Life-Cycle Cost Evaluations of the Effects of Pavement Maintenance

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Several recent trends in highway programs suggest an increasingly important role for maintenance in future pavement management, operations, data collection, and research. The movement toward life-cycle costing as the economic framework for pavement management decisions will cause managers to consider maintenance as one of a spectrum of options available and to evaluate trade-offs among these alternatives in a more flexible, integrated decision-making process. Furthermore, maintenance is a prime candidate for emerging technologies and research in improved data acquisition and processing, nondestructive testing and evaluation, management of the maintenance function, and materials and equipment needed for maintenance performance. The ways in which the technical, economic, and management aspects of maintenance can be incorporated in life-cycle costing and the results of different assumptions in these areas and their implications for pavement performance and costs are explored. A microcomputer-based procedure for pavement life-cycle costing was employed. The program emphasizes pavement policy at the network level and includes an analytic treatment of routine maintenance that accounts for relative levels of effort and the technological effectiveness of maintenance activities, as well as their scheduling and costs. The benefits of maintenance are expressed as reductions in user costs of vehicle operation as a function of pavement condition; the discounted benefits are compared with the discounted costs of maintenance performance to assess the value of different maintenance options and the technological characteristics of maintenance. The findings affirm the substantial benefits of maintenance relative to costs, the benefits of further improvements in maintenance technology, the long-term benefits of early and frequent maintenance, and the need for management decisions to reinforce the inherent technological capabilities of maintenance in correcting pavement condition.

Recent trends in highway programs suggest that pavement maintenance will occupy an increasingly important role, entailing a more sophisticated treatment, in future pavement management, operations, data collection, and research. The Interstate system and concurrent programs of road construction during the past four decades are ending, resulting in not only more mileage to maintain, but also an inventory of higher-standard, more intensely used roads. Sources of highway financing are continuing to shift from the federal government to state and local governments (historically the providers of road maintenance) and to the private sector (which stands to become more involved in the maintenance and rehabilitation of the maturing road system). Emerging technologies hold several potential applications to both preventive and responsive maintenance and related tasks of highway inspection, ranging from new methods of nondestructive testing and field data collection and analysis to developments in computer hardware and software technology. These and other trends are reflected in new federal policy directives that promise to change the ways in which maintenance and other highway activities are viewed, managed, and evaluated.

Pavement activities in particular are of interest to policy makers because of

- The high visibility of pavements to the motoring public and their close association with perceptions of the highway network overall;
- The strong implications of pavement condition for road structure, operation, and safety;
- The major proportion of highway infrastructure investment represented by pavements;
- The significant trade-offs inherent among options in pavement design, construction, inspection, maintenance, rehabilitation, and reconstruction;
- The need for a long-term perspective in the analysis of pavement strategies; and
- The resulting importance of pavements to management at all levels in federal, state, and local government.

These ideas have been captured in two recent federal pronouncements that will guide future highway transportation policy and, by implication, influence future directions of pavement maintenance management: (*a*) FHWA's new policy on pavement management and eligibility of pavement projects for federal aid and (*b*) the U.S. Department of Transportation's (DOT's) National Transportation Policy.

The FHWA policy on pavements requires states to implement pavement management systems by 1993 and describes the systems' requirements and their proposed applications to specific highway functional classes in the federal-aid system (*1*). An important methodological advance is the recommendation of a life-cycle economic analysis as the framework within which pavement alternatives will be evaluated. The importance of timely, effective pavement maintenance (both preventive and responsive) is clearly recognized. However, because routine maintenance is not eligible for federal aid, the FHWA policy statement does not elaborate on its analysis in pavement management. Nevertheless, the role of maintenance may be inferred from the FHWA guidelines in several areas:

- The requirement for a life-cycle analysis implicitly includes maintenance as one set of actions to be evaluated, complementing pavement design, construction, rehabilitation, and reconstruction.
- Maintenance history is one variable that influences pavement performance (together with traffic, pavement structural

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and materials properties, environment, construction quality, subgrade and drainage, and variability in these parameters)

- Maintenance of the pavement surface (through activities like joint and crack sealing) is critical to retarding water from entering the pavement foundation, which forestalls a primary cause of premature failure.
- Because maintenance is funded differently from capital projects, it is one of the decision variables managers have at their disposal to allocate resources throughout a road network and over time, meet critical road priorities, and remain within budget constraints.

DOT's National Transportation Policy is a much broader, more comprehensive statement of federal objectives, priorities, and strategies in highways and other modes of transportation (*2*). This recently completed report establishes the context for new federal directions in transportation into the next century. Among its many findings and recommendations, several have important implications for pavement maintenance:

- Maintaining existing transportation assets is identified as "the most immediate task for the transportation sector." The national policy envisions this task as a shared responsibility, with the federal government emphasizing capital repairs in its aid programs and state and local governments taking the lead in managing and maintaining facilities.
- The plan adopts a more flexible perspective on aid programs, seeking to encourage a broader range of options and to eliminate "unnecessary or unwise investment."
- The national policy recognizes the potential role of the private sector to join with the public sector in providing needed transportation infrastructure and encourages the elimination or the mitigation of barriers to private-sector participation in planning, owning, financing, building, maintaining, and managing transport facilities and services. Federal policies should also provide better incentives for increased participation by other levels of government and the private sector.
- The importance of early maintenance is emphasized, both to preserve existing assets and to reduce the long-term costs of facility repair. In some cases, "Federal-aid programs have detracted from effective maintenance by tending to encourage new construction at the expense of maintenance."

Taken together, all these trends suggest a number of changes that will affect pavement maintenance in the coming years:

- The role of highway maintenance will continue to evolve in terms of both the increasing demand for maintenance work and the limited supply of increasingly sophisticated maintenance services.
- In allocating highway resources in the future, managers will consider maintenance as one of a spectrum of available options, and will evaluate the trade-offs among the alternatives in a more flexible, integrated decision-making framework. In addition to maintenance, the range of options will include different levels of design and construction quality; various frequencies and levels of inspection, rehabilitation, and reconstruction; and regulatory options governing, for example, vehicle size and weight—all able to be addressed within the life-cycle cost framework proposed by FHWA (*1*).
- Emerging technologies and research dedicated specifically to maintenance will enable much-improved data acquisition and processing, nondestructive testing and evaluation, management of the maintenance function, and performance of maintenance activities.

