APPLICATION OF MECHANISTIC-EMPIRICAL AND LIFE-CYCLE COST ANALYSES FOR OPTIMIZING FLEXIBLE PAVEMENT MAINTENANCE AND REHABILITATION

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ABSTRACT

In this study an attempt was made to evaluate and select an optimal Maintenance and Rehabilitation (M&R) strategy for a designed flexible pavement by integrating Life Cycle Cost Analysis (LCCA) and Mechanistic-Empirical (M-E) design procedures. A 11.27-Km long section of 4-lane Highway 53, in Lake County, California is considered for this project level study. A flexible pavement structure was designed for a 20-year service life using the California M-E design program, CalME, and the incremental-recursive damage analysis method. Three M&R strategies namely, Extended Pavement Preservation (EPP), Preservation-Preservation-Rehabilitation (PPR) and Rehabilitation only (R) available in the CalME program were evaluated. Each M&R strategy requires application of such strategy as certain levels of distresses (rutting and cracking) are reached. The California-customized RealCost LCCA program was also employed to compare the various M&R strategies using the Equivalent Uniform Annual Cost (EUAC). LCCA demonstrated that EPP was the best economical alternative to maintain the pavement in a good usable condition for as long as 80 years of service. The methodology employed in this paper also demonstrated that extended life pavement may be achieved from a 20-year design by selecting the optimal preservation techniques and optimizing their time of application.

INTRODUCTION

The California mechanistic-empirical (M-E) design procedure for asphalt surfaced pavements (CalME) was developed beginning in the late 1990s with one of its primary aims to emphasize pavement rehabilitation and preservation, which account for more than 90 percent of the California Department of Transportation (Caltrans) pavement program, rather than new pavements (1). CalME incorporates research products from the Strategic Highway Research Program (SHRP), an incremental-recursive analysis procedure, and results of accelerated pavement testing from the Caltrans' Heavy Vehicle Simulators (HVS) and test tracks such as Westrack and MnROAD.

This paper presents a case study in which M-E analysis and Life Cycle Cost Analysis (LCCA) were integrated to find the most cost effective strategy for a state highway segment, including consideration of "pavement preservation" and the concept of "perpetual pavement". LCCA is an engineering economic analysis tool useful in comparing the relative economic merits of competing construction and rehabilitation design alternatives for a single project (2). Pavement preservation is defined as "A program employing a network level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety and meet motorists' expectations (3)."

According to the Federal Highway Administration (FHWA), a pavement preservation program consists primarily of three components; namely Minor Rehabilitation, Preventive Maintenance, and Routine Maintenance (4). Pavement preservation addresses pavements whose structural sections are still in good condition and have a significant amount of remaining service life (5). Performing a series of successive pavement preservation treatments during the life of the pavement is less disruptive to uniform traffic flow than long closures normally associated with major rehabilitation or reconstruction (3). Rehabilitation is defined as "Restoration of an existing pavement that is severely distressed to a good condition by the application of non-routine maintenance."(6) Caltrans has found that delaying pavement preservation by applying a thin overlay on an existing pavement with a Pavement Condition Index (PCI) of 60 instead of 80 would result in an increase in equivalent annual treatment costs between 70 to 100% (7). In the context of perpetual pavements, it is necessary to periodically replace the surface course in order to fulfill the aim of avoiding structural deterioration (8).

Traditional LCCA can be used for calculating the present worth costs for pavement alternatives and it is the primary tool used for economic comparisons. The main purpose of these concepts is to develop a framework in which more cost-effective pavements are produced (8). To obtain a perpetual pavement, it is important to design a pavement such that all forms of distress are in the top few inches of the pavement (9). Equivalent Uniform Annual Cost (EUAC) represents the Net Present Value (NPV) of all discounted costs and benefits of an alternative as if they occur uniformly throughout the analysis period. EUAC is a particularly useful indicator when budgets are established on an annual basis (10) or when alternatives with different life spans are to be compared, and is calculated from:

$$EAUC = NPV \times \frac{i(1+i)^n}{(1+i)^n - 1} \qquad \text{Equation}$$

where i = discount rate, and n = number of years into future. The LCCA analysis period should be sufficiently long to reflect long-term cost differences associated with reasonable design strategies (9).

The objective of this paper is to demonstrate the effectiveness and necessity of integrating M-E analysis and LCCA for designing cost-effective longer-life flexible pavements.

PAVEMENT STRUCTURE DESIGN

Figure 1 shows the framework used in this paper to optimize the design of a flexible pavement using an integrated system of mechanistic-empirical and life cycle cost analyses. A new pavement structure is designed with the use of M-E analysis to satisfy all conditions of climate, traffic, and design life, as well as a set of desired performance criteria. Once an acceptable design has been obtained, a series of M&R strategies using various types of materials may be applied and rechecked with M-E analysis, followed by LCCA to determine the EUAC and select the most cost-effective M&R strategy to be used over the life of the project. Two programs are used in the analysis. CalME, the California M-E program, is a tool used for designing rehabilitation of asphalt surfaced pavements as well as new pavement, and is explained in (1). RealCost is the LCCA tool developed by the FHWA (10), which has been customized for use by Caltrans (11).

The pavement that was selected for analysis in this paper is a section of 11.27 Km-4-lane State Route 53 in Lake County, California (District 1) with a climate characterized as "Low Mountain" (12). The pavement is subjected to a traffic characterized by load spectrum Group 1a in CalME as defined in (13). The rehabilitation design life was selected to be 20 years accounting for an equivalent traffic of 46.2 million ESALs; or a Traffic Index (TI) of 14.2 (6). The subgrade type is well graded sand SW based on USCS system (6). The Incremental-Recursive design procedure in CalME (1) was used to design the pavement structure. The incremental recursive procedure works in the increments of time and uses the output from one increment, recursively, as input to the next increment. The procedure predicts the pavement in terms of layer moduli, crack propagation, permanent deformation and roughness as a function of time. It does not carry an automatic design for required conditions, but helps to check the performance of the design prepared by Caltrans' present method.

