration and Extent of Various Distresses

Type of Distress	Extent of distress corresponding to: (1)	
	I = 70, "should"	
	I = 40, "must"	
Delams	5%	
	10%	
Overlay Debonding	7.5%	
	15%	
Patching	7.5%	
	15%	
Scaling	6/(d)%	(2)
	12/(d)%	(2)
Rutting	~ 0.5 in.	(3)
	~ 1.0 in.	(3)

(1) Based on percent of deck area

(2) "d" is the depth of scaling in inches

(3) Determined based on the depth of rutting

PERFORMANCE TREND ESTABLISHMENT

After the historical condition data are translated into historical condition indices for each bridge deck, BDMS performs a regression analysis to establish performance trends for each site. BDMS uses least squares non-linear regression for this purpose. The relation between the condition index (I) and age in years (A) for any newly constructed or reconstructed deck can be expressed as

$$I = 100 - m\,A^{b}$$

The boundary condition in this relation is satisfied, since when A is equal to zero (i.e, the date of construction or reconstruction) I will be equal to 100. The value of m (coefficient) and the value of b (exponent) determine the shape of the I-A curve. This curve is linear when b is equal to 1. The curve becomes concave for values of b less than 1 and it becomes convex for the values of b larger than 1 (see Figure 2). The value of m determines the slope of the curve. Larger values of m indicate steeper curves.

The values of m and b are based on a deck's historical condition indices, to find the best fit I-A curve. First, BDMS uses the following relation to find the value of m while it assumes a value for b:

$$m = \frac{\sum_{i=1}^{N} A_i^{b}\,(100-I_i)}{\sum_{i=1}^{N} A_i^{2b}} \tag{1}$$

Formula 1 is derived from the characteristics of the least-squares curve, or

$$\frac{\partial \sum_{i=1}^{N} (I_{est\text{-}i} - I_i)^2}{\partial m} = 0$$

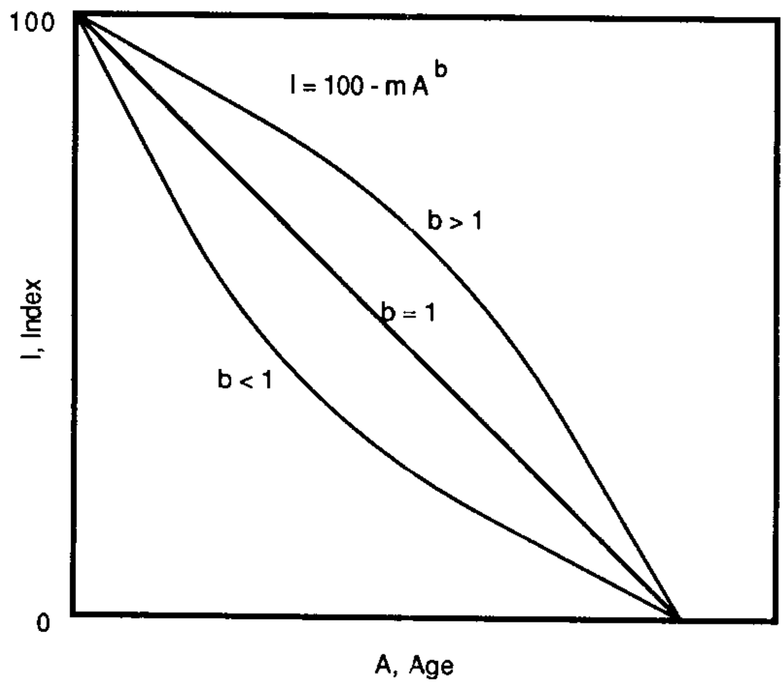


Figure 2. Examples of I-A Curve Shapes Based on the Value of Exponent b

Next, BDMS finds the value of r^2, or coefficient of determination, from the following relation:

$$r^2 = 1 - \frac{\sum_{i=1}^{N} (I_{est-i} - I_i)^2}{\sum_{i=1}^{N} (\bar{I} - I_i)^2} \qquad (2)$$

in which I_{est-i} is the estimated condition index for those values of m and b and $\bar{I}$ is the average of I_i's. BDMS continues this process and substitutes a number of exponents (b) and finds their corresponding coefficient (m) and coefficient of determination r^2. The curve that fits the best is the one with the highest r^2 value. The value of r^2 can range from 1 to 0. When r^2 is equal to 1 there is a perfect correlation. The value of r^2 should not be less than a minimum acceptable (minimum r^2 of 0.75 is suggested) in order to produce a reasonably good curve. Otherwise, a typical curve is fitted through the first and last points. A typical curve is also fitted when the project being considered does not have at least three indices. Typical equations can be assigned for the following factors:

- geographical area
- type of overlay
- traffic level
- chloride contamination of the base deck
- level of rehabilitation of the base deck

Those typical curves can only be generated some time after data acquisition on bridge decks.

Figure 3 is an example of a bridge deck performance curve and its interaction with "should" and "must" indices. As shown in Figure 3, those indices determine the ideal time frame for reconstruction. That time frame changes as the value of "should" and "must" indices change.

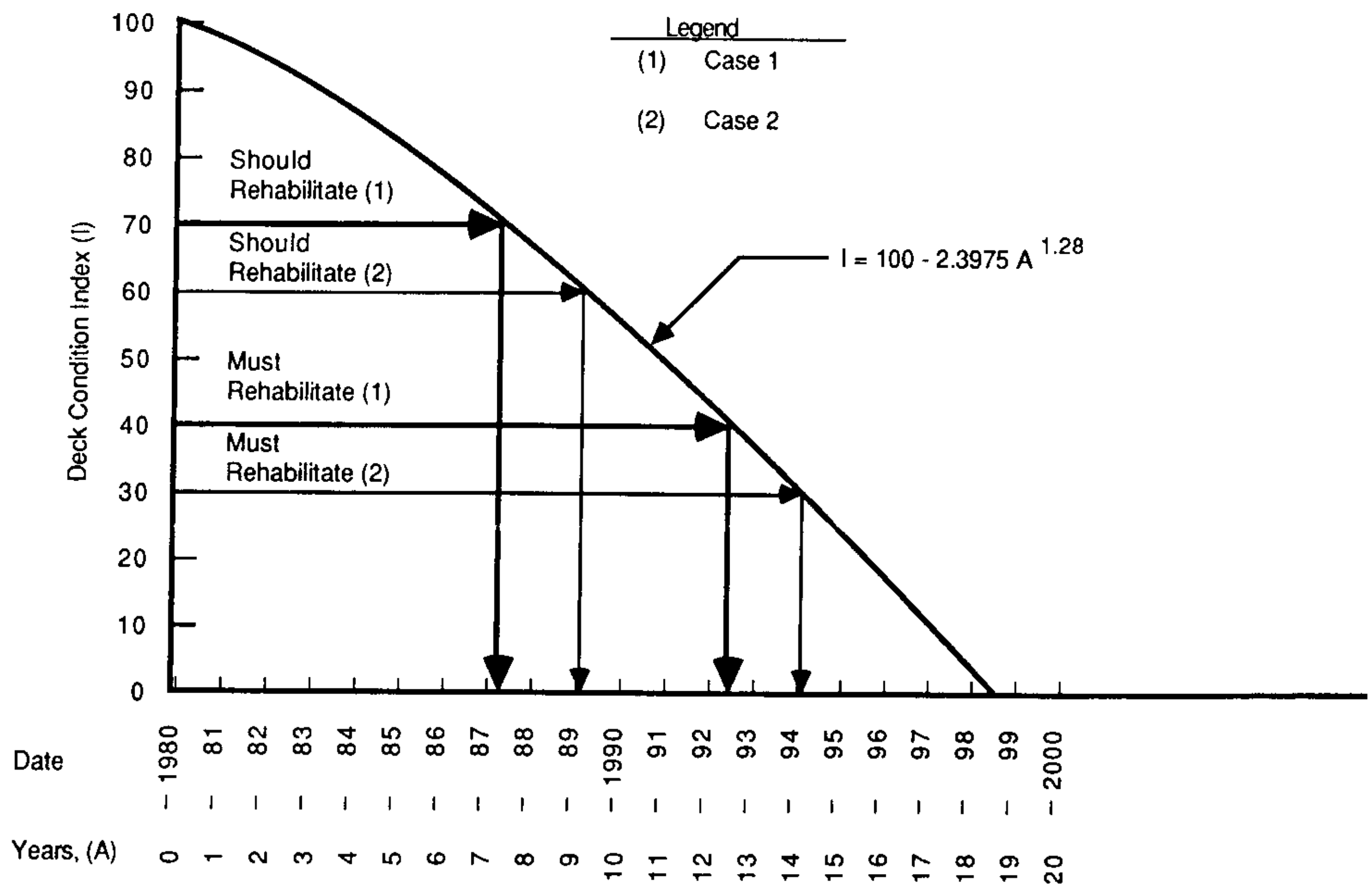


Figure 3. Example of Performance Curve and Its Interaction with "Should" and "Must" Levels

CHAPTER 4
OPTIMIZING AT PROJECT LEVEL

After the ideal reconstruction time frame is known for a bridge deck (see Figure 3), the BDMS will

1. determine the type of reconstruction for that project,
2. predict the performance of the reconstructed deck and the performance of any further reconstruction, and
3. determine the optimum date for the reconstruction (or reconstructions) for the most cost effectiveness, as well as the associated cost.

TYPE OF RECONSTRUCTION

In order to define the type of reconstruction, protected decks are classified as shown in Figure 4. The reconstruction of overlay protected decks includes rehabilitation and/or re-protection, depending on their classification. Presently, procedures for the reconstruction of overlaid decks are not fully defined. Below are suggested procedures for the reconstruction of overlaid decks.

On decks protected with ACM, the deteriorated ACM should be removed and replaced with new ACM. Current methods of removing ACM (milling) preclude the use of ACM for reconstruction. NCHRP Report 297 (5) suggests a procedure for solving this problem. However, WSDOT has decks that were protected with ACM but that would qualify for LMC according to the present WSDOT protective system selection criteria. For those decks, the ACM should be removed and replaced with LMC.

On decks protected with LMC, the worn LMC should be resurfaced by scarification and the application of a thin layer of latex-modified mortar (LMM) (or other systems such as ultra-thin polymer concrete overlays) in order to reduce the accumulation of dead loads. However, if a considerable amount of LMC is debonded and the debonding progresses continuously, that LMC may need to be removed and replaced with a new LMC, regardless of the possibility that the

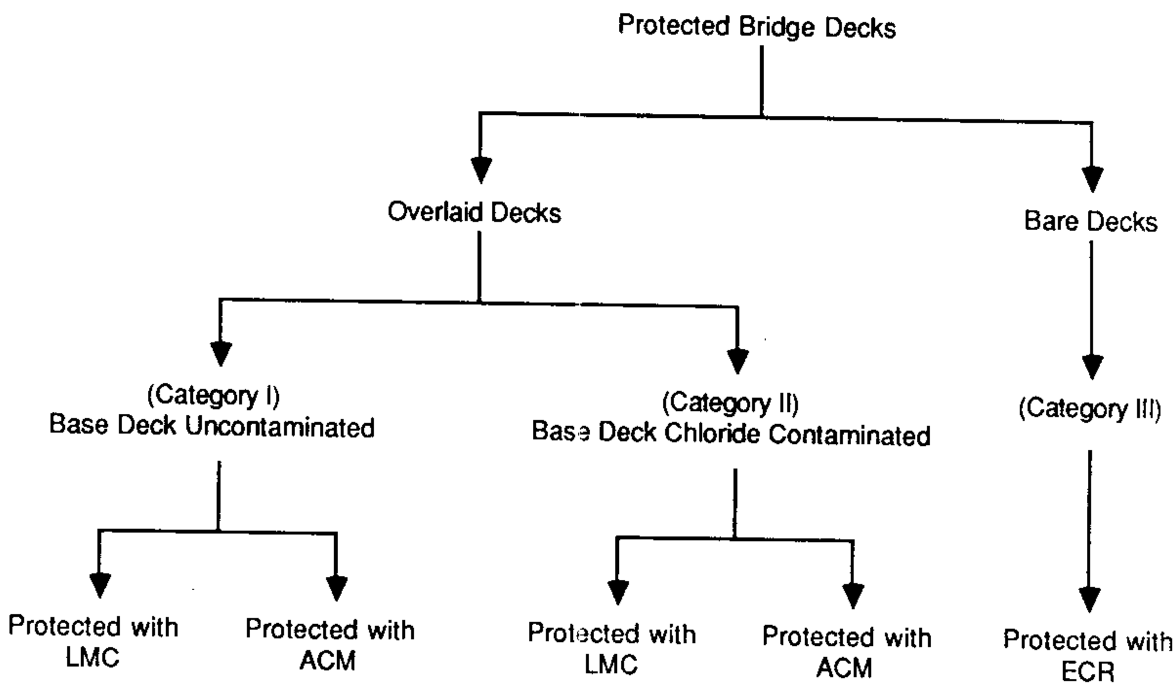


Figure 4. Classification of Protected Bridge Decks for Reconstruction Strategies

Table 8. Suggested Criteria for Total Removing and Replacing Latex-modified Concrete Overlay

Remove & replace LMC, if debonding & stripping exceed 1% of deck area after 12 years or less of service, or if it exceeds:								
Percent:	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
After Years:	13	14	15	16	17	18	19	20
and: if average growth of debonding & stripping between the last survey & the survey before that exceeds 0.5% of deck area per year								

debonding may be rehabilitated. If that overlay stays in place, the same type of bond problem may continue after the rehabilitation. A criterion such as the one given in Table 8 may be used by the BDMS to predict the type of re-protection.

