BEYOND CONVENTIONAL LCCA: LONG TERM RETURN ON PAVEMENT INVESTMENTS

Ralph Haas, The Norman W. McLeod Engineering Professor and
Distinguished Professor Emeritus
University of Waterloo
haas@uwaterloo.ca

Susan Tighe, Associate Professor of Civil Engineering and
Canada Research Chair in
Pavements and Infrastructure Management
University of Waterloo
sltighe@uwaterloo.ca

Lynne Cowe Falls, Assistant Professor of Civil Engineering
University of Calgary
lcowefal@ucalgary.ca

Paper prepared for presentation
at the Pavements Session
at the 2005 Annual Conference of the
Transportation Association of Canada
Calgary, Alberta

ABSTRACT

It is becoming increasingly necessary in life cycle analysis (LCA) of infrastructure assets, including pavements, to take a longer term approach than in past, conventional practice. This is largely for reasons of ensuring sustainability and assessing the future impacts of today's decisions.

Life cycle analysis can be primarily in terms of life cycle cost analysis (LCCA) but can also include considerations of resource conservation, environmental impacts, energy balance, etc. In any case, a key question is what constitutes a reasonable time horizon for life cycle analysis. The suggestion is that it should involve short, medium and long term periods, in the order of 25, 50 and 100 years, respectively. Further, using this approach, it is possible to develop a context for LCA of likely and uncertain societal activities, including transportation, over the short, medium and long terms.

Conventional LCCA is directed to comparing competing alternative investment strategies and can involve a range of stakeholders, from the elected level to the public at large to suppliers and consultants. Of the methods available, present worth of costs is almost exclusively the method used in the pavement field. However, when medium to longer term life cycle periods are involved, rate-of-return and cost-effectiveness formulations can be applicable and should be considered.

A numerical example is provided which shows how an agency can determine the internal rate of return (IRR) for two investment alternatives involving different pavement designs and a life cycle period of 50 years. As well, a cost-effectiveness example is provided for a sidewalk network and again a life cycle period of 50 years which shows how the best investment alternative has been identified.

Conventional LCCA for calculating present worth of costs will undoubtedly continue to be used in the pavement field as a primary tool. However, going beyond conventional LCCA and using a rate-of-return or cost-effectiveness formulation, especially for medium to longer term life cycle periods, should be given more consideration.

INTRODUCTION

Conventionally, asset management and in particular component pavement management systems, have used life cycle cost analysis (LCCA) which discounts current and future expenditures to present worth. Benefits can be included, usually as discounted user cost savings. At the discount rates used by most agencies, generally ranging from 4% to 8%, any expenditures or benefits in the order of 30 years or more approach a small present worth value. Yet, there is a trend toward expecting a long or very long term service life from many of our infrastructure assets, including pavements.

Consequently, there is a need to rethink or reformulate our current approach to life cycle analysis. Such a new approach would consider both the short term and long term, where the former can continue to use conventional discounted values; alternatively, it can use internal rate of return.

For the longer term, a rate of return approach which considers such factors as resource conservation, environmental savings/protection, user benefits, etc. would be appropriate.

This paper addresses the need for an overall approach to pavement investment analysis, which incorporates both the short term and long term. More specifically, the paper has the following objectives:

- A description of the basic need and rationale for a long term approach,
- Definition of what constitutes short and long term,
- Review of the conventional LCCA methodology and its context in a long term life cycle analysis (LCA),
- Description of an overall framework for short to long term LCA
- Rate of return formulation and quantitative illustrations of the methodology
- Conclusions and recommendations for use of the methodology

RATIONALE FOR AND DEFINITION OF A LONG TERM APPROACH

Basic Considerations in Life Cycle Analysis

One of the fundamental premises of asset management is that it involves a life cycle. In other words, any actions and/or investments should be considered in terms of performance over some life cycle and the associated economics over that life cycle. Additional factors may be included such as environmental effects, societal impacts and the like.

Closely coupled with the concept of life cycle analysis (LCA) is the issue of sustainability. Increasingly, we are being required to design and implement works which have explicitly incorporated the consideration of sustainability. Certainly that is a key aspect of Canada's National Guide for Sustainable Municipal Infrastructure [www.InfraGuide.ca]. In order to assess whether sustainability is being achieved requires the use of life cycle analysis.

Since sustainability is a long term consideration, life cycle analysis should also involve a long term approach. But this brings up the question of what constitutes a long term approach and what are the key elements. Subsequent discussion will address the question.

First, however, it is useful to review the basic purpose and components of life cycle analysis. Regarding the basic purpose, [Hudson, et al] have pointed out that this includes the following:

- Comparison of alternative (competing) strategies over a life cycle period, using economics principles
- Identification of what strategy(s), when and where offer the best value on expenditures and/or return on investment
- Providing objectively based decision support, but not the decision itself

If the LCA is in terms of life cycle economic analysis (LCCA) it can not, however, answer questions of equity among competing infrastructure types (eg., public housing vs parks and recreation vs roads vs underground services, etc.) because of social, political and other considerations.

