EUPAVE
EUROPEAN CONCRETE PAVING ASSOCIATION

# A guide on the basic principles of Life-Cycle Cost Analysis (LCCA) of pavements

## CONTENTS

## PREFACE

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The EU Directives on Public Procurement and Concessions[1], which are applicable since 18 April 2016, establish rules on the procedures for procurement by contracting authorities with respect to public contracts as well as design contests, whose value is estimated to be not less than certain thresholds. They definitely impact the way more than 250 000 public authorities in the EU countries spend on a large part of the €1,9 trillion paid for public procurement every year in Europe, which accounts for around 18% of the EU GDP.

One of the goals of this legislation is to have bids assessed on the basis of the best price-quality ratio, which should always include a price or cost element using a cost-effectiveness approach, such as life-cycle costing and foreseeing the possibility of including the best price-quality ratio.

Life-cycle costing is unfortunately rarely applied today in Europe in procurement of transport infrastructure, despite the savings it can offer over the life of an asset of infrastructure, such as a road. By focusing on the initial cost of construction in assessing bids, as is currently often the case, authorities fail to capture cost savings that are possible thanks to durable, low-maintenance solutions. Thanks to the new Directives, there is an opportunity for Member States to update their procurement practices and save tax-payers' money, while also benefiting the environment. Furthermore, promoting healthy competition by means of open tendering processes has proven to reduce costs for public authorities.

EUPAVE is committed to providing further guidance by offering its technical expertise and know-how to its members and all contracting authorities in the European Union who wish to use cost-effectiveness approaches to provide better value for money and more sustainable infrastructure.

That is why EUPAVE decided to draft this guide on LCCA (Life Cycle Cost Analysis) of pavements in order to provide a general insight in the approach and good practice in conducting such analysis.

Special thanks goes to Mr. Manu Diependaele, consultant in LCCA and author of this publication, who reviewed and collected a comprehensive amount of information and reference documents and turned them into a new, clear and concise European guide, explaining the principles and the procedures to follow. Furthermore, he is available to interested road authorities for further assistance and consultancy.

On behalf of EUPAVE, I also explicitly express my gratitude to our American colleagues from ACPA (American Concrete Pavement Association) and the FHWA (Federal Highway Administration) for sharing their rich experience in LCCA with us and providing us important guidance through their well-documented and illustrated manuals.

I hope you will enjoy reading this guide and you will be able to use the knowledge in future investment decisions.

[1] Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on public procurement (replacing Directive 2004/18/EC), Directive 2014/25/EU of the European Parliament and of the Council of 26 February 2014 on procurement by entities operating in the water, energy, transport and postal services sectors (replacing Directive 2004/17/EC), and Directive 2014/23/EU of the European Parliament and of the Council of 26 February 2014 on the award of concession contracts

## 1 - SCOPE

Worldwide many publications on the issue of LCCA are available in different degrees of detailing.

In these publications the same fundamental principles and a widely accepted procedure are used for conducting a LCCA. These principles and procedure are applicable for any type of asset. The intent of this Publication is to highlight the essence of the principles and procedure in the field of pavement and this regardless of the type of pavement materials used, the highway agency or country involved.

In conducting a LCCA two approaches are to be distinguished i.e.:

- The deterministic approach
- The probabilistic approach (also called Risk Analysis Approach)

Furthermore, the two major types of costs involved are:

- The agency costs
- Tthe user costs

Within the scope of this Publication:

- The deterministic approach will be described in detail whereas the principles of the probabilistic approach will be mentioned briefly.
- The agency costs (initial and future) will be dealt with specifically both in the theoretical description and in the examples, whereas the user costs will only be theoretically described in general.

The degree of detailing in this Publication, of both the deterministic approach and the agency costs, is such that it enables any professional to conduct a LCCA by applying the standard procedure of a LCCA as described in this EUPAVE Publication and by using an excel spread sheet. For a more advanced application of the procedure that includes user costs and/or risk analysis, specific software is more appropriate or necessary and is available on the market.

This Publication provides references to this specific software.

The Publication is structured as follows:

- Chapter 1. Scope
- Chapter 2. Introduction
- Chapter 3. LCCA Standard Procedure
- Chapter 4. Special Topics
- Chapter 5. Examples of LCCA
- Chapter 6. References

Considering the concise concept of the Publication, the formulas used in the LCCA procedure, will be explained to the extent that is necessary to understand the procedure.

The main references that were used for the preparation of this publication are listed in Chapter 6. In the text the references are only mentioned where considered appropriate or where parts are literally taken over from a reference.

The LCCA procedure itself, as described in this publication is primarily taken over from Ref. 1 and to some extent from Ref. 2. Where considered appropiate tables or graphs are taken over from these references as well.

# 2 - INTRODUCTION

## 1. LIFE CYCLE COST ANALYSIS – GENERAL

### Life Cycle Cost Analysis (LCCA) – Definition

LCCA is an analysis technique based on well-founded economic principles used to evaluate the long-term economic efficiency between competing alternative investment options. LCCA can be applied to different types of assets and to a wide variety of investment-related decision levels. LCCA for pavements is typically performed to compare competing pavement designs, over a defined analysis period, taking into account all significant present and future costs (agency, user and other relevant costs) over the life of the pavement and expressing these costs in present value.

Because much of the pavement networks consist of either asphalt or concrete pavement, many publications focus on LCCA of these two alternative types of pavement and on their subsequent comparison. However, LCCA can as well be conducted to evaluate and compare the economic worth of alternative designs of the same type of pavement.

### Purpose and importance of a LCCA results

In principle, the purpose of a LCCA for pavements is to identify the design strategy that will render the best value for the investment, by determining the lowest long-term cost to provide the expected performance of the pavement type selected. However, LCCA results should not be interpreted in an absolute way. The results are not decisions in and of themselves but they are a useful support tool to make decisions. The analytical evaluation itself of a LCCA is often as important as the LCCA results.

### Effect of input parameters

The relative influence of individual LCC-factors on analysis results may vary from major to minor to insignificant. The level of detail incorporated in a LCCA should be consistent with the level of investment decision under consideration. For example, slight differences in future costs have a marginal effect on the discounted present value. Including such factors unnecessarily complicates the analysis without providing tangible improvement in the analysis results. Including all factors in every analysis is frequently not productive. In conducting a LCCA, analysts should evaluate all factors for inclusion and explain the rationale for eliminating factors. Such explanations make analysis results more supportable when they are scrutinised by critics who are not pleased with the analysis outcome.

## 2. APPROACHES

For conducting a LCCA two approaches are possible: either a deterministic approach or a probabilistic approach.

- The deterministic approach to LCCA is the traditional and simplest approach in that it applies procedures and techniques without regard for the variability of the input parameters. The input parameters are introduced as discrete values. This is the primary disadvantage of this approach.
- The probabilistic approach (also called Risk Analysis Approach) is based on the same basic procedural steps but it characterises uncertainty in that it allows all significant input parameters to vary simultaneously.

At present, the deterministic approach is mostly used. Yet, the Risk Analysis Approach is advocated as computer simulation techniques have made it more accessible and because it better matches the reality of variability of the input parameters.

## 3. ECONOMIC WORTH INDICATOR FOR LCCA

The Alternatives considered in a LCCA are compared using a common measure of economic worth. The economic worth of an investment may be expressed in a number of ways. In the practice of LCCA of pavements, investment alternatives are most commonly compared on the basis of the Net Present Value (NPV) or in terms of an Equivalent Uniform Annual Cost (EUAC).

Sometimes, the Benefit/Cost or B/C Ratio is considered, which represents the net discounted benefits of an alternative divided by net discounted costs.

**Net Present Value (NPV)**, sometimes called Net Present Worth (NPW) is the net discounted monetary present value of future cash flows i.e. costs (e.g. maintenance or preservation costs) minus future benefits (e.g. residual value).

Discounting costs and benefits transforms cash outflows (costs) and cash inflows (benefits), occurring in different time periods in the future, to their present values which are a common unit of measurement.

The basic formula for computing the present value PV of a one-time future cash flow FC is:

$$PV = FC \times \left[\frac{1}{(1+D)^y}\right]$$

In this equation,

PV = Present Value

FC = Future Cash flow

$f_{PV} = \left[\frac{1}{(1+D)^y}\right]$

is referred to as the Present Value factor

D = discount rate

y = year into the future in which the one-time future cash flow (cost or benefit) occurs

Taking into account that it is common practice in a LCCA for pavements to use the real discount rate r (see hereinafter), the general formula for the net present value (NPV) of several subsequent future cash flows (as well costs as benefits) occurring at different times in the future is as follows:

$$NPV = IC + \sum_{k=1}^{Q} FC_k \left[\frac{1}{(1+r)^{y_k}}\right] - RV\left[\frac{1}{(1+r)^p}\right]$$

In this equation:

NPV = net present value of the alternative

IC = Initial Cost of construction

$FC_k$ = Future Cost of activity k

RV = Residual Value of the pavement (is a benefit, negative cost)

r = real discount rate

$y_k$ = year into the future of cash flow of activity k

Q = total number of activities

p = number of years in analysis period

Another economic indicator that can be considered to compare alternatives is the **Equivalent Uniform Annual Cost (EUAC).** The EUAC represents the NPV of all discounted costs and benefits of an Alternative x as if they were to occur uniformly and annually throughout the analysis period. EUAC is a more appropriate indicator when budgets are established on an annual basis.

The method of determining the EUAC is the following:

- first determine the of the future costs and benefits
- then use the following formula to convert this NPV into a EUAC:

$$EUAC = NPV * \left[\frac{r(1+r)^n}{(1+r)^n - 1}\right]$$

In this equation is:

r = real discount rate

n = number of years over which the future EUAC reoccurs

Whether NPV or EUAC is used, the added value to the decision supported by the LCCA will be the same.

The decision to use EUAC or NPV is up to the analyst. When decision-makers are accustomed to using annualised costs, EUAC may be a more useful form for the analysis results. Because it presents an annualised amount, EUAC may not emphasise the overall magnitude of the difference between alternatives as much as PV would and may convey an artificial evenness in cost flows. However, EUAC may present decision makers with a feel for how a design alternative affects agency resources over the analysis period, particularly if the project in question will be bond financed. [Ref. 5].

## 4. COST ESTIMATES AND DISCOUNT RATES FOR LCCA

In the equations hereinbefore, the following two economic input parameters are of primary importance for the LCCA results:

- The cost estimate of the initial construction and of each of the future periodic maintenance or rehabilitation activities for each of the competing alternatives.
- The discount rate which accounts for the time value of money and converts futures cash flows into present values.

**Cost estimates**

Estimates of future costs and benefits can be made in two ways: either using "constant" cash flows or using "nominal" cash flows.

Constant cash flows (also called real cash flows) reflect cash flows with the same or constant purchasing power over time. In such cases, the cost of performing an activity would not change as a function of the future year in which it would be accomplished. For example: if a jointed plain concrete pavement (JPCP) costs € 40,00/ today, then € 40,00/ should be used for cost estimates of JPCP in the future.

Nominal cash flows, on the other hand, reflect cash flows that fluctuate in purchasing power as a function of time. They are normally used to include future general price rises resulting from inflation. When using nominal cash flows, the estimated cost of an activity in the future would change as a function of the future year in which it is accomplished. In this case if the JPCP costs € 40,00 $m^2$/ today and if the inflation would be 3%, the cost estimate for the JPCP at 1 year from today would be € 40,00/$m^2$ x 1,03 = € 41,20/$m^2$.

**Discount rates**

The discount rate used in a LCCA can be either a "constant" discount rate (mostly called "real" discount rate) or a "nominal" discount rate.

The real discount rate, also known as the real interest rate, is commonly used in engineering economics and reflects the rate of change over time in the true value of money taking into account fluctuations in both nominal interest rate and the rate of inflation. Real discount rates should be used in conjunction with future cost estimates that are expressed in constant cash flows.

The nominal discount rate includes the inflation component. Nominal discount rates should only be used in conjunction with future cost estimates that are expressed in nominal cash flows.

The real discount rate can be determined using the following mathematical formula:

$$r = \frac{1 + i_{int}}{1 + i_{inf}} - 1$$

where:
$r$ = real discount rate, %
$i_{int}$ = nominal interest rate (also called market interest rate), %
$i_{inf}$ = inflation rate, %

The real discount rate r can also be approximated as follows, if the interest rate exceeds the inflation rate:

$$r \approx i_{int} - i_{inf}$$

High real discount rates favour alternatives that have low initial costs and high future costs (e.g. often asphalt pavements), while low real discount rates favour alternatives with higher initial costs and lower future costs (e.g. mostly the case for concrete pavements).

**Caution**

While LCCA can be conducted using either constant or nominal cash flows, there are two cautions.

1. In any given LCCA, constant and nominal cash flows cannot be mixed in the same analysis (i.e., all costs must be expressed in either constant cash flows or all costs must be in nominal cash flows).
2. The selection of the discount rate (further discussed hereinafter) must be consistent with the type of cash flow used (i.e., use constant cash flows and real discount rates or nominal cash flows and nominal discount rates).

**Common practice**

The current practice followed by most highway agencies consists of conducting LCCA using constant cash flows and a single (also called "general") real discount rate. This combination eliminates the need to estimate and include the inflation portion in the present value calculations. This also allows the analyst to use today's cost of materials for the future periodic maintenance or rehabilitation costs, which facilitates considerably the cost calculations.

This approach of the calculations is often also used to avoid the complexities in calculating local or material-specific real discount rates. The latter can be used to account for price changes of materials that allows to improve the results of the LCCA. How this can be done is mentioned in Chapter 4, Special Topics.

# 3 - LCCA STANDARD PROCEDURE

This chapter identifies and briefly describes the essence of the procedural steps involved in conducting a life cycle cost analysis (LCCA) according to the deterministic approach.

The basic procedural steps include:

1. Establish alternative pavement design strategies and select analysis period
2. Determine performance periods and activity timing
3. Select discount rate
4. Estimate agency costs
5. Estimate user costs
6. Develop cash flow stream diagrams
7. Calculate net present value
8. Analysis of results and sensitivity analysis
9. Re-evaluate design strategies

While the steps are generally sequential, the sequence can be altered to meet specific LCCA needs. The following sections discuss each step.

## 1. ESTABLISH ALTERNATIVE PAVEMENT DESIGN STRATEGIES AND SELECT ANALYSIS PERIOD

The primary purpose of a LCCA is to quantify the long-term implication of initial pavement design decisions on the future cost of periodic maintenance and rehabilitation activities necessary to maintain some pre-established minimum acceptable level of service for some specified time.

The first step in conducting a LCCA of alternative pavement designs is to identify the alternative pavement design strategies for the analysis period under consideration.

**Analysis Period**

The **Analysis Period** is the time horizon over which initial and future cost are evaluated. The Analysis Period is not necessarily the same as the design period or performance life as is illustrated on Figure 3-1.

The analysis period should be sufficiently long to encompass long-term cost differences associated with reasonable design strategies. The analysis period should generally always be longer than the pavement design period (initial performance life), except in the case of extremely long-lived pavements.

As a rule of thumb, the analysis period should be long enough to incorporate at least one rehabilitation activity. The FHWA's September 1996 Final LCCA Policy statement recommends an analysis period of at least 35 years for all pavement projects, including new or total reconstruction projects as well as rehabilitation, restoration, and resurfacing projects [Ref. 1]. ACPA recommends an analysis period of 45 to 50+ years so that at least one major rehabilitation or reconstruction is captured for each alternative [Ref. 2].

At times, a shorter analysis period may be appropriate, particularly when pavement design alternatives are developed to buy time (e.g. 10 to 15 years) until a total reconstruction is realised. Furthermore, it is sometimes appropriate to slightly adapt the length of the analysis period in order to avoid the estimation of the remaining service life for at least one alternative. For example, if one or more alternative strategies would reach a minimum acceptable serviceability at year 44, then a 44-year analysis period could be assumed. Such adaptation is acceptable because the analysis period is subject to an estimation like any other parameter is.

Regardless of the length of the analysis period selected, the analysis period used should be the same for all alternatives considered in the analysis.

Most of the time the performance life of the alternatives differs so that one or more of the alternatives being compared may have a performance life that extends beyond the end of the chosen analysis period. For these alternatives, the pavement structure presumably would have some Remaining Service Life (RSL). The RSL can be included in the LCCA in a variety of ways, as discussed later.

Figure 3-1. Analysis period for a pavement design alternative

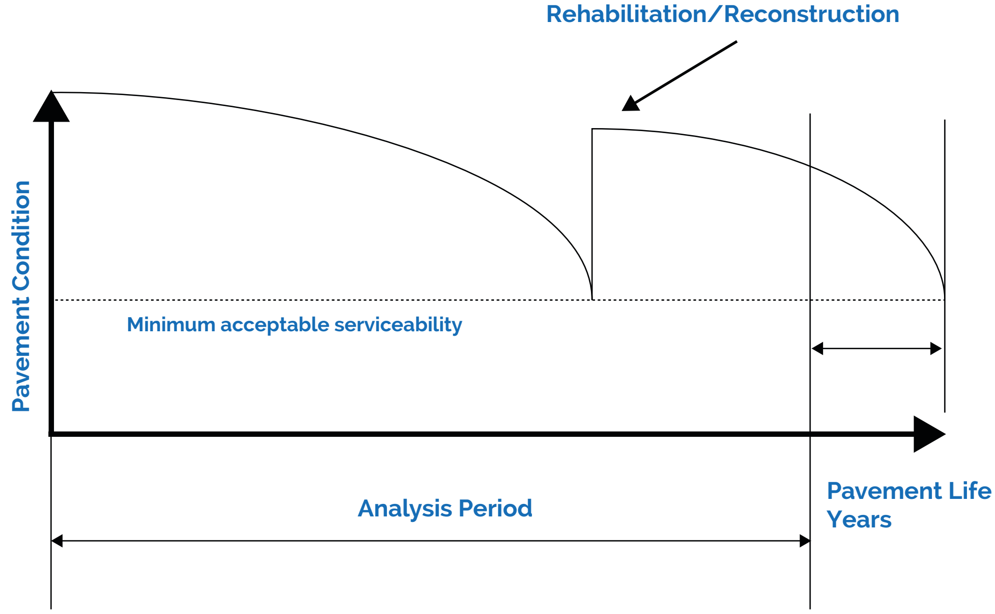
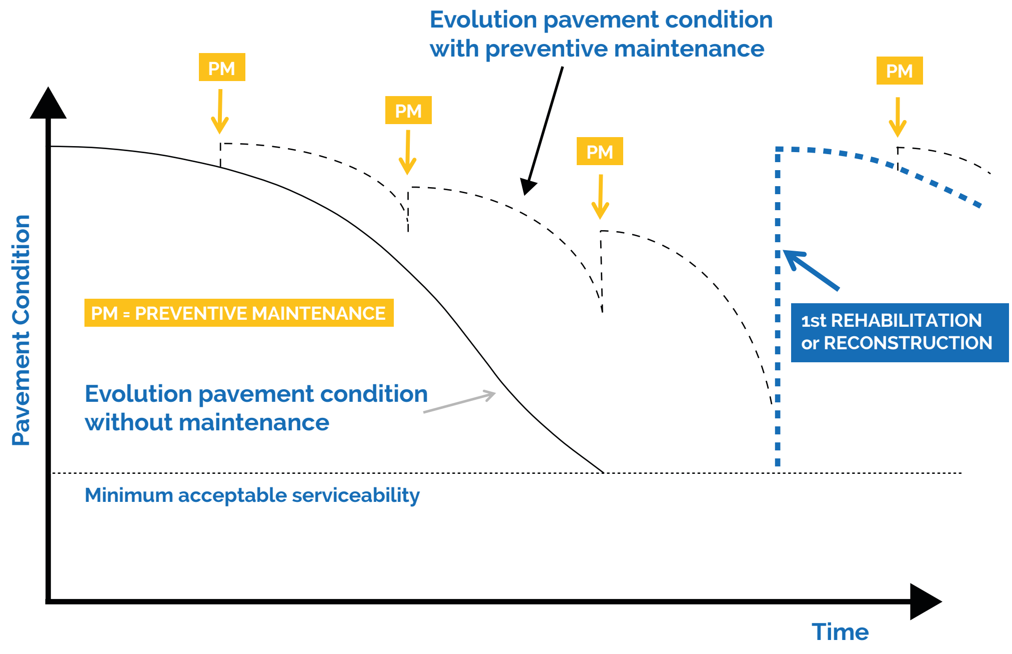



Figure 3-1 shows a typical analysis period for a pavement design alternative.
Note that the curve in this figure is a simplified theoretical representation that is commonly used in LCCA publications to depict the evolution of the pavement condition with preventive maintenance. The actual stepped evolution of the pavement condition is schematised in Figure 3-2 hereinafter.

