A Review and Recommendations for Canadian LCCA Guidelines

Mizan Moges, MSc. Eng., EIT
Corresponding Author
Email: Mizan.Moges@Stantec.com

Amr Ayed, Ph.D., P. Eng.

Giannin Viecili, M. Eng.

Amir Abd El Halim, Ph.D., P. Eng.

Stantec Consulting Ltd.
100-300 Hagey Boulevard
Waterloo ON N2L 0A4

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Harry Sturm, P. Eng.
Stantec Consulting Ltd.

Sherry Sullivan, M.A.Sc, P.Eng., LEED AP
Cement Association of Canada

ABSTRACT

Life Cycle Cost Analysis (LCCA) is an engineering tool that is used to facilitate sound investment decision-making in the management of infrastructure. Transportation agencies can use LCCA in the selection of cost-effective pavement designs, and evaluation of future maintenance, rehabilitation, and/or reconstruction strategies. Using LCCA can also increase transparency in the project selection process, ensuring agencies make strategic decisions that maximize the expected value of their investments.

This paper reviews the current LCCA practices in place across transportation agencies in Canada and 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 practice guidelines 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 study is to develop a Canadian LCCA Standard Practice Guideline based on best practices. The guideline provides guidance on LCCA for alternate pavement-type bidding. The guideline is also instrumental in the development of user-friendly excel based tool to aid in the analysis of life cycle costs of alternate pavement designs.

The study reviewed best practices relating to length of analysis period, discount rate, (agency, user, and environmental) costs, economic criteria method, and computational approach for life cycle cost analysis. Based on the review, recommended practices for conducting LCCA in pavement design were identified and are proposed as input for a Standard Practice Guideline.

INTRODUCTION

Background

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 incorporate LCCA in their economic analysis. Nova Scotia uses LCCA exclusively in the selection of equivalent pavement-type alternatives, British Columbia uses LCCA for all large capital projects excluding rehab programs, and 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 used by transportation 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. Variation in user costs components incorporated into the LCCA has also been documented in the State-of-the-Practice Survey Summary [Tighe et al. 2010].

Study Objectives and Scope

The objective of this study is to review the current LCCA practices in place across Canada and in select international agencies, and recommend a Canadian LCCA Standard of Practice Guideline. The guideline, outlined in this study, is intended to provide a reference of LCCA methodology for alternate pavement-type bidding. The guideline will also be used in the development of a user-friendly excel based tool to aid in the analysis of life cycle costs of alternate pavement designs.

The review focused on the LCCA practices used by the provinces of Alberta, British Columbia, Manitoba, Nova Scotia, Ontario, Quebec, and Saskatchewan. The LCCA practice guidelines 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.

REVIEW AND GAP ANALYSIS OF LCCA PRACTICES

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

Analysis Period

The analysis period is the time frame under which the cost difference between alternatives is compared. According to the FHWA Technical Bulletin [Walls et al. 1998], 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 APA likewise recommends that the analysis period be no less than 40 years and that it includes at least one rehabilitation activity for each pavement option.

A review of the analysis period used by provincial agencies across Canada found that analysis period in the range of 25 to 80 years is used to compare pavement alternatives. A summary of the analysis periods currently used by agencies across Canada are detailed in Table 1.

Table 1: Analysis Period Used by Provincial Agencies

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.

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. The service life and rehabilitation schedule currently used by the provincial agencies in Canada is summarized in Table 2.

Table 2: Service Life and Rehabilitation Schedule Used by Provincial Agencies

	Initial Service Life		Rehabilitation Activity & Service Life/Activity Timing	
	Flexible Pavements	Rigid Pavements	Flexible Pavements	Rigid Pavements
Alberta	20 yrs.	30 yrs.	Hot-In-Place Recycle, 8-11 yrs. Mill & Inlay, 10-13 yrs. Two Lift overlay, 8-20 yrs. Reprofile & overlay, 15-20 yrs.	N/A
British Columbia	20 yrs.	30 yrs.	(Mill and) Resurface, 15+ yrs.	N/A
Manitoba	20 yrs.	Doweled JPCP: 20 yrs.	Mill and Resurface, 15 yrs.	Diamond Grinding, 15 yrs. CPR, 12 yrs.
Nova Scotia	20 yrs.	40 yrs.	(Mill and) Resurface, 12 yrs.	Diamond Grinding @18 yrs. CPR, 10 yrs.
Ontario*	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	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	15 yrs.	N/A	Mill & fill HMA overlay, 15 yrs. Base Treatment and Double Seal/HMA overlay, 15 yrs.	N/A

* 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.

