# Developing Robust Rehabilitation Scenario Profiles for Life Cycle Cost Analysis

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**Abstract**

Life Cycle Cost Analysis (LCCA) is an economic procedure often used to compare competing pavement designs. For the LCCA to be meaningful and reliable, the analysis must reflect the most likely activities for each alternative being evaluated. Currently, most state highway agencies (SHA) apply a standard, policy-set, rehabilitation schedule to all pavements based on "historical" performance, which may or may not be representative of the given design. The fact is that there are many different rehabilitation scenarios that could be performed when the pavement requires rehabilitation and which one is selected will impact the results. This paper shows how SHAs can use the American Association of Highway and Transportation Officials' (AASHTO) Mechanistic Empirical Pavement Design Guide to determine *when rehabilitation activities are required*, and Decision Tree Analysis to examine multiple scenarios of *which rehabilitation activities are to be done*. By using these two processes, it is possible to develop multiple rehabilitation schedules that are specific to a given pavement design, which makes the LCCA more robust and reliable. Finally, a case study is shown to demonstrate the extent to which these processes could affect the outcome of an LCCA.

## Introduction

Life cycle cost analysis (LCCA) is an economic process used to compare competing pavement designs over an analysis period considering all significant costs expressed in equivalent net present value (NPV) dollars. Since alternate pavement designs vary in terms of initial cost and future maintenance requirements, LCCA quantifies the total costs of ownership over the pavement life and is an essential tool for transportation agencies to select pavement designs that provide the best value. While the mechanics of performing an LCCA for a pavement are not difficult, it is essential that a standardized and comprehensive pavement LCCA framework, such as found in (FHWA, 1998), be used to ensure that short-term gains do not come at the expense of long-term deficits. Currently, LCCA is primarily used as a comparison tool between asphalt and concrete in the pavement type selection process, which means that for the LCCA comparisons to be meaningful and reliable, the LCCA should reflect the most likely activities for each alternative over the analysis period.

In determining the rehabilitation activities and timing schedules, most agencies apply a single, standard, policy-set rehabilitation scenario to all pavements based on *historical performance*. While this approach seems reasonable, historical data is often based on old designs that have different design features and traffic

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volumes than current designs. Unless the historical data is from pavements with the same design features and applications, it will not be representative of the performance of the specific design being evaluated and its use could bias the results.

As an example of how historical data can be misleading,

Figure 1 is a summary of a Georgia Department of Transportation (GDOT) study that evaluated Georgia's historical concrete pavement performance (Tsai, Wu, & Wang, 2012). Over the last 50 years, GDOT has had 4 basic concrete pavement designs. The first pavements built in the 1960s, consisted of non-doweled Jointed Plain Concrete Pavements (JPCP) with joint spacing of 6.0 m (20 feet) or greater on soil / soil cement stabilized subgrades. The average time to first rehabilitation was 17 years, though the actual time varied from as little as 10 years to as high as 29 years (as shown by the error bars). The next era consisted of non-doweled JPCPs with joint spacing of 6.0 m (20 feet) or greater on graded aggregate bases (GAB). In the mid-1970s, GDOT started using dowels and reduced the joint spacing to 6.0 m (20 feet). These pavements were used until the 1990s and at the time of this study, the average pavement age was 29 years; however, none had received a major rehabilitation. The last era of pavements, which are being used today, are doweled JPCP with 4.5 m (15 feet) joint spacing, 3.9 m (13-foot) widened lanes on a 75 mm (3-in) asphalt base over GAB, and as of the time of the study, none have had any rehabilitation.

The overall average time to first rehabilitation for these pavements is 17 years, which is close to 20 years that GDOT uses in their LCCA. However, as can be seen, 20 years is not representative of the 3rd and current era of pavements with their improved design features. As such, while using the policy-set rehabilitation schedules simplifies the LCCA process, using 20 years as the age for first rehabilitation of the current designs greatly underestimates the actual pavement performance and will artificially increase the LCCA because these activities will most likely not be done, which means the LCCA will not be representative of the true ownership costs of the pavements and any comparisons to other alternatives are not valid.

**Using MEPDG to Determine WHEN to Rehabilitate**

The American Association of Highway and Transportation Officials' (AASHTO) Mechanistic Empirical Pavement Design Guide (MEPDG) was adopted by AASHTO in 2011 as its pavement design procedure (AASHTO, 2011). Unlike other pavement

