NCAT Report 20-05

LIFE CYCLE COST ANALYSIS – END OF LIFE CONSIDERATIONS

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1 INTRODUCTION

1.1 Overview of Life Cycle Cost Analysis End of Life

Life Cycle Cost Analysis (LCCA) is a technique used by many state highway agencies (SHAs) to evaluate the overall expected costs of competing pavement alternatives, primarily between asphalt and concrete designs. Whereas the majority of design-bid-build projects primarily focus on a project's initial construction costs, an LCCA considers expected costs over the life of each pavement alternative and is a process for identifying the best long-term value among pavement alternatives. In addition to the initial construction costs, future anticipated costs such as maintenance, and rehabilitation costs, as well as user costs, are discounted back to the present time to account for the time value of money. Any of the pavement value remaining at the end of the analysis period (i.e. salvage value) can be discounted back to its present value. A typical expenditure stream diagram for a project is shown in Figure 1.

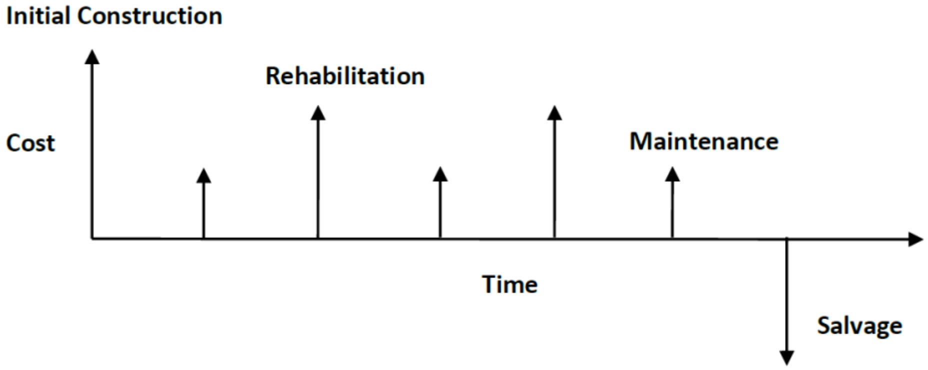

Figure 1. Stream of Expenditures for a Paving Project

Estimating future costs and the timing of future maintenance activities for an LCCA can be a daunting task for SHAs. In addition, estimating any residual service life of the alternatives at the end of the analysis period can also be exceptionally challenging. However, proper consideration of these inputs is essential to conducting an LCCA that properly identifies the best pavement option.

Although significant efforts have been placed on accurately determining many of the LCCA input values, one area that has received little attention is properly considering the costs associated with the end of life of a pavement. Thus, this report discusses pavement end of life considerations of LCCAs. For additional information on conducting LCCAs, NCAT Report 19-03 "Best Practices for Determining Life Cycle Costs of Asphalt Pavements" by Drs. Fan Gu and Nam Tran is recommended.

1.2 Limitations of Current Methodology

FHWA guidelines recommend estimating a remaining service life value at the end of an LCCA analysis period or assigning a credit (salvage value) for the remaining pavement as a recyclable material. The value of recycling the pavement materials can be difficult to estimate as those values will depend on unknown supply and demand conditions in the future marketplace. Thus, salvage values typically tend to be very low and makes them almost negligible when coupled with the impact of discounting the values back to present time (*Flannery et al., 2016*).

In cases where the service life of the pavement extends beyond the LCCA analysis period, it is recommended that a value of the remaining service life be included in the LCCA. However, difficulties in determining accurate service lives of pavement alternatives lead many SHAs to not include remaining service life in their analyses (*Flannery et al., 2016*).

In addition to these two challenges, there are other problems associated with the manner in which LCCA methodologies address pavement end of life scenarios. Additional issues include:

1) Current LCCA policies only consider the remaining service life of the last rehabilitation and ignore the underlying pavement layers.

For flexible pavements composed of a combination of asphalt layers, granular base, and subgrade, it is very rare to encounter a pavement that requires complete reconstruction at the end of its service life. Unless the base or subgrade layers have failed, flexible pavements are capable of being rehabilitated multiple times by milling and replacing the upper asphalt layers or adding a structural asphalt overlay. In general, this cycle of just milling and resurfacing the asphalt layers continues for many years beyond the analysis period of the LCCA. While some LCCA policies consider the remaining service life of asphalt layers from the last rehabilitation, they do not consider the underlying pavement remaining in service. This is especially critical when an LCCA is being conducted to determine the economy of constructing a perpetual pavement.

2) Many LCCAs do not include all costs related to end of life rehabilitation.

In contrast to flexible pavements that are typically rehabilitated numerous times, PCC pavements are much more likely to require some type of significant reconstruction activity at the end their service lives. These reconstruction activities generally involve either:

- The full-depth removal of the existing PCC pavement followed by the placement of a new concrete or asphalt pavement, or
- Slab fracturing (e.g. rubblization, crack and seating, or break and seating) followed by the construction of a new pavement structure that is essentially built over the failed PCC pavement. This new pavement could be a concrete overlay or an asphalt overlay.

Each of these reconstruction options are costly and exceptionally disruptive to traffic for extended periods of time. In many cases, these end of life impacts are not included in an LCCA since they may occur beyond the analysis period.

2 RESEARCH OBJECTIVES AND SCOPE

Performing an LCCA to develop a more robust economic analysis of pavement type alternatives is of great importance for transportation agencies as budgets continue to be constrained. Consequently, the data used in an LCCA must be credible, reasonable, objective, and unbiased. All appropriate factors must be considered in the analysis, including pavement end of life costs. This report focuses on consequences that arise at the end of a pavement's serviceable life and contrasts how those consequences are very different for asphalt and concrete pavements.

3 LCCA END OF LIFE LITERATURE REVIEW

3.1 Basic Concepts

The terminology for LCCA end of life has evolved slightly over the years, but the basic concepts have generally remained the same. In 1998, FHWA published an interim technical bulletin titled *Life-Cycle Cost Analysis in Pavement Design*, which defined salvage value as the remaining value of the pavement alternative at the end of the analysis period and is included in the LCCA as a negative cost (Walls and Smith, 1998). Salvage value is made up of two parts: residual value, which is defined as the net value from recycling the pavement, and serviceable life, which is the remaining life in a pavement alternative at the end of the analysis period. With regard to serviceable life, FHWA gives the following scenario:

> *For example, over a 35-year analysis, Alternative A reaches terminal serviceability at year 35, while Alternative B requires a 10-year design rehabilitation at year 30. In this case, the serviceable life of Alternative A at year 35 would be 0, as it has reached its terminal serviceability. Conversely, Alternative B receives a 10-year design rehabilitation at year 30 and will have 5 years of serviceable life at year 35, the year the analysis terminates. The value of the serviceable life of Alternative B at year 35 could be calculated as a percent of design life remaining at the end of the analysis period (5 of 10 years or 50 percent) multiplied by the cost of Alternative B's rehabilitation at year 30 (Walls and Smith, 1998).*

In 2002, FHWA issued a Life-Cycle Cost Analysis Primer noting that one or more alternatives could have service lives that exceed the analysis period. The portion of the service life that exceeds the analysis period is known as remaining service life (RSL). Failure to account for differing RSLs can result in an economic bias toward one or another alternative in the LCCA (FHWA, 2002).

