Life Cycle Cost Analysis of

Asphalt and Concrete Pavements

by

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ABSTRACT

This report describes a life cycle cost analysis (LCCA) for road pavements and evaluates its impact on pavement type choice. Working from literature, historical data and interviews, the LCCA technique is described and an overview of the road and street system in Iceland is presented. The LCCA methodology developed here is tested on a hypothetical project (road section in Reykjavík).

The purpose of this project is to develop a calculation model based on LCCA methodology. LCCA is tested for six traffic groups: 2.500, 5.000, 7.500, 10.000, 12.500, and 15.000 veh/day/lane. For each traffic group, two scenarios are built: one with asphalt pavement and one with concrete pavement. An analysis period of 40 years was chosen for this project: thus the cost for asphalt and concrete pavements are evaluated for this analysis period. Construction, rehabilitation and user costs are included in the model. A 6% discount rate is used for the base case scenario, and the allowed rut depth is 3.5 cm.

As was to be expected, a flexible pavement is more suitable for lower volumes of traffic, and with increased traffic, concrete pavements are more competitive. Test results show that when traffic is around 14000 veh/day/lane, asphalt and concrete are competitive. It is very surprising how little the difference actually is between asphalt and concrete pavements if we take into account the cost over the whole design period. Results could be slightly different if a different discount rate were to be used or the unit price were to fluctuate. Too low a rate of return could favour a more expensive project, which could thus shift from being unprofitable to profitable. Unit price changes have the same effect.

Key words: Life cycle cost analysis; Asphalt pavement; Concrete pavement.

ÁGRIP

Vistferilskostnaðargreining á malbikuðu og steyptu slitlagi

Ritgerð þessi lýsir vistferilskostnaðargreiningu á bundnu slitlagi fyrir vegi og metur áhrif slíkrar greiningar á slitlagsval. Í ritgerðinni er stuðst við fræðirit, söguleg gögn sem og viðtöl. Aðferðafræðin við vistferilskostnaðargreiningu er útlistuð og gefið yfirlit yfir vega- og gatnakerfið hér á landi. Vistferilskostnaðargreiningu er beitt á ímyndað verkefni (vegarkafla í Reykjavík).

Markmið verkefnisins er að þróa reiknilíkan fyrir vistferilskostnaðargreiningu. Líkanið er gert fyrir og prófað á sex umferðarflokkum, 2.500, 5.000, 7.500, 10.000, 12.500 og 15.000 ökutæki/dag/akrein. Fyrir hvern umferðarflokk eru tvær slitlagsgerðir skoðaðar, malbiksslitlag og steypt slitlag. Líkanið reiknar samanlagðan stofn- og viðhaldskostnað fyrir hvora slitlagsgerð, sem og kostnað vegfarenda vegna umferðatafa, fyrir 40 ára tímabil og finnur núvirði hans. Gengið er út frá 6% reiknivöxtum og gert er ráð fyrir að leyfileg hjólfaradýpt sé allt að 3.5 cm.

Eins og við var búist, þá kom í ljós að malbiksslitlag hentar betur en steypt slitlag þar sem umferð er ekki mikil, en eftir því sem umferðin eykst verður steypt slitlag samkeppnishæfara. Niðurstöðurnar sýna að þegar umferðin er um 14.000 ökutæki/dag/akrein eru þessar tvær slitlagsgerðir mjög sambærilegar, og í raun er mjög lítill munur á kostnaði yfir 40 ára tímabil. Þó er vert að hafa í huga að niðurstöðurnar eru viðkvæmar fyrir breytingum á forsendum, svo sem einingaverðum sem og öðrum breytum. Lægri reiknivextir draga taum dýrara slitlags sem getur þar með orðið hagstæðara en ódýrt slitlag.

Lykilorð: Vistferilskostnaðargreining. Malbiksslitlag. Steypt slitlag.

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1. INTRODUCTION

The purpose of this project is to develop a model, based on Life Cycle Cost Analysis (LCCA) methodology, which could assist in the pavement selection process and hopefully help to improve the road and street system.

The dramatic increase in traffic in built-up areas, such as the Capital Area, results in more and more construction of new roads and modernization of old ones. Therefore, this requires further studies on how road pavements are selected.

Agencies could make more informed and better investment decisions, because pavement type has a significant impact on future cost and service quality. Traffic growth, especially in heavy axle traffic, can cause damage to pavements much quicker than expected, in turn causing more maintenance and thereby increasing agencies' and users' costs. Pavement type decision is usually based on traffic level, soil conditions, atmospheric factors and costs. In many cases, the initial construction cost is the main consideration; the future maintenance and rehabilitation costs may sometimes be forgotten.

LCCA is a process that compares the long-term economic worth of competing alternatives and the results could be useful as a decision-supporting tool. According to the American Association of State Highway and Transportation Officials (AASHTO) Guide for the Design of Pavement Structures, life cycle costs "refer to all costs which are involved in the provision of a pavement during its complete life cycle" (AASHTO, 1993). That means that all pavement options are evaluated by taking into account different agencies' and users' costs. Agencies' costs include initial construction costs as well as future costs of rehabilitation, maintenance and facility operation. User costs are a result of many different issues, for instance increased delay costs, increased vehicle operating costs or changes in accident costs due to future maintenance actions.

LCCA results primarily depend on the accuracy of the input parameters. The more parameters are included in the analysis, the more informed the final results will be. Even if the input parameters are considered fairly "accurate" there is a need to perform a sensitivity analysis for these parameters, because cost can be somewhat different if another discount rate is used; changes in material or oil prices can also have the analogous impact.

Most sensitive parameters should be analysed very carefully and the final result should reflect this. This project is not able to cover all issues regarding data inputs, and of course, on some of them, special studies and analysis are needed.

In this project, the LCCA methodology will be tested by comparing concrete and asphalt pavements on a hypothetical highway in the Capital Area, using historical and foreign countries' experience regarding concrete pavements and domestic up-to-date prices for asphalt pavements.

There are a number of stakeholders for the Life Cycle Cost Analysis of pavements, including: the elected level (i.e. the city council), senior administrators, technical and operational level personnel, taxpayers, interest groups, contractors and suppliers, consultants and transportation agencies. In the case of pavements on arterial streets in Reykjavík, the following table provides an overview of the main stakeholder groups as well as their perspectives, direct or indirect, towards the choice of pavement types.

Table 1-1: *Stakeholders and their concern regarding choice of pavement*

	Costs	Environmental impact	Level of service	Traffic safety	Market access
General public		x		x	
Road users	x	(x)	x	x	
Constructors, manufactures	x			(x)	x
Road and street agencies	x	(x)	(x)	x	

x – Direct; (x) - Indirect

Roads users would benefit by saving time, reducing vehicle operating costs and the provision of an increased level of services (LOS). Road and street agencies gain by optimising maintenance costs and timing these operations appropriately in order to minimize the reduction in the level of service for the users. Producers of pavement materials and contractors also have a better overview of the market and a clearer idea of what they are competing against. This is very much the case for the asphalt and concrete industries.

2. LCC METHODOLOGY AND LATEST RESEARCH

There are several ways to select the best pavement type. However, no specific selection method is used in Iceland, since there is no competition between its asphalt and concrete industries.