Rehabilitation during reconstruction may involve rebonding of the debonded LMC. This may be done with a polymer injection, or debonded areas may be removed and patched. The success of polymer injection depends to a great degree on the viscosity of the resin. Extremely low-viscosity resins may not be retained in the cracks and instead may be absorbed by the pores in the concrete. If the base deck is salt-contaminated, then rehabilitation may also involve removal of the deteriorated concrete around the rebar and patching. The latter type of rehabilitation can apply to both LMC and ACM overlaid decks.

Reconstruction of bare decks with ECR should involve only overlaying of their worn surfaces with either conventional Portland cement concrete (PCC) (after scarification) or ACM. The level of ADT and the nature of the route (i.e., interstate, non-interstate), according to the present WSDOT protective system selection criteria, will determine the type of overlay.

PERFORMANCE OF RECONSTRUCTED DECKS

The BDMS bases its prediction of the performance of the deck after proposed reconstruction on the historical condition data already available for that deck. This process involves adapting the historical condition data so that the adapted data represent the reconstructed deck. Once the adapted historical condition data are provided, a regression analysis, as described previously, will establish the performance trend. To accomplish this, bridge decks are again categorized according to Figure 4. Below are procedures for adapting historical condition data that will produce a typical performance for the reconstruction. These procedures account for certain characteristics existent in each site that affect performance.

Category I — Overlaid Decks, Base Deck Uncontaminated

After reconstruction, Category I decks are subject to all the types of distress listed in Table 2 except spalls and delams caused by bar corrosion.

Subcategory I-a. This category includes decks covered by LMC which should be resurfaced with LMM.

- **Stripping and debonding of the overlay**

  Add to the debonding values obtained for the existing construction the typical values determined from the suggested relation in Table 9. This is because there will be two bonded interfaces, the original one and the new one. The original interface will behave in the same manner, while typical performance may be expected from the new interface.

- **Patching**

  Do not include patching for the reconstructed deck, since it is already included in the adapted values of other distresses.

- **Scaling of concrete**

  Use the values obtained for the existing construction, since the distress primarily depends on environmental factors.

- **Wear and rutting**

  Use the values obtained for the existing construction, since the distress primarily depends on environmental factors.

- **Surface cracking**

  Multiply the values obtained for the existing construction by the following crack factor (CF):

  $$CF = \frac{25\%}{C\%} \qquad (3)$$

  where C is the percentage of cracking of the existing construction that corresponds to five years of service. C may be found using a linear relation.

Table 9. Typical Values of Stripping and Debonding (D) for Concrete Overlays

$$D = (a)\ 0.313 \times 10^{-4}\ A^4$$

where $a = 0.75$ for ADT < 5,000

$a = 1$ for 5,000 < ADT < 15,000

$a = 1.25$ ADT > 15,000

and A is the Service Period in Years

Table 10. Typical Values of Stripping and Debonding (D) for Asphalt Concrete/Membrane Overlays

$$D = (a)\ 2.963 \times 10^{-3}\ A^3$$

where $a = 0.75$ for ADT < 5,000

$a = 1$ for 5,000 < ADT < 15,000

$a = 1.25$ for ADT > 15,000

and A is the Service Period in Years

Subcategory I-b. This category includes decks to be overlaid with LMC after the existing LMC has been removed.

- **Stripping and debonding of the overlay**

  Determine typical values using the relation in Table 9.

- **Other distresses**

  Adaptation of the remaining distresses follows the procedure used for subcategory I-a bridge decks.

Subcategory I-c. This category includes decks to be overlaid with LMC after the existing ACM has been removed.

- **Stripping and debonding of the overlay**

  Determine typical values using the relation in Table 9.

- **Patching**

  Do not include patching, since it is included in the values of other distresses.

- **Scaling of concrete**

  Find the values of the distress from the average performance of LMC overlays that represent the same climatic conditions.

- **Wear and rutting**

  Multiply the values of wear depth obtained for the existing ACM by 1/2 to represent wear for the concrete surface.

- **Surface Cracking**

  Find the values of the distress from the average performance of LMC overlays that represent the same structural and climatic conditions.

Subcategory I-d. This subcategory includes decks to be overlaid with ACM after their existing ACM has been removed.

- **Stripping and debonding of the overlay**

  Determine typical values using the suggested relation in Table 10.

- **Patching**

  Do not include patching, since it is included in the values of other distresses.

- **Wear and rutting**

  Use the values obtained for the existing ACM, since the distress depends primarily on environmental conditions.

- **Surface cracking**

  Use the cracking values obtained for the existing ACM, since the distress depends primarily on environmental conditions.

Category II. Overlaid Decks, Base Deck Chloride Contaminated

After reconstruction, Category II decks are subject to all the types of distress listed in Table 2.

Subcategory II-a. This comprises decks protected by LMC and to be resurfaced with LMM.

- **Spalls and delams**

  Use the values obtained for the existing construction after multiplying them by the following spall and delam factor (SF) to incorporate the effects of a typical amount of surface cracking on the distress.

  $$SF = \frac{25\%}{C\%} \qquad (4)$$

  where C is the percentage of cracking of the existing construction that corresponds to five years of service. C may be found using a linear relation. If the value of C exceeds 50 percent, use C = 50 percent.

- **Other distresses**

  Adaptation of the remaining distresses follows the same procedure used for Subcategory I-a bridge decks.

Subcategory II-b. This includes decks to be overlaid with LMC after the existing LMC has been removed.

- **Spalls and delams**

  Adaptation of the distress follows the procedure used for Subcategory II-a bridge decks.

- **Other distresses**

  Adaptation of the remaining distresses follows the procedure used for Subcategory I-b bridge decks.

Subcategory II-c. This category comprises decks to be overlaid with LMC after their existing ACM has been removed.

- **Spalls and delams**

  Adapt the distress values by multiplying them by 3/4 to account for the relative effectiveness of typical LMC over ACM in retarding the progression of continuing corrosion-induced deterioration.

- **Other distresses**

  Adaptation of the remaining distresses follows the procedure used for Subcategory I-c bridge decks.

Subcategory II-d. This includes decks to be overlaid with ACM after their existing ACM has been removed.

- **Spalls and delams**

  Use the distress obtained for the existing construction.

- **Other distresses**

  Adaptation of the remaining distresses follows the procedure used for Subcategory I-d bridge decks.

Subcategory II-e. This includes existing decks protected either with LMC or ACM that is to be totally removed and replaced with a deck containing ECR. The BDMS evaluates the alternative of total removal and replacement of the deck for every deck in Category II so that a more cost-effective strategy may be selected. After reconstruction, Category II-e decks are subject to all the types of distress listed in Table 2, except spalls and delams and stripping and debonding of overlays.

- **Patching**

  Patching is included in the adapted values of the types of distress listed in the following.

- **Scaling of concrete**

  Use the values obtained for the existing construction if it is LMC. If the existing construction is ACM, find the values of the distress from the average performance of bare decks with ECR (or LMC overlays) that represent the same climatic conditions.

- **Wear and rutting**

  Use the values obtained for the existing construction if it is LMC. If the existing construction is ACM, multiply the values of wear depth obtained for the ACM by 1/2 to represent wear for the concrete surface.

- **Surface cracking**

  Find the values of the distress from the average performance of bare decks containing ECR (or conventional bare decks) that represent the same structural and climatic conditions.

Category III: Bare Decks with ECR

After reconstruction, Category III bridges are subject to all the types of distresses listed in Table 2, except spalls and delams.

Subcategory III-a. This comprises bare decks to be overlaid with PCC.

- **Stripping and debonding of the overlay**

  Determine typical values using the relation in Table 9.

- **Patching**

  Patching is included in the values of other types of distress.

- **Scaling of concrete**

  Use the values obtained for the existing construction.

- **Wear and rutting**

  Use the values obtained for the existing construction.

- **Surface cracking**

  Use the values obtained for the existing construction, since plastic shrinkage cracking is not a concern with a conventional concrete overlay because of its higher water/cement ratio.

Subcategory III-b. This includes bare decks to be overlaid with ACM.

- **Stripping and debonding of the overlay**

  Determine typical values using the relation in Table 10.

- **Patching**

  Patching is included in the values of other types of distress.

- **Wear and rutting**

  Multiply the values of wear depth obtained for the existing concrete surface by 2 to represent wear for the asphalt concrete surface.

- **Surface cracking**

  Find the values of the distress from average performance of ACM overlays that represent the same climatic conditions.

OPTIMUM TIME FOR RECONSTRUCTION

After the type of reconstruction for a bridge deck is known, the BDMS determines the optimum and most cost effective date for that reconstruction (or reconstructions). This is achieved by an economic analysis of all the strategies possible within a set time frame called the "consideration period." The consideration period begins with the present time and extends for 20 years, but it can be limited by the remaining life of the superstructure or substructure. The reconstruction strategies possible are those that do not occur before "should" conditions have been reached and those that maintain a minimum level of "must" conditions throughout the consideration period. All costs associated with each reconstruction strategy, including maintenance costs, are then computed in current dollars and totaled for comparison with other strategies. The most cost-effective strategy is the one with the least total cost. In order to compute a cost in present dollars, that cost item (expressed in today's value) is discounted to present worth by multiplying it by the following discount factor:

$$DF = \frac{1}{(1 + EI)^N} \tag{5}$$

where

DF = Discount Factor

EI = Effective Interest Rate = Interest rate minus inflation rate

N = Number of each consecutive years in the Consideration Period

Cost Categories

Major reconstruction cost items and maintenance cost items that involve bridge decks are categorized and presented in Table 11. Included in Table 11 is also the salvage value. Salvage value conveys a meaning of "worth" (or negative cost) at the end of the consideration period and applies to protective overlays installed or to a new deck if the old deck was removed and replaced. Certain cost items in Table 11 are time dependent even in the absence of inflation. Those cost items include rehabilitation cost and maintenance cost. This is because they depend on the amount of deterioration, which in turn is time dependent. The amount of salvage value, on the other hand, depends on the date of the last reconstruction. The procedures for systematically estimating rehabilitation cost, maintenance cost, and salvage value will be presented later.

Examples of Reconstruction Strategies

Figure 5 is an example of the reconstruction and maintenance scenarios possible within the consideration period for Category I bridge decks, uncontaminated overlaid decks. Note that only subcategories I-a and I-d are included in Figure 5. Also illustrated in Figure 5 is the performance curve established for the deck based on the historical condition data, as well as the performance curve predicted for the reconstructed deck based on the adaptation of the historical condition data.

