Optimum Flexible Pavement Life-Cycle Analysis Model

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Abstract: A flexible pavement life-cycle model has been developed to yield an optimum maintenance and rehabilitation plan. The model incorporates into the optimization process both performance and cost associated with a life-cycle analysis period for a given pavement structure (project). A single life-cycle indicator called ''life-cycle disutility'' has been introduced and defined as the ratio of cost to performance. The optimum plan is the one associated with the minimum life-cycle disutility value. The model evaluates several potential maintenance and rehabilitaton plans generated according to two defined decision policy options. The first decision policy option requires a fixed analysis period, whereas the second one involves a variable analysis period. Both options require a specified number of major rehabilitation cycles. Pavement life-cycle cost includes initial construction, scheduled major rehabilitation cycles, and routine maintenance and added user cost. Pavement life-cycle performance is defined as the area under the life-cycle performance curve either generated from actual pavement distress data or based on an incremental analysis of the American Association of State Highway and Transportation Officials basic design equation of flexible pavement.

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Introduction

An effective life-cycle analysis model must utilize a mechanism that incorporates both the anticipated long-term pavement performance and related costs. It must also provide the pavement engineers with practical options in developing potential maintenance and rehabilitation (M&R) plans on the project level. While some highway agencies have developed procedures to perform pavement life-cycle analysis (NVDOT 1988; FHWA 1994; CalTrans 1995) these procedures mainly perform an economic comparison based on predefined pavement design alternatives and specified M&R plans, with a fixed analysis period. These procedures neither account for the long-term performance of potential M&R plans nor provide the pavement engineers with a cost-effective mechanism to evaluate them.

The flexible pavement life-cycle analysis model presented in this paper not only incorporates performance and cost in its decision policy approach, but can also be used as an effective pavement management tool that is capable of yielding an optimum M&R plan on the project level. Currently, there are several project-level pavement management systems (RTAC 1977; World Bank 1985; Hass et al. 1994; Delwar and Papagiannakis 1998), but none of them applies an optimum decision policy that incorporates both performance prediction and economic cost assessment in performing a long-term pavement life-cycle analysis. They mainly perform life-cycle cost analysis (LCCA) and economic comparison among a selected number of pavement design alternatives and treatment options.

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The developed optimum life-cycle analysis model requires the use of pavement performance curves. A performance curve is constructed for a particular pavement structure either based on actual pavement distress data or estimated using other appropriate techniques such as the one developed using the American Association of State Highway and Transportation Officials (AASHTO) design method, which is based on the serviceability concept (Abaza et al. 2001). Several researchers have developed a variety of techniques to predict pavement performance trends that are mostly based on stochastic methods (George et al. 1989; Gopinath et al. 1994; Shahin et al. 1994). The performance prediction technique used in the presented pavement life-cycle analysis model is based on an incremental analysis of the AASHTO basic design equation of flexible pavement (AASHTO 1993).

The objective of the developed decision policy is establishing an optimum M&R project-level plan that yields the best overall return in terms of pavement life-cycle disutility. The pavement life-cycle disutility is defined as the ratio of life-cycle cost to life-cycle performance. Pavement life-cycle cost includes all cost elements incurred over an analysis period, namely, initial pavement construction, maintenance and rehabilitation, and added user cost. Pavement life-cycle performance is defined as the area under the life-cycle performance curve estimated over the same analysis period (Yoder and Witczak 1975; Haung 1993). The deployed decision policy provides two options: (1) a fixed analysis period with a fixed number of major rehabilitation cycles scheduled at equal time intervals; or (2) a variable analysis period with a fixed number of major rehabilitation cycles scheduled at unequal time intervals. Each option provides a different approach to planning and scheduling M&R plans. In the first option, the terminal performance condition index associated with each major rehabilitation cycle is considered part of the model output data. In the second option, the terminal performance condition index for each major rehabilitation cycle needs to be specified. Also, the basis for economic comparison among potential M&R plans is different for each option, as will be presented in the methodology section. The performance condition index is defined as any appropriate

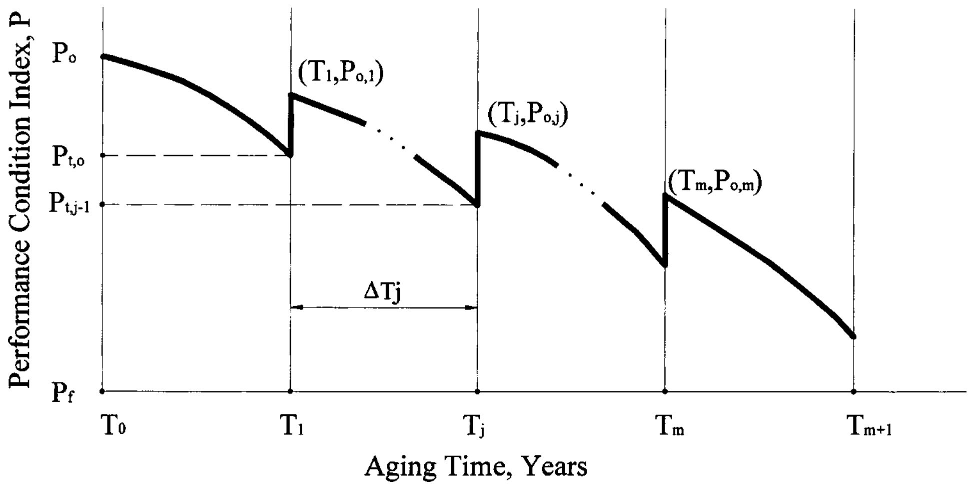

Fig. 1. Typical pavement life-cycle performance curve

index that numerically rates the pavement condition over time. Two popular examples are the pavement condition index (PCI), which rates the pavement on a scale of zero to a hundred, and the present serviceability index (PSI), with a scale rating of zero to five.