The road standard *"Veghönnunarreglur Vegagerðarinnar"* (ICERA, 2009a) prepared by the Icelandic Road Administration (ICERA) do not mention road or pavement type and thickness according to the road type. In addition, the Norwegian road standard *"Vegbygging. Håndbok 018"* (NPRA, 2005a), which recommends pavement types and thickness according to Equivalent Single Axle Loads (ESALs) during the roads' design lifetime, is generally used among the road specialists in Iceland. However, decisions in Iceland are mostly based on experience and historical data. In other countries, several techniques are used for pavement selection, one of which is LCCA.

Life Cycle Cost Analysis provides a methodology for computing the cost of a product or service during its lifetime. It is used to compare competing design alternatives over the lives of each alternative, considering all significant costs and benefits, expressed in equivalent monetary units (ACPA, 2002). For infrastructure assets such as roads, a large proportion of the total cost over the lifetime of these assets is incurred after construction, i.e. during their service lives. It is possible to avoid most of the "unknown" costs by introducing long-term costs into the pavement valuation processes instead of comparing only initial material and construction costs (ACPA, 2002).

The steps involved in the LCCA methodology are as follows (Walls & Smith, 1998):

1. Establish alternative design strategies
2. Determine activity timing
3. Estimate agency costs
4. Estimate user costs
5. Determine life-cycle cost.

The first step in the LCCA process is to define realistic design options. For every likely option, it is important to identify initial construction or rehabilitation activities, as well as to predict future rehabilitation and maintenance activities and the times of those individual actions. Hence, a plan of activities must be created for each design option.

The next step is to estimate costs for all activities. It is recommended to include not only direct agency expenses (construction or maintenance activities) but also user costs, in order to get a better picture of the impact of maintenance/repair (Hass, Tighe, & Falls, 2005).

After cost is defined for every possible option, then the total life-cycle costs for each competing alternative can be calculated. LCCA uses discounting to convert future costs to present values so that the lifetime costs of different alternatives can be directly compared (Boardman, Greenberg, Vining, & Weimer, 2006). Figure 2-1 represents costs that could be included in the calculation and LCCA process.

All costs in LCCA are divided into four groups: construction, agencies, user and environmental costs. These costs are individually calculated for each competing alternative. If one of the alternatives does not include a certain cost, then the others should also exclude this cost: only then can the alternatives be fairly compared. For example, if one alternative includes road markings into LCCA, then the other alternatives must include road markings too. Some of the costs can be difficult to quantify, so their inclusion in the project can be optional. To be able to fairly compare all opportunities, the discount rate and analysis period should be the same for all alternatives (FHWA, 2002). There are different methods to compare life-cycle costs. The most common are the Net Present Worth method (NPW), the Benefit Cost Ratio (B/C ratio), the Internal Rate of Return (IRR), and the Equivalent Uniform Annual Cost (EUAC) method, with the most popular being the IRR and NPW methods.

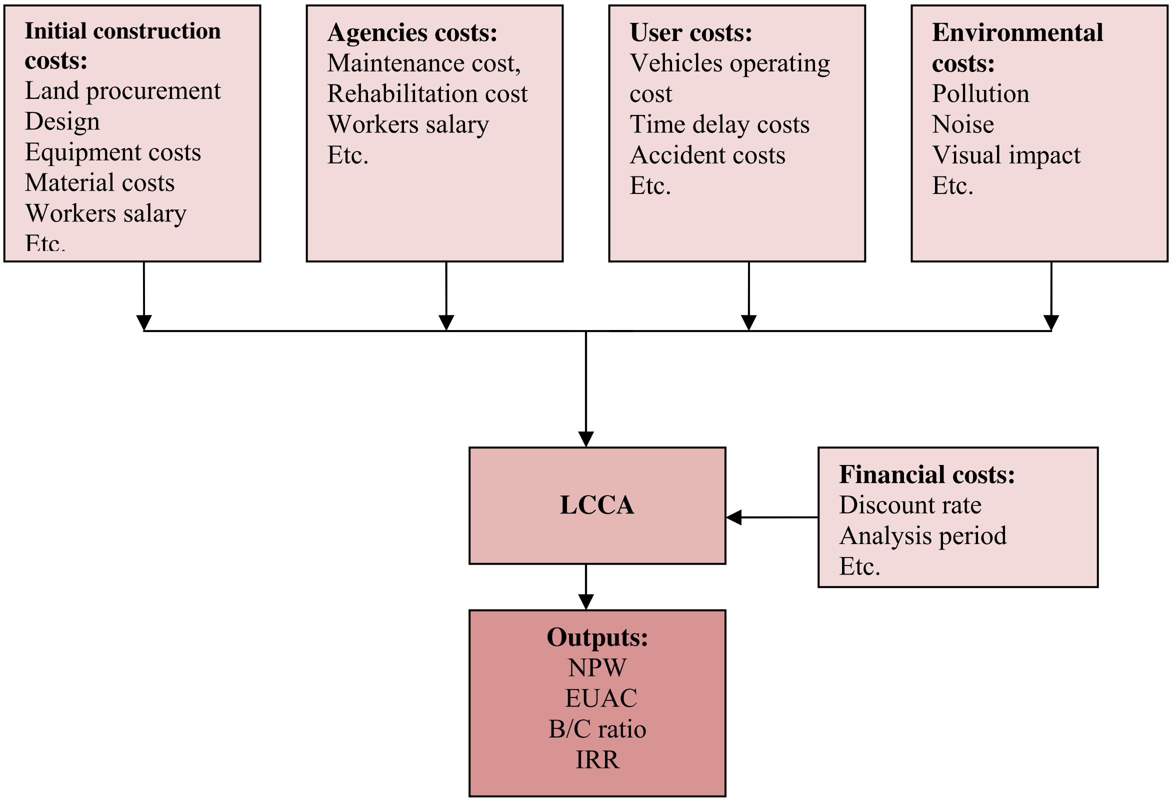

Figure 2-1: *A flowchart describing LCCA process for pavement type selection*

2.1 Economic analysis components

Evaluation Methods

Several economic analysis techniques can be used to assess pavement type options. The two most popular are the Net Present Worth (NPW) method and the Internal Rate of Return method (IRR). The IRR method simply asks what rate of return makes the Net Present Worth equal to zero. In some countries, the Equivalent Uniform Annual Cost (EUAC) method is also common. The EUAC method is developed from the NPW so as to explain the average cost an agency will pay per year over the analysis period. All costs including initial construction and future maintenance, are distributed equally. This method can be used to evaluate and compare options even though this value system may not seem realistic in times when little pavement action is required (VDOT, 2002).

The result of the NPW method is a lump sum of initial and future costs in today's monetary value. For actions that take place in the first year of the analysis period, the NPW cost is the same as the actual cost, as there is no correction for inflation and interest. For future maintenance and rehabilitation activities, the NPW cost is less than the actual cost (based on today's unit prices) since total costs are discounted (VDOT, 2002). It should be noted that for two identical actions that occur 30 years apart, the later action will cost much less once they are discounted to the present cost. The NPW method is the more widely used approach for pavement LCCA. It gives an indication of how much a pavement alternative will cost over the analysis period and it can be used to compare alternatives to find the lowest cost (Jensson, 1993). Equation 1 calculates the Net Present Worth of an alternative.

$$NPW = C_0 + \sum_{n=1}^{N} \frac{M_n + O_n + U_n}{(1+i)^n} - \frac{S}{(1+i)^N} \tag{1}$$

Where C_0 = initial construction cost; n = a specific year; i = discount rate; M_n = maintenance cost in year n; O_n = operating cost in year n; U_n = user cost in year n; S = salvage value; N = analysis period.

