# Bridge Deck Rehabilitation Decision Making

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ABSTRACT

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.

The existence of a serious national problem, deteriorating bridge decks, was first recognized in the early 1960s when the Portland Cement Association and the Bureau of Public Roads (now the Federal Highway Administration) reported on studies carried out in cooperation with 10 state highway agencies (1,2). In 1973 the Federal Highway Administration (FHWA) estimated the cost for bridge deck repairs in the United States to be $70 million per year (3). Two years later the same agency revised this figure to $200 million per year (4). In 1977 FHWA reported that 65,507 bridges (about 10 percent of the nation's bridges) had badly deteriorated decks (5). In the same year The Road Information Program (TRIP) reported that, in the winter of 1976-1977 alone, 1,626 bridges had been rendered unusable, mainly as a consequence of spalling. Repair or replacement costs for these bridges were estimated to be $1 billion. An Environmental Protection Agency study published in 1977 placed the annual damage to bridge decks at $500 million (6). In 1979 the General Accounting Office (GAO) reported to Congress that the cost for repairing the country's deteriorated bridge decks stood at $6.3 billion (7). A 1981 GAO report (8) estimated the number of deficient bridges to be well in excess of 100,000. The estimated rehabilitation or replacement cost was placed at $33.2 billion. Significant proportions--about one-half of the number of bridges and one-third to one-half of the projected cost--are related to bridge deck deterioration problems. The remainder reflect structural or functional deficiencies.

The major cause of bridge deck deterioration is deicing salts applied to maintain trafficable winter roadway conditions. The problem has become so acute during the past two decades because of the increasing use of deicing salts in pursuit of an all-weather "bare pavement" policy promulgated by highway agencies beginning in the 1950s. In 1947 less than one-half million tons of road salt was used in the United States. Salt usage increased to a peak of 11 to 12 million tons in the mid-1970s. One report indicated that the average road salt application on 25 bridge decks studied in the Denver, Colorado, area was over 1 lb per square foot per year (9).

The deicer salts (sodium chloride and calcium chloride) produce corrosion of the reinforcing steel in concrete. Normally (i.e., at low chloride ion concentrations), concrete provides an environment that inhibits corrosion of reinforcing steel. Corrosion may begin when chloride concentrations reach about 1.2 lb per square yard of concrete at the location of the steel (10). The resulting corrosion products occupy more space than did the original steel, producing stresses that cause the concrete to crack along horizontal fracture planes, which eventually become spalls.

The study reported here was undertaken to develop rational strategies for the protection, repair, rehabilitation, and replacement of bridge decks based on cost-effectiveness. The objective of the study was to provide means for optimizing the allocation of limited funds. The methodology described has since been adopted by the Pennsylvania Department of Transportation as official policy.

## POLICIES

Policies for the protection, repair, rehabilitation, and replacement of concrete bridge decks require decision making at two levels. First, criteria are necessary to define the points at which various actions are required, and, second, decisions must be made about what action shall be taken. The action criteria for five current or recent bridge deck policies are given in Table 1 as typical of the range of prevailing attitudes. With the exception of the criterion for replacement in the Ontario policy, the decision criteria are quite arbitrary--a factor that is underscored by the wide variation in the values presented in Table 1.

When action has been triggered by the appropriate criterion, a decision is needed about methodology. Figure 1 shows a compendium of the potential methods for effecting protection, repair, rehabilitation, or replacement of bridge decks. Some of the methods presented are still experimental (e.g., deep polymer impregnation) and some are not currently in favor due to questionable effectiveness (e.g., galvanized reinforcement) or technical problems (e.g., internally sealed concrete).

The review that was carried out for the development of the current Pennsylvania Department of Transportation policy revealed little rationale, nationwide, both for the selection of trigger levels for action criteria and for the selection of method after the need for action is indicated. Furthermore, contemplation of current practices and policies from several points of view inevitably led to the deduc-