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.

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 OMB 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 U.S. government's Office of Management and Budget (OMB).

A review of the discount rates used by the provincial agencies considered in the study found a rate of discount ranging between 3 to 6%. The discount rates currently used by agencies across Canada are outlined in Table 3.

Table 3: Discount Rate Used by Provincial Agencies

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.

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, and 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 ACPA bulletin suggests estimating the residual value of alternatives either as a salvage value, RSL, or value of alternatives if used as a support layer. The APA position paper suggests using the FHWA approach or considering the residual value as some percentage of the initial pavement construction cost.

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.

The methods currently used by the provincial agencies to determine the residual value of pavement alternatives are summarized in Table 4.

Table 4: Residual Value Computation Method Used by Provincial Agencies

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.

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 due to 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 only (PDO).

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, which 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 has been adopted by some state agencies to avoid user costs from overwhelming the agency costs [Salem et al. 2008]. Another approach suggested includes integrating user costs in the selection process, only when the life cycle of competing 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. 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 FHWA 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 [Walls et al. 1998] provides a detailed twelve-step procedure for calculating the user costs components during a work zone operation.

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 considers the user delay costs only to reflect the costs of construction delays incurred by the public.

The World Bank's LCCA tool (HDM-4) calculates the road user costs by predicting physical quantities of resource consumption and then multiplying these quantities by the corresponding user specified unit costs. HDM-4 uses models to quantify the following road user cost components: fuel consumption, oil consumption, tire consumption, maintenance and repair, vehicle depreciation, travel time and safety. The details of the models are given in Volume 7 of the HDM-4 publication series [Bennett et al. 2001].

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 in Table 5.

Table 5: User Cost Components Considered for LCCA by Provincial Agencies

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 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 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.

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 HDM-4 model generates the environmental costs based on three environmental externalities of vehicle use: emissions, noise, and energy consumption. In the model, the effect of the following air pollutants associated with vehicle emissions are estimated: Hydrocarbons (HC), Carbon Monoxide (CO), Carbon Dioxide (CO2), Nitric Oxides (NOx), Sulphur Dioxide (SO2), Lead (Pb) and Particulate Matter (PM). HDM-4 estimates the economic cost of noise effect in urban areas as a function of the value of the pavement alternative. For the energy balance analysis, HDM-4 considers the energy used by vehicles as well as the energy used for construction, maintenance and rehabilitation works. Volume 7 of the HDM-4 series [Bennett et al. 2001] discusses in detail how the environmental effects are calculated.

The environmental impact of pavement projects may also 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].

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 in Table 6. Ontario, Quebec, and British Columbia consider environmental impacts of pavement projects outside the LCCA realm.

Table 6: Environmental Cost Components Considered for LCCA by Alberta Transportation

Alberta	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): $96.5, • CO2 (Carbon Dioxide): $40.00, • NOx (Nitrogen Oxides): $30,000.00, • PM10 (Particular Matter): $244,000.00, • SOx (Sulphur Oxides): $102,000.00, and • VOC (Volatile Organic Compounds): $2,000.00

Ontario uses GreenPave, a rating system that evaluates the sustainability of pavements (new construction and rehabilitation projects). It measures the "greenness" of design alternatives and construction practices. Projects are evaluated on criteria under four categories, namely; Pavement Technologies, Materials & Resources, Energy & Atmosphere, and Innovation & Design Process [MERO 2014].