Benefit-cost ratio identifies the relationship between the cost and benefits of each alternative. Projects with a benefit-cost ratio greater than one have greater benefits than costs as well as positive net benefits. The higher the ratio is, the greater the benefits relative to the costs are (Boardman, Greenberg, Vining, & Weimer, 2006).

Analysis Period

According to the FHWA Technical Bulletin, life cycle cost analysis periods should be long enough to reflect long-term differences associated with reasonable maintenance strategies. In general, the analysis period should be longer than the pavement design period and long enough to include at least one complete rehabilitation activity (VDOT, 2002).

The FHWA recommends an analysis period of at least 35 years for all pavement projects, including new or total reconstruction projects and rehabilitation, restoration, and resurfacing projects (Walls & Smith, 1998). However, in Norway, it is more common to use 10- or 20-year analysis periods in road design (NPRA, 2005a). The main reason for that is that over a long period, such as 40 years, significant changes in the economic situation, traffic, and even technology are more likely.

Discount Rate

The time value of money must be taken into account in order to calculate the cost of the future activities: for that reason, in LCCA, the discount rate is used.

The discount rate accounts not only for the increased costs related to the future activities but also for the economic benefit that the agency would get if those funds were instead put into a saving (interest-bearing) account. The FHWA suggests using discount rates in the range of 3 to 5% (Walls & Smith, 1998). Traditionally, this value has ranged from 2% to 5% in the USA.

For example, a few years ago the Norwegian Ministry of Finance modified the discount rate for public investments, including road investments. The ministry has advised that the discount rate for typical public projects, including roads, should be set at 4%, where 2% is for risk-free component and 2% for the risk mark-up (NPRA, 2005b). However, the Ministry of Transport can increase the discount rate if they decide that a project has exceptionally high risk.

Long-term discount rates on borrowings by government agencies are around 6% in Iceland, although before the 2008 world economic crises, the discount rate was gradually getting lower. While a country's economic situation is unclear, it is very difficult to offer predictions for the future; therefore, the use of the 6% discount rate is still acceptable.

Sensitivity Analysis

As with any kind of analysis or research, it is important to understand which parameters make the biggest contribution to the final results. For example: the pavement subgrade strength and traffic loading have the major impact on the design outcome in the pavement design procedure. For LCCA, many variables can affect the final NPW for a pavement alternative. For instance, the unit price of a material is very important and can cause an alternative to go from the lowest NPW to the highest. Therefore, it is very important to use reasonable unit prices that reflect reality.

Other factors that can greatly influence the LCCA results are the discount rate, analysis period and timing of activities (Buncher, 2004). By changing some parameters, it is relatively easy to find out which inputs have major impacts on the final results.

2.2 Cost factors

Initial construction

The initial costs have a major impact on the total NPW. The initial costs are determined at year zero of the analysis period. Although numerous activities are performed during the construction, reconstruction or major rehabilitation of a pavement, only those activities that are specific to a pavement alternative should be included in the initial costs (VDOT, 2002). By focusing on these activities, the specialist can concentrate on estimating the quantities and costs related to these activities.

It can be rather difficult to forecast exact initial construction costs. Each situation is very unique and depends on many aspects: geological, economical, environmental, qualifications (work-specific) etc. In the end, total construction costs can exceed estimated costs but can also be less than expected. Therefore, it is recommended to add an extra percentage for unexpected costs.

Maintenance and rehabilitation costs

All pavement types need maintenance, which can be preventive (routine) or corrective, during their service life. At a certain time, a pavement must be renewed.

Maintenance and rehabilitation cost includes materials, equipment, staff salaries etc. The timing and amount of these activities vary from year to year. In Iceland, they are usually concentrated on the summer months, June to September. Cost data for preventive type maintenance are often not very easy to obtain or to predict.

Some agencies do not include maintenance and operation costs in their LCCA of pavements, but exclusion of these costs would mean inaccurate results in the end, especially when comparing asphalt and concrete pavements. This is mainly because the difference between asphalt and concrete pavements is primarily due to differences in maintenance and rehabilitation costs.

User costs

By calculating users' costs, we can see the impact of road works on road users. User costs will differ during maintenance and rehabilitation periods. During rehabilitation and maintenance, user costs can increase dramatically. It is obvious that road works cause delay and increase vehicle operating costs, as well as the number of traffic accidents.

User costs can be divided into following categories:

Vehicle operating costs. Mostly as a result of increased fuel usage, wear on tyres and other parts, and other factors, vehicle operating costs increase during maintenance periods. In-service vehicle operating costs are a function of pavement serviceability level, which is often difficult to estimate (Tapan, 2002).

User delay costs. User delay costs are connected with road users' time. Usually time saving is mentioned as one of the key benefits in transportation projects.

User costs mostly increase during maintenance and rehabilitation periods, when traffic is completely shut down or diverted into other lanes. Time delay cost is mostly due to changes in speed. Speed changes are the additional cost of slowing from one speed to another and returning to the original speed (Walls & Smith, 1998). Time value depends on the vehicle type and the purpose of the trip (USDOT, 1997). However, user delay costs are one of the most difficult and most controversial life-cycle cost analysis parameters: they are extremely difficult to calculate because it is necessary to put a monetary value on individuals' delay time (Walls & Smith, 1998).

Dr. S. Einarsson and Dr. H. Sigþórsson recently published research on the profitability of investments in road building here in Iceland. Where they dealt with average time value for the vehicles, they took into account a range of factors, such as the purpose of the trip, the time of the trip etc. Calculations were based on "Handbook 140" from the Norwegian Road Administration, but of course with reference to Iceland's economic and social situation (Einarsson & Sigþórsson, 2009). The average value of the time for passenger vehicle was calculated to be 1695 kr/ hour.

Crash costs. Crash costs include damage to the users' and others' vehicles and public/private property, as well as injuries (Tapan, 2002). Road accident cost is usually calculated from accident rate and economic costs specified for various types of accident severity and functional road classes.

This LCCA model is not going to include any vehicle operation costs or crash costs due to lack of information, since specific studies must be performed for these cost components.

Salvage Value

The pavement worth that the agency has at the end of the LCCA period is called the salvage value. However, if maintenance or rehabilitation is scheduled close to the end of the analysis period, then it is obvious that it extends the life of the pavement, and therefore the agency gains from that, since it increases total pavement value.

The FHWA, in its Interim Technical Bulletin on LCCA, recognizes that a pavement's functional life represents a more significant component of salvage value than does its residual value as recycled material (FHWA, 1998). According to the Bulletin, the salvage value has very little impact on LCCA results when value is discounted over 35 years or more (VDOT, 2002). Therefore this LCCA model is not going to include salvage value.

Typical costs for the construction of pavements in Iceland will be further discussed in chapter 4 and can be found in appendix B. Some of these are actual results from bids or actual estimates from agencies. These cost figures are also partly based on information from constructors and manufactures.

2.3 Latest research in Iceland on LCCA

The efficiency of concrete pavements has been discussed among specialists for many years, since in Iceland there is no competition between asphalt and concrete manufacturers in road construction. These discussions are usually associated with costs during the lifetime of the pavement. Worldwide studies on pavement types usually do not apply in Iceland, due to the use of studded tyres, which is much higher than in other countries.

