LCCA STANDARD PRACTICE GUIDELINE – FINAL REPORT

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Sign-off Sheet

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Executive Summary

This project reviewed the LCCA practices in place across transportation agencies in Canada as well as in select international agencies. The review focuses on the LCCA policies of the provinces of Alberta, British Columbia, Manitoba, Nova Scotia, Ontario, Quebec, and Saskatchewan. The LCCA practices of the Federal Highway Administration (FHWA), American Concrete Pavement Association (ACPA), Asphalt Pavement Alliance (APA), and the World Bank (WB) are also reviewed.

The objective of the project was to develop a Canadian LCCA Standard Practice Guideline based on best practices. The guideline provides a reference guide on LCCA for alternate pavement-type bidding. The project also included the development of user-friendly excel spreadsheet (based on the guideline) to aid in the analysis of life cycle costs of alternate pavement designs.

Based on the review of LCCA practices, the study identified recommended practices in conducting life cycle cost analysis in pavement design. The practices relate to the: length of analysis period, discount rate, (agency, user, and environmental) costs, economic criteria method, and LCCA computational approach. These recommendations can be found in Chapter 3.

Abbreviations

AASHTO	American Association of State Highway Transportation Officials
ACPA	American Cement Pavement Association
APA	Asphalt Pavement Alliance
AI	Asphalt Institute
BC	British Columbia
BC Ratio	Benefit Cost Ratio
DARWin	Design, Analysis, and Rehabilitation for Windows
EUAC	Equivalent Uniform Annual Cost
FHWA	Federal Highway Administration
FYRR	First Year Rate of Return
GAO	U.S. Government Accountability Office
HDM	Highway Development and Management
IRR	Internal Rate of Return
LCCA	Life Cycle Cost Analysis
MAE	Multiple Account Evaluation
MCA	Multicriteria Analysis
MEPDG	Mechanistic-Empirical Pavement Design Guide
MTO	Ministry of Transportation Ontario
NRW	Net Present Value
NRV	Net Present Worth
NSTPW	Nova Scotia Transportation and Public Works

OMB	Office of Management and Budget
OPAC	Ontario Pavement Analysis of Costs
PDO	Personal Damage Only
PW	Present Worth
SHA	State Highway Agency
TAC	Transportation Association of Canada
VOC	Vehicle Operating Cost
WB	World Bank
WZ	Work Zone

1.0 INTRODUCTION

1.1 BACKGROUND

Building and maintaining an effective transportation system is vital in connecting communities. In addition, it provides for the safe, efficient movement of people and goods across regions. It is therefore essential for transportation agencies to utilize tools that facilitate sound investment decision-making to ensure the associated benefits of road infrastructures are sustained. Life-Cycle Cost Analysis (LCCA) is one analysis tool based on the principles of economic analysis to evaluate the overall long-term economic feasibility between alternative investment options. Some key benefits of LCCA include:

- Selection of cost-effective pavement designs;
- Maximization of the value of capital investments in budget-constrained environment;
- Evaluation of feasible future maintenance, rehabilitation, and/or reconstruction strategies; and
- Increased transparency of the project analysis and selection process.

The LCCA process consists of five steps. While the steps are generally sequential, the sequence can be altered as per the project requirements. The FHWA Technical Interim Bulletin [FHWA 2002] describes the steps involved in LCCA as follows.

Step 1: Establish Design Alternatives.
The first step in conducting an LCCA involves the identification of alternative pavement design strategies for the analysis period under consideration. The analysis period, the common timeframe for which initial and future costs for all alternatives will be evaluated, is also defined in this step.

Step 2: Determine Activity Timing.
In the second step, the performance period for each design alternative and the timing of maintenance and rehabilitation activities is determined. The timing and expected life of rehabilitation activities is typically based on existing pavement performance records. The projections can rely on the judgment of experienced engineers, when actual performance data is unavailable or is not applicable.

Step 3: Estimate Costs.
The third step involves estimating costs accruing to highway agencies (agency costs) and to users of the road system related to agency construction and maintenance activities.

Step 4: Compute Life-Cycle Cost.
In this step, the total life cycle costs for each alternative is calculated and compared. To assist in visualizing the quantity and timing of expenditures projected over the life of the analysis period, expenditure stream diagrams may be developed.

Step 5: Analyze Results and Reevaluate Alternatives.

This step involves analyzing and interpreting the LCCA results. The analysis procedure is dependent on the computational approach used. In the analysis of deterministic-based LCCA, the percent difference in the life cycle cost of competing alternatives is computed to determine the "best" alternative. Deterministic LCCA accompanied with sensitivity analysis can allow the determination of the most likely scenario where the selected input values are most likely to occur. In probabilistic LCCA, the selection of the most economical alternative is based on risk tolerance.

The LCCA process concludes with the reevaluation of the findings to determine if modifications to any of the proposed alternatives might be required prior to the selection of the feasible alternative. Revisions might include structural design changes, altered traffic plans, reductions in construction periods, or changes in rehabilitation strategies. The LCCA process is summarized in the flowchart below.

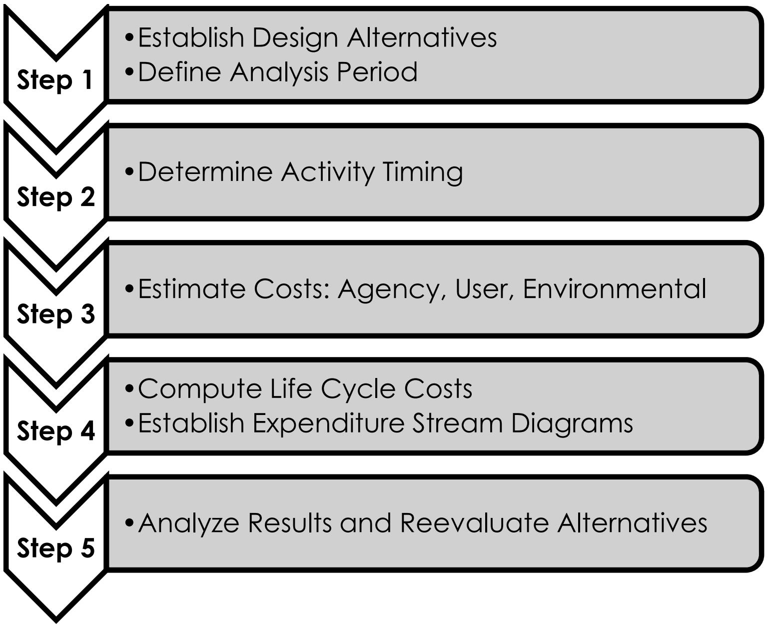

Figure 1.1: Life Cycle Cost Analysis (LCCA) Process

1.2 OBJECTIVE AND SCOPE OF PROJECT

The objective of this project was to develop a LCCA Standard of Practice Guideline for alternate pavement-type bidding. This document provides a reference guide of best practices of LCCA for highway agencies across Canada. The following methodology was used.

I. Research and review of current LCCA practices

This task involved the compilation and review of current LCCA practices in place across Canada. The review mainly focused on the LCCA policies used by the provinces of Alberta, British Columbia, Manitoba, Nova Scotia, Ontario, Quebec, and Saskatchewan.

The LCCA practices of the Federal Highway Administration (FHWA), American Concrete Pavement Association (ACPA), Asphalt Pavement Alliance (APA), and the World Bank (WB) were also reviewed to identify best practices.

II. Gap analysis

Current practices in the provincial agencies were reviewed, the missing data, or gaps in terms of best practices were identified.

III. Development of LCCA Standard of Practice Guideline and Excel Spreadsheet tool

Following the gap analysis, a Standard of Practice Guideline for conducting LCCA was also developed based on best practices and procedures.

IV. Development of Excel based LCCA tool

A user-friendly Excel spreadsheet was developed per the LCCA Standard Practice Guideline to aid in the calculation of Life Cycle Costs of alternative pavement designs. Users will have the option to input the LCCA parameters in the evaluation and selection of the most feasible alternative.

2.0 REVIEW AND GAP ANALYSIS OF LCCA PRACTICES

In Canada, most provincial agencies use LCCA as a primary decision tool for selecting pavement design and/or rehabilitation alternatives. Currently New Brunswick, Newfoundland and Labrador, and Prince Edward Island do not use LCCA in their economic analysis. Nova Scotia uses LCCA exclusively in the selection of equivalent pavement-type alternatives, BC uses LCCA for all large capital projects excluding rehab programs while Saskatchewan uses LCCA to some degree in the analysis of pavement treatment alternatives. Ontario, Quebec, and Manitoba use LCCA in the analysis of pavement-type and treatment alternatives.

Due to the lack of a standard LCCA guideline, there is large variation in the LCCA practice employed by highway agencies across Canada. ACPA's Agency Practices Explorer indicates the difference in the LCCA practices is mainly in terms of the length of analysis period, discounting rate, and the evaluation of agency and user related costs. The variation in the components of user costs incorporated into the LCCA has been documented in the State-of-the-Practice Survey Summary [Tighe et al. 2010].

In this chapter, the LCCA approach employed by each agency in Canada is reviewed. The guidelines and documents used for the review of the LCCA practices of the agencies include:

- *Benefit Cost Model and User Guide* [Alberta Transportation 2015],
- *Benefit Cost Analysis Guidebook* [British Columbia Ministry of Transportation and Infrastructure 2014],
- *Selection of Pavement Type Based on Life Cycle Cost* [Manitoba Infrastructure and Transportation 2016],
- Report on *Investigation on the Use of Flexible and Rigid Pavements* [Nova Scotia Transportation & Public Works 2005],
- *Pavement Design and Rehabilitation Manual* [Ontario Ministry of Transportation 2013],
- *Guidelines for the Use of Life Cycle Cost Analysis on MTO Freeway Projects* [Lane et al. 2005],
- *Departmental Policy on Pavement Type Selection* [Ministère des Transports du Québec 2002],
- *L'Orientation ministérielle sur le choix des types de chaussées [*Ministère des Transports du Québec 2002].

Also in the review, the LCCA guidelines of the Federal Highway Administration (FHWA), American Concrete Pavement Association (ACPA), Asphalt Pavement Alliance (APA), and the World Bank are examined. FHWA's *Life Cycle Cost Analysis in Pavement Design* [Walls et al. 1998] provides recommendations on best practices for conducting LCCA in pavement design. The interim technical bulletin also serves as guidance to State Highway Agencies (SHA) in the management of their transportation assets. ACPA's *Life-Cycle Cost Analysis: A Tool for Better Pavement Investment and Engineering Decisions* and APA's *Life-Cycle Cost Analysis: A Position Paper,* similarly provide guidelines for comparing equivalent competing pavement design alternatives.

The LCCA model of the World Bank, documented in HDM-4 publication series, details the LCCA procedure used in the model.

The review of the LCCA practices relates to the following LCCA parameters: analysis period, performance period and activity timing, discount rate, agency costs, user costs, environmental costs, and economic evaluation methods. In addition, the LCCA computational approach and analysis tools/software used are evaluated.

2.1 LENGTH OF ANALYSIS PERIOD

The analysis period is the time frame under which the cost difference between alternatives is compared. According to the FHWA Technical Bulletin, the analysis period should be long enough to include the initial construction or major rehabilitation action and at least one subsequent rehabilitation action for each alternative. The FHWA further recommends a minimum analysis period of 35 years for all pavement projects, including new or total reconstruction projects as well as rehabilitation, restoration, and resurfacing projects. ACPA's guideline recommends an analysis period of 45-50+ years so that at least one rehabilitation effort is captured for each alternate. The Asphalt Pavement Alliance likewise recommends that the analysis period be no less than 40 years and that it include at least one rehabilitation activity for each pavement option.

The AASHTO Guide for Design of Pavement Structures [AASHTO 1993] on the other hand, recommends selecting the analysis period based on the highway conditions.

Table 2.1 shows the AASHTO recommended analysis period suited for different highway conditions.

Table 2.1: AASHTO Recommended Analysis Period [AASHTO 1993]

Highway Conditions	Analysis Period (Years)
High - volume urban	30-50
High - volume rural	20-50
Low - volume paved	15-25
Low - volume aggregate surface	10-20

Review of LCCA practices of provincial agencies revealed that analysis period in the range of 25 to a maximum of 80 years is used for comparison of pavement design alternatives. A summary of the analysis period currently used by agencies across Canada is detailed below.

Alberta	The analysis time frame in Alberta's Benefit Cost Model is user-defined. A time frame of up to eighty (80) years, including the construction period, may be used for the analysis of alternative projects.
British Columbia	British Columbia's Ministry of Transportation & Infrastructure models the costs and benefits associated with highway improvement projects over a 25-year analysis period.
Manitoba	Manitoba's standard LCCA guide recommends a 50-year analysis period for evaluation of alternative options.
Nova Scotia	The Nova Scotia Transportation & Public Works (NSTPW) uses a 40-year analysis period in the comparison of pavement types.
Ontario	The Ministry of Transportation of Ontario (MTO) recommends that a 50-year analysis period be used for the selection of freeway pavement design. This includes high-volume roadways with greater than 1 million Equivalent Single Axel Loads (ESALs) per year (current or projected within 5 years), for all freeways and 400 series highway projects and for all concrete pavements (any facility type). For any other rehabilitation and expansion projects, the analysis period recommended is 30 years.
Quebec	Quebec's policy document on LCCA recommends a 50-year analysis period for the comparison and selection of pavement types.
Saskatchewan	Saskatchewan's Ministry of Highways & Infrastructure uses a 60-year lifecycle period in the selection of pavement preservation treatments.

Recommended Practice	The analysis period over which alternatives are evaluated should be longer than the pavement service life and as a rule long enough to incorporate at least one rehabilitation activity. Analysis period of 50 years would be a reasonable time frame to include at least one major rehab activity for both asphalt and concrete pavements and hence is recommended for LCCA of alternative pavements.