Nevertheless, it has been shown that a generic protocol for LCCA, covering a range of infrastructure components, is possible and applicable at the following three levels [Haas, Cowe Falls and Tighe 2001]:

- Strategic, where cost estimates are carried out for various levels of service (LOS) targets to establish needs, for comparison to financial forecasts.
- Network of system wide where LCCA is carried out for alternative programs in order to determine an optimal program, for specified budget(s).
- Project or site specific where LCCA is used to identify the most cost-effective alternative for that project/link/site specific area.

Life cycle economic analysis can be extended to include asset value, as pointed out by [Cowe Falls, Haas and Tighe 2005] and even risk analysis [Haas 2005]. In schematic terms, a more comprehensive life cycle analysis (LCA) concept applicable to civil infrastructure in general is illustrated in Figure 1.

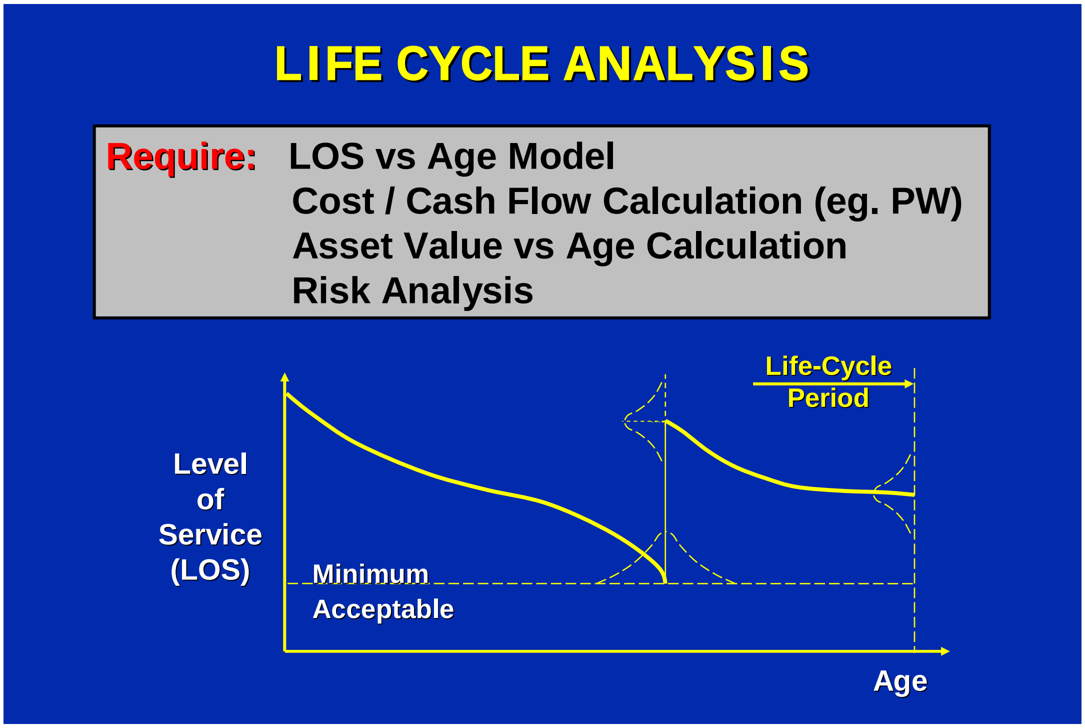

Figure 1 Concept of Life Cycle Analysis

Developing/applying a generic level of service (LOS) concept has been the subject of considerable attention in the City of Edmonton's Infrastructure Strategy [Siu and Cloake and Siu 2002]. Their LOS concept has a five point ranking (A,B,C,D and F), applicable to each of three classifications: physical condition, demand/capacity and functionality. For each combination of infrastructure type (or sub type) and classification a "translator" is used to convert A,B,C,D or F to a numerical scale.

Regarding pavements, the LOS concept has been well established, originally in terms of Riding Comfort Index (RCI), and currently a commonly used index is IRI, The International Roughness Index [TAC 1997].

Definition: How Far Ahead is the Future?

A time horizon for which there is a reasonably good degree of reliability in forecasting demand, calculating life cycle economics and forecasting the level of service or functional adequacy of civil infrastructure is no longer satisfactory. It is too short. The reason is that our actions today can have very long term impacts on resource conservation, environmental degradation and sustainability. In the latter case it is essential that capability is retained for periodic renewal/rehabilitation/repair of the infrastructure.

Consequently, it is useful to consider a time horizon consisting of the short, medium and long term. It has been suggested that these should be in the order of [Haas 2003]:

- 25 years for short term
- 50 years for medium term
- 100 plus years for long term

The number of years appropriate to individual works or systems may fit into one, two or all three categories. For example, a software design package might only be very short term, while a long life pavement would be both short and medium term and a bridge would be short to medium to long term. Another example would be the 99 year term for the "sale" of Hwy. 407 ETR [Mylvaganam and Borins 2004].