The developed optimum pavement life-cycle model requires the use of appropriate pavement maintenance and rehabilitation works. Maintenance works in this model are defined as necessary routine activities undertaken for the purpose of maintaining safe and acceptable road driving conditions. These activities mainly include crack sealing and pothole patching, and they contribute very little to extending the pavement service life. Rehabilitation works are major periodic activities undertaken for the purpose of extending the pavement service life. These major activities include resurfacing (plain asphaltic overlay), resurfacing combined with other treatments such as cold planning or partial reconstruction, and complete reconstruction.

While routine maintenance does not increase the service life of pavement, it has a direct influence on added user cost. The more money spent on routine maintenance, the less added user cost is incurred. This is especially true in the late stages of the pavement service life. Added user cost is also inversely related to the number of major rehabilitation cycles applied over a given analysis period. It is expected to decrease if major rehabilitation is performed more frequently for the same level of routine maintenance work.

Methodology

The developed pavement life-cycle analysis model is designed to yield an optimum pavement maintenance and rehabilitation plan for a given pavement structure (project). The two major life-cycle parameters considered in this model are performance and cost. A third parameter that relates the two together has been introduced and called life-cycle disutility. It is defined as the cost in dollars of one unit area under the pavement life-cycle performance curve. The optimization process takes place with respect to this new parameter and yields an optimum M&R plan that is associated with a minimum life-cycle disutility value.

Fig. 1 demonstrates a typical life-cycle performance curve for an original pavement structural section with an applied number of major rehabilitation cycles denoted (m). The original pavement structural section is designed to provide an initial performance condition index value (P_o) and a terminal value $(P_{t,o})$. The first major rehabilitation cycle is applied once the original pavement structure reaches its specified terminal performance condition index value. Major rehabilitation extends the pavement service life, as indicated by the instantaneous increase in the performance condition index corresponding to each major rehabilitation cycle shown in Fig. 1.

Fig. 1 shows the initial and terminal performance condition indices ($P_{o,j}$ and $P_{t,j}$) associated with each major rehabilitation cycle considered over an analysis period (T_{m+1}) in years. These two performance index values associated with the jth rehabilitation cycle represent two key parameters in the successful application of this model. They are estimated based on design standards and construction practices, and on field experience in evaluating and testing rehabilitated pavements. The AASHTO design method of flexible pavement provides a similar mechanism by which these parameters can be defined based on the serviceability concept (AASHTO 1993).

Typically, if, for example, major rehabilitation consists of resurfacing only, the initial performance condition index of the jth cycle is expected to be lower than the corresponding value for the preceding cycle, as shown in Fig. 1. The terminal performance condition index of the jth cycle depends on the selected decision policy option. In the first option, it is determined as part of the model output data, whereas in the second option, it needs to be specified for each cycle as part of the input data requirements.

The scheduled rehabilitation time (T_j) of the jth cycle is sum of the scheduled time for the preceding cycle and the incremental time interval (ΔT_j). The incremental time interval is constant in the first option and is determined based on a specified fixed analysis period (T_{m+1}) and a fixed number of major rehabilitation cycles (m). In the second option, the incremental time interval is variable for each cycle and is estimated from the corresponding performance curve based on a specified terminal performance index value. The two decision policy options are described in more detail in the subsequent subsections.

A pavement life-cycle performance curve is constructed using individual performance curves. An individual performance curve can be generated for the original pavement structure and for each rehabilitated one based on specified initial and terminal performance condition indices and other design requirements, using the AASHTO performance prediction model presented in a subsequent subsection. Then, based on the individual performance curves and the data requirements for the selected decision policy option, a pavement life-cycle performance curve is constructed.

First Decision Policy Option

The decision policy in this option requires a fixed life-cycle analysis period (T_{m+1}) and a constant number of major rehabilitation cycles (m). The resulting incremental time interval (ΔT_j) between successive rehabilitation cycles is constant, as indicated by Eq. (1):

$$T_j=\frac{T_{m+1}}{1+m},\quad T_j=j\times\Delta T_j,\quad j=1,2,\ldots,m \tag{1}$$

where T_j = scheduled rehabilitation time for the jth cycle; and m = number of deployed major rehabilitation cycles in a fixed analysis period T_{m+1}. The terminal performance condition index value for the original pavement structure and each rehabilitation cycle is estimated from the corresponding individual performance curves using the resulting incremental time interval. The pavement life-cycle performance curve is then constructed from curve segments obtained from individual performance curves defined by the initial and terminal performance condition indices.