Table 11. Cost Categories for Reconstruction of Bridge Decks

Reconstruction Costs, Bare Decks with ECR

- Surface Preparation (Scarifying, Sand Blasting)
- Protection (PCC, ACM)
- Traffic Controi

Reconstruction Costs, Overlaid Decks

- Surface Preparation (Scarifying LMC, Removing LMC, Removing ACM)
- Rehabilitation (Removal of Delaminated Concrete and Patching
- Rehabilitaiton (Rebonding of LMC, removing of debonded concrete and patching)
- Protection (LMM, LMC, ACM)
- Traffic Control

Maintenance Costs

- Patching of Spalls Including Traffic Control
- Patching of Stripped Overlays Including Traffic Control

Salvage Value (End of Construction Period)

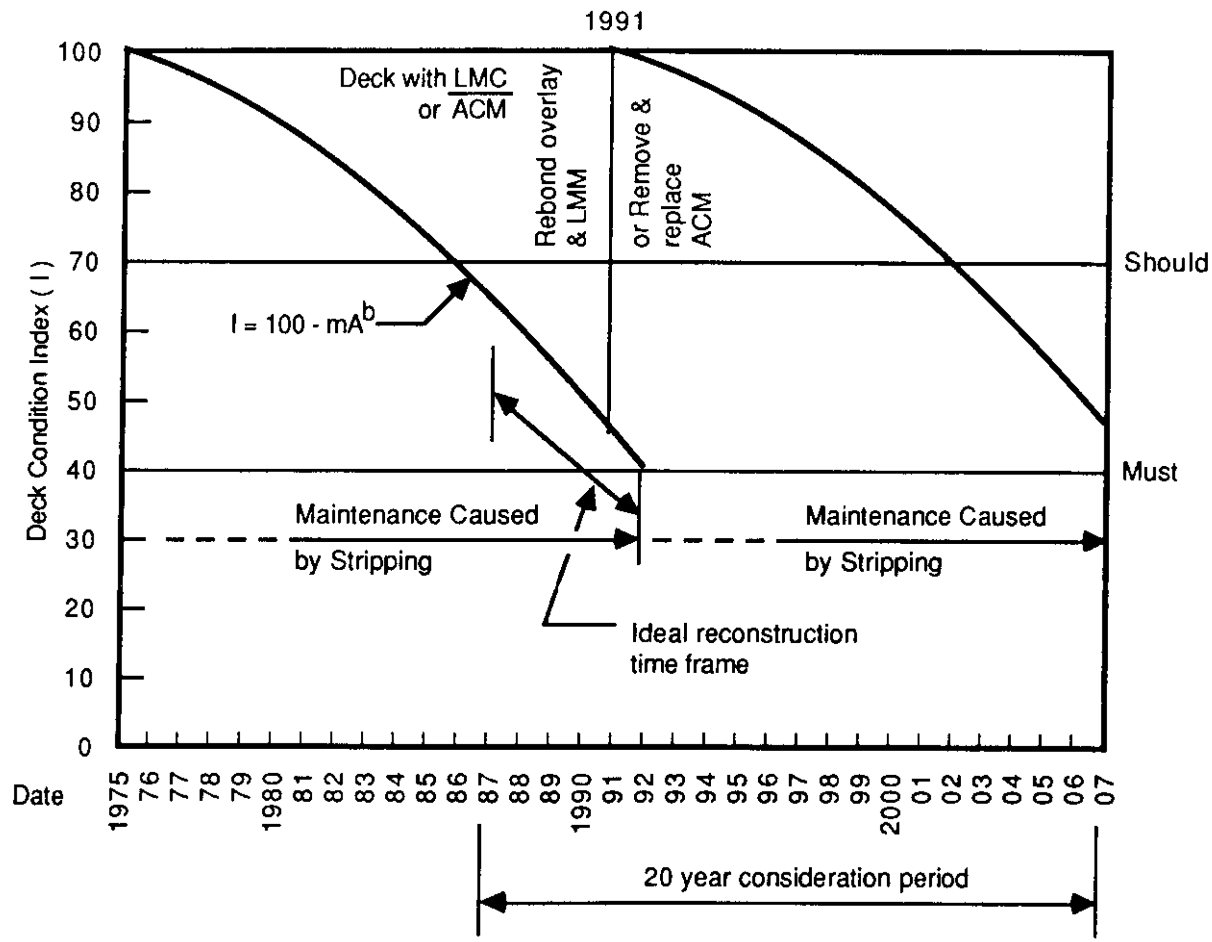


Figure 5. Reconstruction Strategies, Uncontaminated Overlaid Decks

The reconstruction date (1991) is within the ideal reconstruction time frame, which begins with the year corresponding to the "should" condition or with the year next to the present year (1988), whichever comes later, and ends with the year corresponding to the "must" condition (1992). According to Figure 5, there won't be a need for the second cycle of reconstruction, since the condition of the reconstructed deck will not reach the "must" condition before the end of the consideration period. To select the optimum strategy, the BDMS assigns the reconstruction to all the possible application dates within the ideal reconstruction time frame and subsequently estimates the total present worth involved with each strategy. The optimum strategy, as discussed earlier, is the one with the least total present worth.

Figure 6 is an example of the reconstruction and maintenance scenarios possible within the consideration period for Category II bridge decks, chloride contaminated overlaid decks. Similar to Figure 5, only subcategories II-a and II-d are included in Figure 6. Unlike Figure 5, the example in Figure 6 involves two cycles of reconstruction, since the reconstructed deck will reach the "must" condition before the end of the consideration period. Figure 7 presents an application of the systematic procedure that the BDMS follows to identify the optimum reconstruction strategy from the "valid" strategies. In this procedure, all combinations of reconstructions are assigned all possible dates for application within the ideal reconstruction time frames and tested for "validity" within the consideration period. The "valid" strategies are the ones that would not allow the condition of the bridge deck reach or fall below the "must" condition at the end of consideration period. The optimum strategy is then selected from the valid strategies following a cost analysis.

Figure 8 is an example of a reconstruction and maintenance scenario for Category II bridge decks when the reconstruction alternative is total removal of the existing deck and replacement with a deck that contains ECR (Subcategory II-e). This alternative is based on deferred reconstruction. The time of reconstruction is when the condition of the existing construction reaches a level beyond which the feasibility of maintenance is questionable. This condition, called the "must replace deck" condition, is set at I = 20 in Figure 8. As discussed earlier, the cost representing this

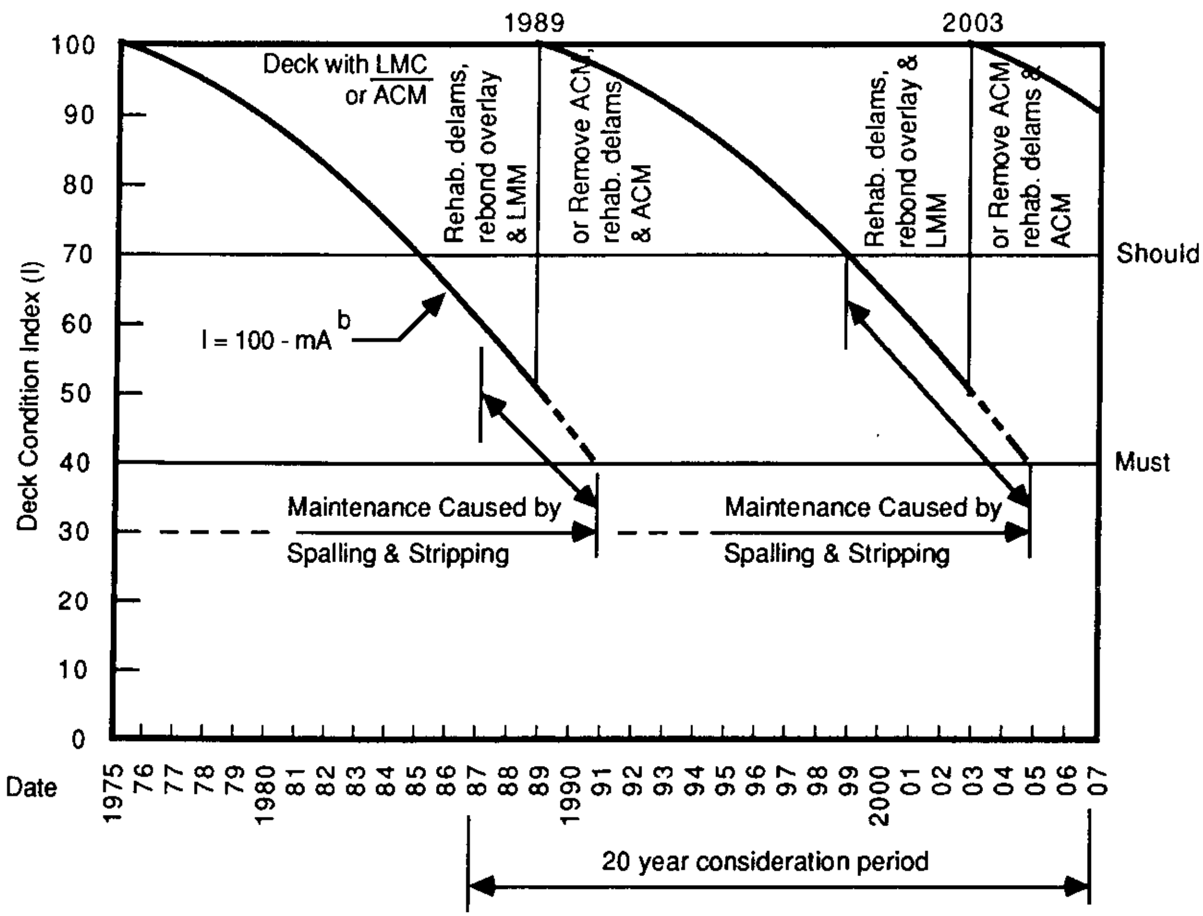
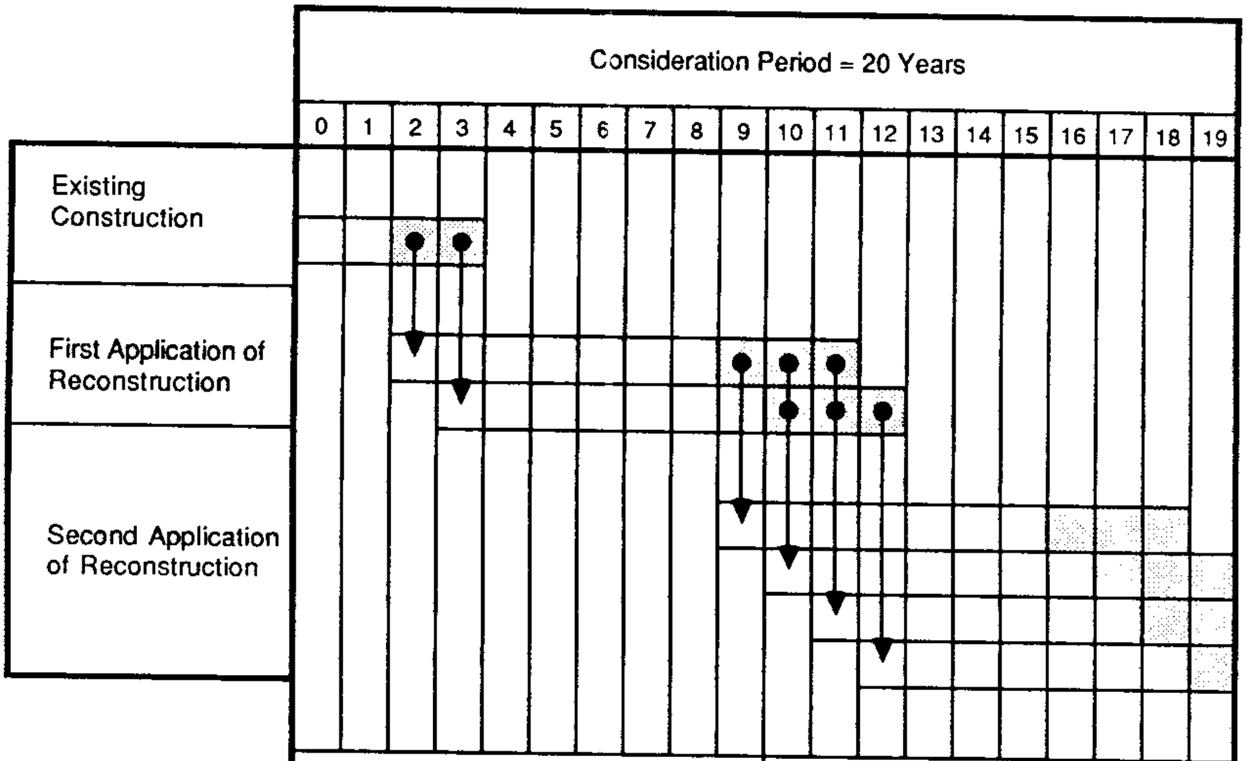


Figure 6. Reconstruction Strategies, Chloride Contaminated, Overlaid Decks



All Possible Strategies	Validity
(I-2) (II- 9)	Not Valid, condition below "must"
(I-2) (II-10)	Not Valid, condition reaches "must"
(I-2) (II-11)	Valid
(I-3) (II-10)	Not Valid, condition reaches "must"
(I-3) (II-11)	Valid
(I-3) (II-12)	Valid

Legend

Ideal reconstruction time frame

(I-2) (II-9) (First application of reconstruction at the second year of consideration period) followed by (Second application of reconstruction at the 9th year of consideration period)