Quebec considers project-relevant parameters related to environmental impacts in Multicriteria Analysis (MCA). MCA involves the analysis of quantifiable and non- quantifiable criteria whose importance varies depending on the pavement option. Criterions relating to environmental impacts that are 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. Typical issues considered in the environmental impact assessment are: land requirements, fuel, CO, site rehabilitation, wildlife, water pollution. Noise pollution is evaluated under the social impact account of MAE.

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 Cost-effectiveness method. Uddin et al. (2013) distinguish between these methods as follows:

The *Net Present Value (NPV)*, also called *Net Present Worth (NPW)*, method compares the discounted monetary value of expected net benefits of alternatives, derived from the difference between the present worth of benefits and the present worth of costs of alternatives. The *Equivalent Uniform Annual Costs (EUAC*) method compares the NPV of all initial costs and all future recurring expenditures of alternatives spread uniformly over the analysis period. The *Internal Rate of Return (IRR)* method involves the determination of the discount rate necessary to make the discounted cost and benefits equal (i.e. NPV of zero).

The *Benefit-Cost Ratio (B/C Ratio)* on the other hand involves expressing the ratio of the present worth of benefits to the present worth of costs, or the ratio of the equivalent uniform annual benefits to the equivalent uniform annual costs, for comparison of alternatives. Lastly, the *Cost-effectiveness* method compares alternatives based on the ratio of the effectiveness (calculated as area under the performance curve multiplied by traffic volume and length of road section) divided by the present worth of costs summarized over the length of the facility.

The FHWA recommends the NPW method for evaluating project alternatives. The FHWA also recognizes the EUAC 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 also 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 in Table 7.

Table 7: Economic Criterion Methods Used by Provincial Agencies

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.

LCCA Computational Approach

Two computational approaches are commonly used for the life cycle cost analyses: deterministic and probabilistic approach. 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 of Transport Canada 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.

The FHWA promotes the use of a probabilistic-based LCCA. ACPA also recognizes the advantages of using the probabilistic LCCA procedure over a deterministic approach. The APA uses the principles recommended by FHWA and employs software that use either deterministic or probabilistic analyses. The FHWA Interim Bulletin [Walls et al. 1998] provides a detailed discussion on probability-based LCCA.

The LCCA computational approaches adopted by the provincial agencies is summarized in Table 8.

Table 8: LCCA Computational Approach Used by Provincial Agencies

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.

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 below.

RealCost is FHWA's MS Excel based LCCA software package that is designed based on 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.

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 offers the option 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 ACPA. It is a structural design software, with an LCCA module which can perform a detailed cost/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 tools used by Canadian agencies are summarized in Table 9 below.

Table 9: LCCA Tool/Software Used by Provincial Agencies

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.

SUMMARY AND RECOMMENDED LCCA PRACTICE GUIDELINES

A summary of the LCCA practices of the provinces considered in the study, the FHWA, ACPA, APA and the World Bank is presented in Table 10.

Based on the review discussed in the preceding sub-sections, the recommended practice in conducting life cycle cost analysis of pavement design is outlined in Table 11. The study recommends that the selection of feasible pavement alternatives should be primarily based on the life cycle analysis of agency costs. User costs and 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.