Second Decision Policy Option

This decision policy option deals with a variable life-cycle analysis period (T_{m+1}) based on a specified number of major rehabilitation cycles (m). This option requires the specification of a terminal pavement condition index value ($P_{t,j}$) for the original pavement structure and each major rehabilitation cycle. The incremental time interval (ΔT_j) between successive rehabilitation cycles is variable and estimated separately for each cycle. The scheduled rehabilitation time (T_j) for the jth cycle is calculated using Eq. (2):

$$T_j=T_{j-1}+\Delta T_j,\quad j=1,2,\ldots,m+1 \tag{2}$$

$$T_0=0.0$$

The incremental time interval (ΔT_j) for the jth cycle is estimated based on the terminal serviceability index and individual performance curve corresponding to the (j-1)th cycle, and it is estimated for the first cycle from the performance curve corresponding to the original pavement structure based on its terminal serviceability index value ($P_{t,o}$). The last incremental time interval (ΔT_{m+1}) is estimated from the performance curve corresponding to the mth rehabilitation cycle based on its terminal serviceability index value ($P_{t,m}$). Similar to the first decision policy option, a life-cycle performance curve is then constructed from the resulting individual curve segments.

Optimum Pavement Life-Cycle Performance

Evaluation of potential pavement maintenance and rehabilitation plans can be made using a newly introduced performance indicator called relative performance. Performance is defined as the integral of the pavement performance curve. Therefore, the area falling under the life-cycle curve is by definition an indication of performance (Yoder and Witczak 1975; Huang 1993). Relative performance is defined as the ratio of the area corresponding to a pavement life-cycle curve to that of a perfect performance. A perfect performance is the one represented by a hypothetical horizontal straight line. The optimum pavement maintenance and rehabilitation plan is the one associated with the maximum life-cycle relative performance value. Life-cycle relative performance is mathematically stated by Eq. (3):

$$RP_{LC}=\frac{A_{LC}}{(P_o-P_f)T_{m+1}} \tag{3}$$

where RP_{LC} = pavement life-cycle relative performance; A_{LC} = area under pavement life-cycle performance curve; P_o = initial performance condition index value of original pavement; P_f = pavement life-cycle failure performance condition index value; and T_{m+1} = length of a life-cycle analysis period in years. Evaluation of potential maintenance and rehabilitation plans based solely on pavement life-cycle relative performance is not considered an effective approach, since it does not take into consideration life-cycle cost.

Optimum Pavement Life-Cycle Cost

The cost elements incurred over the life-cycle analysis period include construction cost of the original pavement, rehabilitation cost of a number of major rehabilitation cycles, routine maintenance cost, and added user cost. Routine maintenance and added user costs are estimated as one cost element in the developed model, since they are directly related to each other and both are estimated on an annual basis. In the presence of an active routine maintenance program, added user cost will be minimal. The procedure for estimating the pavement life-cycle cost based on engineering economy principles is different for each decision policy option. The present worth method can be used in the first decision policy option, since the length of the life-cycle analysis period is constant for all potential M&R plans. The present worth of the pavement life-cycle cost for this option is calculated from Eq. (4):

$$P_{LC}=C_c+M_c\times f(P/A,r,T_{m+1})+\sum_{j=1}^{m}R_j\times f(P/F,r,T_j) \tag{4}$$

$$f(P/A,r,T_{m+1})=\left[\frac{(1+r)^{T_{m+1}}-1}{r(1+r)^{T_{m+1}}}\right]$$

$$f(P/F,r,T_j)=\frac{1}{(1+r)^{T_j}}$$

where P_{LC} = pavement life-cycle present worth cost for a given M&R plan (\$/m^2); C_c = initial construction cost of original pavement structure (\$/m^2); M_c = annual routine maintenance and added user cost (\$/m^2); R_j = future rehabilitation cost of the jth cycle ($j=1,2,\ldots,m$); T_{m+1} = length of life-cycle analysis period in years; r = annual interest rate; m = number of deployed major rehabilitation cycles in an analysis period; T_j = scheduled rehabilitation time of the jth cycle in years from Eqs. (1) or (2); $f(P/A,r,T_{m+1})$ = factor converting a uniform annual cost to a present one; and $f(P/F,r,T_j)$ = factor converting a future cost to a present one.

Potential M&R plans can be compared using pavement life-cycle present worth cost values. Considering life-cycle cost only, the optimum M&R plan is the one associated with the minimum life-cycle present worth cost value. The equivalent annual cost method is used in the second decision policy option with a variable life-cycle analysis period. The pavement life-cycle equivalent annual cost is calculated for each potential M&R plan from previously presented cost parameters using Eq. (5):

$$EA_{LC}=P_{LC}\times f(A/P,r,T_{m+1}) \tag{5}$$

$$f(A/P,r,T_{m+1})=\left[\frac{r(1+r)^{T_{m+1}}}{(1+r)^{T_{m+1}}-1}\right]$$

where EA_{LC} = pavement life-cycle equivalent annual cost ($\$/\text{m}^2$); P_{LC} = pavement life-cycle present worth cost obtained from Eq. (4) for variable T_{m+1} periods; and $f(A/P,r,T_{m+1})$ = factor converting a present cost to an equivalent uniform annual one.