If we can identify those features of our society which will exist, and/or which we will need, in the future, this can provide a context for life cycle analysis. Table 1 uses the foregoing time horizons to identify some of the major examples of human activities that will involve civil infrastructure. As well, they are categorized as involving a reasonable degree of certainty or a relatively high level of uncertainty.

While Table 1 is speculative in nature, it is reasonable to say that the need for transporting people and goods will exist into the foreseeable future; moreover that there will be at least a medium if not long term vital role for pavements. Of course the structural, materials, construction and maintenance technologies involved may undergo substantive changes. In turn, it should be reasonable to include an LCA formulation for pavements that should be capable of incorporating life cycle periods or time horizons of at least 50 years or more.

Table 1 Speculation on future societal activities as a context for life cycle analysis
Adapted from [Haas 2003]

Future	Reasonable Certainty	Uncertain
Short Term	• Need for clean water • Deteriorating infrastructure • Population growth • Widespread emphasis on security • Need for effective waste treatment and disposal or recycling • Pavements as essential to transportation • Rewarding time to be a transportation engineer	• Sufficient funding for infrastructure deterioration? Public awareness? • Rate of environmental degradation? • Effectiveness of security? • Effective succession planning (people, technology, information)? • Extent of nanotechnology applications in civil engineering?
Medium Term	• Need for clean water • Continued large scale urban growth • Need for human habitat • Continued need for effective waste treatment and disposal or recycling • Globalization of technology • Continued need to transport people and goods; pavements essential • Availability of "super materials" • Major changes in the education and training of transportation engineers	• Widespread use of quantum computing? • Population growth levels off? • Start of providing infrastructure on Mars? • Widespread telecommuting? • Less transportation of people? • Decreased use of petroleum for energy and transportation? • Widespread use of "smart infrastructure"? • Globalization of water market? • Reduced environmental degradation?
Long Term	• Need for clean water • Need for human habitat • Need to treat and dispose waste • Widespread automation in all civil engineering activities • Need to move people and goods (social, recreational, economic, and food supply reasons)	• Teleportation? • Building infrastructure on other planets? • Widespread use of non conventional energy source(s)? • Major conflicts over global water shortages? • Replacement of most engineering functions by robots? • Extent of infrastructure gap/backlog?

CONVENTIONAL LCCA METHODOLOGY

Objectives of LCCA, Stakeholders Involved and Misconceptions

Life cycle cost analysis (LCCA) uses economic principles to compare competing alternative investment strategies [FHWA 1998]. It has always been an important tool in supporting decisions on the most cost-effective structure (roads, utilities, buildings, etc.) or rehabilitation treatment [Bradbury et al. 2000].

LCCA is also important in determining the affordability of a project, including both the initial construction costs and any future costs that may occur [Zimmerman and Grogg 2000]. LCCA should be used to identify where, what, and when do we get the best value/return on investment for our funds/expenditures.

Any investment or expenditure, particularly that of assuming financial liability or obligation (such as a road, purchase of a building, take-over of a business, etc.), should be accompanied by due diligence. In the private sector, this can be very rigorous, involving careful examination of the "books", any existing litigation, any environmental cleanup liabilities, etc.

Infrastructure investments thus deserve their form of "due diligence" in terms of life cycle cost analysis. While due diligence is not (yet) a common term in the infrastructure area, a proper application of LCCA could certainly be considered due diligence.

The potential stakeholders/clients for LCCA, where public sector investments are involved, include the following:

- Elected level (Council or Legislature)
- Senior administrators
- Technical/Operating level personnel
- Taxpayers or public at large
- Interest Groups
- Contractors/Suppliers and Consultants

How these stakeholders view or use the results of LCCA, however, may well vary. For example, Interest Groups could see an LCCA as only one element toward a decision (e.g., considerations of equity, political impact, social impact, etc. may also be relevant to them).

Stakeholders can also harbour misconceptions about LCCA. Some of these are:

- LCCA can resolve equity among competing infrastructure elements. This is not correct
- LCCA can result in distortions of budgets from one exercise to the next. In fact though, LCCA is generally used under a scenario of planned budgets. However, LCCA can explore "what if" scenarios of different budget levels.
- LCCA is a guessing game because of large uncertainties in forecasts of costs, predictions of condition or performance, expected budgets, etc. However, even with uncertainties,

there is a better chance of identifying and implementing the most cost-effective strategies than by simply using judgement.

- LCCA is a substitute for the responsibility of making decisions. In fact, however, the role of LCCA is to support or enhance decision-making.
- LCCA may be able to identify the most cost-effective strategies but politics will prevail. While politicians have the ultimate responsibility of answering to the electorate, many politicians actually welcome LCCA as they can say the selected strategies are based on a fair (objective) competition for limited available funds.