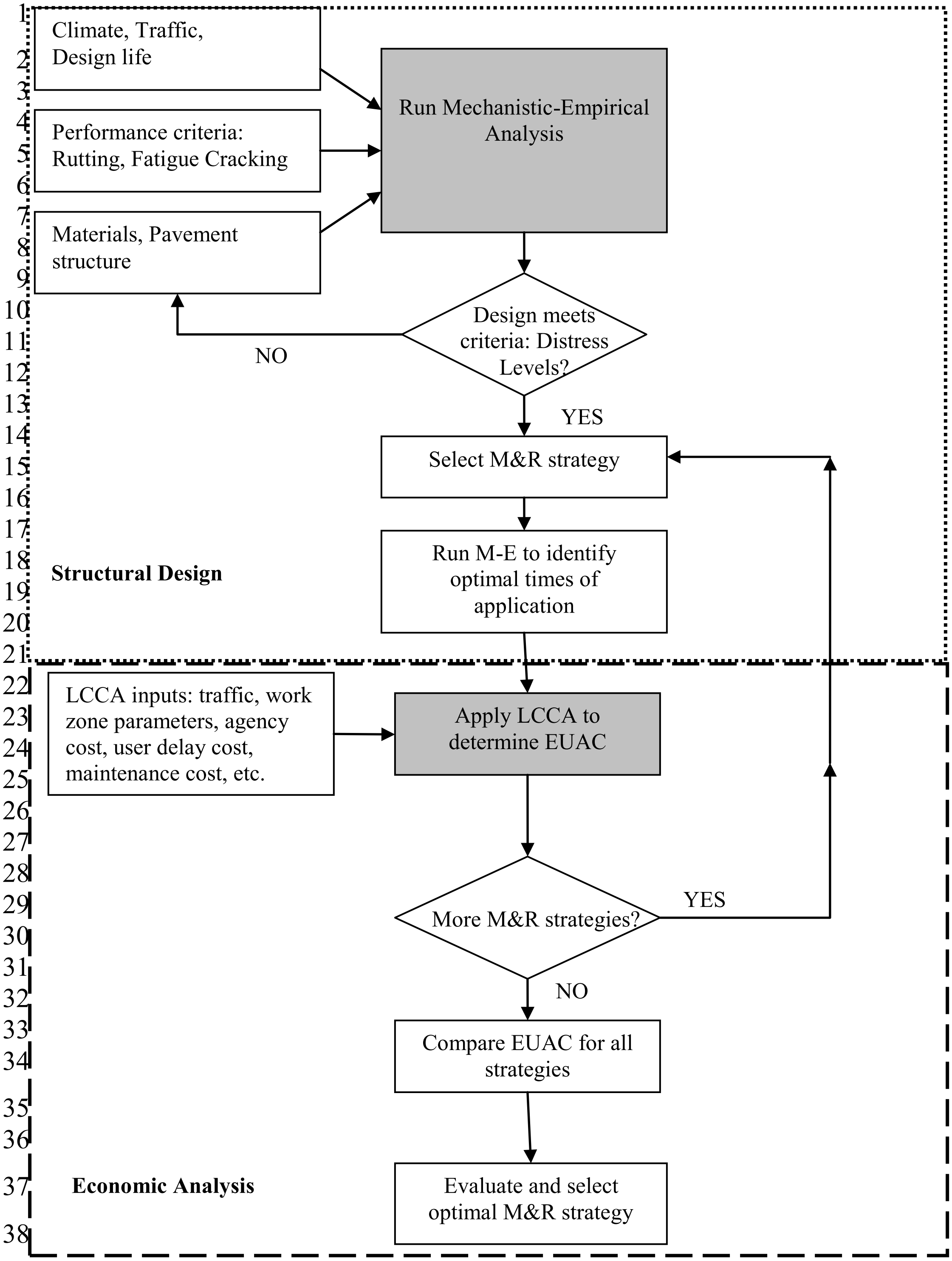

FIGURE 1: Integration of CalME and LCCA

Despite the existence of many distress mechanisms, rutting in the bituminous layers and fatigue cracks are considered the dominant distresses. Fatigue is one of the main distress mechanisms caused by the excessive tensile strains at the bottom of the bituminous layer due to repeated loading. Rutting in the surface layer is the mechanism caused by the consolidation or lateral movement of the bituminous materials near the surface due to repeated loading. The other major distress in the pavement caused due to the environment effect is aging. An aging/ hardening model is embedded in the software that accounts for the increase in the modulus due to the aging of the pavement. The distress thresholds used in the design were 10 mm down rutting (rut depth below the original plane of the surface, not counting upward movement at the edges of the wheel path) and a cracking density of 0.5 m/m^2 in the hot mix asphalt (HMA) layer. Figure 2 shows the CalME design screen based on the traffic, climate and materials inputs.

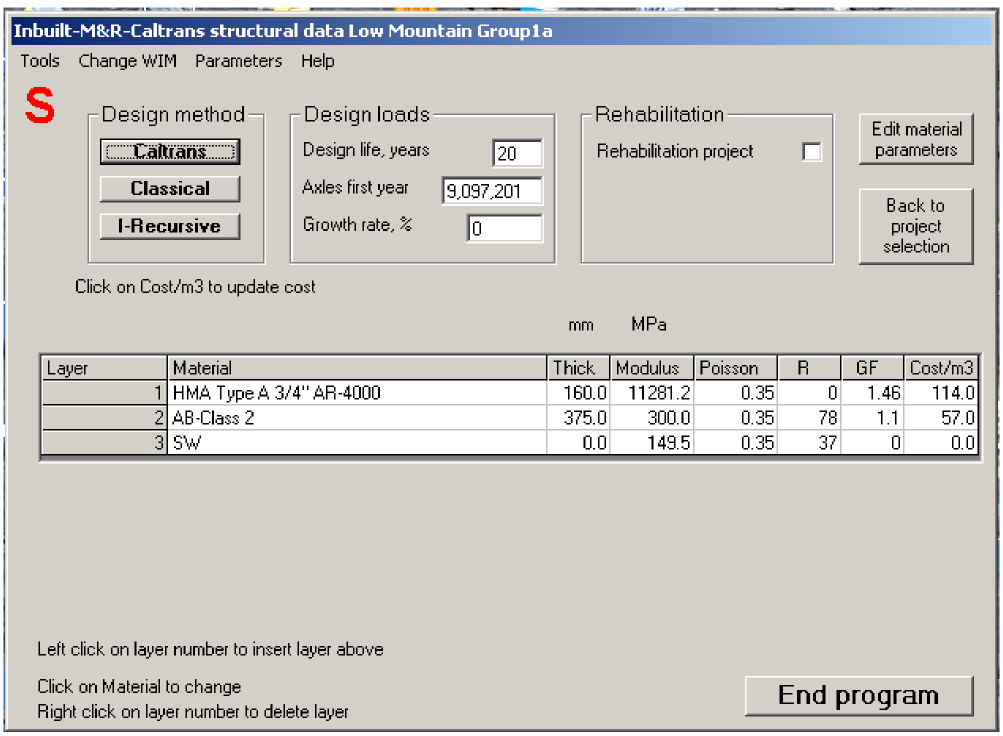

FIGURE 2: CalME main input screen

Deterministic analyses with CalME utilizing wander in the wheel paths were performed to check the pavement performance based on both the rutting and cracking performance criteria. Several structure thicknesses utilizing a surface layer of hot mix asphalt (HMA) with 19 mm (¾ inch) maximum size aggregate mix and AR-4000 (corresponding to PG 64-10 typically) binder, and an aggregate base layer (AB) Class 2 (6) were analyzed. The initial structure was obtained using the Caltrans empirical method based on a subgrade R-value and TI (6). M-E analysis yielded a final 20-year structure consisting of 160 mm HMA and a 375 mm AB layer (as shown in Figure 3). The progressions of down rutting and cracking for this structure are shown in Figures 4 and 5, respectively. The corresponding rutting life was approximately 25 years, and the fatigue cracking life was 19 years (closest to 20 year design life). The increase in rutting after year 19 is primarily associated with loss of stiffness of the HMA layer after it cracks.

