NCAT Report 19-03

BEST PRACTICES FOR DETERMINING LIFE CYCLE COSTS OF ASPHALT PAVEMENTS

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1 INTRODUCTION

State highway agencies (SHAs) continually face important financial decisions when planning a new or reconstructed highway. For example, what is the initial investment for the highway? How much is needed periodically to maintain the highway in good pavement condition? What materials should be used to build the pavement? The answers to these questions may require a life cycle cost analysis (LCCA) based on the time value of money concept to assist in the final decision.

To help SHAs and other agencies conduct such an analysis, this report provides best practices for properly determining inputs for use in their LCCA procedures and calculating the life cycle costs of pavement alternatives. The report is of immediate interest to engineers in SHAs, consulting firms, and the paving industry with responsibility for conducting LCCA as part of the pavement type selection process.

1.1 Life Cycle Cost Analysis

LCCA is often used by SHAs to evaluate the overall long-term costs of investment alternatives. It considers anticipated costs over the life of each pavement alternative and is considered as a fair and balanced process for identifying the best long-term value among pavement alternatives.

SHAs use LCCA to choose the most cost-effective project alternatives, especially when planning new or reconstructed roadways. When SHAs conduct LCCA for pavement type selection, many of the common costs associated with construction and maintenance of competing pavement structures are excluded, such as building the bridges, drainage structures, signs and signals. Therefore, the LCCA for pavement type selection currently only includes costs that are unique to each pavement structure, including initial construction costs, anticipated costs for future maintenance and rehabilitation, user costs, and terminal value for each pavement alternative, as illustrated in Figure 1. Terminal value is defined as the value of an alternative at the end of the analysis period, which can be its remaining service life value or salvage value.

To enable a fair comparison among pavement alternatives, future anticipated costs, such as maintenance and rehabilitation costs and user costs, are first “discounted” to the present to account for the time value of money. If a pavement alternative has any value remaining at the end of the analysis period, a terminal value is also discounted back to its present value. The net present value (NPV) of initial construction, discounted future costs and discounted terminal value is then determined for each alternative using the common economics formula shown in Equation 1. Finally, the pavement alternative(s) with the lowest life cycle cost (i.e., NPV) is typically the preferred alternative(s) when life cycle costs between alternatives differ greater than a set value (e.g., 10 percent). In some situations, multiple pavement structures are designed and evaluated. In addition to LCCA, SHAs may also consider other project factors in the final pavement type selection that are not easily quantified in an economic analysis, especially when life cycle costs between the considered alternatives differ less than the set value.

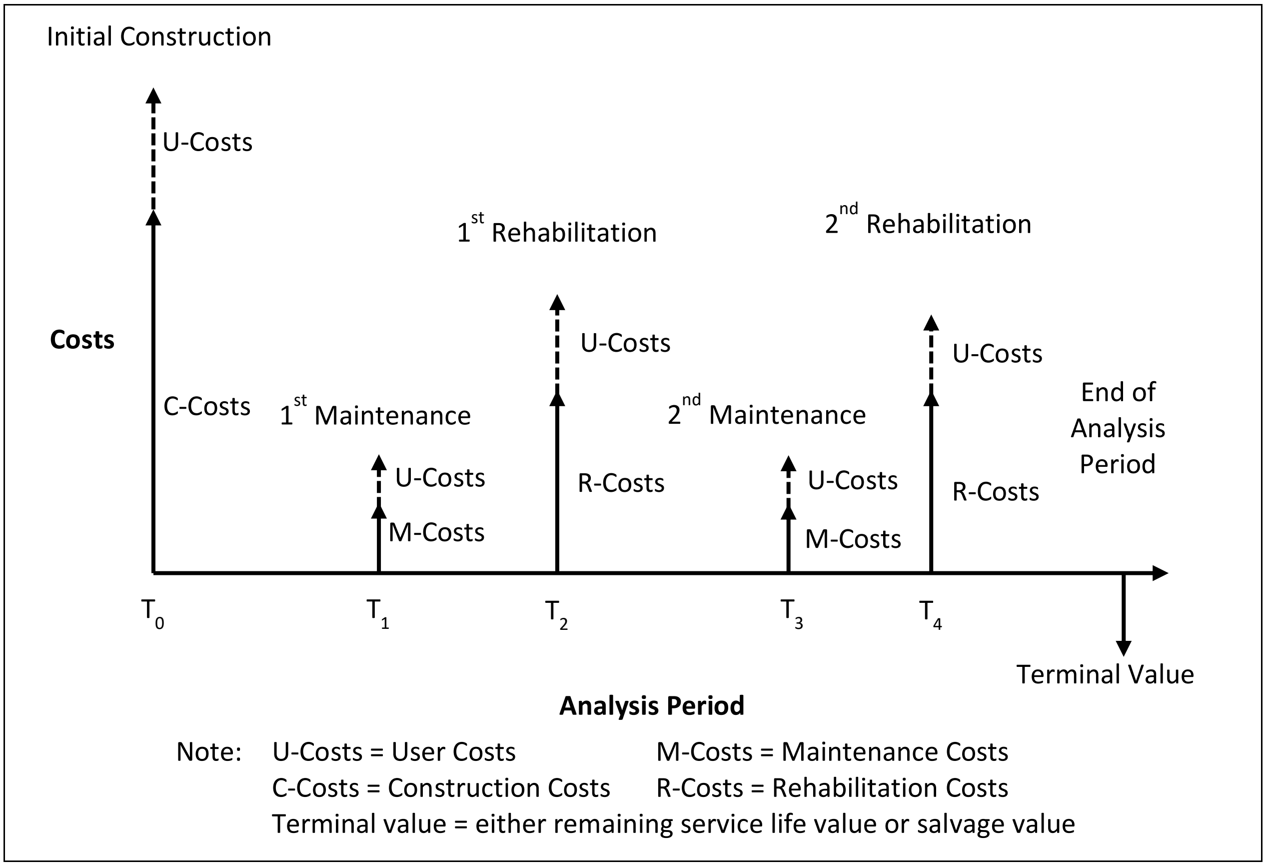

Figure 1. Life Cycle Cost Analysis Diagram for a Paving Project

$$NPV = Initial\ Const.\ Cost + \sum_{k=1}^{N} Future\ Cost_k \left[\frac{1}{(1+i)^{n_k}}\right] - Terminal\ Value \left[\frac{1}{(1+i)^{n_e}}\right] \quad (1)$$

where

- N = future costs incurred over analysis period;
- i = discount rate, percent;
- n_k = number of years from initial construction to the k^{th} expenditure; and
- n_e = analysis period, year.

Currently, there are two computation approaches to conducting a LCCA: deterministic and probabilistic methods. The deterministic approach assigns a fixed and discrete value to each LCCA input variable. In the probabilistic method, the value of each LCCA input can be variable and defined by a probability distribution. The probabilistic LCCA accounts for uncertainty and variation in input variables, but the deterministic LCCA is much easier to perform and compare its results.

The calculation and comparison of NPVs is straightforward in LCCA; however, the determination of the inputs can be challenging, especially estimating the future costs of maintenance and rehabilitation activities, their timing, and their corresponding user costs identified within each pavement alternative's life span. Thus, there is a need to develop some guidance on how each of these inputs can be properly determined for use in the LCCA.

1.2 Objective

The objective of this document is to provide best practices to help SHAs properly determine inputs for use in their LCCA procedures and to calculate the life cycle costs of pavement alternatives.

1.3 Organization of Best Practices Manual

This manual includes five sections, as follows:

1. The introduction that discusses the need and objective of this manual;
2. An overview of LCCA for pavement type selection in the United States;
3. Best practices for determining each of the critical inputs to calculate the life cycle cost of asphalt pavement;
4. An example to illustrate the impact of each input on the life cycle cost, with detailed information being included in Appendix A; and
5. A summary of the key findings and recommendations.

This manual is prepared based on a literature search of reports from previous studies on life cycle cost analysis and surveys of SHAs on current LCCA practices previously conducted by the American Association of State Highway and Transportation Officials (AASHTO), SHAs, and research organizations. This information was verified or updated based a review of state LCCA practices available online or through assistance from some of the Federal Highway Administration (FHWA) division offices. Additional pavement performance and cost data from SHAs are used as examples to illustrate the best practices for determining the inputs discussed in this manual.

2 LIFE CYCLE COST ANALYSIS FOR PAVEMENT TYPE SELECTION IN THE UNITED STATES

In the United States, the concept of LCCA was first mentioned in the "Red Book" published by the American Association of State Highway Officials (AASHO) in 1960 (*AASHO, 1960*). It was developed as a tool to help AASHO members make investment decisions on pavement projects based on their projected economic cost and predicted performance. These LCCA concepts were expanded and included in subsequent editions of the *AASHTO Guide for Design of Pavement Structures*. FHWA continues recommending LCCA as an important reference when making investment decisions. These SHAs incorporated AASHTO's LCCA policies and recommendations into their pavement design and selection manuals, making various local adaptations using performance data from their pavement management systems and costs determined from previously built projects, among other factors.