RSL value is different from residual value and exists in cases where the alternative continues in operation beyond the end of the analysis period, whereas residual value requires termination of the operation, which rarely occurs in highways. Residual value is obtained only when some actual value can be realized from the sale or reuse of scrap materials. When applied at the end of the analysis period, RSL value and residual value can generally be considered mutually exclusive (FHWA, 2002).

Ozbay et al. (2003) defined salvage value as the value of the project at the end of the analysis period and noted that the discounted salvage value is deducted from the total costs when calculating the net present value. It was further noted that there is no general consensus on how to estimate salvage value, primarily because infrastructure projects are seldom terminated at the end of an analysis period. One approach used to determine this component is by summing the estimated costs of demolition and removal of the pavement and the estimated value of the recycled materials. A second approach identified was to calculate the relative value of the remaining serviceability of the alternative with respect to the cost of the last rehabilitation activity, which is the RSL approach. Since each approach is not necessarily straightforward, another alternative is to adjust the analysis period so that the remaining serviceability is the same for all alternatives and the salvage value can be omitted from calculations (Ozbay et al., 2003). In 2008, Rangaraju et al. noted that salvage value has two components: the residual value, which refers to the value from recycling the pavement, and the remaining life value in a pavement alternative at the end of the analysis period.

In 2015, FHWA issued a supplement to the 1998 interim technical bulletin on Life Cycle Cost Analysis (FHWA, 2015). In this supplement, salvage value was defined as the value of an investment alternative at the end of the analysis period, which consists of two fundamental components: residual value and serviceable life. Residual value was defined as the net value from pavement recycling. It is noted that the difference of residual values between pavement design strategies is not significant, and, when discounted over a period of 40 years or longer, tends to have little effect on LCCA results. Serviceable life is defined as the more significant salvage value component and is the remaining life in a pavement alternative at the end of the analysis period. It is primarily used to account for differences in remaining pavement life between alternative pavement design strategies at the end of the analysis period. The supplement recommended to only consider the cost of the last rehabilitation when determining a value for RSL, the same as was recommended in their 1998 Interim Technical Bulletin (FHWA, 2015).

In 2013, West et al. defined salvage value as the expected worth of the investment at the end of the analysis period, which should reflect the residual value of the last rehabilitation and the remaining pavement structure at the end of the analysis period. A further recommendation of that study (in this case, Alabama) was that the analysis period should be long enough to consider the reconstruction of pavements that have reached their terminal serviceability. Many of the PCC pavements in Alabama had been rubblized or broken and seated, while asphalt pavements that were built during the same time period were still in service with only periodic resurfacings to maintain a high level of serviceability. A typical expenditure stream diagram for the concept of removing or rubblizing a pavement is shown in Figure 2. West et al. further recommended that a monetary salvage value should be credited to asphalt pavement alternatives at the end of the analysis period because much of the original asphalt structure will continue to be a primary element of the pavement for an indefinite period of time. In addition, if the asphalt pavement is resurfaced near the end of the analysis period, that portion of the overlay’s remaining service life beyond the analysis period should also be recouped in the LCCA.

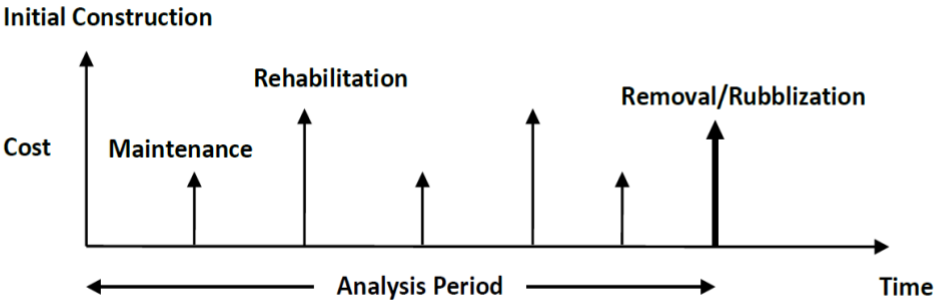

Figure 2. Stream of Potential Expenditures for Concrete Pavement (West et al., 2013)

Gu and Tran (2019) utilized the term terminal value as the expected worth of a pavement alternative at the end of the LCCA analysis period. Terminal value is comprised of two parts: remaining service life value and salvage value. As previously defined, salvage value is the value of reusing or recycling materials that are removed from the pavement. The RSL value is the value of the pavement alternative when its service life extends beyond the end of the analysis period. They provided equations for calculating the RSL value for the layers rehabilitated immediately prior to the end of the analysis period and the RSL value of the underlying layers based on their estimated remaining structural capacity. The rationale for including this in the RSL was that underlying layers are often structurally sound and are rarely removed and replaced at the end of the analysis period.

3.2 Current Agency Practices

A 2008 survey on LCCA practices conducted for the South Carolina Department of Transportation found that of the 23 states that responded, 12 did not consider salvage value or remaining service life in their LCCA calculations, while 10 states always did (Rangarju et al. 2008). Of these 10 states, 8 indicated that only RSL was included in the analysis, while one agency indicated that both residual value of the pavement and RSL were included. One other state agency reported that the benefit of using any recycled bituminous or concrete material was incorporated into the initial cost estimate instead of assigning a salvage value at the end of the analysis period.

A survey conducted as part of NCHRP Synthesis 494 (Flannery et al. 2016) found that 26 of the 41 respondents used LCCA to select between project alternatives. The survey indicated that only 24% of the responding agencies included salvage value, while 27% included remaining service life. The survey also inquired regarding information that agencies lacked when conducting an LCCA, and 20% indicated that there was inadequate information on determining salvage value, while 24% indicted there was inadequate information on determining remaining service life value.

A review of LCCA procedures for selected states indicated the following:

Alabama DOT: ALDOT does not currently consider a salvage value for asphalt or concrete pavements.

Colorado DOT: A 40-year analysis period was chosen by CDOT because FHWA's LCCA Policy Statement recommends an analysis period of at least 35 years for all pavement projects. CDOT established pavement rehabilitation cycles to prevent having to use a salvage value. Unmodified HMA has a 10-year rehab life, which easily led to a 40-year analysis period.

Florida DOT: FDOT only uses remaining service life value of the last rehabilitation and does not include salvage value in their LCCA calculations.

Georgia DOT: The Georgia DOT defines salvage value as the prorated value of the most recent rehabilitation based on the remaining service life of the rehabilitation. The discounted salvage value is subtracted from the sum of the other cost values.

Ohio DOT: ODOT does not use salvage value. The timing on their methodology attempts to result in approximately equal pavement conditions at the end of the analysis period for both alternatives. The salvage values are considered equal and are not included in the analysis.

Virginia DOT: VDOT notes that at the end of the LCCA period, the pavement structure may be defined as having some remaining value to the managing agency, known as the salvage value. They further note that: *"Estimating a dollar figure for this component could be complex. Fortunately, the dollar figures for the 'salvage value' for the competing pavement types when discounted 50 years to PW are not expected to be significantly different".* Consequently, for simplicity, VDOT disregards the salvage value for the competing pavement types in its LCCA process.

Wisconsin DOT: For alternatives that have rehabilitation cycles that extend beyond 50 years, a "rehabilitation salvage value" is calculated and credited back into the alternative's "total facility cost." The "rehabilitation salvage value" calculation consists of discounting the linearly prorated rehabilitation cost.