2.2 SERVICE LIFE AND ACTIVITY TIMING

The service life or performance period of a pavement is the period of time from completion of construction until the condition of the pavement is considered to be unacceptable, and rehabilitation is required [Lane et al. 2005]. Based on the AASHTO 1993 guideline, rehabilitation activities include: resurfacing to provide improved structural capacity, replacing/restoring malfunctioning joints, pavement undersealing, grinding of pavements to restore smoothness, removing deteriorated materials, strengthening of bases or subbases, cracking and seating of PCC pavements with AC overlay and adding drains.

To design the pavement service life and rehabilitation strategies, three methodologies are mainly used. These include: experience-based methods, empirical methods, and mechanistic-empirical methods. The Pavement Design and Management Guide [TAC 2011] distinguishes between the design methods as follows.

Experience-based method is a procedure based on standard sections and uses past experience to select the most appropriate design for a particular situation. The major limitation of this method concerns the extrapolation of past experiences into future conditions that incorporate constant changes in climate, traffic, materials, and construction techniques.

Empirical pavement design methods use the results of measured response, such as deflection, on different pavement structures to establish limits for a successful pavement structure under various volumes of traffic. Similar to the experience-based methods, empirical methods also rely on past experience when extrapolating for future designs. The 1993 AASHTO Guide for Design of Pavement Structures and its associated software application Design, Analysis, and Rehabilitation for Windows (DARWin), has been cited in the literature as the most widely used empirical-based design method.

Mechanistic-empirical methods of pavement design relate stress, strain and deflection at critical points in the pavement structure to observed performance under various conditions of climate and traffic loading. Mechanistic-empirical method has the advantage of considerable flexibility because it is theory based, can use past experiences for calibration and has the potential for transfer from one environment to another. A number of mechanistic-empirical design methods have been developed over the years including, Mechanistic-Empirical Pavement Design Guide (MEPDG) (and its associated software - AASHTOWare Pavement ME Design), Ontario Pavement Analysis of Costs (OPAC), the Shell Method, Asphalt Institute (AI) Design Method and the American Concrete Pavement Association (ACPA) StreetPave design software.

Most agencies currently determine the rehabilitation activities and timing using a standard rehabilitation schedule based on historical performance. While this practice seems reasonable, the study of Mack et al. points out that it may not be representative of the current design features and traffic loading conditions. Their study proposes instead, using the AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG) in conjunction with Decision Tree Analysis for determining the timing and range of possible rehabilitation activities specific to a given pavement design. This approach addresses uncertainties from varying rehabilitation schedules and results in predictable range of costs with probabilities accounting for risk associated with each alternative.

The design methods used by the provincial agencies, and the agency recommended estimates of initial service life as well as the rehabilitation strategies for flexible and rigid pavement designs are summarized in Table 2.2 below.

Table 2.2: Summary of Design Methods, Service Life, and Rehabilitation Strategies Used by Provincial Agencies in Canada

	Design Method(s) Used	Initial Pavement Type & Service Life		Rehabilitation Activity & Service Life/Activity Timing	
		Flexible Pavements	Rigid Pavements	Flexible Pavements	Rigid Pavements
Alberta	AASHTO '93 StreetPave*	AC: 20 yrs.	30 yrs.	HIR, 8-11 yrs. Mill & Inlay, 10-13 yrs. Two Lift overlay, 8-20 yrs. Reprofile and overlay, 15-20 yrs.	N/A
British Columbia	AASHTO '93 AASHTO '04 ELMOD Shell Method	AC: 20 yrs.	30 yrs.	(Mill and) Resurface, 15+ yrs.	N/A
Manitoba	AASHTO '93 MEPDG	AC: 20 yrs.	Doweled JPCP: 20 yrs.	Mill and Resurface, 15 yrs.	Diamond Grinding, 15 yrs. CPR, 12 yrs.
Nova Scotia	AASHTO '93	AC: 20 yrs.	40 yrs.	(Mill and) Resurface, 12 yrs.	Diamond Grinding, @ 18 yrs. CPR, 10 yrs.
Ontario* **	AASHTO '93 MEPDG OPAC StreetPave Experience-based	Deep Strength AC DFC: 19 yrs. SMA: 21 yrs.	Doweled JPCP: 28 yrs.	Mill and Resurface, DFC: 12 yrs. SMA: 13 yrs.	Diamond Grinding, 10 yrs. CPR, 10 yrs. Resurfacing, 12 yrs.
Quebec	AASHTO '93 CHAUSSEE 2	AC: 25-30 yrs.	30 yrs.	Mill and Resurface, 8-12 yrs. Reconstruction, @38-49 yrs.	CPR, 10 yrs. AC overlay, @ 39 yrs. Reconstruction, @ 46-49 yrs.
Saskatchewan	Shell Method (modified) AI Method**	AC: 15 yrs.	N/A	Mill and fill HMA overlay, 15 yrs. Base Treatment and Double Seal/HMA overlay, 15 yrs.	N/A

Notes * Design method used for rigid pavements only.

** Design method used for flexible pavements only.

*** Service life projections based on an initial 2 million ESALs/year for flexible pavements and 3 million ESALs/year for rigid pavements, with a 3.4 percent compound ESAL growth rate.

Recommended Practice	The rehabilitation strategy for alternative pavements should reflect the current design features and traffic loading conditions. The service life ranges recommended for pavement preservation/rehabilitation treatments is given in Table 3.1 and Table 3.2.

2.3 DISCOUNT RATE

The discount rate is a percentage value used for comparing the alternative uses of funds and costs over a period of time by reducing the future costs to present value. It is usually the difference between the interest rate for borrowing money and the inflation rate. Two types of discount rates may be used in LCCA: real and nominal discount rate. The Office of Management and Budget [OMB Circular A-94 1992] describes the real discount rate as the discount rate that reflects the true time value of money and that has been adjusted to eliminate the effect of expected inflation. In contrast, the nominal discount rate is defined in OMB as the rate of interest after adjustment for inflation. For analyses like LCCA which cover several decades, real discount rates are recommended because inflation is difficult to forecast and merely introduces another uncertainty into the evaluation [Hudson et. al. 1997].

The FHWA LCCA guideline recommends that the choice of discount rate should reflect historical trends of discount rate over long periods of time. The FHWA also recommends using real discount rates consistent with OMB circular A-94, Appendix C to discount the future costs and benefits of a project to present day values. The forecast of real interest rate on treasury notes and bonds of specified maturities based on economic assumptions from the 2018 budget is: 5-year (-0.3%), 10-year (0.1%), 20-year (0.5%) and 30-year (0.7%). For programs with durations longer than 30 years, OMB circular No. A-94 suggests using the 30-year interest rate in cost-effectiveness analysis.

The ACPA LCCA bulletin advises that the discount rate selected should take into account past trends and be routinely updated to reflect current and forecasted economic conditions. The bulletin recommends calculating the real discount rate from the interest and inflation rates representative of the local conditions. However, to avoid all complexities in calculating a real discount rate for use in LCCA, ACPA supports the use of the U.S. government's Office of Management and Budget (OMB) issued real discount rates.

The APA notes the difficulty of selecting the discount rate in life-cycle costing, due to the uncertainty associated with future interest rates and inflation. It proposes using a real discount rate. The real discount rate is based on published information from the OMB.

The choice of a discount rate has been found to directly influence the LCCA outcomes [Gransberg 2004]. If for instance, a high discount rate is used in the analysis, alternatives with lower initial capital expenditure may be favored over those that involve higher future investments. Hence, the selection of a proper discount rate and the assessment of the sensitivity of the analysis using several discount rates is essential in life cycle cost analysis [Daniel et al. 2004].

A review of the discount rates across provincial agencies found that rate of discount ranging between 3 to 6 % is presently used. The discount rates currently used by agencies across Canada are outlined as follows.

Alberta	Alberta's Benefit Cost Model recommends that a real discount rate should be used to account for the time value of money, and bring all future dollar values back to the base year. Accordingly, the model uses a real discount rate of 4%.
British Columbia	The British Columbia Ministry of Transportation & Infrastructure uses real discount rate prescribed by the B.C. Ministry of Finance. The current discount rate used is 6%.
Manitoba	There is no fixed discount rate in Manitoba's LCCA guide. Manitoba's Transportation and Infrastructure uses the discount rate prescribed by the departments Financial Services. Currently, a discount rate of 3% is used.
Nova Scotia	The Nova Scotia Transportation & Public Works (NSTPW) uses a discount rate of 4%.
Ontario	Ontario uses a social nominal discount rate, which reflects the social benefits foregone by not investing funds elsewhere in the economy. As of October 2016, the discount rate used by MTO to convert future costs to present-day costs is set at 4.5% (from 0 to 30 years) and 4% (from 31 to 75 years).
Quebec	Quebec's policy document recommends a discount rate of 5%, with a standard deviation of 0.5%.
Saskatchewan	Saskatchewan's Ministry of Highways & Infrastructure uses a discount rate prescribed by Saskatchewan's Ministry of Finance. The discount rate mostly used is 4%. No discount rate is used when using the equivalent annual cash flow method.

Recommended Practice	Real discount rates are recommended for the discounting of future investments. Due to significant fluctuations in real discount rate in Canada over the last five decades, a 10-year rolling average discount rate is recommended for use in LCCA. The 10-year average discount rate for the period between 2006 – 2015 is approximately 1.9%. It is also recommended that the discount rate is routinely updated to reflect current economic conditions.

2.4 AGENCY COSTS

Agency costs include all costs incurred directly by the agency over the life of the project. These consist of the costs of initial construction, future maintenance, and rehabilitation, and associated administrative and engineering costs. Residual value is a negative agency costs representing the expected value of the pavement alternative at the end of the analysis period.

ACPA's LCCA bulletin defines the residual value in one of three ways: the net value of the pavement if it is recycled at the end of its life (salvage value), the value of the remaining service life (RSL) at the end of the analysis, or the value of the existing pavement as a support layer for an overlay at the end of the analysis period. Several factors may affect the residual value of a pavement structure including: volume, location, durability, degree of contamination, and anticipated use at the end of design period [Uddin et. al. 2013].

There is no general consensus in the literature on how to determine the residual value of a pavement alternative. Furthermore, due to the uncertainty in accurately determining the residual value of a pavement alternative, residual value has often been overlooked in the life cycle cost analysis. Adjusting the analysis period so that the all pavement alternatives have equal serviceable life has been suggested as an approach to omit the residual value from calculations [Ozbay et. al. 2003].

The approach outlined in the FHWA Technical Bulletin entails determining the value of the remaining serviceability of the alternative as a prorated share of the last rehabilitation cost. The APA position paper suggests using the FHWA approach or considering the residual value as some percentage of the initial pavement construction cost. The ACPA bulletin on the other hand, suggests estimating the residual value of alternatives either as a salvage value, RSL, or value of alternatives if used as a support layer.

The accurate estimation of initial agency costs is a critical step in LCCA. Hence, to ensure the objectivity and credibility of the agency cost estimates, the U.S. Government Accountability Office (GAO) provides further guidance on developing and managing capital program costs, supplementing the FHWA LCCA guideline. The GAO's Cost Guide offers guidance on the cost-estimating process, use of independent cost estimates, documentation of analysis, and when to update a cost estimate. The Cost Estimating and Assessment Guide (GAO-09-3SP) details the best practices in developing reliable cost estimates.

Sustained competition between paving industries can also help ensure that the cost estimates used for LCCA are viable. Based on agency bid information published by Oman Systems, agencies with more balanced paving markets are generally found to see lower costs and less variability in unit prices for both asphalt and concrete pavement. Hence, instilling completion between pavement industries can help agencies maintain predictable and low unit prices [Mack et al. 2016].

The method currently used by the provincial agencies for determining the residual value of pavement alternatives is summarized as follows.

Alberta	In Alberta's Benefit Cost model, the residual value is estimated based on the remaining life of the asset beyond the 80-year forecast timeframe. The determination of the residual value involves a simple calculation using a linear relationship for the value remaining in the last rehabilitation treatment.
British Columbia	British Columbia's Ministry of Transportation & Infrastructure accounts for the residual value at the end of the analysis period. The present value of the residual value is estimated as a percentage of the initial cost. The residual value of resurfacing is estimated as: Resurfacing cost * (1-N/10), where N is the number of years remaining to the end of the analysis period.
Manitoba	Manitoba's LCCA guide accounts for the residual value of the final rehabilitation treatment at the end of the analysis period.
Nova Scotia	Nova Scotia's Transportation & Public Works (NSTPW) assumes the residual costs of alternatives to be equal and thus does not factor in the residual value in LCCA.

Ontario	In MTO's LCCA procedure, the residual value is determined at the end of the analysis period by dividing the remaining life of the last rehabilitation treatment, by the expected life of that treatment. The result is then multiplied by the cost of the last rehabilitation. The basic equation used is as follows: $SV = (L_{rem}/L_{exp}) * C_{pvt}$ Where: SV = Salvage value, $; L_{rem} = Remaining life of last rehabilitation treatment, years; L_{exp} = Expected life of last rehabilitation treatment, years; and C_{pvt} = Cost of final rehabilitation treatment, $. The resulting residual value is then converted to a PW benefit.
Quebec	Quebec's policy document accounts for the residual value of the pavement at the end of the analysis period.
Saskatchewan	Saskatchewan's Ministry of Highways & Infrastructure does not consider the residual costs when evaluating alternate treatment options.

Recommended Practice	In developing the agency cost estimates, it is recommended to use GAO's Cost Estimating Guidelines to ensure the estimate reflects actual costs and changes. The agency costs should include all the costs incurred by the agency over the life of the project, including: initial construction costs; future rehabilitation and maintenance costs; and supplemental costs, such as design and overhead expenses. The remaining value of the investment at the end of the analysis period should also be included as a negative cost. The prorated method is the recommended method to estimate the residual value of alternatives.