Figure 7. Identifying Valid Strategies within Consideration Period

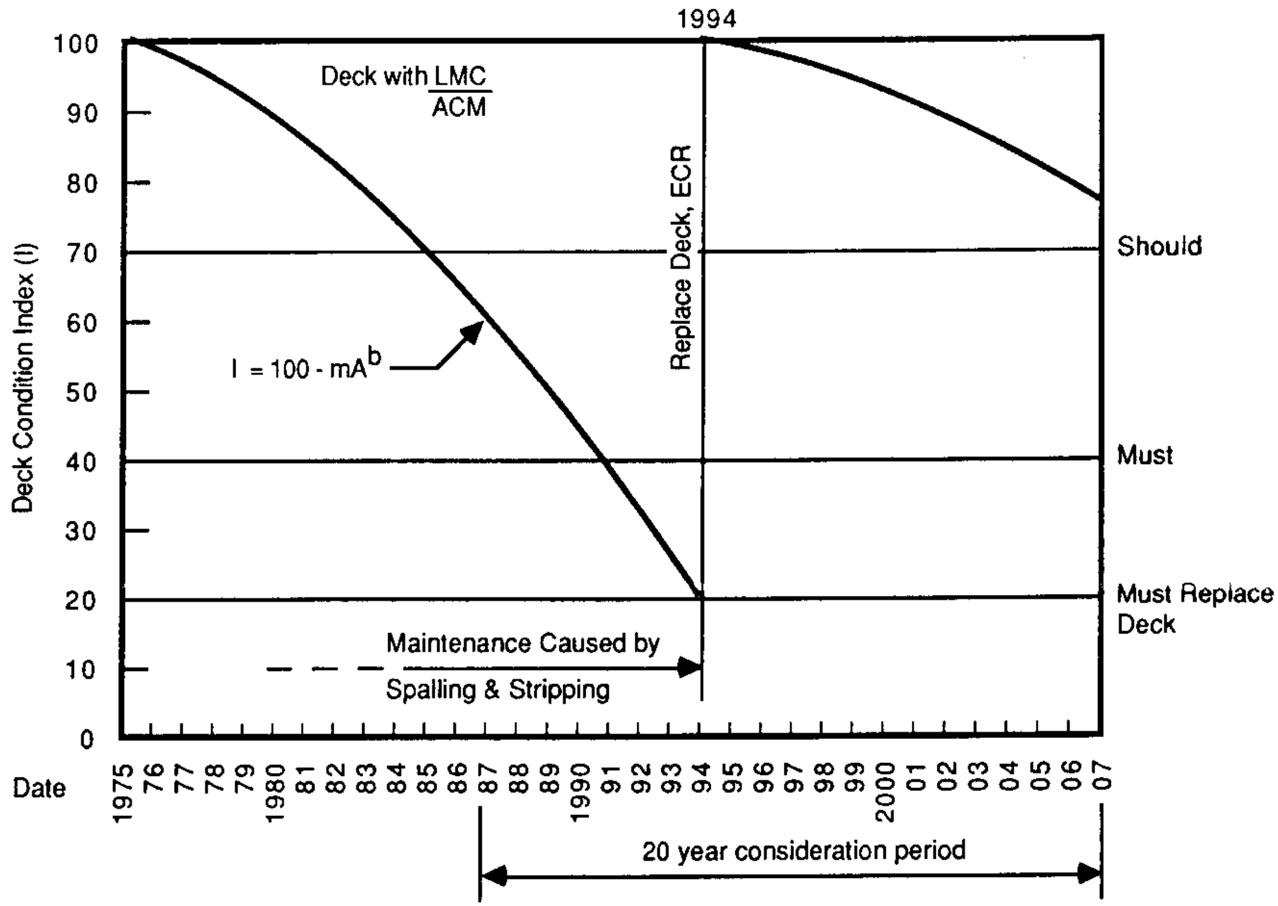


Figure 8. Deck Replacement Strategy, Contaminated Overlaid Decks

unique strategy is compared to the cost of the optimum strategy for every deck in Category II, so that total deck removal and replacement may be identified as the most cost-effective strategy.

Figure 9 presents a reconstruction scenario for Category III bridge decks, bare decks with ECR. The figure represents both subcategories III-a and III-b. The optimum date for reconstruction (overlaying the deck) is determined by assigning reconstruction at every possible date and selecting the "valid" strategy associated with the lowest cost. However, the first cycle of reconstruction involves only overlaying to address the problems of wear and lack of skid qualities, and it does not include any time dependent rehabilitation, nor does it involve major maintenance. Therefore, the output from an analysis of economy should indicate the date corresponding to the "must" condition as the optimum date for the first cycle of reconstruction.

COST ESTIMATE PROCEDURES

Estimating the Cost of Rehabilitation

In order to estimate how much rehabilitation will cost, one must estimate the magnitude of the rehabilitation to be performed during reconstruction and multiply that figure by the unit cost of the rehabilitation. Rehabilitation includes the repair of debonded concrete overlays and/or the repair of concrete delaminated by corrosion (Table 11).

BDMS estimates the magnitude of either the debonding or the delamination at the time of reconstruction by analyzing the condition data representing that class of distress and determining an average rate of distress over time. The relation between the magnitude of distress (MD) and the age at the time of reconstruction (A) is

$$MD = MD_F + r(A - A_F) \qquad (6)$$

in which

MD_F = magnitude of distress when it occurs first, $MD_F > 0$,

A_F = age of construction corresponding to MD_F, and

$$r = \text{average rate of distress} = \frac{MD_L - MD_F}{A_L - A_F} \qquad (7)$$

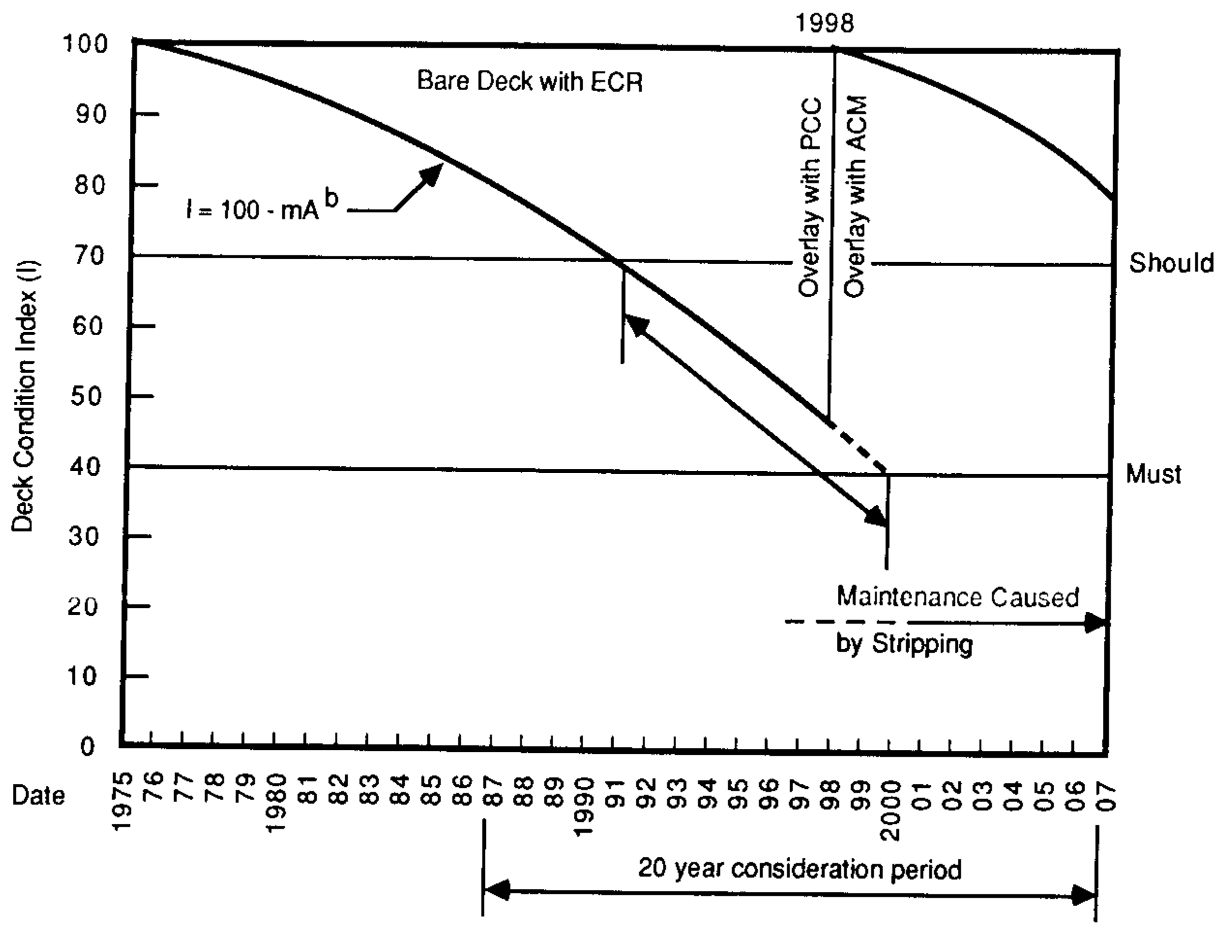


Figure 9. Reconstruction Strategies, Bare Decks with Epoxy-coated Rebar

in which

MD_L = magnitude of distress obtained in the last survey, and

A_L = age of construction corresponding to MD_L

If MD_F also corresponds to the last survey then

$$r = \frac{MD_F}{A_F - A_P} \tag{8}$$

in which

A_P = age of construction corresponding to the previous survey

For the next cycle of reconstruction, the magnitude of distress can be estimated by conducting the same type of analysis on the adapted condition data. However, to estimate debonding, Tables 9 and 10 can be used instead of that analysis for all types of reconstruction except those in categories I-a and II-a.

Estimating Maintenance Cost

The BDMS considers one type of maintenance, patching of deck spalls caused by

1. debonding and stripping of the overlay, and
2. concrete delaminations in the base deck.

Maintenance can occur at any time preceding reconstruction. Figure 10 depicts the general relationship between annual maintenance and age adopted by the BDMS. In order to estimate annual maintenance costs, the BDMS estimates how much annual spalling may occur using the procedure described below and multiplies that figure by the unit cost of temporary patching, including the cost of traffic control.

LMC Overlaid Decks. The relationship in Figure 10 is best represented by the following function for concrete overlaid decks:

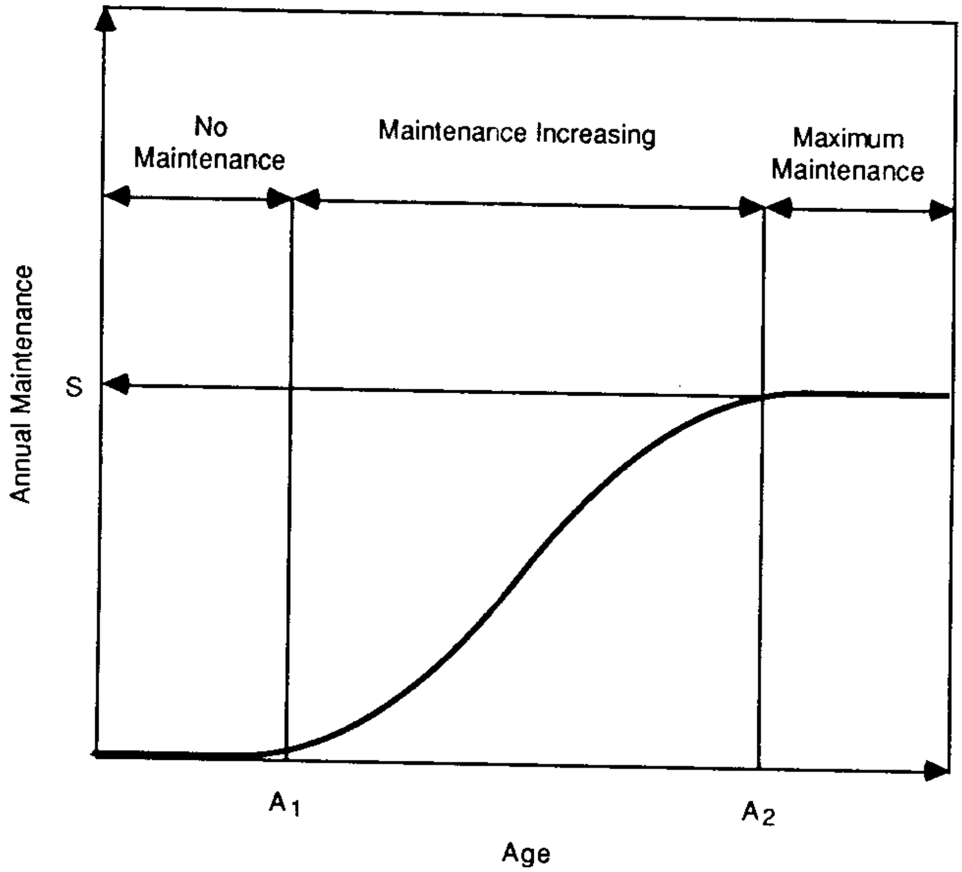


Figure 10. General Relation between Annual Maintenance and Age of Construction [adapted from Ref. 3]

$$\text{Magnitude of Annual Spalling} = \frac{S}{1 + e^{12-A}} \qquad (9)$$

in which

A = Age of overlay in years

S = Maximum (leveled off) amount of annual spalling in terms of percent of deck area, and

e = Base of Napierian logarithm, approximately equal to 2.7

According to this function, annual maintenance is 95 percent of the maximum in 15 years and the maximum in 20 years. The magnitude of cumulative spalling in 20 years is equal to 8.5 S. Assuming that in 20 years 1/3 of the debonding and 1/4 of the delams will turn into spalls after the deck is overlaid with LMC, then S can be estimated approximately as follows:

$$S = \frac{CS_1 + CS_2}{8.5} \qquad (10)$$

in which

CS_1 = Cumulative spalls caused by debonding, and

CS_2 = Cumulative spalls caused by delams

CS_1 = 1/3 (magnitude of debonding in 20 years), and (11)

CS_2 = 1/4 (magnitude of delams in 20 years) (12)

The magnitudes of debonding and delams in 20 years can be estimated using the procedure described in this report for estimating the cost of rehabilitation.

