Life-Cycle Evaluation of Flexible Pavement Preventive Maintenance

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Abstract: This study investigates the cost effectiveness of various levels of life-cycle preventive maintenance (PM) for three asphaltic concrete pavement functional class families. For each family, the effectiveness and cost associated with each of several alternative life-cycle PM strategies were estimated. For each strategy, effectiveness was estimated as the increase in service life relative to a base-case strategy, and the cost was estimated in terms of agency and user costs associated with the treatments comprising that strategy. Using the estimated costs and effectiveness, statistical models were developed to describe the relationship between life-cycle PM effort and its efficacy in extending the pavement life, per unit cost. It is shown that increasing PM is generally associated with increasing cost effectiveness (but only up to a certain turning point beyond which cost effectiveness decreases). It was determined that the maximum cost effectiveness and the corresponding level of annualized PM are influenced by the pavement functional class and cost components considered. A general methodology is hereby provided for pavement managers to estimate the expected changes in pavement service life arising from changes in PM expenditure.

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Introduction

At the current time, highway agencies are increasingly moving towards the use of life-cycle concepts in planning and budgeting for their pavement investments and are also grappling with the integration of maintenance programs in their existing pavement management systems. Consistent with such issues is the practice of preventive maintenance (PM) which involves application of maintenance prior to the onset of significant deterioration. Preventive maintenance, which is deservedly getting attention among highway pavement managers, potentially increases average pavement performance, and service life and shows much promise in reducing long-term costs of highway facilities (O'Brien 1989; Zimmerman 1995; Geoffroy 1996; Mamlouk and Zaniewski 1998). However, a pertinent issue is the extent to which preventive maintenance extends the pavement service life. Related to this issue is balancing act associated with PM application. Preventive maintenance requires an adequate balance between sustained performance on one hand and increased maintenance costs on the other hand: if preventive maintenance is applied too infrequently, user costs and reactive maintenance costs increase and overall life-cycle costs can be very high. On the other hand, if preventive maintenance is applied too frequently, it is uneconomical because the excessive expenditure outweighs the additional benefits of extended pavement life and increased average pavement condition. In a conceptual illustration that illustrates such dichotomy,Mamlouk and Zaniewski (1998) implied that increasing PM effort (represented as frequency of PM treatments or reciprocal of PM treatment intervals) leads to increasing cost-effectiveness up to a point after which it leads to decreasing cost effectiveness. To date however, it appears that this hypothesis has not been adequately investigated using real data from in-service pavements. Also, agencies seek the level of PM expenditure that corresponds to maximum cost effectiveness, for each pavement class. Such knowledge is useful for network-level pavement management, and preservation needs assessment and budgeting.

Highway agencies are therefore interested in addressing the following vital issues:

1. On what basis can agencies determine that their current levels of PM expenditure are too high, too low, or just right?
2. Is it always cost-effective to keep increasing PM expenditure?
3. How do the above trends vary by pavement functional class?
4. Does the inclusion of user cost influence the nature of relationship between PM and its cost effectiveness?

The present study sets out to answer these questions using data from in-service state highway pavements in Indiana. The study does not specifically address the issue of the optimal PM strategy (specific combination of PM treatment types and timings) over the life cycle of a pavement. Nevertheless, the strategies formulated in the present study consist of various treatment types and timings and vary by the level of PM effort (expenditures associated with various sets of PM treatment types and timings). For purposes of the present study, effectiveness is defined not as

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the overall service life, but rather as the increase in service life relative to a base case (the "do nothing" strategy). Also for purposes of the study, a life-cycle is defined as the period between two successive resurfacing activities, between reconstruction and subsequent resurfacing activity, or between resurfacing and subsequent reconstruction activity. As such, the data collected were for pavements that were within such phases.

Study Background

Scope of Maintenance Terminology

Highway pavement maintenance terminology has evolved from one characterized by purely routine affairs (such as spot repairs of localized distresses that are undertaken by in-house crews and funded from force accounts) to one that includes relatively major treatments carried out under contractual agreements (such as microsurfacing and thin overlays). The widening of maintenance terminology to include such capital-intensive work has been spurred in part by various pieces of legislations over the last 2 decades that encouraged the use of preventive maintenance activities on the National Highway System (NHS). With current consideration of thin hot mix asphalt (HMA) overlay and microsurfacing as "maintenance"activities, the efficacy of highway maintenance in extending pavement service life is likely to become more and more perceptible. Consequently, the current philosophy of maintenance effectiveness evaluation includes certain methodologies and concepts (such as work zone queuing user costs) that were once reserved for capital work (Geoffroy 1996) such as the user costs associated with queuing delay at work zones.