**TABLE 1 Action Criteria Associated with Some Current or Recent Bridge Deck Policies**

| Percent of Deck With: | FHWA (11) | | | AASHTO (12) | | | Minn. (13) | | | Neb. (12) | | | Ontario (14) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Spot Repair/ Protect | Reha-bili-tate | Re-place | Spot Repair/ Protect | Reha-bili-tate | Re-place | Spot Repair/ Protect | Reha-bili-tate | Re-place | Spot Repair/ Protect | Reha-bili-tate | Re-place | Spot Repair/ Protect | Reha-bili-tate | Re-place |
| Visible Spalls (incl. patched areas) | 0%, or | 0-5%, or | >5%, or | ≤ 10% (combined) or | 11-59% (combined) or | ≥ 60% (combined) or | < 20% (combined) | 20-40% (combined) | > 40% (combined) | 0% or | ≤ 25% (combined) or | ≥ 25% (combined) or | No policy criteria | >5% or | If economic evaluation dictates |
| Delamina-tions | 0-5% (combined) | 5-40% (combined) | > 40% (combined) | | | | | | | | | | | | |
| Corrosion potentials > 0.35 v (CSE) | | | | ≤10% | 11-59% | ≥60% | | | | <25% | 25-50% | >50% | | >20% | |

tion that the most rational approach is one that results in minimum life-cycle costs for bridges, given present deck conditions. This has the effect of combining the two levels of decision making into only one that has an identifiable and quantifiable basis (life-cycle cost). In broad terms the policy developed for the Pennsylvania Department of Transportation involves the identification of technically feasible alternative strategies for perpetual service for each bridge deck, based on the present condition of the deck, and evaluation of the alternatives using accepted engineering economic analysis procedures.