Methods

The basic methods for LCCA have been described extensively in the literature, including textbooks by [Hudson et al 1997, Townley 1998] and in particular the applicability to pavements [TAC 1997, Haas et all 1994]. While the following five methods are applicable, the present worth and cost-effectiveness methods have been used almost exclusively in the pavement field:

- Equivalent uniform annual cost method
- Benefit-cost-ratio method
- Rate-of-return method
- Percent worth method for costs, or benefits or benefits minus costs, termed the net present value method
- Cost-effectiveness method

Regarding the present worth method, there is no need to state the formulation herein except to indicate that it involves the discounting of all future sums to the present using a present worth factor:

$$Pwf = 1/(l+i)^n$$

Where i = discount rate and n is the number of years to when the sum will be expended, or saved. For calculating the present worth of costs, the items can include initial construction or acquisition costs, future construction/rehabilitation/renovation and maintenance/operating costs, user costs (if applicable) and salvage/decommissioning/disposal costs. The present worth formulation is primarily applicable to mutually exclusive investments, or savings, in projects. It can be applied to a network or system wide set of projects but to find the minimum total cost requires an optimization (eg., linear or dynamic programming model) or a marginal cost-effectiveness model [Haas et al 1994].

Calculating the present worth of benefits can include direct user benefits (eg., savings in vehicle operating and/or user costs in comparing alternatives), indirect user benefits and indirect user benefits.

Net present value is then the difference between the present worth of benefits minus the present worth of costs; eg.,

$$NPV_{x1} = PWB_{x2,n} - PWC_{x1,n}$$

Where NPV_{x1} is the net present value of alternative x_1 for an analysis period of n years, $PWB_{x1,n}$ is the present worth of benefits and $PWC_{x1,n}$ is the present worth of benefits, where the mutually exclusive alternatives range from x_1, x_2…….to $x_{n.}$

The present worth method has a number of advantages in that it is easier to comprehend value in present day terms and the method is computationally simple and straightforward. In fact, [Townley 1998] recommends it for all public sector projects.

The rate-of-return method, often termed the "internal rate-of-return" particularly in the highway field, determines the discount rate at which the costs and benefits of an investment are equal. In applying the method, it is usual practice to compare each alternative with a base alternative, in increasing order of costs. Proceeding on the basics of such paired comparisons will indicate the alternative with the highest rate of return. The rate-of-return method has a major advantage in that the results are easy to comprehend because of familiarity with business investments. However, it must be remembered that it is only in private sector investments, such as for the 407 ETR (Mylvaganam and Borins 2004], where it becomes a "real" return.

The cost-effectiveness method has been extensively used in the pavement field [Haas et al 1994, TAC 1997] because an appropriate measure of effectiveness exists. It is the area under the performance curve, weighted by traffic and length. Essentially, it becomes a surrogate for benefits in terms of user cost savings when comparing alternatives with different performance curves. While such user cost savings can be determined directly from vehicle operating cost and user delay costs (due to interruptions) relationships, it is difficult to establish these relationships regionally without substantive effort to calibrate the models in the World Bank's HDM4 package [World Bank 2001].

FRAMEWORK FOR SHORT TO LONG TERM LCA

The major elements which should be incorporated into a framework for life cycle analysis of civil infrastructure, and particularly pavements, include the following:

- Functional class of facility (eg., for highways this would be local, collector, arterial and freeway)
- Life cycle period (short, medium and long term)
- Public sector or private sector
- Most appropriate LCCA method
- Other considerations (resource conversion, environmental impacts, etc.)

Table 2 provides a framework for the applicability of LCAA method(s) according to the foregoing elements. While the preferred or likely method(s) are based largely on opinion, they can provide guidance to those having the responsibility for LCCA. It may be noted that Table 2 does not include the benefit cost ratio method, largely because it is susceptible to misleading results in certain situations.

Table 2 Applicability of LCCA Methods in Likely/Preferred Order

	Functional Class of Highway							
	Local		Collector		Arterial		Freeway	
LCAA Period	Public[2] Sector	Private[2] Sector	Public[2] Sector	Private[2] Sector	Public[2] Sector	Private[2] Sector	Public[2] Sector	Private[2] Sector
Short[1] term	C/E[3] PWC AC	-	C/E PWC AC	-	C/E PWC AC IRR	IRR	C/E PWC IRR	IRR
Medium[1] Term	C/E PWC AC	-	C/E PWC AC	-	C/E PWC AC IRR	IRR	C/E IRR	IRR
Long[1] Term	-	-	-	-	-	-	IRR	IRR

Notes: 1. Short term can be up to 30 years; medium term 40 to 60 years; long term beyond 50 years
2. Public sector means a public investment; private sector means private investment
3. C/E is cost-effectiveness method; PWC is present worth of costs method; AC is annual cost method; IRR is internal-rate-of-return method

RATE-OF-RETURN EXAMPLE

This example is intended to illustrate the key features of calculating a rate-of-return on highway investment alternatives. It involves a multi lane urban bypass which the authority wishes to assess for its financial feasibility as an electronic toll route.