Life-Cycle Evaluation of Pavement Maintenance: Some Selected Past Studies

Life-cycle concepts have been advocated or used widely within and outside the maintenance arena to study treatment effectiveness or to identify specific types and/or timings of pavement rehabilitation or reconstruction (Darter et al. 1985; Peterson 1985; Chong and Phang 1988; Sharaf et al. 1988; Joseph 1992; Walls and Smith 1998). In a study that developed decision trees for selecting specific preventive maintenance strategies, effectiveness was measured on the basis of extra service life and the equivalent annual cost of the strategy (Hicks et al. 1997). In Indiana, past LCCA-based studies of maintenance cost effectiveness were carried out by Mouaket et al. (1992) and Al-Mansour and Sinha (1994). Using various problem formulations, a number of researchers have sought to identify the optimal frequency of pavement interventions or identification of specific treatment actions over construction life cycle or rehabilitation life cycle (Friesz and Fernandez 1979; Colucci-Rios and Sinha 1985; Markow and Balta 1985; Murakami and Turnquist 1985; Tsunokawa and Schofer 1994; Li and Madanat 2002; Labi et al. 2003; Lamptey 2004).

Unlike most past studies that focused on reconstruction life cycles and/or sought to determine the specific types and timings of specific rehabilitation (resurfacing) treatments over such periods, the present study rather focuses on the rehabilitation life cycle and investigates the optimal level of preventive maintenance expenditure (in terms of dollars per lane-mile) over that period. The present study addresses this issue by considering the efficacy of preventive maintenance in extending pavement life specifically beyond the "do nothing" scenario, for flexible (asphaltic concrete) pavements using data from the state of Indiana. The present study also investigates the relationship between the PM effort on one hand and PM cost effectiveness on the other hand.

Measure of Effectiveness Used for Study

Long-term effectiveness of pavement maintenance has generally been measured in terms of the monetary cost reduction associated with enhanced vehicle operation on an improved pavement, extension in pavement life, increase in average pavement condition, or increase in area under the performance curve, typically with respect to a base case (typically the "do nothing" alternative). With regard to the first measure, some studies have developed relationships that relate improvement in pavement surface condition to vehicle operating costs. With regard to the other three measures, maintenance effectiveness is based on the rationale that adequate maintenance yields gently sloping performance curves that is indicative of enhanced average condition over pavement life cycle and/or longer service life. In contrast, poorly maintained pavements typically have steeply sloping curves that are indicative of poor pavement condition, shorter service lives, and smaller areas bounded by the performance curve. In the present paper, effectiveness of a preventive maintenance strategy was expressed as the increase in remaining service life relative to a base case (do nothing) strategy, and was therefore determined as the time taken for the pavement to revert to a certain threshold pavement condition, as reflected by the pavement performance curve.

Framework for Present Study

In the present study, in-service pavement sections were grouped into three families on the basis of their functional class. For each functional class, the zero-maintenance performance curve was established using data from LTPP's Indiana pavement sections. The study then formulated several alternative PM strategies for each pavement family, estimated the performance jumps and costs of constituent treatments and thereby determined the overall life-cycle performance trends from which the service life corresponding to each strategy was estimated. A PM strategy, also referred to in some literature as PM schedule, or PM program, may be defined as a set of PM treatment types applied a prespecified frequency or when the pavement surface condition reaches a certain threshold (Hicks et al. 1997), over the life cycle.

Formulation of Strategies

An example of a formulated strategy used in the study is provided as Table 1. Strategies formulated in the present study ranged from liberal to conservative. Unlike those of a preventive nature, corrective (reactive) maintenance activities are typically not scheduled (that is, they are carried out as and when needed), and were therefore incorporated in the present paper as default treatment options in each formulated PM strategy. Lower levels of preventive maintenance have been found to translate to higher

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Table 1. Example of Preventive Maintenance Strategy Pavement Family III—Asphalt–Concrete Non-National Highway System Pavements