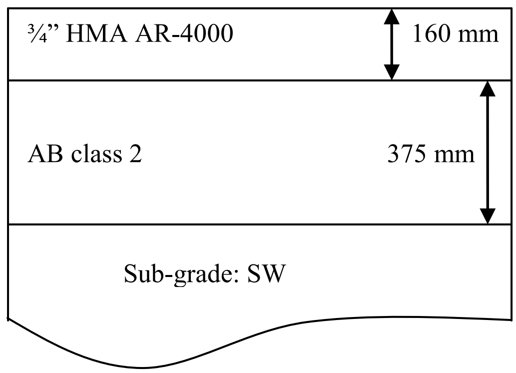

Figure 3: Pavement structure used in the analysis

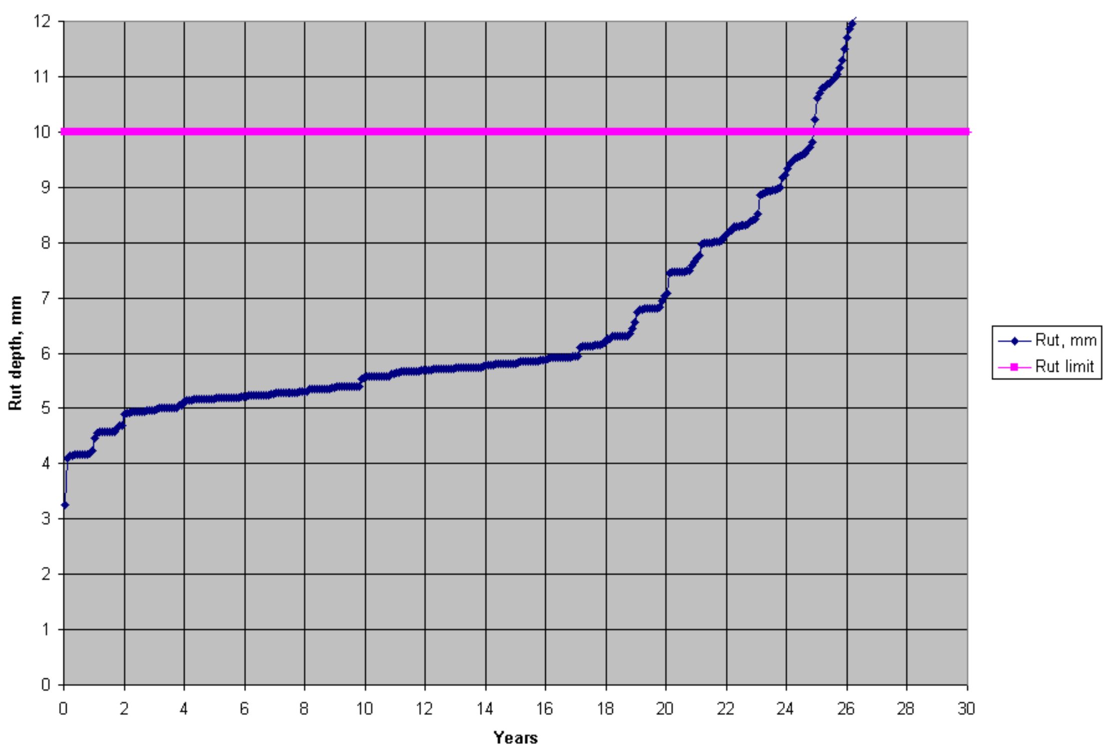

FIGURE 4: Predicted progression of rut with time after construction.

As per Figure 4, it is observed that the rut in the first year is 3.2 mm and 50 percent of the rutting threshold is reached in the first four years. The rut determined in CalME is the down rut in the wheel path relative to outside the wheelpath. Based on observations from many studies, downward rutting was used in the calibration of the rut models. The maximum rut depth occurring during initial years was due to the initial consolidation of the asphalt mixture caused by traffic. The models then predict that the rut will progress at a slower rate until the cracking density has advanced.

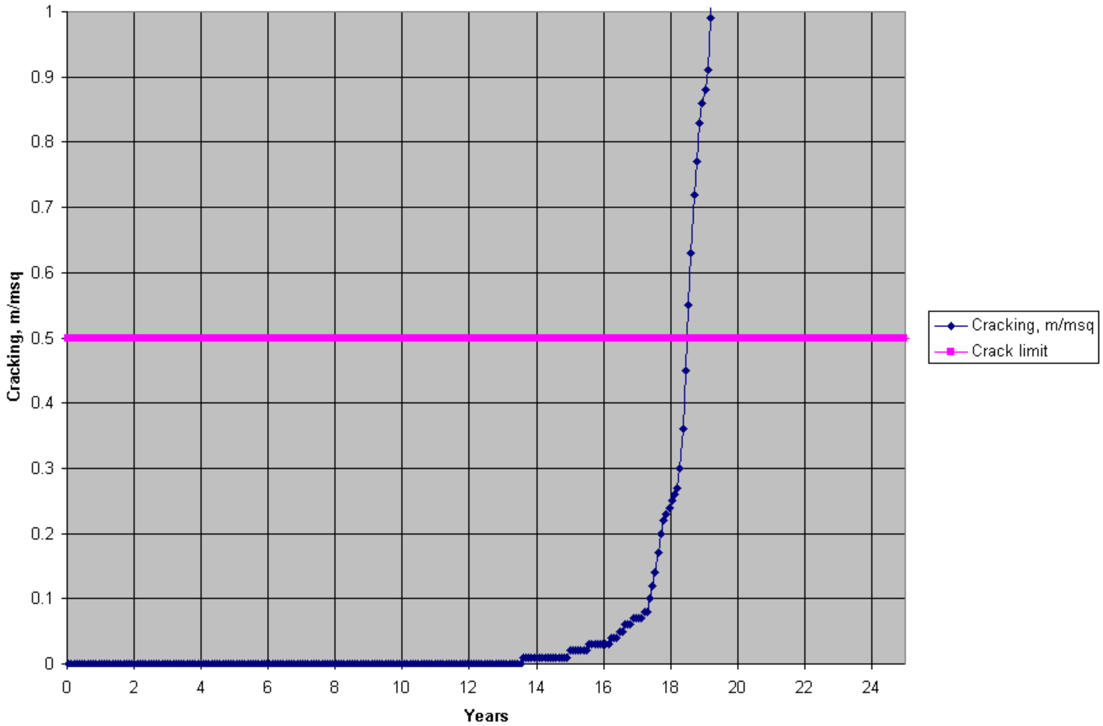

FIGURE 5: Predicted progression of cracking with time after construction.