ACM Overlaid Decks

The relationship in Figure 10 is best represented by the following function for asphalt overlaid decks:

$$\text{Magnitude of Annual Spalling} = \frac{S}{1 + e^{7-A}} \qquad (13)$$

According to this function, annual maintenance is 95 percent of the maximum in 10 years and the maximum in 15 years. The magnitude of cumulative spalling in 15 years is equal to 8.5 S.

Assuming that in 15 years 1/2 of the debonding and 1/3 of the delams will turn into spalls after the deck is overlaid with asphalt concrete, then S can be estimated approximately as follows:

$$S = \frac{CS_1 + CS_2}{8.5}$$

in which

$$CS_1 = 1/2 \text{ (magnitude of debonding in 15 years), and} \qquad (11\text{-}1)$$

$$CS_2 = 1/3 \text{ (magnitude of delams in 15 years)} \qquad (12\text{-}1)$$

The magnitudes of debonding and delams in 15 years can be estimated using the procedure presented in this report for estimating the cost of rehabilitation.

Estimating Salvage Value

Salvage value in the BDMS applies to the remaining useful life of overlays beyond the consideration period, unless the deck is totally removed and replaced. In the latter case the BDMS considers the salvage value of the new deck relative to the old deck.

Figure 11 illustrates how the remaining useful life of an overlay is determined. According to Figure 11:

$$\text{Remaining useful life} = A_{must} - A_{used}$$

However, if the bridge's useful service life ends before A_{must}, then A_{must} is adjusted accordingly. In this model, the useful service life of the bridge is estimated as the life of the supporting superstructure or the substructure, whichever is smaller. The salvage value of the overlay can then be found using the following equation:

$$\text{Salvage value} = \text{(cost of overlay)} \times \frac{A_{must} - A_{used}}{A_{must}} \qquad (15)$$

The salvage value of the new deck relative to the old one applies to the remaining useful life of the new deck relative to the remaining useful life of the old one when determination of the deck life is based on structural fatigue. The following equation may be used to find the relative salvage value:

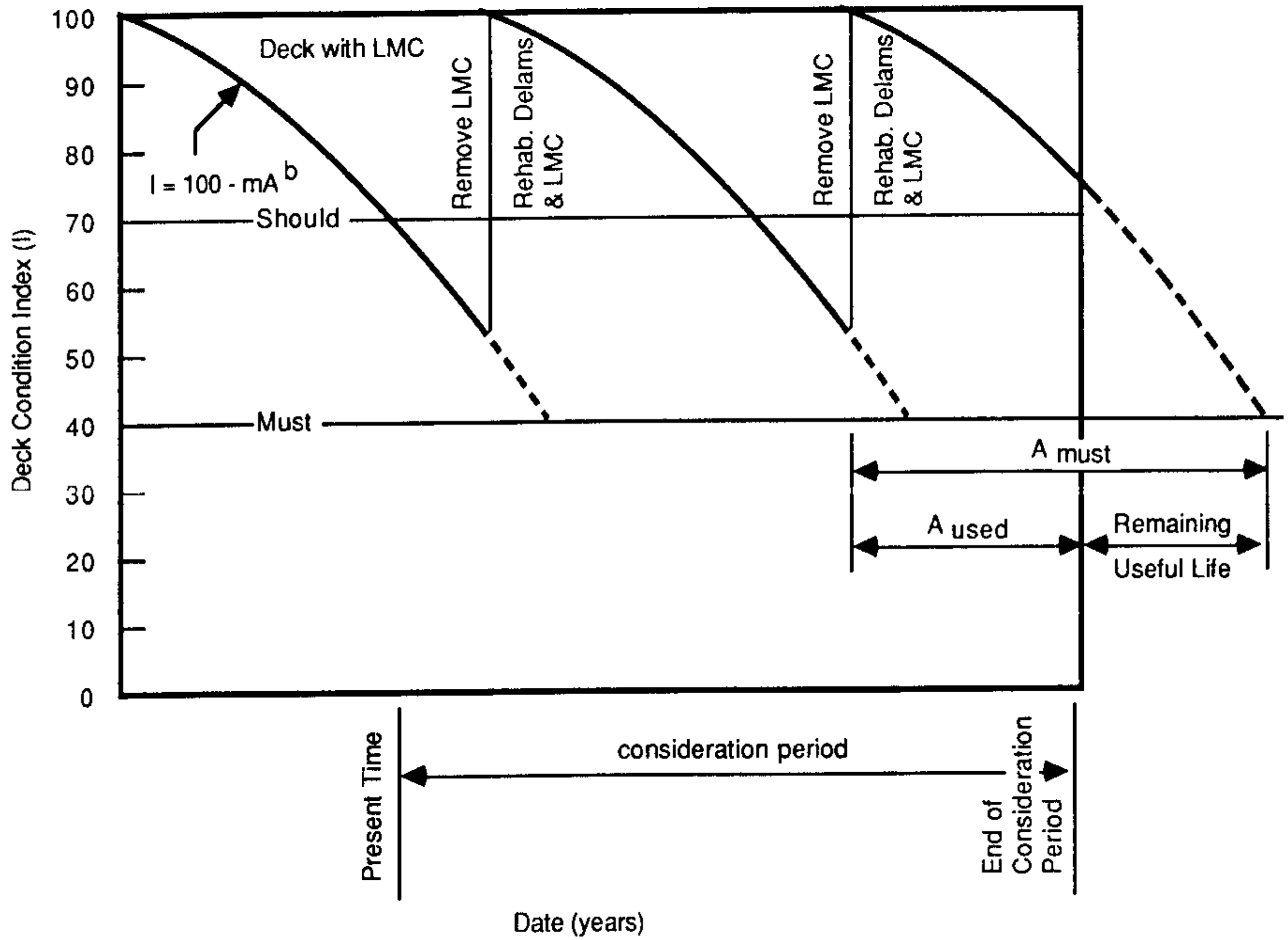


Figure 11. Illustration of Remaining Useful Life of an Overlay

$$\text{Relative salvage value} = (\text{cost of deck replacement}) \times \left(\frac{AR_1}{AT_1} - \frac{AR_2}{AT_2}\right) \qquad (16)$$

in which

AR_1 = Remaining life of new deck (beyond consideration period) or the bridge whichever arrives first.

AT_1 = Total life of new deck or the bridge as of the time of deck replacement, whichever comes first.

AR_2 = Remaining life of old deck (beyond consideration period) or the bridge whichever arrives first.

AT_2 = Total life of old deck or the bridge as of the time of construction of the old deck, whichever arrives first.

EXAMPLE OF TABULATED OPTIMIZED STRATEGY

Table 12 presents the tabulation of the optimized strategy determined by the BDMS for an imaginary bridge. The BDMS will produce similar tables for each bridge in the network so that their conditions can be predicted and, accordingly, ideal reconstruction schemes and their associated costs will be known.

The first and second columns ("Date" and "Year") in Table 12 correspond to a 20-year consideration period, with 1987 representing the present year. The fourth column ("Type of Protective Strategy") indicates overlaying and/or resurfacing. Columns 5 through 8 ("Reconstruction Cost") represent cost in terms of 1987 cost. The same is true for the ninth column ("Maintenance Cost"). Column 11 ("Present Worth") gives present worth while taking both the interest rate and inflation rate into consideration. The determination of present worth is only for comparing among different strategies so that the optimum strategy will have the least total present worth. The last column ("Inflated Cost") determines the actual cost associated with the reconstruction schemes (or maintenance) in the year they would be reconstructed. The values in this column are found by multiplying the reconstruction costs (or maintenance) in the table by $(1 + INF)^N$, in which INF is the inflation rate and N is the number of each consecutive year in the consideration period.

Table 12. Example of Tabulated Optimized Strategy

Bridge No: 90/XXX
Superstructure: 5-Span Cont. T-Beam
Deck Area: 10,000 s.f.
ADT: 10,000

Deck Built in 1960 and $\overline{cl}$ contaminated
Last Protected in 1975 with LMC & Rehab.
Last Survey in 1986
Delam: 6.5 %
Debond: 2.1 %

Date	Year	Deck Condition Index, I	Type of Protective Strategy	Reconstruction Cost ($)				Maintenance Cost ($)	Discount Factor	Present Worth, $	Inflated Cost, $
				Surface Prep.	Rehabilitation	Protection	Traffic Control				
1987	0	62						473	1	473	473
88	1	57						812	0.961	780	860
89	2	49-100	LMC	7,500	21,000	28,500	20,000		0.925	62,438	75,844
1990	3	99							0.888		
91	4	97							0.854		
92	5	95							0.821		
93	6	92							0.790		
94	7	88							0.759		
95	8	85							0.730		
96	9	80						11	0.702	8	19
97	10	76						29	0.675	20	52
98	11	70						80	0.649	52	152
99	12	65						194	0.624	121	390
2000	13	60						473	0.600	284	1,009
01	14	53						812	0.577	469	1,835
02	15	46-100	LMC	7,500	28,392	28,500	20,000		0.555	46,837	202,250
03	16	99							0.534		
04	17	97							0.513		
05	18	95							0.493		
06	19	92							0.474		

Subtotal	$111,482
Salvage Value	7,817
Total Strategy Cost	$103,665

Interest Rate = 10%, Inflation Rate = 6%, Effective Interest Rate = 4%

CHAPTER 5
NETWORK-LEVEL PROGRAMMING

After the optimal reconstruction strategies of the individual bridge decks and their associated costs have been obtained (see Table 12), the BDMS aggregates, summarizes, and tabulates that information to forecast overall bridge deck conditions, required reconstruction, and the associated cost for the bridge network. An example of this tabulation is illustrated in Table 13. In this example, the network condition and reconstruction forecasting is limited to six consecutive years (three bienniums), with 1987 representing the present year. Network reconstruction planning and budget allocations are generally not done for more than six years at a time. Note that the network condition index is the weighted average index based on bridge deck area. Table 13 forecasts network reconstruction in terms of the number of decks, their total length, and their total area. Table 13 also forecasts the cost associated with the reconstruction in inflated dollars so that a meaningful budget allocation can be made.

BUDGET CONSTRAINTS

The budget predictions in Table 13 are done to satisfy the ideal reconstruction, without consideration for any constraints. Budgets predicted in this manner usually result in a significant demand for reconstruction funding in the first year, since there normally exists a backlog of reconstruction in every system. From a management standpoint, a tremendous fluctuation in budget allocations from one year to the next may not be desirable or it simply may not be possible to fund a program such as this due to a lack of reconstruction funds. Budget allocations, or budget constraints, are determined by management based on many factors, including the availability of funds. Thus, specific projects may need to be delayed. Projects can be most logically delayed by prioritizing all of the projects based on their effect on system performance. A method for prioritizing bridge decks will be presented later.