Strategy number	Overall maintenance scenario: Details of strategy (preventive maintenance elements)[a]: Thin HMA overlay	Microsurfacing	Chip sealing	Crack sealing	Default actions: Corrective maintenance elements (typically applied as needed, but 3 year application intervals is assumed)[b]
0	—	—	—	—	—
1		FA: 11 years	FA: 6 years FT: 3 years after microsurfacing	FA: 3 years FT: 3 years after micro-surfacing or chip sealing	Shallow patching, deep patching, premix leveling, and bump grinding
2	FA: 12 years	FA: 7 years NA: 15th year	—	FA: 4 years FT: 2–3 years after micro-surfacing or thin overlay	Shallow patching, deep patching, premix leveling, and bump grinding
3	FA: 4 years FT: 4 years	—	—	—	Shallow patching, deep patching, premix leveling, and bump grinding
4	FA: 6 years FT: 6 years	FA: 3 years FT: 3 years	FA: 3 years FT: 3 years	FA: 2 years FT: 2 years after thin overlay	Shallow patching, deep patching, premix leveling, and bump grinding
5	FA: 12 years	FA: 9 years NA: 18th year	FA: 5 years	FA: 3 years FT: 2–3 years after chip sealing or thin overlay	Shallow patching, deep patching, premix leveling, and bump grinding
6	FA: 5 years NA: 15 years	FA: 6 years	—	FA: 3 years FT: 3 years after micro-surfacing or thin overlay	Shallow patching, deep patching, premix leveling, and bump grinding
7	FA: 5 years NA: 15 years	FA: 6 years NA: 12 years	—	FA: 3 years NA: 18 years	Shallow patching, deep patching, premix leveling, and bump grinding
8	FA: 15 years	FA: 6 years	—	FA: 3 years FT: 3 years after micro-surfacing or thin overlay	Shallow patching, deep patching, premix leveling, and bump grinding
9	FA: 6 years FT: 6 years	—	FA: 3 years FT: 3 years after thin overlay	Every year except at times of other treatments	Shallow patching, deep patching, premix leveling, and bump grinding
10	—	FA: 6 years FT: 6 years	—	—	Shallow patching, deep patching, premix leveling, and bump grinding
11	—	FA: 6 years FT: 6 years	—	—	Shallow patching, deep patching, premix leveling, and bump grinding
12	FA: 3 years FT: 3 years	FA: 3 years FT: 3 years	FA: 3 years FT: 3 years	FA: 3 years FT: 3 years	Shallow patching, deep patching, premix leveling, and bump grinding
13	FA: 6 years FT: 6 years	FA: 3 years FT: 3 years after thin overlay	—	—	Shallow patching, deep patching, premix leveling, and bump grinding
14	FA: 6 years FT: 6 years	FA: 3 years FT: 3 years after thin overlay	—	Every year except at times of other treatments	Shallow patching, deep patching, premix leveling, and bump grinding

Note: Details of all PM strategies formulated for all pavement families are presented in Labi and Sinha (2003).
[a]FA=age of first application; FT=frequency thereafter (after first application); NA=year of next application.
[b]Assumption of a 3 year response yielded the most perceptible relationship between PM and subsequent CM.

levels of subsequent corrective maintenance, and vice versa (Labi and Sinha 2003). Therefore, each PM strategy also consists of a default set of corrective maintenance treatments that are carried out every year but whose levels are a function of the amount of previous preventive maintenance.

Determination of Life-Cycle Effectiveness of Each Preventive Maintenance Strategy

The life-cycle effectiveness of each strategy was estimated in terms of the service life as reflected by the pavement performance curve. Service life extensions are made possible by various jumps in the performance curve at times of maintenance application. The base-case (zero-maintenance) performance curve was developed using data from zero-maintenance LTPP pavement sections in Indiana. The general form of the performance model is presented in the following equation:

$$\mathrm{IRI} = A \times e^{b \times x} \qquad (1)$$

where IRI=International Roughness Index of the pavement section in year x, and A and B=constants.

The performance models are presented in Table 2(a). Using the base-case performance curve, the performance trend for each preventive maintenance strategy was developed using the performance jump (PJ) models for preventive maintenance treatments associated with that strategy. Such performance jumps the magnitudes of which have been the subject of past research

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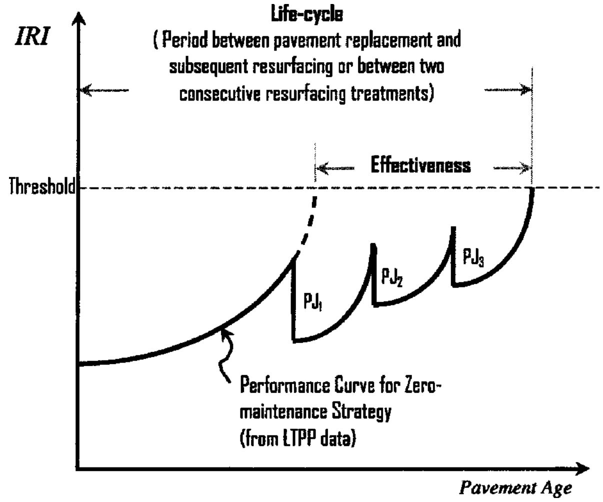

Fig. 1. Increased service life due to preventive maintenance applications (for Illustration, only three treatments are shown)

(Rajagopal and George 1991; Smith et al. 1993; Al-Mansour and Sinha 1994). For the present study, the magnitudes of such jumps were obtained from a previous study (Labi and Sinha 2003) that developed performance jump models for various treatments [Table 2(b)]. For a given strategy, overall effectiveness was expressed by the extended service life relative to the base case strategy.