A small number of studies have been published on similar matters during the past 20-30 years here in Iceland, comparing different aspects of the paving material. It could be said that these studies started with a report written in 1987 by H. Ólafsson, which argues that at 5.000 AADT, plain concrete becomes competitive to asphalt, and increasingly so at higher AADT (Ólafsson, 1987).

Without going into deeper discussion, it is possible to summarize the main findings from this body of research, as represented in the table below.

Table 2-1: *LCCA research summary*

Author	Publishing year	Result	Design life	Description
H. Ólafsson	1987	Concrete becomes competitive when AADT>5.000	40	Plain concrete (Ólafsson, 1987).
P. Jensson	1993	Concrete is suitable for roads with AADT>8.000	40	Analysed roads with AADT 3000, 5.000, 8000, 10.000, and 15.000; 6% discount rate; high strength concrete with very good wear resistance (Jensson, 1993).
Á. Jóhannesson et al.	1997	Asphalt is 14% cheaper	40	AADT 5.000; length 5km; traffic growth 0.75% p.a. (Jóhannesson Á. , 1997).
Línuhönnun	2001	1.C80 when AADT 11.000; C60 when AADT 13.000 2. C80 when AADT 22.000; C60 when AADT 30.000	30	Traffic growth 0.75% p.a. 1. ADDT 5.000- 15.000, two bus lanes 2. AADT 15.000-40000, four lanes (Línuhönnun, 2001).
Hnit	2002	Concrete 0.8 Mkr/km more expensive than asphalt	30	Proposal for Reykjanes road between Straumsvík and Strandarheiði ADDT 4200; two lanes road (Jóhannesson, Á., 2009).
Á. Jóhannesson et al.	2009	1. Concrete 40-50% more expensive 2. Concrete 35-45% more expensive	40	Hringvegur between Reykjavík and Selfoss; SMA 16 and C60; AADT 8000; 1. Traffic growth 2% 2. Traffic growth 4% (Jóhannesson, Á., 2009).

One of the latest studies published on this subject is a report called *"Model for Asphalt and Concrete Pavements Efficiency Comparison"* (original version *"Líkan til samanburðar á hagkvæmni steyptra og malbikaðra slitlaga"*) by Ásbjörn Jóhannesson (Jóhannesson, Á., 2009). In my opinion, this report is very significant because the world economic crises mean that the situation has changed considerably both in asphalt and concrete manufacture and prices for those materials have not increased equally. This report was written after the economic crisis shocked the construction business.

This report was written in 2009 specifically for Hringvegur between Reykjavík and Selfoss but keeping in mind that it might also be used for other roads with similar conditions. The report also includes an Excel model for the calculations.

It represents a model designed to compare the efficiency of concrete and asphalt pavements on a four-lane road with moderate traffic. The model takes into account total construction and maintenance cost for a 40-year design period. Most of the parameters are fixed, with the only changes allowed being unit price and interest rate. Two types of pavement alternative are given: asphalt (SMA 16) and concrete (jointed plain concrete C60). It is possible to choose between a few maintenance options and between 2% and 4% annual yearly traffic growths. The model does not take in account time cost, user cost or other social/environmental costs. Annual average daily traffic is 8000 vehicles, 10% of which are heavy traffic. It is suggested to repave asphalt when ruts reach 2.5 cm, no more than twice in a row, and then resurface. More maintenance possibilities are suggested for concrete pavement. Results show that concrete pavement is 40- 50% more expensive if 2% annual traffic growth is used, and 35-45% more expensive if 4% traffic growth is used (Jóhannesson, Á., 2009).

It is likely that the results would be slightly different if user costs were included in the calculation, but even so, asphalt pavement would probably still be more economical to use. Therefore, it is evident that traffic has to be greater than 8000 veh/day for concrete to be competitive with asphalt.

3. DESCRIPTION OF TODAY'S SITUATION

3.1. Road and street agencies in Iceland

The Ministry of Transport, Communications and Local Government (Samgönguráðuneytið) is responsible for all matters concerning transportation in the country according to the Road Act No. 45/1994 (Alþingi, 2008). The Ministry is divided into four departments and one of them is the Department of Transportation.

Vegagerðin, the Icelandic Road Administration (ICERA), is a governmental institution under the Department of Transportation. ICERA is in charge of the planning, construction and operation of the national road system: its goal is to keep up a good traffic flow and safety on the roads. Its main office is located in Reykjavík but there are four regional offices, which are responsible for the implementation and operation of transport systems in their regions (ICERA, 2005).

According to the Planning and Building Act No. 73/1997, local authorities are responsible for the street system within the municipalities (Alþingi, 2009). There are seventy-six municipalities in Iceland at the moment, but that number is constantly decreasing: it should be mentioned that in 1950 there were 229 municipalities (Samband íslenskra sveitarfélaga, 2010b). Small municipalities are constantly merging together and becoming stronger as they merge. In some cases, collaboration between these institutions (municipalities) leads to power struggle issues due to different political or economical expectations.

Reykjavík municipality is the biggest in terms of area and population. The city council governs the city of Reykjavík according to law number 45/1998 (Samband íslenskra sveitarfélaga, 2010a). Reykjavík municipality is responsible for the maintenance and operation of the city street system and Vegagerðin for the national state roads within the municipality area.

Reykjavík is surrounded by seven municipalities: Hafnarfjörður, Garðabær, Kópavogur, Mosfellsbær, Álftanes, Seltjarnarnes and Kjósarhreppur, which create the capital area. Good cooperation between municipalities and ICERA is necessary in many of the transportation projects, since they involve many different parties with different goals.

Figure 3-1 below represents road and street agencies in Iceland according to their administration levels.

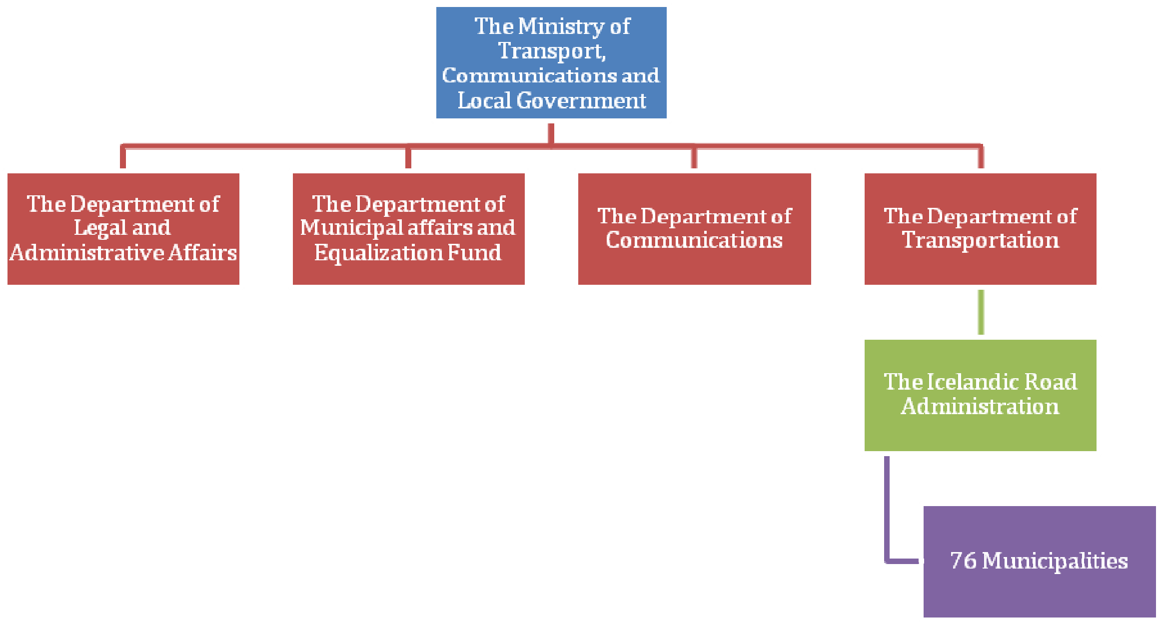

Figure 3-1: *Road and street agencies in Iceland*

3.2. Budget

In Iceland, as in many other countries, urban and local streets are financed through the local government, with money mostly collected from income taxes.