As can be seen in Figure 5, the cracking progression is much more abrupt than the rutting, reflecting the accumulation of damage and the progression of cracking. The predicted cracking reached the 0.5 m/m^2 (equivalent to 5% cracking in this particular project) threshold after nearly 19 years in service. The progression rate of cracking varied in the simulations primarily with the type of HMA used. Depending on the material types used, climate, traffic patterns, etc. the number of years till the first crack appearance can vary.

APPLICATION OF M&R ACTIONS

M&R actions can be applied to an adequately designed pavement to maintain it in acceptable riding condition even beyond its initial design life. Application of the right strategy(ies) at the right time(s) can lead to substantial cost savings and good life extension according to the theory and a limited number of studies in the literature. CalME permits inclusion of different M&R strategies as part of the simulation of pavement performance, a feature which was used for this study to evaluate this theory.

CalME presently accommodates three M&R design strategies involving the application of an HMA overlay. For each strategy, the HMA overlay may be preceded by milling, if required, for grade control. The three M&R design "philosophies" that can be employed in CalME along with their rules of application are based on distress levels reached relative to rutting and cracking threshold limits. The three alternative strategies and their current (included based on recommendations of the Caltrans M-E Technical Working Group for demonstration purposes, but not official Caltrans policy) corresponding trigger rules are explained below:

1) Rehabilitation (R): This will be repeated if:

(i) down rut (total rut) $\geq$ 9 mm and rut in HMA $\geq$ 2 mm. In this case, use 45 mm HMA overlay,

(ii) down rut $\geq$ 9 mm and rut in HMA < 2 mm. In this case, use 75 mm HMA overlay,

(iii) average fatigue cracking $\geq$ 0.5 m/m^2. In this case, if down rut < 8 mm, then different thicknesses of HMA, RAC-G (gap-graded rubberized asphalt), and MB4 (gap-graded terminal blend rubberized asphalt) overlay may be selected (with or without milling), otherwise 60 mm HMA overlay alternative is used.

2) Preservation – Preservation – Rehabilitation (PPR): Use this sequence of applications if:

(i) down rut $\geq$ 5 mm or cracking $\geq$ 0.25 m/m^2. In this case, use 30 mm of HMA, RAC-G, or MB4 overlay (with or without milling),

(ii) down rut $\geq$ 5 mm and cracking $\geq$ 0.25 m/m^2. In this case, use 60 mm HMA overlay,

(iii) after two Preservation actions the next action will be treated as under Rehabilitation, followed by two Preservations, etc.

3) Extended Pavement Preservation (EPP): This will be repeated perpetually if:

(i) down rut $\geq$ 5 mm or cracking $\geq$ 0.25 m/m^2. In this case, use 30 mm HMA, RAC-G, or MB4 overlay (with or without milling)

(ii) down rut ≥ 5 mm and cracking ≥ 0.25 m/m^2. In this case, use 60 mm HMA.

For all strategies above, a minimum M&R action comprised of 30 mm mill-and-30 mm HMA, RAC-G or MB4 fill is used if the age of the wearing course exceeds 17 years based on the existing surface material. This will be called herein the "good-performance strategy."

The method that was employed in this analysis included monitoring the progression of rutting and cracking and applying one type of M&R action (e.g., EPP) as triggered by the rules pertaining to that particular strategy. The simulation is then continued and the progression of both types of distresses (cracking and rutting) is monitored and application of the selected M&R action is performed to reduce the distresses below their desired limits. The process is continued until year 80, the end of the analysis period. The M&R strategies that were applied and their corresponding applications are summarized below in Table 1.

To further illustrate the M&R strategies and how they can affect service life according to the simulations, consider the EPP-HMA strategy. This strategy involves application of 30 mm HMA preservation treatment as either rutting or cracking reaches 50 percent of its limit (i.e., 5 mm down rut and 0.25 m/m^2 cracking).

As can be observed from Table 1, the first preservation treatment was applied to the pavement at year 4 upon reaching 5 mm rutting, as shown in Figure 4. Based on Figure 4 and 5, the fatigue and rutting life of the pavement without any preservation treatment is 19 and 25 years, respectively. After the application of the preservation treatment at year 4, neither rutting nor cracking reached the threshold limits by year 21; hence a nominal 30 mm mill-and-30 mm HMA fill (good-performance strategy) was performed after 17 years since the last preservation application.

Subsequent applications of this good-performance strategy were needed at year 38 and year 55 as predicted by M-E simulations. Subsequently, the M-E performance simulation predicted that a preservation treatment consisting of a 30 mm HMA overlay would be needed at years 67 and 80. These sequences of M&R actions along with their corresponding application year are shown in the first row of Table 1.