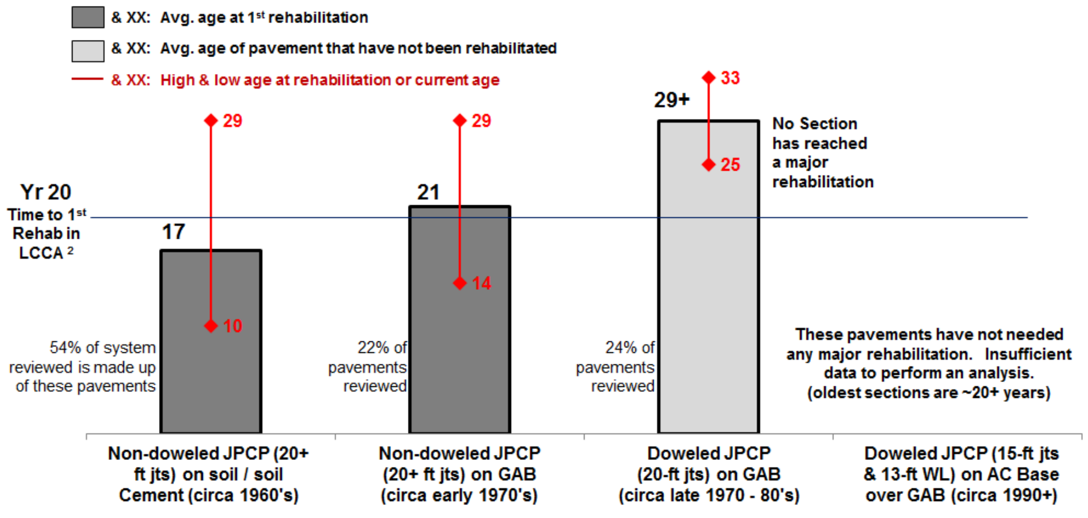
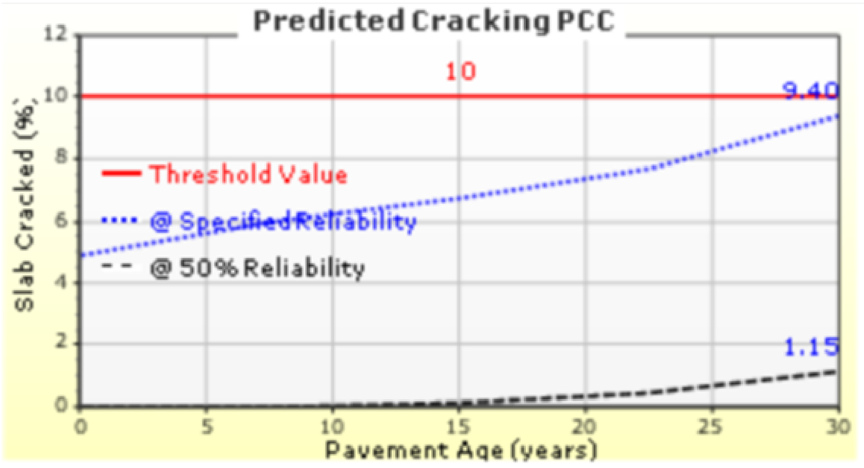
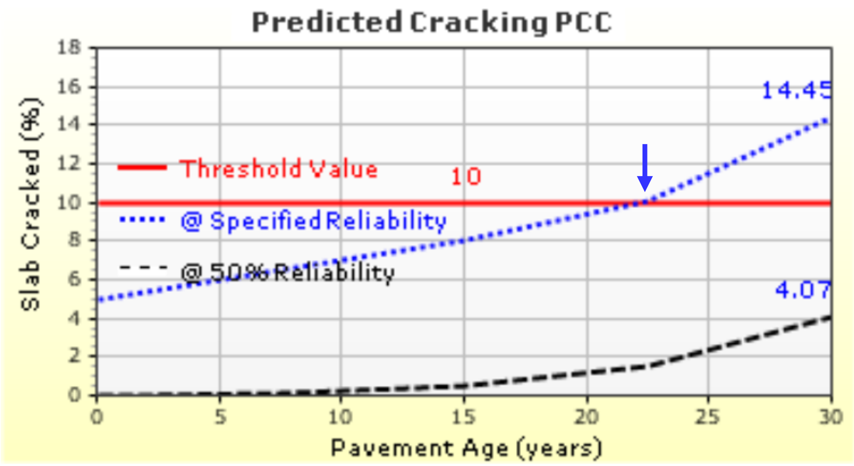



Figure 1. Average Time (Years) to First Major Rehabilitation of Concrete Pavement in Georgia (Tsai, Wu, & Wang, 2012)




a) Typical curve that meets a 30 year pavement design




b) Typical curve that does not meet a 30 year pavement design

Figure 2. Typical Pavement ME pavement performance curves for cracking

design procedures that only provide thickness, MEPDG and the companion software package Pavement ME, predicts performance for key design distresses such as cracking, faulting and roughness. Figure 2 shows typical Pavement ME curves for cracking. The solid horizontal line is the agency pre-defined distress limit that indicates when major rehabilitation is needed (i.e. patching, diamond grinding, AC overlay, etc). The bottom, dashed line is the actual or most likely level of distresses predicted. The middle dotted line is the predicted distresses at the given reliability level (i.e. 90%). Essentially, this line means that 90% of the pavements will have distresses below this level. Designs are typically based on when the dotted reliability line hits the defined distress limit for any of the distress curves (eg cracking, faulting, or IRI). However, hitting the defined distress limit does not mean the pavement is removed and replaced. It means it is time for rehabilitation or preservation activities such as patching, diamond grinding, etc.

This ability to predict pavement performance over the analysis period means it is possible to use that information to determine *when* rehabilitation activities are required for a specific, individual design. In the design phase, engineers can quantify the rate of distress development, determine the year in which the critical distress level is reached, and then apply a rehabilitation activity in the analysis that addresses the given distress. In such a way, LCCA will be more reliable and representative because the rehabilitation activity timing will be specific to that specific design.

**Determining Time to the First Rehabilitation**

Currently, most agencies only analyze their pavements for the design life (e.g. 20 or 30 years) and adjust thickness until the dotted reliability line hits the distress limit at or near the end of the design life. As an example, Figure 2a would be a design that meets the 30 year design criteria for cracking while Figure 2b does not because it requires rehabilitation at Year 23 (it is a 23 year design as shown by the arrow). While this is standard practice, it is difficult to get a design that hits the exact specified time frame, such as 30 years. That is, a 10-inch (250-mm) pavement may perform for 35 years, while a 9.5-inch (238-mm) pavement will only perform for 25 years. The designer would then choose the 10-inch (250-mm) pavement, but use 30 years in the LCCA, which would bias the results by 5 years.