Utah DOT: UDOT does not consider salvage in their LCCA calculations.

3.3 Methods of Determining Accurate Terminal Values

West et al. (2013) proposed several concepts related to accurately establishing terminal values during an LCCA. The first concept was that the LCCA analysis period should be long enough to ensure that the concrete pavement alternative reaches its terminal serviceability, and that the cost of the concrete remediation (rubblization, removal and replacement, crack and seating, break and seating, etc.) be accounted for as a future cost during the analysis. An expenditure stream diagram for this concept is shown in Figure 3.

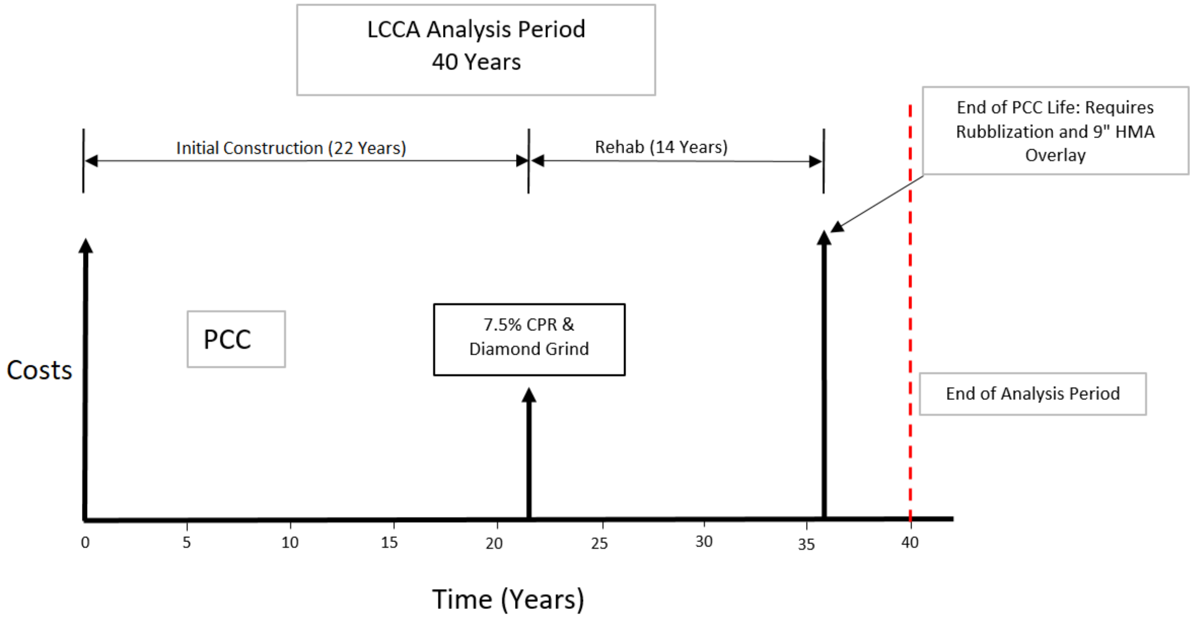

Figure 3. Expenditure Stream with Analysis Period Beyond PCC Life

The second concept is related to determining accurate RSL values for the entire asphalt pavement structure. This would include determining the RSL for the most recent resurfacing that occurred prior to the end of the analysis period, and also determining the RSL for the underlying asphalt layers. This value should be credited because much of the original asphalt structure will continue to function indefinitely as designed in the pavement. The changes in the asphalt structure through the analysis period are shown in Figure 4.

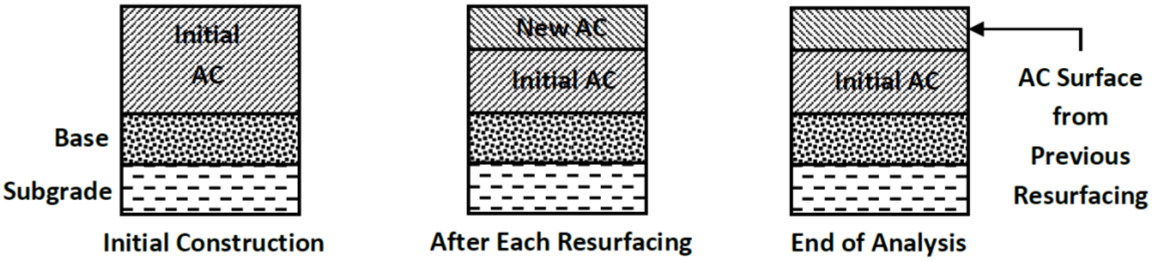

Figure 4. Changes in Asphalt Structure (West et al., 2013)

As shown in Figure 4, with respect to an asphalt pavement alternative, the terminal value consists of two components: the RSL value of the last resurfacing; and the RSL value of the lower asphalt layers remaining from the initial construction. In situations where the underlying base and subgrade of the pavement structure are different than the concrete alternative, the RSL value of those layers should also be determined as described for the second scenario above.

Gu and Tran (2019) proposed several methods of determining the RSL of underlying layers. One approach is to determine the RSL based on the predicted remaining structural capacity of the layers or the structural number when compared to the original design. This involves using analysis with non-destructive testing such as the Falling Weight Deflectometer (FWD) to determine how the structural capacity or structural number changes over time. A second approach is to determine the RSL value based on estimated layer coefficients that are a function of anticipated pavement conditions. The Florida DOT uses this approach on the design of their resurfacing projects (FDOT, 2020) as shown in Table 1.

Table 1. Layer Coefficients of Existing Asphalt Pavements (FDOT, 2020)

Mixture Type	Original Design	Pavement Condition		
		Good[a]	Fair[b]	Poor[c]
FC-1 or FC-4	0.20	0.17	0.15	0.12
FC-3	0.22	0.20	0.17	0.15
FC-9.5 or 12.5	0.44	0.34	0.25	0.15
Type S or SP	0.44	0.34	0.25	0.15

Notes: [a]Good: No cracking and minor rutting; [b]Fair: Moderate cracking and minor rutting; [c]Poor: severe cracking and severe rutting.

In addition, the 1993 AASHTO *Guide for the Design of Pavement Structures* also recommends determining layer coefficients based on the visual condition of the pavement. Both approaches can be utilized to predict the remaining structural capacity/number of an asphalt pavement at the end of the analysis period. The structural number can be predicted and compared to the structural number of the original design to determine the RSL of the underlying asphalt structure. Gu and Tran (2019) developed Equation 1 to determine the RSL of underlying layers.

$$RSL\ of\ Underlying\ Asphalt\ Structure = C_{OD} \times \frac{SN_{EX}}{SN_{OD}} = C_{OD} \times \frac{a_{EX} \times h_{EX}}{a_{OD} \times h_{OD}} \qquad (1)$$

Where:

C_{OD} = cost of the underlying layers in the original design or prior maintenance or rehabilitation;

SN_{EX} = structural number of the underlying layers in the existing asphalt structure;

SN_{OD} = structural number of the underlying layers in the original design or prior maintenance or rehabilitation structure;

a_{EX} = layer coefficient of the underlying layers in the existing asphalt layer;

h_{EX} = thickness of the underlying layers the existing asphalt structure;

a_{OD} = layer coefficient of the new/original asphalt layers; and

h_{OD} = thickness of the underlying layers the original design or prior maintenance or rehabilitation.