Similarly, potential M&R plans with variable life-cycle analysis period can be compared using pavement life-cycle equivalent annual cost values. The equivalent annual cost method can also be applied to the first decision policy option for the purpose of making compatible comparisons. Considering cost only, the plan with the minimum life-cycle equivalent annual cost is selected as the optimum one. Comparison among potential M&R plans based solely on life-cycle cost is not considered an effective approach, since it does not take into consideration anticipated long-term pavement life-cycle performance.

Optimum Pavement Life-Cycle Disutility

The life-cycle disutility parameter is newly introduced as a means to replace both the pavement life-cycle relative performance (RP_{LC}) and the life-cycle cost (P_{LC} or EA_{LC}) by an effective single indicator used in evaluating potential M&R plans. The pavement life-cycle disutility is defined as the ratio of life-cycle cost to life-cycle performance represented by the area under the life-cycle performance curve. It simply assigns a monetary value to pavement performance and provides an effective mechanism by which potential M&R plans can be evaluated. The optimum M&R plan is the one associated with the minimum pavement life-cycle disutility value. The life-cycle disutility for the first decision policy option associated with a fixed analysis period is calculated using Eq. (6):

$$U_{LC}=\frac{P_{LC}}{A_{LC}} \tag{6}$$

where U_{LC} = pavement life-cycle disutility in dollars per unit area under the life-cycle performance curve; P_{LC} = pavement life-cycle present worth cost ($\$/\text{m}^2$) obtained from Eq. (4); and A_{LC} = area under the pavement life-cycle performance curve.

The pavement life-cycle disutility for the second decision policy option with variable analysis period is calculated based on an average annual unit area of performance. The average annual unit area of performance is obtained by dividing the area under a life-cycle performance curve by the corresponding life-cycle analysis period. Then, the pavement life-cycle disutility is defined as the ratio of life-cycle equivalent annual cost to the average annual unit area of performance, as indicated by Eq. (7):

$$U_{LC}=\frac{EA_{LC}}{(A_{LC}/T_{m+1})} \tag{7}$$

where U_{LC} = pavement life-cycle disutility in dollars per unit area under the performance curve; EA_{LC} = pavement life-cycle equivalent annual cost ($\$/\text{m}^2$) obtained from Eq. (5); A_{LC} = area under a pavement life-cycle performance curve; and T_{m+1} = pavement life-cycle analysis period (years) associated with a particular M&R plan.

Eq. (7) can also be used in the first decision policy option for the purpose of making effective and compatible evaluations of potential maintenance and rehabilitation plans considered by both options. The objective in both decision policy options is to yield a minimum pavement life-cycle disutility value. The optimization process is performed using a trial-and-error approach with respect to potential life-cycle parameters. These parameters mainly include the number of deployed major rehabilitation cycles, the length of analysis period, and the initial and terminal performance condition indices. The number of deployed major rehabilitation cycles and the length of analysis period are the two potential parameters used in the optimization process for the first decision policy option. In the second decision policy option, the number of major rehabilitation cycles and the terminal performance condition indices are the two potential parameters used in the optimization process. All other presented life-cycle parameters can be considered in the search for an optimum M&R plan, but in the presented sample calculations only potential ones have been used. A trial-and-error approach is deemed adequate in the search for an optimum M&R plan, because the practical values of potential life-cycle parameters are usually limited.

AASHTO Pavement Life-Cycle Performance Curves

A procedure that applies an incremental analysis of the AASHTO basic design equation has been presented to construct flexible pavement performance curves (Abaza et al. 2001). The procedure provides a simple tool to predict the pavement performance condition at any given future time. This procedure can be used in the absence of actual pavement performance condition data. The two main parameters defining performance are the PSI and 80 kN equivalent single axial load (ESAL) applications. These two parameters are also related to materials properties, drainage and environmental conditions, and performance reliability. The design approach applies all related parameters to obtain a measure of the required structural strength through an index known as the structural number (SN). Eq. (8) provides the basic equation used for the design of flexible pavement (AASHTO 1993):

$$\log W_{80}=Z_R S_o+9.36\log(\text{SN}+1)+\frac{\log\left[\dfrac{\Delta\text{PSI}}{4.2-1.5}\right]}{0.40+\dfrac{1094}{(\text{SN}+1)^{5.19}}}+2.32\log(M_R)-8.27 \tag{8}$$

where W_{80} = number of 80 kN equivalent single axle load applications estimated for a selected design period and design lane; Z_R = standard normal deviate for a specified reliability level; S_o = combined standard error of the traffic prediction and performance prediction; ΔPSI = difference between the initial or present serviceability index (P_o) and the terminal serviceability index (P_t); SN = design structural number indicative of the total required pavement thickness; and M_R = subgrade resilient modulus (must be in pounds per square inch).