Figure 3-2. Actual evolution scheme of pavement condition with preventive maintenance and rehabilitation/reconstruction



**Pavement Design Strategies**

A **Pavement Design Strategy** is the combination of the initial pavement design and the necessary supporting maintenance and rehabilitation activities in the future.

A pavement design strategy typically consists of a combination of:

- An initial pavement design characterised by the pavement type and structure and an expected initial design life (performance life),
- The necessary future maintenance activities in order to realise the envisaged initial design life,
- The rehabilitation/reconstruction activities in the future.

In this step, it is the intent to identify the scope, timing and costs of these activities. Depending on the initial pavement design, Highway Agencies employ a variety of different types of maintenance treatments (preventive maintenance, emergency maintenance, …) and rehabilitation or reconstruction strategies to keep the highway facilities in functional condition.

These strategies depend on several factors such as:

- Extent of the strategy: preventive maintenance, rehabilitation or reconstruction.
- Circumstances differing from country to country: climate, availability and type of materials used, standard practice, the availability of historical data, etc.

Typical strategies are included in the examples presented in Chapter 5 of this Publication.

## 2. DETERMINE PERFORMANCE PERIODS AND ACTIVITY TIMING

The performance life of the initial pavement design has a major impact on LCCA results. This is also the case for the performance life of the subsequent maintenance and rehabilitation activities. The performance life directly affects the frequency of the agency interventions on the highway facility, which in turn affects agency costs as well as user costs during periods of construction and maintenance or rehabilitation activities. Highway Agencies can determine specific performance information for various pavement strategies through analysis of pavement management data and historical experience. If available, operational pavement management systems can provide the data and analysis techniques to evaluate pavement condition and performance and traffic volumes to identify cost-effective strategies for short- and long-term capital projects and maintenance programmes. Performance lives can also be based on the collective experience of senior engineers inside Highway Agencies. [Ref. 1]. Specific pavement performance information is possibly also available in various pavement performance reports.

Finally, useful information can also be obtained from a literature review insofar as materials, techniques and circumstances (climate, traffic, …) are comparable to the local circumstances within the country concerned and to the characteristics of the pavement alternatives being analysed.

For typical examples of design strategies and their performance life, reference is made to Table 2.1 of Ref. 1 or to the examples presented in Chapter 5 hereinafter.

The work zone requirements for initial construction, maintenance, and rehabilitation directly affect highway user costs and should be estimated along with the pavement strategy development. Characteristics of these requirements such as frequency, duration, severity and year of work zone requirement are critical parameters in developing the user costs for the alternatives being studied.

## 3. SELECT DISCOUNT RATE

Discount rates can significantly influence the analysis result. However, a realistic selection of the discount rate is not evident to make because it is (1) related to economic trends in the future and (2) related to a long-term horizon. Therefore, a sensitivity analysis to evaluate the impact of differing real discount rate values is highly recommended for each LCCA performed.

LCCA should use a reasonable discount rate that reflects historical trends over long periods of time. Interest rates and inflation rates fluctuate over time, but the relative difference between them, although not constant, is less variable. This relative difference corresponds approximately to the real discount rate as mentioned in § 2.4.

$r \approx i_{int} - i_{inf}$

Data within the USA on the historical trends over very long periods indicate that the real time value of money was approximately ranging between 3 to 5 percent with an average of approximately 4 percent from approximately 1985 to about 2000. This is illustrated on Figure 3-3 and Figure 3-4 hereinafter.

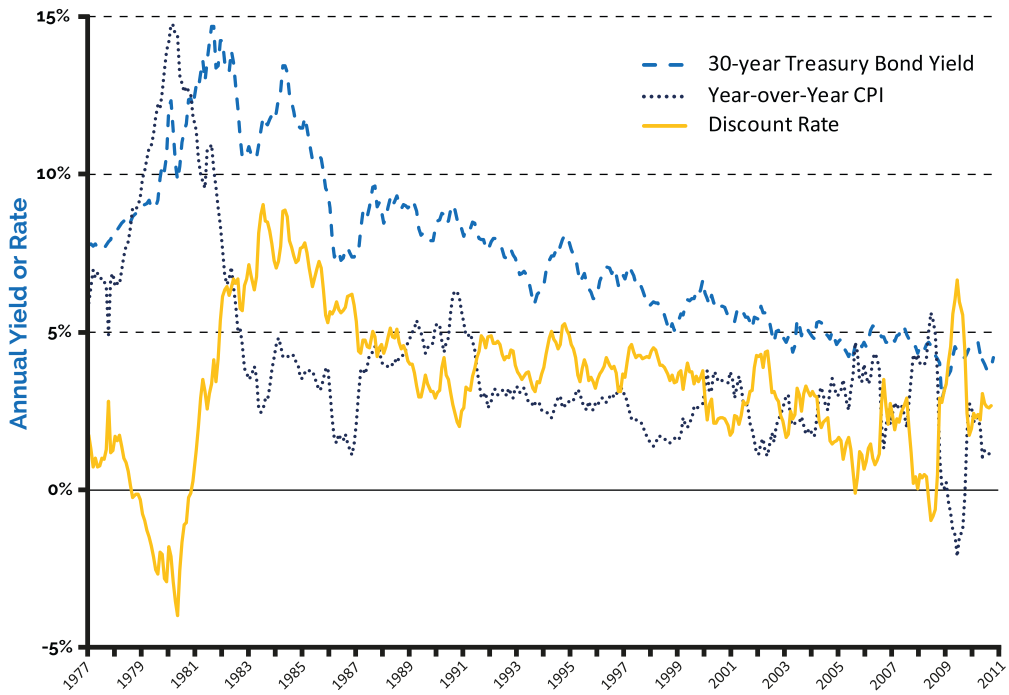
**Trends of values of the real discount rate**

A survey conducted (about 10 years ago) among 39 of the 50 states in the USA, revealed that the real discount rates used by the State Highway Authorities in their LCCAs ranged from < 3% to 5% [Ref.2]. This in itself is remarkable in that, within the same country having comparable economic conditions, a relatively great spread of discount values used, is existing.

Ref. 2 further mentions that the real discount rate in the USA have dropped to an average 2,1% over the last 5 years preceding 2012, which is almost half the historical average of 4% mentioned above. This same trend is even more applicable for European countries, as is mentioned in publications of the ECB (European Central Bank). These sources also mention that real discount rates do not necessarily differ substantially from country to country, certainly not among countries that belong to or deal with the European Economic Area. As a result of this and taking into account the long-term character of the real discount rate and the uncertainty associated with it, real discount rates ranging from 1% to 3% could be justified at present (i.e. 2018) to conduct a LCCA for average European circumstances. Anyhow, whenever the deterministic approach is used, conducting a sensitivity analysis to variations of the real discount rate remains a necessity.

Note that the two graphs on Figure 3-4 match relatively well.

**Figure 3-3. 30-year Treasury bond yield, year-over-year change in Consumer Price Index (CPI) and real discount rate calculated from the two [Ref. 2]**



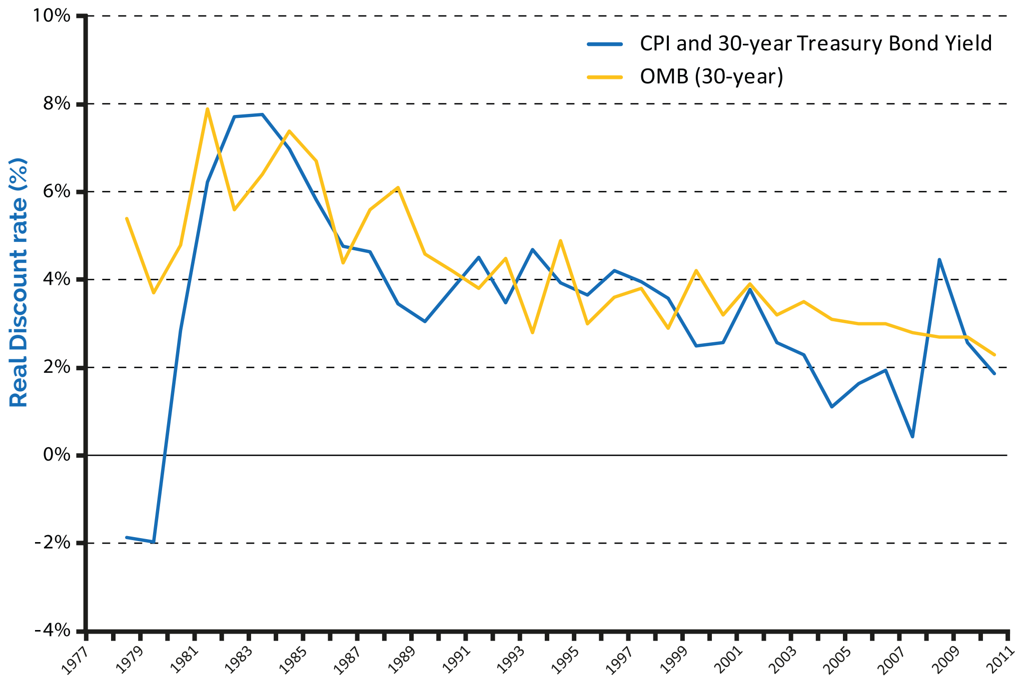



**Figure 3-4. Yearly real discount rates calculated from the CPI and the 30-year Treasury bond yield and those set by the US Office of Management and Budget (OMB) [Ref. 2]**

## 4. ESTIMATE AGENCY COSTS

Agency costs are all the costs incurred directly by the Highway Agency over the analysis period.

**Agency costs** typically include the following cost elements:

- Initial and future costs pertaining to engineering, contract administration, supervision of construction;
- Initial construction costs;
- Future emergency and corrective maintenance, preventive maintenance (e.g. resurfacing) and future rehabilitation or construction cost and the associated engineering and administrative cost;
- Residual value at the end of the analysis period;
- Reconstruction costs.

Agency costs also include maintenance of traffic costs and can include operating costs such as pumping station energy costs, tunnel lighting, and ventilation.

In general, very little data are available about emergency and corrective type maintenance so that estimating the future cost and timing is not evident. However, the costs related to this type of maintenance are in general not very high and show little difference between most alternative pavement strategies. Consequently, when discounted to the present, small cost differences have negligible effect on the present value and are sometimes not taken into account.

The first step in estimating agency costs is to determine construction quantities and unit prices. Unit prices can be determined from historical bid prices on previous projects of comparable scale. If material-specific inflation rates of pavement materials will be accounted for, appropriate methods should be resorted to, as explained in Chapter 4.

Initial agency costs can be divided into pavement and non-pavement costs:

- Pavement costs include items such as subgrade preparation, base, subbase and surface material costs; associated labour and equipment costs, etc.;
- Non pavement costs are costs that affect the overall cost of the project but are not directly related to the pavement structure, such as extra fill or cut due to different grade elevations, traffic control and signing, median and fill slopes, utilities, culvert extensions, …; associated labour and equipment costs, etc.. Initial agency costs can account for 50 to 90 percent of the project LCCA cost.

LCCA comparisons are always made between mutually exclusive competing alternatives. A LCCA needs only to consider differential costs between alternatives. Costs common to all alternatives cancel out, these cost factors are generally noted and excluded from LCCA calculations. It is good practice to clearly mention such costs in the LCCA report.

For example, the cost of the subbase or base can be excluded if this layer is identical for the pavement alternatives considered. Furthermore, engineering and administrative costs may be excluded from the initial agency cost if they are comparable for all alternatives.

For a complete reconstruction project of an existing pavement, the demolition costs at the end of its performance life, need not necessarily to be considered in analysing competing alternatives, because these costs are mostly minor and/or do not differ substantially between alternatives.

Furthermore, agency costs do not always have to represent the whole project and can reflect global prices only. For example, for the pavement itself, the determination of the agency costs per kilometre can be sufficient to adequately compare the alternatives. This was done for the LCCA conducted for the Antwerp Ring Road in 2002 [Ref. 4].

**Residual value**

When appropriate, the estimated residual value at the end of the analysis period, should be included as a negative cost. The residual value typically is defined in one of two ways:

1. The net value that the pavement would have in the market if it is recycled at the end of its life;
2. The value of the remaining service life (RSL) at the end of the analysis period.

Whichever way residual value is defined for rehabilitation strategy alternatives, it must be defined the same way for all alternatives and should reflect what the agency realistically expects to do with the pavement structure at the end of the analysis period. Residual value should only be taken into account whenever the alternatives are expected to have significantly different residual values at the end of the analysis period.

**Residual Value through recycling** refers to the net value from recycling the pavement. The differential residual value between pavement design strategies is generally not very large, and, when discounted over a period of 35 years or more, tends to have little effect on LCCA results.

If it is assumed that the pavement is to be recycled at the end of the analysis period, the residual value through recycling is the monetary value of the recycled materials minus the costs of removal and recycling. The residual value of the pavement structure as recycled materials may be different for the different alternatives but may also be similar.

**Residual value through remaining service life.** The residual value (RV) through remaining service life (RSL) represents the more significant residual value component and is the remaining life in a pavement alternative at the end of the analysis period. It is primarily used to account for differences in remaining pavement life between alternative pavement design strategies at the end of the analysis period.

The FWHA [Ref. 1] recommends that the residual value be determined as the portion of the cost of the last rehabilitation equal to the portion of the remaining life of the last rehabilitation.

For example (see Figure 3.5), at the end of the analysis period of 40 year, Alternative A reaches terminal serviceability, while Alternative B requires a 15-year rehabilitation at year 35. In this case, the performance life of Alternative A at year 40 would be 0, as it has reached its terminal serviceability. Conversely, Alternative B receives a 15-year design rehabilitation at year 35 and will have 10 years of remaining service life at year 40, at the end of the analysis period. One way of estimating the value of the remaining service life (RSL) of Alternative B at year 40 is as a percent of the service life remaining at the end of the analysis period (i.e. 10 out of 15 years or 67%) multiplied by the cost of Alternative B's rehabilitation at year 35. A detailed example of this approach is given in Table 3-1 and Table 3-2.

This approach of calculation of the RSL attributes worth only to the last rehabilitation, instead of to the pavement structure as a whole. Alternative approaches are presently being looked at, in an attempt towards a more realistic approach to estimate the RSL.

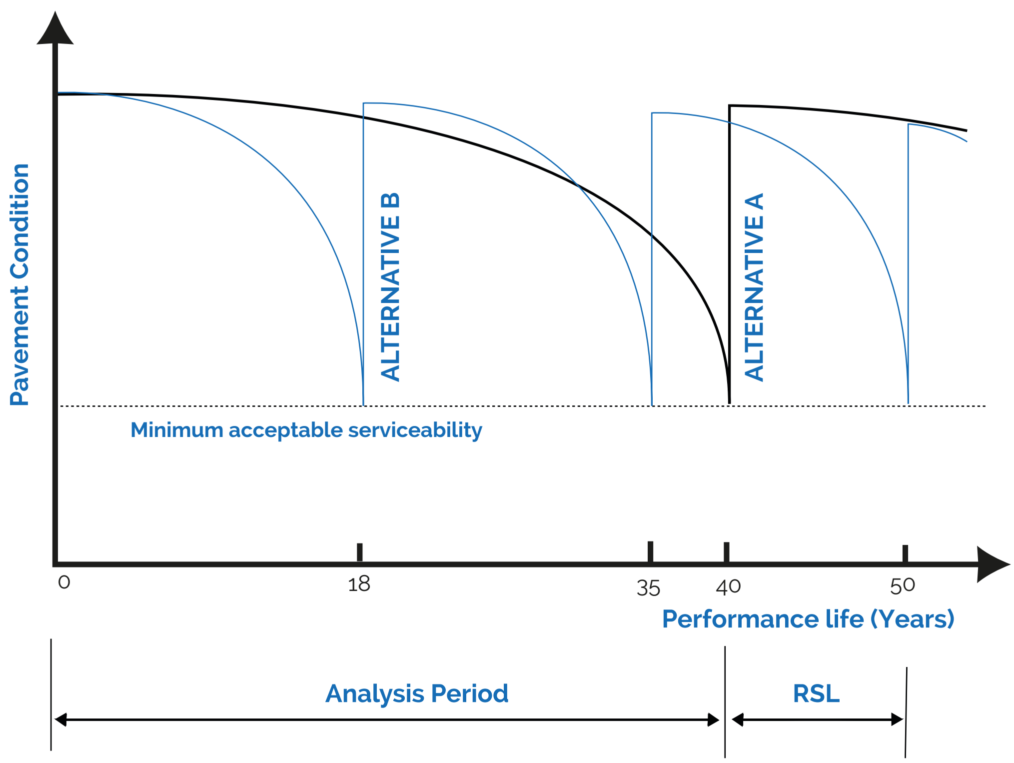
## 5. ESTIMATE USER COSTS

Considering the scope of this Publication user costs are not addressed in detail. However, it is important that the analyst understand the major factors influencing work zone user costs as this understanding can help to minimise the effect of future rehabilitation activities on highway users. Therefore, the components and the general principles to estimate the work zone user costs are briefly described hereinafter.

### User costs in general

For a comprehensive description of the procedure to estimate the work zone user costs, reference is made to Ref 2, Chapter 2 and 3.

Figure 3-5. Schematic performance life curves for Alternatives A and B



In the most general sense, user costs are costs incurred by the highway user over the life of the project. In LCCA, the user costs of concern are the differential user costs resulting from differences in long-term pavement design decisions and the related maintenance and rehabilitation implications.