In addition to this, money comes from the government (ICERA) for the construction of state roads within urban communities. This money is collected from specially earmarked sources of income determined by the Icelandic Parliament through taxes on petrol and diesel etc. (ICERA, 2009b). Traffic on arterial streets in the capital area is growing faster than gross domestic product (GDP); therefore, it is understandable that very careful planning is needed in order to make prudent use of limited funds for transportation infrastructure. If not, then we can expect the quality of the street system to deteriorate over time, especially since ICERA´s total budget has decreased dramatically since 2008, by around 53%. The 2010 budget is similar to the budget for the year 2000. Around 37% of ICERA´s 2009 yearly budget was used for the maintenance of national roads.

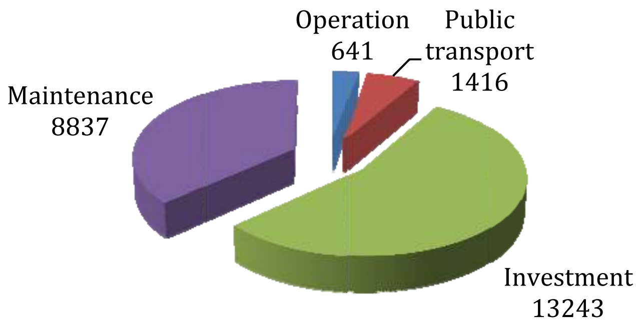

Figure 3-2: *ICERA 2009 yearly budget (Mkr per year) (Haraldsson, 2010)*

The biggest part of the road budget in Reykjavík is financed through collected taxes. Approximately half of the budget for the new road development is from the ICERA.

3.3. Road and street system

Organized road construction in Iceland began in the beginning of the 20th century. The extent of proper roads for motorized traffic have dramatically increased since World War II, at the same time as the number of vehicles in the country increased dramatically (see Figure 3-3), (Reynarsson, 1999). In 1950 there were 24 inhabitants per passenger car and there are now 1.7 per passenger car, expressing the fact that life is becoming more mobile. Almost all traffic congestion in the country is concentrated in or around the capital area, since the biggest part of the population lives there.

People are also becoming more and more dependent on automobiles in Iceland, even though there are other possibilities: public transportation, walking or cycling. High car ownership and the large amount of land used for roads and parking shows that dependence on private cars is high. As a result, planning decisions have provided more for automobile users and less consideration has been given to the support of other modes of transport.

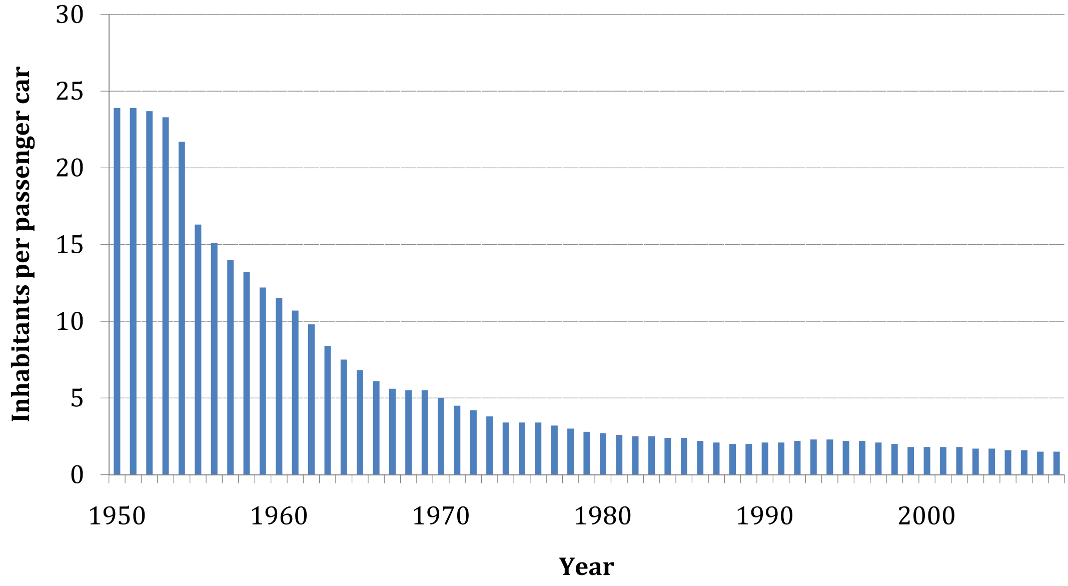

Figure 3-3: *Inhabitants per passenger car in the years 1950-2008 based on Statistics Iceland data (Statistics Iceland, 2009d)*

The following figures show the classification of Icelandic roads and the extension of each class. It should be noted that the distances are expressed in length of roads and not lane kilometres.

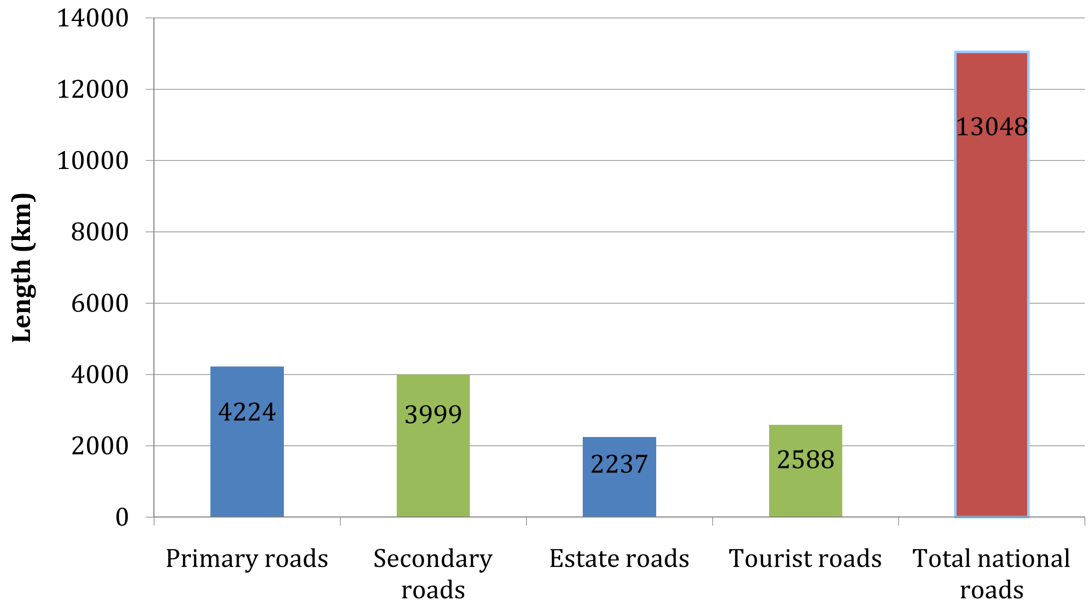

Figure 3-4: *Length of national roads by category in 2008 (Statistics Iceland, 2009b)*

The capital area is comprised of Reykjavík and seven other urban municipalities. The total population of the capital area is about 202.000 inhabitants, of whom about 120.000

reside in the City of Reykjavík. Reykjavík has around 460 km of streets (RVK, 2010). Streets in Iceland are divided into four categories: Major arterials, Minor arterials, Collectors and Local streets. The highest traffic, as expected, is on the major and minor arterials.