A more precise way is to analyze the pavement design for the full analysis period used in the LCCA, and then apply the first rehabilitation predicted by the Pavement ME as shown in Figure 3. In this case, this first rehabilitation is required at Year 33. The amount of pavement that needs rehabilitation is estimated based on the amount of distress at the 50% reliability curve at the time of rehabilitation, which for this case is about 5% of the slabs. Looking at the pavement performance for the entire analysis period – rather than just the design period – also allows the designer to delay rehabilitation activities to a later time but still match the rehabilitation activity to the predicted distress in the pavement at that given time.

Another reason to extend the Pavement ME analysis period is that it can add insight. As an example, Figure 4 shows two pavement designs that both meet a 20 year pavement design life (the Pavement ME results have been re-plotted in order to show both pavements on a single plot). Both pavements are 200 mm (8-inch) JPCP designs, but the first design is the standard design with 4.5 m (15-foot) joint spacing, 3.6 m (12-foot) wide lanes on a 75 mm (3-in) asphalt base over a 300 mm (12-in) GAB. The second design is an optimized design with 3.6 m (12-foot) joint spacing, 3.9 m (13-foot) wide lanes on a 150 mm (6-in) GAB. As can be seen, both pavements exceed the 20 year design criteria. It can also be seen that the cracking remains relatively flat for the first 20 years. If a designer were to analyze these pavements only for 20 years, they would say the pavements have similar, if not identical performance. However, as one looks at the performance curves beyond 20 years, cracking for the standard design increases at a faster rate than the optimized design due to the longer joint spacing, and increased curling and warping. This shows that

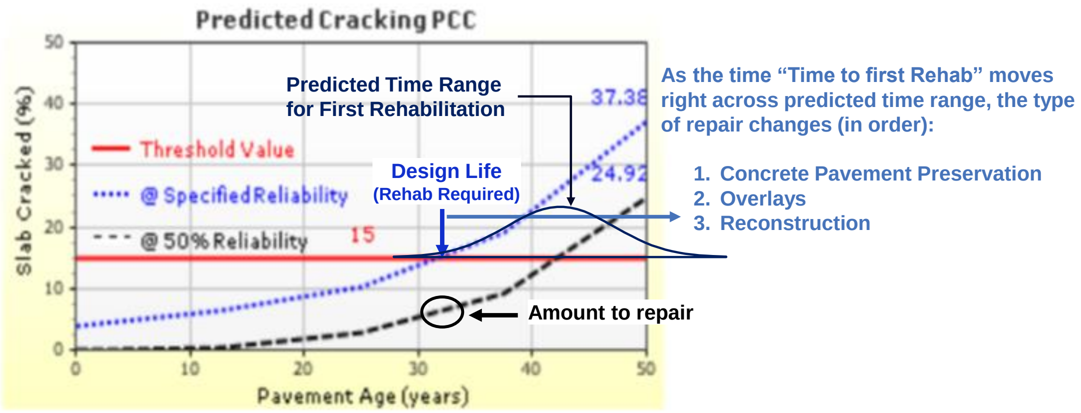



Figure 3. Interpretation of a typical Pavement ME pavement performance curve

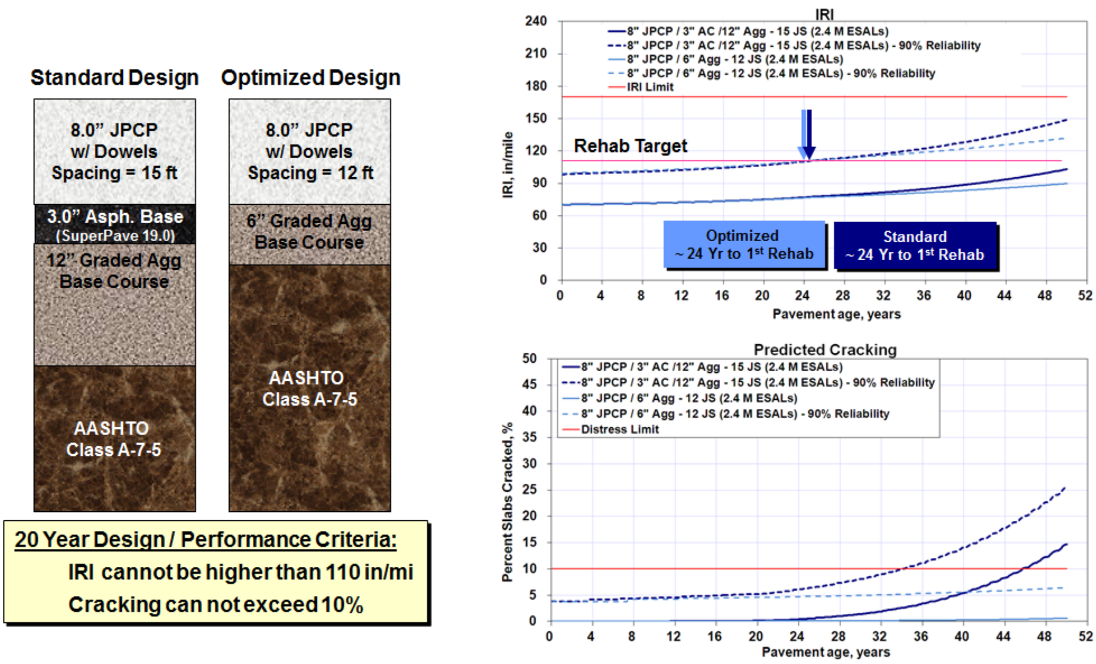



Figure 4. Pavement-ME IRI & Cracking Performance curves for two potential JPCP Design

the optimized design, which many would consider a *poorer* design because it does not have a stabilized base, is actually the better pavement.