Determination of Life-Cycle Cost of Each Preventative Maintenance Strategy

The life-cycle cost of each strategy is the sum of the costs of its constituent treatments. Costs were discounted to their present worth values (at 5% discount rate) to account for the time value of money as reflected in the opportunity costs of maintenance investments. Two types of cost analysis were carried out: one that involved agency costs only; and one that involved both agency and user costs. Agency costs comprised basic (maintenance treatment) costs, and user costs consisted of workzone traffic queuing delay costs. The generalized cost model for a preventive maintenance strategy per lane-mile, COST, is therefore given by

$$\mathrm{COST} = \sum_{i=1}^{N} \sum_{j=1}^{M} [(\mathrm{MC}_j + \mathrm{DC}_j)^{\times}\mathrm{PWF}(r,Y)^{\times}X_{jt}] \qquad (2)$$

where MC_j=basic cost of maintenance treatment type j per lane-mile; DC_j=queuing delay cost associated with maintenance treatment type j; M=number of treatments (associated with the strategy) carried out in a given year; N=length of pavement rehabilitation life-cycle; PWF (r,Y)=present worth factor at a discount rate (r) and number of years since last rehabilitation of higher treatment (Y) at time of treatment j; X_{jt}=1 if treatment j is applied in year t; 0 if otherwise. Where the analysis involved agency costs only, the user cost term was equated to zero.

Eq. (2) shows that the total cost of each constituent treatment comprises the agency cost (contractual treatment costs) only or the agency cost and user (queuing delay) costs associated with the treatment. It was assumed that costs of various treatments at a point in time, or costs of the same or different treatments at various points in time are independent of each other. Therefore, the overall cost of each preventive maintenance strategy is simply the algebraic sum of total costs of its constituent treatments.

Table 2. Treatment Performance Jumps and Costs and Performance Trend Models

(a) Zero-maintenance performance trend models using LTPP data		
Pavement family I (AC interstates)	$\mathrm{IRI}=45.314^{\times}e^{0.1161^{\times}\mathrm{Age}}$ (R^2=0.927)	
Pavement family II (AC NHS noninterstates)	$\mathrm{IRI}=60.301^{\times}e^{0.096^{\times}\mathrm{Age}}$ (R^2=0.929)	
Pavement family III (AC non-NHS)	$\mathrm{IRI}=68.796^{\times}e^{0.1074^{\times}\mathrm{Age}}$ (R^2=0.930)	
(b) Performance jump models		
Treatment	Average performance jump (IRI)	Average unit cost ($ per lane mile)
Thin HMA overlay	71	61,664
Microsurfacing	21	27,434
Chip sealing	11	4,799
Crack sealing	3	444
(c) Gompertz models for corrective and preventive maintenance relationship: $\mathrm{CM}_{3\text{-year}}=\alpha^{\times}\beta\hat{}(\gamma^{\mathrm{PM}}_{3\text{-year}})$		
Pavements within first half of their typical service lives	α	0.7632
	β	3.8866
	γ	0.5582
Pavements within second half of their typical service lives	α	39.0885
	β	0.7601
	γ	0.1978

Note: Performance jump models are based on average initial pavement condition. $\mathrm{PM}_{3\text{-year}}$=total preventive maintenance expenditure in a given 3 year period. $\mathrm{CM}_{3\text{-year}}$=total corrective maintenance expenditure in a subsequent 3 year period. Data on initial pavement condition, treatment effectiveness, and costs are available in Labi and Sinha (2003).

Basic (Maintenance Treatment) Costs

Average cost values for various preventive maintenance treatment types in Indiana (Labi and Sinha 2003) were used for present study [Table 2(a)]. Corrective maintenance costs were also included on an aggregate basis—Gompertz models developed by Labi and Sinha (2003) and shown in Table 2(c)—enable estimation of the expected aggregate level (expenditure) of corrective maintenance subsequent to previous preventive maintenance expenditure on a 3 year cycle.

Other Costs

Where user costs were considered in the cost equation, queuing delay costs were used as they typically constitute, by far, the largest aspect of user costs. User costs of vehicle operation associated with normal highway use were assumed to be negligible due to the generally good condition of asphalt–concrete (AC) pavements on the Indiana state highway network. Also, crash costs were assumed to be negligible and were excluded from the analysis. The queuing costs associated with each strategy were estimated using methodologies established in past research (Walls and Smith 1998; Lamptey 2004). Such queuing costs were estimated by considering the duration of application (and hence, workzone) of each constituent treatment, traffic, and workzone characteristics such as volume, percentage of trucks, speed limit, queue dissipation capacity, workzone configuration, and values of travel time.

In the case where both agency and user costs were considered in the analysis, an important issue is the relationship between the unit values of agency cost and user cost. In other words,

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Table 3. Cost Effectiveness of Various Strategies for Pavement Family III (Asphalt–Concrete National Highway System-Noninterstates) on Basis of Both Agency and User Costs

Strategy number	Life cycle preventive maintenance (PM) agency cost only a	Life-cycle total maintenance (preventive+corrective) (agency+user cost) b	Effectiveness (incremental service life relative to base case) (years) c	Cost effectiveness on basis of agency+user cost (years per $10^6) $d=c/b$
15	$14,950	$223,588	19	40.25
14	$12,772	$192,065	16.5	33.84
11	$749	$38,204	10.5	13.09
10	$2,706	$47,495	11	21.05
9	$9,890	$188,663	16.5	34.45
8	$2,979	$52,458	11	19.06
7	$10,450	$155,408	16	38.61
6	$6,583	$98,804	14	40.48
5	$6,518	$19,357	14	33.51
4	$13,025	$196,938	17	35.54
2	$6,145	$93,354	13.7	39.63
1	$3,004	$74,459	12	26.86
0	$0	$0	10	0