Ideally, life-cycle costing procedures envisioned for pavement management will anticipate these trends and enable managers to account for them as part of their analyses of pavement options. Indeed, tools are already available to incorporate maintenance in an economic analysis of pavements, as will be described. However, maintenance has suffered from a lack of dedicated research that is only now beginning to be rectified, particularly through the maintenance component of the Strategic Highway Research Program. This research is considering, for example, the effectiveness of different pavement maintenance treatments and the investigation of new methods of nondestructive testing specifically intended for preventive maintenance. The results of these efforts will begin to provide the field validation of how different maintenance activities affect the condition of the pavement and, therefore, what their benefits are in relation to their costs. In the meantime, findings such as those to be described, derived from the results of computer simulations, provide a framework for understanding the life-cycle implications of maintenance for pavement performance and costs. They illustrate the types of relationships that can be expected to result and indicate generally how life-cycle analyses of pavement maintenance need to be structured.

METHODOLOGICAL APPROACH

Historical Perspective

Life-cycle costing of capital assets is not a new concept. It has been applied by industry to plant and equipment for many years. With respect to U.S. highways, basic concepts of engineering economy were formulated more than 100 years ago and began to be applied in studies of highway improvements in the 1920s. More recently, concepts and principles of highway engineering economy in the modern U.S. highway system were compiled, organized, and quantified by Winfrey (*3,4*). This work not only defined a methodological framework, but also focused in detail on the important cost components (e.g., construction and maintenance costs on the agency side and road user consequences on the benefits side) and engineering or technological data affecting these costs (e.g., traffic characteristics, accidents, vehicle power performance, etc.).

These concepts and methods historically have been applied primarily in the context of improvements in the highway system (new construction or major reconstruction and, later, rehabilitation). Routine maintenance, by contrast, was more difficult to incorporate in this framework through the 1960s and early 1970s—not for theoretical reasons, but because of lack of good data in the appropriate form. For example, whereas estimates of annual maintenance costs could be obtained on a systemwide basis, "the desired specific highway maintenance expenses [needed for economic studies of a particular highway link or project] are not available" (*3*). The problem was summarized as follows (*5*):

> There has been much interest over the past decade in the evaluation of highway development, but little has been written on the evaluation of highway maintenance. In practice, maintenance expenditure decisions have continued to be made largely on the traditional and simple grounds that maintenance is necessary to preserve the road assets. While this is frequently true, it is a rough judgement. Moreover, it fails to consider whether the expenditure is justified, for instance, by savings in vehicle operating costs; and it affords no means of quantifying the returns from other expenditures.
>
> This lack of interest in the economics of road maintenance has been due doubtless to its Cinderella image, compared with the more virile image of driving new roads through virgin territory. Perhaps also the lack of interest has been due partly to the feeling that road maintenance would fall away as better roads were built (savings in maintenance are frequently included as a benefit in road construction programmes). Partly, perhaps, it reflected the notion that road maintenance raised no separate problems from those of road construction. While the "Cinderella image" remains a matter of opinion, neither of the other two ideas has turned out to be correct.

At least three factors began to change this situation in the United States in the 1970s: (*a*) the growing realization of the role of maintenance in road preservation, (*b*) the widespread implementation of maintenance management systems in state DOTs, and (*c*) the successful integration of maintenance in an economic decision support framework by international lending agencies like the World Bank. A strong motivation existed to incorporate road maintenance in an analytic framework for projects overseas: particularly in developing countries in tropical climates, low-volume roads that were poorly maintained did not fulfill their design lives. Case studies of these roads illustrated dramatically the trade-offs that existed not only between design standards and maintenance standards, but also between the level of service afforded by the road (a function of design standards, construction quality, and standards of maintenance and rehabilitation) and the consequences to road users. The trade-offs were structured within a life-cycle economic analysis of design, construction, and maintenance standards and technologies as early as 1969 and culminated in the documentation of the World Bank's Highway Design and Maintenance Standards Study and its related computerized procedure, the Highway Design Model (HDM-III) (*6,7*).

Approaches to Pavement Maintenance

The evolution of these techniques in U.S. practice has been summarized with respect to pavement construction, rehabilitation, and maintenance in several sources (*8–10*). Also, applications of life-cycle economic analysis to highways (especially to evaluate construction and rehabilitation alternatives) are described in the pavement management literature and, more recently, in the development of bridge management systems. In focusing on pavement routine maintenance, two approaches to the problem that have been employed in life-cycle cost routines are outlined.

An example of the first approach is given by FHWA's EAROMAR-2 system, a project-level, life-cycle cost procedure for flexible, rigid, and composite pavements (*11*). The specific maintenance-related benefit considered in EAROMAR-2 is the contribution of crack sealing, joint sealing, and patching to the preservation of an impervious pavement surface. When such activities are not performed with sufficient frequency, EAROMAR-2 simulates a progression of events leading from infiltration of water through surface discontinuities to decreases in pavement strength, incremental increases in the rate of deterioration, and resulting increases in life-cycle costs.

The structure of this detailed type of simulation permits an explicit treatment not only of the life-cycle impacts of pavement maintenance, but also of the interactions between maintenance and other factors affecting pavement performance and costs (e.g., the structural and materials properties of the pavement cross section, local environment, and traffic). EAROMAR-2 was applied to a study of the impacts of deferred pavement maintenance. The results indicated that regular and frequent sealing of pavement cracks and other discontinuities could lengthen pavement service life up to about 4 years for both flexible and rigid surfaces (*12*).

The second approach is simpler and more direct. Rather than accounting for the action of maintenance in countering pavement damage mechanisms, it assigns some adjustment due to maintenance directly to the simulation of pavement condition. The adjustment may be in one of two forms: a reduction in the rate of future deterioration or a modest improvement in the measure of current pavement condition. Although this approach lacks the technical sophistication of EAROMAR-2, its simplicity presents the following advantages: a computational economy better suited to network-level pavement analyses; the ability to analyze maintenance activities whose impacts cannot be easily described in more detailed, mechanistic formulations; compatibility with a broader treatment of the technological characteristics of maintenance; and greater ease in implementing on a microcomputer.