**Determining *Time* for Subsequent Rehabilitation Activities**

There are 4 basic approaches to determine the time for subsequent rehabilitation activities. The simplest approach is to use standard rehabilitation performance lives of different rehabilitation activities based on historical performance of similar rehabilitation activities in the area. While easy, this has the same pitfalls that assuming a standard performance period has for a new pavement. The second procedure is to estimate rehabilitation timing using traffic counts. That is, estimate the life of the original pavement using Pavement ME and determine how many vehicles will be carried over that time. Next, assume that each major rehabilitation will carry that same amount of traffic as the original pavement and determine the life of each rehabilitation activity by matching the traffic carried by the rehabilitation activity to the original pavement's traffic. The advantage of this procedure is that it is still relatively simple and takes into account growing traffic. However, it cannot distinguish between long-term impacts of different design features such as that shown in Figure 4.

The third, and most rigorous approach, is to use Pavement ME to evaluate the performance of rehabilitated pavements. That is, Pavement ME is capable of modelling the performance of rehabilitated pavements and the design engineer can input the predicted distress remaining after a given rehabilitation into Pavement ME to see how the rehabilitated pavement will perform. The process to do this is:

1. Run the pavement design for the full analysis period. When the performance curve hits "predefined" distress, record traffic and distress values.
2. Develop and run Pavement ME in rehabilitation mode for the remaining years in the analysis period (e.g. for Figure 4, the time is 50 – 24 = 26 years) for the type of rehabilitation to be analysed (overlay or preservation activity). Update traffic, pavement condition, and any thickness change to coincide with the current pavement properties and the rehabilitated pavement condition.

3. When performance curve hits the "predefined" distress again, record traffic and distress values. Repeat until the end of the analysis period is reached.

Once all the Pavement ME runs are complete, the designer can combine the data to determine the rehabilitation timing profile. The advantage of this process is that it is rigorous, can account for both preservation work and overlays, and can account for thickness changes due to the rehabilitation work. The disadvantage is that it requires great care to ensure all inputs (traffic, bonding, materials, strength, etc.) match the condition in the original pavement.

The final approach is to adjust the performance curves for the amount of distress repaired and to assume that performance curves follow the same curve prior to the rehabilitation. This process is less rigorous than procedure 3, and does not account for the increase in thickness that will occur with a concrete or asphalt overlay. However, it is simpler, gives reasonable answers, and does not require additional Pavement ME runs. Rather, it requires some manipulation of the Pavement ME predicted distress data in the Pavement ME output file. The process to adjust the performance curves is similar to that used in approach 2.

1. Run the pavement design for the full analysis period. When the performance curve hits "predefined" distress, repair the pavement to its original condition.
2. Assume that the pavement performance curves will follow the same shape as the original curves, just shifted down to account for the pavement repairs. To make this adjustment, use the following formula:

$$D'_{Rtn} = D_o + (D_{Rtn} - D_{Rtn-1}) \qquad (1)$$

   Where: $D'_{Rtn}$ is the adjusted distress level at any time after rehabilitation, which occurs at time $t_n$ (i.e., $D_{Rt1}$); $D_o$ is the original distress level for a given distress (i.e., IRI, cracking, or faulting); $D_{Rtn}$ is the distress level at time $t_n$ from the Pavement ME analysis; and $D_{Rtn-1}$ is the distress level at rehabilitation, which occurs at time $t_{n-1}$, from the Pavement ME analysis. For example, $D_{Rt1-1}$ is the distress level one month before the first rehabilitation, which occurs at time $t_1$, from the Pavement ME analysis.
3. When the performance curve hits the predefined distress again, i.e. $D'_{Rtn}$, again assume that the pavement will be repaired to its original condition. Adjust the curves with equation (1) as before, except using the distress level from Pavement ME analysis at the new time $t_2$, which is the time of the next rehabilitation.
4. Continue repeating the process until the pavement reaches the end of the analysis period.

A major advantage of approaches 2, 3 and 4 over assuming a standard rehabilitation life is that they take into account increasing traffic and its impact on future performance (i.e. a repair that lasted 10 years previously may not last 10 years for the next rehabilitation due to the extra loading).

Figure 5 is a graphical representation of the resultant LCCA rehabilitation schedule using approach 4 for the pavement shown in Figure 4. At year 24, the 90% reliability curve hits the pre-defined distress limit. At this point the pavement is rehabilitated, using preservation activities (patching and diamond grinding), which brings the pavement back to its original smoothness. From that point, the pavement performance is assumed to follow the same slope as original Pavement ME analysis, and the curves are shifted down. When the 90% curve hits the predefined distress limit again, a second rehabilitation is done, and so on.