Two preliminary long life pavement designs are being considered, and the basic parameters are listed in Table 3. One is a heavy duty flexible pavement, with a life cycle period of 50 years. The other is a portland cement concrete pavement, again with a life cycle period of 50 years.

Other costs independent of these two alternatives, are also provided so a total cost picture can be developed. Everything is pro-rated on a per km basis.

Traffic volumes are provided, as well as toll charges. Estimates for growth rates are also given.

What is also given in the example are approximate, preliminary cost estimates for bridges, barrier walls/ median dividers, grading and landscaping, drainage and interchanges. These add substantially to the total costs and certainly would have to be further assessed in more comprehensive and detailed analysis. However, the intent of the example is really to illustrate the process and to show how alternatives can be compared for the rate-of-return that they would generate.

What is also not given but may influence a final decision on more detailed or expanded design alternatives are the following (and these can become particularly relevant for long life designs):

- Resource conservation (eg., aggregate consumption)
- Future recyclability
- Functionality beyond the short term
- Environmental impacts (eg., noise, solar absorption/heat generated, energy balance)

Table 4 provides calculations of costs and revenues for the example. Three discount rates, 5%, 12% and 20%, which represents quite a wide range, are used to illustrate how much variation will exist in net present value (NPV).

At the low rate of 5%, as might be expected, discounted revenues are quite substantial, while at the high rate of 20%, again as might be expected, net revenues are relatively quite small. However, total discounted costs do not vary to the same extent, primarily because of the effect of very large initial costs. It may also be noted that the total discounted costs for Alternatives A and B are very close, and this suggests that in comparison, the difference between the two alternatives is insignificant.

The internal rate of return (IRR) at which the NPV=0 obviously lies between i=12% and 20%, and has been calculated at 16%. This means that if the authority had to borrow money at say 6%, a net return of 10% could be realized.

Table 3 Basic Parameters for the Rate-of-Return Example

- Alternative A (heavy duty flexible pavement)
  - 40 mm surface course; 80 mm binder course, 120 mm (rich) asphalt base, 150 mm granular base, 450 mm granular subbase on clay subgrade
  - initial service life 20 years; then mill 25 mm and add 40 mm new surface; repeat at 35 years; end of life at 50 years
  - initial cost $282,000/lane-km; rehab. cost $88,000/lane-km at 20 and 35 years
  - annual maint. cost $2,000/lane-km initially rising by $1,000/lane-km each year to first rehab., then back to $2,000/lane-km and rising similarly to second rehab, and so on
  - residual value at 50 years – 0

- Alternative B (plain jointed, dowelled, PCCP)
  - 250 mm slab thickness; 250 mm OGDL; ave. joint spacing 4.5 m; clay subgrade
  - diamond grinding at 20 years $$45,000/lane-km
  - initial service life 30 years; then major joint restoration; 125 mm unbonded concrete overlay at 40 years; end of analysis period 50 years
  - initial cost $361,000/lane-km; major restoration at 30 years $82,000/lane-km; overlay at 40 years $198,000/lane-km
  - annual maint. Costs $2,000/lane-km initially and rising by same increments as for Altern. A
  - residual value at 50 years = $140,000/lane-km

- Other Costs (independent of pavement alternative)
  - electronic toll system, $228,000/lane-km on prorated basis, with major maint./upgrades at 10, 20, 30 and 40 years of $50,000/lane-km
  - admin., toll collection, traffic control, etc., $42,000/lane-km initially rising by $2,500/lane-km per year through analysis period
  - snow and ice control, right-of-way maint., etc., $42,000/lane-km/year throughout
  - pro-rated bridge & interchange construction, medians, grading, drainage, extra ROW, etc. – initial cost $3,900,000/lane-km

- Traffic Volumes and Toll Charges
  - initial AADT 12,000/lane-km, rising by 2%/year (compounded); 15% commercial traffic
  - initial toll charges .14/lane-km, pro-rated for commercial and peak and off-peak, rising by 2%/year (compounded)

Table 4a Calculations for the Rate-of-Return Example

Costs (Per Lane-km)		PW for i =		
• **Alternative A**		5%	12%	20%
	Initial Cost, $282,000/lane-km	282,000	282,000	282,000
	Mill 25mm, add 40mm at 20 years, $88,000/lane-km	33,166	9,123	2,295
	Mill 25mm, add 40mm at 35 years, $88,000/lane-km	15,954	1,667	149
	Maint. Costs, $2,000/lane-km, year 1……..year 50	242,081	87,929	39,415
	Residual Value at 50 Years	0	0	0
	ETS, initial cost, $228,000/lane-km	228,000	228,000	228,000
	Maint./upgrades of ETS @ 10, 20, 30, and 40 years, $50,000 each/lane-km	30,696 18,844 11,569 7,102	16,099 5,183 1,669 537	8,075 1,304 211 34
	Admin., toll collec., etc., $42,000/lane-km, year 1…….year 50	1,549,176	580,956	326,900
	Snow/ice control, ROW, etc., $42,000/lane-km/year throughout	808,749	390,789	251,977
	Pro-rated bridge & interchange const., medians, grading, drainage, extra ROW, etc. initial cost, $3.9m/lane-km	3,900,000	3,900,000	3,900,000
	Total	**$7,127,337**	**$5,503,952**	**$5,040,361**
REVENUES (Per Lane-km)				
	Initial tolls, 12,000 X .14/lane-km x 350 days	$ 588,000.00	$ 588,000.00	$ 588,000.00
	Future tolls, 12,240 year 2 x .1402/lane-km X 350 days in year 2…….year 50	21,994,691	6,676,761	3,191,278
	Total	**$22,582,691**	**$7,264,761**	**$3,779,278**