Because of these advantages, the second approach was used to develop the findings of this paper. The model used was developed for FHWA (*10*). Pavement condition is measured in terms of a pavement condition index (PCI) on a scale of 0 to 100; the pavement deterioration model predicts the annual reduction in PCI as a function of pavement structure, traffic loads, and an age-related term to reflect nonload causes of damage. The effects of routine maintenance are expressed in terms of limited, positive adjustments in the value of the current PCI. Costs are computed both on the agency side (for pavement construction, rehabilitation, and routine maintenance) and on the road user side (for vehicle operation and travel time, both as affected by current pavement condition).

A complete knowledge of the mathematical functions used in these predictions is not necessary for the purposes of this paper; that information is provided elsewhere (*10*). A more detailed explanation of the models simulating the effects of pavement maintenance itself, however, will be useful. This development is given in the following two sections.

Conceptual Development

Pavement maintenance is modeled as a periodic, limited adjustment in current PCI. Over time, the cumulative effect of these adjustments is to reduce the rate of pavement deterioration. The degree to which maintenance offsets the deterioration trend depends on three aspects of maintenance: the effectiveness of maintenance in counteracting pavement damage, the relative level of maintenance performed, and the variation in the level of maintenance over time.

The concept of effectiveness captures two technological characteristics of maintenance: (*a*) the inherent limitation of maintenance in its ability to affect pavement condition and (*b*) the dependence of this effect on the prior condition of the pavement. The first characteristic is qualitative and helps distinguish maintenance from more intensive activities such as rehabilitation or major repairs. For example, simulation results suggest that the beneficial effects of activities like slurry seals or fog seals of asphalt pavements do not exceed a gain of about 18 PCI points (*10*). The second characteristic derives from the experience that maintenance does not necessarily have the same beneficial effect throughout a pavement's life. For example, a new pavement may receive no benefits from maintenance because there is little or no damage to correct. At the other extreme, a severely deteriorated pavement may also derive little benefit from maintenance because its distress has proceeded too far. Thus, the maximum benefits of maintenance may lie in some midrange of pavement condition, although it is also possible to conceive of maintenance activities whose effectiveness plots are skewed [e.g., analytic studies of pavement patching suggest that maximum effectiveness occurs later in the pavement's life (*13*)].

Maintenance policies do not always call for 100 percent of existing damage to be repaired. Thus, the level of maintenance performed is a variable that must be superimposed on the consideration of effectiveness. The level of maintenance can be expressed conveniently through some relative measure—for example, a percentage or a scaled value. The latter will be used in this study. Level of maintenance will be defined on a scale of 0 to 10, with 0 indicating no maintenance and 10 indicating full maintenance. However, the level of maintenance is a potential value, because maintenance effectiveness also controls the degree of adjustment actually accomplished in pavement condition. Therefore, maintenance has little effect, regardless of the level specified, when the pavement is new or when it has deteriorated significantly.

The third effect represented in the maintenance model is the variation in the level of maintenance over time. It represents management decisions on when in the pavement life cycle to adjust the level of maintenance performed. Furthermore, it recognizes that pavement maintenance is not a one-time event, but rather comprises a series of periodic activities during some interval of the pavement's life. In this context, for example, a policy of "excellent maintenance" implies repeated performance of a mix of well-executed maintenance activities during some time, not simply a single instance of a high-quality maintenance treatment.

The second and third effects—the level of maintenance performed and the time variation of these levels—are under the control of management and can therefore be viewed as elements of maintenance policy. Maintenance effectiveness, on the other hand, is a technical matter. Maintenance effectiveness is sensitive to both the characteristics of pavement construction (i.e., how "receptive" the pavement is to maintenance) and the technology of maintenance itself. Improvements in either of these areas can change the degree to which maintenance can influence the condition of a pavement throughout its service life. Both the level of maintenance and its effectiveness can limit the adjustment in pavement condition that is achieved in any given year. The maintenance effectiveness defines the maximum adjustment that is technically possible; the level of maintenance and its scheduling define what percentage of total maintenance benefit available will be realized in the field.

Mathematical Development

These ideas can be reinforced more precisely in the mathematical models used to simulate pavement maintenance in each year t of the pavement life cycle. Assume that a pavement deterioration model is available to compute the annual incremental loss in PCI as a function of pavement structure, materials, traffic, environment, and other relevant factors. The adjustment in pavement condition due to routine maintenance in year t is as follows:

$$\Delta p_t = (L(t)/10)E \qquad \Delta p_t \leq \Delta P_t \tag{1}$$

where

Δp_t = the adjustment in pavement PCI due to routine maintenance in year t;
$L(t)$ = the level of pavement routine maintenance performance in year t on a scale of 0 to 10, as discussed above;
E = the effectiveness of routine maintenance at the current value of PCI, P_t; and
ΔP_t = the incremental loss in PCI due to pavement deterioration in year t.

Equation 1 limits the beneficial impact that maintenance has on pavement condition to that allowed by (*a*) the level of pavement routine maintenance specified by the manager, (*b*) the technological effectiveness of maintenance, and (*c*) the incremental deterioration in pavement condition. The third constraint inhibits maintenance from significantly improving pavement condition (a situation characterizing rehabilitation rather than routine maintenance). Thus, under ideal conditions, it is possible for maintenance to just offset the rate of deterioration, with no decrease or increase in pavement condition during this period. More typically, the limits imposed by either the maintenance level of performance or the maintenance effectiveness in Equation 1 will cause the predicted adjustment Δp_t to be less than the current rate of deterioration, resulting in a long-term decline in pavement condition to the point of rehabilitation or reconstruction.

For purposes of life-cycle costing, routine maintenance costs are modeled as a linear function of maintenance policy:

$$C(t) = \frac{cL(t)}{5} AR(t) \tag{2}$$

where

$C(t)$ = the pavement routine maintenance cost in year t, in dollars;
c = the unit maintenance cost, in constant dollars per lane mile per year, input as part of the description

of maintenance activities, and geared to average maintenance performance [i.e., maintenance level $L(t) = 5$];

$L(t)$ = the relative level of maintenance performance in year t;

A = the lane miles of pavement being maintained; and

$R(t)$ = the ratio of the following quantities: the actual adjustment due to routine maintenance and the total adjustment theoretically possible in year t, as computed by Equation 3.

$$R(t) = \frac{\Delta p_t}{EL(t)/10} \qquad (3)$$

A comparison of Equations 1 and 3 shows that the ratio $R(t)$ will be less than 1.0 when Δp_t is limited by ΔP_t (i.e., when the incremental pavement damage bounds the incremental maintenance that can be performed). Therefore, the maintenance ratio term $R(t)$ acts as a proportional adjustment to the costs calculated in Equation 2 to account for this effective cap on the amount of maintenance that can actually be performed.