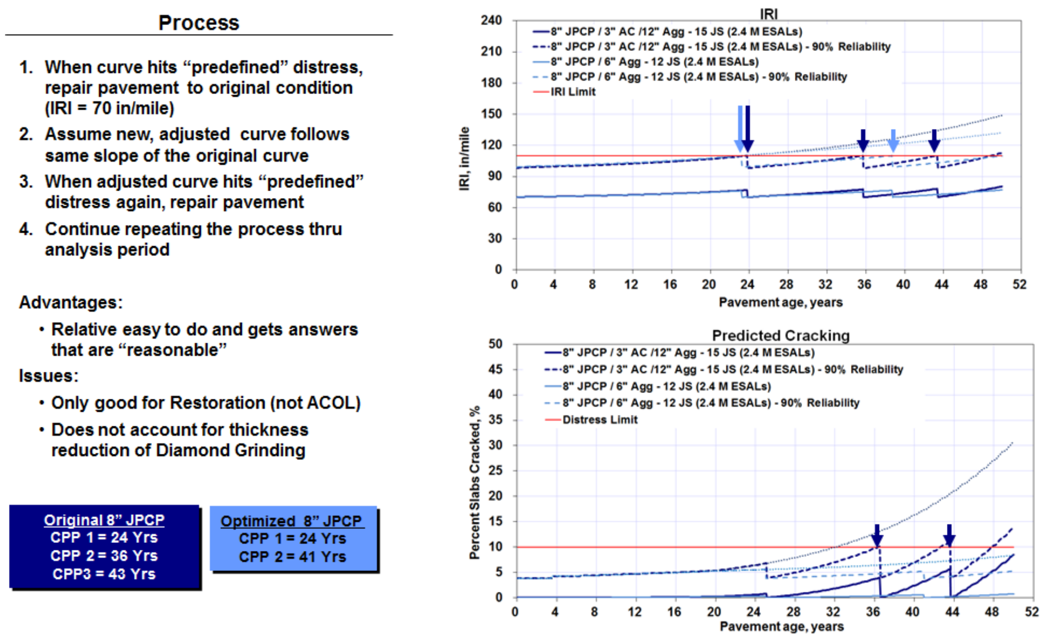



Figure 5. Resultant LCCA rehabilitation schedules by adjusting the Pavement-ME prediction performance curves using approach 4 for two potential JPCP designs

Table 1 summarizes the rehabilitation timing for the pavement using the state DOT standard policy rehabilitation timing for a 50 year analysis period vs the other predicted rehabilitation timing processes. Key items to note are:

1. Time to first rehabilitation is 4 years later than assumed in the policy LCCA schedule
2. The time for the second rehabilitation is close to the policy, but it is shorter for the standard design and longer for the optimized design
3. The standard design actually requires a third rehabilitation, which is not captured in policy LCCA schedule.

The key point to recognize before discussing *what activities* to use in the LCCA is that this process can fundamentally change how pavements are designed. That is, historically pavement thickness has been based on carrying traffic for a given design period (e.g., 30 years of traffic). With this process, agencies can develop a number of designs, along with required rehabilitation activities, to provide a given performance level (i.e., cracking less than 15% at all times) over the analysis period, and then compare the LCCA results to determine which is the most cost effective.

**Using Decision Tree Analysis to Account for WHICH Activities may Occur**

While a few SHA LCCA guidelines recognize that pavements can be rehabilitated

Table 1 - Comparison of rehabilitation timing using the different prediction procedures

| | | | *Pavement-ME* | | | |
|---|---|---|---|---|---|---|
| | | | *Run Pavement-ME in Rehab Mode* | | *Adjust Performance Curves* | |
| | **Standard DOT Policy** | **Based on Same Traffic** | **Standard** | **Optimized** | **Standard** | **Optimized** |
| **Initial Const.** | **Yr 0** | **Yr 0** | **Yr 0** | **Yr 0** | **Yr 0** | **Yr 0** |
| **Rehab 1** | **20** | **24** | **24** | **24** | **24** | **24** |
| **Rehab 2** | **40** | **36** | **38** | **43** | **36** | **41** |
| **Rehab 3** | | **44** | **45** | | **43** | |

using several different activities, most guidelines provide a single, or standard, set of activities. There may be different activities for different classification of roadways (e.g., urban interstates vs rural farm to market roadways), but a single standard is used. The fact is that for any pavement design, there are many different rehabilitation scenarios could be performed when the pavement needs rehabilitation and what activities are selected will have a large impact on the results.

Decision tree analysis (DTA) is a numerical analysis procedure that accounts for all, or most, of the possible alternatives for a future course of action. DTA is commonly used in operations research, decision analysis, and other research areas to help identify the optimal strategy to reach a goal. It has recently been applied to pavement engineering as a way to look at all the rehabilitation alternatives, from minor repairs to extreme interventions (Pour & Jeong, 2012; Pour & Jeong, 2013).

As an example, rehabilitation activities for concrete pavements typically consist of either concrete pavement preservation (CPP) or an asphalt overlay. However, for each of these, there are a number of other factors that will impact the final LCCA results considerably. Some of these other factors include:

- How much patching will be done on a CPP project? Is it 1%, 5%, 10%?
- How thick will the AC overlay be? Is it 2 inches or 6 inches? Will there be pre-overlay repairs? If so how much?
- What are the options for second rehabilitation activities? Will CPP or overlay be used? How much patching will be done or how thick AC overlay will it be?

Depending on how each of these decisions is made in developing the rehabilitation strategy, the LCCA results can change significantly, impacting which pavement is selected in the pavement type selection process. The selection of activities also influences the *risk profile* between the two alternates, which will be demonstrated later in this paper.