In situations where the underlying base and/or subgrade of the pavement alternative is different than the concrete alternative, the RSL value of those layers should also be determined. One option is to use non-destructive testing to determine how the structural characteristics of these layers typically change over time. Pavement base and subgrade layers rarely deteriorate with time with proper materials selection, drainage, and construction. Thus, another method of determining the RSL of those layers would be to use an engineering estimate to determine a reasonable predicted life expectancy. For example, if it is common for bases and subgrades to last a minimum of 60 years historically, and the LCCA analysis period will end at 35 years, the RSL would be 25 years and the RSL value would be (25/60) x cost of the original construction for both the base and subgrade.

4 TRADITIONAL PCC AND ASPHALT PAVEMENT REHABILITATION METHODOLOGIES

4.1 PCC Rehabilitation

When a concrete pavement structure reaches its terminal serviceability, some type of major rehabilitation or reconstruction activity is typically necessary. West et al. (2013) defined rehabilitation as structural enhancements that extend the service life of an existing pavement and/or improve its load carrying capacity. Examples of major rehabilitation for concrete pavements include full-depth slab replacement, including the full or partial repair of broken slabs and deteriorated joints, retrofit of dowel bars, under-sealing, addition of longitudinal edge-drains, diamond grinding, asphalt overlays, and bonded concrete overlays.

Reconstruction, on the other hand, is the replacement of the entire existing concrete pavement and is required when a pavement has failed structurally or when the required amount of joint repair and slab replacement has become uneconomical. The existing concrete pavement is either completely removed or fractured for use as an aggregate base layer under an overlay. Examples of concrete reconstruction include slab fracturing (e.g., rubblization, break and seat, and crack and seat) followed by an asphalt overlay; unbonded concrete overlays; or complete removal of the concrete pavement and replacement by a new concrete or asphalt pavement (West et al. 2013).

As part of a NAPA project on the Benefits of Rehabilitating Concrete Pavements with Asphalt Overlay, West et al. (2020) conducted a survey to gather information on methods used to rehabilitate concrete pavements with asphalt overlays in the United States. State asphalt pavement associations (SAPAs), state and local agency representatives, slab fracturing equipment manufacturers, and consulting pavement design engineers were surveyed. As shown in Figure 5, the three most common methods of PCC rehabilitation were rubblization, minimum restoration of PCC, and maximum restoration of PCC. Minimum restoration of PCC (as defined in this survey) only includes the sealing of joints, surface diamond grinding, etc., and is not considered a major rehabilitation. Maximum restoration of PCC includes the full or partial repair of broken slabs and deteriorated joints, retrofit of dowel bars, installation of edge drains, etc. Crack and seating, stress absorbing membrane interlayers, and special crack-resistant asphalt mixtures were also frequently used for PCC rehabilitation to retard reflective cracking.

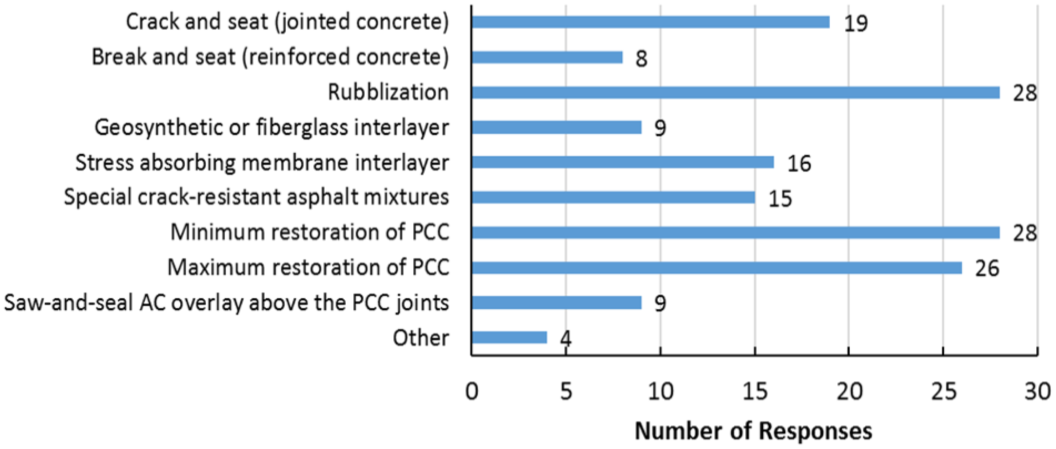

Figure 5. PCC Rehabilitation Techniques Used by Participants' Organizations in the Past 10 Years (West et al., 2020)

As part of this project, a survey on typical methods of PCC and asphalt pavement rehabilitation at the end of their serviceable life was distributed to the SAPAs. While there was only a limited response to the survey (only nine SAPAs responded), a summary of their responses is shown in Table 2.

Table 2. SAPA Responses on Typical Methods of PCC Rehabilitation

Concrete Rehabilitation		
Method	**%**	**Lane Miles**[a]
Asphalt overlay	71	22,682
Maximum restoration of PCC	17	5,305
Slab fracturing plus asphalt overlay[b]	5	1,693
Remove and replace with PCC	3	927
Remove and replace with asphalt pavement	3	838
PCC overlay	1	243

Notes: [a]The survey requested the number of lane miles for various rehabilitation methods over the past 20 years, however, the reported numbers represented various periods of time; [b]Slab fracturing includes responses for cracking and seating, breaking and seating, and rubblization.

Unpublished data collected by Antigo Construction, Inc. over the past twenty years indicates that there have been over 550 PCC rubblization projects in 31 states, which would indicate that rubblization is a more prevalent method of PCC rehabilitation than indicated by the SAPA survey reflected in Table 2.

4.2 Asphalt Pavement Rehabilitation

As noted previously, it is rare for asphalt pavements to require complete reconstruction at the end of their service life. Distresses are typically localized to the upper asphalt layers, which normally only requires milling to an appropriate depth and resurfacing with one or two layers of an asphalt mixture. In general, this cycle of milling and resurfacing an asphalt pavement can continue for many years beyond the analysis period of the LCCA.

Responses to the survey sent to the SAPAs on methods of asphalt pavement rehabilitation at the end of their serviceable lives are summarized in Table 3. Results from this limited survey support the assertion that it is very uncommon for asphalt pavements to either be fully reconstructed or milled full depth.

Table 3. SAPA Responses on Typical Methods of Asphalt Pavement Rehabilitation

Asphalt Rehabilitation		
Method	**%**	**Lane Miles[a]**
Asphalt overlay with no milling	51	135,100
Milling less than full depth and overlay	47	124,776
Full reconstruction	1	2,760
Milling full depth and overlay	1	1,250

Note: [a]The survey requested the number of lane miles for various rehabilitation methods over the past 20 years, however, the reported numbers represented various periods of time.

4.3 Rehabilitation Costs

Ahmed (2012) evaluated agency costs in Indiana from 2001 – 2006 for various types of maintenance and rehabilitation treatments for PCC and asphalt pavements. A summary of agency costs ($/lane-mile) for Interstate projects for asphalt and PCC pavements are shown in Tables 4 and 5, respectively. While this data is somewhat outdated, it provides a reference point on the various costs of rehabilitation for both PCC and asphalt.