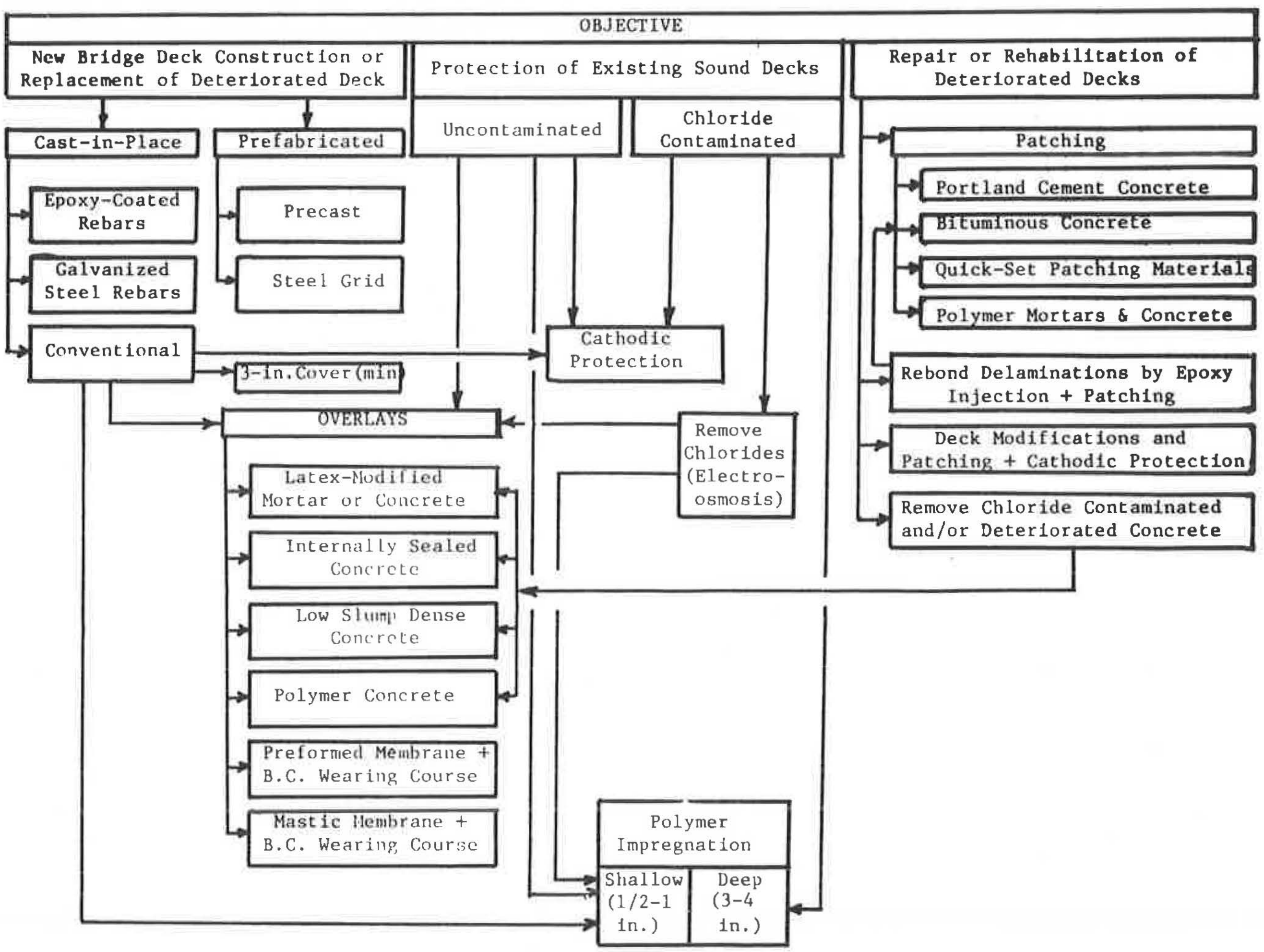


FIGURE 1 Potential methods for effecting protection, repair, rehabilitation, or replacement of bridge decks.

## ECONOMIC ANALYSIS MODEL

### Scenarios and Possible Actions

At any given time in the life of a given bridge deck, one of two scenarios is applicable: the deck is either sound or deteriorated to some degree. If sound, nothing can be done or the deck can be protected from future deterioration. The protective action taken will depend on whether the deck is critically contaminated with chloride ion (as shown in Figure 1). If deteriorated, the actions available depend on the degree of deterioration (Figure 1) and, in order of increasing severity, fall into the following categories:

- Spot patching (bituminous or rigid),
- Bituminous concrete overlayment (for rideability),
- Rehabilitation (using rigid overlays following removal of deteriorated concrete), and
- Deck replacement.

Depending on the present deck condition and the actions taken in a particular alternative, the likelihood exists that a deck will eventually have to be replaced. Therefore, it is also necessary that the expected life-cycle cash flow situation for deck replacement, based on the state-of-the-art situation for new deck construction, be determined.

### Planning Horizon

In general, bridge deck sites are long-lived features. Therefore, it is most convenient and sufficiently accurate in most instances to assume perpetual service as opposed to the selection of a specific planning horizon. However, if it is known that a specific bridge site will be used for less than 50 years, a planning horizon of specific length should be used. The cost difference between 50-year, or greater, and perpetual service is small relative to the uncertainties in predicting future actions and costs. Therefore, the economic model presented here will be based on perpetual service.

### Model

The economic model used here involves the determination of the present worth of perpetual service (capitalized cost) for each alternative using the principles of engineering economic analysis. Discrete cash flow and discrete compounding are assumed. In generalized form the mathematical model is

$$\text{Capitalized cost} = A + B(P/A,i,f) + \sum_{n=1}^{a} [C_n(P/G,i,b_n) + D_n(P/A,i,b_n)]\ (P/F,i,c_n)$$
$$+ \sum_{o=1}^{d} E_o(P/F,i,e_o) + (P/F,i,f)(1/i)\left((A/P,i,g)\left\{F + \sum_{p=1}^{h} [H_p(P/G,i,j_p) + J_p(P/A,i,j_p)] \times (P/F,i,k_p) + \sum_{q=1}^{\ell} K_q(P/F,i,m_q)\right\} + G\right)$$

where

- A = initial repair costs;
- B = uniform annual maintenance and operating costs for present deck from present to time of deck replacement;
- C = annual increases in maintenance costs for present deck due to increasing deterioration (e.g., spall patching);
- D = cost in first year of annually increasing maintenance costs for present deck;
- E = single future expenditures for present deck;
- F = first cost of replacement deck;
- G = uniform annual maintenance and operating costs for replacement deck over life of replacement deck;
- H = annual increases in maintenance costs for replacement deck due to increasing deterioration (e.g., spall patching);
- J = cost in first year of annually increasing maintenance costs for replacement deck;
- K = single future expenditures for replacement deck;
- $a$ = number of periods of increasing maintenance costs for present deck;
- b = duration of increasing maintenance costs for present deck due to progressive deterioration;
- c = time from present to beginning of increasing maintenance costs for present deck due to progressive deterioration;
- $d$ = number of single future expenditures for present deck;
- e = time to single future expenditures for present deck;
- f = time to expected deck replacement;
- g = life of replacement deck;
- $h$ = number of periods of increasing maintenance costs for replacement deck;
- i = interest rate (decimal);
- j = duration of increasing maintenance costs for replacement deck due to progressive deterioration;
- k = time to beginning of increasing maintenance costs for replacement deck (from time of deck replacement);
- $\ell$ = number of single future expenditures for replacement deck;
- m = time to single future expenditures for replacement deck (from time of replacement);
- $n,o,p,q$ = counters;
- (A/P) = capital recovery factor (A/P,i%,n) = $i(1+i)^n/[(1+i)^n - 1]$;
- (P/A) = uniform series present worth factor (P/A,i%,n) = $[(1+i)^n - 1]/i(1+i)^n$;
- (P/F) = single payment present worth factor (P/F,i%,n) = $1/(1+i)^n$; and
- (P/G) = gradient present worth factor (P/G,i%,n) = $(1/i)\{[(1+i)^n - 1/i(1+i)^n] - [n/(1+i)^n]\}$.