Based on the state standard manuals for pavement design and selection reviewed when developing this guidance document and the information gathered from surveys presented in NCHRP Synthesis 494 (*Flannery et al., 2016*) and through the assistance of some of the FHWA division offices in this study, it was found that 42 out of 50 states and the District of Columbia have procedures for conducting LCCAs, as shown in Figure 2.

In addition, while the LCCA for pavement type selection and investment decision making processes is based on NPV, methods for determining inputs to calculate NPV vary from one state to another. The length of analysis and performance periods, calculation of future costs, and inclusion of user costs and terminal value in the LCCA are among the factors varied by SHAs based on their own economic needs, assumptions, past experiences, and historical data. Advancements and new developments in asphalt pavement technologies such as new mixture design methods, use of polymer modified binders, and more efficient mixing, placement, and compaction technologies can also affect multiple inputs for LCCA. Due to these differences, inputs for conducting LCCA are not determined the same across the country.

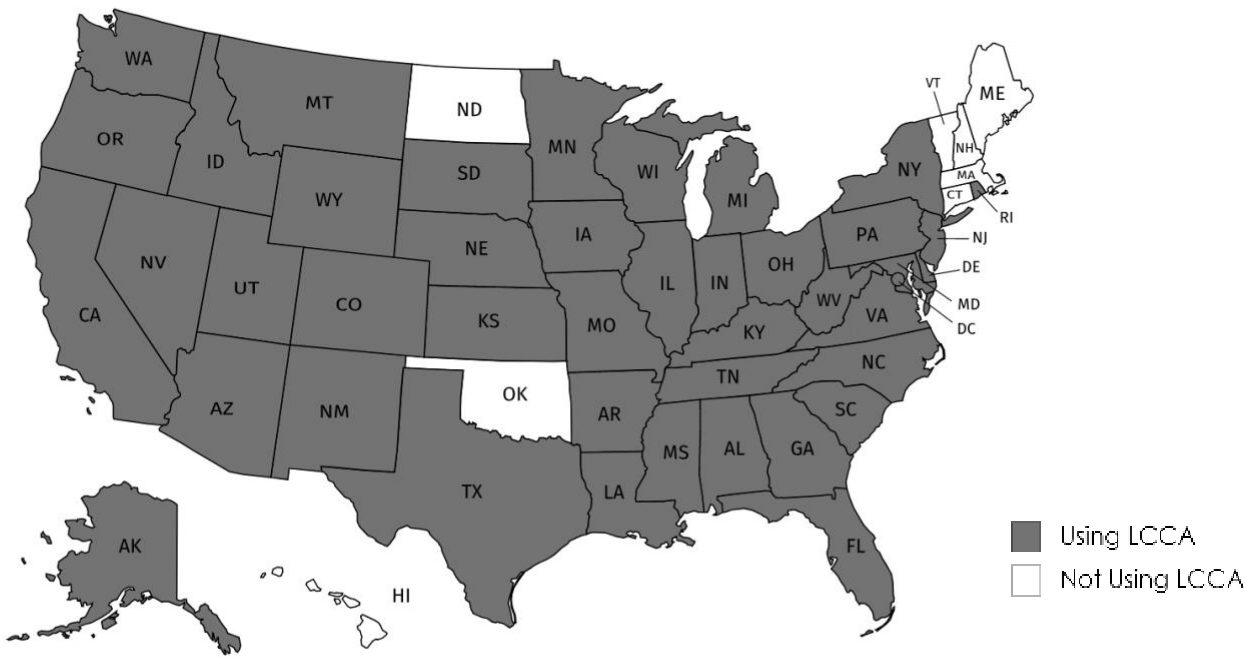

Figure 2. Use of LCCA for Pavement Type Selection in the U.S. by State

3 BEST PRACTICES FOR DETERMINING LCCA INPUTS FOR ASPHALT PAVEMENTS

This section provides best practices for determining the critical inputs to calculate the life cycle cost of asphalt pavement. Each subsection discusses an input, starting with a brief definition, followed by state of practice, best practices, and an example for determining each input.

3.1 Analysis Period

Analysis period is the length of time, in years, over which the alternatives are evaluated in an LCCA. It is one of the most important parameters in the determination of the life cycle cost of each pavement. FHWA recommends that the analysis period used in LCCA be long enough to capture several maintenance and rehabilitation cycles of the alternatives. However, each alternative does not need to have the same number of maintenance or rehabilitation activities during the analysis period (*FHWA, 2002*). In addition, depending on the condition and age of the facility, the analysis period may include reconstruction of the facility (*FHWA, 1996*). However, the analysis period should not be too long to reduce uncertainties in the determination of LCCA inputs for future activities (*FHWA, 2002*).

Based on a recent review of LCCA procedures, 23 SHAs specify a single analysis period while the remaining nine SHAs provide a range of analysis periods depending on factors such as pavement type and roadway classification. The state of Kansas, for example, requires LCCAs to be conducted with an analysis period of 40 years, while the analysis period in a LCCA in the state of Nevada could range from 25 to 40 years depending on the highway classification. Figure 3 shows analysis periods (or the longest analysis periods) provided in the LCCA procedures from the 42 states with the Minnesota Department of Transportation (MnDOT) specifying 35-year analysis period when traffic is less than 7 million equivalent single axle loads (ESALs), and 50-year analysis period when traffic is greater than 7 million ESALs. As presented, most states use an analysis period of 40 years or greater. The mean, median and mode of the analysis periods used by SHAs are 39.2 years, 40 years, and 40 years, respectively.

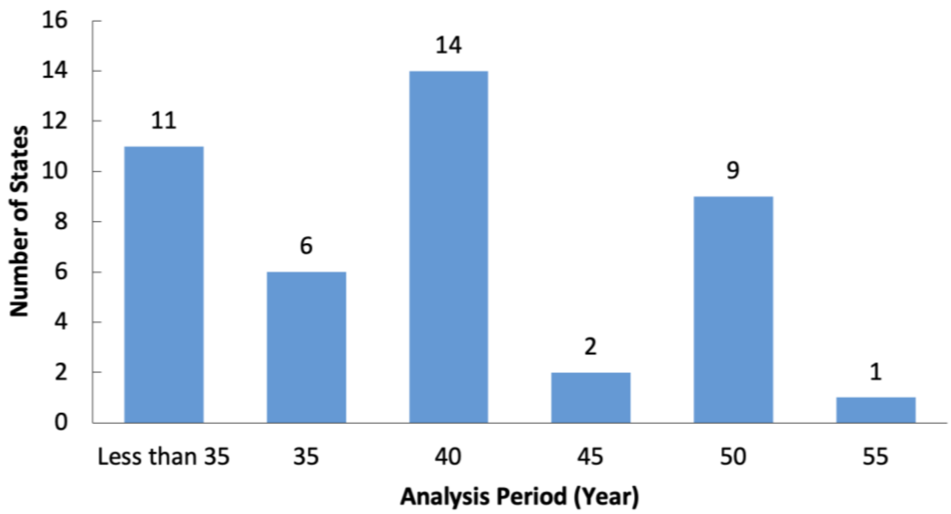

Figure 3. Analysis Period Suggested by States from SHA Pavement Selection Manuals

One best practice for determining the analysis period is to set it long enough to account for one major rehabilitation or reconstruction of at least one pavement alternative but to avoid longer time periods, which increase uncertainties with predicting the future inputs. The following example illustrates how this method was utilized to determine the analysis period in a previous study by West et al. (2013).

For interstate highways and major freight corridors for which LCCA is primarily used, concrete pavements eventually reach their terminal service life and are often removed and replaced with new pavements. Data from several states in the southeast show that the average age of concrete pavements is less than 35 years, as briefly described below (*West et al., 2013*).

- In Alabama, 134 miles of concrete pavement on 24 interstate projects have been reconstructed by rubblization or "break and seat" since 1995 because it was no longer feasible to maintain these concrete pavements. The average age of the pavements at the time they were reconstructed was 32 years.
- In Louisiana, 161 miles of concrete on interstates were rubblized from 1998 to 2010 (*Rauhut et al., 2000*). The Louisiana Department of Transportation and Development's

(LaDOTD) pavement management database indicates that the average age of the concrete pavements at the time they were rubblized was 33.9 years.

- The Florida Department of Transportation (FDOT) rubblized 47 miles of concrete pavements on I-10 in the Florida panhandle between 1999 and 2001. The average age of those rubblized concrete pavements was 28.2 years (*Taylor, 2012*).
- The Kentucky Transportation Cabinet (KYTC) reported that the average age of concrete pavements when they were demolished and overlayed with asphalt using the "break and seat" method was 25.5 years (*KYTC, 2006*).

In these southeast states, an analysis period of 35 or 40 years can be selected to include multiple maintenance and major rehabilitation activities for both asphalt and concrete pavements in these states. The same selected analysis period should be used for each alternative in the LCCA.

3.2 Performance Periods

Performance periods are the average time span in years for a newly constructed or rehabilitated pavement to reach the agency's threshold for maintenance or rehabilitation. The performance period for a new pavement includes the initial performance period, and the maintenance or rehabilitation performance period after the first maintenance or rehabilitation. The initial performance period is usually longer than the maintenance/rehabilitation performance period. The maintenance/rehabilitation performance period is dependent on specific maintenance and rehabilitation strategies planned for each pavement alternative. If a pavement alternative is maintained and/or rehabilitated using the same strategy during the analysis period, the same maintenance/rehabilitation performance period can be used in the LCCA. These performance periods directly influence the frequency of agency intervention on pavements, which further affect the agency costs (e.g., maintenance and rehabilitation costs) and user costs in the LCCA.