Table 4. Summary of Agency Costs in Indiana for Interstate Asphalt Pavement Rehabilitation (Ahmed, 2012)

Treatment Type	Unit Cost ($/Lane-Mile) – 2010 Constant $				
	Mean	**Minimum**	**Maximum**	**Std. Dev.**	**Sample Size**
Functional HMA overlay[a]	$89,481	$47,824	$409,619	$93,376	14
Structural HMA overlay[b]	$370,412	$44,347	$2,714,978	$659,441	14
Resurfacing (partial 3R)	$152,905	$11,892	$408,182	$119,254	13
Mill full depth[c] & AC overlay	$171,846	$17,618	$380,455	$148,257	6
Road reconstruction	$2,504,774	$517,855	$4,471,955	$1,125,679	9

Notes: [a]A functional treatment of an asphalt pavement is applied with the objective of restoring pavement smoothness to near new condition on a pavement that is structurally sufficient. An HMA functional treatment consists of an intermediate course (placement of which is preceded by milling) and a surface course. [b]A structural treatment of an asphalt pavement strengthens the existing structure to current design requirements and restores the pavement smoothness to a new condition. An HMA structural treatment will consist of base, intermediate and surface courses, with milling of the existing pavement. [c]Milling full depth in this case refers to completely removing all of the asphalt layers down to the aggregate base.

Table 5. Summary of Agency Costs in Indiana for Interstate PCC Rehabilitation (Ahmed, 2012)

Treatment Type	Unit Cost ($/Lane-Mile) – 2010 Constant $				
	Mean	Minimum	Maximum	Std. Dev.	Sample Size
Cleaning and joint sealing	$212,847	$97,146	$36,280	$56,420	8
Concrete pavement restoration (CPR)[a]	$150,057	$24,027	$550,022	$173,050	7
Asphalt functional overlay on PCC pavement (PCCP)[b]	$89,481	$47,824	$409,619	$93,376	14
Repair PCCP & asphalt overlay	$491,865	$2,883	$844,367	$345,803	15
PCCP overlay on PCC pavement	$737,585	$737,585	$737,585	-	1
Crack and seat PCCP & asphalt overlay	$519,405	$117,711	$209,844	$864,941	11
Rubblize PCCP & asphalt overlay	$757,057	$425,913	$1,256,176	$239,717	12
Road reconstruction	$2,793,015	$358,469	$10,665,746	$2,918,320	12

Notes: [a]CPR may consist of crack sealing, partial; and full depth patching, resealing of joints, undersealing, diamond grinding, or retrofit dowel bars; [b]A functional treatment of a PCC pavement is applied with the objective of restoring pavement smoothness to near new condition on a pavement that is structurally sufficient. A PCCP functional treatment may consist of an HMA overlay, or concrete pavement restoration (CPR) to correct functional distresses.

4.4 Reconstruction/Rehabilitation Impacts

Depending on the type of pavement and the level of distress, reconstruction/rehabilitation can have significant impacts in a number of areas, such as costs, time of construction, and maintenance of traffic as well as user delays and associated user costs.

4.4.1 *PCC Reconstruction*

As discussed previously, when a concrete pavement reaches the end of its serviceable life and major rehabilitation efforts, such as joint repair and slab replacement, have become uneconomical, the pavement must be reconstructed. This typically involves either the full-depth removal of the existing concrete pavement or some type of slab fracturing operation followed by the placement of a new concrete or asphalt pavement. From an engineering and performance perspective, these are the most optimal solutions. However, economics – specifically the ability to fund the PCC reconstruction project, along with the disruption to traffic – are generally the driving forces in determining the method that the SHA ultimately selects when addressing a concrete pavement at the end of its serviceable life.

Due to limited funding, as well as considerations for traffic impacts, the most common method that SHAs currently use to address failed PCC pavements is to simply overlay them with asphalt (Table 2), in many cases without any treatment to the underlying PCC pavement. In many instances, SHAs use an asphalt overlay as temporary solution; however, due to the costs of the PCC reconstruction, the overlay remains in place for an excessive period of time. While this is a suitable approach as a temporary solution, it does not address long-term problems associated with the underlying PCC joints and cracks that reflect up through the asphalt overlay, causing the new asphalt overlay to deteriorate prematurely. This cracking develops very early in the life of the overlay, which in turn creates long-standing maintenance problems along with a shortened pavement performance life. In addition, this accelerated deterioration is readily apparent to the traveling public due to the decrease in ride quality, as well as numerous travel delays resulting from maintenance and resurfacing activities – which ultimately increase user costs.

The next most common method used by SHAs to reconstruct a failed PCC pavement is slab fracturing (crack and seating, break and seating, or rubblization) followed by the placement of an asphalt or PCC pavement overlay. While this method is a better engineering alternative than just an asphalt overlay, especially with regard to preventing reflective cracking, there are still a number of significant problems associated with this method that make this a less than desirable solution that should be considered when selecting the initial pavement type. These problems include:

- Construction costs. As shown in Tables 4 and 5, slab fracturing alternatives are significantly greater than costs associated with traditional milling and resurfacing operations on an asphalt pavement.
- Maintenance of traffic during construction. In general, traffic is not allowed on a fractured PCC pavement until it is overlaid. As an example, a rubblized PCC surface is shown in Figure 6. Consequently, this results in longer-term lane closures and traffic delays, or it requires the construction of temporary pavement lanes to handle the traffic. This leads to greater user costs, as well as increased construction costs.

Figure 6. Rubblized PCC Pavement Surface, I-79 West Virginia

- Longer construction duration and user delays. Slab fracturing operations in general are considerably slower than typical milling and resurfacing operations, and as a result, the project is under construction for a longer period of time, which again, results in a greater impact on the traveling public, highway freight movements, and increased user costs.
- Grade and elevation changes. These are probably the most significant types of problems that SHAs face on a slab fracturing project. Once the PCC pavement is properly fractured, it is then overlaid with either an asphalt or PCC pavement. Consequently, the

elevation of the pavement surface increases depending on the thickness of the overlay, and overlay thicknesses from 6 to 10 inches are common on many of these types of projects. This change in elevation creates the following problems:

- Excessive drop-offs at shoulders/edges of pavement (Figure 7). Drop-offs at the edge of pavement or shoulder create serious safety concerns and typically result in the use of fill material on the shoulders to raise the grade. This construction activity can be very costly and results in increased construction time on the project, which then results in a greater impact on the traveling public, freight movements, and increased user costs.

Figure 7. Excessive Drop-Off, I-10 Texas

- Guardrail/barrier wall heights (Figure 8). The increased thickness of the pavement surface results in the height of the guardrail or barrier wall being too low in many instances, which violates safety standards, necessitating its costly and time-consuming replacement.