**The Ohio DOT Rehabilitation Strategy:**

The Ohio Department of Transportation (ODOT) is one of the state DOTs that recognizes that both concrete and asphalt can be rehabilitated with many different activities (ODOT, 1999) and its practices are being used here to demonstrate how selection of pavement rehabilitation strategies can impact the results of a LCCA. For concrete pavements, ODOT gives the following list of activities as potential options for the first and second rehabilitation for use in their LCCA:

- First rehabilitation (Year 18 – 25): 2% - 10% full-depth rigid repairs, 1% - 5% partial-depth bonded repairs, diamond grinding, 3-inch - 6-inch (~75 - 150 mm) asphalt overlay, sawing and sealing.
- Second rehabilitation (Year 28 – 32): 1% - 3% full- and/or partial-depth repairs, 1.25-inch - 2-inch (~32 - 50 mm) second asphalt overlay with or without milling, 3-inch - 4-inch (~75 - 100 mm) first asphalt overlay, sawing and sealing, micro-surfacing, crack sealing, diamond grinding.

For asphalt pavements, the list of activities that can be done is:

- First rehabilitation (Year 10 – 15): thin asphalt overlay, 1.25-inch - 3-inch (~32 - 75 mm), with or without milling.
- Second rehabilitation (Year 18 – 25): thick asphalt overlay, 3-inch - 7-inch (~75 - 175 mm), with milling, possibly pavement repairs.
- Third rehabilitation (Year 28 – 32): thin asphalt overlay or micro-surfacing or crack sealing.

**Developing a Decision Tree**

Decision trees are a flowchart-like structure that show the relationships among many courses of action and realizations of the future. Typically, a decision tree consists of two kinds of nodes: decision nodes, where an option is to be selected, and chance nodes, where various future realizations along with some probability of occurrence are represented. The combination of decision and chance represents the outcome of the decision. As additional decisions about subsequent activities are made, the branches expand until the end of the analysis period is reached. By systematically working through all potential options for each rehabilitation cycle, all feasible rehabilitation activity paths can be mapped out.

Figure 6(a) shows the graphical representation of a potential decision tree for ODOT's concrete pavement rehabilitation strategies. At the first node a decision has to be made on what type of activity will be done – CPP or asphalt overlay. If CPP is chosen (top node), a second decision has to be made on how much full-depth repair (FDR) should be done (i.e., 2 to 4%, 4 to 7%, or 7 to 10%). If an asphalt overlay is chosen (bottom node), again a second decision needs to be made on how much FDR should be done. Once these decisions are made, the analysis is through the first rehabilitation cycle. At the second rehabilitation, a decision again has to be made on what type of activity will be done - CPP or asphalt overlay. The process repeats itself until the end of the analysis period is reached. For this example, there are 36 different sets of rehabilitation activities (branches) that could be applied to the pavement over its life, with the lowest life cycle cost option being at the top and the highest option at the bottom.

Figure 6(b) is the representation of a potential decision tree for ODOT's asphalt pavement rehabilitation strategies. In both

Figure 6(a) and (b), the dark boxes represent ODOT's standard set of rehabilitation activities used in most of their LCCAs and the pavement's net present value (NPV) is the NPV for this set of activities.

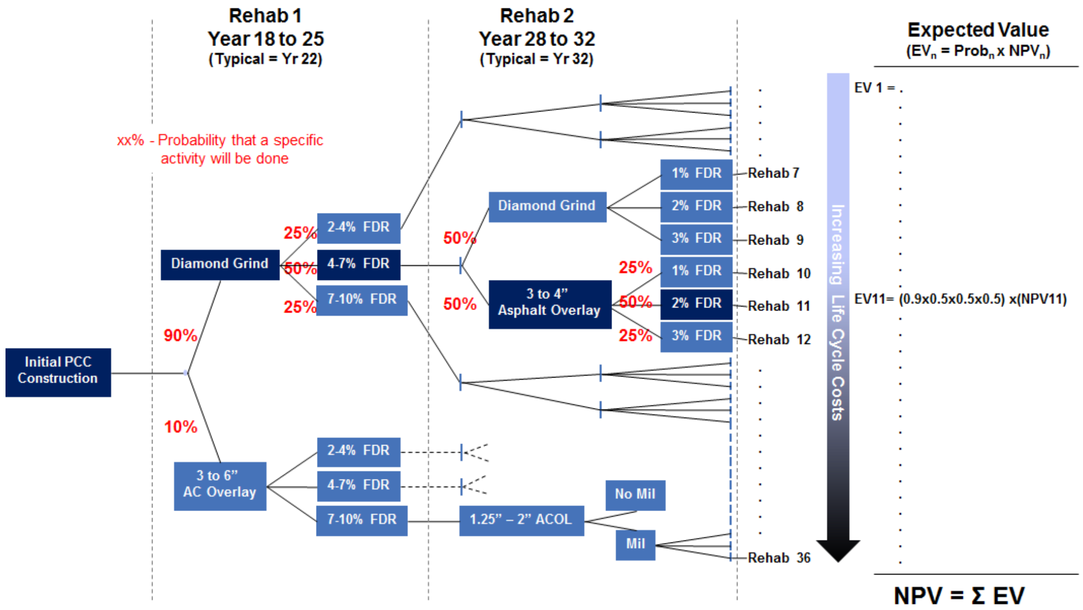
As the decision tree is being made, the analyst assigns a chance to each node that shows the likelihood of that specific activity. For example, ODOT's LCCA manual states: "*Best practice dictates the use of diamond grinding for the first treatment. Placing an asphalt overlay on a concrete pavement brings on a new set of problems and is discouraged as the first predicted maintenance action*." (ODOT, 1999) As such, the likelihood of doing a diamond grinding as the first rehabilitation is high, so it is assigned a probability of 90%, while the asphalt overlay is assigned a probability of 10%. At the second node, ODOT's standard process of using 4-7% FDR was given a probability of 50% and the other two options were given a 25% chance each. This process is continued until all branches have their probability defined.