A cash flow diagram representing the mathematical model is shown in Figure 2. The model is readily adaptable to microcomputer application.

### Costs and Service Lives

The primary data needed for determination of capitalized cost of alternative strategies are the costs and service lives of the components of the strategies. The problems involved in the accurate determination of service lives for systems lacking in field experience are obvious. Cost data are less difficult to determine, but they are also less generally applicable. That is, average cost figures have virtually no meaning for individual cases. This point is emphasized in NCHRP Synthesis of Highway Practice 57 (15,p.44):

> Wide variations in costs can be expected for the same method of repair applied to dif-

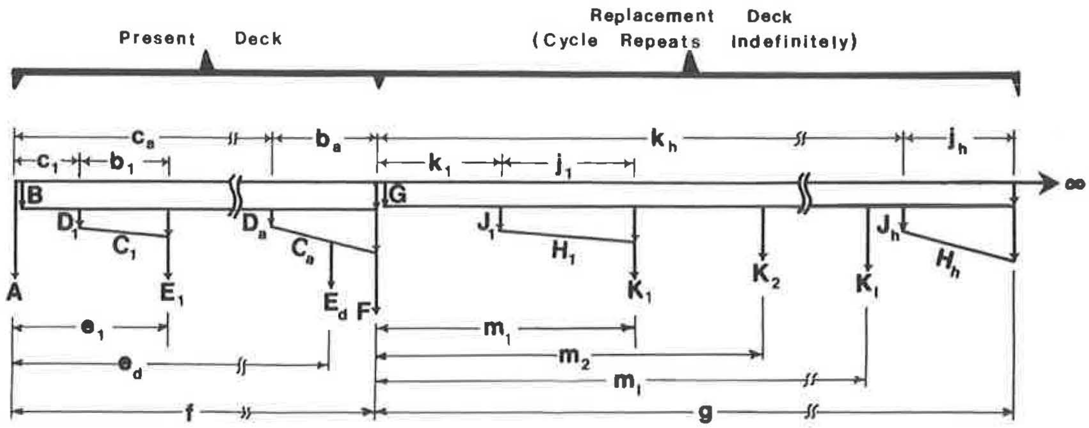


FIGURE 2 Cash flow diagram for capitalized cost evaluation of bridge deck strategies.

ferent structures depending upon the size and location of the structure, traffic volumes, other work included in the same contract, scheduling, and the overall volume of construction work at the time of bidding.

The costs associated with the protection, repair, rehabilitation, and replacement of bridge decks may be classified as follows:

- Installation;
- Annual maintenance;
- Traffic maintenance and protection; and
- Road user costs associated with periods of construction, repair, rehabilitation, or maintenance.

Installation costs are those costs associated with the installation or replacement of a system (e.g., an overlay or a cathodic protection system). They include all direct costs for labor, materials, and deck preparation or modification.

Annual maintenance costs cover the more or less continuous activities necessary to maintain a level of serviceability. They are generally considered to consist of a series of equivalent end-of-year costs that are generally presumed to remain constant or to increase uniformly over a stated period of time. An example is the costs of periodically patching potholes or spalls with bituminous concrete.

Traffic maintenance and protection costs and road user costs to be considered are those associated with periods of construction, repair, rehabilitation, or maintenance.

Within the span of the planning horizon, each alternative might entail several actions, each of which has a service life. For example, a particular strategy for maintaining the serviceability of a certain bridge deck in perpetuum (infinite planning horizon) may involve installing a new deck every 50 years and a new waterproof membrane and wearing course every 10 years. The service lives of the deck and membranes, therefore, are 50 and 10 years, respectively.