User costs are an aggregation of three components of costs:

- Vehicle operating costs (VOC);
- User delay costs;
- Accident costs.

Furthermore, in the LCCA of pavement design alternatives, two categories of user costs can be distinguished: (1) user costs associated with normal operations and (2) user costs associated with work zone operations.

The **normal operations category** reflects highway user costs associated with using a facility during periods free of construction, maintenance, and/or rehabilitation. User costs in this category concern mainly the VOC and are a function of the long-term differences in the pavement performance levels (primarily roughness and surface deflection) of the alternatives.

During normal operating conditions, as a general rule, there should be little difference between delay costs and accident costs resulting from pavement design decisions so that these user costs can be neglected. Furthermore, as long as the pavement performance levels remain relatively high, and performance curves of the alternative designs are similar, there should be little difference between VOC as well. Under these circumstances the VOC can also be neglected. This category of user costs is not further addressed in this Publication.

The **work zone operations category**, however, reflects highway user costs associated with using a facility during periods of construction, maintenance, and/or rehabilitation activities that generally restrict the capacity of the facility and disrupt normal traffic flow. They represent the increased vehicle operating, delay, and accident costs to highway users resulting from construction, maintenance or rehabilitation work zones.

**Work zone user costs – Complexity and importance**

Because of the complexity and uncertainty in predicting user costs with a high degree of accuracy, Highway Agencies do not always take into account user costs as a whole or consider only work zone user costs. According to [Ref. 2] a survey in the USA in 2011 indicates that out of the 40 states that participated in the survey, somewhat more than 50% of them do not consider user costs when conducting a LCCA.

Yet, it is recommended that at least the work zone user costs be considered. Failure to consider user costs may lead in some cases to the selection of undesirably shortlived alternatives. For example [Ref. 2], it is not good practice to recommend major rehabilitation of a busy urban freeway every seven years. Traffic handling and delays in the future might involve a significantly greater cost than constructing a longlived alternative now. Without quantitative consideration of work zone user costs, however, it may be difficult to determine that a longlived solution is best in such a scenario.

**Work zone user costs - Calculation**

Work zone user costs are computed by multiplying the quantity of additional vehicle operating components, delays, and number of accidents by the unit cost rates assigned to these components. In addition to these costs, there are also indirect user costs such as the impact of user delay on delivery fleet size, rolling inventory, just-in-time delivery, etc..

**Work zone user costs - Unit rates**

The availability of national data on unit rates is important. If not available in the own agency, unit rates mentioned in the literature can provide a solution. Unit rates can be obtained from a variety of economic sources and approaches. When the rates reflect prices in the past, they need to be escalated to reflect more current prices.

*The unit rates for Vehicle Operating Costs* in work zones must reflect the following:

- Additional cost for stopping, speed changes and idling as well as for the associated delay for stopping and speed changes;
- The additional fuel consumption due to traffic detours.

*The unit rates for Delay Costs* reflect the monetary value of time spent by the user. They are the most controversial. As a result, several approaches are used to arrive at a unit rate.

The user delay rates are based on (a combination of) factors such as: average wage rate, the type of vehicle (truck versus car), the purpose of the trip (business versus personal) the type of travel (local versus intercity), the vehicle occupancy rate, etc.. The unit rate is expressed as price/person-hour.

*The unit rates for accident costs* represent the cost due to damage to the user's vehicle and/or other vehicles and/or public or private property, as well as costs associated with injury to the user and others.

Work zone accident costs may differ significantly among alternatives, depending on their respective traffic control plans, construction methods, and day versus night or weekend allowable construction time frames. The unit rates applied are a function of: the type (property damage or bodily injury), the severity of the accident (fatal or non-fatal), different rates apply to rural areas versus an urban environment

**Work zone user costs - Quantities**

The quantities of the user costs components are influenced by the:

- Work zone characteristics;
- Traffic characteristics;
- Work zone flow conditions.

**Work zone characteristics**

Each separate work zone must be defined and analysed whenever characteristics of the work zone or the characteristics of the affected traffic are different or change during the work zone operation.

Pavement design performance differences directly affect the frequency and timing of maintenance and rehabilitation activities. Pavement rehabilitation and maintenance activities generally occur at different points in the analysis period with different traffic, and they generally vary in scope and duration. The time that they occur also affects the present value factor.

In order to analyse work zone user costs, work zone characteristics associated with alternative designs and supporting maintenance and rehabilitation strategies must include:

- The frequency and the year of (re) construction, maintenance or rehabilitation activities;
- An estimate of the number of days the work zone will last (construction period);
- The hours of the day and the days of the week, the work zone will be in place;
- The anticipated maintenance of traffic strategy and work zone characteristics;
- Work zone length, posted speed;
- Number and capacity of lanes open, duration of lane closures;
- Timing (hours of the day, days of the week, season of the year, etc.) of lane closures;
- Availability and physical and traffic characteristics of alternative routes.

The strategy for maintaining traffic should include any anticipated restrictions on contractor's or maintenance force's hours of operations or ability to establish lane closures.

Routine reactive-type maintenance (emergency, corrective) work zones tend to be relatively infrequent, of short duration, and outside of peak traffic flow periods. As such, analysts should focus attention on user costs associated with major work zones e.g. during preventive maintenance, rehabilitation or reconstruction.

### Traffic characteristics

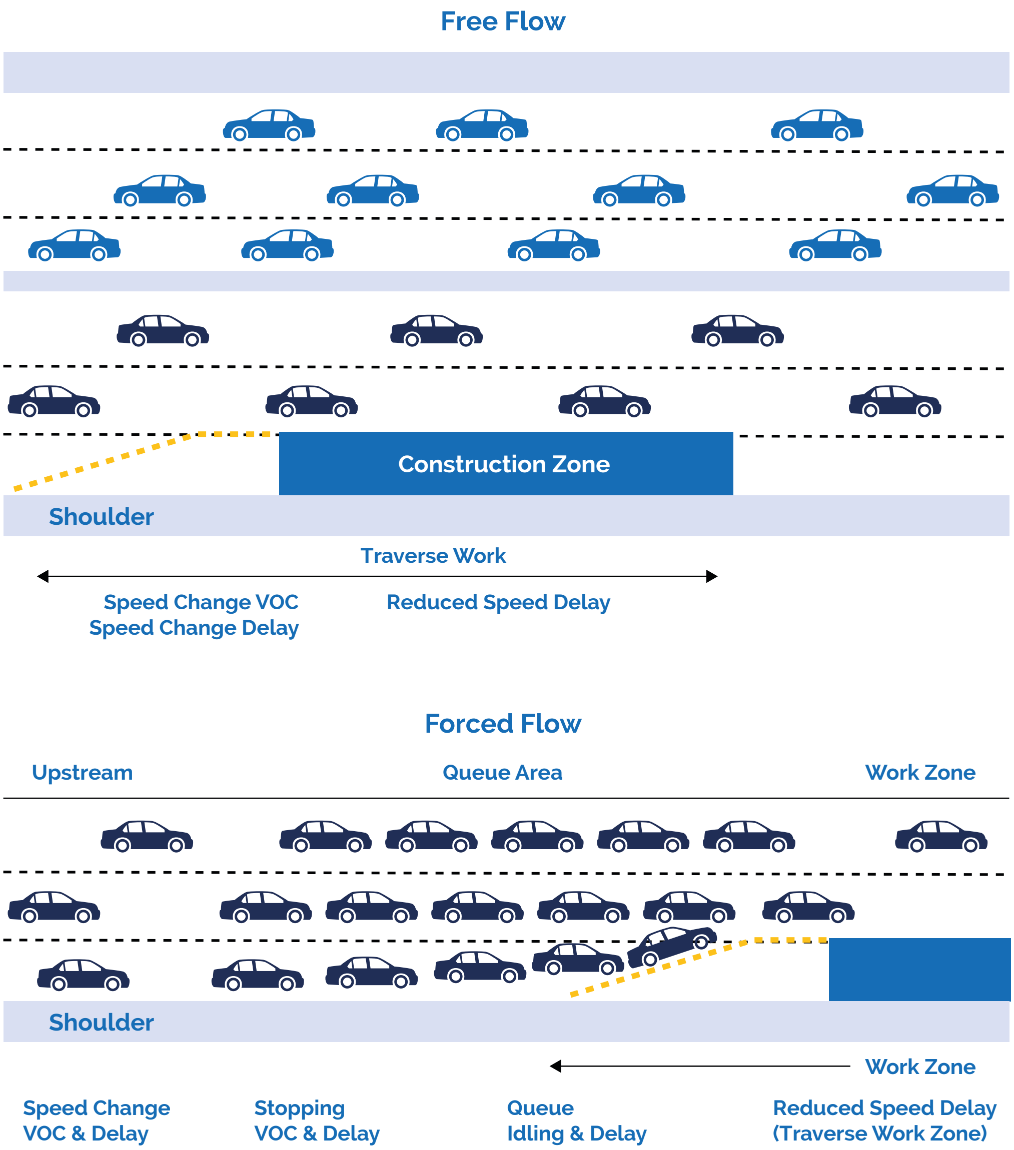
User costs are directly dependent on the volume and operating characteristics of the traffic on the facility. Each construction, maintenance, and rehabilitation activity generally involves some temporary effect on traffic using the facility. The effect can vary from insignificant for minor work zone restrictions on low-volume facilities to highly significant for major lane closures on high-volume facilities.

The major traffic characteristics of interest for each year a work zone will be established include:

- The overall projected Average Annual Daily Traffic (AADT) volumes on both the facility and possibly alternative routes;
- The associated 24-hour directional hourly demand distributions;
- The vehicle classification distribution of the projected traffic streams.

On high-volume routes, distinctions between weekday and weekend traffic demand and hourly distributions become important. Further, seasonal AADT traffic distribution also becomes important when work zones are proposed on recreational routes during seasonal peak periods.

Figure 3-6. Cost components for Free-flow and Forced-flow (level of service F) [Ref. 1]



**Work zone flow conditions**

Depending on the combination of the characteristics of the work zone on the one hand and the characteristics of the traffic on the other hand, user cost calculation procedures will depend on the traffic flow conditions through the work zone i.e. whether a situation of Free-Flow or Forced-Flow conditions exists. Three user cost components are related to free-flow conditions and four are related to forced-flow (queuing) conditions. This is depicted on Figure 3-6 [Ref. 1].

## 6. DEVELOP CASH FLOW DIAGRAMS

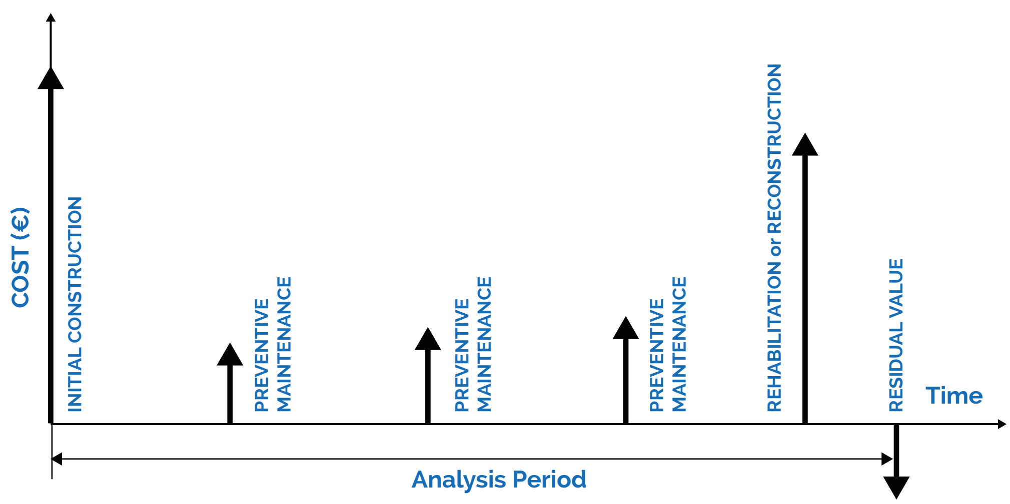
Cash flow diagrams are graphical representations of the inflow and outflow of cash due to subsequent activities as they occur over time e.g. initial construction, preventive maintenance, demolition, rehabilitation/reconstruction. Preparing a cash flow diagram is not absolutely necessary but is often developed for each pavement design strategy to help visualise the extent and timing of cash flows. Figure 3-7 shows a typical cash flow diagram.

Normally, cash outflows (costs) are depicted as upward arrows at the appropriate time they occur, and cash inflows (benefits) are represented as negative cost by downward arrows. The length of the arrows is represented on a relative scale in accordance with the amount of the cash flows, in the year that they occur.

The basic benefits rendered by reactive-type maintenance measures (emergency and corrective) and routine operational maintenance (e.g. road marking maintenance, cleaning and clearing, etc.) in order to provide some pre-established pavement condition level on any given roadway are normally not taken into account in a LCCA of pavement design alternatives and are consequently not depicted on the cash flow diagrams.

As a general practice, the costs (upward arrow) taken into account in a LCCA are both the agency costs and user costs related to preventive maintenance, rehabilitation activities and/or demolition and reconstruction occurring during the analysis period. The only benefit (negative cost) represented by a downward arrow would be the cash inflow associated with any residual value.

Figure 3-7. Typical cash flow diagram for a pavement design alternative



## 7. CALCULATE NET PRESENT VALUE (NPV)

Once all costs and their timing have been developed, future costs are discounted to the base year, i.e. the beginning of the analysis period and added to the initial cost to determine the NPV for the LCCA alternative. As noted in § 2.3, the basic NPV formula for discounting discrete future amounts at various points in time back to some base year is:

$$NPV = IC + \sum_{k=1}^{Q} FC_k \left[\frac{1}{(1+r)^{y_k}}\right] - RV\left[\frac{1}{(1+r)^{p}}\right]$$

In this equation:

NPV = net present value of the alternative

IC = Initial Cost of construction

$FC_k$ = Future Cost of activity k

RV = Residual Value of the pavement (= benefit or negative cost) of the pavement

r = real discount rate (e.g. 0,03 for 3 percent)

$y_k$ = year into the future of cash flow of activity k

Q = total number of activities

p = number of years in analysis period

The present value (PV) for a particular future amount is determined by multiplying the future amount by the appropriate PV factor given by the following formula

$$f_{PV} = \left[\frac{1}{(1+r)^{y}}\right]$$

where

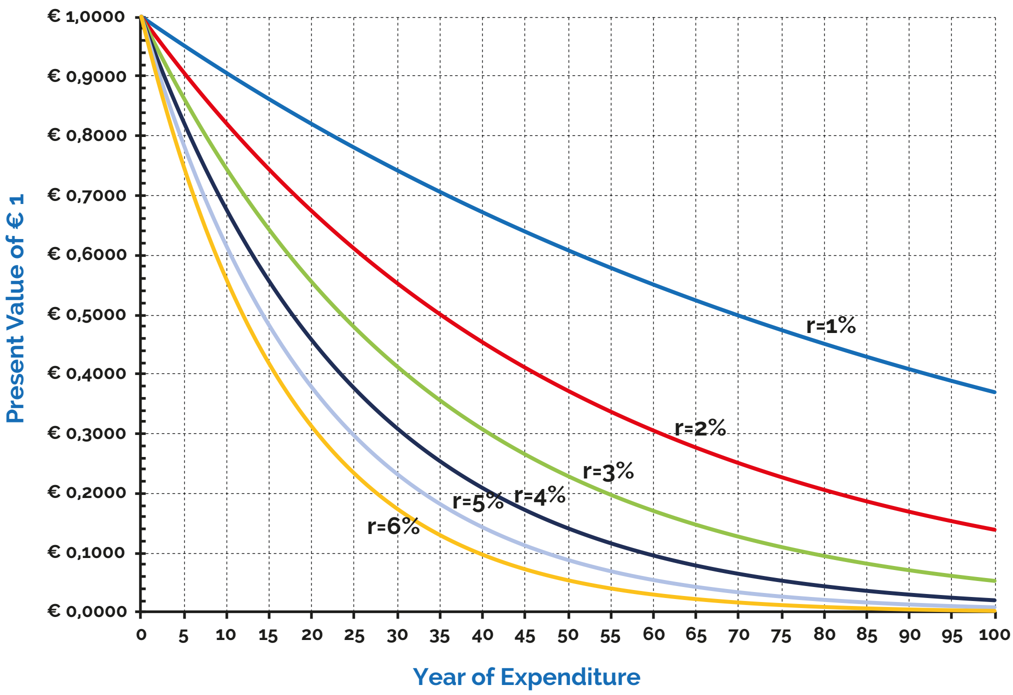
r = real discount rate

y = year into the future in which the one-time future cash flow (cost or benefit) occurs

The initial agency costs are assumed to occur at time n = 0 and are not discounted, i.e., they are counted at full and actual value.

Figure 3-8 hereinafter depicts the present value factor graphically [Ref. 2].

Figure 3-8. Present Value of € 1,00 spent in various years at varying real discount rates



### Example of NPV Computations

An example of NPV computations is provided herewith for the following hypothetical problem. The example is based on a 35-year analysis period and is inspired on a similar hypothetical example in Ref. 1 whereby the monetary value is expressed in euros.

The initial pavement design will cost € 1,1 million and have an associated work zone user cost of € 300 000 at year 0. Additional rehabilitation cost of € 325 000 will be incurred in years 15 and 30. Associated work zone user costs in years 15 and 30 will be € 269 000 and € 361 000 respectively. The residual value through Remaining Service Life at year 35, based on a prorated cost of the year-30 rehabilitation design and remaining life, will be € 216 667 (10/15 of € 325 000). Figure 3-9 shows the cash flow diagram for the example problem.

Note that estimated user costs drop in year 15 and go back up in year 30. This is consistent with a longer duration initial work zone followed by short duration rehabilitation work zones impacted by continually increasing traffic volumes over time. Table 3-1 shows the results of PV computations using PV factors for a real discount rate of 4% for single future amounts for the example expenditure stream diagram. The bottom line of Table 3-1 shows the total NPV of the sum of the individual PVs.