Almost all streets in Reykjavík area are paved with asphalt. The main highway around Iceland, Route 1, circles Iceland in 1334 kilometres (Haraldsson, 2010). Quite a large proportion of Iceland's national road system is made up of gravel roads, even some of the main highways. It should be mentioned that only 12 km of concrete roads fall under ICERA's responsibility.

3.4. Demographics

The collection of economic and demographic data is very important for transport planning needs. Demographic data, such as automobile ownership and population prognosis, can help identify further transportation needs. The increased number of vehicles increases traffic volume and total mobility, and is a reason for increased agencies' costs.

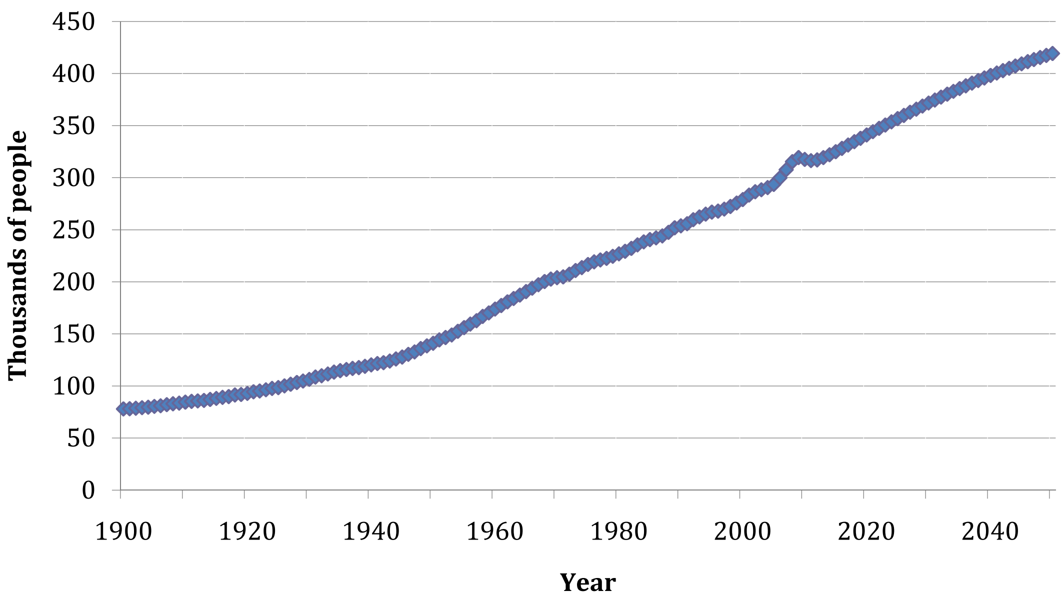

Figure 3-5: *Population history and projections in Iceland, year 1900-2050 (Statistics Iceland, 2009c)*

According to the National Registry, the population of Iceland had exceeded 300,000 by 1 January 2010 (Statistics Iceland, 2009c). There was actually a population decrease of 0.54% between 1 January 2008 and 1 January 2009 as compared to a 1.2% increase one year earlier or 2.5% two years earlier. The population increase could be explained by the high number of immigrants, even though natural increase is high in Iceland. The decline of the population could be explained by the high number of emigrants, both Icelanders and foreigners, who moved from Iceland due to the country's economical situation. The net migration is projected to be negative until 2012 (Statistics Iceland, 2009c), although it is clear that the relationship between net migration and the country's economic situation is very close.

Passenger car ownership is extremely high in Iceland, with about 667 cars per 1000 inhabitants (1.5 inhabitants per passenger car in 2008: see Figure 3-3), while the corresponding figure for the US is only 451 and in Norway and Sweden is around 460 (The world bank, 2010). Population projections show that by 2030-2040, Iceland's population could well exceed 400.000 people. This suggests that the number of vehicles will increase significantly, as well as the volume of traffic on the roads, which will lead to the need to build new roads or improve existing ones.

3.5. Safety issues

International road signs and regulations apply in the country. Some of the rural roads are gravel and are not suitable for fast driving. The general speed limit is 50 km/h in urban areas, 80 km/h on gravel roads and 90 km/h on the hard surfaces (Umferðarstofa, 2008). Iceland has one of the lowest traffic-death rates in the world per 100.000 people (see Figure 3-6). In the years 2003-2007 there were on average 7.4 traffic deaths in Iceland per 100.000 people (Statistics Iceland, 2009a), compared with 14.7 in the United States. Compared to other Scandinavian countries like Norway or Sweden, however, the death rate from traffic accidents in Iceland is higher. The situation in Iceland is very similar to Germany and Denmark, but its population and road net levels are not comparable to these countries.

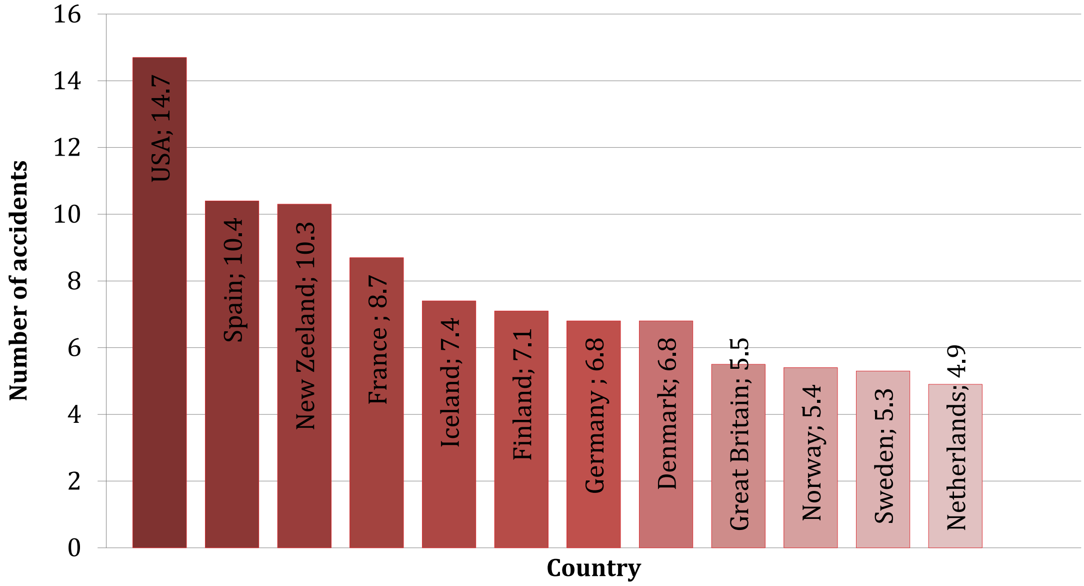

Figure 3-6: *Accidents involving death per 100,000 people for years 2003-2007 (Haraldsson, 2010), (Umferðarstofa, 2008)*

Maintenance and rehabilitation activities increase accident risk on the road, as normal traffic flow is disturbed. Even with good road markings and information signs, traffic accident risk increases compared with the usual traffic flow situation.