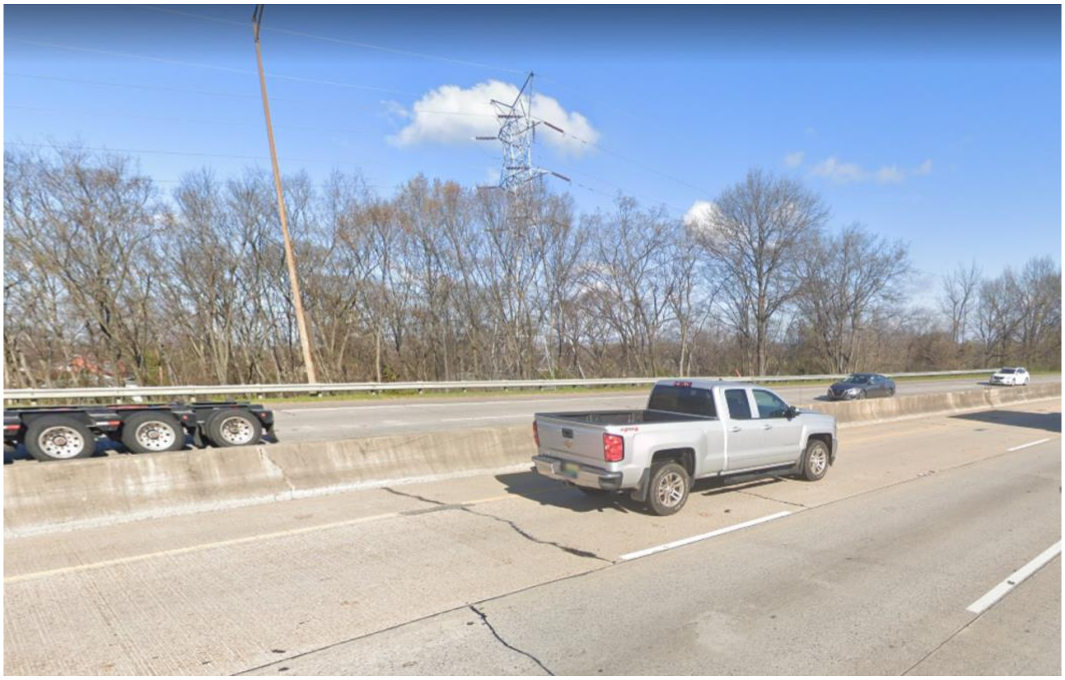

Figure 8. Inadequate Barrier Wall Height, I-85 Georgia

- Clearances under bridges and overpasses (Figure 9). In many locations, raising the elevation of the pavement surface results in inadequate clearances. This results in the need to either completely remove and replace the pavement underneath the structure or to equip it with sensing devices to alert motorists of the low clearance.

Figure 9. Inadequate Bridge Clearance, Location Unknown

- Other impacts (Figure 10). Changes in the elevation of the pavement also creates problems with the surface being at the proper height to tie-in to bridges, drainage structures, curbs, and gutters.

Figure 10. Tie-ins to Curb and Gutter and Drainage Inlets, 1st Avenue, New York City

The other remaining alternative with respect to PCC reconstruction is removal and replacement, which from an engineering perspective is the optimal method of reconstructing a PCC pavement at the end of its serviceable life, as it eliminates many of the issues encountered with overlaying the PCC pavement, such as reflective cracking as well as the negative impacts of grade and elevation changes. However, as shown in Table 5, this method is the most costly alternative and creates significant delays to users. In urban areas, complete removal of a terminal PCC pavement and replacement with either a new concrete or asphalt pavement might be the most appropriate method of reconstruction to avoid having to make other costly adjustments to other elements in the right of way described above, such as bridges, overpasses, barrier walls, and drainage structures. However, the user costs associated with shutting down a roadway for reconstruction, along with the impact on local businesses as well as maintenance of traffic issues, can be overwhelming in urban areas.

4.4.2 *Asphalt Rehabilitation*

The impacts associated with the rehabilitation of an asphalt pavement are significantly less than those encountered with the reconstruction of a PCC pavement. Asphalt pavements rarely need to be fully reconstructed since distresses are typically localized to the upper asphalt layers. As a result, the majority of pavements are either overlaid by an additional thickness of asphalt without milling, or they are milled to an appropriate depth and resurfaced with one or more layers of an asphalt mixture. However, several problems can occur during the rehabilitation of an asphalt pavement, primarily due to drop-offs and operating traffic on a milled surface.

- Drop-offs. Depending on the thickness of the overlay or the milling depth, drop-offs can occur either between lanes or at the edge of pavement. These problems are typically addressed by sequencing the milling and paving operations to minimize drop-offs; by utilizing wedges between lanes; and in extreme cases, placing physical barriers adjacent to the drop-off between lanes during construction.

- Milled surface. Many SHAs have restrictions on allowing traffic on a milled surface. This is due to safety considerations (specifically with motorcyclists); noise complaints; and, in some instances, inadequate underlying pavement thickness or concerns with scabbing. However, if traffic is not allowed on the milled surface, it is quite common that the lane will only be closed for one work shift while it is being milled and resurfaced.

In general, the key impacts associated with pavement reconstruction/rehabilitation, such as costs, time of construction, maintenance of traffic, user delays, and associated user costs are all typically minimized when rehabilitating an asphalt pavement as compared to a concrete pavement.

5 AGENCY EXPERIENCES

A number of factors are involved in determining which method of concrete rehabilitation is the most appropriate for an agency. In some instances, it is related to the budget available or it may be a factor of engineering or traffic considerations. The following agency experiences demonstrate the variety of considerations involved in selecting the most appropriate method of rehabilitation.

5.1 Rubblization

The West Virginia Department of Highways (WVDOH) began routinely using rubblization as a means of addressing deteriorated jointed plain concrete pavements (JPCP) in 2017. Their reasons for choosing rubblization included the following factors:

- A 10-mile section of the West Virginia Turnpike was rubblized in 1989, which had excellent performance.
- Total removal and replacement of the existing concrete with new PCC was considered too expensive and time consuming.
- Construction related delays to the motoring public due to removing the old pavement and replacing with a new concrete pavement were considered unacceptable.
- PCC slab repair and patching were too expensive and time consuming. Traffic flow was difficult to maintain during patching and slab replacement operations. PCC patches didn’t address all of the distresses in the pavement.
- Asphalt overlays without rubblization did not prevent joints and cracks from reflecting through in a relatively short period of time.
- Complete rubblization has proven far more cost-effective than any other PCC pavement rehabilitation method in West Virginia.

In 2017, 20 lane miles of composite pavement on US-119 were programmed to have the old asphalt overlay removed and underlying concrete pavement repaired and diamond ground. Once the underlying concrete was exposed, it was noted by project staff that it was in such poor condition that it could not withstand traffic, even after repairs. The contractor proposed using rubblization and a new asphalt overlay to put the roadway back into service. Edge drains were installed well before the beginning of the process in order to give the subgrade adequate time to drain prior to rubblization. Following rubblization, the surface was overlaid with nine inches of asphalt. Based on the successful completion of this project, WVDOH awarded 12 additional rubblization projects, which were all constructed successfully (Walbeck et al., 2019).

5.2 Crack and Seating

In 1993 and 1994, the Florida Department of Transportation (FDOT) initiated the construction of seven crack-and-seat projects on I-10 in northwest Florida. These were original projects on the Interstate Highway System in Florida constructed between 1974 and 1976. The original pavement on this heavily trafficked highway was a 9-in. plain-jointed PCC pavement with 20-foot joint spacings on a 12-in. cement-treated base. Due to failed seals on the transverse joints, poor drainage, and moisture susceptible subgrade, all of the PCC pavements deteriorated severely with time and by the mid-1980s were in need of major rehabilitation. In 1985, a highly deteriorated 10-year old PCC pavement on I-10 in Jackson County was removed and replaced with asphalt pavement. However, due to the duration of the construction and excessive costs of the project, FDOT opted to utilize crack and seating for the other deteriorating concrete pavements along the corridor at that time. The average age of those PCC pavements was 19 years when they were rehabilitated. On each project, a gravity-type breaker was used to crack the original pavement into 36-in. maximum size pieces. The cracked slabs were seated using a heavy pneumatic tired roller, followed by the placement of an asphalt rubber membrane interlayer, 4 in. of asphalt pavement, and an asphalt open-graded friction course (OGFC) surface mix. All the crack-and-seated sections were retrofitted with edge drains. Follow-up evaluations by FDOT assessed rideability, rutting, cracking, and patching. After seven years, performance was comparable to a traditional asphalt pavement placed on top of a granular base (Choubane et al. 2000). Ensuing crack and seat projects along this same corridor were less successful, primarily due to challenges with adequately cracking the existing slabs. Consequently, a number of these pavements suffered from severe reflection cracking. In the early 2000's, FDOT changed the other I-10 PCC projects to rubblization, however, high subgrade moisture contents resulted in excessive permanent deformations in the subgrade on these early projects, and all subsequent projects were ultimately changed back to crack and seating and the rubblization process was discontinued.