FHWA guidelines recommend that SHAs determine performance periods for different pavement strategies through analysis of state pavement management system (PMS) data and historical experience, which may be supplemented with national, regional, or local sources (*FHWA, 2002; Walls and Smith, 1998*). Table 1 summarizes performance periods of asphalt pavements determined by distress type using the Long-Term Pavement Performance (LTPP) nationwide data (*Von Quintus et al., 2005*). These performance periods represent the average life expectancies of interstate highways and other U.S. highways and state routes in the LTPP database.

Table 2 presents the performance periods being used by SHAs from a national survey (*West et al., 2013*). The mean, median and mode of initial performance period for asphalt pavements is 14.9 years, 15 years, and 20 years, respectively, and the mean, median, and mode of maintenance/rehabilitation performance period is 11.8 years, 11.5 years and 10 years, respectively.

Table 1. Performance Periods of Asphalt Pavements based on LTPP Data (*Von Quintus et al., 2005*)

Distress Type	Initial Performance Period		Main./Rehab. Performance Period
	Interstate Highways	U.S. Highways and State Routes	Paved Roadways
Fatigue cracking	22	25	14
Transverse cracking	19	22	10
Longitudinal cracking in wheel path	22	28	15
Longitudinal cracking outside wheel path	18	22	13
Rutting	17	22	13
International Roughness Index	20	22	13

Table 2. Asphalt Pavement Performance Periods Used by State Highway Agencies

State	Perform. Periods (yrs.)		State	Perform. Periods (yrs.)	
	Initial	Main./Rehab.		Initial	Main./Rehab.
Alabama	12	8	Montana	15	12
Alaska	15	15	Nevada	20	20
Arizona	15	5	New Jersey	15	15
Arkansas	12	8	New Mexico	12	8
California	20	5	New York	12	8
Delaware	12	8	Nebraska	20	15
Florida	14	14	North Carolina	10	10
Georgia	10	10	Ohio	12	10
Idaho	12	12	Oregon	20	20
Illinois	20	20	Pennsylvania	10	10
Indiana	20	15	Rhode Island	20	11
Iowa	20	N/A	South Carolina	12	10
Kansas	10	10	South Dakota	16	16
Kentucky	10	10	Tennessee	10	10
Louisiana	15	15	Texas	10-12	10-12
Maryland	15	12	Utah	10	10
Massachusetts	18	16	Virginia	12	10
Michigan	13	13	Washington	15	15
Minn < 7 MESALs	20	15	West Virginia	22	4
Minn > 7 MESALs	15	12	Wisconsin	18	12
Mississippi	12	10	Wyoming	20	15
Missouri	20	13			

For some states, the performance periods used in their LCCA procedures were determined based on historical experience from decades ago and did not account for more recent improvements in asphalt material and pavement technologies or implementation of new specifications. For example, the use of polymer modified asphalt binders and stone matrix asphalt mixtures significantly improve the long-term performance of pavement when compared to unmodified asphalt mixtures. An analysis of more recent pavement performance data from the Alabama Department of Transportation indicated an average maintenance/rehabilitation performance period was extended from 8 years to 13.4 years for asphalt overlays due to the emerging asphalt technologies (*West et al., 2013*). Thus, SHAs need to review their PMS data periodically to make sure the performance periods used in LCCA reflect actual pavement performance and do not fall behind continuous advancements made in specifications and construction methods.

3.3 Agency Initial Construction Costs and Future Maintenance and Rehabilitation Costs

Agency costs include costs associated with the pavement alternatives incurred by the agency over the analysis period. They typically include initial construction costs, subsequent maintenance costs, rehabilitation design and construction costs during the analysis period. Walls and Smith (1998) suggested that LCCA need only consider differential costs between alternatives. Thus, the costs common to the alternatives, such as silt fence, drainage structures, and seeding, are often excluded from LCCA calculations. A brief discussion of each cost item follows.

- Initial construction costs are determined based on the quantities and unit prices of materials at the time of new construction. Initial construction quantities are dependent on the design of the new pavement, while initial material unit prices may vary based on the construction quantities and project location.
- Future activities costs depend on the quantities in the maintenance and rehabilitation activities and the future material unit prices. The maintenance activities are often scheduled based on regional/state pavement management data and historical experience. The maintenance/rehabilitation activity timings are determined on the basis of the recommended initial and maintenance/rehabilitation performance periods.
- The unit prices of initial construction and future activities are determined at the time of conducting LCCA, and they are kept constant throughout the analysis period. The escalation in future prices is accounted in a real discount rate, which is utilized to discount the future costs to its present values.
- Most agencies exclude the administrative costs, such as expenses for public hearings, informational meetings and permits, from LCCA since the differential of these costs is not significant, and when discounted over the analysis period, tends to have little effect on LCCA results.

After reviewing LCCA procedures in the pavement design manuals of various SHAs, it was found that not all SHAs specified a method for determining unit prices of construction materials for use in LCCA. Very few states conducted a thorough analysis of historical construction cost data and published their analysis results periodically or annually.

A best practice for determining the unit prices of construction materials for use in LCCA is to analyze the cost data available from a state's construction projects in the last few years (e.g., last five years). Cost indices can be used to normalize cost data from the earlier years to the most recent year. Using multiple-year cost data would yield a more stable trend for long-term LCCA while considering recent economic conditions. This analysis can be updated annually or periodically to show most recent prices.

An example of such analysis is a study conducted by the Colorado Department of Transportation (CDOT) to determine the unit prices for conducting LCCA (*Perkins, 2015*). In this analysis, the cost of maintenance and rehabilitation methods used on interstates, state highway, and principal arterials from 2009 through 2014 were compiled and analyzed. Cost data from prior years were normalized to 2014 prices using the Colorado Construction Cost Index. The data were then divided into smaller data sets based on project size and category. Tables 4, 5, and 6 show example cost data and results determined from this analysis for full depth reclamation projects and asphalt mill-and-fill projects with less than 10,000 tons of mixture and greater than 10,000 tons of mixture, respectively.

Table 3. Unit Prices for Full Depth Reclamation Projects (*Perkins, 2015*)

Description	Amount
Number of projects	22
Total square yards	2,033,398
Total normalized dollar amount	$3,992,506
Normalized average per square yard	$1.80

Table 4. Mill-and-Fill Unit Prices for Projects with Less Than 10,000 Tons (*Perkins, 2015*)

Mixture Type	Description	Amount
Mixtures Selected	Number of projects	51
	Total tons	212,732
	Total normalized dollar amount	$16,296,645
	Normalized average per ton	$76.61
PG 64-22	Number of projects	15
	Total tons	28,333
	Total normalized dollar amount	$2,418,438
	Normalized average per ton	$85.36
PG 58-28	Number of projects	7
	Total tons	21,216
	Total normalized dollar amount	2,730,082
	Normalized average per ton	$128.68
PG 76-28	Number of projects	17
	Total tons	110,791
	Total normalized dollar amount	$7,000,711
	Normalized average per ton	$63.18

Table 5. Mill-and-Fill Unit Prices for Projects with More Than 10,000 Tons (*Perkins, 2015*)

Mixture Type	Description	Amount
Mixtures Selected	Number of projects	63
	Total tons	1,751,060
	Total normalized dollar amount	$127,667,932
	Normalized average per ton	$72.56
PG 58-34	Number of projects	4
	Total tons	95,697
	Total normalized dollar amount	$8,251,056
	Normalized average per ton	$86.22
PG 64-22	Number of projects	5
	Total tons	136,753
	Total normalized dollar amount	$9,562,261
	Normalized average per ton	$69.92
PG 58-28	Number of projects	21
	Total tons	688,657
	Total normalized dollar amount	$48,738,394
	Normalized average per ton	$70.77
PG 76-28	Number of projects	10
	Total tons	207,138
	Total normalized dollar amount	$12,558,276
	Normalized average per ton	$60.63
SMA	Number of projects	13
	Total tons	345,467
	Total normalized dollar amount	$30,229,383
	Normalized average per ton	$87.50

3.4 Terminal Value

Terminal value represents the expected worth of a pavement alternative at the end of the analysis period. It is comprised of two mutually exclusive components: remaining service life (RSL) value and salvage value. RSL value represents the residual value of a pavement alternative when its service life extends beyond the end of the analysis period. Salvage value is the net value determined from reusing or recycling materials removed from a pavement alternative at the end of its life if it occurs before or at the end of the analysis period.

3.4.1 Current Practice for Determining Terminal Value

The current practice assumes that the differential salvage value between pavement alternatives is generally not significant and tends to have a negligible effect on LCCA results over the analysis period. Compared to the salvage value, the RSL value is considered as the more substantial component for terminal value. Accordingly, the current practice only accounts for the RSL value as the terminal value of a pavement alternative. In addition, most SHAs only account for the RSL value of the last maintenance or rehabilitation activity.