Figure 3-9. Cash flow diagram for agency and user costs [Ref. 1]

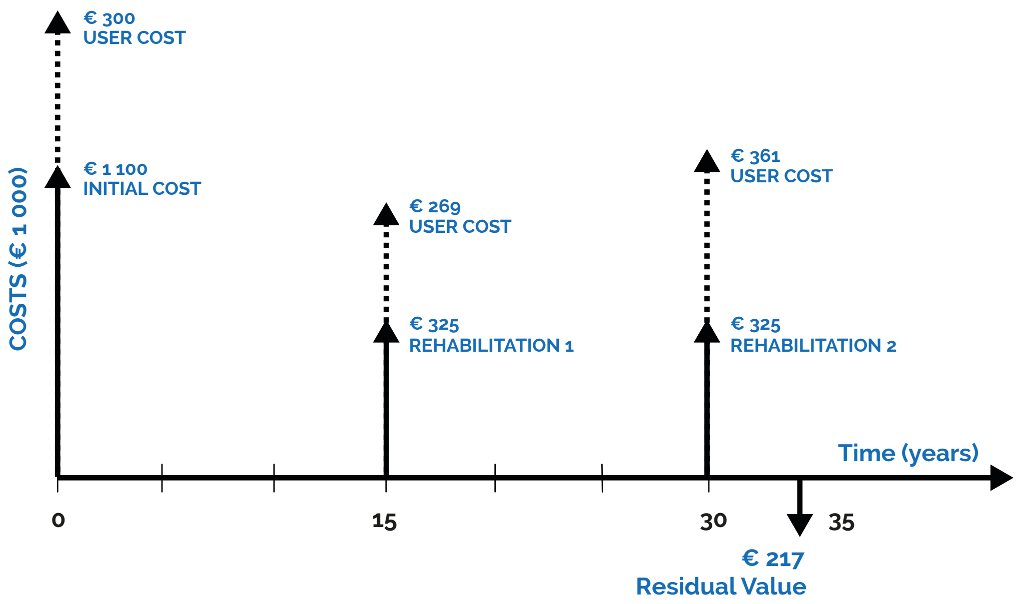


Table 3-1. NPV calculation using 4 percent discount rate factors

| Cost Component of Activity | Years | Costs (€ 1 000) | PV Factor | PV Cost (€ 1 000) |
|---|---|---|---|---|
| Initial Construction | 0 | 1 100 | 1,0000 | 1 100 |
| Initial Work Zone User Cost | 0 | 300 | 1,0000 | 300 |
| Rehabilitation 1 | 15 | 325 | 0,5553 | 180 |
| Rehabilitation 1 Work Zone User Cost | 15 | 269 | 0,5553 | 149 |
| Rehabilitation 2 | 30 | 325 | 0,3083 | 100 |
| Rehabilitation 2 Work Zone User Cost | 30 | 361 | 0,3083 | 111 |
| Residual Value through RSL | 35 | -217 | 0,2534 | -55 |
| Total NPV | | | | 1 886 |

## 8. ANALYSIS OF RESULTS AND SENSITIVITY ANALYSIS

LCCA results are dependent on the values of the different input parameters. The value of these parameters is subject to uncertainty and variability primarily due to the fact that for most of the parameters assumptions, projections and estimates need to be made in the future. When performing a LCCA according to the deterministic approach, this variability of the parameter inputs is disregarded, which is a major disadvantage of this approach.

Therefore, once completed, the LCCA of each design alternative should, be subjected to a sensitivity analysis, as a minimum step to cope with this disadvantage. A sensitivity analysis is a technique used to determine the influence of differences in major LCAA input parameters on the LCCA results. In a sensitivity analysis, major input values are varied (either within some percentage of the initial value or over a range of values) while all other input values remain constant and the amount of change in results is scrutinised. The input variables may then be ranked according to their effect on the results. Sensitivity analysis allows the analyst to subjectively get a feel for the impact of the variability of individual inputs on overall LCCA results.

Many times, a sensitivity analysis will focus on best case/worst case scenarios in an attempt to bracket outcomes. As a minimum a life cycle cost sensitivity analysis, should be made to evaluate the influence of the discount rate used on the results of the LCCA. Sensitivity analyses may be carried out using common spreadsheet-based applications such as Microsoft Excel, Lotus or Quattro Pro.

As an example, Tables 3-2 and 3-3 [Ref. 1] present the results of a spreadsheet analysis of the sensitivity of NPV of two example pavement design strategies to discount rate ranges from 2 to 6 percent for a 35-year analysis period. The total NPV at discount rates ranging from 2 to 6 percent are shown at the bottom of the columns.

Table 3-2. Sensitivity analysis – Alternative 1

| Cost Component of Activity | Year | Cost (€ 1 000) | Net present Value NPV (€ 1 000) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 2,0% | 3,0% | 4,0% | 5,0% | 6,0% |
| Initial Construction | 0 | 975 | 975 | 975 | 975 | 975 | 975 |
| Initial WZ User Cost | 0 | 200 | 200 | 200 | 200 | 200 | 200 |
| Rehabilitation 1 | 10 | 200 | 164 | 149 | 135 | 123 | 112 |
| Rehabilitation 1 WZ User Cost | 10 | 269 | 220 | 200 | 182 | 165 | 150 |
| Rehabilitation 2 | 20 | 200 | 135 | 111 | 91 | 75 | 62 |
| Rehabilitation 2 WZ User Cost | 20 | 361 | 243 | 200 | 165 | 136 | 113 |
| Rehabilitation 3 | 30 | 200 | 110 | 82 | 62 | 46 | 35 |
| Rehabilitation 3 WZ User Cost | 30 | 485 | 268 | 200 | 150 | 112 | 85 |
| Residual Value | 35 | -100 | -50 | -36 | -25 | -18 | -13 |
| Total NPV | | | 2 265 | 2 081 | 1 935 | 1 814 | 1 719 |

Table 3-3. Sensitivity analysis – Alternative 2

| Cost Component of Activity | Year | Cost (€ 1 000) | Net present Value NPV (€ 1 000) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 2,0% | 3,0% | 4,0% | 5,0% | 6,0% |
| Initial Construction | 0 | 1 100 | 1 100 | 1 100 | 1 100 | 1 100 | 1 100 |
| Initial WZ User Cost | 0 | 300 | 300 | 300 | 300 | 300 | 300 |
| Rehabilitation 1 | 15 | 325 | 241 | 209 | 180 | 156 | 136 |
| Rehabilitation 1 WZ User Cost | 15 | 269 | 200 | 173 | 149 | 129 | 112 |
| Rehabilitation 2 | 30 | 325 | 179 | 134 | 100 | 75 | 57 |
| Rehabilitation 2 WZ User Cost | 30 | 361 | 199 | 149 | 111 | 84 | 63 |
| Residual Value | 35 | -217 | -108 | -77 | -55 | -39 | -28 |
| Total NPV | | | 2 111 | 1 988 | 1 886 | 1 805 | 1 740 |

Alternative 1 has a lower initial agency (construction) cost than Alternative 2, and, because of a shorter construction period, it also has a lower user cost than Alternative 2. Alternative 1 requires three identical 10-year rehabilitations compared to two identical 15-year design rehabilitations for Alternative 2. User costs for Alternative 1 increase as a result of increased traffic levels by the time the rehabilitations are executed. User costs for Alternative 2 first decrease due to a shorter work zone period and then increase as a result of increased traffic levels when the second rehabilitation occurs.

Both alternatives have a different remaining service life at year 35. Alternative 1 has 5 years and Alternative 2 has 10 years of residual value through RSL. One way of estimating the residual value, is to calculate it as a prorated share of the last rehabilitation cost. For Alternative 1 this amounts to 50% (5 years remaining on a 10-year rehabilitation design) of its last rehabilitation cost. This results in 50% of the € 200 000 at year-30 rehabilitation cost i.e. € 100 000. The residual value of Alternative 2, on the other hand, is 66.6% (10 years remaining on a 15-year rehabilitation design) of its last rehabilitation cost. This translates into 66.6 percent of the € 325 000 at year-30 rehabilitation cost, i.e. € 217 000.

Table 3-4. Comparison of alternative NPVs ($ 1 000) to discount rate

| Comparison | Real Discount Rate | | | | |
|---|---|---|---|---|---|
| | 2% | 3% | 4% | 5% | 6% |
| Total NPV Alternative 1 | 2 266 | 2 081 | 1 934 | 1 815 | 1 718 |
| Total NPV Alternative 2 | 2 112 | 1 987 | 1 885 | 1 805 | 1 739 |
| Cost Advantage Alt. 2 versus Alt. 1 | 154 | 94 | 49 | 10 | -21 |

Table 3-4 shows a direct comparison of the total NPV of both alternatives at varying discount rates. Inspection of this table reveals that the NPV of both alternatives decreases as the discount rate increases. This results from the reduced present value of future costs at higher discount rates. Because the amount and timing of future costs differ between alternatives, the effect of discount rate on NPV is different for each alternative.

In this example, Alternative 1 is more expensive than Alternative 2 at discount rates of 5 percent and lower, while Alternative 2 is more expensive than Alternative 1 at discount rates of 6 percent or more. Figure 3-10 shows these results graphically.

Figure 3-10. Sensitivity of NPV (€ 1 000) to discount rate

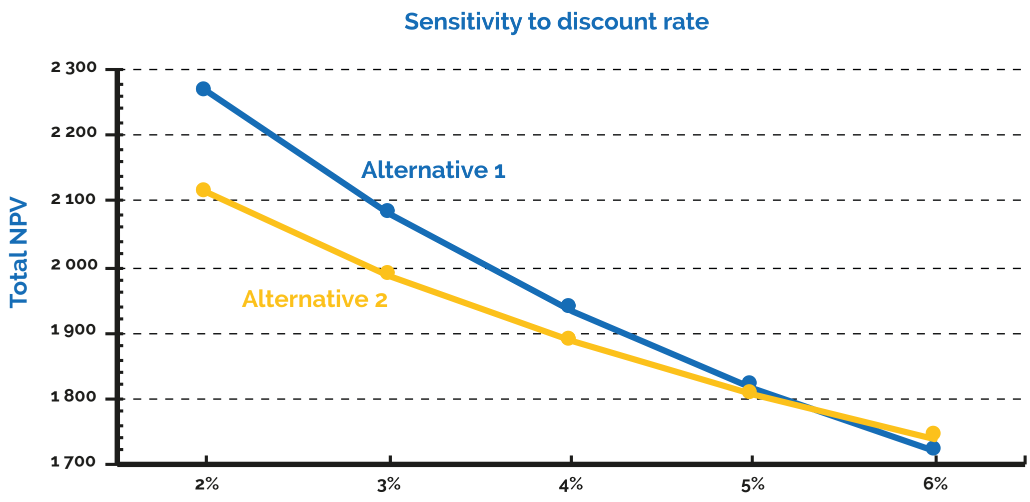


Table 3-5. Sensitivity to user cost (€ 1 000) and discount rate

| Cost Component | Real Discount Rate | | | | |
|---|---|---|---|---|---|
| | 2% | 3% | 4% | 5% | 6% |
| Alternative 1 Agency Cost | 1 334 | 1 281 | 1 238 | 1 201 | 1 171 |
| Alternative 2 Agency Cost | 1 413 | 1 366 | 1 326 | 1 292 | 1 264 |
| Agency Cost Advantage Alt. 2 versus Alt. 1 | -79 | -85 | -88 | -91 | -93 |
| Alternative 1 User Cost | 932 | 800 | 696 | 613 | 547 |
| Alternative 2 User Cost | 699 | 621 | 561 | 513 | 475 |
| User Cost Advantage Alt. 2 versus Alt. 1 | 233 | 179 | 135 | 100 | 72 |
| Incremental Benefit/Cost Alt. 2 vs. Alt. 2 | 2,95 | 2,11 | 1,53 | 1,10 | 0,77 |

Table 3-5 [Ref.1] separates agency and user cost differences for the same range of discount rates. Inspection of this table reveals that Alternative 2 has a higher agency cost than Alternative 1 at all discount rates considered. Further, Alternative 2 has lower user cost than Alternative 1 at all discount rates considered.

The above example demonstrates that the decision to include or exclude user costs can significantly affect the LCCA results. In an effort to put the agency and user costs in perspective, the bottom row of Table 3-5 includes an incremental B/C comparison of the reduction in user costs as a function of increased agency costs. The incremental B/C data in Table 3-5 is computed by dividing the reduction in user costs (i.e., benefits) associated with selecting Alternative 2 in lieu of Alternative 1 by the added agency cost(s) associated with selection of Alternative 2.

Similar sensitivity analyses can also be conducted for other input variables such as those related to agency costs, user costs, performance lives of pavement, length of analysis period, etc.

## 9. RE-EVALUATE DESIGN STRATEGIES

After having computed the net present value for each alternative and after subsequently having performed some sensitivity analyses, the analyst needs to re-evaluate the competing design strategies. As mentioned above, the overall benefit of conducting a life cycle cost analysis is not necessarily the LCCA results themselves, but rather how the designer can use the information resulting from the analysis to modify the proposed alternatives and develop more cost-effective strategies.

LCCA results are just one of many factors that influence the ultimate selection of a pavement design strategy. The final decision may include a number of additional factors outside the LCCA process, such as local politics, availability of funding, industry capability to perform the required construction, and agency experience with a particular pavement type, as well as the accuracy of the pavement design and rehabilitation models. When such other factors weigh heavily in the final pavement design selection, it is imperative to document their influence on the final decision.

# 4 - SPECIAL LCCA TOPICS

The results of a LCCA depend on a number of variable factors and parameters. It is important to have the necessary understanding of this variability and of the method to deal with it. In this regard, the following special topics are addressed in this Publication:

- Accounting for material-specific inflation rates and variability of discount rates;
- Probabilistic approach for a LCCA;
- Methods to deal with unequal performance lives.

## 1. ACCOUNTING FOR MATERIAL-SPECIFIC INFLATION RATES IN LCCA

As mentioned in Chapter 2, most highway agencies are conducting a LCCA using constant cash flows and a single (also called "general") real discount rate. This approach is oftentimes used to avoid the complexities in calculating local or material-specific real discount rates in order to account for real price changes in materials.

The drawback of this approach is that it implicitly assumes that the inflation rate for all materials matches the general rate of inflation. However, recent studies of the historic price evolutions of paving materials within the USA have shown that this is not the case for certain materials and that significant differences exist in material-specific inflation rates. This is graphically depicted on Figure 4-1 [Ref. 2].

The full lines represent the actual evolution of the index values. The dotted lines depict the trend lines of the Compound Annual Growth Rate (CAGR) of concrete products and asphalt products as opposed to the Consumer Price Index (CPI) in the USA. The concrete products PPI and the CPI over the timeframe shown are similar (3.6% and 3.9%, respectively) which indicates that concrete products have tracked relatively close to the US Consumer Price Index (CPI). Concrete prices appear to be more stable and easier to forecast for the future. However, this is not the case for the asphalt products the inflation rate of which is significantly higher (5.5%). This difference in inflation between materials is significant enough that it should be accounted for in a comprehensive LCCA.

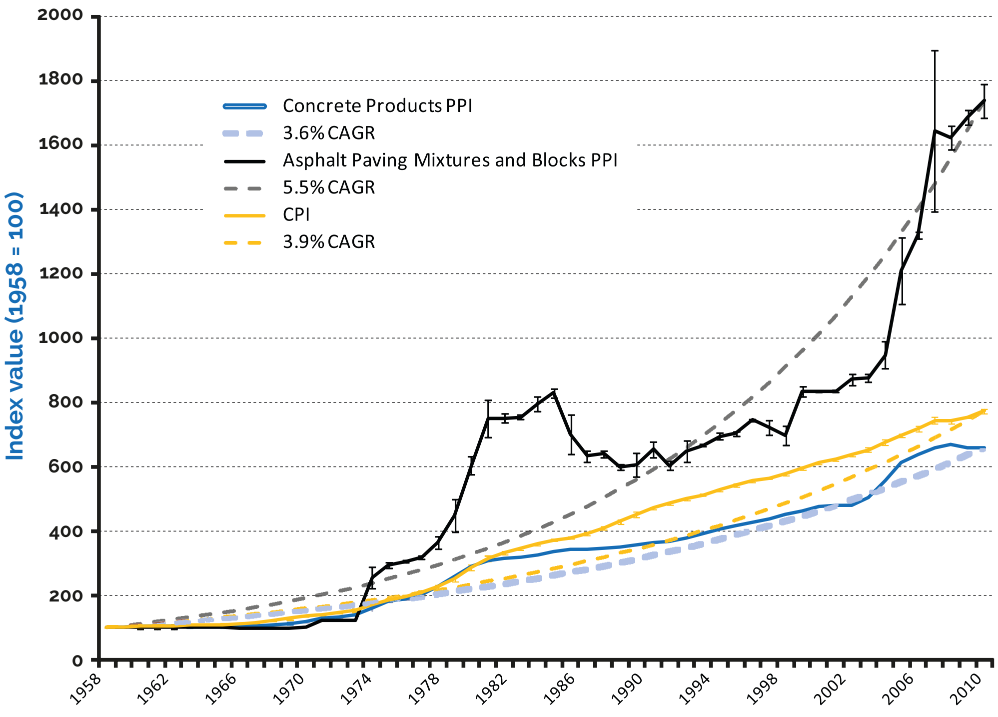



Figure 4-1. USA - Producer Price Index (PPI) for concrete products and asphalt mixtures and blocks versus Consumer Price Index (CPI) from 1958 to 2011. [Ref. 2]

Presently, specialised publications are focussing on the issue of material-specific inflation rates of pavement materials in order to improve LCCA results and to yield them more realistic. For more details and specifics reference is made to these publications e.g. [Ref. 2], [Ref. 3].

## 2. PROBABILISTIC APPROACH - SUMMARY [REF. 2]

The standard procedure explained above to perform a LCCA concerns the so called deterministic approach to the problem because a single defined value or assumption is made for each input variable. The input variables are treated as discrete fixed variables, as if the values were certain.

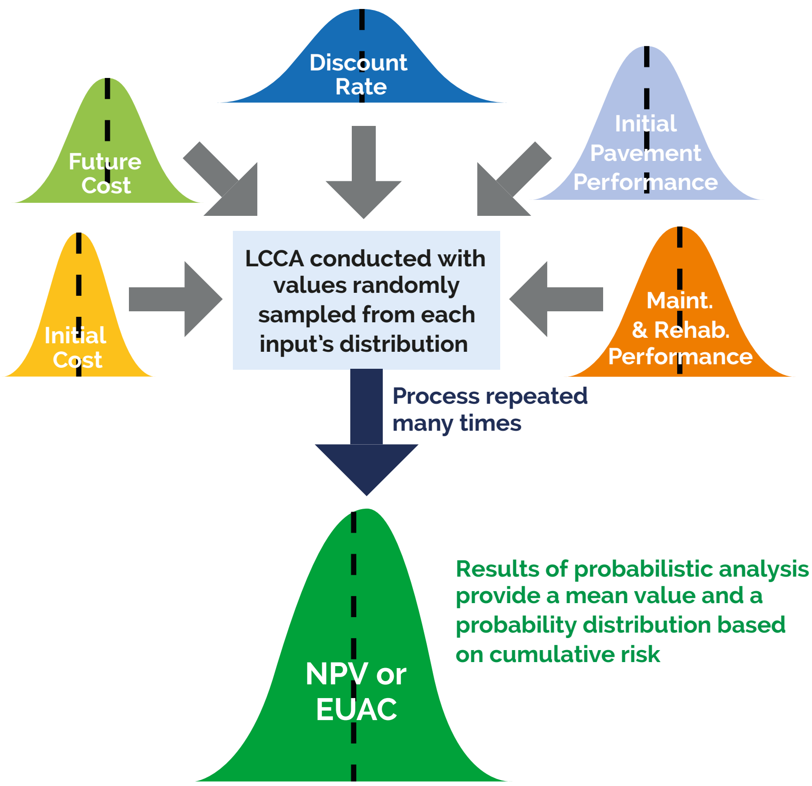
Many assumptions, estimates, and projections feed the LCCA process. The variability associated with these inputs can have a major influence on the confidence the analyst can place in LCCA results.