3.6. Types of pavement in Iceland

Road and street pavements in Iceland, as in other countries, consist of various layers, each with its own characteristics and thickness. As a rule, the strongest material is in the wearing course or surface layer, with weaker layers below. The layer under the surface is called the base and is usually mechanically stabilised, but can also be stabilised with asphalt or cement. Below the base, there is the subbase, usually untreated aggregate from a nearby gravel pit. Below that is the untreated subgrade.

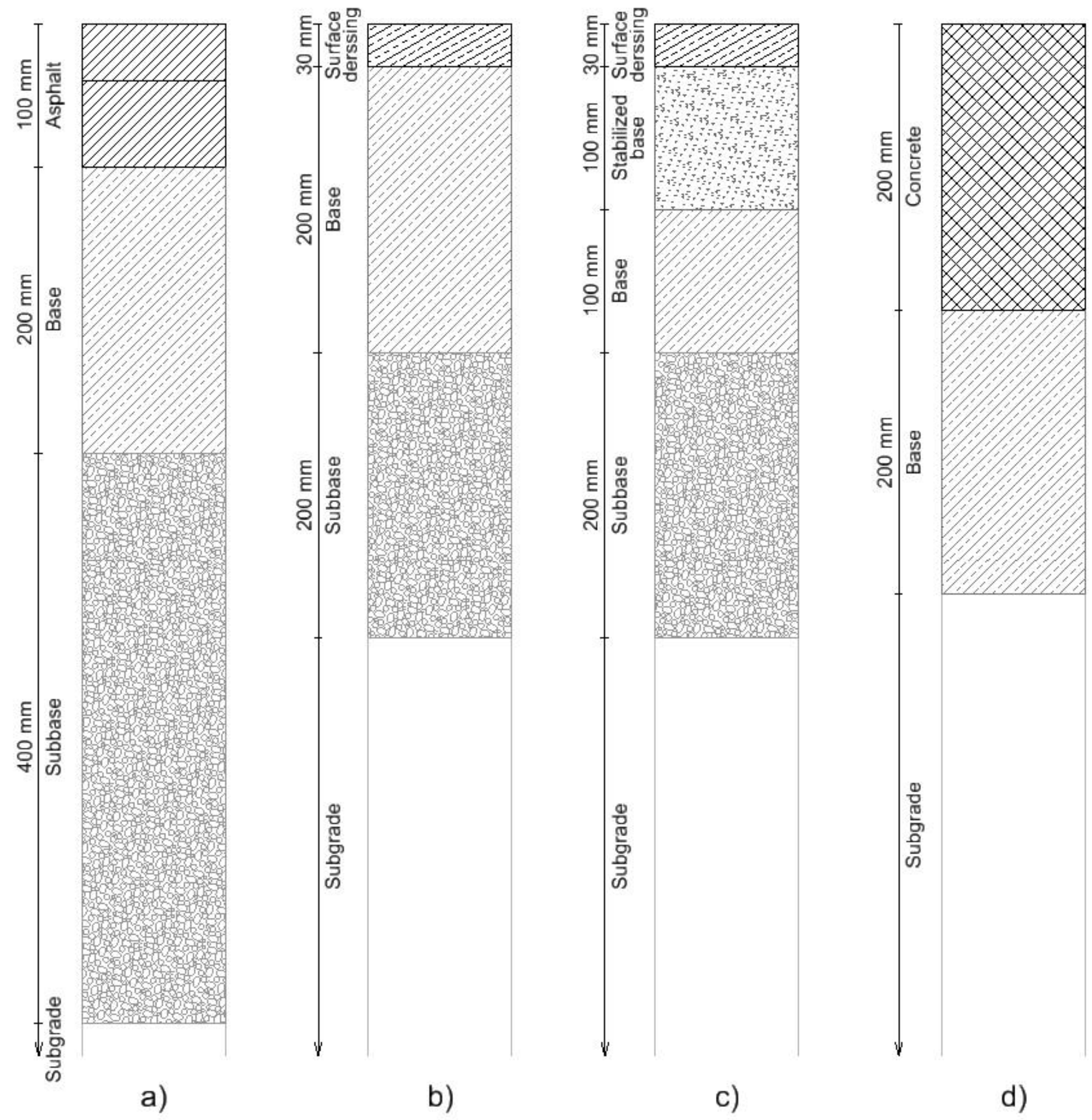

Figure 3-7: *Typical cross section of roads in Iceland (Þorsteinsson, 2006)*

Figure 3-7 shows typical cross sections of roads in Iceland. Type a) is asphalt pavement, which is the most popular type in urban and suburban areas. There are two types with surface dressing, one with granular base, type b), and the other with stabilized base, type c), and these cross sections are to be found outside the capital area. Concrete pavement, type d), is found on only a few kilometres in Iceland. Asphalt and concrete pavements will be compared later in this report using life cycle costs methodology.

Surface layers

There are four main types of surfacing on Icelandic roads and streets, as shown in Figure 3-7. In addition to these, there is surfacing on walkways and pedestrian areas with block pavement. That kind of surfacing is not covered here.

1. **Asphalt** or hot mix asphalt (HMA). The most common surface type in urban areas and on the most trafficked rural roads. It is used for new surfaces as well as overlaying old ones. Several types of HMA are produced in asphalt plants in Iceland for different categories of roads and traffic.

2. **Concrete**. For more than thirty years, the only concrete roads and streets built have been experimental. In the 1960s and early 1970s, a considerable proportion of paved rural roads had concrete surfacing. The Road Administration now has only about 12 km of concrete roads.

3. **Gravel**. This type of surfacing is typical for very low volume rural or highland roads. Many roads in this category, especially mountain roads, often lack structural stability and/or the proper geometry to be called anything more than dirt roads. Frequent load restrictions occur on gravel roads, especially during the spring thaw.

4. **Surface dressing**. One or two layers of surface dressing are used outside built-up areas if annual average daily traffic (AADT) is no more than 3000 vehicles per day. Geometry and structural capacity are sometimes insufficient; hence cross-sections are sometimes inadequate for heavy vehicles.

Base layers

Base courses are the structural elements of the pavement. They are built for drainage and stabilizing purposes as well as to distribute traffic wheel loads over the whole foundation. Base courses may or may not be stabilized. Stabilization is the process of preparing subbase soils to provide a higher load-bearing capacity, so they can better withstand heavy traffic stresses and reduce pavement thickness. Stabilization involves mixing the soils thoroughly with suitable binders, so that after proper compaction and curing, the soil will be more stable and provide for a stronger base as desired.

Base type and structure mainly depends on the surface layer type. The base quality for gravel roads or roads with surface dressing is generally inferior to those intended for asphalt and concrete, and will therefore not be discussed in this section. However, the materials used for base layers are often the same, just with different physical parameters. Materials' physical parameters usually depend on preparation method and particle size.