NPV (Total PW of Revenue – Total PW of Costs)	**$15,455,354**	**$1,760,809**	**-$1,261,083**

Table 4b Calculations for the Rate-of-Return Example

Costs (Per Lane-km)		PW for i =		
• **Alternative B**		5%	12%	20%
	Initial Cost, $361,000/lane-km	361,000	361,000	361,000
	Diamond Grinding @ 20 years, $35,000/lane-km	16,960	4,665	1,174
	Major joint restoration @ 30 years, $45,000/lane-km	18,973	2,737	345
	Overlay at 40 years, $198,000/lane-km	28,125	2,128	135
	Maint. Costs, $2,000/lane-km, year 1……..year 50	202,278	71,294	39,169
	Residual Value at 50 Years, $140,000/lane-km	12,209	484	15
	ETS, initial cost, $228,000/lane-km	228,000	228,000	228,000
	Maint./upgrades of ETS @ 10, 20, 30, and 40 years, $50,000 each/lane-km	30,696 18,844 11,569 7,102	16,099 5,183 1,669 537	8,075 1,304 211 34
	Admin., toll collec., etc., $42,000/lane-km, year 1…….year 50	1,549,176	580,956	326,900
	Snow/ice control, ROW, etc., $42,000/lane-km/year throughout	808,749	390,789	251,977
	Pro-rated bridge & interchange const., medians, grading, drainage, extra ROW, etc. initial cost, $3.9m/lane-km	3,900,000	3,900,000	3,900,000
	Total	**$7,193,680**	**$5,565,542**	**$5,118,340**
REVENUES (Per Lane-km)				
	Initial tolls, 12,000 X .14/lane-km x 350 days	$ 588,000	$ 588,000	$ 588,000
	Future tolls, 12,240 year 2 x .1402/lane-km X 350 days in year 2…….year 50	21,994,691	6,676,761	3,191,278
	Total	**$22,582,691**	**$7,264,761**	**$3,779,278**

NPV (Total PW of Revenue – Total PW of Costs)	**$15,389,011**	**$1,699,219**	**-$1,339,062**

COST EFFECTIVENESS EXAMPLE

It has been previously noted that a cost effectiveness formulation has been widely used in the pavement field, particularly at the network level and particularly because the effectiveness calculation becomes a convenient surrogate for a direct calculation of benefits. Effectiveness is the area under the performance curve, weighted by traffic and length of section. The actual calculation is effectiveness divided by cost, so that increasing number represent more attractive options. In essence, this is a return on investment method.

The example provided herein is part of a comprehensive study carried out for the City of Edmonton on its 4,000 km network of sidewalks [Haas et al 2003]. Different sidewalk types were included in the study, but a reasonably good composite and linear performance model for all types was developed, which is

$$VCI = -0.038A + 5.1016$$

Where VCI = visual condition index, scale of 1 to 5, transferable to a level of service (LOS) indicator
A = Age in years
R^2 for the model = 0.83 (2800 data points)

A VCI of 3.1 was determined to be the minimum acceptable, and the foregoing equation gives 53 years at which this age is reached. Since performance models for individual types are tightly grouped, an initial service life of 50 years was used as an approximation.

VCI predictions for each section in the network were carried out for a 20 year and a 50 year life cycle for the following basic options:

1. No capital funds; only maintenance/trip hazard repairs. This may not be an acceptable option but it provides a baseline for comparison. It can be referred to as a "do nothing" option but maintenance expenditures still occur.
2. Replacement of one neighbourhood (10 km) per year, plus maintenance repairs according to trip hazards allocated to the various LOS. This is a minimal option in that the expectation is a continuing decline in LOS.
3. Replacement of 10 km in year 1, 20 km in year 2, etc., "ramped up" to 70 km or 7 neighbourhoods per year in year 7 and thereafter. This option would be expected to keep a relatively constant LOS (e.g., preserve the investment) over the long term.
4. Replacement of 10 km in year 1, 20 km in year 2, 30 km in year 3, 40 km in year 4, and then staying constant at 40 km/year. This option is put forth as sort of "mid way" between Options 2 and 3., with the recognition that it is not a preservation of investment option like 3.