Note: Column 6 presents observed values of cost effectiveness, while Fig. 1 shows the fitted values. Expenditures values are expressed in 1995 dollars.

what weights should be given to each of these two costs before they are added together to get a total cost? Direct addition of agency cost to user cost implicitly assumes that $1 of agency cost is equivalent to $1 of user cost. This approach seems to have been used (at least, implicitly) in most past research (Darter et al. 1985; Peterson 1985). However, recent literature shows a school of thought that is averse to such direct summation of these two costs, arguing that the value of each agency cost dollar is different from that of the user cost dollar, because agency costs are directly and physically borne by the agency, while the user costs are not so visible (Lamptey 2004). It has therefore been suggested that only a fraction of user costs should be considered and added to the agency costs. But what fraction should be used? The present study carried out the analysis using two scenarios: where only agency costs were considered (implying that the user cost dollar have a value of zero), and where both agency and user costs were considered with an agency-to-user cost value ratio of 1 (that is, agency and user costs were assumed to have equal weights, and were therefore summed directly to obtain overall cost).

Determining Cost Effectiveness of Each Strategy

The cost effectiveness of each strategy k was computed as the ratio of the incremental benefit (pavement life extension) to incremental cost for the strategy relative to the base case (zero-maintenance strategy, ICE_k, as shown in the following equation):

$$ICE_k = (LCE_k - LCE_0)/(LCC_k - LCC_0) \quad (3)$$

where LCE_k, LCE_0=life-cycle effectiveness (service life) associated with strategy k and the base strategy, respectively; and LCC_k, LCC_0=life-cycle costs associated with strategy k and the base strategy, respectively.

Data Used for Study and Pavement Family Descriptions

Data used for the study was from *INDIPAVE 2000*, a database of pavement condition, weather, pavement structure, traffic, contracts, maintenance, at a sample of 5,000 1.61 km (1 mi.) state highway pavement sections in Indiana. Estimation of queuing costs was done on the basis of data pertaining to typical practice in Indiana as well as default data in queuing cost estimation methods (Walls and Smith 1998). The values of travel time used were $15.19 for passenger cars and $33.17 for single and multiple unit trucks. In Indiana, AC pavements are often described as flexible pavements, with either an underlying concrete pavement, untreated base, or stabilized material. Brief descriptions of the pavement families and their share of the 11, 300 mi. state highway network are herein presented.

1. Pavement Family I (AC Interstates): Comprising approximately 9% of the state highway system (85% of the Interstate system), AC Interstate pavements typically have relatively high design and construction features compared to AC pavements at other functional classes. Typical treatments are: thin HMA overlay, microsurfacing, crack sealing.
2. Pavement Family II (AC NHS noninterstates): This family is comprised of approximately 10% of the state highway system (62% of the NHS noninterstate system). Most of these pavements are on United States roads and state roads that were built to relatively high design standards and attract high traffic volumes compared to other United States and state roads. Typical treatments are: thin HMA overlay, microsurfacing, and crack sealing. High traffic volumes on these roads generally preclude the application of chip seals.
3. Pavement Family III (AC non-NHS): Non-NHS ACS pavements constitute approximately 69% of the state highway system (92% of the non-NHS system). Table 3 presents the cost effectiveness of various strategies for pavement Family III (AC NHS Non-interstates) on the basis of both agency and user costs.These are typically state roads and United States roads on the minor arterial or collector systems. Due to the relatively low traffic volumes on such roads, the use of chip sealing is generally considered a viable preventive maintenance treatment for these pavements. Typical treatments are: thin HMA overlay, microsurfacing, chip sealing, and crack sealing.

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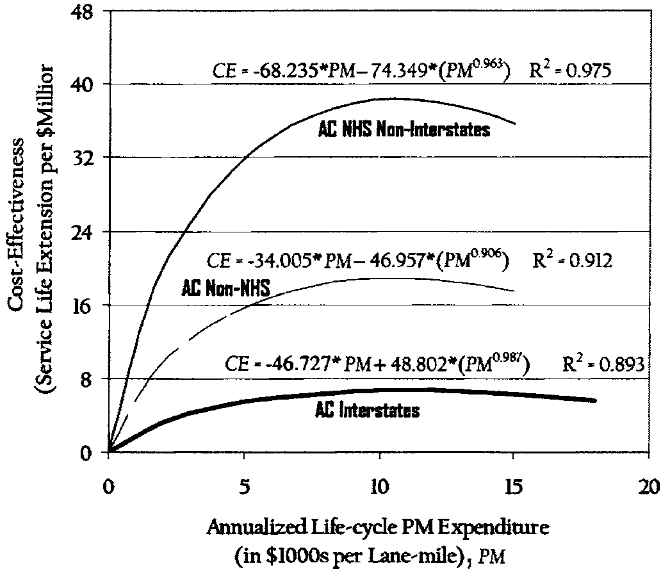

Fig. 2. Preventive maintenance cost-effectiveness trends by pavement family on basis of both agency and user cost

Results

The developed models for assessing preventive maintenance cost effectiveness are herein presented and discussed.