TABLE 1: Summary of M&R actions and corresponding time of application

M&R strategy	Action year	M&R1	Action year	M&R2	Action year	M&R3	Action year	M&R4	Action year	M&R5	Action year	M&R6
EPP-HMA	4	30 mm HMA	21	Mill 30 mm HMA	38	Mill 30 mm HMA	55	Mill 30 mm HMA	67	30 mm HMA	80	30 mm HMA
EPP-HMA-low crack	4	30 mm HMA	21	Mill 30 mm HMA	38	Mill 30 mm HMA	55	Mill 30 mm HMA	64	30 mm HMA	77	30 mm HMA
EPP-MB4	4	30 mm MB4	21	Mill 30 mm MB4	38	Mill 30 mm MB4	55	Mill 30 mm MB4	63	30 mm MB4	73	30 mm MB4
EPP-RAC-G	4	30 mm RAC-G	21	Mill 30 mm RAC-G	38	Mill 30 mm RAC-G	55	Mill 30 mm RAC-G	67	30 mm RAC-G	80	30 mm RAC-G
PPR-105 mm-HMA	4	30 mm HMA	21	Mill 30 mm HMA	38	Mill 30 mm HMA	55	Mill 30 mm HMA	67	30 mm HMA	0	
PPR-30 mm-MB4	4	30 mm MB4	21	Mill 30 mm MB4	38	Mill 30 mm MB4	55	Mill 30 mm MB4	63	30 mm MB4	75	30 mm MB4
PPR-30 mm-RAC-G	4	30 mm RAC-G	21	Mill 30 mm RAC-G	38	Mill 30 mm RAC-G	55	Mill 30 mm RAC-G	67	30 mm RAC-G	0	
PPR-45 mm-MB4	4	30 mm MB4	21	Mill 30 mm MB4	38	Mill 30 mm MB4	55	Mill 30 mm MB4	63	30 mm MB4	75	45 mm MB4
PPR-45 mm-RAC-G	4	30 mm RAC-G	21	Mill 30 mm RAC-G	38	Mill 30 mm RAC-G	55	Mill 30 mm RAC-G	67	30 mm RAC-G	0	
PPR-60 mm-HMA	4	30 mm HMA	21	Mill 30 mm HMA	38	Mill 30 mm HMA	55	Mill 30 mm HMA	67	30 mm HMA	0	
PPR-60 mm-MB4	4	30 mm MB4	21	Mill 30 mm MB4	38	Mill 30 mm MB4	55	Mill 30 mm MB4	63	30 mm MB4	75	60 mm MB4
PPR-60 mm-RAC-G	4	30 mm RAC-G	21	Mill 30 mm RAC-G	38	Mill 30 mm RAC-G	55	Mill 30 mm RAC-G	67	30 mm RAC-G	0	
PPR-75 mm-HMA	4	30 mm HMA	21	Mill 30 mm HMA	38	Mill 30 mm HMA	55	Mill 30 mm HMA	67	30 mm HMA	0	

TABLE 1: Summary of M&R actions and corresponding time of application (contd.)

M&R strategy	Action year	M&R1	Action year	M&R2	Action year	M&R3	Action year	M&R4	Action year	M&R5	Action year	M&R6
PPR-60 mm-MB4	4	30 mm MB4	21	Mill 30 mm MB4	38	Mill 30 mm MB4	55	Mill 30 mm MB4	63	30 mm MB4	75	60 mm MB4
PPR-60 mm-RAC-G	4	30 mm RAC-G	21	Mill 30 mm RAC-G	38	Mill 30 mm RAC-G	55	Mill 30 mm RAC-G	67	30 mm RAC-G	0	
PPR-75 mm-HMA	4	30 mm HMA	21	Mill 30 mm HMA	38	Mill 30 mm HMA	55	Mill 30 mm HMA	67	30 mm HMA	0	
R-105 mm-HMA	17	Mill 30 mm HMA	25	105 mm HMA	42	Mill 30 mm HMA	59	Mill 30 mm HMA	76	Mill 30 mm HMA	0	
R-30 mm-MB4	17	Mill 30 mm MB4	26	30 mm MB4	28	30 mm MB4	35	30 mm MB4	52	Mill 30 mm MB4	69	Mill 30 mm MB4
R-30 mm-RAC-G	17	Mill 30 mm RAC-G	25	30 mm RAC-G	29	30 mm RAC-G	38	30 mm RAC-G	53	30 mm RAC-G	70	Mill 30 mm RAC-G
R-45mm-MB4	17	Mill 30 mm MB4	26	45 mm MB4	30	45 mm MB4	47	Mill 30 mm MB4	64	Mill 30 mm MB4	81	Mill 30 mm MB4
R-45 mm-RAC-G	17	Mill 30 mm RAC-G	25	45 mm RAC-G	32	45 mm RAC-G	49	Mill 30 mm RAC-G	66	Mill 30 mm RAC-G	0	
R-60 mm-HMA	17	Mill 30 mm HMA	25	60 mm HMA	38	60 mm HMA	55	Mill 30 mm HMA	72	Mill 30 mm HMA	0	
R-60mm-MB4	17	Mill 30 mm MB4	26	60 mm MB4	34	60 mm MB4	51	Mill 30 mm MB4	68	Mill 30 mm MB4	0	
R-60 mm-RAC-G	17	Mill 30 mm RAC-G	25	60 mm RAC-G	38	60 mm RAC-G	55	Mill 30 mm RAC-G	72	Mill 30 mm RAC-G	0	
R-75 mm-HMA	17	Mill 30 mm HMA	25	75 mm HMA	42	Mill 30 mm HMA	59	Mill 30 mm HMA	76	Mill 30 mm HMA	0	

The predicted propagation of the distresses in response to application of the EPP-HMA strategy is shown in Figure 6 for rutting and in Figure 7 for cracking. It is observed from Figures 6 and 7 that the deterioration of the pavement towards the end of the analysis period is much faster than during the design life reflecting continuing aging and damage to the original HMA layer considered in the CalME models.