As a minimum step to deal with the uncertainty of input parameters, a sensitivity analysis can be conducted as explained above. However, a primary drawback of a sensitivity analysis is that the analysis gives equal weight to any input value and assumptions, regardless of the likelihood of occurring. In other words, the extreme values (best case and worst case) are given the same likelihood of occurrence as the expected value, which is not realistic.

In a probabilistic approach to LCCA, the variability of each input is accounted for and used to generate a probability distribution for the calculated life cycle cost. The spread of the probability distribution of the calculated life cycle cost illustrates how much the actual life cycle cost may vary based on the variability of the inputs as is schematically depicted on Figure 4-2.

The probabilistic approach to a LCCA is a relatively new concept but has recently become more accessible due to the availability of appropriate software. The FHWA's probabilistic LCCA procedure, as used in their RealCost LCCA software, relies on Monte Carlo simulations to select a random value for each input variable from its probability distribution and then compute the NPV or EUAC for the selected values. The probability distribution of the NPV is characterised in the program outputs by the mean value and standard deviation; minimum and maximum net present values also are reported. Costs incurred closer to the beginning of the analysis period typically can be estimated with a higher degree of certainty than costs incurred later in the analysis period. Thus, initial costs can be estimated with a narrower probability distribution than future costs.

Figure 4-2. Schematic of a probabilistic analysis process (after NCHRP in Ref. 2)



## 3. METHODS TO DEAL WITH UNEQUAL PERFORMANCE LIVES

There are two methods to deal with unequal performance lives in LCCA

a. Determine the residual value of the alternatives;
b. Determine the NPV over a so called "infinite horizon".

**Determine the residual value of the alternatives**

If the end of the analysis period coincides with the end of the performance period of a pavement alternative, the pavement has a residual value, i.e. a residual value through recycling. If this is not the case, i.e. when the performance life extends beyond the end of the analysis period, a residual value through remaining service life (RSL) has to be determined. A residual value is accounted for as a benefit (negative cost) in the calculations of the NPV of the alternatives. Of the different types of residual value, the residual value through RSL is the most important one and the most difficult one to estimate. An example as to how this can be done, is described earlier in this Publication.

This difficulty can be avoided by determining the NPV over a so called "infinite horizon" as explained hereinafter.

**Determine the NPV over a so called "infinite horizon"**

Subsequent to the initial construction, the performance life of each pavement strategy comprises a typical cycle of activities i.e. "routine-type maintenance – demolition – rehabilitation/reconstruction". By assuming that this typical cycle of activities is repeated up to infinity for each pavement strategy, there is no need to estimate the residual value through RSL. In fact, this corresponds to implicitly assuming that the analysis period extends over an infinite number of years.

The over an Infinite Horizon (∞H) is calculated as follows:

**Step 1** – Determine the net present value ($NPV_L$) of all costs and benefits during a typical cycle of the performance life L (number of years), subsequent to the initial construction cost. This is expressed by the following formula:

$$NPV_L = \sum_{k=1}^{Q} FC_k \left[\frac{1}{(1+r)^{y_k}}\right] - RV\left[\frac{1}{(1+r)^L}\right]$$

**Step 2** – Calculate the Factor Infinite Horizon $F_{\infty H_L}$ for the alternative concerned using the following formula:

$$F_{\infty H_L} = \left[\frac{(1+r)^L}{(1+r)^L - 1}\right]$$

**Step 3** – Determine the NPV over an infinite horizon $NPV_{\infty H}$ of the alternative concerned by the following formula:

$$NPV_{\infty H} = IC + NPV_L * F_{\infty H_L}$$

In the above equations:

IC = Initial Cost of construction
$FC_k$ = Future Cost of activity k, including demolition, recycling and reconstruction
RV = Residual value through recycling
r = real discount rate
$y_k$ = year into the future of cash flow of activity k
Q = total number of activities
L = number of years of performance life between initial construction and reconstruction of the alternative

This approach is not widely spread in the practice of LCCA for pavement assets. This may be partly due to the drawback that, in this approach, it is assumed that the typical cycle of activities during the first performance life, from initial construction to reconstruction, remains the same up to infinity, which is not necessarily the case. This approach was used for the LCCA of the Antwerp Ring Road R1 in 2002. [Ref. 4].

# 5 – LCCA EXAMPLES

## GENERAL

In the international literature pertaining to LCCA many examples for specific projects are available. In this chapter two examples are presented taken from this international literature. Only a summary is given. For more details reference is made to the references concerned.

Considering the fact that this publication concentrates on the deterministic approach, the examples presented are limited to a description of the standard steps of the deterministic analysis conducted. For the examples for which also a probabilistic analysis was conducted, the reader is referred to the literature source for details in this regard.

For each of the examples the cost data are only valid for the project described and in the year of construction of the project. Moreover, the cost data and details of the pavement structures should not be utilised for similar other projects because these data and details are dependent on many variables that are typical for each project and for each region or country, worldwide.

### EXAMPLE 1 LOCAL ROAD

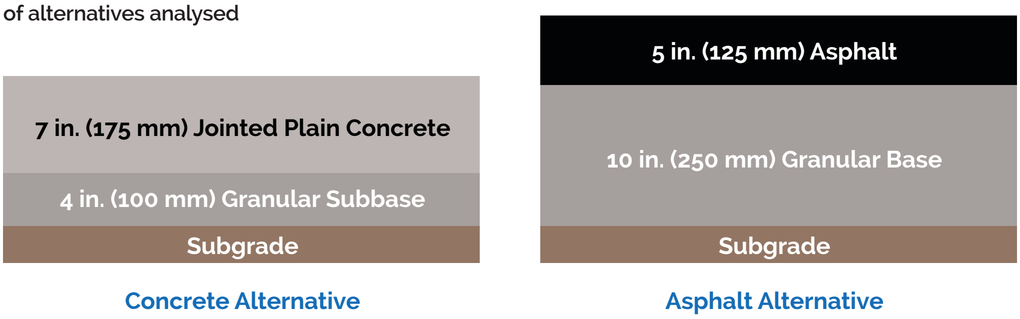
### EXAMPLE 1A CALCULATION NPV WITH DETERMINISTIC APPROACH [TAKEN OVER FROM REF. 2]

The first example concerns a LCCA calculation (executed in 2008) according to the deterministic approach for a local road. Specifics about this example are summarised hereinafter. A more detailed description and discussion of this example, including the results of a probabilisitc approach, are given in Ref. 2. The imperial units and $ -values are retained in order to maintain the relation with the details in Ref. 2.

The project scope consists of the reconstruction of approximately 10 000 SY (8 360 m$^2$) of pavement on Diversey Boulevard street in Whitefish Bay, Wisconsin. The existing concrete pavement (80 years old in 2008) was still in good condition.

The two pavement structures that were analysed are depicted Figure 5-1.

Figure 5-1. Pavement structure of alternatives analysed




**Step 1** – Select analysis period: The analysis period chosen was 90 years, considering the long performance life of the existing concrete pavement.

**Step 2** – Select real discount rate:

The real discount rate selected for the deterministic calculation is 3%.

**Step 3** – Estimate initial Agency Costs:

The initial agency costs are summarised in Table 5-1 and Table 5-2. Note that the initial cost of the asphalt alternative is about 15% less than that of the concrete alternative.

## CONCRETE ALTERNATIVE

Table 5-1. Concrete Alternative – Initial Agency Costs

| Description of Work | Quantity | Unit Price | Total Cost |
|---|---|---|---|
| 7 in. Concrete Pavement | 10,000 SY | $ 22.00/SY | $ 220,000 |
| Concrete Curb and Gutter | 5,580 LF | $ 11 .00/LF | $ 61,380 |
| 4 in. Aggregate Subbase | 3,120 Ton | $ 10.50/Ton | $ 32,760 |
| Unclassified Excavation | 4,600 CY | $ 13.00/CY | $ 59,800 |
| | TOTAL INITIAL AGENCY COST | | $ 373,940 |

## ASPHALT ALTERNATIVE

Table 5-2. Asphalt Alternative – Initial Agency Costs

| Description of Work | Quantity | Unit Price | Total Cost |
|---|---|---|---|
| 2 in. Asphalt Surface Course | 1,150 Ton | $ 48.42/Ton | $ 55,683 |
| Tack Coat 2 | 250 gal | $ 1 .25/gal | $ 313 |
| 3 in. Asphalt Lower Course | 1,725 Ton | $ 42.10/Ton | $ 72,623 |
| Tack Coat 1 | 200 gal | $ 1.25/gal | $ 250 |
| Concrete Curb and Gutter | 5,580 LF | $ 11.00/LF | $ 61,380 |
| 10 in. Aggregate Base | 5,200 Ton | $ 10.50/Ton | $ 54,600 |
| Unclassified Excavation | 5,230 CY | $ 14.00/CY | $ 73,220 |
| | TOTAL INITIAL AGENCY COST | | $ 313,053 |

**Step 4** – Estimate User Costs.

User costs were not considered in these calculations.

**Step 5** – Estimate Future Agency Costs

### CONCRETE ALTERNATIVE

Table 5-3. Concrete Alternative – Future Agency Costs

| Year | Type of Work | Description of Work | Quantity | Unit Price Total | Cost |
|---|---|---|---|---|---|
| 15 | Maintenance | Joint Sealing (15%) | 2,250 LF | $ 0.50/LF | $ 1,125 |
| 30 | Maintenance | Joint Sealing (30%) | 4,500 LF | $ 0.50/LF | $ 2,250 |
| 30 | Preservation | Full Depth Repair (2% Panels @ 6 ft Repair) | 40 CY | $ 180/CY | $ 7,200 |
| 30 | Preservation | Partial Depth Repair (3% Joint Repaired) | 180 LF | $ 15.00/LF | $ 2,700 |
| 45 | Maintenance | Joint Sealing (30%) | 4,500 LF | $ 0.50/LF | $ 2,250 |
| 60 | Maintenance | Joint Sealing (30%) | 4,500 LF | $ 0.50/LF | $ 2,250 |
| 60 | Preservation | Full Depth Repair (4% Panels @ 6 ft Repair) | 80 CY | $ 180/CY | $ 14,400 |
| 60 | Preservation | Partial Depth Repair (6% Joint Repaired) | 360 LF | $ 15.00/LF | $ 5,400 |
| 75 | Maintenance | Joint Sealing (30%) | 4,500 LF | $ 0.50/LF | $ 2,250 |

### ASPHALT ALTERNATIVE

Table 5-4. Asphalt Alternative – Future Agency Costs

| Year | Type of Work | Description of Work | Quantity | Unit Price Total | Cost |
|---|---|---|---|---|---|
| 3 | Maintenance | Crack Sealing | 3,000 LF | $ 0.50/LF | $ 1,500 |
| 7 | Maintenance | Crack Sealing | 4000 LF | $ 0.50/LF | $ 2,000 |
| 15 | Preservation | Seal Coat | 10,000 SY | $ 1 .75/SY | $ 17,500 |
| 15 | Maintenance | Crack Sealing | 5000 LF | $ 0.50/LF | $ 2,500 |
| 22 | Maintenance | Crack Sealing | 6,000 LF | $ 0.50/LF | $ 3,000 |
| 30 | Reconstruct | Remove Pavement | 10,000 SY | $ 2.00/SY | $ 20,000 |
| 30 | Reconstruct | Pavement Replacement | 1 LS | $ 318,068/LS | $ 318,068 |
| 33 | Maintenance | Crack Sealing | 3000 LF | $ 0.50/LF | $ 1 ,500 |
| 37 | Maintenance | Crack Sealing | 4,000 LF | $ 0.50/LF | $ 2,000 |
| 45 | Preservation | Seal Coat | 10,000 SY | $ 1 .75/SY | $ 17,500 |
| 45 | Maintenance | Crack Sealing | 5,000 LF | $ 0.50/LF | $ 2,500 |
| 52 | Maintenance | Crack Sealing | 6000 LF | $ 0.50/LF | $ 3,000 |
| 60 | Reconstruct | Remove Pavement | 10,000 SY | $ 2.00/SY | $ 20,000 |
| 60 | Reconstruct | Pavement Replacement | 1 LS | $ 318,068/LS | $ 318,068 |
| 63 | Maintenance | Crack Sealing | 3,000 LF | $ 0.50/LF | $ 1,500 |
| 67 | Maintenance | Crack Sealing | 4000 LF | $ 0.50/LF | $ 2,000 |
| 75 | Preservation | Seal Coat | 10,000 SY | $ 1 .75/SY | $ 17,500 |
| 75 | Maintenance | Crack Sealing | 5000 LF | $ 0.50/LF | $ 2,500 |
| 82 | Maintenance | Crack Sealing | 6,000 LF | $ 0.50/LF | $ 3,000 |

**Step 6** – Estimate Residual Value

The residual value of each alternative is not taken into account because:

- The NPV of this residual value would be very small considering the long analysis period of 90 years
- At the end of this period each alternative is nearing the end of its performance life
- The residual values are assumed to be similar

**Step 7** – Calculate NPV of Alternatives and Compare Alternatives

Adding up the future agency costs occurring in the same year of expenditure results in the cash flow diagram for each alternative as shown in Figure 5-2 and Figure 5-3. The result of the NPV calculations are summarised in Table 5-5 and in Table 5-6.

### CONCRETE ALTERNATIVE

**Figure 5-2. Concrete Alternative – Cash flow diagram**

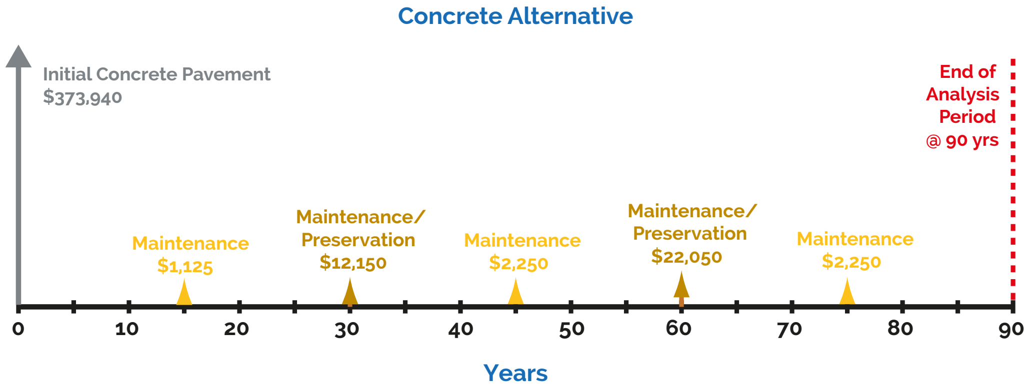



**Table 5-5. Concrete Alternative – NPV Calculation (r=3%)**

| Year | Type of Work | Total Cost | Present Worth |
|---|---|---|---|
| 0 | Initial Construction | $ 373,940 | $ 373,940 |
| 15 | Maintenance | $ 1,125 | $ 722 |
| 30 | Maintenance/Preservation | $ 12,150 | $ 5,006 |
| 45 | Maintenance | $ 2,250 | $ 595 |
| 60 | Maintenance/Preservation | $ 22,050 | $ 3,743 |
| 75 | Maintenance | $ 2,250 | $ 245 |
| | | TOTAL NET PRESENT VALUE | $ 384,250 |

### ASPHALT ALTERNATIVE

Figure 5-3. Asphalt Alternative – Cash flow diagram

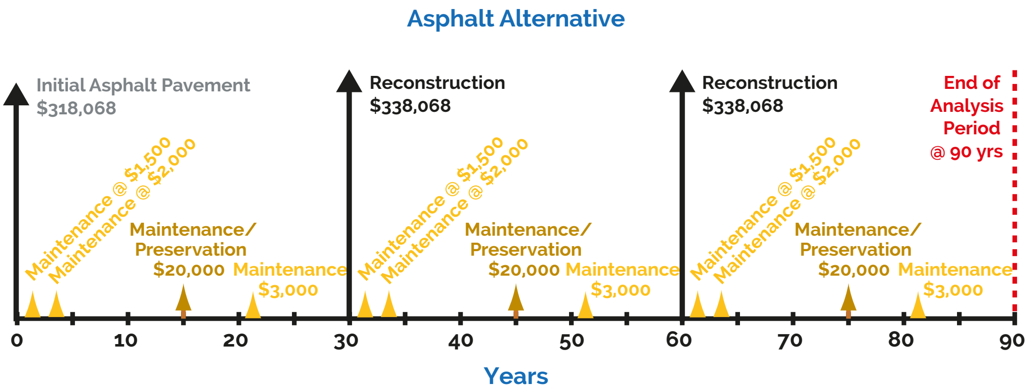



Table 5-6. Asphalt Alternative – NPV Calculation (r=3%)

| Year | Type of Work | Total Cost | Present Worth |
|---|---|---|---|
| 0 | Initial Construction | $ 318,068 | $ 318,068 |
| 3 | Maintenance | $ 1,500 | $ 1,373 |
| 7 | Maintenance | $ 2,000 | $ 1,626 |
| 15 | Maintenance/Preservation | $ 20,000 | $ 12,837 |
| 22 | Maintenance | $ 3,000 | $ 1,566 |
| 30 | Reconstruction | $ 338,068 | $ 139,280 |
| 33 | Maintenance | $ 1,500 | $ 566 |
| 37 | Maintenance | $ 2,000 | $ 670 |
| 45 | Maintenance/Preservation | $ 20,000 | $ 5,289 |
| 52 | Maintenance | $ 3,000 | $ 645 |
| 60 | Reconstruction | $ 338,068 | $ 57,381 |
| 63 | Maintenance | $ 1,500 | $ 233 |
| 67 | Maintenance | $ 2,000 | $ 276 |
| 75 | Maintenance/Preservation | $ 20,000 | $ 2,179 |
| 82 | Maintenance | $ 3,000 | v266 |
| | | TOTAL NET PRESENT VALUE | $ 542,254 |

From the NPV results it is seen that, based on the deterministic analysis, the NPV of the concrete alternative is 29% lower than the NPV of the asphalt alternative over the analysis period of 90 years.