In the design mode and after all related parameters are estimated, Eq. (8) is solved for the design structural number (SN) by trial and error or using the equivalent AASHTO design chart (AASHTO 1993). The approach used to define a pavement performance curve as a function of the present serviceability index and 80 kN ESAL applications or service time is based on the direct use of Eq. (8). The incremental 80 kN ESAL applications $(W_{80})_i$ are calculated by specifying varying values of the incremental change in the present serviceability index (ΔPSI_i). The incremental change in the present serviceability index is defined as the difference between the initial serviceability index (P_o) and the incremental present serviceability index (PSI_i). The incremental present serviceability index is varied between its assigned initial value and its failure one of 1.5, according to AASHTO. Fig. 2 illustrates the basic concept by which the difference between two successive data points can be used to construct a pavement performance curve. The estimated incremental change in

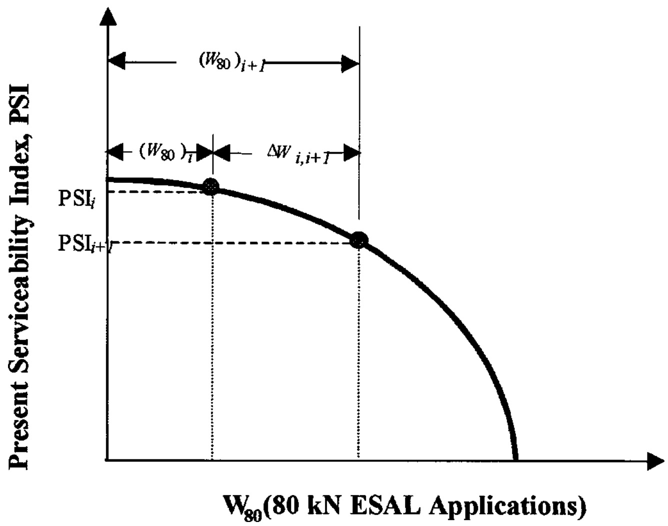

Fig. 2. Basic pavement performance curve

load applications ($\Delta W_{i,i+1}$) can then be converted into an equivalent incremental service time interval ($\Delta T_{i,i+1}$) using Eq. (9). The assumption made in establishing Eq. (9) is that the 80 kN ESAL applications increase linearly with time. A computer system has been designed using visual basic programming language with one of its main functions as solving the mathematical algorithm presented as follows:

$$\Delta T_{i,i+1}=\frac{\Delta W_{i,i+1}}{W_T}T \tag{9}$$

where

$$\Delta W_{i,i+1}=(W_{80})_{i+1}-(W_{80})_i, \quad i=1,2,\ldots,n$$

$$(W_{80})_i=F(\Delta\mathrm{PSI}_i,\mathrm{SN},M_R,Z_R,S_o) \text{ from Eq. (8)}$$

$$(W_{80})_{i+1}=F(\Delta\mathrm{PSI}_{i+1},\mathrm{SN},M_R,Z_R,S_o) \text{ from Eq. (8)}$$

$$W_T=\sum_{i=1}^{n}\Delta W_{i,i+1}$$

[Note that W_T is also the total number of 80 kN ESAL applications estimated over a design life of T years.]

$$\mathrm{SN}=F(W_T,\Delta\mathrm{PSI},Z_R,S_o,M_R) \text{ from Eq. (8)}$$

$$T=\sum_{i=1}^{n}\Delta T_{i,i+1}$$

$$N_{T_{i+1}}=\sum_i \Delta W_{i,i+1}=(W_{80})_{i+1}, N_{T_1}=0.0$$

where $N_{T_{i+1}}$ = cumulative number of 80 kN ESAL applications estimated over a service life of T_{i+1} years. Also:

$$T_{i+1}=\sum_i \Delta T_{i,i+1}, \quad T_1=0.0$$

where T_{i+1} = cumulative service time in years associated with the cumulative 80 kN ESAL applications ($N_{T_{i+1}}$). In addition:

$$\Delta\mathrm{PSI}_i=P_o-\mathrm{PSI}_i$$

$$\mathrm{PSI}_i=P_o-(i-1)\Delta P, \quad i=1,2,\ldots,n+1$$

$$n=\frac{P_o-1.5}{\Delta P}$$

ΔP is the specified incremental change in the PSI value used to generate $(n+1)$ data points to be used in the construction of a particular pavement performance curve. It must be specified either as a tenth or hundredth of a point to ensure n will be an integer. In the computer system, one hundredth of a point has been specified with the corresponding computer time being very small. A performance curve is then constructed by plotting the incremental present serviceability index (PSI_i) versus the cumulative aging time (T_{i+1}).

An individual performance curve for a new pavement structure or a rehabilitated one can be generated using the presented incremental procedure by specifying all related input parameters. Differences between new pavements and rehabilitated ones in certain key input parameters are expected. The initial and terminal serviceability indices are certainly two of these differing parameters. Therefore, a unique individual performance curve is generated for new pavement and each major rehabilitation cycle in the life-cycle analysis period. A pavement life-cycle performance curve is then constructed by pasting individual performance curve segments defined as required by the deployed decision policy option. The incremental data points used to generate individual performance curves are also used to calculate the area under the life-cycle performance curve that is needed for applying presented optimum life-cycle analysis procedures.