Since pavement alternatives usually have different maintenance and rehabilitation strategies and service lives, their RSLs are not the same at the end of the analysis period. Equation 2 shows how the RSL value is calculated based on the current practice as the cost of the last maintenance or rehabilitation activity multiplied by the ratio of the RSL of the activity over its total service life.

$$RSL\ Value = C_{Last\ Activity} \times \frac{N_{RSL}}{N_{SL}} \tag{2}$$

where

$C_{Last\ Activity}$ = cost of last maintenance or rehabilitation activity;
N_{RSL} = remaining service life of last maintenance or rehabilitation activity; and
N_{SL} = total service life of last maintenance or rehabilitation activity.

Since the current practice considers the RSL value of the pavement layers that are last maintained or rehabilitated prior to the end of the analysis period, only the RSL value of the last overlay or mill/inlay is typically considered for asphalt pavement alternatives even though the underlying asphalt layers still have remaining service life (while concrete pavement alternatives are typically removed and replaced or slab fractured at the end of the analysis period). To address this, the following section describes an approach to considering the RSL value of the underlying asphalt layers, which are not part of the last maintenance or rehabilitation, at the end of the analysis period.

3.4.2 RSL Value of Underlying Pavement Layers Not Part of Last Intervention

While the current practice (Equation 2) can be utilized to determine the RSL value of the surface layers that are maintained or rehabilitated right before the end of the analysis period, it cannot be used to calculate the RSL value of the underlying layers from the original construction or from a prior maintenance/rehabilitation activity. For long-life asphalt pavements (*Tran et al., 2015*), the underlying layers are often structurally sound and are rarely removed and replaced at the end of the analysis period. In these cases, the RSL value of the underlying layers can be determined based on their remaining structural capacity or structural number when compared to the original design or prior maintenance/rehabilitation structure.

One approach is to compare the historical structural capacity or structural number of asphalt pavements determined based on non-destructive testing such as the Falling Weight Deflectometer (FWD) to determine how their structural capacity or structural number changes overtime. Another approach is to determine the RSL value using layer coefficients recommended based on existing pavement conditions. As an example, Table 6 shows the layer coefficients recommended for three asphalt mixture types by the Florida Department of Transportation (FDOT). An asphalt pavement that is in a fair condition at the end of the analysis period may have layer coefficients of 0.25 and 0.20 for its SP-12.5 mix and binder mix layers, respectively. Similarly, Chapter 5 of the *1993 AASHTO Guide for the Design of Pavement Structures* recommends layer coefficients based on the visual condition of the pavement. Both approaches can be utilized to determine the remaining structural capacity/number of an asphalt pavement at the end of the analysis period.

Table 6. Layer Coefficients of Existing Asphalt Pavements (*FDOT, 2016*)

Asphalt Mixture Type	Original Design	Pavement Condition		
		Good[c]	Fair[d]	Poor[e]
FC-12.5[a]	0.44	0.34	0.25	0.15
SP-12.5[b]	0.44	0.34	0.25	0.15
Binder mixture	0.30	0.25	0.20	0.15

Note: [a]FC: Friction Course; [b]SP: Superpave Mixture; [c]Good: No Cracking and Minor Rutting; [d]Fair: Moderate Cracking and Minor Rutting; [e]Poor: Severe Cracking and Severe Rutting;

Based on the remaining structural number, the RSL value of the underlying asphalt layers can be calculated using Equation 3 as the cost of the underlying layers in the original design or a prior maintenance/rehabilitation activity multiplied by the ratio of the structural number of the underlying layers in the existing asphalt structure over their structural number in the original design or prior maintenance/rehabilitation. An example of this calculation is shown in Table B11 of Appendix B.

$$RSL\ Value\ of\ Underlying\ Asphalt\ Structure = C_{OD} \times \frac{SN_{Ex}}{SN_{OD}} = C_{OD} \times \frac{a_{Ex} \times h_{Ex}}{a_{OD} \times h_{OD}} \quad (3)$$

where

C_{OD} = cost of the underlying layers in the original design or prior maintenance/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/rehabilitation structure;
a_{Es} = 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/rehabilitation.

3.4.3 Salvage Values of Asphalt and Concrete Pavement Alternatives

Most asphalt pavements have not been removed and replaced since initial construction. These pavements have been rehabilitated and continue to perform. Therefore, they should not be considered for removal and replacement at the end of the analysis period in a LCCA. However, if reconstruction is included for an asphalt pavement alternative, its salvage value should be determined. Asphalt and concrete pavement materials removed from old pavement structures have significantly different salvage values. Figure 4 show estimated salvage values of reclaimed asphalt pavement (RAP) and recycled concrete aggregate (RCA). While RCA is often recycled as aggregate base or as part of a stabilized sub-base layer, RAP is reused in new asphalt mixtures, and the recycled asphalt binder can be fully or partially counted towards the total asphalt binder available in the new mixtures. Thus, as illustrated in Figure 4, the estimated salvage value of RAP is \$25.1 per ton, which is three times higher than that of RCA. The unit costs of these materials were recommended by material suppliers for this estimate and they may change in the future.

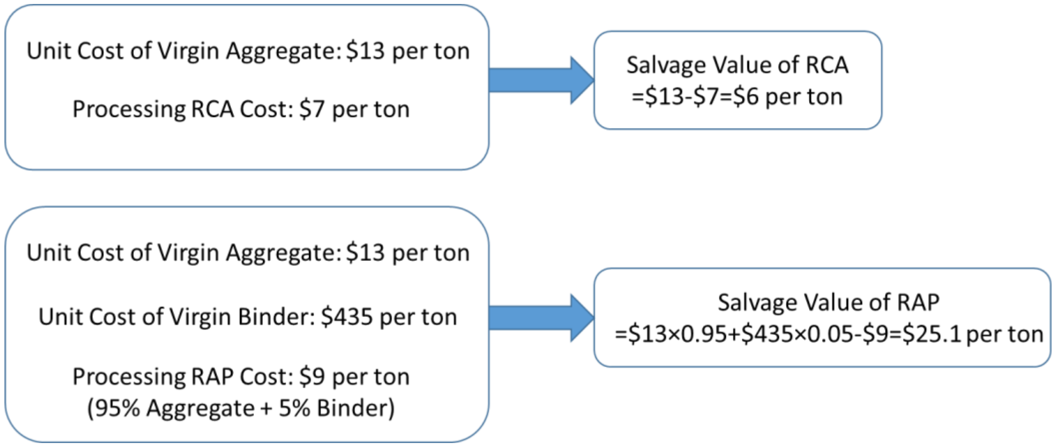

Figure 4. Estimated Salvage Values of RAP and RAC Materials

In summary, terminal value is the expected worth of a pavement alternative at the end of the analysis period. It can be either RSL value or salvage value. In the current practice, RSL value represents the residual value of an improvement when its service life extends beyond the end of the analysis period. Accordingly, the RSL value for asphalt pavements only accounts for the residual value of the last resurfacing activity. A better approach to determining the RSL value for asphalt pavements is to consider the remaining service life of both the last rehabilitated layers and the underlying asphalt layers that are still in place, as discussed in this section. In cases asphalt pavement alternatives are removed and replaced at the end of the analysis period, the salvage value should consider the differential worth of RAP and RCA materials.

3.5 Discount Rate

The discount rate accounts for the time-value growth of money. When performing a LCCA, a discount rate is used to calculate the present value of future costs and returns. A cost or return in the future is worth less to the owner agency today than in the year the activity occurs. In essence, the discount rate is an interest rate in reverse. Discount rate selection is a critical process in LCCA, because it directly impacts the total estimated cost of each alternative.

Discount rates can be reflected in real or nominal terms. The real discount rates reflect the true time value of money with no inflation premium, while the nominal discount rates consider the inflation of future investments. Walls and Smith (1998) suggested that LCCA should be conducted using real discount rates, eliminating the need to estimate and include an inflation premium for both costs and discount rates. The Office of Management and Budget (OMB) has recommended a real interest rate annually in OMB Circular A-94, which is used to represent an estimate of the average rate of return on private investment before taxes and after inflation (*OMB, 2018*).

Discount rates can significantly influence the LCCA results. Therefore, the selection of a real discount rate should reflect the historical trends over long periods of time. Table 8 shows the discount rates used by the SHAs according to a national survey in 2010 (*West et al., 2013*). As shown in Table 8, most states have a real discount rate in the 3.0 to 4.0 percent range, and very few states are under 3.0 percent or over 4.4 percent.