2.5 USER COSTS

User costs are the indirect costs which accrue to the road user over the life of the project. User costs are an aggregation of three cost components: delay-of-use costs, vehicle operating costs, and collision costs. The *delay-of-use (user delay)* costs are costs that develop when the normal flow of traffic is disrupted due to construction or rehabilitation works. *Vehicle operating costs (VOC)* are user costs incurred as a result of a deteriorated and rough roadway. VOC includes costs associated with fuel and oil consumption, tire wear, maintenance, parts replacement, and vehicle depreciation [AASHTO 1993]. *Collision (crash) costs* on the other hand, are those costs attributed to motor vehicle collisions and include the costs of fatalities, injuries, and property damage.

Most literature on LCCA comment on the challenge of incorporating user costs into LCCA. The difficulty in quantifying user costs has been cited by many for the reluctance to incorporate user costs into life cycle cost analysis. In addition, user costs are often found to substantially exceed agency costs. This compels decision makers to give less weight to user costs than to their own agency cost figures [FHWA 2002]. Capping user costs at a percentage of agency costs preventing user costs from overwhelming agency costs has been adopted by some state agencies to overcome this problem [Salem et al. 2008]. Another approach includes integrating user costs in selection only when the life cycle of alternatives is within 10% of the alternative with the lowest life cycle cost [Salem et al. 2008].

The FHWA guideline recommends including user costs associated with work zone operations in LCCA. These costs reflect the costs incurred during periods of activities that generally restrict the capacity of the facility and disrupt the normal traffic flow. The guideline identifies seven work zone user costs components. These include: speed change delay, speed change VOC, reduced speed delay, stopping delay, stopping VOC, queue idling VOC, and queue speed delay. The FHWA bulletin provides a detailed twelve-step procedure for calculating the user costs components during a work zone operation. A summary of the procedures is presented below.

Step 1: Project future year traffic demand.
This step involves projecting future year hourly traffic demand volumes for each vehicle class for the year the work zones will be in place, from current or base year AADT, using compound traffic growth factors.

Step 2: Calculate work zone directional hourly demand.
In this step, directional hourly traffic distribution is determined from agency traffic data on the roadway being analyzed or from traffic data on similar facilities. If such data is not available, the guideline suggests using default hourly distributions for various roadway types in urban and rural settings from MicroBENCOST (Texas Transportation Institute’s Benefit Cost Analysis software package).

Step 3: Determine roadway capacity.
This step requires determining the capacity of the road under three conditions: (i) the free flow capacity of the facility under normal operating condition, (ii) the capacity of the facility when the work zone is in place, and (iii) the capacity of the facility to dissipate traffic from a standing queue.

Step 4: Identify the user cost components.
The fourth step entails comparing the roadway capacity with the hourly demand for the facility.

Step 5: Quantify traffic affected by each component.
This step quantifies the number of vehicles involved with each cost component. This requires identification of the number of the vehicles that traverse the work zone, traverse the queue, stop for the queue, and slow down.

Step 6: Compute reduced speed delay.
The next step is the computation of the delay time through the work zone and queue.

Step 7: Select and assign VOC cost rates.
This step assigns VOC rates to vehicle classes.

Step 8: Select and assign delay cost rates.
This step assigns the delay cost rates to each vehicle class.

Step 9: Assign traffic to vehicle classes.
This step entails the distribution of the directional traffic affected by the various cost components to the appropriate vehicle classes for each cost component.

Step 10: Compute individual user costs components by vehicle class.
This step involves computation of daily user costs by vehicle class for each cost component by multiplying the affected traffic by the appropriate unit cost rates (either VOC or delay) for the various components.

Step 11: Sum total work zone user costs.
In this step, the sum total of work zone user costs is determined.

Step 12: Address circuitry and crash costs.
The final step in calculating user costs addresses circuity and crash costs. Circuity refers to the additional mileage that users travel on a detour to avoid a work zone.

The FHWA recommended values of travel time per vehicle (delay cost rates) are shown in Table 2.3.

Table 2.3: FHWA Recommended Values of Travel Time [Walls et al. 1998]

Passenger Cars	Trucks	
	Single-Unit	Combinations
$10 to 13	$17 to 20	$21 to 24

For the calculation of work zone crash costs, the FHWA Technical Bulletin recommends using MicroBENCOST default crash cost rates shown in Table 2.4. The table shows the crash rate by facility and collision type. The collision types are categorized into: fatality, non-fatal injury, and personal damage only (PDO).

Table 2.4: MicroBENCOST Default Crash Cost Rates ($1000, August 1996$) [Walls et al. 1998]

Intersection or Facility Type	Fatality		Nonfatal Injury		PDO	
	Rural	Urban	Rural	Urban	Rural	Urban
RR Grade Crossing	$1.125	$1.109	$28.1	$14.8	$1.77	$3.45
Intersection/Interchange	$1.182	$1.040	$24.4	$16.0	$2.21	$1.51
Bridge	$1.240	$1.091	$27.8	$16.0	$2.39	$1.42
Highway Segment	$1.240	$1.091	$27.8	$16.0	$2.39	$1.42

ACPA's guide identifies three primary forms of user costs: work zone user costs, vehicle operating costs, and delay costs due to capacity issues and accidents. It recommends considering any user costs that differ significantly among the alternatives being compared, alongside the agency costs in an LCCA. The APA on the other hand, considers only the user delay costs to reflect the costs of construction delays incurred by the public.

Road user costs in HDM-4 are calculated by predicting physical quantities of resource consumption and then multiplying these quantities by the corresponding user specified unit costs. The models used in HDM-4 to quantify the road user cost components are summarized in Table 2.5 as follows.

Table 2.5: Models used in HDM-4 to quantify user cost components

Fuel Consumption	$IFC = max\ (FCmin,\ \xi\ Ptot\ (1 + dFUEL))$ Where: IFC is the instantaneous fuel consumption in mL/s, FCmin is the minimum fuel consumption in mL/s, ξ is the fuel-to-power efficiency factor in mL/kW/s, Ptot are the total vehicle power requirements, dFUEL is the additional fuel due to accelerations
Oil Consumption	$OIL = OILCONT + OILOPER*SFC$ Where: OIL is the oil consumption in L/1000 km, OILCONT is the oil loss due to contamination in L/1000 km, OILOPER is the oil loss due to operation in L/1000 km, SFC is the fuel consumption in L/1000 km
Tire Consumption	$TC = \frac{NUM\_Wheels*EQNT}{MODFAC}$ Where: TC is the tire consumption, NUM_Wheels is the number of wheels, EQNT is the number of equivalent new tires consumed per 1000 km, MODFAC is the tire life modification factor
Maintenance and Repair	$PARTS = \{K0_{pc}\ [CKM_{kp}\ (a_0 + a_1\ RI)] + K1_{pc}\}\ (1 + CPCON\ dFUEL)$ Where: PARTS is standardized parts consumption as a fraction of the replacement vehicle price per 1000 km, CKM is the vehicle cumulative kilometer, CPCON is the congestion elasticity factor (default = 0.1), dFUEL is the additional fuel consumption due to congestion as a decimal, RI is adjusted roughness, $K0_{pc}$ is a rotational calibration factor (default = 1.0), $K1_{pc}$ is a translational calibration factor (default = 0.0), a_0, a_1 and k_p are model parameters $LH = K0_{lh}\ [a_0\ PC^{a_1}] + K1_{lh}$ Where: LH is the number of labor hours per 1000 km, $K0_{lh}$ is the rotation calibration factor (default = 1), $K1_{lh}$ is the translation calibration factor (default = 0), a_0 and a_1 are model constants

Vehicle Depreciation	$DEP = 1000 \frac{(1 - 0.01RVPLTPCT)}{LIFEKM}$ Where: DEP is the depreciation cost as a fraction of the replacement vehicle price, less tires, RVPLTPCT is the residual vehicle price in per cent, LIFEKM represents the lifetime utilization
Travel Time	$PWH = \frac{1000\ PAX\ {*}PCTWK}{100\ S}$ Where: PWH is the annual number of working passenger-hours per 1000 veh-km, PAX is the number of passengers (non-crew occupants) in the Vehicle, PCTWK is the percentage of passengers on work-purpose journey $PNH = \frac{1000\ PAX\ (100 - PCTWK)}{100\ S}$ Where: PNH is the annual number of non-working passenger-hours per 1000 veh-km, $CH = \frac{1000\ (100 - PP)}{100\ S}$ Where: CH is the number of hours per crew member per 1000 veh-km, PP is the percentage of vehicle use on private trips $CARGOH = \frac{1000}{S}$ Where: CARGOH is the annual number of cargo holding hours per 1000 veh-km
Safety	$ACCRATE = EXPOSURE\ ACCYR$ Where: ACCRATE is the accident rate in accidents per 100 million veh-km, ACCYR is the number of accidents per year, EXPOSURE is the annual exposure to accidents

In HDM-4, the road user costs can be calculated for motorized (motorcycles, cars, buses, trucks, etc.) and non-motorized transport (bicycles, human powered tricycles, animal pulled carts, etc.). Similar to the approach used by FHWA, HDM-4 can incorporate the work zone effects in the analysis. The HDM-4 work zone effects model calculates the travel time and VOC associated with speed change cycles at road works.

The review of the LCCA practices across provincial agencies found that with the exceptions of Alberta, British Columbia and Quebec, all other agencies generally exclude the user costs from LCCA. The user costs components currently considered by the provincial agencies are discussed as follows.

Alberta	Alberta's Benefit Cost model considers the three user cost components (VOC, travel time and collision costs) in the analysis. For estimating the vehicle running costs, the model recommends two approaches: the California and Texas approach. The *California (Fuel & Non-Fuel)* approach estimates vehicle running costs using fuel and non-fuel vehicle operating costs for each vehicle type based on the segment length and running speed. The vehicle operating costs under this option are currently based on a value of $0.505/km/passenger. The *Texas* approach is an approach recommended only when gradient and/or curvature improvements are an important feature of an alternative being evaluated. This option utilizes curvature and gradient cost factors to estimate VOC. The model estimates collision costs using collision rates per hundred million vehicle kilometers travelled for highway type and location (urban/rural). Six combinations of surface type (gravel/paved), and road type (2 lane, 4 lane undivided, 4 lane divided expressway, 4 lane divided freeway, 6+ lane) can be input into the model. The model also categorizes the collisions based on severity into: fatal, non-fatal injury and property damage only. The collision rates and cost by road and severity type are shown in Table 2.6 and Table 2.7, respectively. The value of travel time is quantified in terms of travel time costs, either for business/work related trips or non-business travel associated with leisure. The model uses the average wage rates to measure the cost of travelers' time for business/work related trips. For leisure trips, 50% of the rate used for business/work travel time is used.
British Columbia	British Columbia's Ministry of Transportation & Infrastructure considers all 3 categories of road user costs in LCCA. The report document on Default Values for Benefit Cost Analysis in BC provides details of the road user costs. The unit prices for automobile and truck operating costs, based on 2012 dollars, are shown in Table 2.8 and Table 2.9, respectively. The auto and bus value of travel time (in 2012 dollars) is estimated as $15.94/hr. The total time value of truck for 2012, including time related depreciation, fixed ownership fees, cargo costs and truck driver time is estimated as: $46.03 (straight truck) and $53.30 (combination truck). The average costs of collision costs (in 2012 dollars) are given as: $6,385,999 (fatal crash), $135,577 (non-fatal collisions), and $11,367 (property damage only crash).
Manitoba	Manitoba's guide does not include user costs for the purposes of the life cycle cost analysis. The difficulty in quantifying the user costs and the lack of an accepted model has been cited for the exclusion of user costs in the LCCA.
Nova Scotia	The Nova Scotia Transportation & Public Works (NSTPW) does not consider user costs in LCCA.
Ontario	MTO currently does not consider user costs in LCCA due to the difficulty of quantifying the user costs. The Asset Management Group at MTO is currently assessing the implementation of user cost models to accommodate user costs into LCCA.
Quebec	Quebec's policy document on pavement type selection considers the cost to road users due to traffic delays during construction and rehabilitation work. The user delay costs are determined based on the following factors: the number of days traffic will be affected, the direction(s) affected, the proportion of traffic affected in a given direction, roadway capacity, hours of work, speed reductions at the work zone, the presence or absence of a detour, and the inflation factor.
Saskatchewan	Saskatchewan's Ministry of Highways & Infrastructure does not incorporate user costs in LCCA.

Recommended Practice	User costs are proposed to be used as secondary decision criteria for equivalent alternatives. One or more alternatives are considered to be equivalent, when the NPW of alternatives is within 10% of the alternative with lowest NPW. For the analysis of the user costs, QuickZone 2.0 is proposed.

Table 2.6: Rural Collision Rates by Road and Surface Type [Alberta Transportation 2015]

Surface Type	Road Type	Collision Rate	Fatal Collision	Injury Collision	PDO	Total
Gravel	2 Lane (gravel)	136,630	0.6%	14.9%	84.5%	100.0%
Paved	2 Lane (paved)	117,330	1.1%	11.7%	87.2%	100.0%
Paved	4 Ln Undivided	78,580	0.0%	0.0%	100.0%	100.0%
Paved	4 Ln Divided @ Grade	61,300	0.7%	15.4%	83.9%	100.0%
Paved	4 Ln Divided Not @ Grade	54,590	0.4%	17.7%	81.9%	100.0%
Paved	6 + Lanes	54,510	0.4%	18.2%	81.4%	100.0%

Table 2.7: Collision Cost by Road Type and Severity [Alberta Transportation 2015]

Type	Fatal Collision	Injury Collision	PDO Collision
Rural	$ 9,120,367	$ 66,744	$ 5,851
Urban	$ 9,464,015	$ 59,919	$ 8,520

Table 2.8: Unit Prices for Automobile Operating Costs – BC (2012) [Apex Engineering Limited 2012]

Vehicle Type	Fuel Costs ($/L)	Oil Costs ($/L)	Tires Cost ($/vehicle)	Depreciation ($/vehicle)	Maintenance & Repair ($/1000km)
Small Passenger	$0.898	$4.40	$384	$20,535	$21.80
Medium/large Passenger	$0.898	$4.40	$588	$25,365	$46.00
Pickup/van	$0.898	$4.40	$964	$30,820	$25.50
Buses	$0.978	$4.00	$3,200	$400,000	$538.40

Table 2.9: Unit Prices for Truck Operating Costs – BC (2012) [Apex Engineering Limited 2012]

Vehicle Description	Fuel ($/L)	Oil ($/L)	Tires ($/vehicle)	Value for Depreciation ($/Vehicle)	Maintenance and Repairs ($/1000km)
2-Axle Single Unit	$0.90	$4.40	$2,400	$23,582	$538
3-Axle Single Unit	$0.39	$4.40	$4,000	$27,000	$538
4-Axle Semi	$1.29	$4.40	$5,600	$32,000	$403
5-Axle Semi	$0.00	$4.40	$7,200	$39,433	$403
6-Axle Semi	$0.18	$4.40	$8,800	$44,476	$792
A, B or C Train	$0.21	$4.40	$12,000	$47,978	$929

2.6 ENVIRONMENTAL COSTS

Environmental costs are costs associated with the negative environmental impacts of project alternatives. Environmental impacts may be in forms of emissions, noise pollution, visual pollutions, etc. [Hudson et. al. 1997]. Among these, only the costs of air pollution and noise have been monetized in the evaluation of transportation projects [Ozbay et al. 2003].