The difficulty in attempting to predict service lives is somewhat mitigated by two factors:

- As service life increases, variation in service life has diminishing effect on calculated equivalent cost. As noted previously, there is little difference, economically, between a long service life (50 to 100 years) and infinite service life.
- If the average service lives of relatively short-lived actions are reasonably well known, rather large variations on an individual basis will have relatively little effect over the long run. For example, it can be shown that, if the service life for a particular action falls between 9 and 21 years, 95 percent of the time (typical of rigid overlays), the equivalent cost based on using an average life of 15 years will underestimate the true cost by only 4 percent in the long run (16).

### Interest Rate

Interest rate is the expression of the time value of money in engineering economic evaluations. Prevailing interest rates are generally not appropriate because they include an inflation factor. The true cost of long-term borrowing is considered to be on the order of 4 to 6 percent (17). There are conditions in the evaluation of alternatives in the highway sector where inflation should be taken into account. For a detailed discussion of the latter point see Cady (18). In the Pennsylvania Department of Transportation policy the interest rate is taken to be 5 percent and inflation is ignored.

## PROCEDURE

The procedure involved in applying the bridge deck protection, repair, rehabilitation, or replacement policy described in this paper is summarized in Figure 3.

### Uncovered Decks

The average rebar cover should be determined for all bridge decks not overlaid with bituminous concrete using commercial devices available for this purpose. It has been reported that the standard deviation for rebar cover on bridge decks averages about 0.4 in. (19). Assuming that the reported ±1/8-in. accuracy (15) of the cover measurement equipment represents the 95 percent confidence interval, the number of random readings required to determine the average rebar cover within the accuracy of the equipment is

$$[(1.960)(0.4)]/(0.125)^2 = 40$$

Annual inspections of uncovered decks should include

- Visual examination;
- Sounding (delamination detection); and
- Coring, if necessary.

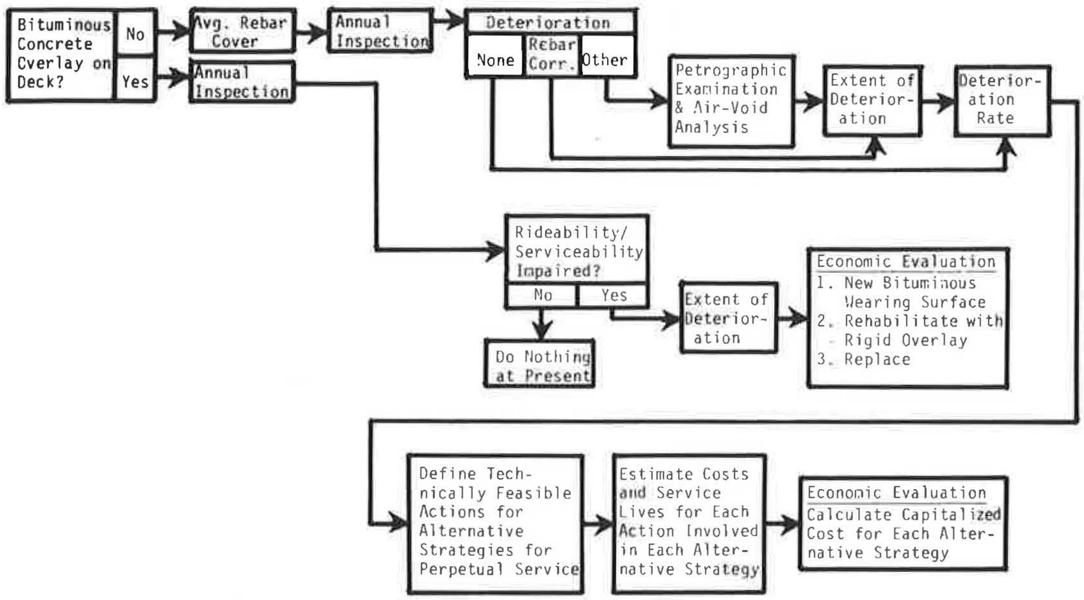


**FIGURE 3 Summary of policy for protection, repair, rehabilitation, or replacement of bridge decks.**

Visual inspection provides rough, approximate answers to two questions relative to bridge deck condition: what are the sources and what is the extent of the problem? The experienced observer can, from the physical appearance of forms of deterioration present, usually determine the sources of problems. Although corrosion of reinforcement is the most serious cause of bridge deck distress, it is not the only problem area found on bridge decks. The appropriate actions will, of course, vary with the nature of the distress. For example, if a bridge deck is deteriorating under the action of freezing and thawing as a result of insufficient air entrainment, cathodic protection will do nothing to mitigate the problem. The extent of visible deterioration should be mapped. Photographs should be taken for documentation.