Model Requirements and Sample Results

The model data requirements are of two types. The first type is the data needed to generate the pavement life-cycle performance curves using the described AASHTO procedure. The second type is related to the selected decision policy option and associated life-cycle cost. A sample problem is presented based on selected practical values for a given flexible pavement structural section (project).

Pavement Life-Cycle Performance Input Data

1. The generation of an AASHTO performance curve for a new pavement structure requires the following input data: $W_T = 1\times10^6$; $M_R=10{,}000$, $T=20$; $P_o=4.5$; $P_f=1.5$; $Z_R=-1.645$; $S_o=0.35$; $\Delta\mathrm{PSI}=3.0$, $\Delta P=0.01$.
2. The generation of an AASHTO performance curve for each major rehabilitation cycle requires similar data. In this example, the initial serviceability index ($P_{o,j}$) has been reduced by 0.2 for each rehabilitation cycle in relation to its value for the preceding cycle. Other input parameters have been assigned the same values as for the new pavement. The terminal PSI value ($P_{t,j}$) needs to be specified for each rehabilitation cycle in a particular analysis period generated using the second decision policy option. The same terminal PSI value has been assigned to all rehabilitation cycles in the same analysis period. Three cases have been considered using 2.0, 2.5, and 3.0 terminal PSI values.

Decision Policy and Pavement Life-Cycle Cost Input Data

1. For the application of the first decision policy option, a fixed-time analysis period of forty years has been specified. The number of major rehabilitation cycles (m) needs to be specified. Six potential cases have been investigated by varying the number of rehabilitation cycles from one to six.

Table 1. Sample Life-Cycle Performance and Cost Parameters for 40-Year Analysis Period

m	ΔT_j (years)	A_{LC}	RP_{LC}	C_C (\$/m^2)	R_C (\$/m^2)	M_C (\$/m^2)	P_{LC} (\$/m^2)	EA_{LC} (\$/m^2)	U_{LC}
1	20.00	66.20	0.551	25	25	3.00	108.19	4.68	2.83
2	13.33	82.71	0.689	25	19.00	2.55	105.39	4.56	2.21
3	10.00	89.21	0.743	25	16.00	2.00	98.58	4.26	1.91
4[a]	8.00	90.67	0.755	25	14.20	1.56	93.62	4.05	1.79[a]
5[a]	6.67	87.79	0.731	25	13.00	1.22	90.66	3.92	1.79[a]
6	5.71	85.14	0.709	25	12.14	1.00	90.14	3.90	1.83

[a]Optimum solutions.

2. For the application of the second decision policy option, a variable-time analysis period has been generated based on a specified number of major rehabilitation cycles and a terminal PSI value ($P_{t,j}$) for each cycle. Six potential cases have been considered using one and two cycles ($m=1$ and $m=2$) with each investigated by the three specified terminal PSI values (i.e., 2.0, 2.5, and 3.0).
3. The life-cycle cost elements have been estimated based on prevailing local market prices. The cost unit for initial pavement construction (C_c) has been assigned as \$25/m^2. The major rehabilitation cost (R_c) and the routine maintenance and added user cost (M_c) are estimated using Eqs. (10) and (11), respectively. These equations are simply constructed to generate cost units based on a convenient and systematic procedure:

$$R_c \text{ (\$/m}^2) = 25 - 0.9(20.0\text{-}\Delta T) \geqslant 12.00 \qquad (10)$$

$$M_c \text{ (\$/m}^2) = 3.0 - 0.01(20.0\text{-}\Delta T)^2 \geqslant 1.00 \qquad (11)$$

The cost units obtained from Eqs. (10) and (11) have minimum values that should be used if the incremental time interval (ΔT) between successive rehabilitation cycles becomes small. The routine maintenance and added user cost unit obtained from Eq. (11) assumes that regular routine maintenance will be performed resulting in no added cost to users. Otherwise, the corresponding \$3.0/m^2 maximum cost unit, obtained when $\Delta T=20$ years, would be substantially higher in the absence of an active routine maintenance program. An annual interest rate of 3% has been used in the economic evaluations.

Optimum Pavement Life-Cycle Analysis Results

Table 1 provides sample life-cycle analysis results obtained using the first decision policy option. Six cases are presented with a different number of deployed major rehabilitation cycles. The incremental time interval (ΔT_j) between any two adjacent rehabilitation cycles is constant for a given number of cycles based on a fixed forty-year analysis period. The case with four major rehabilitation cycles ($m=4$), scheduled at equal time intervals of eight years, provides an optimum M&R plan. This optimum plan is identified by its 1.79 minimum life-cycle disutility value (U_{LC}). It is associated with a maximum 0.755 life-cycle relative performance (RP_{LC}). Also, the case with five rehabilitation cycles provides another optimum plan with the same disutility value. The case with six rehabilitation cycles provides the minimum life-cycle cost value (P_{LC} or EA_{LC}), which is not by itself a reliable indication of yielding an optimum M&R plan, and neither is the life-cycle relative performance. The optimum maintenance and rehabilitation plan is one that provides the minimum life-cycle disutility value.