Environmental costs are usually difficult to quantify and often not considered fully in analyzing transportation alternatives [Lamptey et al. 2005]. Few LCCA tools consider environmental costs for alternative investment strategies. Among them, the Highway Development and Management Tools (HDM-4) model developed by the World Bank, is noted in the literature as a comprehensive tool for the environmental as well as economic evaluation of alternatives. The model generates the environmental costs based on three environmental externalities of vehicle use: emissions, noise, and energy consumption. The HDM-4 guide [Bennett et al. 2001] discusses in detail how the environmental effects are calculated in the model. A summary of the procedures is presented as follows.

The model estimates the effect of the following air pollutants associated with vehicle emissions: Hydrocarbons (HC), Carbon Monoxide (CO), Carbon Dioxide (CO2), Nitric Oxides (NOx), Sulphur Dioxide (SO2), Lead (Pb) and Particulate Matter (PM). The emission rates are predicted using the following formula:

$TPEi = EOEi \times CPFi$

Where:
TPEi is the tailpipe emissions in g/km for emission type i;
EOEi is the engine out emission in g/km for emission type I, and
CPFi is the catalyst pass fraction for emission type i.

The HDM-4 model recommends accounting for the impact of noise traffic in urban areas, particularly in areas where there is a significant population bordering a heavily trafficked road. The model estimates the economic cost of noise effect as a function of the value of the pavement alternative as:

$$NSCST = \frac{[L_{eq}(24h) - 50]\ PV\ \frac{DR}{FR}}{\frac{NUM\_LANES}{2}}$$

Where:
Leq is the equivalent acoustic level measured over a 24- hour observation period,
PV is property value in cost/property,
DR is depreciation rate per excess dB (A),
FR is property frontage width in meters, and
NSCST is the noise cost in cost/lane-m.

For energy balance analysis, HDM-4 considers the energy used by motorized and non-motorized vehicles as well as the energy used for construction, maintenance and rehabilitation works. The energy consumption is measured by the following indicators:

- Average energy use per kilometer by mode;
- Energy use per passenger kilometer for passenger transport modes; and,
- Energy use per ton kilometer for freight transport modes.

The environmental impact of pavement projects can be exclusively assessed, without incorporating the associated costs into the LCCA. The Athena Pavement LCA software, formerly known as the Impact Estimator for Highways, is one tool that can be used to assess the environmental impacts only of alternative pavement options. The tool compares the impacts of materials production, construction, and maintenance & rehabilitation activities of options over a given analysis period. The applications of the tool for weighing the environmental implications of alternatives, to aid in decision making, has been documented in the literature [Ahammed et al. 2016].

Greenroads® Rating System is another tool used to measure and manage sustainability on transportation projects. Categories of environmental assessment in Greenroads include: Environment & Water, Access and Equity, Construction Activities, Materials & Resources, and Pavement Technology. Eligible construction projects can be certified through this tool, for a fee, to be Bronze, Silver, Gold or Evergreen certified.

The FHWA, ACPA and APA guidelines do not incorporate environmental costs into the LCCA. The review of provincial agencies also revealed that, apart from Alberta, no provincial agency considers environmental costs. The environmental costs considered in Alberta's Benefit Cost Model are summarized below. Ontario, Quebec, and British Columbia consider environmental impacts of pavement projects outside the LCCA realm.

Alberta's Benefit Cost Model includes the emissions component of environmental costs in the LCCA. The model estimates emission costs. Emission cost are based on fuel consumption per number of vehicle kilometers travelled by each vehicle type, and running speed on each segment of the project. These calculations are based on data from the California Life-Cycle Benefit/Cost Analysis Model, including the emission values. The effect of six pollutants is considered in the emissions calculations. The emission costs (per tonne/km) for the pollutants considered in the model are listed as follows.

- CO (Carbon Monoxide): $96.50
- CO2 (Carbon Dioxide): $40.00
- NOx (Nitrogen Oxides): $30,000.00
- PM10 (Particular Matter): $244,000.00
- SOx (Sulphur Oxides): $102,000.00
- VOC (Volatile Organic Compounds): $2,000.00

Ontario uses GreenPave, a rating system that evaluates the sustainability of pavements (in new construction and rehabilitation projects). It measures the "greenness" of design alternatives and construction practices. Projects ae evaluated on criteria under four categories. The 'greenness" of a project is rated based on the total number of points scored. An overview of the categories evaluated in GreenPave and the credit point distribution is illustrated in Figure 2.1 below.

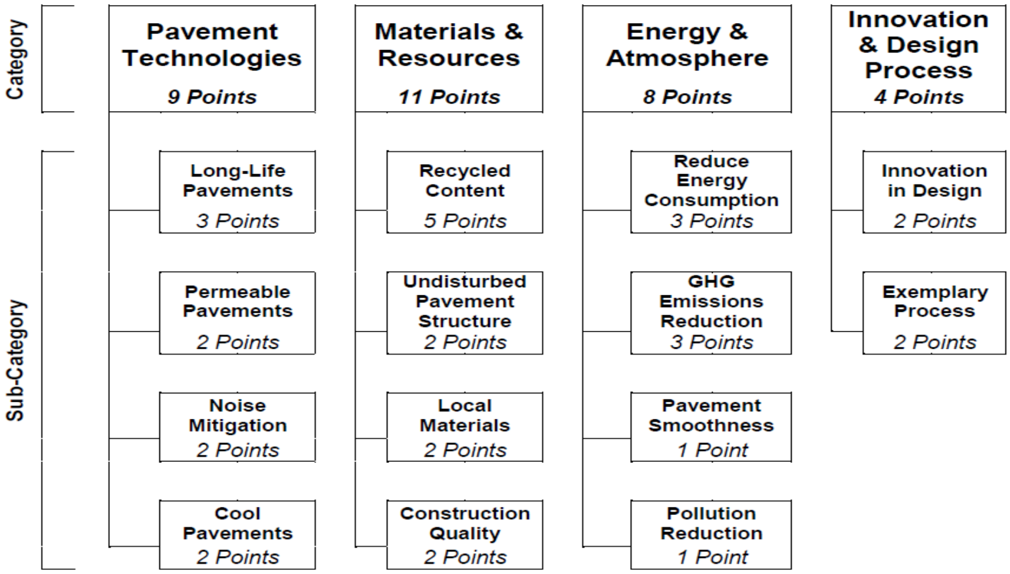

Figure 2.1: Overview of Categories and Credit Point Distribution in GreenPave [MERO 2014]

Quebec considers project-relevant parameters related to environmental impacts in Multicriteria Analysis (MCA). In MCA analysis is completed on quantifiable and non- quantifiable criteria. The criteria importance varies depending on the pavement option, and the selection of an option with the highest overall score in criterions considered. Criterions relating to environmental impacts assessed in MCA include: traffic noise, reuse of waste from reconstruction, pollution due to fuel consumption, quality of ecosystem & climate change, and resource depletion.

British Columbia uses Multiple Account Evaluation (MAE) to evaluate the environmental, economic development, and social/community impacts of road projects, in addition to the evaluation of the agency costs and road user benefits of projects. Land requirements, fuel, CO, site rehabilitation, wildlife, water pollution are typical issues considered in the environmental impact assessment of options. Noise pollution is evaluated under the social impact account of MAE.

Recommended Practice	Environmental costs are proposed to be used as secondary decision criteria for equivalent alternatives. One or more alternatives are considered to be equivalent, when the NPW of alternatives is within 10% of the alternative with lowest NPW. For comparison of environmental impacts of equivalent alternatives, the Athena Pavement LCA software is proposed.

2.7 ECONOMIC EVALUATION METHOD

There are various methods available for the evaluation of investment options. The most common methods include: Net Present Value, Equivalent Uniform Annual Costs, Benefit-Cost Ratio, Internal Rate of Return and Break Even Point. FHWA's LCCA guide, Transport Canada's Guide to Benefit-Cost Analysis, and ACPA's LCCA guide discuss these methods as follows.

Net Present Value (NPV), also called *Net Present Worth (NPW)*, is the discounted monetary value of expected net benefits, computed by subtracting discounted costs and negative effects from discounted benefits. A positive NPV implies that selection of that option would leave society better off than it would be with the do- nothing scenario. Any option with a negative NPV is considered to be economically undesirable and is generally recommended to be avoided. The preferred option, from an economic perspective, is noted to be the one with the largest positive NPV.

Equivalent Uniform Annual Costs (EUAC) refers to the NPV of all discounted cost and benefits of an alternative spread uniformly over the analysis period. EUAC is noted to be particularly useful when comparing alternates with different analysis periods, assuming that the same set of activities will be repeated indefinitely.

Internal Rate of Return (IRR) represents the discount rate necessary to make the discounted cost and benefits equal (i.e. NPV of zero). The calculation of IRR is the reverse of the process for determining the NPV. While the IRR does not generally provide an acceptable decision criterion, it is recognized to provide useful information, particularly in situations of budgetary constraints or uncertainty over the appropriate discount rate.

Benefit-Cost Ratio (B/C Ratio) represents the present value of the discounted benefits divided by the present value of the discounted costs and negative effects. When using B/C ratio method, an option is considered attractive if the ratio is greater than 1.0. The preferred option, from an economic perspective, is pointed out to be the one with the highest ratio. The B/C ratio method is deemed to be unsuitable for the evaluation of pavement projects because of the difficulty in sorting out benefits and costs arising from the projects. Other drawbacks associated with this method include, difficulty in valuation of benefits and in the identification of the option with the greatest payoff.

Break Even Point (also known as *Pay-back Period),* refers to the time period required for the investment returns to recover the investment costs. The Break-even point is indicated to be a poor measure of economic desirability of alternatives, because it ignores net benefits beyond the payback period.

The FHWA recommends the NPW method for evaluating project alternatives. The FHWA also recognizes the Uniform Equivalent Annual Cost as an acceptable indicator of economic efficiency, provided it is derived from NPV. Benefit/Cost (B/C) ratios are generally not recommended by the FHWA, because of the difficulty in sorting out cost and benefits for use in the B/C ratios.

ACPA's guideline and APA's position paper similarly endorse the use of NPW method to compare alternates. The ACPA in addition, suggests the use of EUAC method to compare alternates with different analysis periods. The HDM-4 model on the other hand uses four economic indicators to assess the economic feasibility of project alternatives, including the base-line alternative. These include: Net Present Value, (Internal, and First Year) Rate of Return, and Benefit Cost ratio.

The economic criterion method(s) currently used by agencies across Canada are summarized as follows.

Alberta	Six measures are used in Alberta's Benefit Cost Model. These include: IRR, NPV, B/C Ratio, Break Even Point, Investment Costs, and Non-Investment Cost Savings. The relative desirability of each alternative is compared to the base scenario (doing-nothing) alternative using all six measures (where applicable). The model defines *Break Even Point* as the time required for the investment returns to recover the investment costs. The *Investment Costs* is defined as the net present value of construction plus any rehabilitation costs that are invested in the project over the forecast period, minus the residual value of the project at the end of the forecast period. The *Non-Investment Cost Savings* associated with each Alternative, is described as the cost savings for that Alternative as compared to the base alternative.
British Columbia	Net Present Worth and Benefit Cost Ratio methods are used by British Columbia's Ministry of Transportation & Infrastructure for benefit cost analysis.
Manitoba	Net Present Worth method is recommended for comparison of alternatives in Manitoba's guide.

Nova Scotia	Net Present Worth method is used by Nova Scotia's Transportation & Public Works (NSTPW) to compare the economic feasibility of alternatives.
Ontario	Net Present Worth method is the preferred method for comparing alternative pavement designs by MTO.
Quebec	Net Present Value is Quebec's policy document recommended method for evaluating alternate pavement options.
Saskatchewan	Net Present Worth and Equivalent Annualized Cash Flow (EACF) methods are used by Saskatchewan's Ministry of Highways & Infrastructure in the economic analysis of alternate treatments.

Recommended Practice	The Net Present Worth (NPW) method is the recommended measure of life cycle costs of competing alternatives.