Sounding to determine the extent of fracture planes (delaminations) that have not yet produced visible surface manifestations should be carried out using a chain drag or equipment commercially available for this purpose.

Coring would be done only if necessary to determine the cause or causes and extent of deterioration other than reinforcement-corrosion-related for the purposes of strength, petrographic, and air-void analyses. The general rule for core sampling uncovered decks is at least one specimen per 2,000 $ft^2$ (20).

Annual inspections provide the data required to define the extent of needed repair or rehabilitation and the rates at which deterioration may be expected to proceed. Deterioration rates are important even for decks found to be in sound condition because they permit evaluation of protection alternatives. Whenever possible, deterioration rates for individual decks should be based on successive annual inspections. This, of course, is not possible for decks that have not yet begun to deteriorate, nor for the first evaluation of any deck. If the cause or potential cause of deterioration is rebar corrosion, a technique is available for estimating the time to development of deterioration and the deterioration rate based on average rebar cover (21).

When the deck condition (including the time to expected deterioration of currently sound decks) and deterioration rate have been determined, alternative strategies for perpetual service can be defined. The costs and service lives associated with the actions contained within each alternative strategy must then be estimated. Finally, the appropriate strategy for the bridge is determined by comparing capitalized costs computed using the economic analysis model.

### Covered Decks

Annual visual inspections should also be carried out on bridge decks covered with bituminous concrete wearing surfaces. When rideability or serviceability conditions require remedial action, the structural adequacy of the deck should be evaluated and economic analyses carried out to determine whether the deck should (a) receive a new wearing course; (b) be rehabilitated with a rigid, low-permeability overlay; or (c) be scheduled for replacement. If coring is necessary to ascertain the condition of a deteriorating covered deck, at least one specimen per 500 to 700 $ft^2$ should be obtained (20).

## APPLICATION

The application of the methodology described in this paper will be demonstrated for one alternative solution involving a common bridge deck scenario.

### Bridge Data

- Average rebar cover by Pachometer survey = 1.8 in.,
- Percentage of deck spalled (including areas previously patched with bituminous concrete) = 4 percent, and
- Deck age = 10 years.

There are no prior inspection data.

### Evaluate the Alternatives

- Continue patching until 20 percent of the deck surface is deteriorated (spalls, bituminous concrete-patched spalls, and delaminations);

- Apply bituminous concrete overlays (estimated life 8 years) until 40 percent of the original deck surface is deteriorated (spalls and fracture planes);
- Apply latex-modified concrete (LMC) overlay; or
- Install new deck with epoxy-coated rebars 10 years after the LMC overlay.

Procedure

1. Using Figure 5 and Equation 21 in Cady and Weyers (21), the expected deterioration (spalls and delaminations) at the beginning of the maintenance (patching with bituminous concrete) period = (0.5) (10%) = 5%.
2. Using Figure 6 in Cady and Weyer (21), the estimated deck age at rehabilitation (LMC overlay) = 20 years (i.e., 10 years from present).
3. Using Figure 7 in Cady and Weyer (21), the estimated deck age at the beginning of maintenance (bituminous concrete patching) period = 5 years (i.e., 5 years ago).
4. Calculate the estimated deterioration rate: (40% - 5%)/(20 yr - 5 yr) = 2.3%/yr.
5. Calculate the time to bituminous concrete overlaying from the present: Percentage deterioration at present = (4)(4%) = 16% based on the assumption that the area of visible spalls is typically about one-fourth of the total deteriorated area (spalls and delaminations). Time to bituminous concrete overlay = (20% = 16%)/2.3%/yr = 1.7, or 2 yr.
6. It has estimated (see item 2) that the deck will have to be rehabilitated (LMC overlay) in 10 years. Therefore, the period of time over which bituminous concrete overlays will be used is 10 - 2 = 8 years.
7. Estimated costs and services lives:

| Action | (Cost ($/ft²) | Expected Life (yr) |
|---|---|---|
| Bituminous concrete patching | 1.23 | 0.67 |
| Bituminous concrete overlay | 0.44 | 8 |
| Deck modifications | 1.00 | |
| Traffic maintenance and protection | 0.25 | |
| Total | 2.92 | |
| Latex-modified concrete overlay | 4.09 | 10 |
| Scarification of 60% of deck surface at $0.61/ft² | 0.37 | |
| Concrete removal to 1 in. below reinforcing steel on 40 percent of deck surface at $14.75/ft² | 5.90 | |
| Traffic maintenance and protection | 1.00 | |
| Total | 11.36 | |
| New deck (epoxy-coated reinforcing bars) | 14.29 | 40 |
| Old deck removal | 11.56 | |
| Traffic maintenance and protection | 2.00 | |
| Total | 27.85 | |

8. Estimate the period of patching on the replacement deck having epoxy-coated rebars. Research work carried out by the Federal Highway Administration (22) indicates that epoxy-coated rebars should give about five times as long maintenance-free service as black steel. This translates to average values of 35 years for 2-in. average cover to 70 years for 2-in. minimum cover. Therefore, assume 40 years for the expected maintenance-free life of epoxy-coated rebar reinforced bridge decks. At the end of this period, assume that the deterioration rate is the same as for black steel. (a) Therefore, patching on the replacement deck begins 40 years after installation = 40 + 20 = 60 years from present. (b) Assuming 2.1%/yr deterioration rate (21) for 20% deterioration (the point at which bituminous concrete overlay is required), period of bituminous concrete patching = 20%/(2.1%/yr) = 9.5 or 10 yr (i.e., years 61-70).
9. Assume an 8-year life for the bituminous concrete overlay and a 10-year life for the subsequent LMC overlay.
10. Summary of actions to be taken.

| Step | Time (yr) | Action |
|---|---|---|
| 1. | 0 (present) -2 | Patch with bituminous concrete |
| 2. | 2 | Overlay with bituminous concrete |
| 3. | 10 | Overlay with latex-modified concrete |
| 4. | 20 | Replace deck (epoxy-coated rebars) |
| 5. | 61-70 | Patch with bituminous concrete |
| 6. | 70 | Overlay with bituminous concrete |
| 7. | 78 | Overlay with latex-modified concrete |
| 8. | 88 | Repeat Steps 4-7 in perpetuum. |

11. Interest rate: Assume average long-term borrowing rate that includes effects of infilation ("true" interest rate) = 5 percent.
12. Cash flow diagram--see Figure 4.
13. Calculations

A = 0
B = 0
$C_1$ = [($1.23/ft²)/0.67 yr] (0.023)(1/4) = $0.011/ft² yr

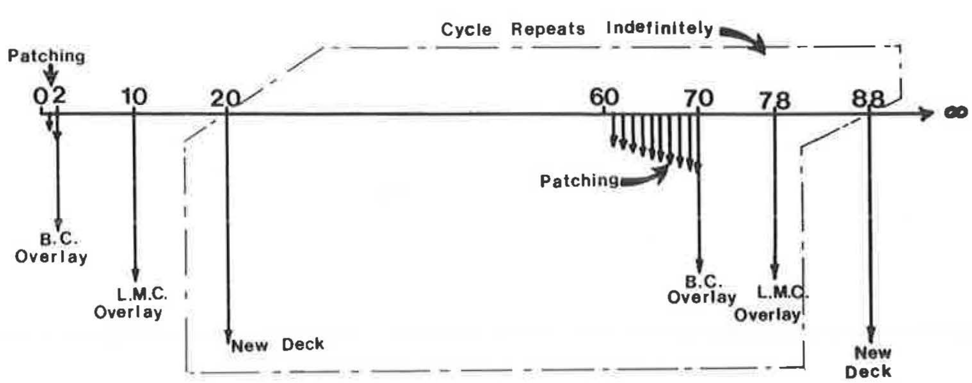


FIGURE 4 Cash flow diagram for example.