Unit cost details for maintenance/trips hazards and for replacement are available in [Haas et al 2003]. To summarize, about 9,000 repairs at an average cost of $55 are required each year for the current LOS. Different numbers of repairs, depending on what option was under consideration, and the corresponding performance prediction, were also estimated for the cost calculations.

Replacement costs were $150/m. Different discount rates were evaluated, with 4% being selected for final analysis and recommendations.

Effectiveness was calculated as the sum of areas under the performance curves, weighted by section lengths. Weighting by traffic was not necessary in view of this being a sidewalk network. Cost effectiveness was calculated for each option as the total effectiveness divided by present worth of costs. This ratio does not have meaning within itself, as in the case of a benefit/cost ratio, but it provides a comparative indicator between options.

Since the focus herein is on the longer term, only the 50 year LCCA will be provided. First, a comparison of the impact of each option on the average VCI over a period of 50 years is shown in Figure 2. As would be expected, the greater the yearly replacement length the smaller the increments the CFI decreases by. The greatest difference exists between 10 km/year replacement (Option 2) and 10, 20, …40 km/year (Option 4) replacement while the differences between no replacement (Option 1) versus 10 km/year (Option 2) and 10, 20, …40 km/year (Option 4 versus 10, 20, …70 km/year (Option 3) are fairly similar.

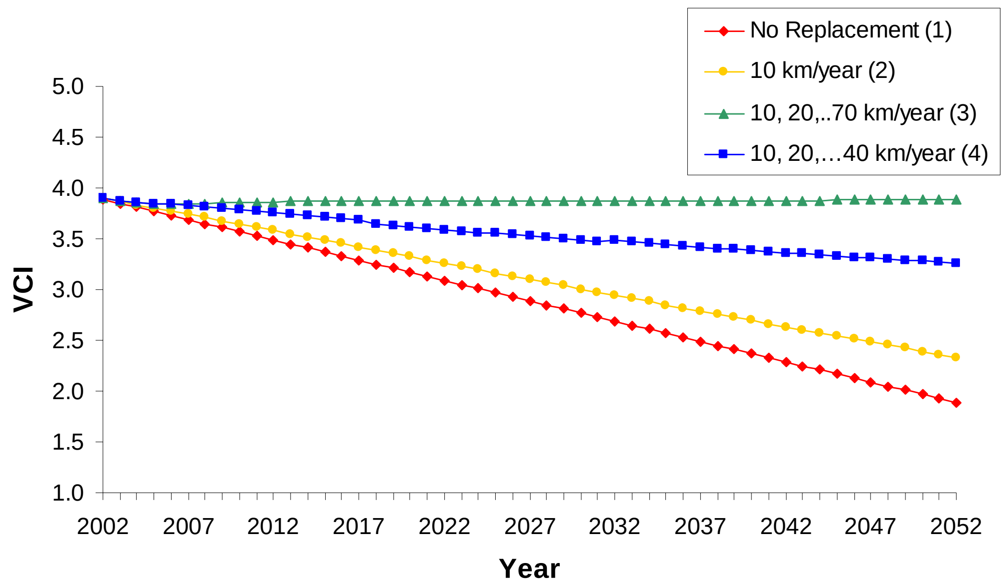

Figure 2: VCI over 50 years for Option 1, 2, 3 and 4

While a 20-year analysis period is reasonable for the short term, the actual service life for concrete sidewalks is about 50 years. Thus an analysis period of 50 years, to at least incorporate one life-cycle period, would also be appropriate.

Table 5 shows the results. Two things are immediately apparent. First, there is a significant increase in cost-effectiveness for all options in comparison to the base (Option 1). Second, Option 4 (replacement of 10 km in year 1, ramping up to 40 km/year in year 4, and levelling off/constant thereafter, plus maintenance) is the best; eg., it offers the best return on investment.

Table 5: LCCA Summary Results for 50 Year Period

Option	Total Effectiveness at 50 years ($x 10^6$)	PW of Maint. Plus Repl. Cost ($x 10^6$)	PW of Accrued Liability Cost ($x 10^6$)	Total PW of Costs ($x 10^6$)	Cost Effectiveness Ratio
1	574.5	$54.2	$41.1	$95.3	6.0
2	617.4	$52.5	$36.2	$88.7	7.0
3	769.1	$110.9	$6.7	$117.7	6.5
4	706.0	$73.1	$21.	$94.4	7.5

This clearly indicates that for infrastructure with a long service life, such as sidewalks, the analysis period should extend to at least one service life cycle. Not withstanding that a fair degree of approximation is involved, the investment strategy for such infrastructure should be long term.