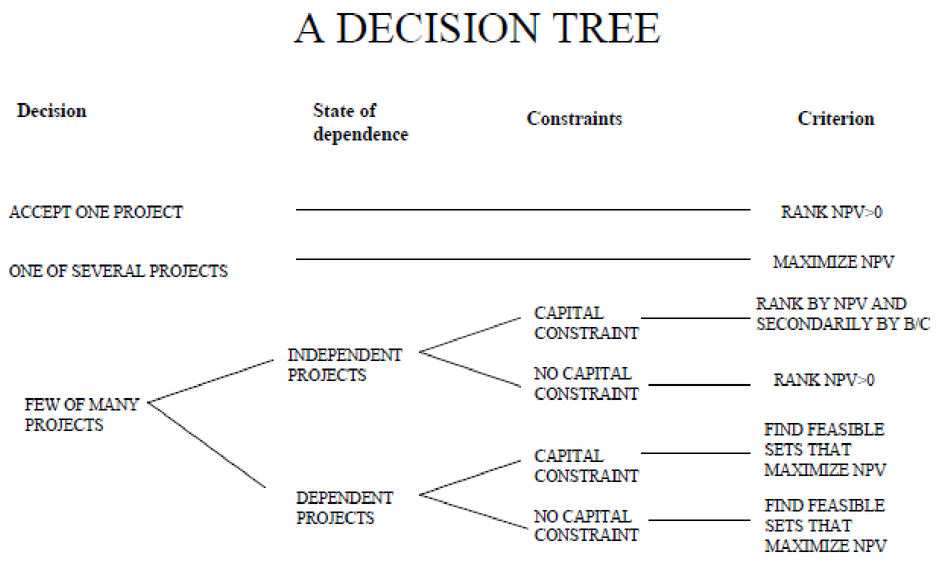

Figure 2.2: Decision Tree used by BC's Ministry of Transportation & Infrastructure for the Selection of Projects

2.8 LCCA COMPUTATIONAL APPROACH

Two computational approaches may be used for the life cycle cost analyses: deterministic and probabilistic. The FHWA Interim Bulletin [Walls et al. 1998] differentiates between the two approaches as follows. The *deterministic approach* applies procedures and techniques without regard for the variability of the inputs. The *probabilistic approach* on the other hand, characterizes uncertainty by combining probability descriptions of analysis inputs using computer simulations, to identify a range of outcomes as well as the likelihood of occurrence. While the probabilistic approach defines the input parameters by frequency or probability distribution, the deterministic approach treats the inputs as discrete fixed values. The inputs for a deterministic-based LCCA are usually derived from historic data or engineering judgement.

The literature recommends the use of the probabilistic approach to compute lifecycle cost analyses as it accounts for the variability associated with the input parameters. However, if historical data are unavailable to model a probability distribution for the uncertain inputs, the use of the deterministic approach with sensitivity analyses on inputs is acceptable [Ozbay et al. 2004].

Sensitivity analysis involves varying the input parameters and testing how this affects the outcome. The Guide to Benefit-Cost Analysis in Transport Canada [Transport Canada 1994] suggests using any of following risk factors for sensitivity analysis: traffic forecasts, discount rate, fuel prices, cost estimates, technology and technical performance, logistics, and timing of future activities. Other factors used include the roughness, speed limit, and traffic sensitivity of road user costs [Bennett et al. 2001].

Although sensitivity analysis addresses the concerns associated with the uncertainty of some input parameters, it suffers from three limitations [Christensen et al. 2005]. The first issue relates to the difficulty of identifying the dominant alternative among considered design options, when input parameters such as discount rate are varied and the ranking of the alternatives is disturbed. The second shortcoming is the inability of sensitivity analysis to give decision makers insight into the combined and simultaneous influence of the variability of several input parameters on LCC outcomes. Thirdly, due to the absence of probability distributions, sensitivity analysis fails to predict the likelihood that particular values will occur.

Realizing the limitations in the deterministic sensitivity analysis, the FHWA promotes the use of a probabilistic-based LCCA. ACPA also recognizes the advantages of using the probabilistic LCCA procedure. The APA also uses the principles recommended by FHWA and employs software that use either deterministic or probabilistic analyses. The FHWA Interim Bulletin provides a detailed discussion on the probability-based LCCA. A summary of the steps used in the probabilistic approach is presented below.

Step 1: Identify the structure and layout of the problem
This step involves reducing the problem to its most basic elements and describing it in the form of an analytical model.

Step 2: Quantify uncertainty using probability
The second step is to develop probability distributions for the uncertain variables identified in the first step. Different types of probability distribution may be used. The most commonly used distribution types include: normal, uniform, triangular distributions.

Step 3: Perform simulation
The next step is to run a simulation of the model to obtain results. A simulation is essentially a rigorous extension of a sensitivity analysis using the Monte Carlo sampling process. This process

uses different randomly selected sets of values from the input probability distributions to calculate separate discrete results. The results are arrayed in the form of a distribution covering all possible outcomes.

Step 4: Analyze and interpret results
The final step of the probabilistic approach is the interpretation of the results. This involves the comparison of the probability distribution of the alternatives to gauge the risk associated with each alternative.

The LCCA computational approaches adopted by the provincial agencies is as follows.

Alberta	Deterministic-based LCCA is used by Alberta Transportation. Sensitivity analysis can be optionally performed for the discount rate and four costs: capital, operating & maintenance, road user and emissions costs.
British Columbia	Deterministic-based LCCA, with sensitivity analysis is used by BC's Ministry of Transportation & Infrastructure. The Benefit Cost Guideline recommends investigating the sensitivities of the following: • Optimal timing of the preferred option, • ± 2 % variation in discount rate, • ± 10 % variation in capital cost estimates, • ± 25 % variation in capital cost estimates, • ± 10 % variation in base year traffic volumes and proposed routes, and • ± 0.5 % variation in traffic growth rates for the existing and proposed routes. The guideline also suggests the optional investigation of the sensitivities of the following: • Duration of construction, • Timing of rehabilitation, and • Claim (accident) costs.
Manitoba	Deterministic-based LCCA is used by Manitoba in the life cycle cost analysis of pavement projects.
Nova Scotia	Deterministic-based LCCA is used by Nova Scotia's Transportation & Public Works (NSTPW).
Ontario	Deterministic-based LCCA is used by MTO for routine life cycle cost analysis. However, a probabilistic LCCA is recommended for complex projects particularly when alternative bids maybe considered between rigid and flexible pavements. A probabilistic-based LCCA is used for high-volume roadways with greater than 1 million ESALs per year (design lane, current or projected within 5 years), for all freeways and 400 series highways, and for all concrete pavements (any facility type). For the probabilistic analysis, normal probability distributions are assigned to the following inputs, using the recommended mean and standard deviation values for: discount rate, unit cost of individual pay items, service life of each initial pavement type and service life of each rehabilitation type.
Quebec	Probabilistic-based LCCA is recommended in Quebec's policy document. The document also recommends evaluating the uncertainties affecting the following parameters: discount rate, activity lifetime, activity costs, and traffic growth rate.
Saskatchewan	Deterministic-based LCCA is used by Saskatchewan's Ministry of Highways & Infrastructure.

Recommended Practice	A probabilistic approach is recommended for LCCA. However, given the lack of historical data to model a probability distribution for the uncertain inputs, a deterministic-based computational approach with sensitivity analysis may be acceptable. Sensitivity analyses should account at minimum the variability in the discount rate. The variations in the discount rate suggested for sensitivity analyses is ± 1.5 %.

2.9 LCCA TOOL/SOFTWARE

Different LCCA packages are used by transport agencies across the globe to analyze life cycle costs of pavements. Comprehensive LCCA tools noted in the literature include; RealCost, APA model, StreetPave, and HDM-4 package. A brief description of the packages is presented as follows.

RealCost is FHWA's MS Excel based LCCA software package that is designed according to the FHWA Technical Bulletin. It calculates life-cycle values for both agency and user costs associated with construction and rehabilitation. The software also automates FHWA's work zone user cost calculation method. RealCost can perform both deterministic sensitivity analysis and probabilistic risk analysis of pavement alternatives.

Asphalt Pavement Alliance (APA) model is also based on FHWA Technical Bulletin. It calculates the net present value of different pavement (up to four) alternatives using either probabilistic or deterministic analyses. The software has the ability to include or exclude user delay costs from the complete analysis or any single work activity. APA comes into two versions: LCCA Original and LCCAExpress. The latter APA version is a simplified version, geared to less complex projects.

StreetPave is a software package developed by the Asphalt Concrete Pavement Association (ACPA). It is structural design software, with an LCCA module which can perform a detailed cos/benefit analysis. The software can concurrently design equivalent concrete and asphalt pavements and evaluate the cost-effective alternative.

The *Highway Development and Management Tools (HDM-4)* model was developed by the World Bank and is widely used to appraise the technical and economic aspects of road investment projects. It estimates road user costs and benefits, infrastructure costs, and costs associated with vehicle externalities, including energy consumption and emissions for alternative investment strategies. The software can be used for the analysis of projects, programs, or the strategic analysis of road networks. HDM-4 serves as a tool for the analysis, planning, management and appraisal of road maintenance, improvements, and investment decisions.

The LCCA tool currently used by Canadian agencies is summarized below.

Alberta	An MS Excel Spreadsheet based on the Benefit Cost Model is used in Alberta to calculate life cycle costs.
British Columbia	MS Excel based spreadsheets ShortBEN and Safety-BenCost are used by BC's Ministry of Transportation & Infrastructure. ShortBEN is used for preliminary evaluation of highway projects, and calculates the NPW and BC ratio based on incremental costs and benefits (sans safety benefits). Safety-BenCost quantifies the safety improvements based on the Ministry's Collision Prediction Model (CPM) and Collision Modification Factor (CMF). Other tools used for Benefit-Cost Analysis include: Conceptual Cost Estimating Tool, Highway Cost Estimating using the Elemental Parametric Method, and Highway Planning Cost Estimating System.
Manitoba	FHWA's RealCost is adopted by Manitoba for the calculation of pavement life cycle costs.
Nova Scotia	The LCCA module in DARWin is used by Nova Scotia's Transportation & Public Works (NSTPW) to calculate life cycle costs of alternate pavements.
Ontario	MS Excel spreadsheet, with Crystal Ball® as add-in feature, is used by MTO. Crystal Ball®, a statistical software package, allows a probabilistic-based analysis for the selection of the alternative with the lowest LCC and the least risk. Ontario Pavement Analysis of Costs (OPAC) is also used by MTO to conduct LCCA of different alternatives. OPAC can calculate the various cost inputs including: initial construction costs, maintenance and rehabilitation costs, user costs and residual value. OPAC offers the option to exclude user costs in the analysis or to input other values.
Quebec	FHWA's RealCost is used by Quebec's Ministry of Transportation for life cycle cost analysis of pavement alternatives.
Saskatchewan	Microsoft Excel and Life Cycle Costing (LCC) software are used by Saskatchewan's Ministry of Highways & Infrastructure uses to determine the financial sustainability of preservation treatments.

2.10 SUMMARY

Based on the review of the LCCA practices discussed in the preceding sub-sections, the missing data, or gaps in terms of best practices were identified. Table 2.10 gives an overview of the gap analysis of the LCCA practices between the provinces considered in the study, the FHWA, ACPA, APA, and the World Bank. Any gap in the LCCA practice is highlighted with red (for complete gap) or yellow (for partial gap). Segments highlighted with green indicate no gap in terms of best practices.

Table 2.10: Gap Analysis of LCCA Practices

	LCCA Input Parameters										LCCA Computational Approach	LCCA Tools
	Analysis Period	Discount Rate	Economic Evaluation Method	Residual Value	User Costs			Environmental Costs				
					Vehicle Operating Costs	User Delay Costs	Crash Costs	Emission Costs	Noise Pollution Costs	Energy Consumption		
Alberta	User-defined (Up to 80 years)	Real discount rate: 4 %	NPW, IRR, B/C Ratio, Break Even Point, PW Costs, PW Benefits	Considered	All three user cost components considered			Only Emission Costs considered			Deterministic Sensitivity Analysis (optional)	MS Excel Spreadsheet
British Columbia	25 years	Real discount rate: 6%	NPW BC Ratio	Considered	All three user cost components considered			*Considered Independently			Deterministic (with Sensitivity Analysis)	ShortBEN, Safety-BenCost
Manitoba	50 years	Real discount rate: 3%	NPW	Considered	Not considered			Not considered			Deterministic	RealCost
Nova Scotia	40 years	Real discount rate: 4 %	NPW	Not considered	Not considered			Not considered			Deterministic	DARWin
Ontario	50 years	Nominal social discount rate: 4.5% (0 to 30 yrs.), 4% (31 to 75 yrs.)	NPW	Considered	Not considered			**Considered Independently			Deterministic Probabilistic	MS Excel with Crystal Ball®, OPAC 2000
Quebec	50 years	Real discount rate: 5%	NPW	Considered	Only user delay costs considered			*** Considered Independently			Probabilistic	RealCost
Saskatchewan	60 years	Real discount rate: 4%	NPW EACF	Not considered	Not considered			Not considered			Deterministic	MS Excel, LCC
FHWA	Minimum of 35 years	Real discount rate based on OMB	NPW (preferred), EUAC (also accepted)	Considered	Work zone user costs (VOC and delay) plus crash costs considered			Not considered			Probabilistic	RealCost
ACPA	45-50+ years	Real discount rate based on OMB	NPW EUAC	Considered	All three user cost components considered			Not considered			Probabilistic	StreetPave
APA	Minimum of 40 years	Real discount rate based on OMB	NPW	Considered	Only user delay costs considered			Not considered			Deterministic Probabilistic	LCCA Original, LCCAExpress
World Bank	User-defined	User-defined	NPW, IRR, FYRR, BC Ratio	Considered	All three user cost components considered			All three components of environmental costs considered			Deterministic (with Sensitivity Analysis)	HDM-4

*Considered in Multiple Account Evaluation.

**Considered using GreenPave Rating Scheme for equivalent alternatives.

***Considered in Multicriteria Analysis.

3.0 RECOMMENDED LCCA PRACTICE GUIDELINE

It has been found that agencies with a stronger balance of flexible and rigid pavement types see lower costs and less variability in unit prices. Increased competition between pavement industries can help agencies refine construction quality, reduce risks, and increase cost efficiency. Competition among asphalt and concrete industries can also bring value to the tax payers through reduced costs and extending of agency budgets. Figure 3.1 and 3.2 below illustrate the relationship between the share of spending on the two alternatives and the unit costs, based on agency bid information published by Oman Systems. Data shown in the figures reflect five-year average balances of pavement types used.