Cost-Effectiveness Models for Life-Cycle Preventive Maintenance

Trends were investigated for effectiveness as well as cost effectiveness. The effectiveness models (not presented in this paper) showed that preventive maintenance effectiveness (in terms of pavement life extensions) generally increases with increasing PM effort in a somewhat S-shape fashion, generally flattening out after a certain level of PM is reached.

The developed cost-effectiveness models suggest that PM cost effectiveness generally increases with increasing preventive maintenance effort, up to a certain maximum, after which it declines with increasing effort, and therefore seems to confirm the hypothesis set forth by Mamlouk and Zaniewski (1998). It is seen that the postoptimum rate cost-effectiveness decline rate is generally lower than the preoptimum rate of increase. In other words, at below-optimum PM levels, there is a large increase in cost effectiveness per unit change in PM expenditure, while there is a relatively small increase in such benefits at above-optimum PM levels.

It was found that the curves generally fit the following functional form:

$$Y = b^{*}X - a(X^{c}) \tag{4}$$

where a,b,c=constants that control the shape of the cost-effectiveness curve; Y=cost effectiveness of preventive maintenance; and X=preventive maintenance effort (expenditure) per lane-mile, expressed in dollar value. The cost effectiveness analysis was carried out first for agency costs only, and then on the basis of both agency and user costs (see Fig. 1).

Findings on Basis of Both Agency and User Costs

Fig. 2 shows a fitted-values plot of the developed cost-effectiveness models for each pavement family on the basis of both agency and user costs. The cost effectiveness per unit PM expenditure increases in a decreasing fashion up to a certain point. On the basis of both agency and user costs, maximum cost-effectiveness values of: (1) 38 years/$1 million is attained at an annualized PM expenditure of $10,000 per lane-mile for AC NHS noninterstates; (2) 18 years/$1 million is afforded at a similar PM level for AC Non-NHS pavements; and (3) 7 years/$1 million is earned at an annualized PM expenditure of approximately $12,000 per lane-mile, for AC interstates pavements. AC interstates appear to be least sensitive (from a cost-effectiveness perspective) to increases or decreases in PM expenditure. On the other hand, AC NHS noninterstates are most sensitive in that regard. For example, doubling PM expenditure for AC NHS noninterstate pavements with an existing PM level of $1,000 per lane mile per year would be twice and four times more cost effective than a similar situation for AC non-NHS and AC interstate pavements, respectively.

Findings on Basis of Agency Costs Only

On the basis of agency costs only, a fitted-values plot of the developed cost-effectiveness models for each pavement family was plotted and was found to be similar to that plotted on the basis of agency and user costs. The only exception was in the value of cost effectiveness. For AC NHS noninterstates, a maximum cost effectiveness of 3 years/$1000; for AC non-NHS pavements, a maximum cost effectiveness is 1.9 years/$1000; and for interstates, a maximum cost effectiveness of 0.6 years/$1000. The cost effectiveness values are higher when only agency costs are considered compared to when both agency and user costs are considered, obviously because the denominator of the cost-effectiveness equation is decreased considerably by excluding the user costs. However, it is seen that when only agency costs are considered; (1) there seems to be little or no difference in the overall pattern of relative cost effectiveness across pavement functional classes, compared to the case for both agency and user costs (2) maximum values of cost effectiveness are attained at PM levels that are similar to the case for both agency and user costs.

Discussion

With these results, it is shown that agencies can use currently available data to estimate the optimal level of preventive maintenance effort (expenditure) needed to extend pavement life in the most cost-effective manner. As explained in the "Introduction" of this paper, cost effectiveness is herein expressed as the efficacy of maintenance treatments in extending pavement life beyond that associated with the zero maintenance scenario, per unit dollar of preventive maintenance.

The observed differences in cost effectiveness across pavement families could probably be attributed to differences in the ratio of current average loading levels relative to their current pavement structural and functional integrity (reflected by the design and construction standards). These differences translate to: (1) differences in the innate ability of the pavement structure of various families in accommodating such loads due to either their design or material properties; (2) differences in extent to which functional improvements offered by PM can help the pavement structure withstand the damaging effects of load and weather thereby enhancing the longevity of pavements in that class; and (3) differences in potentials (ceilings) for PM effectiveness in terms of increased pavement condition and subsequently, increased service life. In other words, high class pavements (AC interstates) have high traffic loading but also have a high pavement integrity (due to their superior design and construction

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features) that enable them to counter the effects of high traffic loading. With such high pavement integrity for these pavements, PM seems to have relatively little potential to further increase the pavement integrity. Low class pavements (AC non-NHS) have low traffic loading but also have a relatively low pavement integrity that seems to be adequate to counter the effect of low traffic loading. Medium class pavements (AC NHS noninterstates) have a medium level of loading but seem to benefit most of PM (in terms of cost effectiveness) thus suggesting that their current levels of pavement integrity may be relatively lower than that needed to counter the effects of their current (medium) levels of traffic loading. As such, AC NHS noninterstates seem to stand to benefit most from PM through the enhancement of overall pavement integrity to a level that renders the pavement more "equipped" to withstand the effects of traffic and its interaction with the weather. The AC NHS noninterstates therefore exhibit the highest efficacy of PM in enhancing pavement integrity and subsequently service life.