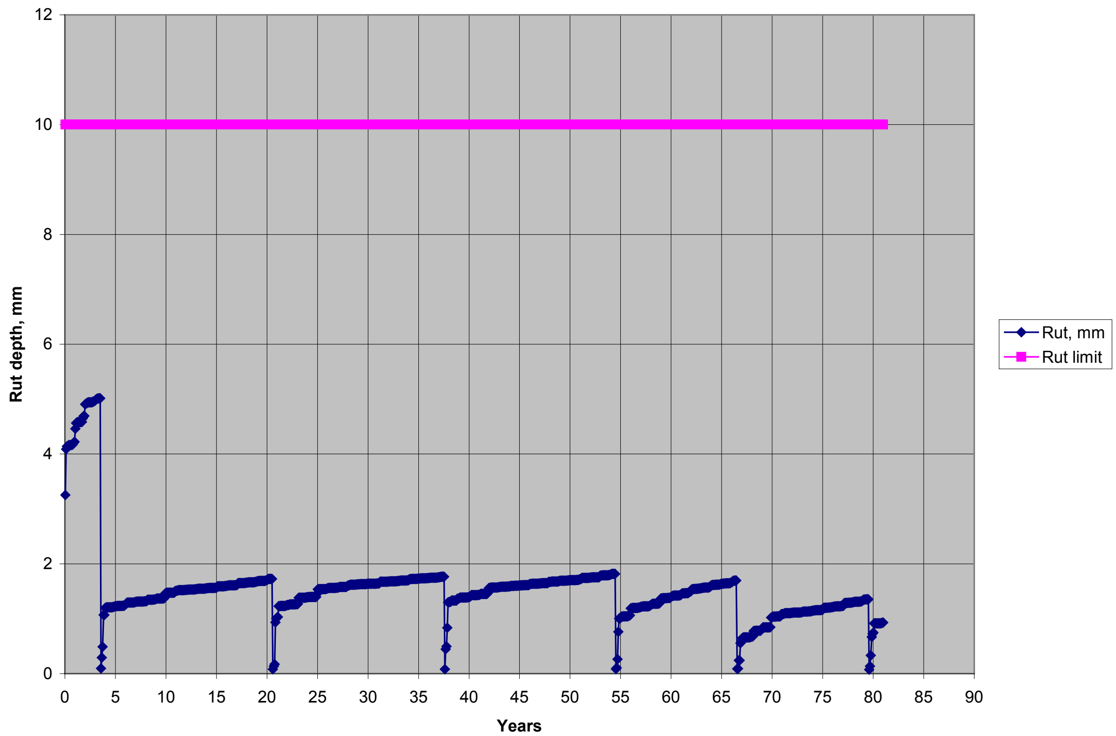

FIGURE 6: Predicted rutting progression upon application of EPP-HMA strategy

Figure 7 shows that cracking can be kept to very low levels (compare to Figure 5) past year 20 upon the application of the M&R actions.

Restraining the cracking past year 60, however, could not be achieved. In other words, the potential of delaying cracking by the application of M&R strategies during earlier stages of pavement service is higher than during later stages. This is due to the aging of the pavement, the presence of more cracks that will reflect up, and various other factors that contribute to pavement deterioration.

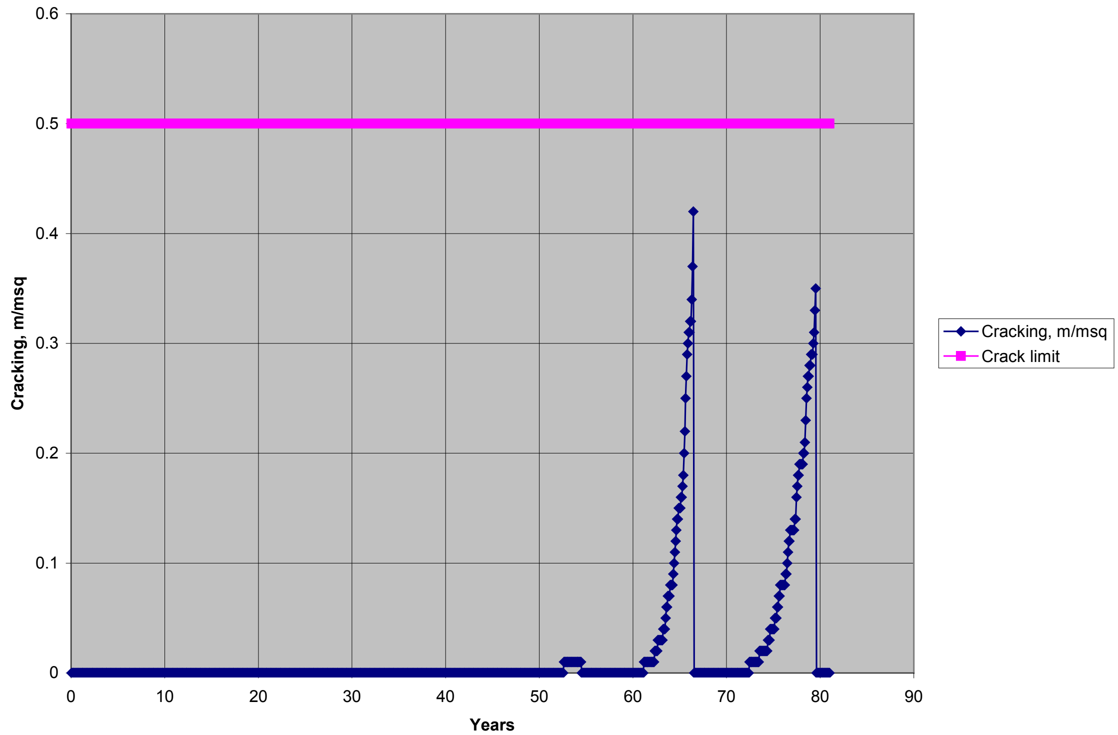

FIGURE 7: Predicted cracks progression upon application of EPP-HMA strategy

EVALUATION OF M&R STRATEGIES WITH LCCA

As can be observed from Figure 6 and 7, all M&R strategies investigated extended the life of the pavement structure considered in this study to 80 years (and beyond) with the application of a series of M&R actions. LCCA, using RealCost (Version 2.2), was performed on each scenario involving application of M&R actions. The various scenarios were cross-compared in terms of EUAC determined with LCCA.

In order to compare the various M&R strategies with LCCA, costs of the materials used in these strategies are needed. A review of historical data available in Caltrans databases was performed. The cost of the materials varies not only with time but also with the amount of material used in the project. Hence, the costs of various preservation treatments were calculated based on the amount of material required for the operation. The average values were obtained from the contract cost database. Table 2 is a summary of the costs for various treatments per lane-Km of pavement. The total length of the example project section of pavement is 11.27 Km-with 4 lanes. The density of asphalt was assumed to be 2.62 tonnes per cubic meter.

TABLE 2: Summary of construction costs per Ln-Km for each M&R strategy (Costs based on the quantity of material)

Item type	Thickness (mm)	Cost (1000 dollars per Ln-Km)
HMA Type A	30 mm	23
HMA Type A	45 mm	41
HMA Type A	60 mm	49
HMA Type A	75 mm	50
HMA Type A	105 mm	78
RAC-G	30 mm	27
RAC-G	45 mm	41
RAC-G	60 mm	54
MB4-D	30 mm	32
MB4-D	45 mm	48
MB4-D	60 mm	64
Cold plane 30mm HMA	30 mm	9 per m^2
AB Class 2	375 mm	52
HMA Type A	160 mm	120

The other costs that are an input to RealCost are user delay and annual maintenance costs. The user delay cost is not expected to be significant in the project considered in this paper as future work will be performed during night and the traffic demand nighttime work zone hours is less than work zone capacity.

The annual maintenance cost calculation was mainly based on the duration between two different actions (in one given alternative). It is assumed that the pavement needs only minimal minor preservation treatments using direct forces for the first three years after application of an M&R action. Subsequently, it is assumed that the cost for the pavement minor preservation increases for each set of three years arithmetically.

A minimal dollar amount of $683/ lane-km was considered for minor preservation per year during the first three years. A running average was calculated to obtain the annual maintenance cost per lane-km per year for each duration. The calculated annual maintenance costs for each year were observed to be in good concurrence with the Caltrans LCCA manual (which was developed based on the empirical data and experience). Table 3 shows a summary of the annual maintenance costs for different durations.