Table 8. Discount Rates Used by State Highway Agencies

State	Discount Rate, %	State	Discount Rate, %
Alabama	4.0	Missouri	Current OMB rate
Alaska	N/A	Montana	Current OMB rate
Arizona	4.0	Nevada	10-year moving average
Arkansas	3.8	New Jersey	4.0
California	4.0	New Mexico	10-year moving average
Colorado	10-year moving average	New York	3.0
Delaware	3.0	Nebraska	3.0
Florida	4.0	North Carolina	4.0
Georgia	4.0	Ohio	Current OMB rate
Idaho	4.0	Oregon	4.0
Illinois	3.0	Pennsylvania	5-year moving average
Indiana	4.0	Rhode Island	5-year moving average
Iowa	3.0	South Dakota	4.4
Kansas	Current OMB rate	Tennessee	3.5
Kentucky	4.0	Texas	10-year moving average
Louisiana	4.0	Utah	4.0
Maine	4.0	Virginia	4.0
Maryland	4.0	Washington	4.0
Michigan	Current OMB rate	West Virginia	4.0-10.0
Minnesota	5-year moving average	Wisconsin	5.0
Mississippi	4.0	Wyoming	3.0

Some states use the real discount rate from OMB Circular A-94. There are two approaches: one is to employ a single-year interest rate as a real discount rate, and the other is to use a moving average value of interest rates in recent years as a real discount rate. Figure 5 compares the single-year real discount rate with the 10-year moving average rate over the past 38 years. As presented, the single-year real interest rate in 2017 is 0.7%, while the 10-year rolling average rate in 2017 is 2.14%. Figure 5 also illustrates that the single-year discount rate fluctuated significantly up and down from year to year, which would introduce considerable inconsistency into LCCA. On the contrary, using a 10-year moving average rate yields a more stable trend. FHWA's *Economic Analysis Primer* states that adjusting the discount rate to reflect short-term funding fluctuations may distort the value of long-term benefits and costs (*FHWA, 2003*). Therefore, the 10-year moving average discount rate is more reflective of FHWA guidance and provides more stable LCCA results while remaining consistent with recent economic conditions.

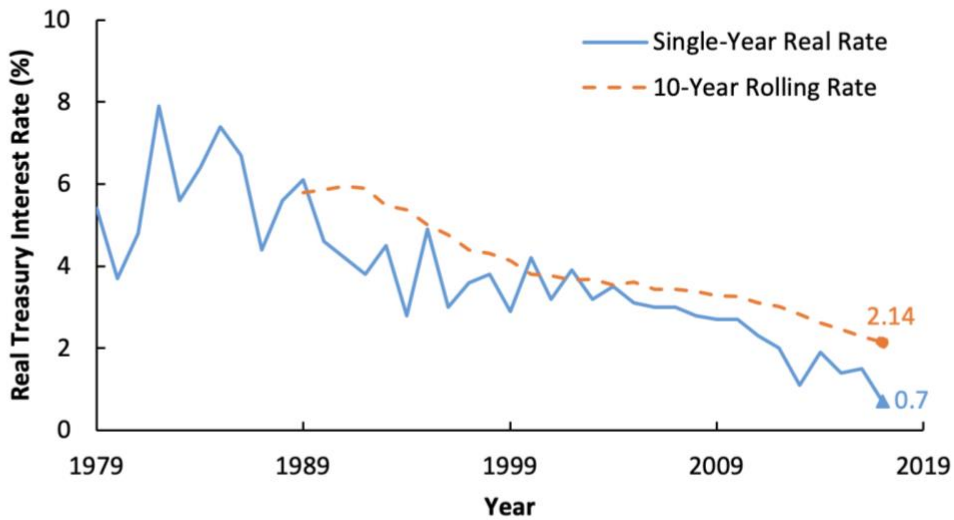

Figure 5. Comparison of Single-Year Rate to 10-Year Moving Average Rate

3.6 User Costs

User costs are those incurred by highway users traveling on the project under consideration for LCCA or users who cannot travel on the project due to agency or self-imposed detour requirements, which include three components:

- Vehicle operating costs (VOC), which are determined by multiplying the quantity of additional VOC components (i.e., work zone speed change, stop, and idling time) incurred by the cost rate assigned to each VOC component.
- User delay costs, which are determined by multiplying the additional hours of travel time by the dollar value of an hour of delay assigned for each vehicle classification.
- Crash costs, which are determined by multiplying the number of additional crashes by the assigned cost rate to each crash type.

A 2005 study commissioned by South Carolina DOT found that only 41% of states responding to the survey calculated user costs in their LCCA, and moreover, the states incorporating user costs into the analysis only accounted for the user delay costs during construction, maintenance, and rehabilitation activities (*Rangaraju et al., 2008*). While the user cost is important, it does not affect the SHA budget, which includes costs of new construction and future maintenance and rehabilitation activities. In addition, it is difficult to calculate it accurately due to the uncertainty of future traffic prediction and the monetary estimate of each user cost component. Therefore, the user costs should only be considered when the net present values of alternatives are within 10 percent of each other (*West et al., 2013*).

In the LCCA, user costs are usually associated with both normal operations and work zone operations. For the pavement alternatives, the above three components of user costs have little difference in the normal operations, especially for the pavements with good performance. However, the VOC and user delay costs are significantly distinct between pavement alternatives when they are in the work zone conditions. Since LCCA is conducted to investigate the differential costs between alternatives, the best practices of LCCA should only consider the VOC and user delay costs associated with work zone operations. A detailed description of the procedure for calculating user costs is included in Appendix A.

4. EXAMPLE

This section provides a LCCA example and sensitivity analysis to examine the impact of each input on the life cycle cost of an asphalt pavement. In this example, the life cycle costs of the asphalt pavement option were determined based on four analyses, including deterministic, deterministic with user cost, probabilistic, and probabilistic with user cost. Detailed information about the life cycle cost calculation is included in Appendix B.

Table 9 shows an asphalt pavement structure utilized in this analysis. Since the pavement alternatives in this example would be built on the same aggregate base and subgrade, only asphalt layers were different from the other pavement option, and thus, were included in the analysis.

Table 9. Asphalt Pavement Structural Design

Layer Number	Material Description	Thickness (in)
1	SMA wearing course	1.5
2	Asphalt binder course	2.0
3	Asphalt base course	10.0

For this example, the following inputs are utilized:

- Analysis Period: 40 years
- Discount Rate: 2.14%
- Initial Performance Period: 18 years
- Maintenance/Rehabilitation Period: 13 years
- Project Length: 1.73 miles
- Number of Lanes in One Direction: 3
- Grade: <2%
- Upstream Speed: 60 mile/h
- Construction Year: 2018
- Base AADT: 56830 vpd
- Maximum AADT: 100000 vpd
- Percent of Passenger Car: 84%
- Percent of Single-Unit Truck: 11.2%
- Percent of Combination Truck: 4.8%
- Traffic Growth Rate: 0.75%
- Work Zone Speed: 40 mile/h
- Lane Closure Plan: One Lane, from 9:00 pm to 5:00 am
- Work Zone Duration: 20 days for 1st intervention (resurfacing), 30 days for 2nd intervention (rehabilitation)

Table 10 summarizes the life cycle costs of the asphalt pavement structure using the deterministic approach with and without user cost. In this case, the inclusion of user cost increases the total life cycle cost by approximately 11 percent.

Table 10. Life Cycle Costs of Flexible Pavement Alternative Using Deterministic Approach

Cost Item	Activity Year	Net Present Value	
		Deterministic Method without User Cost	Deterministic Method with User Cost
Initial construction	2018	$ 2,970,287	$ 2,970,287
1st intervention construction	2036	$ 260,227	$ 260,227
1st intervention user cost	2036	Not calculated	$ 110,995
2nd intervention construction	2049	$ 483,091	$ 483,091
2nd intervention user cost	2049	Not calculated	$ 265,892
RSL value of last intervention	2058	(-) $ 122,852	(-) $ 112,852
RSL value of underlying AC layers	2058	(-) $ 649,368	(-) $ 649,368
Total		$ 2,941385	$ 3,318,272

For the deterministic LCCA, a sensitivity analysis was also conducted to determine the effect of discount rate, initial performance period, and maintenance/rehabilitation performance period on the net present value. Figure 6 shows the effect of discount rate on the life cycle costs of the pavement alternative. As the discount rate increased from 1 to 4 percent, the life cycle costs without user cost increased by 11 percent, while the life cycle costs with user cost remained almost the same. This is because the terminal value (i.e., the sum of RSL values) was slightly greater than the sum of the 1st and 2nd intervention construction costs, but much less than the sum of the 1st and 2nd intervention construction and user costs. Thus, the decrease in the net present value of the salvage value was greater than that of the 1st and 2nd intervention construction costs, but the decrease of 1st and 2nd intervention user costs offset this difference.