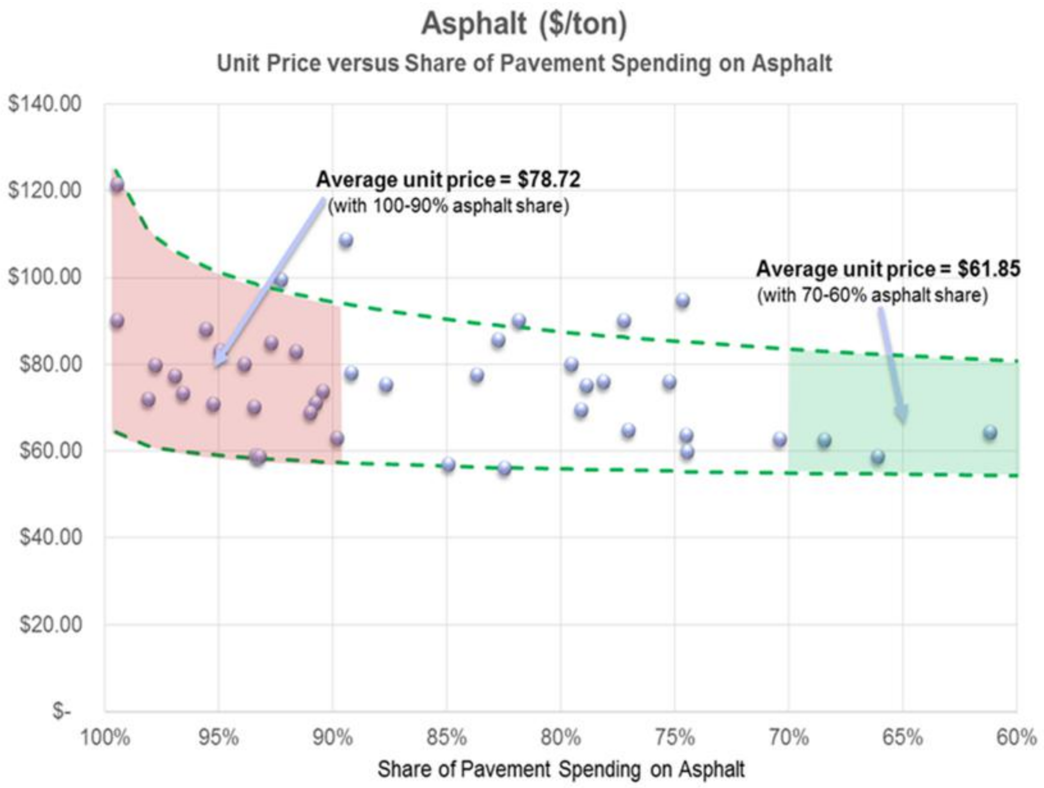

Figure 3.1: Average unit price vs. share of pavement spending for asphalt [Oman Systems, Bid Tabulation Database]

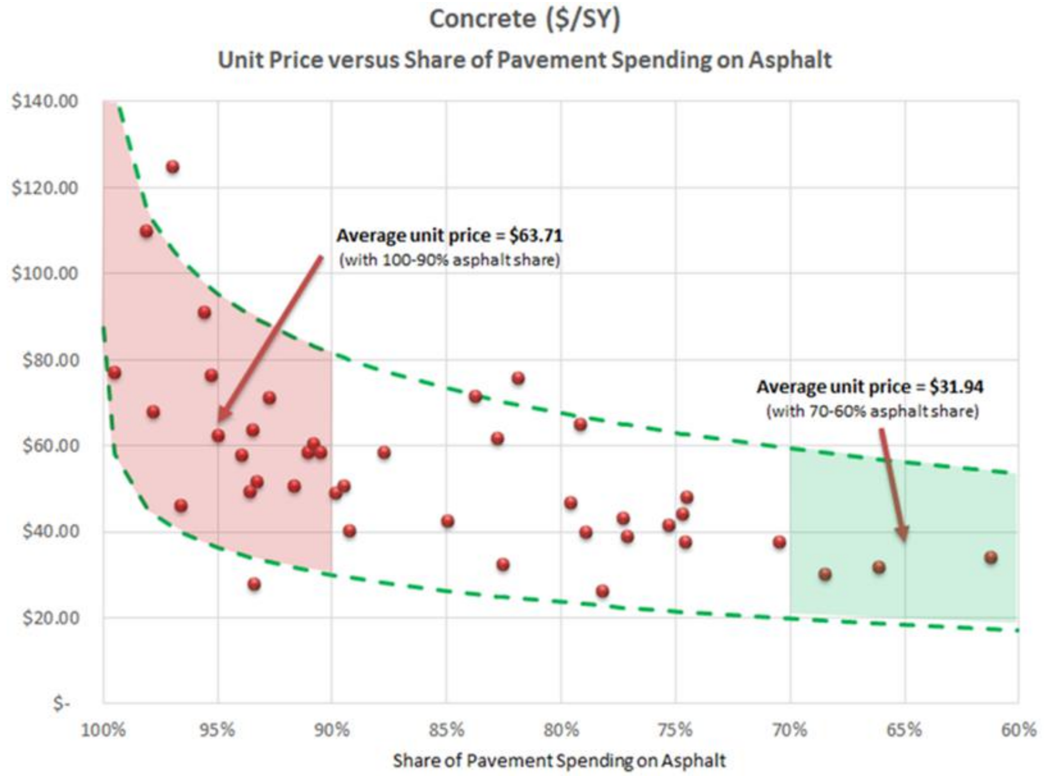

Figure 3.2: Average unit price vs. share of pavement spending for concrete [Oman Systems, Bid Tabulation Database]

Given the benefits of fostering a healthy competition between paving industries, it is important that a standard LCCA guide is developed to facilitate pavement type selection. Based on the review of LCCA practices, the recommended practices in conducting LCCA of pavement design are summarized as follows.

The study recommends that the selection of feasible alternatives should be primarily based on the life cycle analysis of agency costs. User costs and costs associated with environmental impacts are proposed to be used as secondary decision criterions for equivalent alternatives. One or more alternatives are considered to be equivalent, when the NPW of the alternatives is within 10% of the alternative with the lowest NPW.

For the analysis of the user costs, QuickZone 2.0, a spreadsheet-based tool designed by FHWA is proposed. QuickZone was developed to help project planners and engineers consider the impacts of alternate work zone and mitigation strategies on businesses, and motorists. The QuickZone software can estimate the work zone delays, and user costs during construction and maintenance activities. The cost analyses that can be conducted with the software include: travel time delay costs, vehicle operating costs, freight vehicles inventory costs, and economic costs to businesses due to a work zone. Information on QuickZone can be found at https://ops.fhwa.dot.gov/wz/traffic_analysis/quickzone/.

For comparison of environmental impacts of equivalent alternatives, the Athena Pavement LCA software is proposed. Athena Pavement LCA is a free web-based tool that provides environmental LCA results for Canadian regions. It includes a large database on regional materials manufacturing, roadway construction and maintenance life cycle stages. There is flexibility to specify unique pavement systems – sub-base and base granular materials as well as hot and warm mix asphalt and a host of user-specified concrete mix designs. The software allows for quick and easy comparison of multiple design options over a range of expected roadway life spans. The Athena Pavement LCA tool is available at https://pavementlca.com.

The proposed LCCA parameters are outlined below. Instructions for navigating the software, developed based on the parameters, are summarized in Appendix A.

Analysis Period	The analysis period over which alternatives are evaluated should be longer than the pavement service life and as a rule long enough to incorporate at least one rehabilitation activity. As most provincial agencies design concrete pavements with a service life of 30 years, a 50-year analysis period would be a reasonable time frame to include at least one major rehabilitation activity. Hence, an analysis period of 50 years is recommended for LCCA of competing pavement designs.
Discount Rate	Real discount rates are recommended for the discounting of future investments. The analysis of trend in real discount rate (shown in Figure 3.3) illustrates significant fluctuations in the real discount rate over the past five decades. Hence, a 10-year rolling average discount rate is recommended for use in LCCA. The 10-year average discount rate for the period between 2006 – 2015 is approximately 1.9%. It is recommended that the discount rate is routinely updated to reflect the current economic conditions.
Service Life and Activity Timing	The rehabilitation strategy for alternative pavements should reflect the current design features and traffic loading conditions. The service life ranges recommended for pavement preservation/rehabilitation treatments is given in Table 3.1 and Table 3.2 below.
Agency Costs	In developing the agency cost estimates, it is recommended to use GAO's Cost Estimating Guidelines to ensure the estimate reflects actual costs and changes. The agency costs should include all the costs incurred by the agency over the life of the project, including: initial construction costs; future rehabilitation and maintenance costs; and supplemental costs, such as design and overhead expenses. The remaining value of the investment at the end of the analysis period should also be included as a negative cost. The residual value can be estimated using the prorated method, as per the following formula. $RV = (L_{rem}/L_{exp}) * C_{pvt}$ Where: RV = Residual value, \$ L_{rem} = Remaining life of last rehabilitation treatment, years L_{exp} = Expected life of last rehabilitation treatment, years C_{pvt} = Cost of final rehabilitation treatment, \$.

Economic Evaluation Method	The Net Present Worth (Value) method is the recommended measure of life cycle costs of competing alternatives. The NPV can be computed as: Net Present Value (NPV) = Net Future Value x $1/(1+r)^n$ Where: r, is the real discount rate (%), and n, represents the analysis period (years). The Equivalent Uniform Annual Cost (EUAC) method may also be used for the comparison of project alternates.
LCCA Computational Approach	A probabilistic approach is recommended for LCCA. However, given the lack of historical data to model a probability distribution for the uncertain inputs, a deterministic-based computational approach with sensitivity analysis may be acceptable. Sensitivity analyses should account at minimum the variability in the discount rate. The variations in the discount rate suggested for the sensitivity analyses is ± 1.5 %.

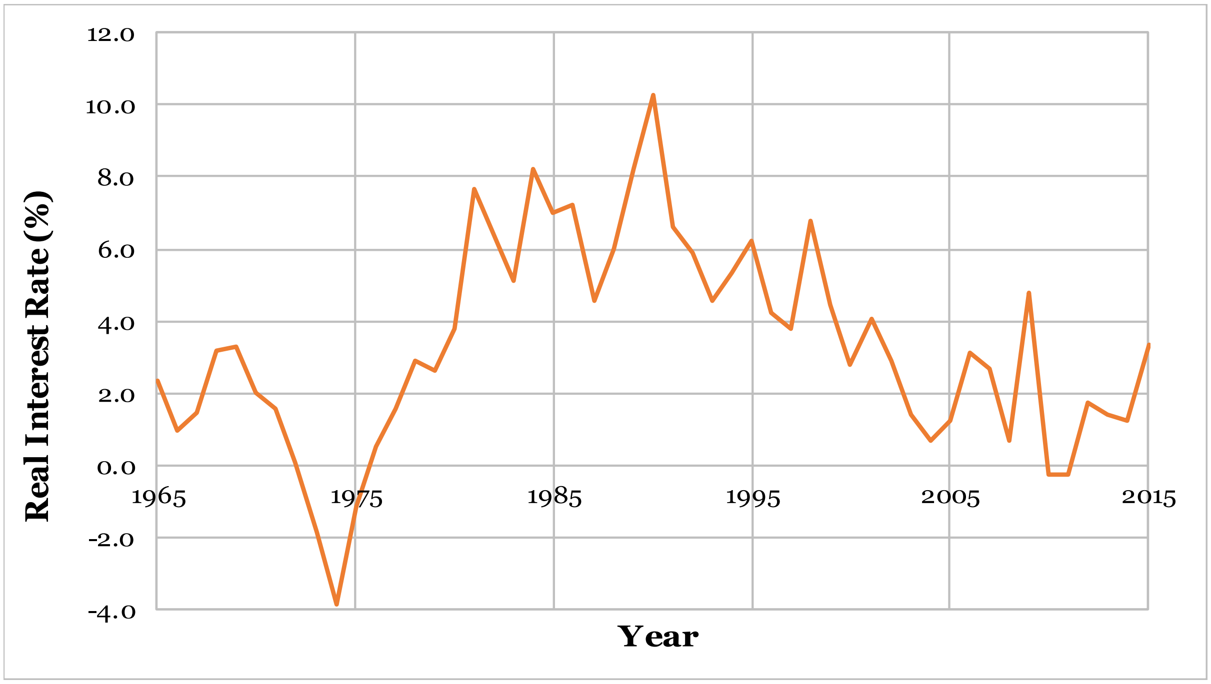

Figure 3.3: Real Interest Rate in Canada [World Bank Data]

Table 3.1: Performance Period for Treatments Applicable to Concrete Pavements[1]

Category		Treatment Techniques	Material Used	Performance Period
Preservation	Preventive maintenance	Crack/joint sealing	AC	5-10
	Corrective maintenance	Partial / full-depth repair and Slab replacement	PCC	5-15
		Concrete patch using asphalt	AC	1-3
		Joint LTE restoration	-	5-15
		Diamond grinding & grooving	-	10-15
	Minor Rehabilitation	Open gradation friction course	AC	5-10
		Thin asphalt overlay (2-4")	AC	5-15
		Bonded concrete overlay (2-4")	PCC	10-20
		Thin concrete overlay (4-8")	PCC	10-20+
		RCC overlay (4-8")	RCC	10-20+
Major Rehabilitation		Asphalt overlay (4-8")	AC	5-20
		Asphalt overlay (>8")	AC	10-20
		Concrete overlay (8-12")	PCC	20-35+
		RCC overlay (>8")	RCC	15-25+
Reconstruction		New asphalt	AC	10-20
		New concrete	PCC	25-35+
		New Roller Compacted Concrete	RCC	15-30+

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[1] Mack, J. W., Wathne, L., and Mu, F. 2016. "Improving Network Investment Results by Implementing Competition and Asset Management in the Pavement Type Selection Process." Presentation at the 11th International Conference on Concrete Pavements, San Antonio, TX.