TABLE 3: Annual Maintenance Cost (MC) calculation

Year	Annual Maintenance Cost ($/L-km)	MC based on Action Yr	total Lane Km	Total MC*1000
1	683			
2	683	683.0	44.8	31
3	683	683.0	44.8	31
4	1366	853.8	44.8	38
*5	1366	956.2	44.8	43
6	1366	1024.5	44.8	46
7	2049	1170.9	44.8	52
8	2049	1280.6	44.8	57
9	2049	1366.0	44.8	61
10	2732	1502.6	44.8	67
11	2732	1614.4	44.8	72
12	2732	1707.5	44.8	76
13	3415	1838.8	44.8	82
14	3415	1951.4	44.8	87
15	3415	2049.0	44.8	92
16	4098	2177.1	44.8	98
17	4098	2290.1	44.8	103
18	4098	2390.5	44.8	107

*MC for year 5: (683+683+683+1366+1366) divided by 5=$956.2/ln-km

Table 4 shows the summary of the input values used in the RealCost. Based on the analysis, and results obtained from the CalME simulations (as shown in Table 1) and the various inputs, the EUAC for the various M&R alternatives were computed and summarized in Table 5. From Table 1, based on the decision tree, the treatments recommended for EPP and PPR were close. To avoid redundancy in the presentation and due to paper length constraint, PPR has not been included in the final analysis operation.

1 **TABLE 4: Summary of the inputs for Real Cost**

Type of Input	Input	Source of Input	Criteria to select this input	Value
Economic Variable	Value of Time for Passenger Cars ($/hour)	RealCost	Default Value	10.46
Economic Variable	Value of Time for Single Unit Trucks ($/hour)	RealCost	Default Value	27.83
Economic Variable	Value of Time for Combination Trucks ($/hour)	RealCost	Default Value	27.83
Discount Rate (%)	Discount Rate (%)	LCCA manual	3-5% range	4%
Traffic Data	AADT Construction Year (total for both directions)	CalME AADT	CalME AADT	12275
Traffic Data	Cars as Percentage of AADT (%)	CalME AADT	CalME AADT	95
Traffic Data	Single Unit Trucks as Percentage of AADT (%)	CalME AADT	CalME AADT	2.5
Traffic Data	Combination Trucks as Percentage of AADT (%)	CalME AADT	CalME AADT	2.5
Traffic Data	Annual Growth Rate of Traffic (%)	Default	default	0.0
Traffic Data	Speed Limit Under Normal Operating Conditions (mph)	Hwy 53	HDM	55
Traffic Data	No of Lanes in Each Direction During Normal Conditions	considered 2	For research purpose	2
Traffic Data	Free Flow Capacity (vphpl)	LCCA manual,Table6	Terrain, No. of Lanes	1950
Traffic Data	Rural or Urban Hourly Traffic Distribution	Hwy 53	Rural	Rural
Traffic Data	Queue Dissipation Capacity (vphpl)	LCCA manual,Table6	Terrain, No. of Lanes	1530
Traffic Data	Maximum AADT (total for both directions)	LCCA manual,Table6	Terrain, No. of Lanes	48305/lane
Traffic Data	Maximum Queue Length (miles)	LCCA manual,Table6	Terrain, No. of Lanes	5
Construction data	Agency Construction Cost ($1000)	Calculated	Thickness, Lane miles	6139
Construction data	Agency Maintenance Cost ($1000)	LCCA manual		Table4
Construction data	Work Zone Length (miles)	Default	LCCA manual	2
Construction data	Work Zone Speed Limit (mph)	LCCA manual	5 miles less than original speed	50
Construction data	Work Zone Capacity (vphpl)	LCCA manual, Table 6	Terrain, No. of Lanes	1360
Construction data	Work Zone Duration (days)	LCCA manual Eq.4	lane miles/production rate	18
Construction data	Production Rate	LCCA manual, Table 8	surface type, daily closure	1.5
Construction data	Activity service life (yrs)	see def LCCA manual		1
Traffic Data	Lane closure	LCCA manual	Inbound and outbound first closure	0 to 6
Traffic Data	Lane closure	LCCA manual	Inbound and outbound second closure	20 to 24

TABLE 5: Summary of EUAC for various M&R alternatives based on RealCost

M&R Strategy	EUAC (1000 dollars)
EPP-HMA	503
EPP-HMA-low crack	503
EPP-MB4	533
EPP-RAC-G	517
PPR-105 mm-HMA	503
PPR-30 mm-MB4	533
PPR-30 mm-RAC-G	517
PPR-45 mm-MB4	533
PPR-45 mm-RAC-G	517
PPR-60 mm-HMA	503
PPR-60 mm-MB4	533
PPR-60 mm-RAC-G	517
PPR-75 mm-HMA	503
R-105 mm-HMA	527
R-30 mm-MB4	524
R-30 mm-RAC-G	503
R-45 mm-MB4	527
R-45 mm-RAC-G	519
R-60 mm-HMA	513
R-60 mm-MB4	539
R-60 mm-RAC-G	529
R-75 mm-HMA	505

Figure 8 shows a comparison of EUAC between the Extended Pavement Preservation (EPP) strategies (with various HMA materials) and Rehabilitation (R) strategies. Although most of the EUAC values for Rehabilitation (R) strategies are higher than the Extended Pavement Preservation (EPP) strategies, the EUAC for R-75 mm HMA is fairly close to the lowest preservation strategy (i.e., EPP-HMA). Hence, further analysis was performed to determine the most economical strategy suitable for this project. This was done through comparing the distress accumulation during the analysis period for these two M&R strategies. The cracking criterion was observed to be more critical than rutting for this particular pavement section, which is consistent with observation of Caltrans pavements.