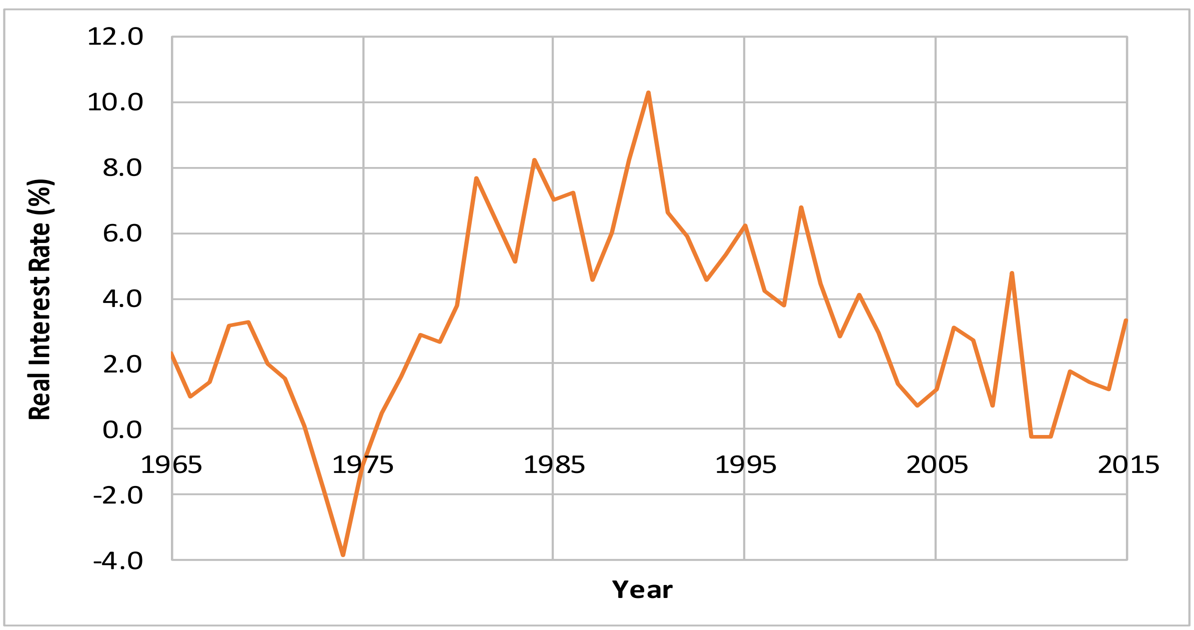

Figure 1: Trend in Real Interest Rate in Canada [World Bank data[1]]

[1] Available at: http://data.worldbank.org/indicator/FR.INR.RINR?end=2015&locations=CA&start=1961&view=chart.

Table 10: Summary of LCCA Practices

Agency	LCCA Input Parameters										LCCA Computational Approach	LCCA Tools
	Analysis Period	Discount Rate	Economic Evaluation Method(s)	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 (with optional Sensitivity Analysis)	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 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 (if costs differ significantly among alternatives)			Not considered			Probabilistic	StreetPave
APA	Minimum 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 in GreenPave Rating Scheme.
***Considered in Multicriteria Analysis.

Table 11: Recommended LCCA Practice Guideline

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 1) 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 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 12 (after ACPA 2012).
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: $\text{Net Present Value (NPV)} = \text{Net Future Value} \times 1/(1+r)^n$ 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 %.

Table 12: Service Life Ranges for Preservation/Rehabilitation Treatments of Pavements [ACPA 2012]

Preservation/Rehabilitation Treatment	Expected Performance Period (years)
Reconstruction:	
Reconstruction with asphalt pavement	8 – 25
Reconstruction with concrete pavement	20 – 40
Asphalt pavement preservation/rehabilitation:	
Structural asphalt overlay of asphalt pavement	6 – 17
Structural concrete overlay of asphalt pavement	15 – 40
Surface recycling without overlay	3 – 8
Nonstructural asphalt overlay of asphalt pavement	3 – 8
Nonstructural concrete overlay of asphalt pavement	5 – 15
Asphalt patching without overlay	4 – 8
Concrete pavement preservation/rehabilitation:	
Structural asphalt overlay of concrete pavement	8 – 20
Concrete overlay of fractured concrete slab	15 – 40
Unbonded concrete overlay of concrete pavement	15 – 40
Nonstructural asphalt overlay of concrete pavement	1 – 8
Bonded concrete overlay of concrete pavement	15 – 30
Restoration without overlay	5 – 15
Diamond grinding of the concrete surface	8 – 20
Composite pavement preservation/rehabilitation:	
Structural asphalt overlay of composite pavement	8 – 20
Concrete overlay of fractured concrete slab	15 – 40
Unbonded concrete overlay of composite pavement	15 – 40
Surface recycling without overlay	3 – 8
Nonstructural asphalt overlay of composite pavement	3 – 8
Nonstructural concrete overlay of composite pavement	5 – 15

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