The life-cycle relative performance starts being directly proportional to the deployed number of major rehabilitation cycles but becomes inversely proportional after it reaches a 0.755 maximum value. The reason for this change in trend is the reduced initial serviceability index value assigned for each successive rehabilitation cycle; had it not been reduced, relative performance would have not changed its directly proportional trend. Fig. 3 shows the life-cycle performance curves associated with the first four cases presented in Table 1. The terminal serviceability index ($P_{t,j}$) associated with each major rehabilitation cycle can directly be read from the corresponding life-cycle performance curve. It can be seen that its value for a particular rehabilitation cycle is

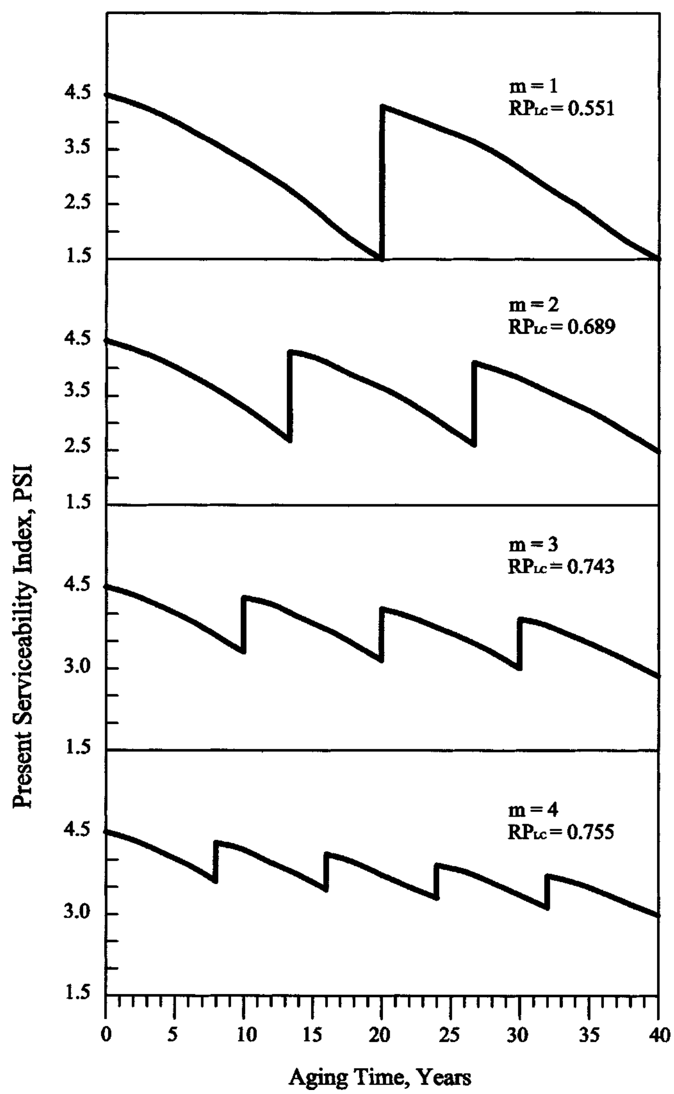

Fig. 3. Sample life-cycle performance curves for 40-year analysis period

Table 2. Sample Life-Cycle Performance and Cost Parameters for Variable Analysis Period

m	$P_{t,j}$	T_{m+1} (years)	A_{LC}	RP_{LC}	C_C (\$/m^2)	R_C (\$/m^2)	M_C (\$/m^2)	EA_{LC} (\$/m^2)	U_{LC}
1	2.0	34.52	64.77	0.625	25	22.66	2.93	4.81	2.56
1	2.5	28.91	60.46	0.697	25	20.23	2.72	4.72	2.26
1[a]	3.0	22.91	52.85	0.769	25	17.62	2.33	4.63	2.01[a]
2	2.0	51.34	93.20	0.605	25	22.66	2.93	4.81	2.61
2	2.5	42.49	86.39	0.678	25	20.23	2.72	4.72	2.32
2	3.0	33.01	74.35	0.751	25	17.62	2.33	4.63	2.06

[a]Optimum solution.

lower than the corresponding value for the preceding cycle, and it is generally increasing as the number of deployed rehabilitation cycles increases, resulting in a consistent improvement in the life-cycle performance.

Table 2 presents sample life-cycle analysis results associated with the second decision policy option. Six cases are presented using two values for the number of major rehabilitation cycles (m) and three values for the terminal serviceability index ($P_{t,j}$). Each presented case results in a different life-cycle analysis period (T_{m+1}). The optimum maintenance and rehabilitation plan is the one associated with a 2.01 minimum life-cycle disutility value. It corresponds to the case with one major rehabilitation cycle and a 3.0 terminal serviceability index value. This optimum case is also associated with a 0.769 maximum life-cycle relative performance value and a 4.63 minimum life-cycle equivalent annual cost value (EA_{LC}).