EXAMPLE ANALYSES

A series of examples using the models in Equations 1 through 3 will illustrate the application of life-cycle costing techniques to pavement maintenance. Different cases will be illustrated by varying, in turn, the technological effectiveness of maintenance, E, and the levels of maintenance effort, $L(t)$. The implications of the results for the technical, managerial, financial, and research aspects of maintenance management will then be explained.

Problem Description

The case study employs the pavement life-cycle cost model (*10*). To provide a basis for comparison, a zero-maintenance pavement deterioration curve was defined as shown in Figure 1. (The PCI at the end of 20 years is predicted to be 34.) The shape of the curve is characteristic of the deterioration model (*10*) and approximates an S-shaped deterioration trend. Any other pavement damage model could have been used as well, and the implications of other model choices will be discussed below. The focus will be on the relative changes in the deterioration trend as a function of different levels and effectiveness of routine maintenance.

The effectiveness of routine maintenance is characterized by the maximum effectiveness possible and the distribution of effectiveness values as a function of pavement condition. Values of effectiveness are measured by the potential adjustment in PCI points due to maintenance (sometimes called add points). Four distributions of effectiveness were tested:

- Early effectiveness, with maintenance providing the maximum benefit when the pavement is in good to excellent condition;
- Midrange effectiveness, with maintenance providing the maximum benefit when the pavement condition is in the middle of the PCI scale, between 40 and 60;
- Delayed effectiveness, with maintenance providing the maximum benefit when the pavement condition is between 30 and 40 on the PCI scale; and
- Late effectiveness, with maintenance providing the maximum benefit when the pavement condition is poor.

For each of these distributions, three levels of maximum effectiveness were tested: 10, 25, and 40 add points. Figures 2 and 3 show two of the effectiveness distributions for a maximum potential adjustment of 25 PCI add points.

Three facts should be noted regarding the definitions of effectiveness. First, the distributions of effectiveness respond to pavement condition, not to time. The labels such as "early" or "late" characterize the maximum potential impact of maintenance with respect to PCI, not age. (PCI may be correlated with age when a pavement first enters service, because the rate of PCI deterioration includes an age-related term. Once

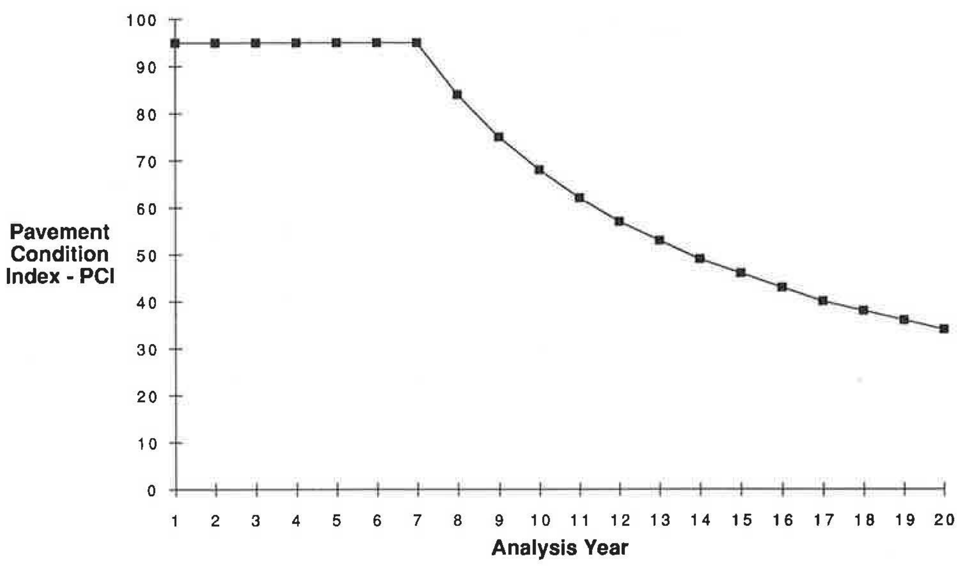

FIGURE 1 Pavement deterioration curve—no maintenance.

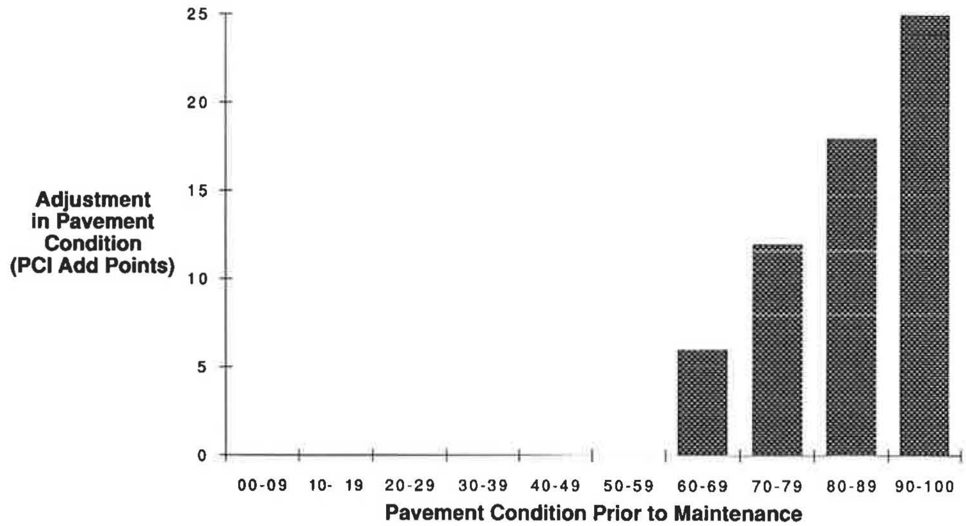

FIGURE 2 Example of early effectiveness (maximum effectiveness = 25 PCI points).