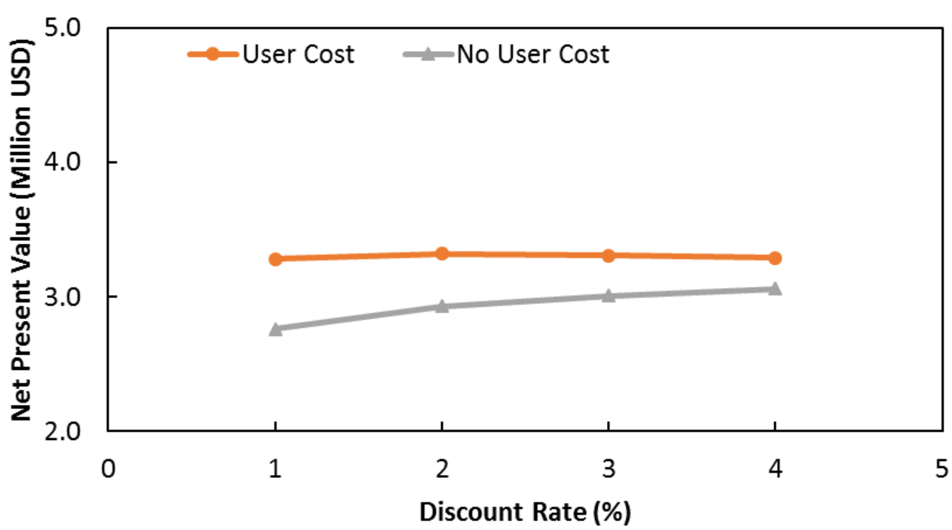

Figure 6. Effect of Discount Rate on Life Cycle Costs of Pavement Alternative

The influence of initial performance period on the life cycle costs of the flexible pavement alternative is shown in Figure 7. Four initial performance periods were included, ranging from 12 to 21 years. As the initial performance period increased from 12 to 21 years, the life cycle costs decreased by 15 percent without user costs and by 13 percent with user costs.

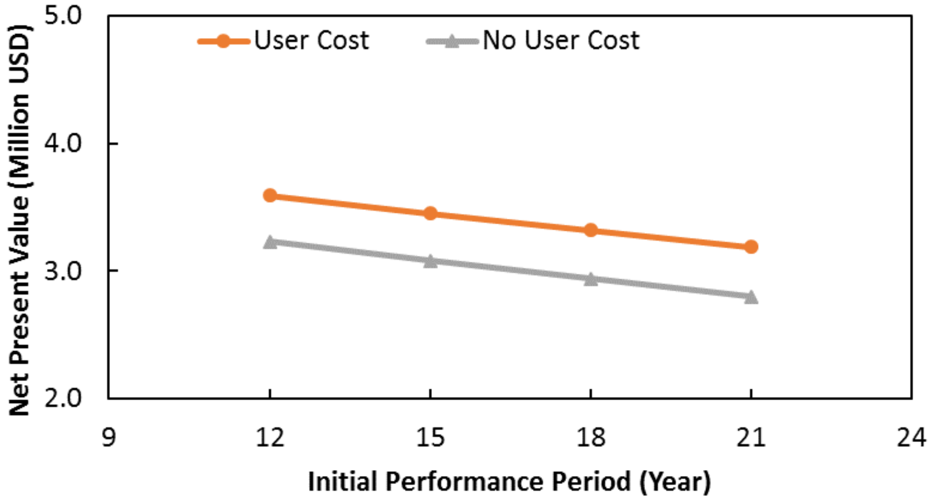

Figure 7. Effect of Initial Performance Period on Life Cycle Costs of Pavement Alternative

Figure 8 presents the impact of maintenance/rehabilitation performance period on the life cycle costs of the pavement alternative. When the maintenance/rehabilitation performance period increased from 10 to 19 years, the life cycle costs of the pavement alternative were reduced by 19 percent without user costs and by 16 percent with user costs. Figures 7 and 8 show that the initial and maintenance/rehabilitation performance periods significantly impact the calculated LCC of the pavement alternative. The validity of LCCA significantly relies on the accuracy of the estimated initial and maintenance/rehabilitation performance periods of pavement alternative.

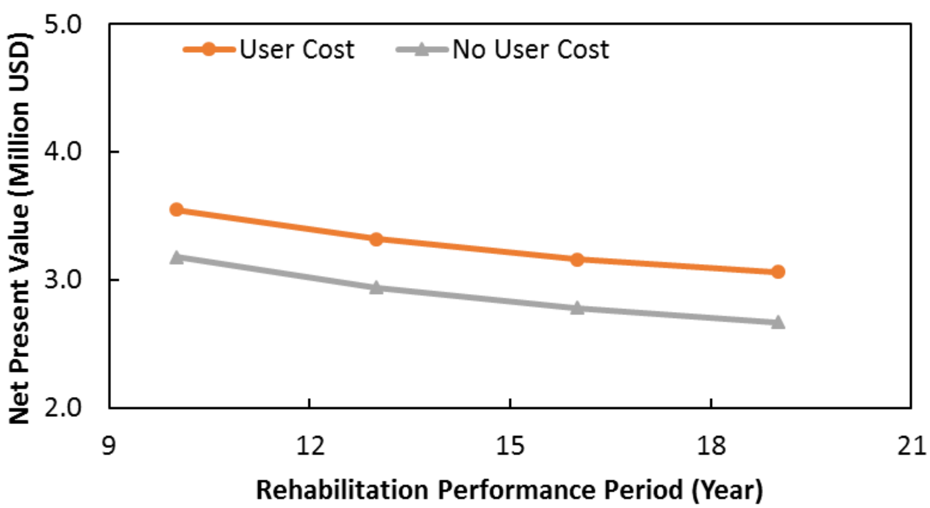

Figure 8. Effect of Maintenance/Rehabilitation Period on Life Cycle Costs of Pavement Alternative

The probabilistic approach was also conducted in this example, which considers the uncertainties of LCCA inputs including discount rate, initial performance period, and maintenance/rehabilitation performance period, which follow the normal distribution with mean value and standard deviation shown below.

- Discount rate: mean value (2.14%), standard deviation (0.5%);
- Initial performance period: mean value (18 years), standard deviation (2 years); and
- Maintenance/rehabilitation performance period: mean value (13 years), standard deviation (2 years).

A Monte Carlo simulation was performed to quantify the impact of the uncertainties of discount rate, initial performance period, and maintenance/rehabilitation performance period on the pavement life cycle costs. Figure 9 presents the life cycle costs of the asphalt pavement option in the wet-no-freeze climatic zone using the probabilistic approach with and without user cost. It should be noted that the 50th percentile life cycle costs determined using the probabilistic approach are comparable to the respective life cycle costs determined using the deterministic approach.

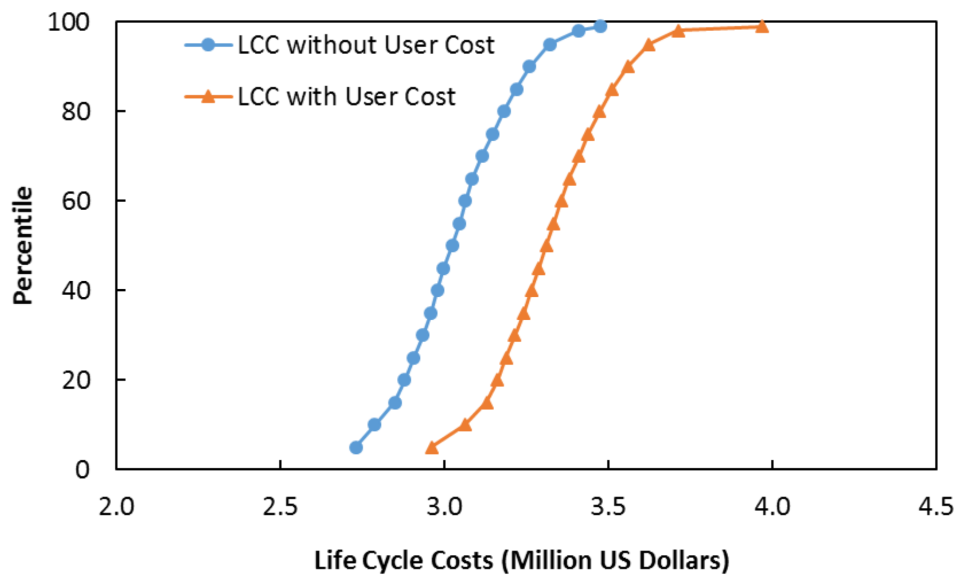

Figure 9. Life Cycle Costs of Designed Pavement Alternative Using Probabilistic Approach

5. SUMMARY

In summary, this document provides guidance in the form of best practices to help highway agencies properly determine inputs for use in their life cycle cost analysis procedures and to calculate the life cycle costs of asphalt pavements. The information provided is of immediate interest to engineers in highway agencies, consulting firms, and the paving industry with responsibility for conducting LCCA for pavement type selection. A summary of the best practice for determining each input follows.