5.3 Asphalt Overlay

When the Virginia Department of Transportation (VDOT) experienced performance problems with their concrete pavements, limited maintenance budgets restricted them to overlaying the pavements with approximately 4 to 5 inches of asphalt pavement with minimal treatment to the PCC. The deteriorated joints and severe cracks in the jointed reinforced PCC pavements reflected through the asphalt pavement within a few years, resulting in ride, cracking, and raveling problems that necessitated resurfacing the pavement approximately every five to six years. In the late 1990s and early 2000s, VDOT began using polymer modified asphalt mixes and then SMA to overlay their existing PCC pavements. These changes increased the life expectancy of their overlays by 8 to 10 years. SMA on conventional projects have a typical life expectancy of 15 to 17 years. It was noted that when SMA was placed on patched CRC pavements, it was not uncommon to get over 20 years of life from the SMA.

5.4 Maximum Restoration of PCC

A successful practice used by the Washington State Department of Transportation (WSDOT) for rehabilitating PCC is to restore the concrete pavement when it nears the end of its serviceable life. WSDOT feels that they have very good performing concrete pavements and believes it is worth the effort to get a few more years of service out of them. Typically, WSDOT PCC restoration includes replacing slabs, repairing spalls, and diamond grinding the surface. This generally provides 8 to 10 years of additional life. After that, they typically crack and seat the PCC followed by an 8- to 9-inch asphalt pavement overlay. Their oldest crack and seat projects with an asphalt overlay are approximately 10 years old and are performing well to date.

5.5 Removal and Replacement

The Pennsylvania Department of Transportation (PennDOT) rehabilitates PCC pavements by a variety of methods. The most common rehabilitation is with an asphalt overlay, generally without any type of concrete pavement restoration. However, there are circumstances where PennDOT requires removal and replacement of the PCC, primarily in situations where there are issues with grade or clearance on bridges and overpasses, or if there are subgrades with very low CBR values. In these situations, the existing PCC pavement is removed and replaced with either an asphalt or another PCC pavement (after grade corrections are made).

5.6 High Performance Asphalt Overlay

In 2013, the New York City Transportation Department rehabilitated 1st Avenue in New York City with a high performance thin overlay. The existing pavement was an 18-inch reinforced concrete pavement that had significantly deteriorated. Potential damage to underground utilities made slab fracturing not feasible, and budget limitations excluded removal and replacement of the PCC. In addition, there were also major concerns with user delays, which limited lane closures. Ultimately, NYCDOT opted to micromill the existing PCC pavement, and then patch and crack seal the more distressed areas as required. They used a PG 76-22 tack coat followed by a fabric interlayer and then placed a 1.5-inch-thick high performing thin overlay mix with a highly modified asphalt binder. The project was completed in September 2013 (Corun, 2015).

6 COST IMPACT EXAMPLES

The cost impact that end of life considerations can have on an LCCA can be demonstrated with the following two examples. It is important to note that these examples are for illustration purposes only, and the costs, discount rates, and performance periods do not represent recommended values. It is essential that each agency determine these values on their own.

Example 1: Impact of calculating terminal values

Project requires the placement of a full-depth asphalt pavement

Analysis Period:	35 Years
Discount Rate:	4.0%
Unit Cost Basis	Per lane mile (12 ft. width)
Est. Asphalt Unit Cost ($/ton):	75.00

Initial Construction (Year 0): Construction of 12.0-in. full-depth asphalt pavement
Initial performance period: 18 years
Cost: $348,500

Rehabilitation 1 (Year 18): Mill 2.0 in. and replace with 2.0-in. asphalt
Rehab-1 performance period: 12 years
Cost: $72,600

Rehabilitation 2 (Year 30): Mill 3.0 in. and replace with 3.0-in. asphalt
Rehab-2 performance period: 12 years
Cost: $108,200

Terminal Value (Year 35): End of analysis period
Note: Since periodic surface renewal is done in response to surface distresses that are confined to the top of the pavement, the bottom 9.0-in. asphalt layer of the initial construction is still intact.

Note: The initial performance period of 18 years is based on findings reported in NCAT Report 18-02 "Review of Initial Service Life Determination in Life Cycle Cost Analysis (LCCA) Procedures and in Practice" (Robbins and Tran, 2018), and was based on an analysis on LTPP data. The rehabilitation performance period of 12 years is based on NCAT Report 19-03 "Best Practices for Determining Life Cycle Costs of Asphalt Pavements" (Gu and Tran, 2019).

Net Present Value (NPV Determinations):

Scenario 1: No terminal/end of life values determined

Activity	Year	Non-Discounted	Discounted (NPV)
Initial construction	0	$348,500	$348,500
Rehabilitation 1	18	$72,600	$35,837
Rehabilitation 2	30	$108,200	$33,360
Terminal	35	0	0
NPV for asphalt pavement			**$417,697**

Scenario 2: RSL for only the last rehabilitation

Activity	Year	Non-Discounted	Discounted (NPV)
Initial construction	0	$348,500	$348,500
Rehabilitation 1	18	$72,600	$35,837
Rehabilitation 2	30	$108,200	$33,360
Terminal (last rehab – RSL 7 years)	35	-$63,117	-$15,995
NPV for asphalt pavement			**$401,703**

Calculations:

$$\text{RSL Value} = -C_{\text{Rehab No.2}} \times \frac{N_{\text{RSL}}}{N_{\text{SL}}} = -\$108{,}200 \text{ x } (7 \text{ years}/12 \text{ years})$$

$$\text{RSL Value} = -\$63{,}117$$

Scenario 3: RSL value for last rehabilitation plus RSL value of original 9.00 in. of asphalt from initial construction

Activity	Year	Non-Discounted	Discounted (NPV)
Initial construction	0	\$348,500	\$348,500
Rehabilitation 1	18	\$72,600	\$35,837
Rehabilitation 2	30	\$108,200	\$33,360
Terminal (last rehab – RSL 7 years)	35	-\$63,117	-\$15,995
Terminal (9” underlying layer)	35	-\$201,972	-\$51,183
NPV for HMA			**\$350,520**

Calculations:

RSL Value for Last Rehabilitation = –\$63,117 (See Scenario 2)

RSL Value for Underlying 9-in. HMA layer: Based on past experiences with similar pavement structures – and using the FDOT Design Procedure to determine the layer coefficient – it is anticipated that the underlying asphalt structure will be in “good” condition with an estimated layer coefficient of 0.34, as compared to the original value of 0.44.

$$\text{RSL Value of Underlying Asphalt Structure} = -C_{OD} \times \frac{a_{EX} \times h_{EX}}{a_{OD} \times h_{OD}}$$

$$\text{RSL Value of Underlying Asphalt Structure} = -\$348{,}500 \times \frac{0.34 \times 9.00}{0.44 \times 12.00}$$

$$\text{RSL Value of Underlying 9-in Asphalt Structure} = -\$201{,}972$$

Summary:

Scenario	NPV	Difference
No terminal/end of life values assigned	\$417,697	-
RSL value for last rehabilitation only	\$401,703	3.8%
RSL value for last rehabilitation plus RSL value of original 8.0 in. HMA layer	\$350,520	16.1%

When considering only the RSL value of the last rehabilitation, the NPV is reduced by 3.8%. However, when considering the RSL value of the underlying asphalt layers in addition to the last rehabilitation, the NPV is reduced by 16.1%.