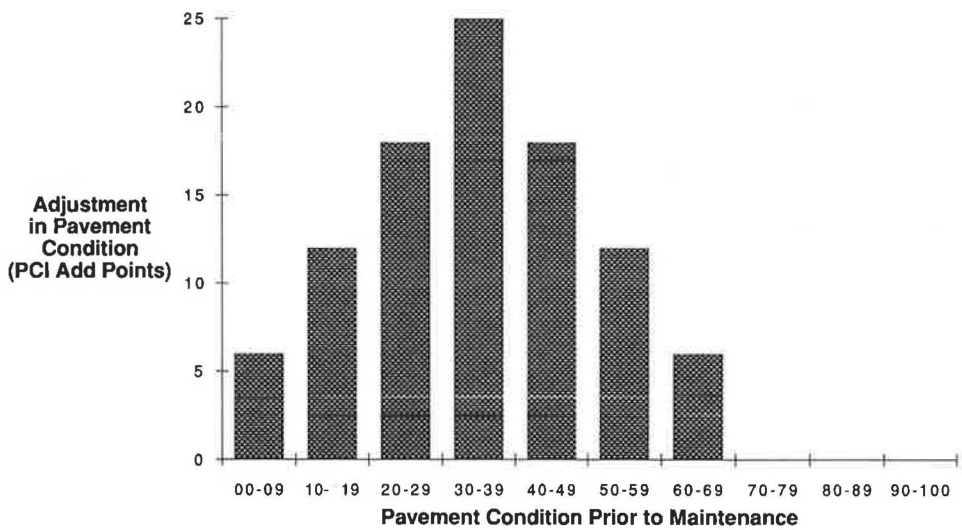

FIGURE 3 Example of delayed effectiveness (maximum effectiveness = 25 PCI points).

maintenance begins to be performed, however, the resulting increments of PCI improvement offset deterioration at least in part, and the relationship between PCI and age weakens.) Second, both the deterioration and the maintenance of the pavement are described in general terms, without distinction of pavement type or maintenance activity. This device is intentional and focuses the discussion on the broader consequences of maintenance policy and technology. Third, the definitions are intended to test a broad range of maintenance possibilities, not all realistic by today's technology. For example, an improvement of 40 PCI points would be a substantial adjustment for routine maintenance to achieve; that level of repair is more typical of rehabilitation. Nevertheless, the purpose of the case study is to probe the implications of different maintenance characteristics for life-cycle costing and to identify parameters for further research. Testing maintenance possibilities at the limits is part of this process.

The PCI add points described by the effectiveness distributions were referred to as potential adjustments, because they may be limited by management decisions on the level of maintenance to be performed. Two levels of maintenance are illustrated extensively in the case study: an average level of 5.0 and a "perfect" level of 10.0. The opposite extreme, zero maintenance, has already been established in Figure 1. An additional level of 2.5 will be introduced in the discussion of economic results. The exploration of this wide range of values will indicate important trends in the relationship of maintenance to pavement performance and costs.

An analysis period of 20 years was selected for this example. The discount rate used was 7 percent. The problem could be analyzed with other combinations of analysis period and discount rate, but the decision was made to focus more on the variation in the maintenance parameters themselves.

Technical Implications: The Role of Effectiveness

The twelve combinations of maintenance effectiveness (four distributions and three maximum values) were imposed on the pavement deterioration curve in Figure 1. To allow the full mobilization of technological effectiveness, the maintenance level was set at 10.0 for this set of runs. An example of the results obtained is shown in Figure 4 for effectiveness distributions limited by maximum potential values of 10 PCI points. (Results for maximum improvements of 25 and 40 points are similar to those shown in Figure 4, but the curves on the right-hand side of the figure are elevated, reflecting the additional improvement due to maintenance.) For each of the four distributions of effectiveness in Figure 4, two curves are drawn: the lower curve (solid symbols) indicates the value of PCI each year before maintenance; the upper curve (hollow symbols), after maintenance.

The results indicate that maintenance effectiveness can influence the long-term trend of pavement condition. Both the distribution of effectiveness and its maximum potential value contribute to this result. For example, maintenance activities with early effectiveness (acting on pavements with PCI of 60 to 100, as shown in Figure 2) maintain pavement condition at a correspondingly high level. Whereas the activities with maximum effectiveness of 10 are able to sustain PCI values in the high 80s (Figure 4), those with a maximum effectiveness of 25 (or 40) are able to sustain a PCI value essentially equal to that of a new pavement. On the other hand, activities with a delayed effectiveness (Figure 3) operate on the pavement in a lower PCI range. For the delayed effectiveness, a maximum adjustment of 10 PCI points will maintain the long-term pavement condition in the high 50s, but a maximum adjustment of 25 (or 40) will maintain pavement condition in the high 60s. Activities with late effectiveness have no influence on the deterioration trend at a maximum value of 10 PCI add points and only a marginal influence at a maximum of 25 add points.

Figure 4 shows pavement condition maintained indefinitely at some level as the result of maintenance—an unrealistic result, particularly over a long period of time. The reason is that the maintenance applications in Figure 4 are idealistic in that their full effectiveness is mobilized (i.e., maintenance level = 10.0). Thus, in these cases the routine maintenance overcomes the incremental deterioration in pavement condition each year. If a realistic maximum effectiveness of 10 PCI is considered, as in Figure 4, but an average level of maintenance of 5.0 is imposed, the result is as shown in Figure 5.

Figure 5 indicates a more realistic trend, particularly for activities with early maintenance effectiveness. There is clearly a benefit of this maintenance, but it does not extend indefinitely. Instead, the curve shows an adjustment of about 8 PCI points above the zero-maintenance trend (which is coincident with the curve for late maintenance effectiveness in Figure 5). This correction translates in Figure 5 into an extension of pavement life of 3 to 4 years, which agrees with other findings (*12*). The midrange and delayed effectiveness curves still show an indefinitely maintained condition in Figure 5, because these activities occur on a more gently sloping part of the deterioration curve and are thus able still to counteract the predicted deterioration each year. This would not be the case, however, if they occurred on a more strongly concave segment of the deterioration function (i.e., where the rate of damage accelerates with time). Thus, the results below may be conservative for activities whose effectiveness occurs later in the pavement's life.