Once the activities and probabilities are defined, the DTA calculates the pavement NPV for each branch, and the expected value (EV) of that NPV is calculated by multiplying the NPV by the probability of that set of activities being done (eqn. 2). Once the expected value for a branch is calculated, the final $EV_{NVP}$ of the pavement alternative is the summation of the all the expected values (eqn 3).

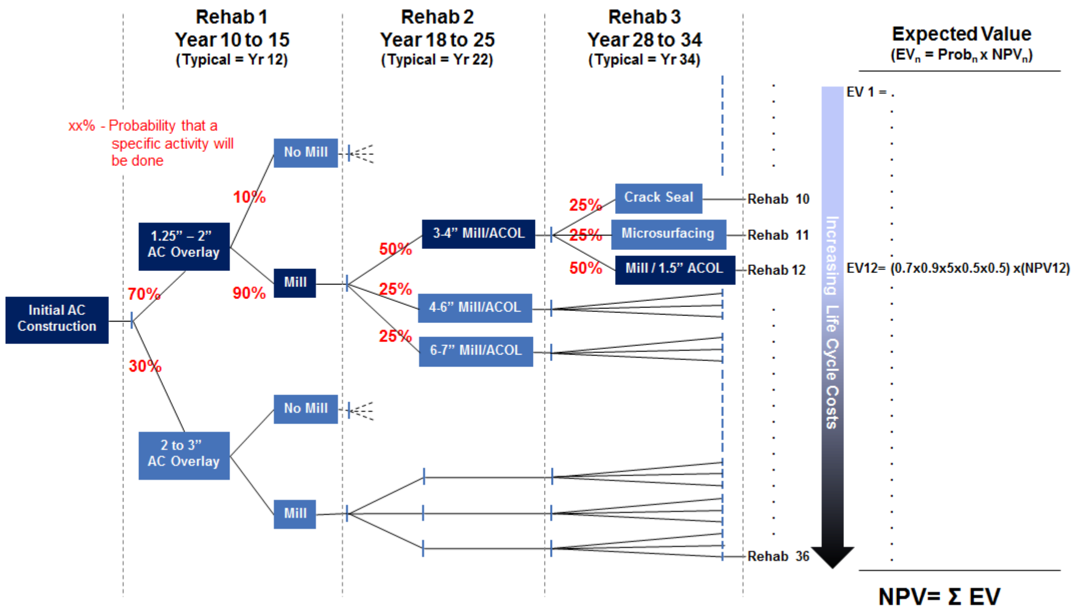
$$EV_i = (\sum Prob_i \ x \ NPV_i) \quad (2)$$

$$EV_{NPV} = \sum EV_i \quad (3)$$

where: $EV_i$ is the expected NPV for rehabilitation activity set *i; $Prob_i$* is the probability that rehabilitation activity set *i (*i.e., branch *i*) is done; $NPV_i$is the NPV of




a) Concrete pavement activities (dark boxes represent ODOT standard activites)




b) Asphalt pavement activities (dark boxes represent ODOT standard activites)

Figure 6. Partial Decision tree of ODOT's pavement rehabilitation activities

rehabilitation activity set *i;* and $EV_{NPV}$ is the overall expected NPV value for the alternative.

## Interpreting the Results of a Decision Tree Analysis

The advantage of using a DTA is that instead of getting a single NPV for the LCCA, the result is a range of NPV results and a probability adjusted $EV_{NPV}$. This additional information provides several insights, which will be demonstrated in the following case study. Figure 7 shows actual pavement designs used in an LCCA for a project in Ohio (ODOT, 2007). Note that this example is being used only to demonstrate how selection of pavement rehabilitation strategies can impact the results of a LCCA and how using a DTA can address the shortcomings of using a single pavement rehabilitation strategy.

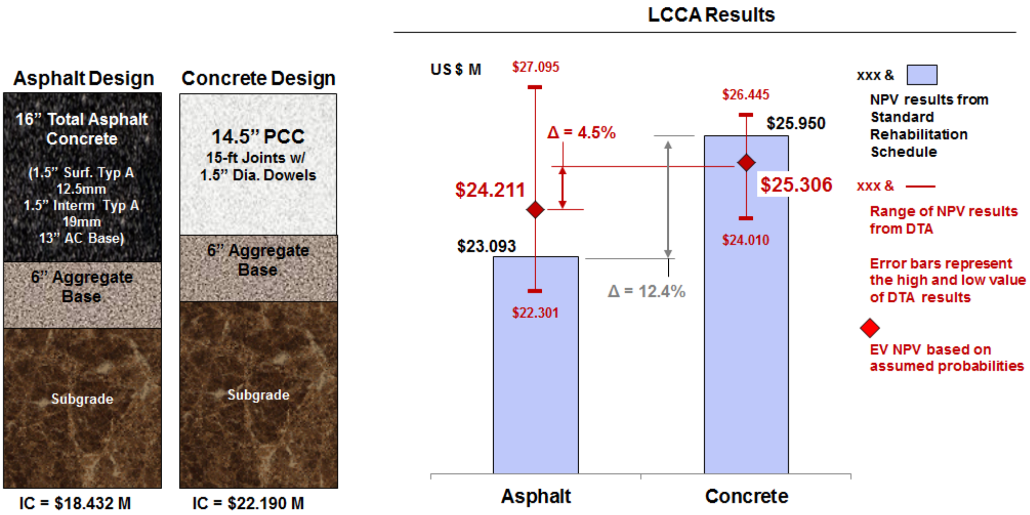



Figure 7 – LCCA results from a decision tree analysis

The two pavement designs are a 400 mm (16-in) asphalt pavement over a 150 mm (6-in) aggregate base and a 363 mm (14.5-in) concrete pavement, with 4.5 m (15-foot) joint spacing also over a 150 mm (6-in) aggregate base. The initial pavement designs, design lives and the standard rehabilitation schedules (dark boxes in