Recommendations: Field Experiment for Life-Cycle Evaluation of Preventive Maintenance

In order to shed more light on the cost-effectiveness evaluation of preventive maintenance strategies over pavement life cycle, field experiments are recommended. This would involve implementation of several alternative strategies (maintenance treatment types and timings) for each pavement family. An advantage of such an experiment would be the acquisition of directly observed data on effectiveness and cost for the purposes of modeling, rather than resorting to the use of such data estimated (simulated) from cost and effectiveness models as done in the present study. Such an experiment would require careful monitoring of pavement condition over time, jumps in pavement condition in response to maintenance treatments, and costs of all preventive and corrective maintenance treatments associated with a given strategy. If a large number of strategies are implemented for each pavement family, it may be possible to have several data points from which more reliable statistical functions could be developed to explain the tradeoff relationships between life-cycle preventive maintenance effort and its effectiveness or cost effectiveness. Furthermore, such an experiment could result in the determination of a single optimal preventive maintenance strategy (the best set of treatment types and timings) over the life cycle, for each pavement family. The LTPP was a critical first step in this direction. Individual states have been encouraged to supplement LTPP experiments, and any such efforts in that direction could include an experimental setup to investigate, at first hand, the life-cycle cost effectiveness of preventive maintenance expenditure (see Table 3).

Summary and Conclusions

The present study evaluated the cost effectiveness of various levels of life-cycle preventive maintenance for each of three pavement families grouped by functional class. The effectiveness and life-cycle cost associated with each of several alternative preventive maintenance strategies were determined for each family. Effectiveness was expressed as the increase in remaining service life relative to a base case (the "do-nothing" strategy) and was determined as the time taken for the pavement performance curve (corresponding to each strategy) to revert to a specified performance threshold. Costs were estimated in terms of agency and user costs associated with the various constituent treatments of a strategy. Using the generated data points, statistical models were developed to relate life-cycle preventive maintenance effort (in dollars per lane-mile) and efficacy of such expenditure in increasing pavement life.

The modeling results show that increasing preventive maintenance is generally associated with increasing cost effectiveness (extended pavement life per unit investment, relative to a base case) but only up to a certain optimal point after which decreasing cost effectiveness is observed. It was determined that the position of the optimal point as well as the sensitivity of such cost effectiveness to the preventive maintenance effort are both influenced by functional class and whether user costs are included in the analysis.

The study results shows that the sensitivity of PM cost effectiveness, as defined for purposes of the paper, is a two-edged sword—it may be good or bad, depending on the current level of PM funding (in relation to the optimal levels), the magnitude of the sensitivity, and whether the agency is faced with decreased PM funding or increased PM funding in a given planning period. For example: for a pavement family that exhibits relatively high sensitivity at a given level of PM, decreasing PM would have relatively adverse impacts on the network utility—in that context, a high sensitivity is bad. For that same pavement family, increased PM funding availability would mean significantly increased system utility, in which context a high sensitivity is good. On the other hand, for a pavement family that exhibits relatively low sensitivity at a given level of PM, decreasing PM would have relatively little impact on the network utility. In that case, a low sensitivity is good, as that network shows resilience to adversity. For that same pavement family, increased PM funding availability would mean little or no increase in system utility, in which context a low sensitivity is bad. "Utility" in the present context simply refers to cost effectiveness.

The study presents a methodological guide for pavement managers to determine optimum pavement preventive maintenance funding levels on the basis of maximum extensions in pavement life beyond the zero-maintenance scenario, and is particularly useful for preventive maintenance budgeting for existing new (just reconstructed or rehabilitated) or future pavements. Future studies in this direction could adopt an experimental field approach, and could generate direct field data that could help not only identify optimal sets of specific treatment types and timings, but also confirm optimal amounts needed for preventive maintenance for each pavement family, such that overall life-cycle cost effectiveness is maximized. At the present time when many highway agencies strive to establish or enhance their existing pavement management databases and systems to include maintenance costs and effectiveness, the resolution of such issues has become increasingly important. Studies with methodologies similar to that presented herewith could be carried out by other highway agencies with their local data to address the issues posed in this paper.

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References

Al-Mansour, A. I., and Sinha, K. C. (1994). "Economic analysis of effectiveness of pavement preventive maintenance." *Transportation Research Record 1442*, Transportation Research Board, Washington, D.C., 31–37.