Management Implications: The Role of Maintenance Level

Figure 5 showed the interaction between the technological effectiveness of maintenance and the level of maintenance

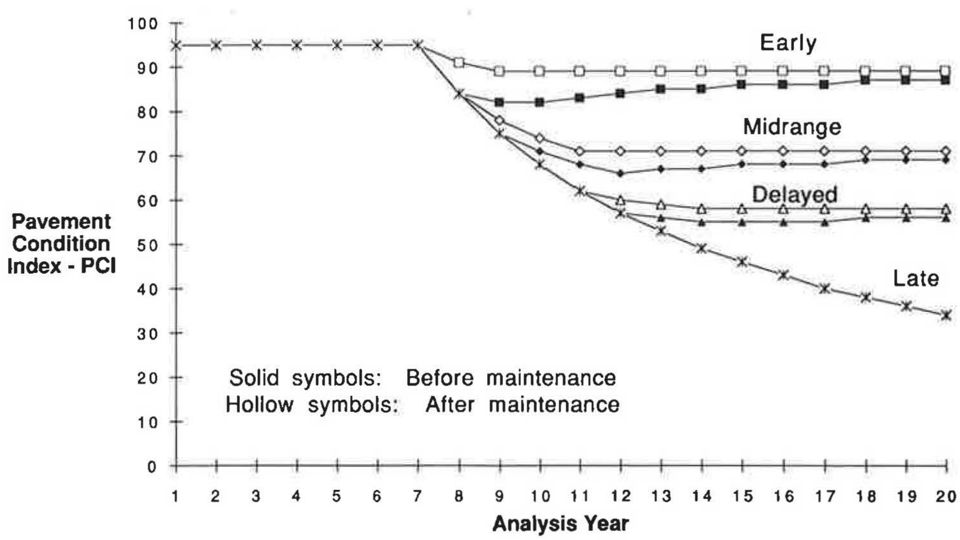

FIGURE 4 Influence of maintenance effectiveness (maximum effectiveness = 10 PCI points, level of maintenance = 10.0).

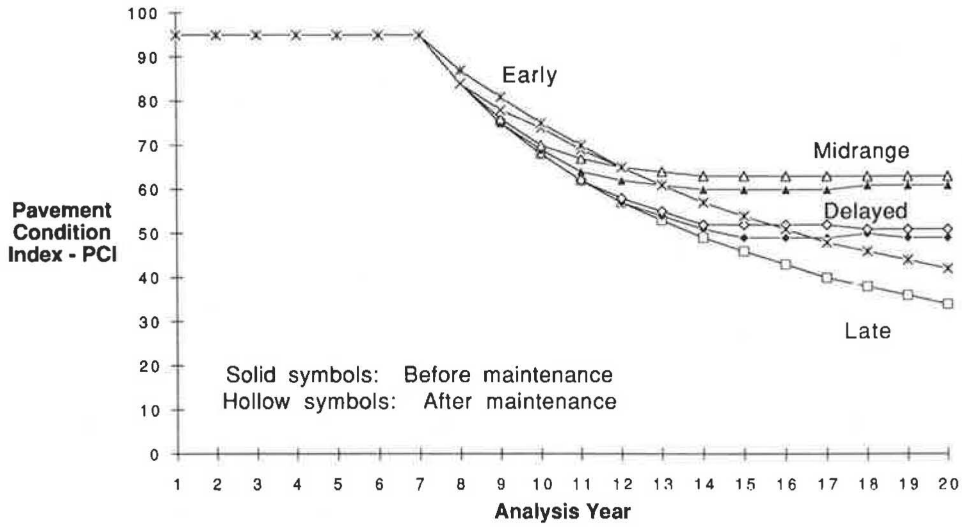

FIGURE 5 Influence of maintenance effectiveness (maximum effectiveness = 10 PCI points, level of maintenance = 5.0).

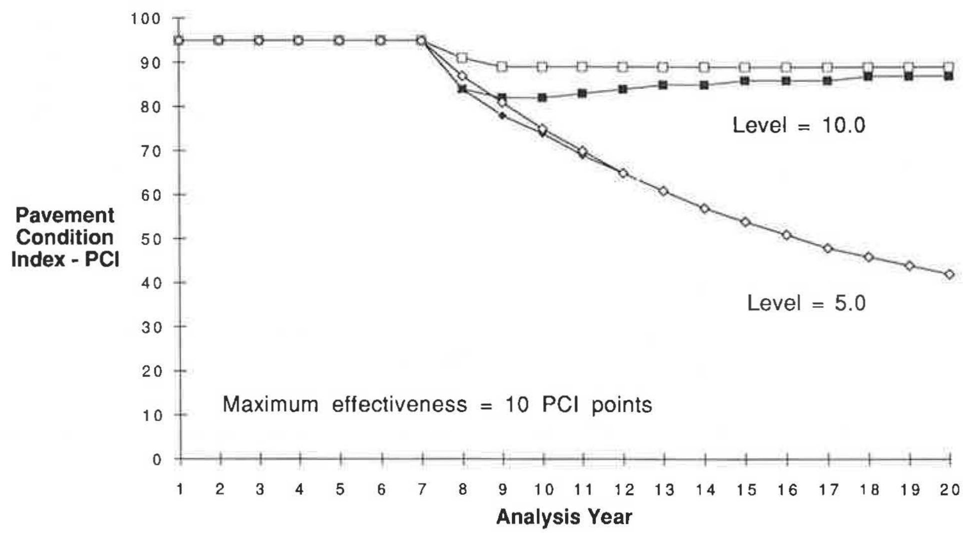

FIGURE 6 Influence of level of maintenance for activities with early effectiveness.

performance specified by management. The interaction is explored further in this section. Figure 6 shows the results of the two levels of maintenance applied to activities of early effectiveness having a maximum adjustment of 10 points. Essentially, it captures the comparison of results between Figures 4 and 5 described above. As before, pairs of curves for each level show, respectively, the PCI values before and after maintenance each year. The divergence in the deterioration trends for the two levels shows dramatically the implications of failing to exploit the full technological benefits of maintenance, especially when the rate of pavement deterioration is rapid. As explained, this type of result occurs not because of the early stage at which this maintenance is performed per se, but rather because in the case under investigation, maintenance with early effectiveness intervenes exactly when the pavement is deteriorating most rapidly. With a different shaped deterioration curve, other examples of maintenance effectiveness would exhibit this type of behavior.