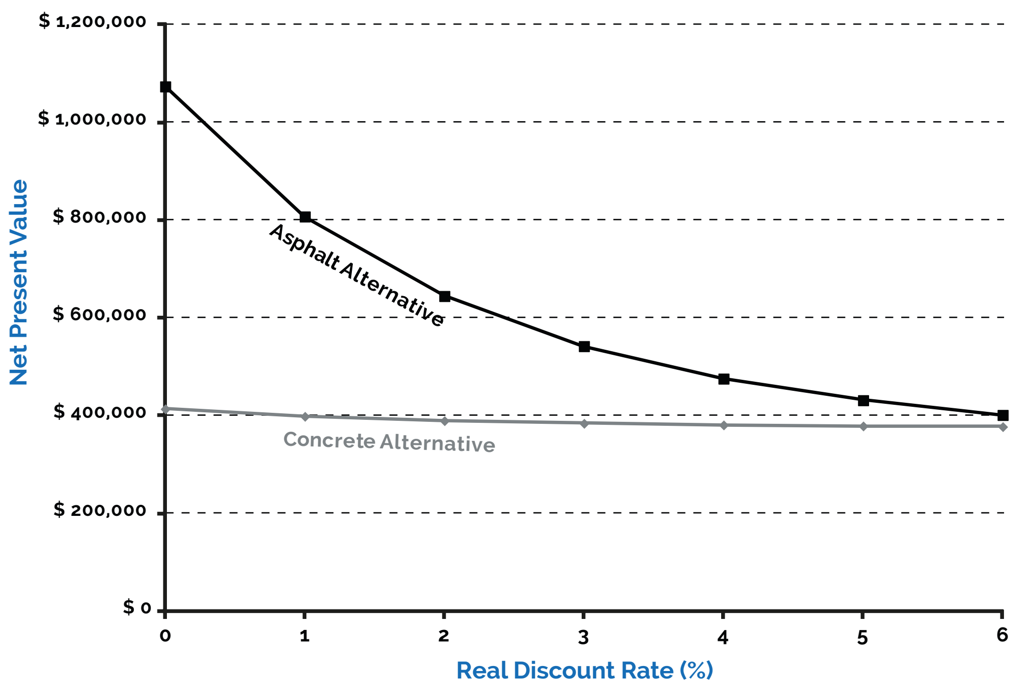
Ref. 2 also highlights the sensitivity of the results with regard to variations of certain parameters and draws the following conclusions.

*Impact of Analysis*
If the analysis period would be taken lower than 30 years, the asphalt alternative would have been more cost-effective. Once the analysis is greater than 30 years the concrete alternative is always more cost-effective.

*Impact of Real Discount Rate*
The sensitivity of the real discount rate on the NPV is shown on Figure 5-4 for real discount rates ranging from 0% to 6%. In comparison with the asphalt alternative, the concrete alternative becomes more cost-effective as the discount rate decreases. For discount rates of 6% the net present values of both alternatives are comparable. For discount rates higher than 6%, the asphalt alternative would even have a lower NPV than the NPV for the concrete alternative. However, considering the historic values of the real discount rate and the current trends in inflation and interest rates, such discount rates are not realistic.

*Impact of variations in future cost predictions*
These sensitivity calculations indicate that activity timing and predictions of future costs have a significant impact on the LCCA results.

**Figure 5-4. Sensitivity of Net Present Values versus varying real discount rates**



### EXAMPLE 1B CALCULATION NPV OVER INFINITE HORIZON - DETERMINISTIC APPROACH

In addition to the above calculations as per Ref. 2, hereinafter, as a matter of example, the results are summarised of the determination of the NPV over an infinite horizon for the above project. This is done according to the method briefly explained in § 5.3 of this publication. The essence of this method is that the NPV be calculated of only one performance life cycle of activities and that this performance life cycle is subsequently assumed to be repeated infinitely.

Table 5-7 and Table 5-8 are a retake of Tables 5-5 and Table 5-6 respectively with the following assumptions and additions:

- Length "L" of one performance life cycle is 90 years for the concrete alternative and 30 years for the asphalt alternative.
- Residual value through recycling is considered similar for both alternatives and is therefore excluded from the calculations.
- The costs of demolition and reconstruction need to be included for both alternatives.

The NPV over an infinite horizon is obtained by multiplying the NPV of one performance life cycle by the factor PV over ∞H. The increase of the NPV due to using the approach over infinite horizon is 7,9% which is 1% more than the increase for the asphalt alternative. This is due to the fact that for the concrete alternative as well demolition and reconstruction costs had to be added as being part of a typical performance life cycle of each pavement alternative.

The NPV over ∞H of the concrete alternative is again 29% lower than the NPV over ∞H of the asphalt. This demonstrates that both approaches (with and without ∞H) lead to the same conclusion.

**CONCRETE ALTERNATIVE**

**Table 5-7. Concrete Alternative – Calculation NPV over infinite horizon (r=3%)**

| Year | Type of Work | Total Cost | Factor PV | PV | Factor PV over ∞H for L=90 years | PV over ∞H |
|---|---|---|---|---|---|---|
| 0 | Initial Construction | $ 373 940 | 1,0000 | $ 373 940 | | $ 373 940 |
| 15 | Maintenance | $ 1 125 | 0,6419 | $ 722 | 1,0752 | $ 776 |
| 30 | Maintenance/Preservation | $ 12 150 | 0,4120 | $ 5 006 | 1,0752 | $ 5 382 |
| 45 | Maintenance | $ 2 250 | 0,2644 | $ 595 | 1,0752 | $ 640 |
| 60 | Maintenance/Preservation | $ 22 050 | 0,1697 | $ 3 743 | 1,0752 | $ 4 024 |
| 75 | Maintenance | $ 2 250 | 0,1089 | $ 245 | 1,0752 | $ 264 |
| 90 | Demolition | $ 20 000 | 0,0699 | $ 1 399 | 1,0752 | $ 1 504 |
| 90 | Reconstruction | $ 373 940 | 0,0699 | $ 26 149 | 1,0752 | $ 28 115 |
| | | | | | **TOTAL NPV over infinite horizon** | **$ 414 644** |
| | | | | | **Increase of NPV with approach ∞H** | **7,9%** |

**ASPHALT ALTERNATIVE**

Table 5-8. Asphalt Alternative – Calculation NPV over infinite horizon (r=3%)

| Year | Type of Work | Total Cost | Factor PV | PV | Factor PV over ∞H for L=30 years | PV over ∞H |
|---|---|---|---|---|---|---|
| 0 | Initial Construction | $ 318 068 | 1,0000 | $ 318 068 | | $ 318 068 |
| 3 | Maintenance | $ 1 500 | 0,9151 | $ 1 373 | 1,7006 | $ 2 334 |
| 7 | Maintenance | $ 2 000 | 0,8131 | $ 1 626 | 1,7006 | $ 2 766 |
| 15 | Maintenance/Preservation | $ 20 000 | 0,6419 | $ 12 837 | 1,7006 | $ 21 832 |
| 22 | Maintenance | $ 3 000 | 0,5219 | $ 1 566 | 1,7006 | $ 2 663 |
| 30 | Demolition | $ 20 000 | 0,4120 | $ 8 240 | 1,7006 | $ 14 013 |
| 30 | Reconstruction | $ 318 068 | 0,4120 | $ 131 040 | 1,7006 | $ 222 852 |
| | | | | | TOTAL NPV over infinite horizon | $ 584 527 |
| | | | | | Increase of NPV with approach ∞H | 7,8% |

## EXAMPLE 2 REHABILITATION OF DUAL CARRIAGEWAY MOTORWAY: ANTWERP RINGROAD R1 IN BELGIUM [REF. 4]

The second example concerns the LCCA (conducted in 2002) at the rehabilitation for the Antwerp Ringroad. The Owner is the Flemish Ministry of Mobility and Public Works, AWV (Agency Roads and Traffic) – Belgium

Project Scope: Renewal of more than 500 000 of motorway pavement on the main line of the dual carriage way, having a total length of 14,2 km in each direction. Each carriageway consists of a minimum of 4 traffic lanes + 1 emergency lane.

More project details are presented in the Proceedings of the 8th International Conference on Concrete Pavements (M. Diependaele & L. Rens - Colorado Springs, 2005, Paper "*The rehabilitation of the Antwerp Ring Road in Continuously Reinforced Concrete Pavement (CRCP)*".

The analysis was performed for two pavement alternatives: concrete pavement (CRCP) and asphalt pavement.

Hereinafter a description is given of the input data, assumptions and results of the LCCA according to a deterministic analysis.

**1. Establish alternative pavement design strategies and select analysis period**

The initial pavement design was based on an envisaged minimum design life of 35 years and was calculated according to the Flemish Pavement Design Manual. This design resulted in two alternative structures i.e. CRCP versus Asphalt Pavement, as described in Table 5-9.

Based on experience with both alternatives of pavement in Belgium, a performance life of 50 years was assumed for the concrete alternative and a performance life of 35 years for the asphalt alternative. During the LCCA, the latter performance life was extended to 36 years in order to have the end of the performance life for the entire asphalt pavement structure coincide with the end of the performance life of the 2nd major preventive maintenance.

Due to the fact that the compated subgrade, sub-base and base of both alternatives of pavement were identical these layers were not considered in the LCCA.

Table 5-9. Details of structure of pavement alternatives

| Concrete (Performance life = 50 years) | | Asphalt (Performance life = 36 years) | |
|---|---|---|---|
| Layer | Thickness | Layer | Thickness |
| CRCP | 230 mm | Bituminous surface course | 40 mm |
| | | Bituminous binder course | 60 mm |
| | | Bituminous base course 2 | 60 mm |
| Bituminous interlayer | 60 mm | Bituminous base course 1 | 70 mm |
| Base of cement stabilised granulated asphalt rubble | 250 mm | Base of cement stabilised granulated asphalt rubble | 250 mm |
| Sub-base of granulated lean concrete rubble | 150 mm | Sub-base of granulated lean concrete rubble | 150 mm |
| Compacted subgrade | variable | Compacted subgrade | variable |

### Analysis period

Both pavement alternatives have significantly different performance lives (36 years versus 50 years). If one would consider the analysis period equal to for example 36 years, the residual life time for the CRCP pavement would have to be determined. In order to avoid this, the LCCA was conducted according to the calculation over an infinite horizon, as explained in § 5.3 of this publication. In fact, this corresponds to an analysis period that is infinite, which makes the determination of the residual life time of any of the alternatives unnecessary.

### 2. Determine performance periods and activity timing

Based on experience and data within the Flemish Highway Agency, the future maintenance activities and the corresponding timing and cost estimates mentioned in Table 5-10 and in Table 5-11 were assumed for the LCCA calculations of the Antwerp Ringroad R1.

Table 5-10. CONCRETE Alternative - Maintenance strategies, timing and costs

| MAINTENANCE strategies and timing for CONCRETE ALTERNATIVE | | | | |
|---|---|---|---|---|
| ACTIVITY | DESCRIPTION | FREQUENCY | ACTIVITY START at | COST(€)/ km |
| Resealing joints | Cleaning and sealing joints | every 5 years | year 15 | € 5 410 |
| Local repairs (e.g. punch-outs, ...) | Saw cut, breaking-up, restore concrete and reinforcement, saw and seal joints, traffic maintenance | every 10 years | year 9 | € 7 015 |
| *Reconstruction* | *Demolition of existing pavement, construction of new CRCP (230 mm) and bituminous interlayer (60 mm), traffic maintenance* | *every 50 years* | *year 50* | *€ 1 063 245* |

Table 5-11. ASPHALT Alternative - Maintenance strategies, timing and costs

| MAINTENANCE strategies and timing for ASPHALT ALTERNATIVE | | | | |
|---|---|---|---|---|
| ACTIVITY | DESCRIPTION | FREQUENCY | ACTIVITY START at | COST(€)/ km |
| Crack and Joint treatment | Cleaning, cutting, and sealing cracks and longitudinal joints, traffic maintenance | every 4 years | year 4 | € 4 200 |
| Pothole and patching repair | Provisional repair (cold-mix asphalt), subsequent repair (hot-mix asphalt), traffic maintenance | every year | year 4 | € 372 |
| Repair surface defects | Milling and filling (hot-mix asphalt), traffic maintenance | every year | year 4 | € 5 178 |
| 1st Major preventive maintenance | Milling and filling (hot-mix asphalt & tack coats) of wearing course + binder course of 2 outer most traffic lanes, traffic marking, traffic maintenance | once | year 12 | € 119 415 |
| 2nd Major preventive maintenance | Milling and filling (hot-mix asphalt & tack coats) of wearing course of all traffic lanes and of binder course of 3 outer most traffic lanes, traffic marking, traffic maintenance | once | year 24 | € 222 085 |
| *Reconstruction* | *Demolition of existing pavement, construction of new asphalt pavement (230 mm), traffic maintenance* | *every 36 years* | *year 36* | *€ 690 772* |

### 3. Select discount rate

The real discount rate that was used for the calculations this LCCA was 4%. At the time of performing the LCCA (2002) this was a generally adopted value. At present, knowing the evolution of the economic situation a lower value would probably be more appropriate. Yet at the time the LCCA was performed, a real discount rate of 4 was considered a good and realistic average for Belgian circumstances.

### 4. Estimate agency costs

Three types of agency costs were considered:

a. Initial agency cost at the initial construction of the pavement
b. Future agency costs for maintenance, involving all types of maintenance i.e. emergency, corrective and preventive maintenance
c. Future agency costs for reconstruction

The cost estimate used in the calculations pertained to a unit section of one carriageway of the motorway pavement having the following dimensions:

- A width of 18,25 m consisting of 4 traffic lanes (3,75 m each) + median shoulder (0,75 m) + emergency lane (2,50 m)
- A length of 1 km (1 000 m)
- A total depth of each pavement alternative, excluding the granular base and sub-base because these layers are the same for both alternatives

The content and the estimate of the initial agency costs per unit section of 1 km long are given Table 5-12.

The content and the estimate of the future agency costs per unit section of 1 km long are listed in the last column of Table 5-10 and Table 5-11.

### 5. Estimate user costs

User costs were not considered in this LCCA.

### 6. Develop cash flow stream diagrams

For the LCCA of the Motorway R1 no cash flow diagram were developed. Instead, a scheme of time versus the occurrence of agency costs was made for each alternative as shown in Figure 5-5 hereinafter.

As indicated in the scheme for the Asphalt alternative, the crack and joint treatment in year 12 and year 24 can be neglected because the wearing course is replaced over half the width during the 1st major preventive maintenance at year 12 and over the full width during the 2nd major maintenance at year 24. For the same reason, only half the cost (from year 12 to 15) and no cost at all (from year 24 to 27) for pothole and patching repair is taken into account.

Table 5-12. Initial Agency Costs

| DESCRIPTION of WORK | QUANTITY (m²) | UNIT PRICE (€/m²) | TOTAL COST (€/km) |
|---|---|---|---|
| CRCP (230 mm) + Bituminous interlayer (60 mm) | 18 250 | 43,56 | 794 970 |
| ASPHALT PAVEMENT (230 mm) | 18 250 | 29,10 | 531 084 |

Figure 5-5. Scheme of agency costs versus time

**Pavement Alternative - CRCP**

| Year | Initial construction | Resealing joints | Local repairs | Recon-struction |
|---|---|---|---|---|
| 0 | x | | | |
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | x | |
| 11 | | | | |
| 12 | | | | |
| 13 | | | | |
| 14 | | | | |
| 15 | | x | | |
| 16 | | | | |
| 17 | | | | |
| 18 | | | | |
| 19 | | | | |
| 20 | | x | x | |
| 21 | | | | |
| 22 | | | | |
| 23 | | | | |
| 24 | | | | |
| 25 | | x | | |
| 26 | | | | |
| 27 | | | | |
| 28 | | | | |
| 29 | | | | |
| 30 | | x | x | |
| 31 | | | | |
| 32 | | | | |
| 33 | | | | |
| 34 | | | | |
| 35 | | x | | |
| 36 | | | | |
| 37 | | | | |
| 38 | | | | |
| 39 | | | | |
| 40 | | x | x | |
| 41 | | | | |
| 42 | | | | |
| 43 | | | | |
| 44 | | | | |
| 45 | | x | | |
| 46 | | | | |
| 47 | | | | |
| 48 | | | | |
| 49 | | | | |
| 50 | | | | x |

**Pavement Alternative - ASPHALT**

| Year | Initial construction | Crack & joint treatment | Pothole & patching repair | Repair surface defects | 1st Major preventive mainte-nance | 2nd Major preventive mainte-nance | Recon-struction |
|---|---|---|---|---|---|---|---|
| 0 | x | | | | | | |
| 1 | | | | | | | |
| 2 | | | | | | | |
| 3 | | | | | | | |
| 4 | | x | x | x | | | |
| 5 | | | x | x | | | |
| 6 | | | x | x | | | |
| 7 | | | x | x | | | |
| 8 | | x | x | x | | | |
| 9 | | | x | x | | | |
| 10 | | | x | x | | | |
| 11 | | | x | x | | | |
| 12 | | | x/2 | x/2 | x | | |
| 13 | | | x/2 | x/2 | | | |
| 14 | | | x/2 | x/2 | | | |
| 15 | | | x/2 | x/2 | | | |
| 16 | | x | x | x | | | |
| 17 | | | x | x | | | |
| 18 | | | x | x | | | |
| 19 | | | x | x | | | |
| 20 | | x | x | x | | | |
| 21 | | | x | x | | | |
| 22 | | | x | x | | | |
| 23 | | | | | | | |
| 24 | | | | | | x | |
| 25 | | | | | | | |
| 26 | | | | | | | |
| 27 | | | | | | | |
| 28 | | x | x | x | | | |
| 29 | | | x | x | | | |
| 30 | | | x | x | | | |
| 31 | | | x | x | | | |
| 32 | | x | x | x | | | |
| 33 | | | x | x | | | |
| 34 | | | x | x | | | |
| 35 | | | x | x | | | |
| 36 | | | | | | | x |

## 7. Calculate net present value

Details of the calculation of net present value (NPV) of all initial and future agency costs are summarised in Table 5-15 and Table 5-16 hereinafter.

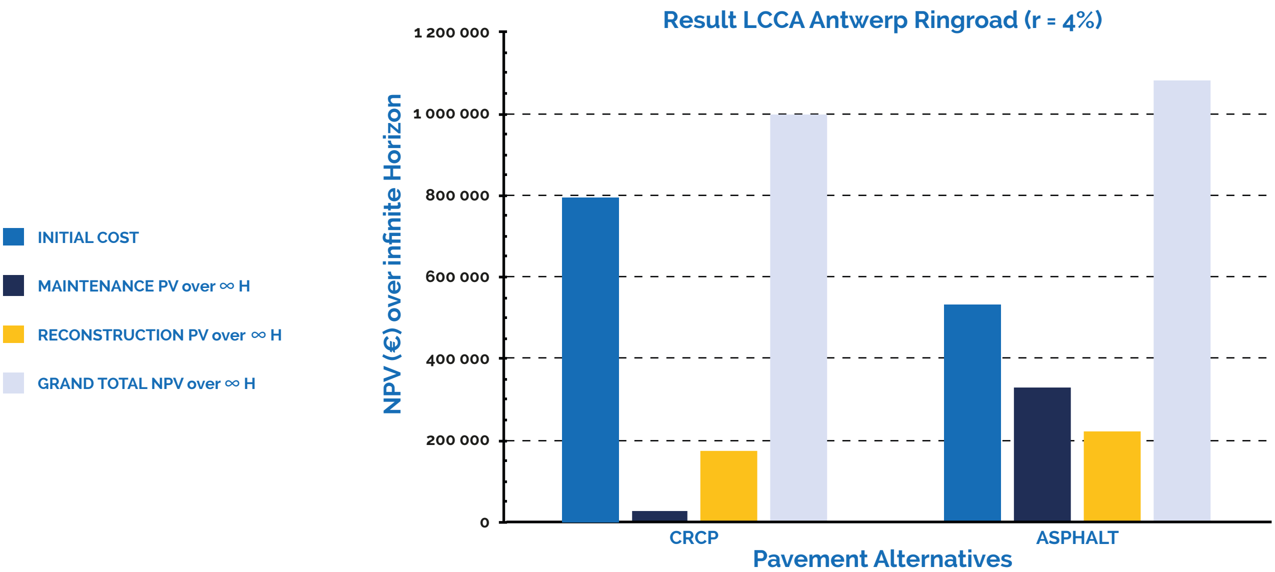
## 8. Analysis of results and sensitivity analysis

The result of the LCCA calculation with a real discount rate of 4,00% leads to the results in Table 5-13 and Figure 5-6 hereinafter.