Table 3.2: Performance Period for Treatments Applicable to Asphalt and Composite Pavements[1]

Category		Treatment Techniques	Material Used	Performance Period
Preservation	Preventive maintenance	Seals (chip/fog/slurry/micro-)	AC	1-5
		Asphalt Rejuvenation	AC	1-5
	Corrective maintenance	Asphalt Patching/Pothole filling	AC	1-5
	Minor Rehabilitation	Asphalt cold/hot in place recycling	AC	5-10
		Open gradation friction course	AC	5-10
		Full Depth Reclamation w/ cement	AC	10-20
		Mill / Thin Asphalt overlay (2-4")	AC	5-15
		Thin asphalt overlay (2-4")	AC	8-15
		Ultrathin concrete overlay (2-4")	PCC	8-15
		Thin concrete overlay (4-8")	PCC	10-20+
		RCC overlay (4-8")	RCC	10-20+
Major Rehabilitation		Asphalt overlay (4-8")	AC	5-20
		Asphalt overlay (>8")	AC	10-20
		Concrete overlay (8-12")	PCC	20-35+
		RCC overlay (>8")	RCC	15-25+
Reconstruction		New asphalt	AC	10-20
		New concrete	PCC	25-35+
		New Roller Compacted Concrete	RCC	15-30+

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APPENDIX A: USER GUIDE

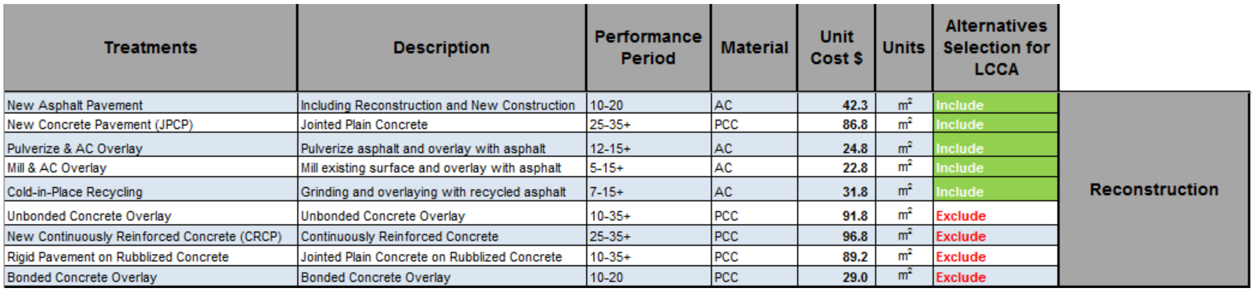
APPENDIX A USER GUIDE

This manual will guide the user through the inputting of variables in the analysis tool. The required inputs and calculation approaches used in the module are discussed as follows.

In the tool, the agency costs of alternate pavement designs are analyzed over a period of 50-years. The steps in the analysis are presented as follows.

Step 1: Select Alternatives

The user can select up to five alternatives for analysis in this module. The following list of alternatives are available for selection (see Figure A.1). The user has the option to customize the unit costs of treatments if the values vary from the default unit costs.

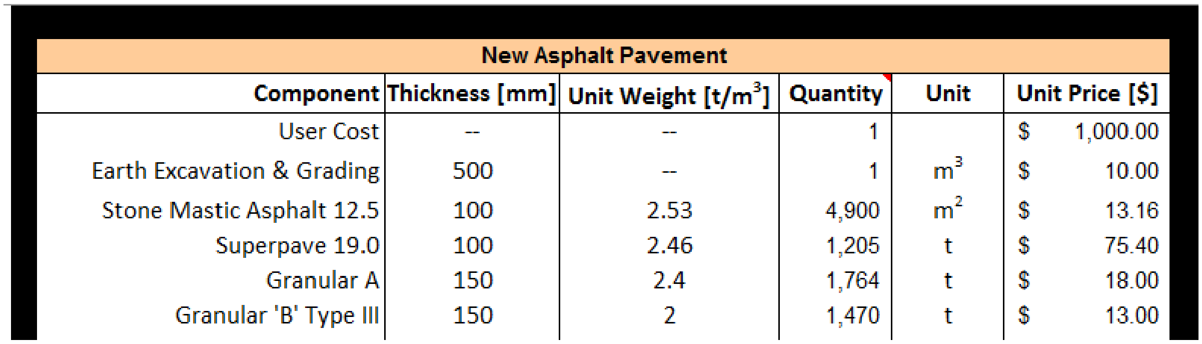


Treatments	Description	Performance Period	Material	Unit Cost $	Units	Alternatives Selection for LCCA	
New Asphalt Pavement	Including Reconstruction and New Construction	10-20	AC	42.3	m^2	Include	Reconstruction
New Concrete Pavement (JPCP)	Jointed Plain Concrete	25-35+	PCC	86.8	m^2	Include	
Pulverize & AC Overlay	Pulverize asphalt and overlay with asphalt	12-15+	AC	24.8	m^2	Include	
Mill & AC Overlay	Mill existing surface and overlay with asphalt	5-15+	AC	22.8	m^2	Include	
Cold-in-Place Recycling	Grinding and overlaying with recycled asphalt	7-15+	AC	31.8	m^2	Include	
Unbonded Concrete Overlay	Unbonded Concrete Overlay	10-35+	PCC	91.8	m^2	Exclude	
New Continuously Reinforced Concrete (CRCP)	Continuously Reinforced Concrete	25-35+	PCC	96.8	m^2	Exclude	
Rigid Pavement on Rubblized Concrete	Jointed Plain Concrete on Rubblized Concrete	10-35+	PCC	89.2	m^2	Exclude	
Bonded Concrete Overlay	Bonded Concrete Overlay	10-20	PCC	29.0	m^2	Exclude	

Figure A.1: List of Alternatives in LCCA Module

Step 2: Specify Design, Quantity, and Unit Price of Components for Selected Alternatives

The user has the option to specify the depth of excavation and design thickness of the pavement layers for each selected alternative. The quantity and unit cost of excavation, and pavement layers are also specified in this step. Figure A.2 illustrates the definition of design and cost components for selected alternatives.

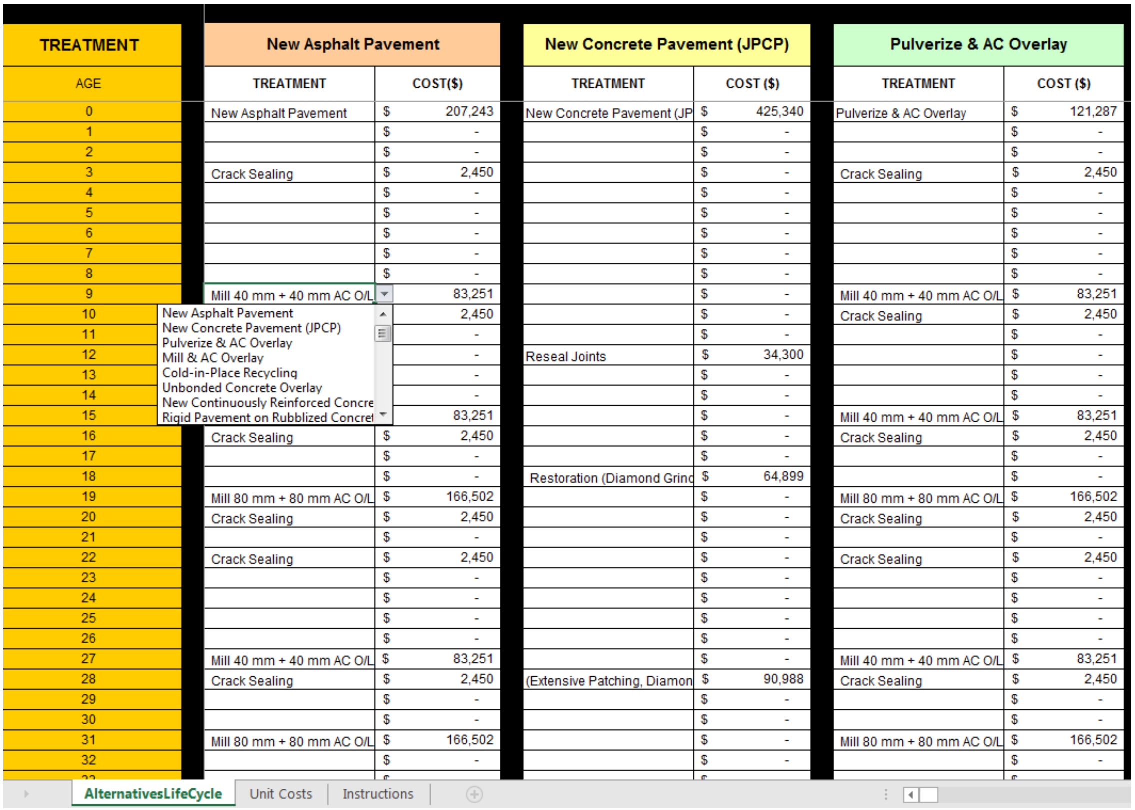


New Asphalt Pavement					
Component	Thickness [mm]	Unit Weight [t/m^3]	Quantity	Unit	Unit Price [$]
User Cost	--	--	1		$ 1,000.00
Earth Excavation & Grading	500	--	1	m^3	$ 10.00
Stone Mastic Asphalt 12.5	100	2.53	4,900	m^2	$ 13.16
Superpave 19.0	100	2.46	1,205	t	$ 75.40
Granular A	150	2.4	1,764	t	$ 18.00
Granular 'B' Type III	150	2	1,470	t	$ 13.00

Figure A.2: Illustration of How to Define Design and Cost Components of Selected Alternatives

Step 3: Define Maintenance/Rehabilitation Strategies for Selected Alternatives

The user can define the maintenance and/or rehabilitation treatments of the alternatives selected for the analysis. The default strategies for 'Full Reconstruction AC' and 'JPCP' represent the recommended practices of MTO. Figure A.3 illustrates how the maintenance and rehab strategies are defined for the alternatives selected.

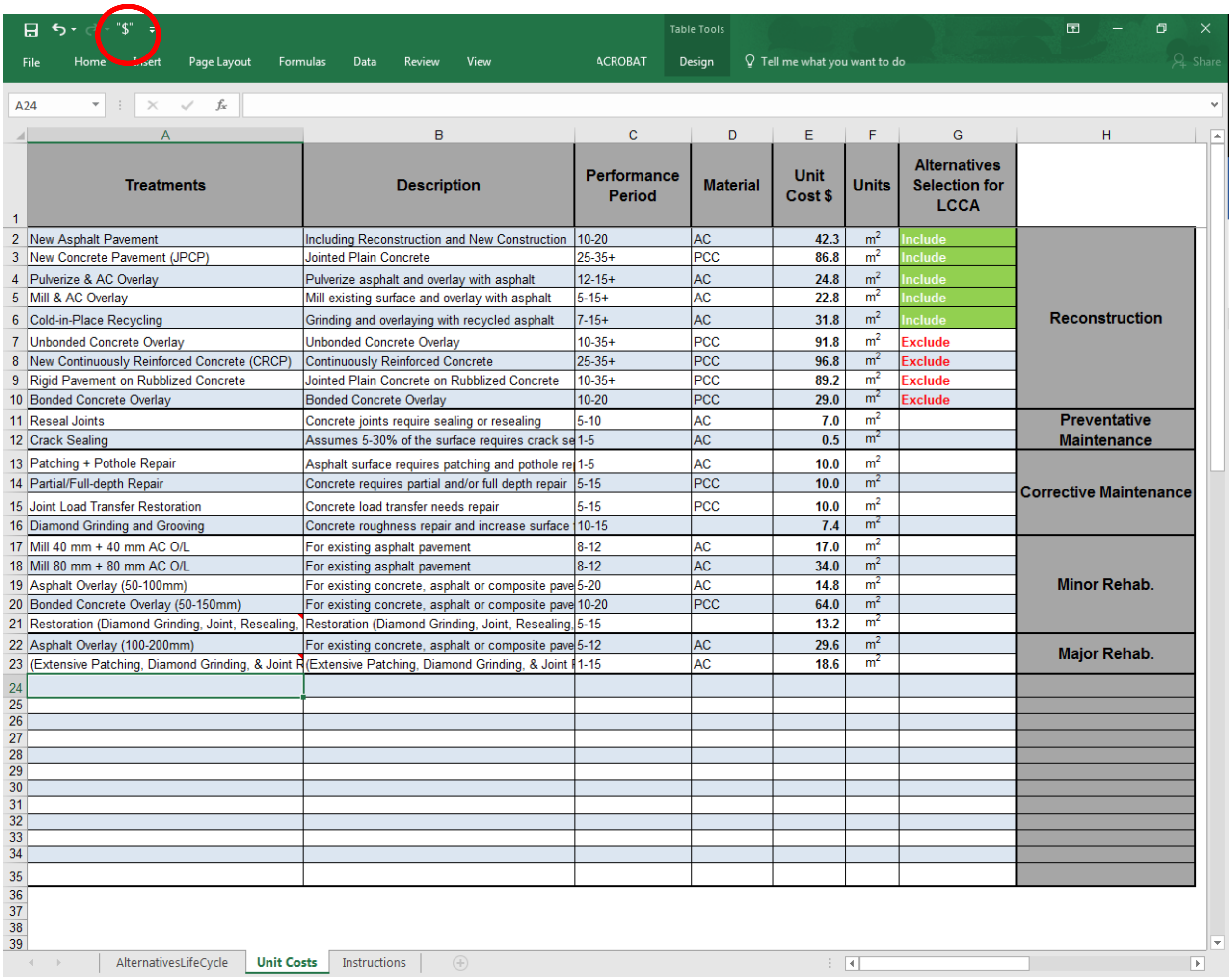


TREATMENT	New Asphalt Pavement		New Concrete Pavement (JPCP)		Pulverize & AC Overlay	
AGE	TREATMENT	COST($)	TREATMENT	COST ($)	TREATMENT	COST ($)
0	New Asphalt Pavement	$ 207,243	New Concrete Pavement (JP	$ 425,340	Pulverize & AC Overlay	$ 121,287
1		$ -		$ -		$ -
2		$ -		$ -		$ -
3	Crack Sealing	$ 2,450		$ -	Crack Sealing	$ 2,450
4		$ -		$ -		$ -
5		$ -		$ -		$ -
6		$ -		$ -		$ -
7		$ -		$ -		$ -
8		$ -		$ -		$ -
9	Mill 40 mm + 40 mm AC O/L	83,251		$ -	Mill 40 mm + 40 mm AC O/L	$ 83,251
10		2,450		$ -	Crack Sealing	$ 2,450
11		-		$ -		$ -
12		-	Reseal Joints	$ 34,300		$ -
13		-		$ -		$ -
14		-		$ -		$ -
15		83,251		$ -	Mill 40 mm + 40 mm AC O/L	$ 83,251
16	Crack Sealing	$ 2,450		$ -	Crack Sealing	$ 2,450
17		$ -		$ -		$ -
18		$ -	Restoration (Diamond Grind	$ 64,899		$ -
19	Mill 80 mm + 80 mm AC O/L	$ 166,502		$ -	Mill 80 mm + 80 mm AC O/L	$ 166,502
20	Crack Sealing	$ 2,450		$ -	Crack Sealing	$ 2,450
21		$ -		$ -		$ -
22	Crack Sealing	$ 2,450		$ -	Crack Sealing	$ 2,450
23		$ -		$ -		$ -
24		$ -		$ -		$ -
25		$ -		$ -		$ -
26		$ -		$ -		$ -
27	Mill 40 mm + 40 mm AC O/L	$ 83,251		$ -	Mill 40 mm + 40 mm AC O/L	$ 83,251
28	Crack Sealing	$ 2,450	(Extensive Patching, Diamon	$ 90,988	Crack Sealing	$ 2,450
29		$ -		$ -		$ -
30		$ -		$ -		$ -
31	Mill 80 mm + 80 mm AC O/L	$ 166,502		$ -	Mill 80 mm + 80 mm AC O/L	$ 166,502
32		$ -		$ -		$ -

Figure A.3: Illustration of How to Define Maintenance and Rehabilitation Strategies

Step 4: Run Analysis

Once the user has completed steps 1-3, the analysis can be run by selecting the '$' button, above the ribbon as shown in Figure A.4.