Figure 12 illustrates the application of a budget constraint. In this example, the BDMS has identified a number of projects for reconstruction in each year for the next three bienniums. The

Table 13. An Example of Network-Level Six-Year Summary of Reconstruction Cost* (All Districts)

Year	Condition Index, I		Projects Acted On		Projects Acted On		Projects Acted On		Inflated Cost ($)
	Before	After	Number	Percent Number	Length (ft.)	Percent Length	Area (s.f.)	Percent Area	
1988	52	89	534	21.4%	156,771	20.8%	5,250,525	21.0%	28,943,519
1989	83	87	28	1.1%	9,281	1.2%	350,035	1.4%	2,026,046
1990	81	86	18	0.7%	4,264	0.6%	183,352	0.7%	1,114,325
1991	80	83	15	0.6%	4,000	0.5%	175,017	0.7%	1,116,856
1992	78	83	20	0.8%	7,274	1.0%	241,691	1.0%	1,619,442
1993	78	86	32	1.3%	10,785	1.4%	400,040	1.6%	2,814,482

* Assuming all network bridges protected and a backlog of reconstruction of protected decks exists in 1988

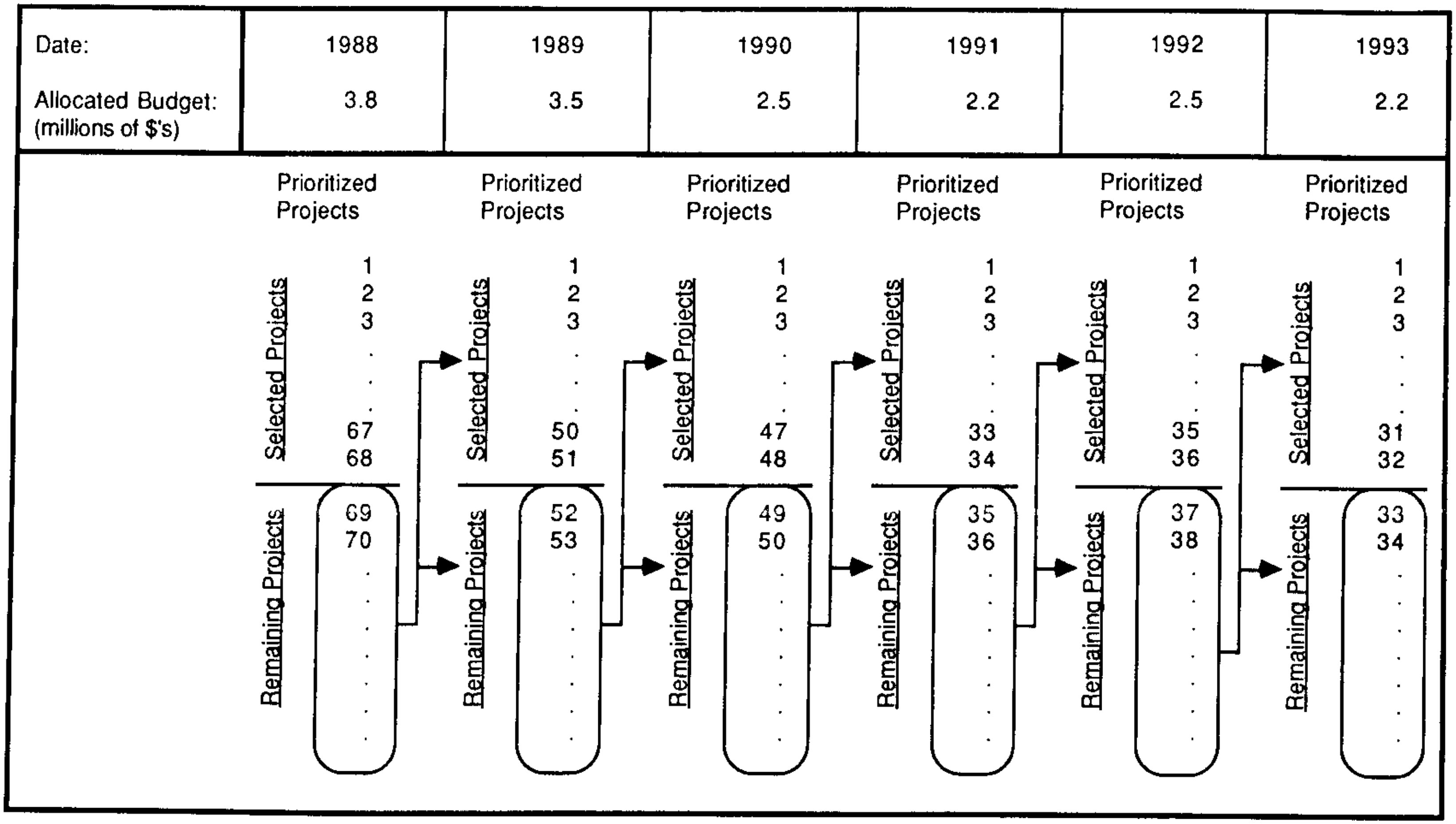


Figure 12. An Example of Applying Budget Constraints

projects in the first year (1988) are arranged in order of priority. Reconstruction costs for that year are accumulated in the same order, one project at a time, until the allocated budget for that year is reached. This determines the selected projects for reconstruction in the first year. The remaining projects are then delayed to the next year and the same process is applied. This process is repeated for all remaining consecutive years in the program. Subsequently, the BDMS summarizes and tabulates the effects of that budget constraint on the network's condition and reconstruction. Table 14 presents an example of the tabulation of those effects. Obviously, the network condition levels in Table 14 are lower than those in Table 13 due to the application of the budget constraint, which limits the volume of reconstruction. The BDMS plots the network bridge deck condition index versus the specified years in the program to graphically represent the impact of any budget allocations on the bridge deck condition level. Figure 13 is an example of that graphic representation. This figure compares the future condition of the network's bridge decks when there are no budget constraints (Table 13) and when there is a budget constraint (Table 14).

CONDITION LEVEL CONSTRAINTS

A graphic representation of the impact of a budget allocation on a network's condition, such as the one in Figure 13, will assist management in adjusting the initial budget allocation, if possible, so that the network condition can be improved. After using the same process several times and examining the results on the network's condition, management will be able to select the most desirable budget.

However, in some systems, management may not desire its network to be below a threshold condition. This is called a condition level constraint. Management determines the magnitude of condition level constraint based on many factors, including public satisfaction with the serviceability of the system. As an example, in Figure 13 the condition level constraint is set at a condition index equal to 70, the "should reconstruct" index. If the network condition were prescribed, management might want to know what budget allocation would be needed to meet that condition level. Figure 14 presents the systematic procedure that the BDMS employs to answer

Table 14. An Example of Effects of Reconstruction Budget Constraints on Network Condition Level (All Districts)

Year	Condition Index, I		Projects Acted On		Projects Acted On		Projects Acted On		Inflated Cost ($)
	Before	After	Number	Percent Number	Length (ft.)	Percent Length	Area (s.f.)	Percent Area	
1988	52	63	68	2.7%	22,825	3.0%	695,389	2.8%	3,800,000
1989	55	62	51	2.0%	16,304	2.2%	604,686	2.4%	3,500,000
1990	52	59	48	1.9%	14,046	1.9%	411,351	1.6%	2,500,000
1991	48	56	34	1.4%	9,030	1.2%	339,528	1.4%	2,200,000
1992	46	55	36	1.4%	13,043	1.7%	373,107	1.5%	2,500,000
1993	45	54	32	1.3%	10,785	1.4%	307,961	1.2%	2,200,000

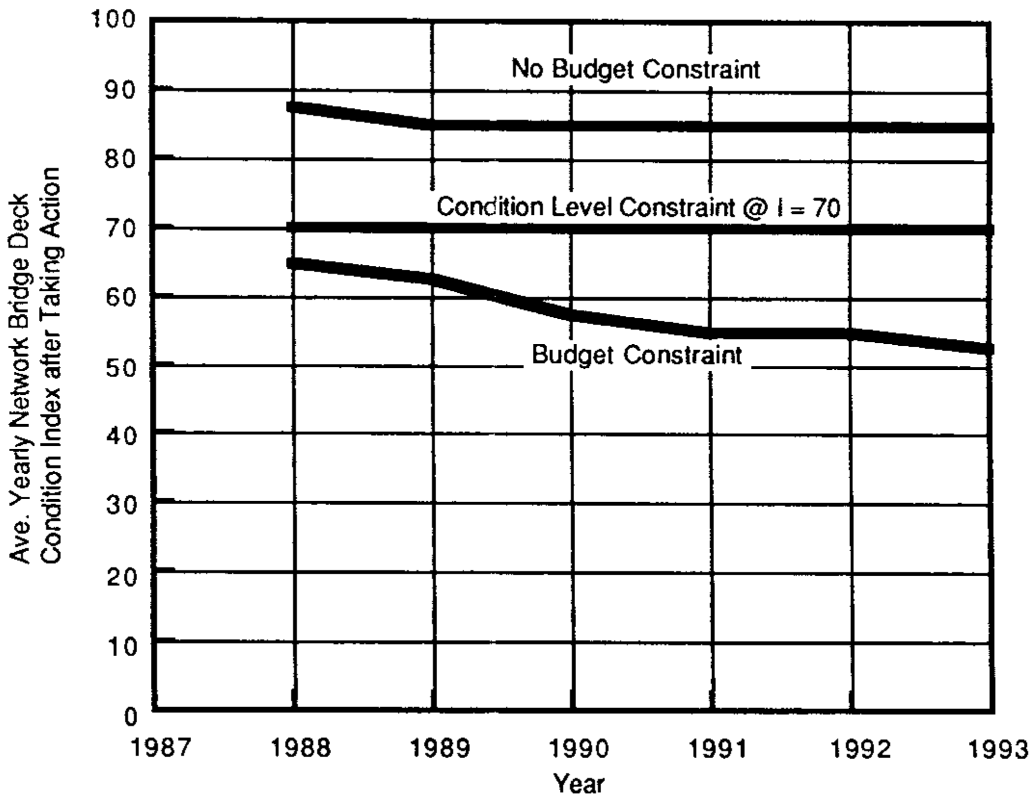
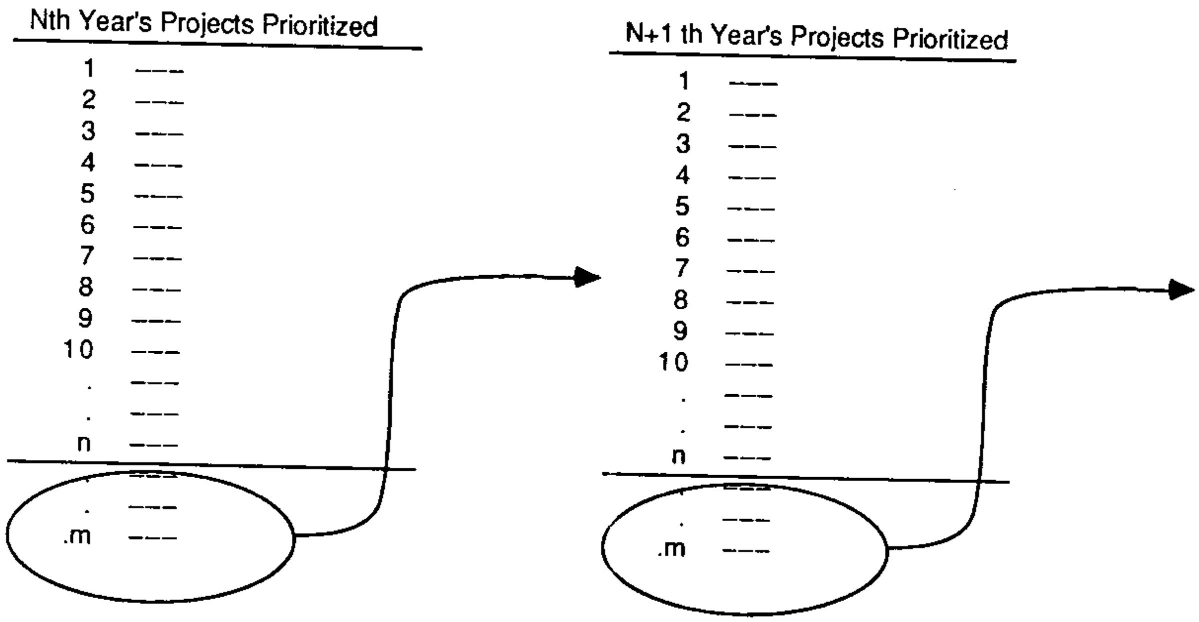


Figure 13. An Example of Impact of a Budget Constraint on Condition Level



where

$$\sum_{i=1}^{n} A(100 - I_i) = A_t(I_a - I_b)$$

A = Area of individual project (s.f.)

A_t = Total area of bridge decks in the system (s.f.)

I_i = Condition rating of individual project

I_a = System average desired rating after taking actions in Nth year

I_b = System average rating before taking actions in Nth year

Figure 14. Process of Determining Budget Allocation to Satisfy Condition Level Constraint

that question. In this procedure, the BDMS first identifies the projects for reconstruction in each year for all consecutive years in the program. This is done independent from any constraint. Next, the projects in the first year are arranged in a priority order. Bridges for reconstruction for that year are selected in the same order, one project at a time, until the network condition for that year has reached the condition level constraint. The remaining projects are then delayed to the next year and the same process is applied. This process is repeated until bridges for reconstruction are identified for all remaining consecutive years in the program. Subsequently, the BDMS summarizes and tabulates the effects of the condition level constraint on network reconstruction and their associated costs. Table 15 shows an example of the tabulation of those effects. A comparison of Table 15 with Table 14 indicates that more reconstruction funds will be required in order to keep the network condition index at 70.

PRIORITIZATION PROCEDURE

The following suggests a systematic procedure for prioritizing protected bridge decks for reconstruction in the face of budget and condition level constraints. This procedure is adapted from the Pennsylvania Bridge Management (4), with the addition of a parameter representing the remaining life of the structure.

Bridge decks are prioritized based on their prioritization indices (PI). The PI for each site is determined as follows:

$$PI = \frac{3375 \times 10^6 (RC)}{(ADT)(ARA)(DP)(RL)^3} \tag{17}$$

in which

RC = Reconstruction cost in dollars

ADT = Average Daily Traffic

ARA = Bridge deck area in square feet

DP = Deficiency points removed by reconstruction, or 100 minus deck condition index before reconstruction

RL = Remaining life of the superstructure or substructure (whichever is smaller) in years. RL will be equal to 15 if the remaining life is greater than 15 years.