- Analysis period is the length of time, in years, over which the life cycle costs of pavement alternatives are evaluated. The best practice for selecting the analysis period is to consider the likelihood of reconstructing one or both pavement alternatives but avoiding longer time periods that increase uncertainties with predicting the future inputs. As an example, the field performance data from several states in the southeast show that the average time for reconstruction of concrete pavements is below 35 years. Thus, an analysis period of 35 or 40 years can be selected to include multiple maintenance and major rehabilitation activities for both asphalt and concrete pavements in these states.
- Performance periods are the average time spans in years for a newly constructed or rehabilitated pavement to reach the agency's threshold for maintenance and/or rehabilitation. The best practice for determining performance periods of pavements is to use the pavement management system data and review the determined performance periods every few years to make sure they do not fall behind continuous advancements made in specifications and construction methods (*Von Quintus et al., 2005*).
- Agency costs include costs associated with the pavement alternatives that are incurred by the agency over the analysis period. They typically include costs for initial construction, subsequent maintenance, rehabilitation, and associated administrative activities. The best practice for determining the unit prices of construction materials for use in LCCA is to analyze the cost data available from construction projects in the state for the last few years. Cost indices can be used to normalize cost data from the earlier years to the most recent year. Using multiple-year cost data would yield a more stable trend for long-term LCCA while considering recent economic conditions. This analysis can be updated annually or periodically to show most recent prices. A cost analysis conducted by the Colorado Department of Transportation is included in this report as an example to show how such an analysis can be performed.
- Terminal value represents the expected worth of a pavement alternative at the end of the analysis period. It is comprised of two mutually exclusive components, including RSL value and salvage value. RSL value is the remaining value of a pavement alternative when its service life extends beyond the end of the analysis period, while salvage value is the net value from reusing and/or recycling the pavement. Currently, most SHAs only consider the RSL value of the last maintenance or rehabilitation activity, which is typically the last resurfacing activity for asphalt pavements, even though the underlying asphalt layers still have some RSL value. Another approach is presented in this document to account for the RSL value of both the last improvement and the underlying asphalt layers that are still in place. In cases asphalt pavement alternatives are removed and replaced at the end of the analysis period, the salvage value should consider the differential worth of RAP and RAC materials.
- A discount rate is used to calculate the present value of future costs and salvage value. In essence, the discount rate is an interest rate in reverse. A single 10-year moving average of real interest rates issued annually by the Office of Management and Budget is recommended for determining the life cycle costs of the pavement alternatives. It yields

a more stable trend while remaining consistent with FHWA guidance and recent economic conditions. In 2017, the 10-year moving average of real interest rate is 2.14%.

- User costs are costs incurred by highway users traveling on the project under consideration for LCCA or users who cannot travel on the project due to agency or self-imposed detour requirements. States incorporating user costs into the analysis only consider the user delay costs during maintenance and rehabilitation activities. While the user cost is important, it is difficult to calculate accurately; thus, it is best to only consider when the net present values of alternatives are within 10 percent of each other (*West et al., 2013*).

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APPENDIX A. CALCULATION OF USER COSTS

Most SHAs that consider user costs only calculate the vehicle operating costs and user delay costs associated with work zone operations. To define a work zone, the following inputs are required:

- Year of maintenance/rehabilitation activity,
- Number of lanes closed,
- Specific hours of lane closure,
- Work zone length,
- Work zone posted speed, and
- Work zone duration.

Figure A1 presents a flowchart to calculate the VOC and user delay costs associated with work zone operations, which are further described below.

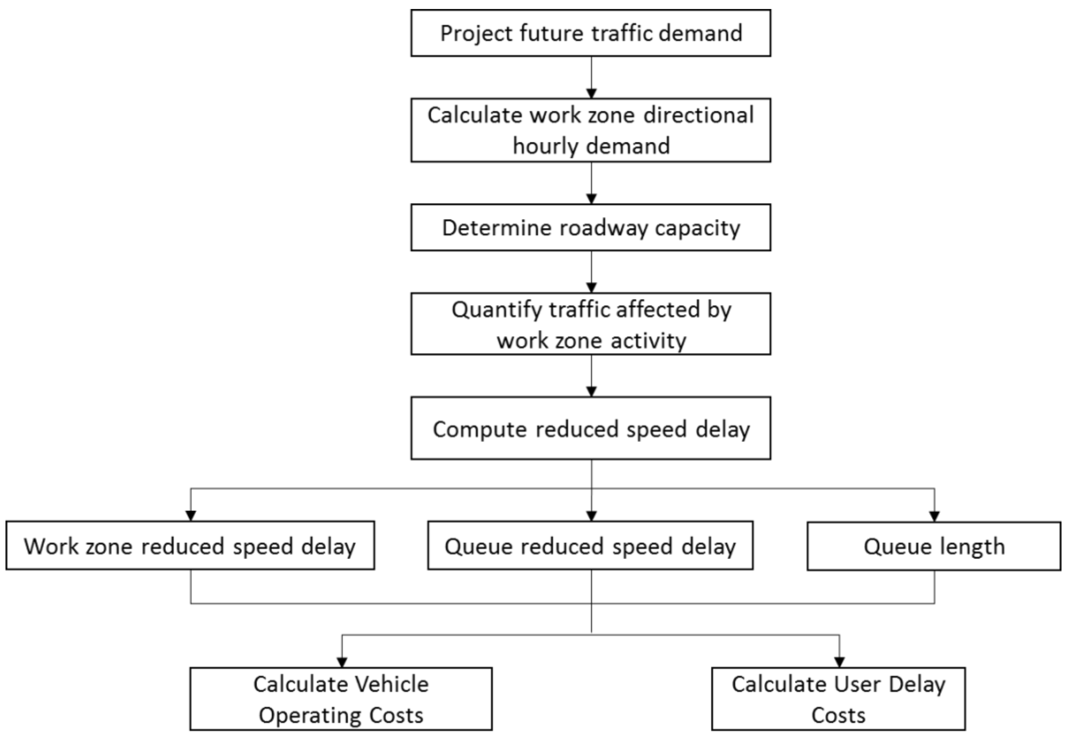

Figure A1. Calculation of Work Zone Associated User Costs

To project future traffic demand, the traffic information to be provided includes base year annual average daily traffic (AADT), percentage of vehicle class (i.e., passenger vehicles, single-unit trucks, and combination trucks), and traffic growth rate. The calculation procedures consider the impact of vehicle class on the VOC and user delay costs.

Directional hourly traffic demands are calculated using agency traffic from the project under consideration or using traffic data from similar facilities. If this data is not available, default hourly distributions for rural and urban areas are available in Walls and Smith (1998).

Roadway capacity is divided into three categories: free-flow road capacity, queue dissipation capacity, and work zone capacity. The free-flow capacity refers to the capacity that the road can handle under free-flow conditions, which is correlated to the truck equivalency factor according to the Transportation Research Board's Highway Capacity Manual (*HCM, 2010*). The queue dissipation capacity is to reflect the capacity of road right after the work zone is removed. According to Walls and Smith (1998), the default queue dissipation capacity is assigned as 1,818 vehicles per lane. The work zone capacity is the road capacity associated with various lane closures, which is estimated from past experience or values from the HCM 2010 as shown in Table A1.

Table A1. Work Zone Capacities from the Highway Capacity Manual

Directional Lanes		Average Capacity
Free Flow Operations	**Work Zone Operations**	**Vehicles per Lane per Hour**
2	1	1,340
3	1	1,170
3	2	1,490
4	2	1,480
4	3	1,520
5	2	1,370

Once road capacity is determined and the lane closure plan is established, the next step is to compare hourly traffic demand against road capacity. If traffic demand is less than road capacity, the traffic will free flow in the work zone. If traffic demand is greater than road capacity, the traffic will queue in the work zone. Thus, the number of vehicles that traverse the work zone, slowdown in the work zone, traverse the queue, and stop for the queue will be quantified.

The reduced speed delay of one vehicle in the free flow work zone and queuing work zone are calculated by Equations A-1 and A-2, respectively. Herein, the queue length is estimated as the product of the number of queued vehicles and the average vehicle length (i.e., 40 feet). The quantified traffic affected by work zone activity is used to compute the total reduced speed delay in both free flow and queuing situations.

$$Work\ Zone\ Delay = \frac{Work\ Zone\ Length}{Work\ Zone\ Speed} - \frac{Work\ Zone\ \ Length}{Upstream\ Speed} \tag{A-1}$$

$$Queue\ Delay = \frac{Queue\ Length}{Queue\ Speed} - \frac{Queue\ \ Length}{Upstream\ Speed} \tag{A-2}$$

The VOC and user delay costs are the product of the number of vehicles affected and the corresponding cost rate. Table A2 shows the VOC rates associated with traffic speed change and idling. As presented, the VOC rates also include a component of added time. The added time cost is estimated by multiplying the added time and the corresponding user delay rates shown in Table A2. In addition, the user delay rates in Table A3 are used to compute the user delay costs associated with the work zone activity.

Table A2. Added Time and Vehicle Running Cost Per 1,000 Stops and Idling Costs (Dec 18)

Initial Speed (mi/h)	Added Time (Hour/1,000 Stops) (Excludes Idling Time)			Added Cost ($/1,000 Stops) (Excludes Idling Time)		
	Pass Cars	Single-Unit Truck	Combination Truck	Pass Cars	Single-Unit Truck	Combination Truck
5	1.02	0.73	1.10	4.30	14.74	53.57
10	1.51	1.47	2.27	14.07	33.01	123.47
15	2.00	2.20	3.48	24.16	54.00	207.09
20	2.49	2.93	4.76	34.64	77.12	302.83
25	2.98	3.67	6.10	45.68	101.93	408.76
30	3.46	4.40	7.56	57.52	127.83	522.95
35	3.94	5.13	9.19	70.20	154.36	643.45
40	4.42	5.87	11.09	83.97	181.59	768.33
45	4.90	6.60	13.39	98.90	207.26	895.68
50	5.37	7.33	16.37	115.21	232.56	1023.58
55	5.84	8.07	20.72	133.00	256.35	1150.03
60	6.31	8.80	27.94	152.48	285.18	1273.06
65	6.78	9.53	NA	173.71	312.04	NA
70	7.25	NA	NA	196.95	NA	NA
75	7.71	NA	NA	222.32	NA	NA
80	8.17	NA	NA	249.92	NA	NA
Idling Cost ($/Vehicle-Hour)				1.1037	1.2238	1.3142

Table A3. FHWA User Delay Rates

Vehicle Type	Value of Time ($/Hour)	
	Aug-96	Dec-18
Passenger car	11.58	18.45
Single-unit truck	18.54	29.54
Combination truck	22.31	35.55

APPENDIX B. LIFE CYCLE COST ANALYSIS EXAMPLE

This appendix describes a step-by-step analysis for determining the life cycle cost of the asphalt pavement structure discussed in the Example presented in Section 4.