	Treatments	Description	Performance Period	Material	Unit Cost $	Units	Alternatives Selection for LCCA	
2	New Asphalt Pavement	Including Reconstruction and New Construction	10-20	AC	42.3	m²	Include	Reconstruction
3	New Concrete Pavement (JPCP)	Jointed Plain Concrete	25-35+	PCC	86.8	m²	Include	
4	Pulverize & AC Overlay	Pulverize asphalt and overlay with asphalt	12-15+	AC	24.8	m²	Include	
5	Mill & AC Overlay	Mill existing surface and overlay with asphalt	5-15+	AC	22.8	m²	Include	
6	Cold-in-Place Recycling	Grinding and overlaying with recycled asphalt	7-15+	AC	31.8	m²	Include	
7	Unbonded Concrete Overlay	Unbonded Concrete Overlay	10-35+	PCC	91.8	m²	Exclude	
8	New Continuously Reinforced Concrete (CRCP)	Continuously Reinforced Concrete	25-35+	PCC	96.8	m²	Exclude	
9	Rigid Pavement on Rubblized Concrete	Jointed Plain Concrete on Rubblized Concrete	10-35+	PCC	89.2	m²	Exclude	
10	Bonded Concrete Overlay	Bonded Concrete Overlay	10-20	PCC	29.0	m²	Exclude	
11	Reseal Joints	Concrete joints require sealing or resealing	5-10	AC	7.0	m²		Preventative Maintenance
12	Crack Sealing	Assumes 5-30% of the surface requires crack se	1-5	AC	0.5	m²		
13	Patching + Pothole Repair	Asphalt surface requires patching and pothole re	1-5	AC	10.0	m²		Corrective Maintenance
14	Partial/Full-depth Repair	Concrete requires partial and/or full depth repair	5-15	PCC	10.0	m²		
15	Joint Load Transfer Restoration	Concrete load transfer needs repair	5-15	PCC	10.0	m²		
16	Diamond Grinding and Grooving	Concrete roughness repair and increase surface	10-15		7.4	m²		
17	Mill 40 mm + 40 mm AC O/L	For existing asphalt pavement	8-12	AC	17.0	m²		Minor Rehab.
18	Mill 80 mm + 80 mm AC O/L	For existing asphalt pavement	8-12	AC	34.0	m²		
19	Asphalt Overlay (50-100mm)	For existing concrete, asphalt or composite pave	5-20	AC	14.8	m²		
20	Bonded Concrete Overlay (50-150mm)	For existing concrete, asphalt or composite pave	10-20	PCC	64.0	m²		
21	Restoration (Diamond Grinding, Joint, Resealing,	Restoration (Diamond Grinding, Joint, Resealing,	5-15		13.2	m²		
22	Asphalt Overlay (100-200mm)	For existing concrete, asphalt or composite pave	5-12	AC	29.6	m²		Major Rehab.
23	(Extensive Patching, Diamond Grinding, & Joint R	(Extensive Patching, Diamond Grinding, & Joint	1-15	AC	18.6	m²		

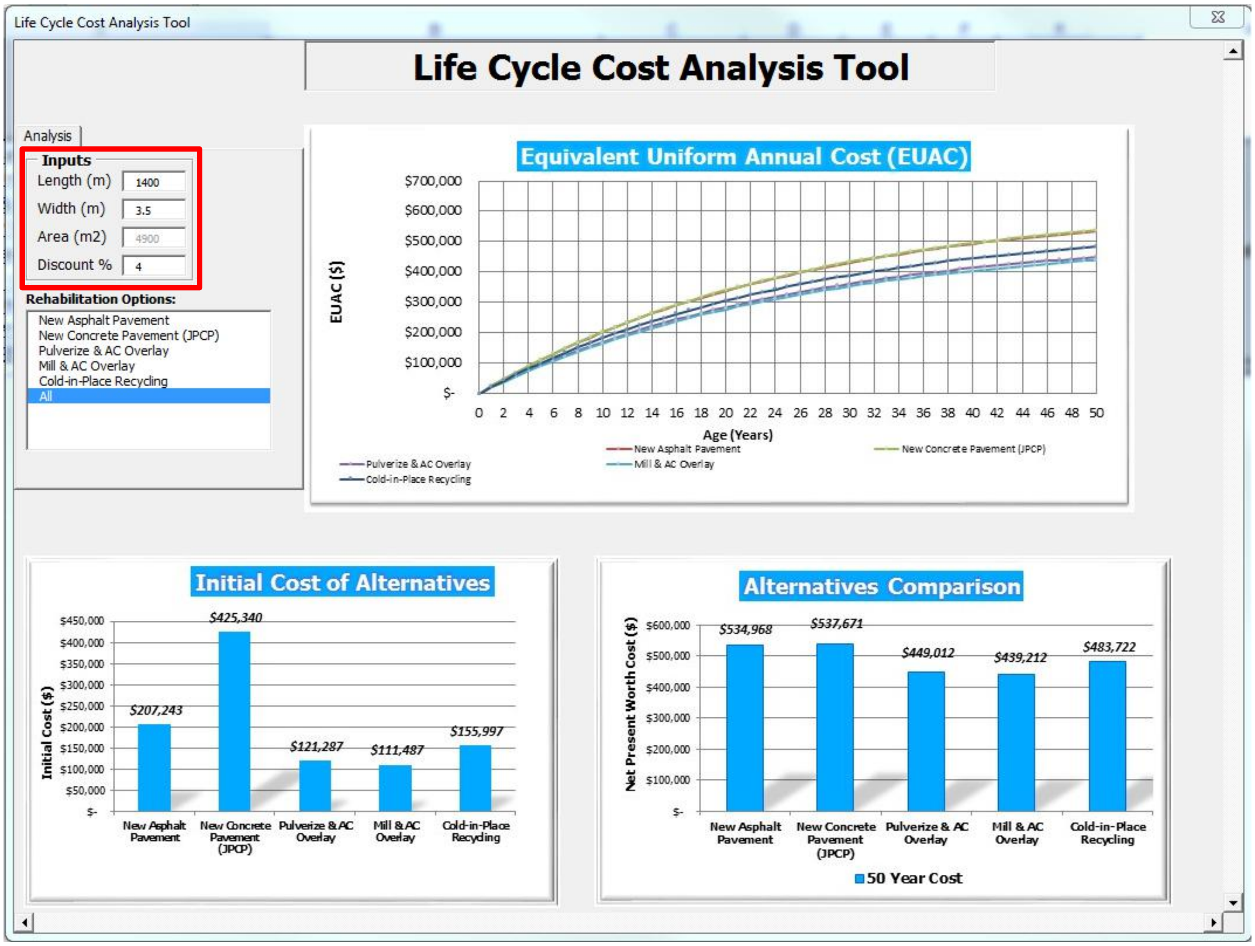
Figure A.4: Illustration of How to Run the Analysis

Step 5: Compare Alternatives

The alternatives selected will be compared using three measures: initial cost, NPW and incremental EUAC. Figure A.5 illustrates how the results of the analysis are presented.

The user has the option to change the inputs such as the length and width of the roadway of which the alternatives are compared and reanalyze the costs of the alternatives. Individual alternatives can also be further analyzed by selecting the treatment from the list. This option allows the user to review the timeline of major rehab treatments for the alternative selected. In addition, the user can evaluate the sensitivity of the analysis to the discount rate used. Figure A.6 illustrates how individual alternatives can be further analyzed.

The user can return to the unit costs tab by closing the results window.



Life Cycle Cost Analysis Tool

Life Cycle Cost Analysis Tool

Analysis

Inputs

Length (m) 1400

Width (m) 3.5

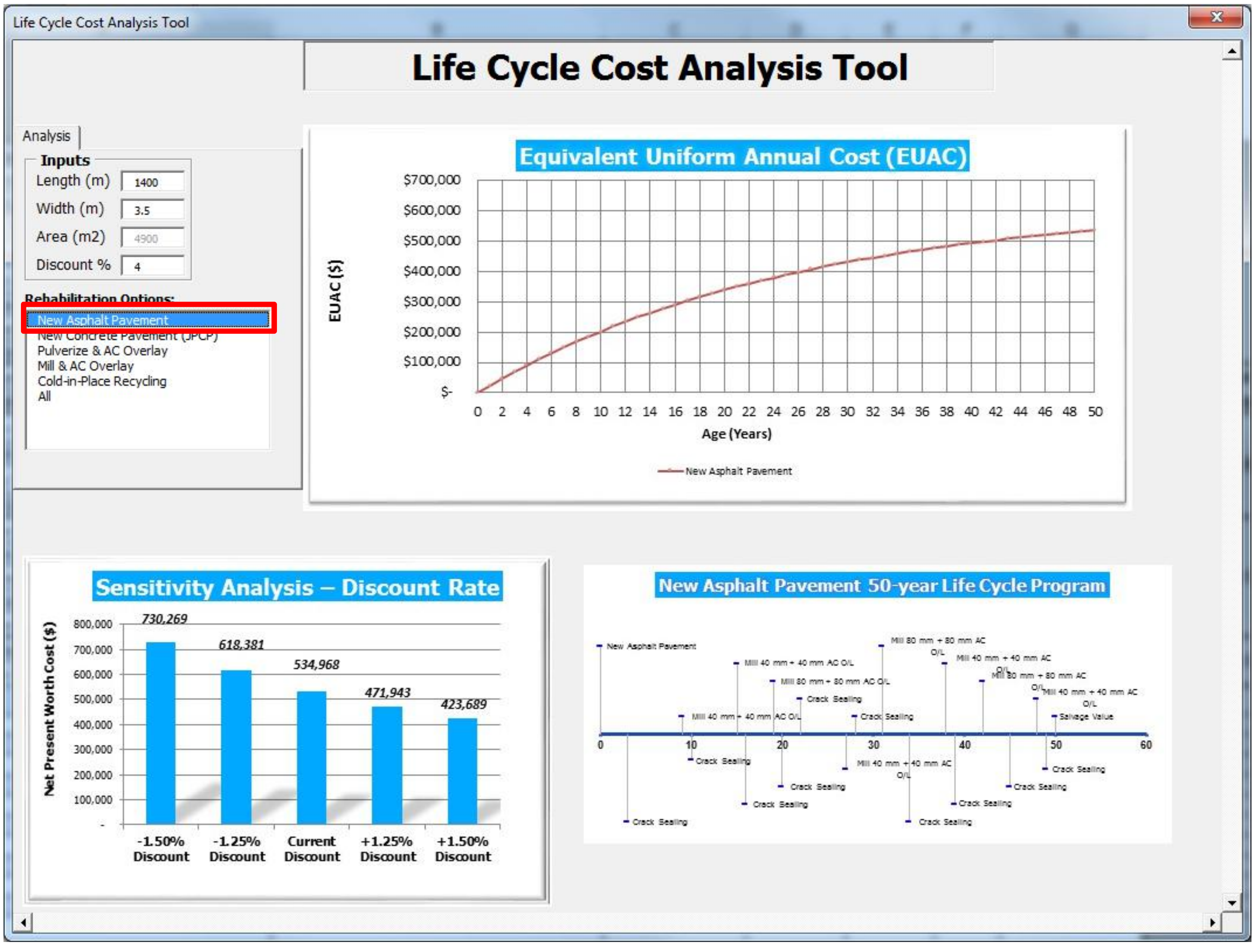
Area (m2) 4900

Discount % 4

Rehabilitation Options:

- New Asphalt Pavement
- New Concrete Pavement (JPCP)
- Pulverize & AC Overlay
- Mill & AC Overlay
- Cold-in-Place Recycling
- All

Figure A.5: Results of Analysis



Life Cycle Cost Analysis Tool

Life Cycle Cost Analysis Tool

Analysis

Inputs

Length (m): 1400
Width (m): 3.5
Area (m2): 4900
Discount %: 4

Rehabilitation Options:

- New Asphalt Pavement
- New Concrete Pavement (JPCP)
- Pulverize & AC Overlay
- Mill & AC Overlay
- Cold-in-Place Recycling
- All

Figure A.6: Evaluation of Individual Alternatives