Economic Implications: The Role of Discounted Costs

Discounted cost streams were computed for each case above (and an additional one for a maintenance level of 2.5), tabulating both highway agency costs for routine maintenance and road user costs. The user cost calculations (*10*) include some sensitivity of vehicle operating costs to pavement condition, and it is these differences that were compared among the maintenance alternatives. A total life-cycle cost analysis could have been performed; however, it would have required assumptions for the scheduling of different levels of maintenance over time as well as policy specifications and costs of rehabilitation activities. The additional assumptions would have not only complicated the presentation of results, but also muted the direct relationship between routine maintenance options and their consequent costs and benefits desired in this study.

Therefore, the approach taken was to compute the discounted value (i.e., present value) of the net life-cycle benefits of each alternative as compared with the zero-maintenance case. The net benefits comprise the discounted values of (*a*) savings in vehicle operating costs due to better pavement conditions arising from maintenance alone (no contribution from rehabilitation activities is considered) less (*b*) the costs of the maintenance performed. The total discounted user costs are typically six orders of magnitude (i.e., a million times) larger than the discounted maintenance costs, a result that is not unusual. What is important, however, is how the discounted user costs change due to maintenance. It is the reductions in discounted user costs that are compared with the discounted maintenance costs to calculate net benefits.

The zero-maintenance assumption provides the computational benchmark needed to quantify net benefits across the diverse cases investigated. Application of these results in practice, however, is properly done on an incremental basis by comparing the current, or base case, maintenance policy (which is generally not one of zero maintenance) with a proposed alternative. Incremental net benefits of an alternative to a base case are easily computed from the results presented below by taking the difference between the respective benefit values. For example, assume that one of the cases discussed below (with discounted net benefits of, say, $40 million) approximates the current maintenance policy of a DOT, and an alternative maintenance policy has net discounted benefits of $50 million. The incremental benefits of the alternative to the DOT would equal $10 million ($50 million less $40 million). The large number of possible combinations of cases investigated makes it difficult to organize all results on an incremental basis in an easily understood format. Therefore, the results have been presented as net discounted benefits relative to zero maintenance. Any two maintenance options can be compared by performing the simple subtraction described above.

Examples of discounted net benefit results are illustrated in Figures 7 to 9 for levels of maintenance of 10.0, 5.0, and 2.5, respectively, and for all 12 combinations of maintenance effectiveness. The costs were generated by assuming a 10-mi length of four-lane highway and discounted at 7 percent over the 20-year analysis period. Basic maintenance costs of $500/lane-mi were assumed for a maintenance level of 5.0, with adjustments as indicated in Equation 2 for other maintenance levels. Even allowing for uncertainty in the exact values of the maintenance and user cost models, the following conclusions are warranted:

1. Within each basic distribution of effectiveness, higher magnitudes of effectiveness are desirable. This finding translates into an implied benefit of improved maintenance technology—one that can improve pavement condition to a greater degree or for a longer period. This effect becomes more pronounced when maintenance performed at later stages in the pavement's life (e.g., the midrange, delayed, and late distributions of effectiveness) or the inability to specify full maintenance each year (i.e., maintenance level is less than 10.0 for at least some part of the pavement's life) is considered.

Although the cost of improved maintenance effectiveness is not included in the cost calculations in Equation 2, the results in Figures 7 through 9 indicate the value associated with the improved measures of effectiveness. For example, for a maintenance level of 5.0, the differences between a maximum effectiveness of 10 PCI and one of 25 PCI range from $10 million for the midrange and late distributions to more than $30 million for the early distribution (on an incremental basis). These values far exceed the discounted cost of maintenance over the 20-year period, which is less than $150,000 in all cases.

Finally, there is little beneficial difference among the magnitudes of early effectiveness for a maintenance level of 10.0 (the first three columns in Figure 7). The reason is that all of these maintenance activities contributed to high levels of

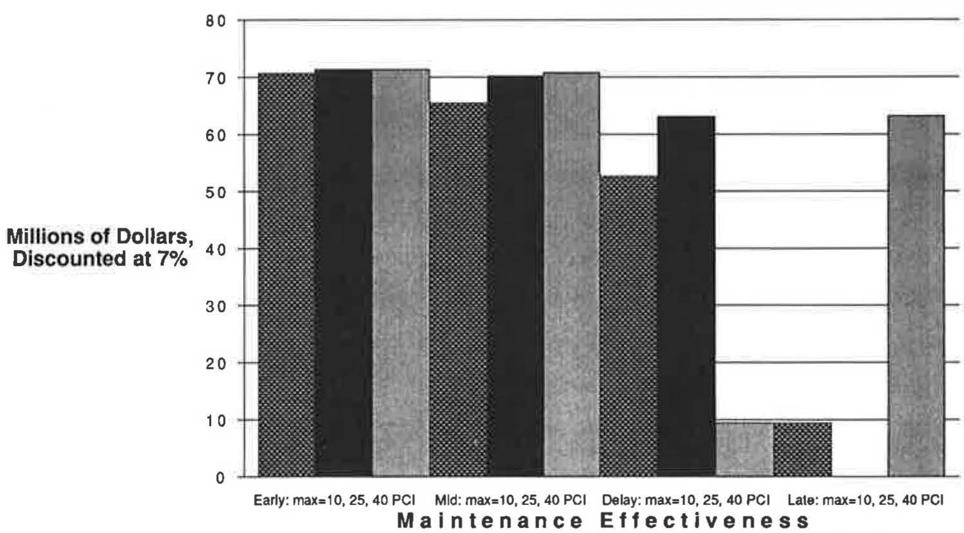

FIGURE 7 Net benefits of maintenance: level = 10.0 for various measures of effectiveness.