$D_1$ = [($1.23/ft²)/0.67 yr] (0.04) = $0.073/ft²/yr (presently 4% of deck is spalled)
$E_1$ = $1.69/ft²
$E_2$ = $11.36/ft²
$F$ = $27.85/ft²
$G$ = 0
$H_1$ = [($1.23/ft²)/0.67 yr] (0.021)(1/4) = $0.010/ft²/yr
$J_1$ = [($1.23/ft²)/0.67 yr] (0.021)(1/4)(1) = $0.010/ft²/yr
$K_1$ = $1.69/ft²
$K_2$ = $11.36/ft²
$a$ = 1
$b_1$ = 2 yr
$c_1$ = 0 yr
$d$ = 2
$e_1$ = 2 yr
$e_2$ = 10 yr
$f$ = 20 yr
$g$ = 68 yr
$h$ = 1
$i$ = 0.05 (5%)
$j_1$ = 10 yr
$k_1$ = 40 yr
$\ell$ = 2
$m_1$ = 50 yr
$m_2$ = 58 yr

$$\text{Capitalized cost} = 0 + 0 + [(0.011)\overset{0.906}{(P/G,5\%,2)} + (0.073)\overset{1.8594}{(P/A,5\%,2)}]\overset{1.0000}{(P/F,5\%,0)} + [(1.69)\overset{0.9070}{(P/F,5\%,2)} + (11.36)\overset{0.6139}{(P/F,5\%,10)}] + \overset{0.3769}{(P/F,5\%,20)}(1/0.05)\left(\overset{0.05188}{A/P,5\%,68)}\{27.85 + [(0.010)\overset{31.649}{(P/G,5\%,10)} + (0.010)\overset{7.7216}{(P/A,5\%,10)}]\overset{0.1420}{(P/F,5\%,40)} + (1.69)\overset{0.0872}{(P/F,5\%,50)} + (11.36)\overset{0.0590}{(P/F,5\%,58)}\} + 0\right) = \$19.89/\text{ft}^2.$$

Similar calculations would be carried out to evaluate the other technically feasible strategies for this bridge deck. The course of action is then dictated by the lowest capitalized cost.

A word of caution regarding the foregoing example: The costs and service lives of the various actions involved in the strategy shown are presented for illustrative purposes only. The values of these parameters (particularly costs) may be expected to vary widely with time, geographic location, and other factors. This underscores the need for sound engineering judgment in developing and costing out the strategies for bridge decks on an individual basis.

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# Setting Maintenance Levels for Aggregate Surface Roads

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ABSTRACT

Aggregate surface road maintenance activity frequency guides based on minimizing total maintenance and user costs were developed for Bolivia's national highway department. The guides result from predicting road roughness and simulating the operation of vehicles on the road. Presented are equations that predict road roughness as a function of traffic volume and equations that relate road roughness to vehicle operating costs in Bolivia.

Aggregate surface road ride quality is defined by the service level for surface maintenance activities. Many agencies execute maintenance in response to surface condition. Others base maintenance frequencies on resource availability (e.g., the number of motor graders that are operational).

Responding to condition on the basis of judgment depends on the person controlling the maintenance activity. Because supervisors change and there are a number of different persons controlling maintenance in any jurisdictional area, there will be a lack of uniformity when this approach is used.

When maintenance service levels are based on resource availability, deficient levels may result. It is useful, therefore, to have objective guides to use in establishing service levels and resource requirements.

## SETTING MAINTENANCE LEVELS FOR AGGREGATE SURFACE ROADS

One basis for establishing objective guides is to compare the costs of alternatives, not only agency costs but user costs. Evaluating the effect of road condition on user costs has received considerable attention in recent years. The World Bank has encouraged and supported a number of studies worldwide to develop relationships between road surface conditions and user costs (1-4). These relationships allow analyses to be made of the user costs to operate on roads in different condition (5-7).

Vehicle operating costs are influenced by the road's traveling surface. This is where the interaction between the vehicle and the road occurs. Therefore, it is primarily defects in this traveling surface that adversely affect road users.

Maximum benefits to the road user occur when a road is kept in its newly constructed condition. This is not economically practical so a lesser level is always sought. The optimum economic level is determined by comparing the costs to maintain or rehabilitate the road with the costs to users at different levels of deterioration. A level is selected on the basis of a strategy that minimizes total overall costs. This optimum strategy depends on the number and composition of users plus the characteristics of the road and the environment in which the road is situated.

From 1981 through 1983, the Bolivian national highway department, Servicio Nacional de Caminos (SNC), conducted studies to improve their highway maintenance practices. The single most costly maintenance activity performed by SNC is aggregate road surface maintenance. Consequently, objective criteria were developed to set maintenance levels for this work. The criteria proposed for establishing maintenance service levels were to minimize total mainte-