Chong, G., and Phang, W. A. (1988). "Improved preventive maintenance: Sealing cracks in flexible pavements in cold regions." *Transportation Research Record 1205*, Transportation Research Board, Washington, D.C., 12–19.

Colucci-Rios, B., and Sinha, K. C. (1985). "Optimal pavement management approach using roughness measurements." *Transportation Research Record 1048*, Transportation Research Board, Washington, D.C., 13–18.

Darter, M. I., Smith, R. E., and Shahin, M. Y. (1985). "Use of life-cycle costing analysis as a basis for determining the cost-effectiveness of maintenance and rehabilitation treatments for developing a network level assignment procedure." *Proc., North American Pavement Management Conf.*, Toronto.

Friesz, T. L., and Fernandez, J. E. (1979). "A model of optimal transport maintenance with demand responsiveness." *Transp. Res., Part B: Methodol.*, 13B, 317–339.

Geoffroy, D. N. (1996). "Cost-effective preventive pavement maintenance." *National Cooperative Highway Research Program Synthesis of Highway Practice 223*. Transportation Research Board, National Research Council, Washington, D.C.

Hicks, R. G., Dunn, K., and Moulthrop, J. S. (1997). "Framework for selecting effective preventive maintenance treatments for flexible pavements." *Transportation Research Record 1597*, Transportation Research Board, Washington, D.C., 32–33.

Joseph, P. (1992). "Crack sealing in flexible pavements: A life cycle cost analysis." *Tech. Rep. No. PAV-92-04*, Research and Development Branch, Ministry of Transportation, Downsville Ont., Canada.

Labi, S., Pasupathy, R., and Sinha, K. C. (2003). "Optimal performance thresholds for intervention in infrastructure asset management." *Presented at Proc., 83rd Annual Meeting of Transportation Research Board*, National Research Council, Washington, D.C.

Labi, S., and Sinha, K. C. (2003). "The effectiveness of maintenance and its impacts on capital expenditures." *Tech. Rep. No. FHWA/IN/JTRP-2002-27*, Joint Transportation Research Program, School of Civil Engineering, Purdue Univ., West Lafayette, Ind.

Lamptey, G. (2004). "Optimal scheduling of pavement preventive maintenance using life cycle cost analysis." MS thesis, Purdue Univ., West Lafayette, Ind.

Li, Y., and Madanat, S. (2002). "A steady-state solution for the optimal pavement resurfacing problem." *Transp. Res., Part A: Policy Pract.*, 36, 525–535.

Mamlouk, M. S., and Zaniewski, J. P. (1998). "Pavement preventive maintenance: Description, effectiveness and treatments."*ASTM STP 1348*, West Conshohocken, Pa., 121–135.

Markow, M., and Balta, W. (1985). "Optimal rehabilitation frequencies for highway pavements." *Transportation Research Record 1035*, Transportation Research Board, Washington, D.C., 31–43.

Mouaket, I. M., Sinha, K. C., and White, T. D. (1992). "Guidelines for management of chip and sand seals coating activities in Indiana." *Transportation Research Record 1344*, Transportation Research Board, Washington D.C., 85–86.

Murakami, K., and Turnquist, M. A. (1985). "A dynamic model for scheduling maintenance of transportation facilities." *Presented at Proc., Transportation Research Board 64th Annual Meeting*, Washington, D.C.

O'Brien, L. G. (1989). "Evolution and benefits of preventive maintenance strategies." *National Cooperative Highway Research Program Synthesis of Highway Practice 153*, Transportation Research Board, National Research Council, Washington, D.C.

Peterson, D. E. (1985). "Life-cycle cost analysis of pavements." *NCHRP Synthesis of Highway Practice 122*, Transportation Research Board, National Research Council, Washington, D.C.

Rajagopal, A. S., and George, K. P. (1991). "Pavement maintenance effectiveness." *Transportation Research Record 1276*, Transportation Research Board, Washington, D.C., 62–66.

Sharaf, E. A., Shahin, M. Y., and Sinha, K. C. (1988). "Analysis of the effect of deferring pavement maintenance." *Transportation Research Record 1205*, Transportation Research Board, Washington, D.C., 29–35.

Smith, R., Freeman, T., and Pendleton, O. (1993). "Pavement maintenance effectiveness." *Strategic Highway Research Program*, National Research Council, Washington, D.C.

Tsunokawa, K., and Schofer, J. L. (1994). "Trend curve optimal control model for highway pavement maintenance: Case study and evaluation." *Transp. Res., Part A: Policy Pract.*, 28A, 151–166.

Walls, J. III, and Smith, M. R. (1998). "Life cycle cost analysis in pavement design—in search of better investment decisions." *Technical Rep. No. FHWA-SA-98-079*, Federal Highway Administration, Washington, D.C.

Zimmerman, K. A. (1995). "Pavement management methodologies to select projects and recommend preservation treatments." *National Cooperative Highway Research Program Synthesis of Highway Practice 222*, Transportation Research Board, National Research Council, Washington, D.C.

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