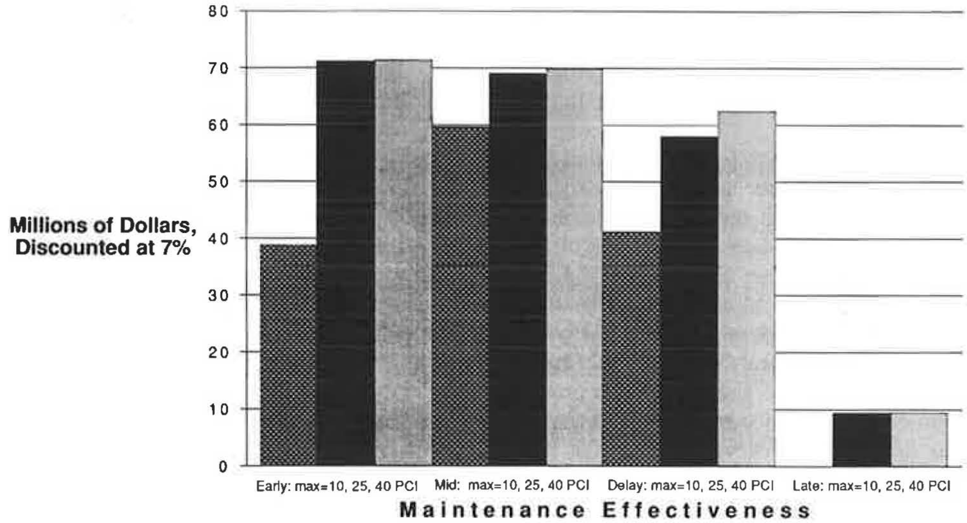

FIGURE 8 Net benefits of maintenance: level = 5.0 for various measures of effectiveness.

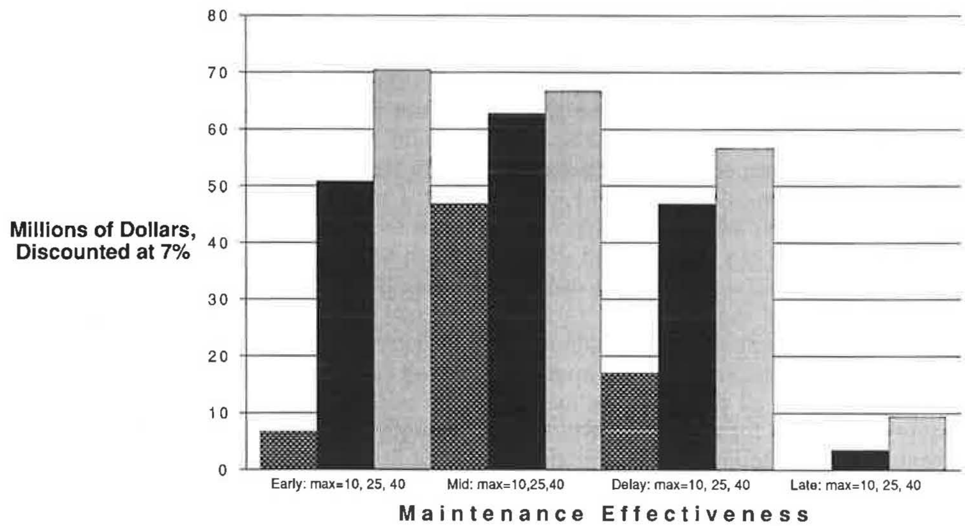

FIGURE 9 Net benefits of maintenance: level = 2.5 for various measures of effectiveness.

pavement performance (e.g., the top curve in Figure 4). This finding highlights the importance of early or preventive maintenance in keeping the condition of the pavement as new as possible for as long as possible.

2. Within the results for any level of maintenance, the net benefits decline for activities with successively later degrees of effectiveness. For example, in Figures 7 to 9, the net benefits decline as one moves from early effectiveness to midrange, delayed, and late effectiveness (basing the comparison on corresponding maximum values: 10, 25, or 40 add points). Furthermore, in the cases studied here, the results are conservative in that (*a*) the predictions for later stages of maintenance effectiveness often assumed indefinite maintenance of pavement condition at some asymptotic level (e.g., as illustrated in Figure 5), resulting in a prolonged period of benefits; and (*b*) the cost calculations do not include any reconciliation of the different terminal conditions of pavements at the end of 20 years. Such corrections (e.g., using a capitalized cost analysis or computation of salvage value and including rehabilitation as well as maintenance) would reduce the net benefits of maintenance in Figures 7 to 9 for the later stages of effectiveness. Somewhat different results are possible for different shapes of deterioration curves. For example, a more concave deterioration trend would derive greater benefits from maintenance with later effectiveness, as noted earlier. This is a point for further research.

3. Both findings are magnified as the level of maintenance is reduced. As the maintenance level is decreased from its maximum of 10.0, one must increasingly depend on (*a*) whatever technological effectiveness maintenance provides and (*b*) exploiting this effectiveness as early as possible to maintain a level of net benefit characterized by higher policies. For example, for the full maintenance policy shown in Figure 7, many of the effectiveness options yield net discounted benefits

between $50 million and $70 million. When the maintenance level is reduced to 2.5 as shown in Figure 9, only the higher magnitudes of each distribution of effectiveness attain this level of benefit. (Activities having early effectiveness limited to 10 and 25 add points suffer because of the magnification of the first conclusion above. The limited early effectiveness cannot be mobilized sufficiently in a constrained maintenance policy to forestall the period of rapid pavement deterioration that coincides.)

CONCLUSION

Through life-cycle costing, the effects of pavement maintenance can be compared with other options for pavement management. Some ways in which the characteristics of pavement maintenance can be expressed analytically, and the implications of these characteristics for pavement management and technology, have been explored. Several conclusions have already been discussed. In addition, the following are conclusions of the study:

- The life-cycle benefits of pavement routine maintenance are high in relation to costs.
- The life-cycle benefits of improvements in maintenance are high and justify, on an economic basis, significant expenditures for technological improvements in items like maintenance inspection, materials, equipment, activity performance, and quality control.
- The life-cycle benefits of early and frequent maintenance performance are high. The longer that maintenance keeps the pavement condition like new and forestalls more rapid rates of deterioration, the more significant are the benefits.
- The life-cycle benefits of managing maintenance better are high, particularly in situations where pavement condition, the rate of pavement deterioration, the level of maintenance, and the effectiveness of maintenance are changing over time.

The interplay of economic, management, and technological issues raised in this case study shows that maintenance offers a rich subject in the management of pavements using life-cycle principles. These findings, supplemented by ongoing research in the field, will provide the basis for integrating maintenance with capital projects, regulatory policies, data collection, and other actions in pavement management. Moreover, these findings suggest a basis for evaluating and justifying future improvements in maintenance data collection and performance.

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