Step 1: Flexible Pavement Structure

The asphalt pavement structure considered in this analysis is shown in Table B1.

Table B1. Structural Design of Asphalt Pavement Alternative

Layer Number	Material Description	Thickness (in)
1	SMA wearing course	1.5
2	Asphalt binder course	2.0
3	Asphalt base course	10.0

Step 2: Inputs of Life Cycle Cost Analysis

The following inputs are used for determining the life cycle cost of the asphalt pavement structure:

Analysis Period: 40 years
Discount Rate: 2.14%
Initial Performance Period: 18 years
Main./Rehab. Period: 13 years
Project Length: 1.73 miles
Number of Lanes in One Direction: 3
Grade: <2%
Upstream Speed: 60 mile/h
Construction Year: 2018

Base AADT: 56830 vpd
Maximum AADT: 100000 vpd
Percent of Passenger Car: 84%
Percent of Single-Unit Car: 11.2%
Percent of Combination Truck: 4.8%
Traffic Growth Rate: 0.75%
Work Zone Speed: 40 mile/h
Lane Closure Plan: One Lane, 9:00 pm to 5:00 am
Work Zone Duration: 20 days for 1st Intervention
30 days for 2nd Intervention

Step 3: Initial Construction Cost

The initial construction cost is calculated in Table B2.

Table B2. Initial Construction Costs

Location	Layer Number	Material Information	Subtotal
Inside Shoulder	1	Wearing course	$ 29,862
	2	Binder course	$ 51,390
	3	Base course	$ 301,437
Outside Shoulder	1	Wearing course	$ 74,561
	2	Binder course	$ 119,880
	3	Base course	$ 611,357
Traffic Lane	1	Wearing course	$ 215,149
	2	Binder course	$ 251,213
	3	Base course	$ 1,315,440
		Total Construction Cost	$ 2,970,287

Step 4: Maintenance and Rehabilitation Costs

There would be two intervention activities during the analysis period. Tables B3 and B4 present the construction costs for the 1st (resurfacing) and 2nd (rehabilitation) activities, respectively.

Table B3. Pay Items for 1st Intervention (Resurfacing)

Location	Layer Number	Material Information	Subtotal
Inside Shoulder	1	Wearing course	$ 29,862
	2	408A052	$ 6,462
Outside Shoulder	1	Wearing course	$ 74,561
	2	408A052	$ 16,154
Traffic Lane	1	423A003	$ 215,149
	2	408A052	$ 38,771
		Total Construction Cost	$ 380,958

Table B4. Pay Items for 2nd Intervention (Rehabilitation)

Location	Layer Number	Material Information	Subtotal
Inside Shoulder	1	Wearing course	$ 29,862
	2	Binder course	$ 53,460
	3	408A055	$ 19,888
Outside Shoulder	1	Wearing course	$ 74,561
	2	Binder course	$ 124,650
	3	408A055	$ 46,406
Traffic Lane	1	423A003	$ 215,149
	2	Binder course	$ 261,278
	3	408A055	$ 106,070
		Total Construction Cost	$ 931,323

Step 5: User Costs

User costs are usually associated with both normal and work zone operations. For this example, the three components of user costs have little difference in the normal operations, especially for pavements with good performance. However, the vehicle operating cost (VOC) and user delay costs are significantly distinct between pavement alternatives when they are in the work zone conditions. Since LCCA is conducted to investigate the differential costs between alternatives, SHAs often consider only the VOC and user delay costs associated with work zone operations. In this study, the calculation of user costs associated with the 1st and 2nd intervention activities are included as follows.

Table B5. Projection of Future Traffic Demand

Activity	1st Intervention	2nd Intervention
Project Year	2036	2049
Passenger Vehicle (vpd)	54,609	60,180
Single-Unit Truck (vpd)	7,281	8,024
Combination Truck (vpd)	3,121	3,139
Total	65,011	71,643

Table B6. Calculation of Work Zone Directional Hourly Demand

Hour	%ADT	Demand	
		1st Intervention	2nd Intervention
0-1	1.2	780	860
1-2	0.8	520	573
2-3	0.7	455	502
3-4	0.5	325	358
4-5	0.7	455	502
5-6	1.7	1105	1218
6-7	5.1	3316	3654
7-8	7.8	5071	5588
8-9	6.3	4096	4514
9-10	5.2	3381	3725
10-11	4.7	3056	3367
11-12	5.3	3446	3797
12-13	5.6	3641	4012
13-14	5.7	3706	4084
14-15	5.9	3836	4227
15-16	6.5	4226	4657
16-17	6.9	4486	4943
17-18	7.5	4876	5373
18-19	5.9	3836	4227
19-20	3.9	2535	2794
20-21	3.9	2535	2794
21-22	3.9	2535	2794
22-23	2.6	1690	1863
23-24	1.7	1105	1218
Total	100	65011	71643

Table B7. Determination of Roadway Capacity

Roadway Capacity Type	Number of Vehicles
Free-Flow Road Capacity	6,390
Queue Dissipation Capacity	5,454
Work Zone Capacity	2,340

Table B8. Summary of Traffic Affected by Work Zone Activity

Activity	Hour	Traverse Work Zone	Traverse Queue	Stop	Slow Down (60-40-60)
1st Intervention	5-21	0	0	0	0
	21-5	7866	3044	3044	4822
2nd Intervention	5-21	0	0	0	0
	21-5	8669	4566	4566	4103

Table B9. Computation of Reduced Speed Delay

Description	1st Intervention	2nd Intervention
Upstream Speed (mile/h)	60	60
Work Zone Speed (mile/h)	40	40
Work Zone Length (mile)	1.73	1.73
Work Zone Reduced Speed Delay (hour)	0.0144	0.0144
Queue Speed (mile/h)	8	8
Average Number of Queued Vehicles	98	277
Average Vehicle Length (ft)	40	40
Queue Length (mile)	0.4	0.9
Queue Reduced Speed Delay (hour)	0.0401	0.093

Table B10. Calculation of User Cost Components

User Cost Components	Activity	
	1st Intervention	2nd Intervention
Speed Change VOC	$ 13,185	$ 22,157
Speed Change Delay Cost	$ 9,564	$ 16,072
Work Zone Reduced Speed Delay Cost	$ 68,114	$ 148,272
Stop VOC	$ 5,888	$ 13,250
Stop Delay Cost	$ 13,597	$ 40,291
Idling VOC	$ 2,716	$ 14,199
Queue Reduced Speed Delay Cost	$ 49,426	$ 258,356
Total User Cost	$ 162,491	$ 512,598

Step 6: Terminal Value

Terminal value represents the expected worth of a pavement alternative at the end of the analysis period. It is composed of two mutually exclusive components, including remaining service life (RSL) value and salvage value. RSL value is the residual value of a pavement alternative when its service life extends beyond the end of the analysis period. While salvage value is the net value determined from reusing or recycling materials removed from a pavement alternative at the end of its life. The calculation of terminal value is discussed in Section 3.4 of this document. In this case, the terminal value is the sum of RSL value of last intervention and that of other asphalt layers.

Table B11. Summary of Terminal Value Components

Inputs		Outputs	
Cost of 2nd Intervention	$931,323	RSL Value of Last Intervention	(-)$286,561
Remaining Service Time (Year)	4		
Total Service Time (Year)	13		
Underlying Layer Cost	$2,859,204	RSL Value of Other Asphalt Layers	(-)$1,514,695
Underlying Layer Original Design Coefficient	0.3 (New)		
Underlying Layer Residual Layer Coefficient	0.2 (Fair)		

Step 7: Sum of Present Values of Cost and Salvage Value Components

Table B12 summarizes the life cycle costs for the pavement alternative determined based on the deterministic approach with and without the user cost.

Table B12. Summary of Life Cycle Cost Analysis

Cost Component	Activity Time	Component Cost	Net Present Value
Initial Construction	2018	$ 2,970,287	$ 2,970,287
1st Intervention Construction	2036	$ 380,958	$ 260,227
1st Intervention User	2049	$ 162,491	$ 110,995
2nd Intervention Construction	2049	$ 931,323	$ 483,091
2nd Intervention User	2049	$ 512,598	$ 265,892
RSL Value of Last Intervention	2058	(-)$ 286,561	(-)$ 122,852
RSL Value of Underlying AC Layers	2058	(-)$ 1,514,695	(-)$ 649,368
Deterministic Approach without User Cost			$2,941,385
Deterministic Approach with User Cost			$ 3,318,272