Lower PI values indicate higher priorities for reconstruction. Lower PI values are obtained when there are

- lower reconstruction costs,
- higher traffic volumes,
- larger bridge deck areas,
- more deficiency points removed, and
- the structure has a longer remaining life.

The parameter $\frac{(RC)}{(ADT)}$ reflects cost per daily vehicle user and yields a form of cost/benefit ratio. Similarly the parameter $\frac{(RC)}{(ARA)}$ reflects cost per unit area and the parameter $\frac{(RC)}{(DP)}$ reflects cost per unit of deficiency removed. A parameter in the form of $\frac{(RC)}{(ADT)(ARA)(DP)}$ combines the effects of traffic volume, area, and deficiency removed and yields a more appropriate reflection of the cost/benefit ratio. Parameter (RL) incorporates the effects of the remaining life of the bridge. In the model presented, parameter (RL) is only effective if the remaining life of the structure is estimated to be less than 15 years, a figure representing the average life of bridge deck reconstruction schemes. A more evolved version of this prioritizing model can incorporate the influence of the type of superstructure so that decks that are integral structural components of bridges are given higher priorities.

Table 15. An Example of Effects of Condition Level Constraint on Network Yearly Reconstruction Budgeting (All Districts)

Year	Condition Index, I		Projects Acted On		Projects Acted On		Projects Acted On		Inflated Cost ($)
	Before	After	Number	Percent Number	Length (ft.)	Percent Length	Area (s.f.)	Percent Area	
1988	52	70	107	4.3%	30,602	4.1%	991,765	4.0%	5,467,108
1989	63	70	71	2.9%	19,564	2.6%	612,561	2.4%	3,545,578
1990	54	70	42	1.7%	14,297	1.9%	458,379	1.8%	2,785,814
1991	62	70	54	2.2%	16,555	2.2%	591,726	2.4%	3,776,044
1992	62	70	56	2.2%	14,799	2.0%	483,381	1.9%	3,238,888
1993	59	70	68	2.7%	19,565	2.6%	616,728	2.5%	4,338,993

CHAPTER 6
EXAMPLE PROBLEM

This example problem illustrates how the systematic procedures introduced in the previous chapters are applied to a realistic bridge deck. This problem forecasts the future condition, necessary reconstruction, and cost associated with the reconstruction and maintenance of an overlay protected bridge deck. Further, it determines the priority of the reconstruction of the bridge in the bridge network.

DESCRIPTION OF THE EXAMPLE BRIDGE DECK

The bridge deck to be examined (Bridge No. 20/xxx) is 10,000 sq. ft. and was built in 1970. It was contaminated with chlorides and was deteriorated enough that in 1980 the deck was rehabilitated and protected with an LMC overlay following the WSDOT's protective system selection criteria. The average daily traffic on the bridge is 9,000 vehicles.

The deck was surveyed in 1982, '84, and '86 as part of a bridge deck management program. The magnitudes of the various types of distress detected in those surveys are shown in Table 16.

DETERMINE THE PERFORMANCE EQUATION FOR THE EXISTING CONSTRUCTION

Table 17 shows how the performance equation for the existing concrete overlaid deck is obtained. The weighting factors assigned to the distress categories in Table 17 are from Table 3. That performance equation was obtained by conducting a linear regression analysis after nonlinearity was removed from the performance equation with logs rather than with formulae (1) and (2). This was done to reduce hand calculations in this particular case, since an automated data processing system was not available.

Table 16. Historical Condition Data for Bridge 20/xxx (overlaid with LMC in 1980)

Distress Categories* \ Year / Age	1982 2 Years	1984 4 Years	1986 6 Years
Spalling & Delams	0.50%	1.00%	1.50%
Stripping & Debonding	0.00%	0.10%	0.50%
Patching	0.00%	0.00%	0.00%
Scaling	0.00% depth = 0.0 in.	0.00% 0.0 in.	0.00% 0.0 in.
Wear & Rutting	25% depth = 0.0 in.	25% 0.0 in.	25% 1/16 in.
Cracking	20%	25%	30%

* Percent of deck area

Table 17. Determining Existing Construction Performance Equation for Bridge 20/xxx (overlaid with LMC in 1980)

Year / Distress * / Age	1982 2 Years	1984 4 Years	1986 6 Years
Spalling & Delams	0.50% (6)	1.00% (6)	1.50% (6)
Stripping & Debonding	0.00% (4)	0.10% (4)	0.50% (4)
Patching	0.00% (4)	0.00% (4)	0.00% (4)
Scaling	0.00% (5 x 0)	0.00% (5 x 0)	0.00% (5 x 0)
Wear & Rutting	25% (2.5 x 0)	25% (2.5 x 0)	25% (2.5/16)
Cracking	20% (1/10)	25% (1/10)	30% (1/10)
Deficiency Points, D	5.0	8.9	17.9
Condition Index, I	95.0	91.1	82.1
Age of Reconstruciton, A	2	4	6

$I = 100 - 2.1694\,A^{1.13}$ ==> $A_{SH,70} = 11$ yrs. $A_{M,40} = 18$ yrs.

* Expressed in terms of deficiency points

DETERMINE THE TYPE OF FUTURE RECONSTRUCTION

Future reconstruction will involve rehabilitation of the delams. Resurfacing of the deck during reconstruction will involve either scarifying 1/4 inch of the existing LMC and applying 3/4 inch of LMM or removing the existing LMC completely and applying 1-1/2 inch of new LMC.

Table 8 is used to determine the type of resurfacing. Assume that reconstruction will be done at A=16 years, or two years before the "must" condition is reached. Using formulae (6) and (7), the magnitude of debonding at A=16 is

$$MD = 0.10\% + r(16 - 4)$$

in which

$$r = \frac{0.50\% - 0.10\%}{6 - 4} = 0.20\% \text{ per year}$$

therefore

$$MD = 0.10\% + 0.20\% \, (16 - 4) = 2.50\%$$

The threshold values of MD and r from Table 8 are 3 percent and 0.5 percent per year, respectively.

Since

$$MD = 2.5\% < 3\% \text{ and}$$

$$r = 0.2\% < 0.5\%$$

then the type of resurfacing will be LMM.

DETERMINE THE PERFORMANCE OF FUTURE RECONSTRUCTION

This deck belongs to Subcategory II-a, since the base deck is contaminated with chlorides, the existing protective system is LMC, and it is to be resurfaced with LMM. The first step is to adapt the historical condition data of the existing construction so that the adapted data represent the future reconstructed deck.

Spalls and Delams

The modification factor for spalls and delams according to formula (4) is

$$SF = \frac{25\%}{C\%}$$

in which

$$C\% = 25\% + \frac{30\% - 25\%}{2} x\ 1 = 27.5\%$$

therefore,

$$SF = \frac{25\%}{27.5\%} = 0.91$$

Stripping and Debonding

The additional values of debonding and stripping belonging to the LMM interface are obtained from Table 9 and are

For $A = 2$ yrs. $\Rightarrow$ 0.00%

$A = 4$ yrs. $\Rightarrow$ 0.01%

$A = 6$ yrs. $\Rightarrow$ 0.04%

Patching

Is not included.

Scaling of Concrete

Use the values obtained for the existing construction.

Wear and Rutting

Use the values obtained for the existing construction.

Surface Cracking

The modification factor for cracking according to formula (3) is

$$CF = \frac{25\%}{C\%} = \frac{25\%}{27.5\%} = 0.91$$

The adapted magnitude of various types of distress are given in Table 18. Accordingly, Table 19 shows how the performance equation for the future reconstruction is obtained.

Table 18. Historical Condition Data for Bridge 20/XXX, Adapted Representing Future Reconstruction (Future LMM Resurfacing)

Distress Categories* \ Year / Age	---	---	---
	2 Years	4 Years	6 Years
Spalling & Delams	0.46%	0.91%	1.37%
Stripping & Debonding	0.00%	0.11%	0.54%
Patching	---	---	---
Scaling	0.00% depth = 0.0 in.	0.00% 0.0 in.	0.00% 0.0 in.
Wear & Rutting	25% depth = 0.0 in.	25% 0.0 in.	25% 1/16 in.
Cracking	18%	23%	27%

* Percent of deck area

Table 19. Determining Future Reconstruction (LMM Resurfacing) Performance Equation for Bridge 20/xxx

Distress* \ Year / Age	----	----	----
	2 Years	4 Years	6 Years
Spalling & Delams	0.46% (6)	0.91% (6)	1.37% (6)
Stripping & Debonding	0.00% (4)	0.11% (4)	0.54% (4)
Patching	---	---	---
Scaling	0.00% (5 x 0)	0.00% (5 x 0)	0.00% (5 x 0)
Wear & Rutting	25% (2.5 x 0)	25% (2.5 x 0)	25% (2.5/16)
Cracking	18% (1/10)	23% (1/10)	27% (1/10)
Deficiency Points, D	4.6	8.2	17.0
Condition Index, I	95.4	91.8	83
Age of Reconstruciton, A	2	4	6
$I = 100 - 1.9514\,A^{1.15}$ ==> $A_{SH,70}$ = 11 yrs. $A_{M,40}$ = 19 yrs.			

* Expressed in terms of deficiency points

DETERMINE THE OPTIMUM DATE FOR RECONSTRUCTION

The optimum date for reconstruction is based on cost effectiveness and is determined by analyzing all possible strategies within the 20-year consideration period for economy. In this example, the consideration period begins with 1987, the present year. The valid reconstruction strategies are those that do not occur before the "should" condition has been reached and that maintain a minimum level of "must" condition throughout the consideration period (see Figure 7). To identify the most cost-effective strategy, all the costs associated with each valid reconstruction strategy, including maintenance costs, are calculated in present dollars and totaled. The most cost-effective strategy is the one with the least total cost. This process will require an automated data processing system due to the size of the calculation involved. Therefore, for the purpose of this example, only the cost analysis for one reconstruction strategy is demonstrated. This strategy assumes that reconstruction will be done at A=16 years. This is five years after the "should" condition and two years before the "must" condition are reached. This strategy is depicted in Figure 15.

Cost Analysis

Table 11 illustrates the cost categories involved in the reconstruction and maintenance of overlaid decks.

Reconstruction in 1996. Surface preparation (scarifying) of 10,000 sq. ft. at $0.75 per sq. ft. is $7,500.

The cost of protection with a 0.75 in. LMM is estimated at $1.90 per sq. ft., or $19,000 for the deck.

Traffic control is estimated at $2.00 per sq. ft., or a total of $20,000.

Rehabilitation includes the repair of delams by removal of the deteriorated concrete around the rebar and patching and repair of the debonded overlay, possibly by polymer injection. The unit cost for repair of the delams is estimated at $30 per sq. ft. and repair of the debonding is estimated