CONCLUSIONS

The following conclusions can be drawn from this paper:

- Life cycle analysis (LCA) of infrastructure investments, including pavements, is increasingly being required to incorporate longer life cycle periods and consider factors in addition to the life cycle cost analysis (LCCA), such as resource conservation and environmental impacts.
- Reasonable life cycle periods for short, medium and long term analysis would be in the order of 25, 50 and 100 years respectively.
- LCCA has as its basic objective the comparison of competing, alternative investment strategies. A range of stakeholders exist for public sector investments, from the elected level to the public at large to suppliers.
- A framework for LCCA applications is suggested which recognizes short, medium and long term cycle periods, functional class of highway, public and private sectors and likely or preferred LCCA method.
- A numerical example has been described which shows how an agency could calculate an internal rate of return (IRR) for two investment alternatives involving different pavement designs. The life cycle period was 50 years.
- Another numerical example, this one involving a sidewalk network (in the City of Edmonton) and 50 year life cycle, has been provided which shows how a cost-effectiveness calculation can identify the best investment alternative.
- As a final point, while conventional LCCA for calculating the present worth of costs for pavement alternatives will likely continue to be the primary economic comparison tool for the foreseeable future, particularly for the public sector, and shorter term life cycle periods, going beyond conventional LCCA and using a rate-of-return or cost-effectiveness formulation, especially for medium to longer term life cycle periods, should be given more attention.

ACKNOWLEDGEMENTS

The authors wish to acknowledge and thank colleagues from the City of Edmonton, Konrad Siu, Theresa Cloake, Paul Szezepanski and Al Cepas for their support and assistance in the Life Cycle Analysis project for sidewalks, the results of which are partially used in an example in this paper. As well, thanks are due to our Research Administrative Officer in the Centre for Pavement and Transportation Technology, Ms. Shelley Bacik, for a key role in the production of this paper.

REFERENCES

[Cloake and Siu 2002] Cloake, Theresa and Konrad Siu "Risk Assessment Modelling for Infrastructure "Presentation to TAC Workshop, Quebec, Quebec, Sept., 2004

[Cowe Falls, Haas and Tighe 2005] Cowe Falls, Lynne, Ralph Haas and Susan Tighe, "Framework for Selection of Asset Valuation Methods for Civil Infrastructure", Paper to be presented to Annual Conf. of the Transportation Association of Canada, Calgary, Sept 2005

[Haas, Cowe Falls and Tighe 2001] Haas, Ralph, Lynne Cowe Falls and Susan Tighe,"Impact Assessment of Life Cycle Cost Analysis" Final Report Prepared for Office of Infrastructure, City of Edmonton, Dec. 31, 2001

[Haas, et al 1994] Haas, Ralph, W. Ronald Hudson and John Zaniewski, "Modern Pavement Management', Krieger Publishing Company, Malabar, 1994.

[Hudson et al 1997] Hudson, W. Ronald, Ralph Haas and Waheed Uddin, "Infrastructure Management", McGraw Hill, New York, 1997.

[Siu and Cloake 2001] Siu, K.L. and Theresa Cloake, "Implementation of An Infrastructure Strategy for the City of Edmonton", Proc., INFRA 2001, Montreal, Nov., 2001

[TAC 1997] Transportation Association of Canada, "Pavement Design and Management Guide", Ottawa, 1997

[Haas 2005] Haas, Ralph ,"Challenges of Managing the Built Infrastructure", Keynote Lecture to 1st Speciality Conference on Infrastructure Technologies, Management and Policy, Proc., 33rd Can. Society for Civil Eng. Annual Conf., Toronto, June, 2005

[Haas et al 2003] Haas, Ralph, Susan Tighe, Lynne Cowe Falls and Angela Jeffray, "Toward a Life Cycle Investment Strategy for Edmonton's $500 Million Infrastructure Asset: It's Sidewalks", Final Report Prepared for Office of Infrastructure, City of Edmonton, Aug. 25, 2003

[Haas 2003] Haas, Ralph, "Innovative, Forward Looking Research is a Vital Element in the Future of Civil Engineering", Canadian Civil Engineer, March/April 2003 Issue

[Mylvaganam and Borins 2004] Mylvaganam, Chandman and Sandford Borins, "If You Build It … Business, Government and Ontario's Electronic Toll Highway", University of Toronto Press, 2004

[Townley 1998] Townley, David, "Principles of Cost-Benefit Analysis in a Canadian Context", Prentice Hall Canada Inc., 1998

[World Bank 2001] "Highway Development and Management – 4 (HDM4), The Highway

	Development and Management Series, Washington, D.C., 2001
[Bradbury et al 2000]	Bradbury A., T.J. Kazmierowski, K. Smith, and H. VonQuintas, "Life Cycle Costing of Freeway Pavements In Ontario", Paper Presented to 79th Transportation Research Board Annual Meeting, Washington D.C., January 2000
[FHWA 1998]	United States Federal Highway Administration, "Life Cycle Cost Analysis In Pavement Design – In Search of Better Investment Decisions", United States Federal Highway Administration, Washington D.C., 1998
[Zimmerman and Grogg 2000]	Zimmerman, K. and Grogg, M., "Applying Economic Concepts From An LCCA to a Pavement Management Analysis", Paper Presented to 79th Transportation Research Board Annual Meeting, Washington D.C., January 2000