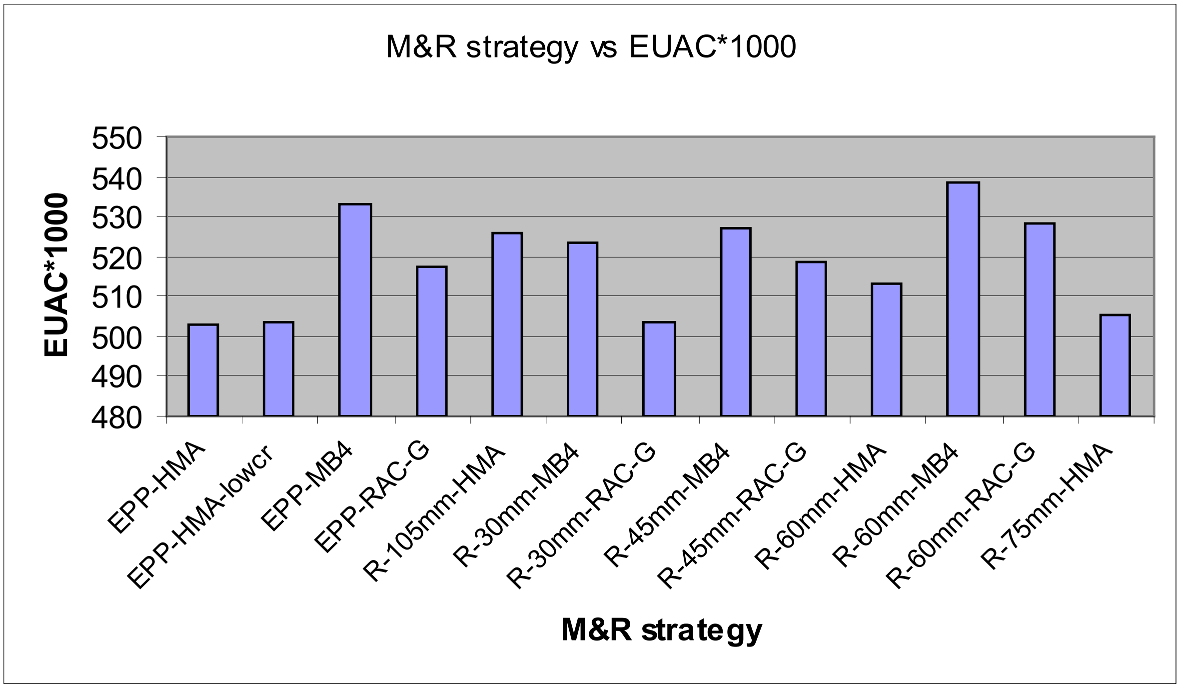

FIGURE 8: EUAC for rehabilitation only (R) and Extended pavement preservation (EPP) strategies

Figures 7 and 9 show the fatigue cracking progression during the analysis period for EPP-HMA and R-75 mm HMA, respectively. For EPP-HMA strategy (Figure 7), as the application of the preservation treatment was performed long before the pavement has deteriorated, cracking was maintained below the threshold limit throughout the analysis period. In the case of R-75 mm HMA strategy, the pavement severely failed in cracking at year 24 as can be seen in Figure 9. Hence, pavement performance with the application of preservation treatments is superior to that with performing rehabilitation. Although EUAC for both strategies were nearly equal, the pavement designer should choose preservation over rehabilitation. This may be encouraged due to the severe cracking of the pavement at year 24 that can allow moisture ingress which was not accounted for in the analysis. Hence, from economic and performance standpoint, the EPP-HMA strategy outperforms all other strategies analyzed.

SUMMARY, CONCLUSIONS, AND FUTURE WORK

This paper illustrated the integrated use of M-E and LCC analyses for designing extended life pavements. Longer life pavements can be achieved by the application of a series of pavement preservations. This was examined with the use of M-E analysis, and cost effectiveness was investigated with the use of LCCA. M-E analysis proves to be a very effective tool in analyzing the effect of the complex interaction of traffic, climate, and materials deterioration on pavement performance. The pavement engineer can compare the cost of application of a series of preservation treatments or rehabilitation and preservation with the help of LCCA.

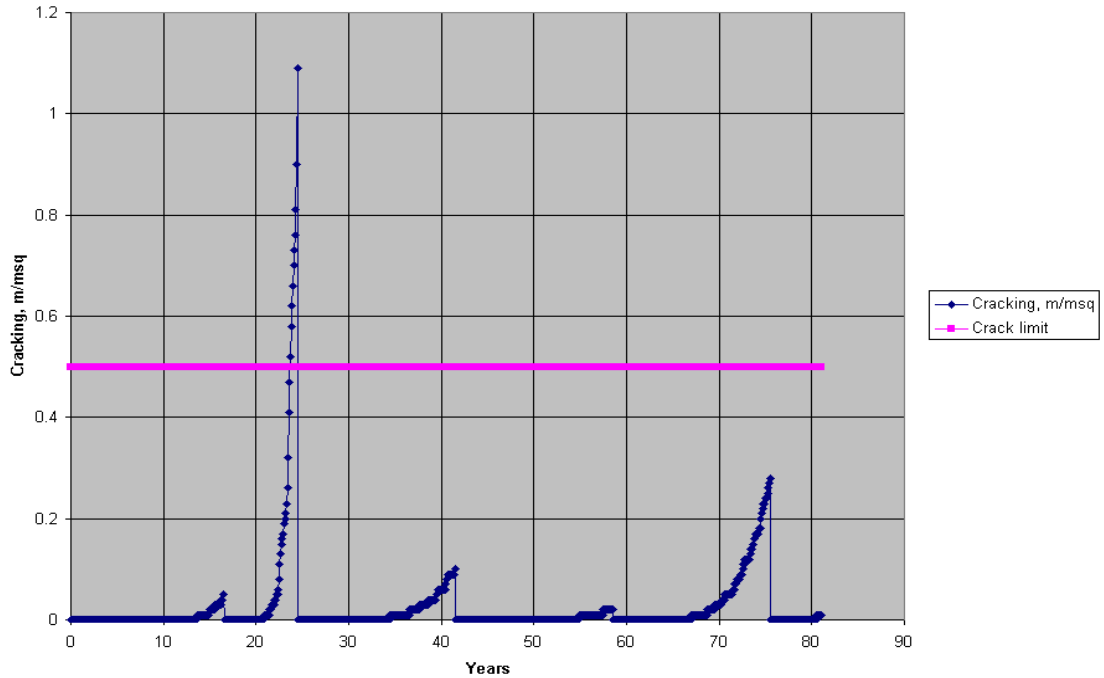

FIGURE 9: Predicted cracking performance with application of R-75 mm HMA

For the pavement structure analyzed in this study, Extended pavement preservation with HMA (EPP-HMA) was found to be the most cost effective M&R strategy. This finding may not hold for another project in a different climate region and with different traffic conditions, for which only project specific M-E/LCC analyses can help identify optimal M&R strategy for use on that project. The major necessity and the benefit of integrating CalME and LCCA is to determine the best economical strategy for a given pavement segment.

Future work includes examining a combination of M&R strategies by the batch mode (rather than testing one strategy at a time) to optimize cost and performance. The effect of climate, traffic, and subgrade conditions will be examined to determine how the M&R strategies rank against each other in terms of their cost effectiveness. Additional work will next be performed with the objective of revising the decision trees for the various M&R strategies considered in this study. It is likely that in the future CalME the studies will be used to provide recommended M&R strategies. CalME performance predictions will be validated and recalibrated where necessary, using PMS data. The method presented in the current paper is only for project level optimization and the authors have plans to extend its applicability to a network level optimization.

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