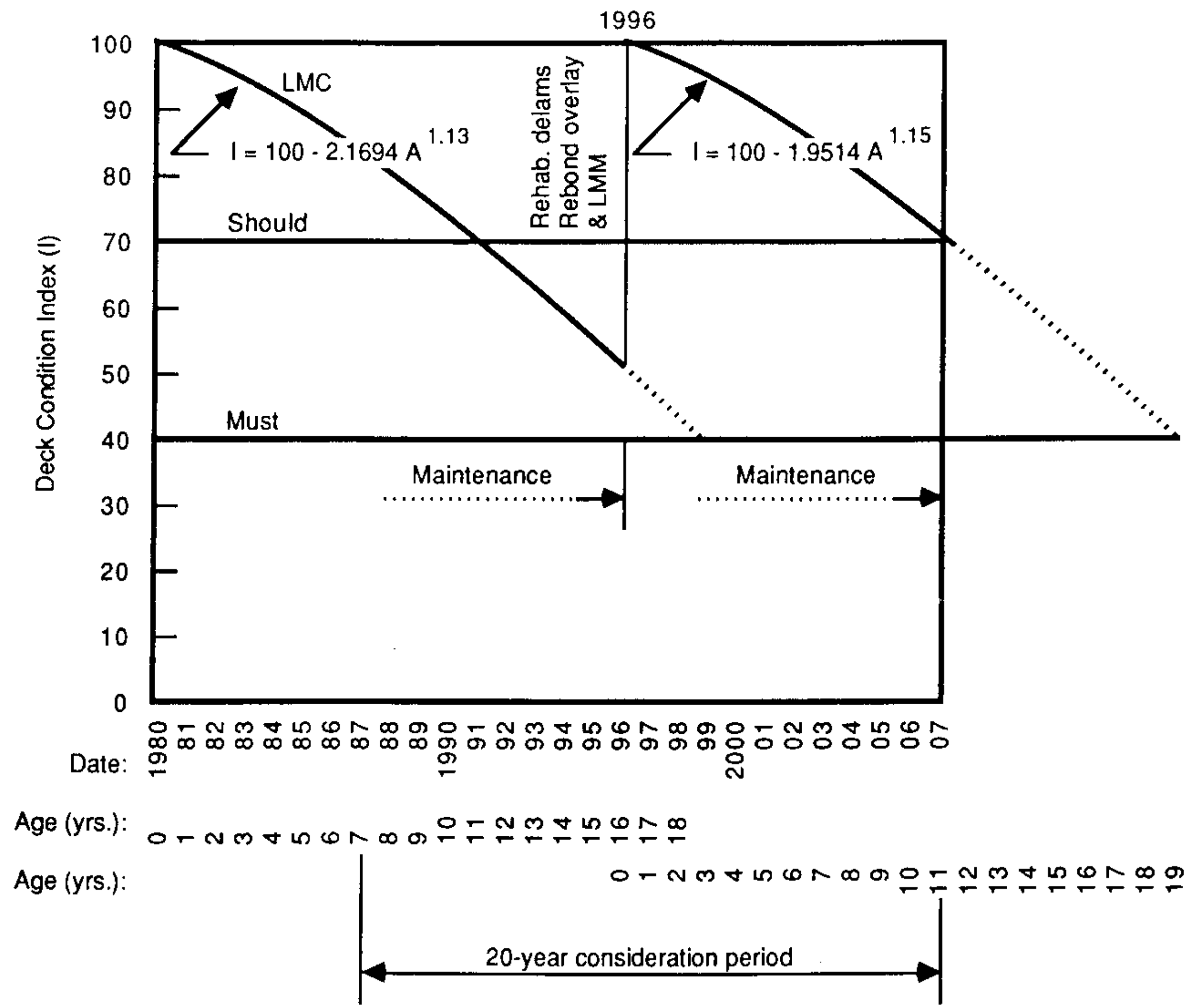


Figure 15. A Valid Reconstruction Strategy for Bridge 20/XXX

at \$5 per sq. ft. Formulae (6) and (7) are used to determine the magnitude of the delams and debonding in 1996.

For delams

$$r = \frac{1.50\% - 0.50\%}{6 - 2} = 0.25\% \text{ per year}$$

Therefore

$$MD = 0.50\% + 0.25\% (16 - 2) = 4.00\%$$

For debonding

MD = 2.50 percent, previously determined in this example problem

Therefore, the cost of rehabilitation will be

For delams

(4.0%)(10,000 sq. ft.)(\$30 per sq. ft.) = \$12,000

For debonding

(2.5%)(10,000 sq. ft.)(\$5 per sq. ft.) = \$1,250

Total rehabilitation cost = \$13,250

Maintenance. Maintenance in the form of temporary patching is necessary because of delaminated and debonded concrete causing surface spalling. The unit cost for temporarily patching the potholes, including mobilization and traffic control, is estimated at \$25 per sq. ft. of patches. The magnitude of annual spalling is determined from formula (9) for each year of service and is equal to $\frac{S}{1 + e^{12-A}}$. In the following, the maximum amount of annual spalling (S) is estimated using formulae (10), (11), and (12) for the existing construction.

Magnitude of delams in 20 years = 0.50% + 0.25% (20-2) = 5.00%

Magnitude of debonding in 20 years = 0.10% + 0.20% (20-4) = 3.30%

Then

CS_2 = 1/4(5.00%) = 1.25%

CS_1 = 1/3(3.30%) = 1.10%

From there

$$S = \frac{1.25\% + 1.10\%}{8.5} = 0.28\% \text{ per year, maximum spalling}$$

Maximum annual maintenance cost = (0.28%)(10,000 sq. ft.)($25 per sq. ft.) = $700

Therefore

$$\text{Maintenance cost per a given service year} = \frac{\$700}{1 + e^{12-A}}$$

Using the same procedure for the deck resurfaced with LMM produces

Magnitude of delams in 20 years = 0.46% + 0.23%(20-2) = 4.60%

Magnitude of debonding in 20 years = 0.11% + 0.22%(20-4) = 3.63%

Then

CS_2 = 1/4(4.60%) = 1.15%

CS_1 = 1/3(3.63%) = 1.21%

From there

$$S = \frac{1.15\% + 1.21\%}{8.5} = 0.27\% \text{ per year, maximum spalling}$$

Maximum annual maintenance cost = (0.27%)(10,000 sq. ft.)($25 per sq. ft.) = $675

Therefore

$$\text{Maintenance cost per a given service year} = \frac{\$675}{1 + e^{12-A}}$$

__Salvage Value__. Salvage value applies to the remaining life of the last overlay in the consideration period. In this case, the last overlay is the LMM applied in 1996. The salvage value of the LMM is found using formula (15).

$$\text{Salvage value} = \$19{,}000 \times \left(\frac{19 - 11}{19}\right) = \$8{,}000$$

__Total Present Worth of the Strategy__. Formula (5) is applied to all cost items in the consideration period to determine their present worth before summation. An interest rate of 10% and inflation rate of 6% are assumed. Table 20 tabulates the bridge deck condition and all cost

Bridge No: 20/XXX
Superstructure: 3-Span Cont. Conc. Slab
Deck Area: 10,000 s.f.
ADT: 9,000

Table 20. Tabulation of Deck Condition and Reconstruction Cost for a Valid Strategy for Bridge 20/xxx

Deck Built in 1974 & Chloride Contaminated
Last Protected in 1980 with LMC & Rehab
Last Surveyed in 1986
Delam: 1.50 %
Debond: 0.50 %

Date	Year	Deck Condition Index, I	Type of Protective Strategy	Reconstruction Cost ($)				Maintenance Cost ($)	Discount Factor	Present Worth, $	Inflated Cost, $
				Surface Prep.	Rehabilitation	Protection	Traffic Control				
1987	0	80							1		
88	1	77						13	0.961	12	14
89	2	74						33	0.925	31	37
1990	3	71						83	0.888	74	99
91	4	67						188	0.854	161	237
92	5	64						350	0.821	287	468
93	6	61						512	0.790	404	726
94	7	57						617	0.759	468	928
95	8	54						667	0.730	487	1,063
96	9	50-100	LMM	7,500	13,250	19,000	20,000		0.702	41,945	100,946
97	10	98							0.675		
98	11	96							0.649		
99	12	93							0.624		
2000	13	90							0.600		
01	14	88							0.577		
02	15	85							0.555		
03	16	82							0.534		
04	17	79						12	0.513	6	32
05	18	76						32	0.493	16	91
06	19	72						80	0.474	38	242
07	20	69						182	0.456	83	584

Interest Rate = 10%, Inflation Rate = 6%, Effective Interest Rate = 10 - 6 = 4%

Subtotal	$44,012
Salvage Value	8,000 (0.456)
Total Strategy Cost	$40,364

items for this strategy. As shown in Table 20, the total present worth cost for this strategy is \$40,364.

DETERMINE PRIORITY OF RECONSTRUCTION

Formula (17) is used to find the priority of reconstructing the deck in 1996.

RC = \$7,500 + \$13,250 + \$19,000 + \$20,000 = \$59,750 (from Table 20)

Note that since priority order is relative and is applied to network reconstruction in a certain year, the inflation factor does not have to be included in the above reconstruction cost.

ADT = 9,000 vehicles per day

ARA = 10,000 sq. ft.

DP = 100-50 = 50 (from Table 20)

RL = 15 (assume the remaining life of the structure is greater than 15 years)

then

$$PI = \frac{3375 \times 10^6 (59{,}750)}{(9{,}000)(10{,}000)(50)(15)^3} = 13.28$$

Lower PI values indicate higher priorities for reconstruction.

CHAPTER 7
CONDITION DATA ACQUISITION

Historical condition data must be available to apply the BDMS. Sufficient data need to be collected from the network's bridge decks and provided to the database so that the BDMS can accurately identify specific bridge decks for reconstruction. This approach requires testing all of the bridge decks in the network, since each bridge deck has its own unique performance characteristics, depending on its construction quality and environment. WSDOT has previously used this approach to collect condition data from the network's unprotected bridge decks in order to program and prioritize their rehabilitation and protection.

The cost of data acquisition can be reduced by optimizing the magnitude of data collected as well as the frequency of data collection. The following measures are suggested.

THE MAGNITUDE OF DATA

On very large bridge decks, test sections should be located and data should be collected from those sections only. Also, testing only those lanes that are more vulnerable to deterioration (i.e., the driving lanes) can reduce the magnitude of data. If these measures are taken, modification factors can be applied to the data so that they will represent the whole bridge deck.

FREQUENCY OF DATA COLLECTION

Data may not need to be collected until the protective systems are five years old. This is because in the early ages of protection, a bridge deck performance curve is usually flat and the rate of deterioration is low. After the first round of data collection takes place, the data collection frequency may be varied from one testing in two years to one testing in eight years, depending on the rate of deterioration in each bridge deck. However, the second round of data collection should occur before the arrival of the "should" condition. The following relation, based on the latter concept, may be used as a guide to the timing of the second round of data collection:

$$T_f = \frac{I_f - (I_{sh} + 10)}{(100 - I_f)/(T_i)} \qquad (18)$$

and $2 \leq T_f \leq 8$ years

in which

T_f = period of time between the first and second round of data collection in years

I_f = bridge deck condition index at the time of the first round of data collection

$I_{sh} + 10$ = "should" condition index, or 70, plus 10; the addition of 10 is to guarantee that the second round of data collection will be done in an appreciable amount of time before the arrival of the "should" condition.

T_i = the number of years between protection of the deck and the first round of data collection (five years)

The third round of data collection should preferably be done about the time of "should" condition. The following relation can be used to determine the timing of the third round of data collection:

$$T_s = \frac{I_s - I_{sh}}{(I_f - I_s)/(T_f)} \qquad (19)$$

and $2 \leq T \geq 6$ years

in which

T_s = period of time between the second and third round of data collection in years

I_s = bridge deck condition index at the time of the second round of data collection

I_{sh} = "should" condition index, or 70

T_f = period of time between the first and second round of data collection in years.

After a bridge deck reaches the "should" condition, data should preferably be collected once every two years.

PRIORITIZATION PROCEDURE FOR TESTING

At the start of the program, the number of protected bridges qualifying for the first round of data collection (i.e., with protective systems five years old or older) may be more than what budget allocations would normally allow. Thus, there may be a need to prioritize bridges for testing, select test bridges, and delay testing of the remaining bridges to the next year. Bridges with older protective systems, bridges with higher levels of chloride contamination in their bridge deck, bridges with larger amounts of rehabilitation in the base deck (i.e., delamination prior to protection), and bridges with higher levels of traffic should be given priority for testing. This is because all of these factors contribute to post-protection deterioration. Also, a factor representing the remaining service life of the structure should be considered so that bridge decks that may be replaced soon will have a lower priority for testing. These discussions lead to the following prioritization index for testing:

$$PIT = \frac{3375 \times 10^9}{(AGE)(CL)(D)(ADT)(RL)^3} \qquad (20)$$

in which

PIT = prioritization index for testing; lower PIT values indicate higher priorities for testing

AGE = age of protection in years

CL = percent of the concrete samples from the base deck with a chloride content exceeding 2 lb/c.y.

D = percent of the deck area delaminated before rehabilitation/protection

ADT = average daily traffic number

RL = remaining life of the superstructure or substructure (whichever is smaller) in years. RL will be equal to 15 if remaining life is greater than 15 years.

CHAPTER 8
IMPLEMENTATION

Implementation of the BDMS will involve two major activities: (1) collecting bridge deck condition data and (2) developing computer software. Below, the approximate costs associated with each of these activities are briefly discussed.

DATA COLLECTION

Assuming an average data collection frequency of one test every five years, the number of bridges tested every year will be

$$\frac{\text{2500 network bridges}}{\text{five years}} = \text{500 bridges per year}$$

An average bridge deck is about 10,000 square feet, and WSDOT's previous experience with bridge deck testing, which has included comprehensive half-cell tests as well as chloride content tests (note that the BDMS does not require the latter two tests), has shown that testing a bridge deck costs about $0.10 per square foot.

At $0.10 per square foot, the cost of testing the network's bridge decks will be $500,000 per year. However, if only the driving lanes of the bridge are tested, the cost will be about $250,000 per year, since all costs involved with the testing operation (including traffic control cost) will be reduced to half. The cost should further be reduced by half again, since BDMS does not require chloride and comprehensive half-cell tests. Therefore, the cost of testing network bridge decks should be about $125,000 per year.

DEVELOPING COMPUTER SOFTWARE

As discussed in the beginning of the report, one reason that the research team decided to pattern the overall structure of the BDMS after WSDOT's PMS was that the automated data processing system already developed for the PMS could be modified and used for the BDMS, thus reducing the cost of providing software for the BDMS significantly. WSDOT PMS software for interpretation, optimization and network programming is listed in the appendix of WSDOT Report No. WA-RD 50.1, "Development and Implementation of Washington State's Pavement Management System."

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