<u>Example 2</u>: Impact of changing analysis period to include PCC end of life

PCC pavement with an analysis period of 35 years vs. 40 years.

Analysis Period:	35 Years vs. 40 years
Discount Rate:	4.0%
Unit Cost Basis	Per lane mile (12 ft. width)
Est. Rubblization Cost[a]:	\$2.81/sy
Edgedrain Cost[b]:	\$21.26/lf
Est. HMA Unit Cost[c]:	\$75.00/ton

Initial Construction (Year 0): Construction of 12-in. PCC pavement
Initial performance period: 22 years
Cost: \$520,000

Rehabilitation 1 (Year 22): 7.5% CPR (Full-depth joint repairs)
Diamond grinding & seal joints
Rehab-1 performance period: 14 years
Cost: $220,000

Rehabilitation 2 (Year 36): When using a 35-year analysis period, no additional rehabilitation activities are required. When using a 40-year analysis period, the PCC will be rubblized, edgedrain installed, and overlayed with 10.5 in of asphalt at year 36. The asphalt will have a performance period of 15 years.

Note: The initial performance period of 22 years for the PCC pavement is based on values from several reports. NCAT Report 19-06 “Determining Initial Service Life for LCCA using Comparable IRI as one of the Criteria” (Robbins and Tran, 2019) reported an average PCC initial service life of 16 years with a 95% confidence interval of 13 to 19 years. NCAT Report 18-02 “Review of Initial Service Life Determination in Life Cycle Cost Analysis (LCCA) Procedures and in Practice” (Robbins and Tran, 2018) reported an average pavement age of existing PCC pavements in the LTPP program of 23.8 years, which was based on an analysis on LTPP data.

Notes on estimated costs: [a]Rubblization costs are determined from summarized bid data from Antigo Construction, Inc. [b]Edgedrain costs are based on historical averages compiled by the Florida DOT. [c]Estimated HMA costs are based on weighted-average Superpave bid prices compiled for NCAT Report 18-03 “Life-Cycle Cost Benefits of Stone Matrix Asphalt” (Yin and West, 2018).

35 Year Analysis Period			
Activity	**Year**	**Non-Discounted**	**Discounted**
Initial construction	0	$520,000	$520,000
Rehab 1 (7.5% CPR, diamond grind)	22	$220,000	$92,830
Terminal value (RSL 1 year)	35	-$15,714	-$3,982
NPV			**$608,848**

Calculations:

$$\text{RSL Value} = -\,C_{\text{Last Activity}} \times \frac{N_{\text{RSL}}}{N_{\text{SL}}} = -\$220{,}000 \text{ x } (1 \text{ years}/14 \text{ years})$$

$$\text{RSL Value} = -\$15{,}714$$

40 Year Analysis Period			
Activity	**Year**	**Non-Discounted**	**Discounted**
Initial Construction	0	$520,000	$520,000
Rehab 1 (7.5% CPR, diamond grind)	22	$220,000	$92,830
Rubblization/edgedrain	36	$132,035	$32,173
Overlay with 10.5-in HMA	36	$304,920	$74,299
Terminal value (RSL 11 years)	40	-$223,608	-$46,575
NPV			**$672,727**

Rubblization and Edgedrain Costs:

Rubblization:	\$2.81/sy x 7040 sy/lane mile = \$19,782;
Edgedrain:	\$21.26/lf x 5280 lf/lane mile = \$112,253;
Total Cost:	\$132,035

Year 36 Asphalt Quantity: (7040 sy x 1155 lbs/sy)/(2000 lbs/ton) = 4,066 tons

Asphalt Cost = 4,066 tons x \$75.00/ton = \$304,920

$\text{RSL Value} = -C_{\text{Last Activity}} \times \frac{N_{RSL}}{N_{SL}}$ = –\$304,920 x (11 years/15 years) = –\$223,608

Summary:

Condition	NPV	Difference
35-year analysis period	\$608,848	-
40-year analysis period	\$672,727	10.5%

Using a longer analysis period that encompasses the end of life of the PCC pavement results in an increased NPV of approximately \$65,000 per lane mile, or a 10.5% increase.

7 SUMMARY AND RECOMMENDATIONS

LCCAs are used by many SHAs to evaluate the overall costs of pavement investment alternatives, primarily between asphalt and concrete pavement designs. Although an LCCA is intended to provide an objective way to compare alternatives, the outcome is highly dependent on realistic inputs and assumptions. Identifying future rehabilitation costs for the pavement alternatives can be challenging. It is just as important to consider an appropriate analysis period for the analysis and the probability of having to reconstruct one or both pavement alternatives and how that should be factored in the LCCA. Properly considering pavement terminal life values is critical to a fair LCCA. Issues that occur at the end of life for pavements include the following:

- Asphalt pavements are rarely fully reconstructed due to structural failures; they are typically rehabilitated indefinitely by milling an appropriate depth and overlaying with an asphalt mixture. These milling and resurfacing operations can be accomplished relatively quickly causing minimal disruptions of traffic.
- The analysis period for an LCCA should be long enough such that the original concrete pavement alternative reaches its terminal serviceability and must be reconstructed.
- PCC pavements require significantly higher costs at the end their service life. Although the most common method of rehabilitation for concrete pavements is an asphalt overlay, this is not an effective choice due to the certainty that the asphalt overlay will have to be frequently replaced due to reflection cracking and other distresses originating from the underlying concrete. In many instances, SHAs use an asphalt overlay as temporary solution; however, due to the costs of the PCC reconstruction, the overlay remains in place for an excessive period of time.
- Removal and replacement of PCC pavements is very costly to the agency and the traveling public. In urban areas, complete removal of a terminal PCC pavement and replacement with either a new concrete pavement or asphalt pavement may be necessary to avoid having to make other costly adjustments to other elements in the

right of way such as bridges, overpasses, barrier walls, and drainage structures. However, the user delays and associated user costs associated with shutting down a roadway for reconstruction can be overwhelming in urban areas.

- In general, the key impacts associated with pavement reconstruction/rehabilitation, such as costs, time of construction, maintenance of traffic, user delays, and associated user costs are all typically minimized when rehabilitating an asphalt pavement as compared to a concrete pavement.
- The value of the remaining service life of the pavement alternatives at the end of the analysis period should be included in an LCCA and should include the RSL of the last rehabilitation and the RSL of the underlying layers. This approach also provides a method that agencies can utilize to test the potential economy of a perpetual pavement option.

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