Table 5-13. Result LCCA for Antwerp Ringroad R1

| RESULT LCCA | | | | |
|---|---|---|---|---|
| r % | TOTAL NPV €/km/Carriageway | | | |
| 4,00 | INITIAL COST | MAINTENANCE PV over ∞H | RECONSTRUCTION PV over ∞H | GRAND TOTAL NPV over ∞H |
| CRCP | € 794 970 | € 28 116 | € 174 112 | € 997 198 |
| ASPHALT | € 531 084 | € 328 047 | € 222 547 | € 1 081 678 |
| Cost Ratio CRCP/ASPHALT | 150% | 9% | 78% | 92% |

Figure 5-6. Bar chart of LCCA result




Although the initial cost of the concrete alternative is 50% higher than that of the asphalt alternative, both alternatives have nearly the same net present value over an infinite horizon for a real discount rate of 4%. This is clearly due to the fact that the asphalt alternative requires a substantially higher present investment to pay for future maintenance and reconstruction.

The difference of future reconstruction costs of both alternatives is proportionally even higher than is the case for the initial cost, i.e. 54%, because of the more expensive demolition at the end of the respective performance lives. However, the present value of the reconstruction of concrete is more than 20% lower than that of the asphalt. This is a direct consequence of the much lower present value factor of 0,1407 at year 50 versus 0,2534 at year 36.

The difference between the net present values over infinite horizon amounts to about € 80 000. This difference should not be interpreted in absolute terms. Indeed the results are dependent on parameters ( real discount rate, performance life,...) that are subject to uncertainty.

Table 5-14 and Figure 5-7 illustrate the impact of the variability of the values of the real discount rate ranging from 1% to 6%.

**Table 5-14. Sensitivity Analysis - Impact of variability of real discount rate on NPV over ∞H**

| Real Discount Rate | Net Present Value over infinite horizon | |
|---|---|---|
| | CRCP | ASPHALT |
| 1% | € 2 572 565 | € 3 536 363 |
| 2% | € 1 485 329 | € 1 884 017 |
| 3% | € 1 148 609 | € 1 344 028 |
| 4% | € 997 198 | € 1 081 678 |
| 5% | € 917 814 | € 929 931 |
| 6% | € 872 689 | € 833 057 |

The sensitivity graph indicates that in comparison with the asphalt alternative, the concrete alternative becomes more cost-effective as the discount rate decreases. The net present values over an infinite horizon of both alternatives are comparable for a discount rate of around 5%. For discount rates higher than 5%, the asphalt alternative would have a slightly lower NPV over ∞H than the NPV over ∞H for the concrete alternative. However, considering the historic values of the real discount rate discount rates higher than 5% to 6% were considered not realistic at the time the LCCA was conducted (2002). This is even more so, taking into account the current trends with regard to the real discount rate.

Figure 5-7. Sensitivity Analysis - Impact of discount rate on NPV over ∞H

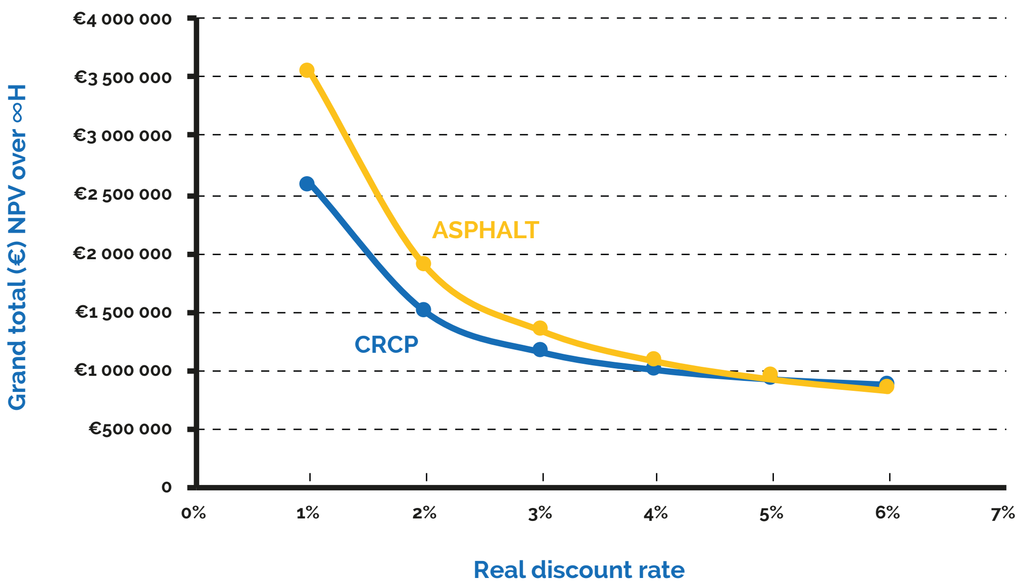


Table 5-15. CRCP Alternative - Details calculations NPV

| Real discount rate | 4,00 % | Performance life of pavement L = 50 years | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| MOTORWAY R1 - CALCULATION PV FOR CRCP ALTERNATIVE | | | | | | | | | |
| YEAR | INITIAL CONSTRUCTION COST | RESEALING JOINTS | LOCAL REPAIRS | RECONSTRUCTION COST | SUBTOTAL FUTURE COSTS | Factor PV | PV | Factor PV over ∞H for L= 50 years | PV over ∞H |
| 0 | € 794 970 | | | | € 794 970 | 1,0000 | € 794 970 | | € 794 970 |
| 10 | | | € 7 016 | | € 7016 | 0,6756 | € 4 740 | 1,1638 | € 5 516 |
| 15 | | € 5 410 | | | € 5 410 | 0,5553 | € 3 004 | 1,1638 | € 3 496 |
| 20 | | € 5 410 | € 7 016 | | € 12 426 | 0,4564 | € 5 671 | 1,1638 | € 6 600 |
| 25 | | € 5 410 | | | € 5 410 | 0,3751 | € 2 029 | 1,1638 | € 2 362 |
| 30 | | € 5 410 | € 7 016 | | € 12 426 | 0,3083 | € 3 831 | 1,1638 | € 4 458 |
| 35 | | € 5 410 | | | € 5 410 | 0,2534 | € 1 371 | 1,1638 | € 1 595 |
| 40 | | € 5 410 | € 7 016 | | € 12 426 | 0,2083 | € 2 588 | 1,1638 | € 3 012 |
| 45 | | € 5 410 | | | € 5 410 | 0,1712 | € 926 | 1,1638 | € 1 078 |
| 50 | | | | € 1 063 245 | € 1 063 245 | 0,1407 | € 149 612 | 1,1638 | € 174 112 |
| | | | | | | | | TOTAL NPV over ∞H | € 997 198 |

Photo: M. Diependaele

Table 5-16. ASPHALT Alternative - Details calculations NPV

| Real discount rate | 4,00 % | Performance life of pavement L = 36 years | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MOTORWAY R1 - CALCULATION PV FOR ASPHALT ALTERNATIVE | | | | | | | | | | | | |
| YEAR | INITIAL CON-STRUCTION COST | CRACK & JOINT TREATMENT | POTHOLE AND PATCHING REPAIR | REPAIR SURFACE DEFECTS | 1st MAJOR PREVENTIVE MAIN-TENANCE | 2nd MAJOR PREVENTIVE MAIN-TENANCE | RE-CONSTRUCTION COST | SUBTOTAL FUTURE COSTS | Factor PV | PV | Factor PV over ∞H for L= 36 years | PV over ∞H |
| 0 | € 531 084 | | | | | | | € 531 084 | 1,0000 | € 531 084 | | € 531.084 |
| 4 | | € 4 200 | € 372 | € 5 178 | | | | € 9 750 | 0,8548 | € 8 334 | 1,3222 | € 11 019 |
| 5 | | | € 372 | € 5 178 | | | | € 5 550 | 0,8219 | € 4 562 | 1,3222 | € 6 031 |
| 6 | | | € 372 | € 5 178 | | | | € 5 550 | 0,7903 | € 4 386 | 1,3222 | € 5 799 |
| 7 | | | € 372 | € 5 178 | | | | € 5 550 | 0,7599 | € 4 218 | 1,3222 | € 5 576 |
| 8 | | € 4 200 | € 372 | € 5 178 | | | | € 9 750 | 0,7307 | € 7 124 | 1,3222 | € 9 419 |
| 9 | | | € 372 | € 5 178 | | | | € 5 550 | 0,7026 | € 3 899 | 1,3222 | € 5 156 |
| 10 | | | € 372 | € 5 178 | | | | € 5 550 | 0,6756 | € 3 749 | 1,3222 | € 4 957 |
| 11 | | | € 372 | € 5 178 | | | | € 5 550 | 0,6496 | € 3 605 | 1,3222 | € 4 767 |
| 12 | | | € 186 | € 2 589 | € 119 415 | | | € 122 190 | 0,6246 | € 76 320 | 1,3222 | € 100 908 |
| 13 | | | € 186 | € 2 589 | | | | € 2 775 | 0,6006 | € 1 667 | 1,3222 | € 2 204 |
| 14 | | | € 186 | € 2 589 | | | | € 2 775 | 0,5775 | € 1 602 | 1,3222 | € 2 119 |
| 15 | | | € 186 | € 2 589 | | | | € 2 775 | 0,5553 | € 1 541 | 1,3222 | € 2 037 |
| 16 | € 4 200 | | € 372 | € 5 178 | | | | € 9 750 | 0,5339 | € 5 206 | 1,3222 | € 6 883 |
| 17 | | | € 372 | € 5 178 | | | | € 5 550 | 0,5134 | € 2 849 | 1,3222 | € 3 767 |
| 18 | | | € 372 | € 5 178 | | | | € 5 550 | 0,4936 | € 2 740 | 1,3222 | € 3 622 |
| 19 | | | € 372 | € 5 178 | | | | € 5 550 | 0,4746 | € 2 634 | 1,3222 | € 3 483 |
| 20 | € 4 200 | | € 372 | € 5 178 | | | | € 9 750 | 0,4564 | € 4 450 | 1,3222 | € 5 883 |
| 21 | | | € 372 | € 5 178 | | | | € 5 550 | 0,4388 | € 2 436 | 1,3222 | € 3 220 |
| 22 | | | € 372 | € 5 178 | | | | € 5 550 | 0,4220 | € 2 342 | 1,3222 | € 3 096 |
| 23 | | | € 372 | € 5 178 | | | | € 5 550 | 0,4057 | € 2 252 | 1,3222 | € 2 977 |
| 24 | | | | | | € 222 085 | | € 222 08 | 0,3901 | € 86 640 | 1,3222 | € 114 553 |
| 28 | | € 4 200 | € 372 | € 5 178 | | | | € 9 750 | 0,3335 | € 3 251 | 1,3222 | € 4 299 |
| 29 | | | € 372 | € 5 178 | | | | € 5 550 | 0,3207 | € 1 780 | 1,3222 | € 2 353 |
| 30 | | | € 372 | € 5 178 | | | | € 5 550 | 0,3083 | € 1 711 | 1,3222 | € 2 262 |
| 31 | | | € 372 | € 5 178 | | | | € 5 550 | 0,2965 | € 1 645 | 1,3222 | € 2 175 |
| 32 | | € 4 200 | € 372 | € 5 178 | | | | € 9 750 | 0,2851 | € 2 779 | 1,3222 | € 3 675 |
| 33 | | | € 372 | € 5 178 | | | | € 5 550 | 0,2741 | € 1 521 | 1,3222 | € 2 011 |
| 34 | | | € 372 | € 5 178 | | | | € 5 550 | 0,2636 | € 1 463 | 1,3222 | € 1 934 |
| 35 | | | € 372 | € 5 178 | | | | € 5 550 | 0,2534 | € 1 406 | 1,3222 | € 1 860 |
| 36 | | | | | | | € 690 772 | € 690 772 | 0,2437 | € 168 319 | 1,3222 | € 222 547 |
| | | | | | | | | | | | TOTAL NPV over ∞H | €1 081 679 |

## 6 - REFERENCES


- [Ref. 1]: FWHA, 1998, Life-Cycle Cost Analysis in Pavement Design, Publication N° FHWA-SA-98-079.

- [Ref. 2]: ACPA, 2012, Life-Cycle Cost Analysis. A Tool for Better Pavement Investment and Engineering Decisions.

- [Ref. 3]: Mack J.W., TRB 2013, Accounting for Material-Specific Inflation Rates in Life-Cycle Cost Analysis for Pavement Type Selection.

- [Ref. 4]: Diependaele Manu, Technum Engineering Consultants, Belgium, 2006. Major Rehabilitation Antwerp Ring Road R1, Choice of pavement based on LCCA calculations.

- [Ref. 5]: FWHA, 2002, LCCA Primer.

## APPENDIX

Table A-1 shows the PV discount factors for a single future payment at 1, 2, 3, 4, 5 and 6 percent real discount rates for up to 100 years into the future. The initial agency costs are assumed to occur at time y = 0 and are not discounted, i.e., they are counted at full and actual value.

**Table A-1. Present value factors - single future payment**

| | PV factor | | | | | |
|---|---|---|---|---|---|---|
| Year | r=1% | r=2% | r=3% | r=4% | r=5% | r=6% |
| 0 | 1,0000 | 1,0000 | 1,0000 | 1,0000 | 1,0000 | 1,0000 |
| 1 | 0,9901 | 0,9804 | 0,9709 | 0,9615 | 0,9524 | 0,9434 |
| 2 | 0,9803 | 0,9612 | 0,9426 | 0,9246 | 0,9070 | 0,8900 |
| 3 | 0,9706 | 0,9423 | 0,9151 | 0,8890 | 0,8638 | 0,8396 |
| 4 | 0,9610 | 0,9238 | 0,8885 | 0,8548 | 0,8227 | 0,7921 |
| 5 | 0,9515 | 0,9057 | 0,8626 | 0,8219 | 0,7835 | 0,7473 |
| 6 | 0,9420 | 0,8880 | 0,8375 | 0,7903 | 0,7462 | 0,7050 |
| 7 | 0,9327 | 0,8706 | 0,8131 | 0,7599 | 0,7107 | 0,6651 |
| 8 | 0,9235 | 0,8535 | 0,7894 | 0,7307 | 0,6768 | 0,6274 |
| 9 | 0,9143 | 0,8368 | 0,7664 | 0,7026 | 0,6446 | 0,5919 |
| 10 | 0,9053 | 0,8203 | 0,7441 | 0,6756 | 0,6139 | 0,5584 |
| 11 | 0,8963 | 0,8043 | 0,7224 | 0,6496 | 0,5847 | 0,5268 |
| 12 | 0,8874 | 0,7885 | 0,7014 | 0,6246 | 0,5568 | 0,4970 |
| 13 | 0,8787 | 0,7730 | 0,6810 | 0,6006 | 0,5303 | 0,4688 |
| 14 | 0,8700 | 0,7579 | 0,6611 | 0,5775 | 0,5051 | 0,4423 |
| 15 | 0,8613 | 0,7430 | 0,6419 | 0,5553 | 0,4810 | 0,4173 |
| 16 | 0,8528 | 0,7284 | 0,6232 | 0,5339 | 0,4581 | 0,3936 |
| 17 | 0,8444 | 0,7142 | 0,6050 | 0,5134 | 0,4363 | 0,3714 |
| 18 | 0,8360 | 0,7002 | 0,5874 | 0,4936 | 0,4155 | 0,3503 |
| 19 | 0,8277 | 0,6864 | 0,5703 | 0,4746 | 0,3957 | 0,3305 |
| 20 | 0,8195 | 0,6730 | 0,5537 | 0,4564 | 0,3769 | 0,3118 |
| 21 | 0,8114 | 0,6598 | 0,5375 | 0,4388 | 0,3589 | 0,2942 |
| 22 | 0,8034 | 0,6468 | 0,5219 | 0,4220 | 0,3418 | 0,2775 |
| 23 | 0,7954 | 0,6342 | 0,5067 | 0,4057 | 0,3256 | 0,2618 |
| 24 | 0,7876 | 0,6217 | 0,4919 | 0,3901 | 0,3101 | 0,2470 |
| 25 | 0,7798 | 0,6095 | 0,4776 | 0,3751 | 0,2953 | 0,2330 |
| 26 | 0,7720 | 0,5976 | 0,4637 | 0,3607 | 0,2812 | 0,2198 |
| 27 | 0,7644 | 0,5859 | 0,4502 | 0,3468 | 0,2678 | 0,2074 |
| 28 | 0,7568 | 0,5744 | 0,4371 | 0,3335 | 0,2551 | 0,1956 |
| 29 | 0,7493 | 0,5631 | 0,4243 | 0,3207 | 0,2429 | 0,1846 |