Table 2 shows that the obtained length of the life-cycle analysis period is directly proportional to the deployed number of major rehabilitation cycles and inversely proportional to the assigned value of terminal serviceability index. The life-cycle relative performance value is directly proportional to the value of terminal serviceability index for the same number of major rehabilitation cycles, whereas the life-cycle equivalent annual cost and life-cycle disutility are inversely proportional to the terminal serviceability index for the same number of major rehabilitation cycles. This last statement indicates the significance of treating the pavement in the early stage of deterioration, a policy that results in an overall cost saving. Fig. 4 shows four life-cycle performance curves corresponding to four of the six cases presented in Table 2. The scheduled rehabilitation time for each cycle can directly be read from the corresponding life-cycle performance curve. The incremental time interval (ΔT_j) between successive rehabilitation cycles is variable in this decision policy option, as evidenced from Fig. 4. Also, the terminal serviceability index is constant for each rehabilitation cycle in the same analysis period, as shown in Fig. 4, a policy that is typically implemented by many highway agencies.

The presented sample life-cycle disutility values for both decision policy options have been calculated using the equivalent annual cost method for the purpose of making effective and compatible comparisons of potential M&R plans considered by both options. The presented sample life-cycle disutility values associated with the first decision policy option are generally lower than the disutility values associated with the second decision policy option. Therefore, the optimum M&R plan is selected based on the first decision policy option, as provided in Table 1.

Conclusions and Recommendations

An effective project-level pavement management tool has been presented with its main objective yielding an optimum maintenance and rehabilitation plan. An optimum maintenance and rehabilitation plan is one corresponding to a minimum life-cycle disutility value derived according to a specified decision policy option. The presented sample results clearly indicate the effectiveness of the life-cycle disutility parameter in replacing the other two traditional life-cycle parameters, namely, performance and cost. It provides a simple yet reliable approach to evaluating potential plans for the maintenance and rehabilitation of flexible pavement, and it can easily be extended to rigid pavement. The presented sample results from the two deployed decision policy options have converged to optimal solutions that accomplish the

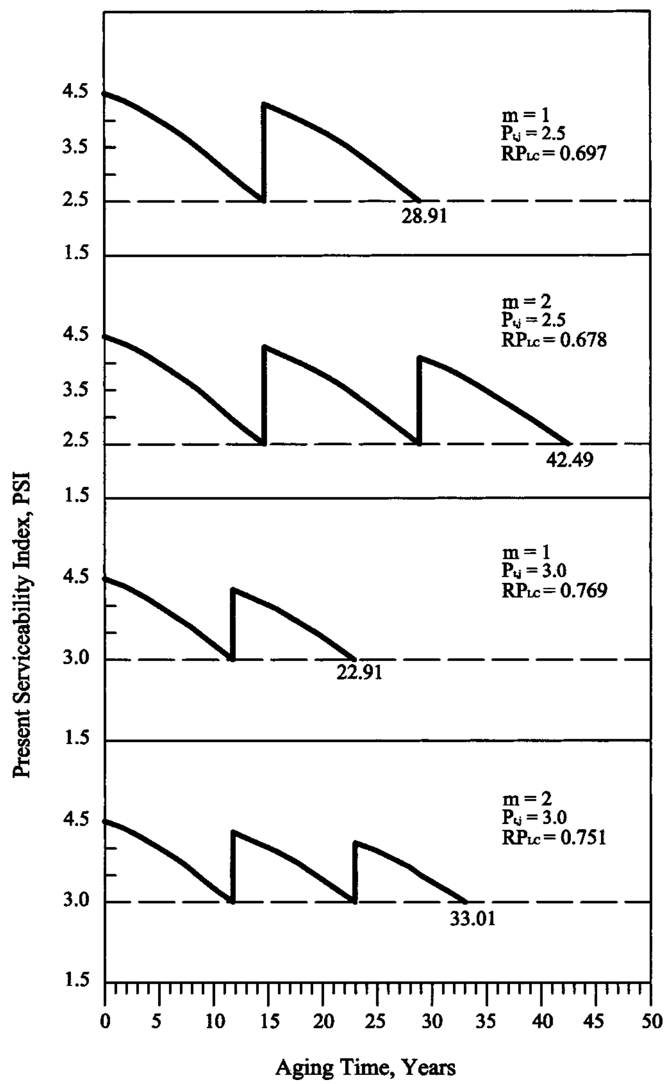

Fig. 4. Sample life-cycle performance curves for variable analysis period

same objective despite the differences in their overall structures and data requirements. Therefore, it is recommended that both options be applied to a particular pavement project by assigning potential values to various model parameters and selecting the maintenance and rehabilitation plan that is associated with the minimum life-cycle disutility value.

The successful application of the presented life-cycle analysis model depends greatly on using reliable pavement performance curves. The presented AASHTO technique used to generate such curves provides an adequate and convenient approach, especially in the absence of actual pavement condition data. Typically, small local governments may not be able to afford the cost of conducting regular pavement testing and evaluation to develop needed performance curves. This model can be of special interest to these localities, but if actual performance curves become available, they can easily be applied to the presented optimum life-cycle analysis techniques. In addition, successful application requires the estimation of reliable cost units, with the cost of routine maintenance and added user cost being the most critical one. The presented sample results assumed an active routine maintenance program associated with minimal added user cost. The estimated routine maintenance and added user cost unit would have been grossly underestimated had it not been the assumed case, and it would have greatly affected the overall optimum outcome, as the added user cost would be substantially higher. The overall outcome in such a case is expected to be higher life-cycle disutility, which means a higher cost to taxpayers.

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