Figure 6) are from ODOT's Pavement Design and Rehabilitation Manual (ODOT, 1999). For this analysis, the pavement design life is 20 years and the analysis period is 50 years.

The light columns show the results of the standard ODOT LCCA rehabilitation schedule. For this project, the asphalt design had a 12.4% LCCA advantage and was subsequently selected in the pavement type selection process. The data on the error bars is the results from the DTA, indicating the range of potential LCCA NPV results from the 36 rehabilitation scenarios and the diamond is the $EV_{NPV}$. It is evident that there is a large increase for the asphalt $EV_{NPV}$ and a slight decrease of the concrete $EV_{NPV}$ as compared to the standard scenarios, which decreases the difference between the alternatives from 12.4% to 4.5%. The reason for the differences between the standard and DTA results is that the implied risk profiles used in the standard LCCA analysis are not the same for the two pavement designs.

The standard LCCA NPV (columns) for the asphalt design is on the low end of the potential $EV_{NPV}$ results (error lines) for asphalt, while the standard LCCA NPV for the concrete is on the high side of the range of $EV_{NPV}$ results. This indicates that there is a high upside risk that the actual NPV of the asphalt design will be higher than the NPV from the standard rehabilitation scenario. By comparison, the NPV of the concrete design has a higher downside risk than standard rehabilitation scenario meaning the actual NPV is more likely to be lower than predicted by the standard LCCA. The key take-away is that the concrete and asphalt NPV results using these standard rehabilitation scenarios do not fall within the same area of their respective bands (i.e. bottom, middle or top) and thus, there is a difference in the risk profiles of the assumed LCCA results that should be acknowledged when comparing results.

An important issue in this process is determining the probabilities to use at each node, which can be subjective. Still, it is important to understand that by defining the different rehabilitation possibilities, a range of LCCA results is calculated that covers the extreme, as well as more likely scenarios. The item that changes, based on the probabilities, is where the $EV_{NPV}$ falls within the band of potential NPV values indicating the uncertainty and relative *risk profile* of the results.

**Combining the MEPDG / Pavement ME Results and DTA**

To truly capture the benefits of these two processes, engineers should combine the MEPDG/Pavement ME results to define when the first activity happens and DTA to account for the range of distress that can occur. For example, as described in Figure 3, the timing for an activity is determined when the predicted distresses at the given reliability level (i.e. 90%) hits the predefined distress level, and the most likely amount of distress to repair is the amount of distress at the 50% reliability curve. What is important to recognize is that at this point, the range of how much to repair actually goes from as much as 15%, but with a low probability (10% in this case), all the way down to doing 0% repair, but again at a low probability. The means engineers can better define the different levels of repair in the DTA analysis.

For example, using Figure 3 and Ohio DOT's concrete decision tree in Figure 6(a), the first rehabilitation, CPP, would occur at year 32, and the estimated 50% patching branch would be 7% and the high and low 25% branches would be about 10% and 4% respectively. Also as shown on the Figure 3, as one moves right across performance prediction graph (i.e. the pavement age increases), the type of repair changes as more distress develop. As such, the engineer can assign a higher level of intervention (i.e. an asphalt overlay), but can adjust the time of that asphalt overlay to something like year 40 to account for the extra time it takes the additional distresses to develop. This means on the 90% CPP branch of Figure 6(a) would occur at year 32 and the 10% overlay branch would occur at year 40.

By judiciously monitoring the pavement prediction performance, and applying a series of rehabilitation activities at the are appropriate for the given condition and time, engineers can more accurately characterize the range of possible future rehabilitation activities for the specific pavements being analyzed, making the LCCA more realistic and robust.

**Summary**

Life cycle cost analysis is used to compare the total ownership cost of pavement designs over a defined analysis period to determine which is the lowest cost alternative. For the comparison to be meaningful and reliable, the analysis should reflect the range of different rehabilitation activities for each pavement alternative that could occur over the analysis period. Currently, most agencies apply a single, standard, policy-set rehabilitation scenario to all pavements based on historical performance. The drawback with this approach is that it assumes that the historical performance used in the analysis will be representative of the performance of the specific design being evaluated. This is unlikely to be true.

This paper described how the AASHTO Pavement ME Design Procedure and decision tree analysis can be used to characterize a range of possible future rehabilitation activities for LCCA. Pavement ME helps determine *when* are rehabilitation activities are required (e.g., timing) and DTA evaluates the range of rehabilitation options and calculates an expected range of costs with probabilities (i.e., expected value), thereby taking into account the associated risk profile of each alterative in the analysis. By systematically adopting and using the methodology laid out in this paper, transportation agencies can develop more robust LCCAs that address the uncertainty that can occur due to different potential rehabilitation schedules, and can facilitate discussion on the outcomes in a comparative LCCA.

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