| Year | r=1% | r=2% | r=3% | r=4% | r=5% | r=6% |
|---|---|---|---|---|---|---|
| 30 | 0,7419 | 0,5521 | 0,4120 | 0,3083 | 0,2314 | 0,1741 |
| 31 | 0,7346 | 0,5412 | 0,4000 | 0,2965 | 0,2204 | 0,1643 |
| 32 | 0,7273 | 0,5306 | 0,3883 | 0,2851 | 0,2099 | 0,1550 |
| 33 | 0,7201 | 0,5202 | 0,3770 | 0,2741 | 0,1999 | 0,1462 |
| 34 | 0,7130 | 0,5100 | 0,3660 | 0,2636 | 0,1904 | 0,1379 |
| 35 | 0,7059 | 0,5000 | 0,3554 | 0,2534 | 0,1813 | 0,1301 |
| 36 | 0,6989 | 0,4902 | 0,3450 | 0,2437 | 0,1727 | 0,1227 |
| 37 | 0,6920 | 0,4806 | 0,3350 | 0,2343 | 0,1644 | 0,1158 |
| 38 | 0,6852 | 0,4712 | 0,3252 | 0,2253 | 0,1566 | 0,1092 |
| 39 | 0,6784 | 0,4619 | 0,3158 | 0,2166 | 0,1491 | 0,1031 |
| 40 | 0,6717 | 0,4529 | 0,3066 | 0,2083 | 0,1420 | 0,0972 |
| 41 | 0,6650 | 0,4440 | 0,2976 | 0,2003 | 0,1353 | 0,0917 |
| 42 | 0,6584 | 0,4353 | 0,2890 | 0,1926 | 0,1288 | 0,0865 |
| 43 | 0,6519 | 0,4268 | 0,2805 | 0,1852 | 0,1227 | 0,0816 |
| 44 | 0,6454 | 0,4184 | 0,2724 | 0,1780 | 0,1169 | 0,0770 |
| 45 | 0,6391 | 0,4102 | 0,2644 | 0,1712 | 0,1113 | 0,0727 |
| 46 | 0,6327 | 0,4022 | 0,2567 | 0,1646 | 0,1060 | 0,0685 |
| 47 | 0,6265 | 0,3943 | 0,2493 | 0,1583 | 0,1009 | 0,0647 |
| 48 | 0,6203 | 0,3865 | 0,2420 | 0,1522 | 0,0961 | 0,0610 |
| 49 | 0,6141 | 0,3790 | 0,2350 | 0,1463 | 0,0916 | 0,0575 |
| 50 | 0,6080 | 0,3715 | 0,2281 | 0,1407 | 0,0872 | 0,0543 |
| 51 | 0,6020 | 0,3642 | 0,2215 | 0,1353 | 0,0831 | 0,0512 |
| 52 | 0,5961 | 0,3571 | 0,2150 | 0,1301 | 0,0791 | 0,0483 |
| 53 | 0,5902 | 0,3501 | 0,2088 | 0,1251 | 0,0753 | 0,0456 |
| 54 | 0,5843 | 0,3432 | 0,2027 | 0,1203 | 0,0717 | 0,0430 |
| 55 | 0,5785 | 0,3365 | 0,1968 | 0,1157 | 0,0683 | 0,0406 |
| 56 | 0,5728 | 0,3299 | 0,1910 | 0,1112 | 0,0651 | 0,0383 |
| 57 | 0,5671 | 0,3234 | 0,1855 | 0,1069 | 0,0620 | 0,0361 |
| 58 | 0,5615 | 0,3171 | 0,1801 | 0,1028 | 0,0590 | 0,0341 |
| 59 | 0,5560 | 0,3109 | 0,1748 | 0,0989 | 0,0562 | 0,0321 |
| 60 | 0,5504 | 0,3048 | 0,1697 | 0,0951 | 0,0535 | 0,0303 |
| 61 | 0,5450 | 0,2988 | 0,1648 | 0,0914 | 0,0510 | 0,0286 |
| 62 | 0,5396 | 0,2929 | 0,1600 | 0,0879 | 0,0486 | 0,0270 |
| 63 | 0,5343 | 0,2872 | 0,1553 | 0,0845 | 0,0462 | 0,0255 |
| 64 | 0,5290 | 0,2816 | 0,1508 | 0,0813 | 0,0440 | 0,0240 |
| 65 | 0,5237 | 0,2761 | 0,1464 | 0,0781 | 0,0419 | 0,0227 |
| 66 | 0,5185 | 0,2706 | 0,1421 | 0,0751 | 0,0399 | 0,0214 |

| Year | r=1% | r=2% | r=3% | r=4% | r=5% | r=6% |
|---|---|---|---|---|---|---|
| 67 | 0,5134 | 0,2653 | 0,1380 | 0,0722 | 0,0380 | 0,0202 |
| 68 | 0,5083 | 0,2601 | 0,1340 | 0,0695 | 0,0362 | 0,0190 |
| 69 | 0,5033 | 0,2550 | 0,1301 | 0,0668 | 0,0345 | 0,0179 |
| 70 | 0,4983 | 0,2500 | 0,1263 | 0,0642 | 0,0329 | 0,0169 |
| 71 | 0,4934 | 0,2451 | 0,1226 | 0,0617 | 0,0313 | 0,0160 |
| 72 | 0,4885 | 0,2403 | 0,1190 | 0,0594 | 0,0298 | 0,0151 |
| 73 | 0,4837 | 0,2356 | 0,1156 | 0,0571 | 0,0284 | 0,0142 |
| 74 | 0,4789 | 0,2310 | 0,1122 | 0,0549 | 0,0270 | 0,0134 |
| 75 | 0,4741 | 0,2265 | 0,1089 | 0,0528 | 0,0258 | 0,0126 |
| 76 | 0,4694 | 0,2220 | 0,1058 | 0,0508 | 0,0245 | 0,0119 |
| 77 | 0,4648 | 0,2177 | 0,1027 | 0,0488 | 0,0234 | 0,0113 |
| 78 | 0,4602 | 0,2134 | 0,0997 | 0,0469 | 0,0222 | 0,0106 |
| 79 | 0,4556 | 0,2092 | 0,0968 | 0,0451 | 0,0212 | 0,0100 |
| 80 | 0,4511 | 0,2051 | 0,0940 | 0,0434 | 0,0202 | 0,0095 |
| 81 | 0,4467 | 0,2011 | 0,0912 | 0,0417 | 0,0192 | 0,0089 |
| 82 | 0,4422 | 0,1971 | 0,0886 | 0,0401 | 0,0183 | 0,0084 |
| 83 | 0,4379 | 0,1933 | 0,0860 | 0,0386 | 0,0174 | 0,0079 |
| 84 | 0,4335 | 0,1895 | 0,0835 | 0,0371 | 0,0166 | 0,0075 |
| 85 | 0,4292 | 0,1858 | 0,0811 | 0,0357 | 0,0158 | 0,0071 |
| 86 | 0,4250 | 0,1821 | 0,0787 | 0,0343 | 0,0151 | 0,0067 |
| 87 | 0,4208 | 0,1786 | 0,0764 | 0,0330 | 0,0143 | 0,0063 |
| 88 | 0,4166 | 0,1751 | 0,0742 | 0,0317 | 0,0137 | 0,0059 |
| 89 | 0,4125 | 0,1716 | 0,0720 | 0,0305 | 0,0130 | 0,0056 |
| 90 | 0,4084 | 0,1683 | 0,0699 | 0,0293 | 0,0124 | 0,0053 |
| 91 | 0,4043 | 0,1650 | 0,0679 | 0,0282 | 0,0118 | 0,0050 |
| 92 | 0,4003 | 0,1617 | 0,0659 | 0,0271 | 0,0112 | 0,0047 |
| 93 | 0,3964 | 0,1586 | 0,0640 | 0,0261 | 0,0107 | 0,0044 |
| 94 | 0,3925 | 0,1554 | 0,0621 | 0,0251 | 0,0102 | 0,0042 |
| 95 | 0,3886 | 0,1524 | 0,0603 | 0,0241 | 0,0097 | 0,0039 |
| 96 | 0,3847 | 0,1494 | 0,0586 | 0,0232 | 0,0092 | 0,0037 |
| 97 | 0,3809 | 0,1465 | 0,0569 | 0,0223 | 0,0088 | 0,0035 |
| 98 | 0,3771 | 0,1436 | 0,0552 | 0,0214 | 0,0084 | 0,0033 |
| 99 | 0,3734 | 0,1408 | 0,0536 | 0,0206 | 0,0080 | 0,0031 |
| 100 | 0,3697 | 0,1380 | 0,0520 | 0,0198 | 0,0076 | 0,0029 |

In Table A-2 hereinafter the Factor is listed as a function of L and of r. In the table, it is seen that the values drop rapidly as the number of years L increase.

Table A-2. Factor infinite Horizon

| L Years | FACTOR infinite Horizon | | | | | |
|---|---|---|---|---|---|---|
| | r=1% | r=2% | r=3% | r=4% | r=5% | r=6% |
| 1 | 101,0000 | 51,0000 | 34,3333 | 26,0000 | 21,0000 | 17,6667 |
| 2 | 50,7512 | 25,7525 | 17,4204 | 13,2549 | 10,7561 | 9,0906 |
| 3 | 34,0022 | 17,3377 | 11,7843 | 9,0087 | 7,3442 | 6,2352 |
| 4 | 25,6281 | 13,1312 | 8,9676 | 6,8873 | 5,6402 | 4,8099 |
| 5 | 20,6040 | 10,6079 | 7,2785 | 5,6157 | 4,6195 | 3,9566 |
| 6 | 17,2548 | 8,9263 | 6,1533 | 4,7690 | 3,9403 | 3,3894 |
| 7 | 14,8628 | 7,7256 | 5,3502 | 4,1652 | 3,4564 | 2,9856 |
| 8 | 13,0690 | 6,8255 | 4,7485 | 3,7132 | 3,0944 | 2,6839 |
| 9 | 11,6740 | 6,1258 | 4,2811 | 3,3623 | 2,8138 | 2,4504 |
| 10 | 10,5582 | 5,5663 | 3,9077 | 3,0823 | 2,5901 | 2,2645 |
| 11 | 9,6454 | 5,1089 | 3,6026 | 2,8537 | 2,4078 | 2,1132 |
| 12 | 8,8849 | 4,7280 | 3,3487 | 2,6638 | 2,2565 | 1,9880 |
| 13 | 8,2415 | 4,4059 | 3,1343 | 2,5036 | 2,1291 | 1,8827 |
| 14 | 7,6901 | 4,1301 | 2,9509 | 2,3667 | 2,0205 | 1,7931 |
| 15 | 7,2124 | 3,8913 | 2,7922 | 2,2485 | 1,9268 | 1,7160 |
| 16 | 6,7945 | 3,6825 | 2,6537 | 2,1455 | 1,8454 | 1,6492 |
| 17 | 6,4258 | 3,4985 | 2,5318 | 2,0550 | 1,7740 | 1,5907 |
| 18 | 6,0982 | 3,3351 | 2,4236 | 1,9748 | 1,7109 | 1,5393 |
| 19 | 5,8052 | 3,1891 | 2,3271 | 1,9035 | 1,6549 | 1,4937 |
| 20 | 5,5415 | 3,0578 | 2,2405 | 1,8395 | 1,6049 | 1,4531 |
| 21 | 5,3031 | 2,9392 | 2,1624 | 1,7820 | 1,5599 | 1,4167 |
| 22 | 5,0864 | 2,8316 | 2,0916 | 1,7300 | 1,5194 | 1,3841 |
| 23 | 4,8886 | 2,7334 | 2,0271 | 1,6827 | 1,4827 | 1,3546 |
| 24 | 4,7073 | 2,6436 | 1,9682 | 1,6397 | 1,4494 | 1,3280 |
| 25 | 4,5407 | 2,5610 | 1,9143 | 1,6003 | 1,4190 | 1,3038 |
| 26 | 4,3869 | 2,4850 | 1,8646 | 1,5642 | 1,3913 | 1,2817 |
| 27 | 4,2446 | 2,4147 | 1,8188 | 1,5310 | 1,3658 | 1,2616 |
| 28 | 4,1124 | 2,3495 | 1,7764 | 1,5003 | 1,3425 | 1,2432 |
| 29 | 3,9895 | 2,2889 | 1,7372 | 1,4720 | 1,3209 | 1,2263 |
| 30 | 3,8748 | 2,2325 | 1,7006 | 1,4458 | 1,3010 | 1,2108 |
| 31 | 3,7676 | 2,1798 | 1,6666 | 1,4214 | 1,2826 | 1,1965 |
| 32 | 3,6671 | 2,1305 | 1,6349 | 1,3987 | 1,2656 | 1,1834 |

| L Years | r=1% | r=2% | r=3% | r=4% | r=5% | r=6% |
|---|---|---|---|---|---|---|
| 33 | 3,5727 | 2,0843 | 1,6052 | 1,3776 | 1,2498 | 1,1712 |
| 34 | 3,4840 | 2,0409 | 1,5774 | 1,3579 | 1,2351 | 1,1600 |
| 35 | 3,4004 | 2,0001 | 1,5513 | 1,3394 | 1,2214 | 1,1496 |
| 36 | 3,3214 | 1,9616 | 1,5268 | 1,3222 | 1,2087 | 1,1399 |
| 37 | 3,2468 | 1,9253 | 1,5037 | 1,3060 | 1,1968 | 1,1310 |
| 38 | 3,1761 | 1,8910 | 1,4820 | 1,2908 | 1,1857 | 1,1226 |
| 39 | 3,1092 | 1,8586 | 1,4615 | 1,2765 | 1,1753 | 1,1149 |
| 40 | 3,0456 | 1,8278 | 1,4421 | 1,2631 | 1,1656 | 1,1077 |
| 41 | 2,9851 | 1,7986 | 1,4237 | 1,2504 | 1,1564 | 1,1010 |
| 42 | 2,9276 | 1,7709 | 1,4064 | 1,2385 | 1,1479 | 1,0947 |
| 43 | 2,8727 | 1,7445 | 1,3899 | 1,2272 | 1,1399 | 1,0889 |
| 44 | 2,8204 | 1,7194 | 1,3743 | 1,2166 | 1,1323 | 1,0834 |
| 45 | 2,7705 | 1,6955 | 1,3595 | 1,2066 | 1,1252 | 1,0783 |
| 46 | 2,7228 | 1,6727 | 1,3454 | 1,1971 | 1,1186 | 1,0736 |
| 47 | 2,6771 | 1,6509 | 1,3320 | 1,1880 | 1,1123 | 1,0691 |
| 48 | 2,6334 | 1,6301 | 1,3193 | 1,1795 | 1,1064 | 1,0650 |
| 49 | 2,5915 | 1,6102 | 1,3071 | 1,1714 | 1,1008 | 1,0611 |
| 50 | 2,5513 | 1,5912 | 1,2955 | 1,1638 | 1,0955 | 1,0574 |
| 51 | 2,5127 | 1,5729 | 1,2845 | 1,1565 | 1,0906 | 1,0540 |
| 52 | 2,4756 | 1,5555 | 1,2739 | 1,1496 | 1,0859 | 1,0508 |
| 53 | 2,4400 | 1,5387 | 1,2638 | 1,1430 | 1,0815 | 1,0478 |
| 54 | 2,4057 | 1,5226 | 1,2542 | 1,1367 | 1,0773 | 1,0449 |
| 55 | 2,3726 | 1,5072 | 1,2450 | 1,1308 | 1,0733 | 1,0423 |
| 56 | 2,3408 | 1,4923 | 1,2361 | 1,1251 | 1,0696 | 1,0398 |
| 57 | 2,3102 | 1,4781 | 1,2277 | 1,1197 | 1,0661 | 1,0375 |
| 58 | 2,2806 | 1,4643 | 1,2196 | 1,1146 | 1,0627 | 1,0353 |
| 59 | 2,2520 | 1,4511 | 1,2119 | 1,1097 | 1,0596 | 1,0332 |
| 60 | 2,2244 | 1,4384 | 1,2044 | 1,1050 | 1,0566 | 1,0313 |
| 61 | 2,1978 | 1,4261 | 1,1973 | 1,1006 | 1,0537 | 1,0294 |
| 62 | 2,1720 | 1,4143 | 1,1905 | 1,0964 | 1,0510 | 1,0277 |
| 63 | 2,1471 | 1,4029 | 1,1839 | 1,0923 | 1,0485 | 1,0261 |
| 64 | 2,1230 | 1,3919 | 1,1776 | 1,0884 | 1,0461 | 1,0246 |
| 65 | 2,0997 | 1,3813 | 1,1715 | 1,0848 | 1,0438 | 1,0232 |
| 66 | 2,0771 | 1,3711 | 1,1657 | 1,0812 | 1,0416 | 1,0218 |
| 67 | 2,0551 | 1,3612 | 1,1601 | 1,0779 | 1,0396 | 1,0206 |
| 68 | 2,0339 | 1,3516 | 1,1547 | 1,0746 | 1,0376 | 1,0194 |
| 69 | 2,0133 | 1,3423 | 1,1495 | 1,0716 | 1,0357 | 1,0183 |

| L Years | r=1% | r=2% | r=3% | r=4% | r=5% | r=6% |
|---|---|---|---|---|---|---|
| 70 | 1,9933 | 1,3334 | 1,1446 | 1,0686 | 1,0340 | 1,0172 |
| 71 | 1,9739 | 1,3247 | 1,1398 | 1,0658 | 1,0323 | 1,0162 |
| 72 | 1,9550 | 1,3163 | 1,1351 | 1,0631 | 1,0307 | 1,0153 |
| 73 | 1,9367 | 1,3082 | 1,1307 | 1,0605 | 1,0292 | 1,0144 |
| 74 | 1,9189 | 1,3004 | 1,1264 | 1,0581 | 1,0278 | 1,0136 |
| 75 | 1,9016 | 1,2928 | 1,1223 | 1,0557 | 1,0264 | 1,0128 |
| 76 | 1,8848 | 1,2854 | 1,1183 | 1,0535 | 1,0251 | 1,0121 |
| 77 | 1,8684 | 1,2782 | 1,1144 | 1,0513 | 1,0239 | 1,0114 |
| 78 | 1,8525 | 1,2713 | 1,1107 | 1,0492 | 1,0228 | 1,0107 |
| 79 | 1,8370 | 1,2646 | 1,1072 | 1,0473 | 1,0216 | 1,0101 |
| 80 | 1,8219 | 1,2580 | 1,1037 | 1,0454 | 1,0206 | 1,0095 |
| 81 | 1,8072 | 1,2517 | 1,1004 | 1,0435 | 1,0196 | 1,0090 |
| 82 | 1,7929 | 1,2456 | 1,0972 | 1,0418 | 1,0186 | 1,0085 |
| 83 | 1,7789 | 1,2396 | 1,0941 | 1,0401 | 1,0177 | 1,0080 |
| 84 | 1,7653 | 1,2338 | 1,0911 | 1,0385 | 1,0169 | 1,0075 |
| 85 | 1,7520 | 1,2282 | 1,0882 | 1,0370 | 1,0161 | 1,0071 |
| 86 | 1,7391 | 1,2227 | 1,0854 | 1,0355 | 1,0153 | 1,0067 |
| 87 | 1,7264 | 1,2174 | 1,0827 | 1,0341 | 1,0145 | 1,0063 |
| 88 | 1,7141 | 1,2122 | 1,0801 | 1,0327 | 1,0138 | 1,0060 |
| 89 | 1,7021 | 1,2072 | 1,0776 | 1,0314 | 1,0132 | 1,0056 |
| 90 | 1,6903 | 1,2023 | 1,0752 | 1,0302 | 1,0125 | 1,0053 |
| 91 | 1,6788 | 1,1976 | 1,0728 | 1,0290 | 1,0119 | 1,0050 |
| 92 | 1,6676 | 1,1929 | 1,0706 | 1,0279 | 1,0114 | 1,0047 |
| 93 | 1,6567 | 1,1884 | 1,0684 | 1,0268 | 1,0108 | 1,0045 |
| 94 | 1,6460 | 1,1841 | 1,0662 | 1,0257 | 1,0103 | 1,0042 |
| 95 | 1,6355 | 1,1798 | 1,0642 | 1,0247 | 1,0098 | 1,0040 |
| 96 | 1,6253 | 1,1757 | 1,0622 | 1,0237 | 1,0093 | 1,0037 |
| 97 | 1,6153 | 1,1716 | 1,0603 | 1,0228 | 1,0089 | 1,0035 |
| 98 | 1,6055 | 1,1677 | 1,0584 | 1,0219 | 1,0085 | 1,0033 |
| 99 | 1,5959 | 1,1639 | 1,0566 | 1,0210 | 1,0080 | 1,0031 |
| 100 | 1,5866 | 1,1601 | 1,0549 | 1,0202 | 1,0077 | 1,0030 |

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