The role of the base is to distribute traffic loads to lower layers; therefore, this layer must be considerably strong and stable to prevent surface layer deformation. It is also very important for the base to have good hydraulic conductivity and be frost resistant, to prevent early pavement damage.

The base layer is usually divided into upper and lower layers. As a rule of thumb, stronger material is always used in the upper base layer. Upper layers can sometimes be stabilized. Both layers should meet the requirements for stability, strength and carrying capacity according to the road type. Materials used in base construction can be broadly divided into two categories: gravel and crushed rock.

Most common base types:

1. **Gravel base** course**.** This is the most common type of base layer type in Iceland. Granular size depends on traffic intensity and material used in wearing course.
2. **Crushed rock base** layer – this is usually 0-100 mm fraction crushed lava. It is currently becoming more popular in Iceland, mostly for environmental reasons, since it is now more difficult to find good quality gravels that meet the required parameters. Sweden and Norway have had good experience in using this type of material (Jóhannesson, Bjarnason, Jónsdóttir, & Árnason, 2010).
3. **Asphalt stabilized base** layer, also called black base – this is an asphalt stabilizer, and is used for waterproofing and cohesion. Soil particles are coated with asphalt, which prevents or slows down the penetration of water, which could otherwise result in decreased soil strength.
4. **Cement stabilized base** layer. Portland cement can be used either to modify and improve the quality of the soil or to transform the soil into a cemented mass with increased strength and durability.

It should be mentioned that recycled asphalt might also be used in base construction but this practice is not very common in Iceland, perhaps for economic reasons.

3.7. Causes of pavement deterioration

Pavement deterioration over time on roads is mainly due to increased traffic volume and loads, studded tyres and freeze-and-thaw cycles during winter. Others factors and distress types are represented in Table 3-1. The table is based on data in a report from Reykjavík city and ICERA in 2003 (Valgeirsson, Hjartarson, Guðfinnsson, & Jóhannesson, 2003).

An ocean climate is dominant in Reykjavík; the mean annual temperature in Reykjavík is about 5˚C. Winters are mild, and the average temperature in January is just below freezing. However, on the other hand there are a relatively high number of frost and thaw cycles during the winter, as shown in Figure 3-8. The results of frequent freeze-thaw cycles are shorter pavement life and decreased pavement quality, ruts and cracks after winter.

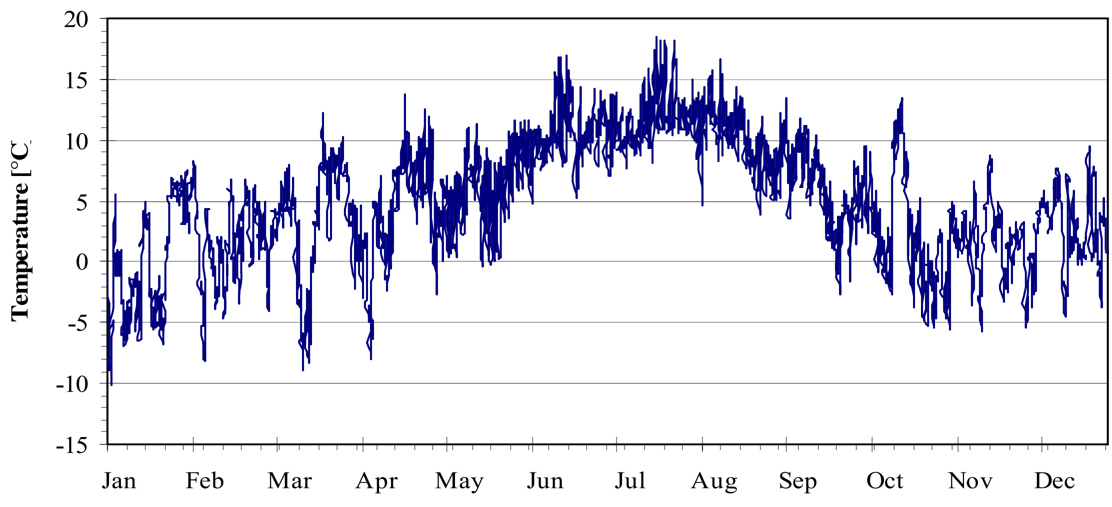

Figure 3-8: *Temperature variations in Reykjavík in 2003, 2 m above ground*

Ruts made by studded tyres or heavy axle traffic are one of the main reasons for the distress and deterioration of city streets. Studded tyres and the steel they contain damage pavements by slowly grinding the pavement surface and forming ruts in the pavement. In Iceland this type of tyre is allowed to be used from 1st November until 15th of April, but information from the tyre industry shows that many drivers are using them in May, even though research on studded tyres consistently shows that vehicles equipped with these tyres require a longer stopping distance on wet or dry pavement than do vehicles equipped with standard tires (WSDOT, 2008). Much of the research on studded tyres comes from Norway, Finland and Sweden, where studded tyres use is widespread in the winter months. These studies all agree on one finding: that pavement wear and rutting due to studded tyre use is huge and very costly. Other reasons for pavement ruts might be poor pavement or base conditions. The accepted rut depth is usually 2- 3.5 cm, depending on the traffic speed.

Pavement is deformed by constantly changing traffic loads. Due to different forms of force at the top and bottom of the pavement, pavements might crack. Increased traffic and existing pavement deterioration might lead to cracks and holes.

Other deterioration types and reasons are presented in the table below.

Table 3-1: *Main reason and distress types of asphalt deterioration in Iceland (Valgeirsson, Hjartarson, Guðfinnsson, & Jóhannesson, 2003)*

	Potholes	Cracks	Ruts	Uneven	Open seams	Peeling	Asphalt separation	Loss of stone	Bleeding
Inadequate tack coat						x			
Heavy traffic		x	x						
Studded tyres		x	x						
Inadequate underlay	x	x	x	x					
Too narrow roads		x							
Insufficient side support		x							
Drainage problems	x	x							
Frost heave		x		x					
Inadequate design	x	x							
Roads over age		x							
Work hasn't been done properly					x				
Big rocks in base				x					
Wrong treatment of material							x		
Incorrect mixture of material	x						x		x
Rain								x	x
Snow machine								x	
Winter season									x (reason un known)
Insufficient binding materials	x							x	
Uneven distribution of the binding material	x							x	

3.8. Rehabilitation procedures

Asphalt

The most popular rehabilitation procedures are listed below:

Resurfacing: this type of rehabilitation includes removing the existing asphalt surface and replacing it with new asphalt material or adding a new overlay.

New asphalt overlays can be placed on existing surfaces. Overlays are used for two purposes:

1. Overlays that are designed to increase strength of the existing pavement. They are placed on top of existing pavement without removing the existing surface layer.
2. Overlays that are designed to replace the existing pavement wearing course. They do not add extra strength to the structure.

Repaving: This is a very good solution for city streets, as it is a relatively quick method of asphalt rehabilitation. The principle of this method is that a machine heats up the existing pavement surface, and in this way the pavement is levelled and a new layer is placed on top - usually a 2 cm layer of new material. This has been a relatively popular rehabilitation method in Iceland in recent years.

Milling and overlay: the old pavement is removed and new pavement overlay is placed in the same place instead of the old one: for example, 4 cm of old damaged pavement are milled out and 4 cm of the new pavement is put in the same place, so that the road elevation is not changed.

Levelling: filling up traffic ruts to improve pavement strength is a common solution, and involves putting a new asphalt overlay on the fixed road. Ruts are mostly filled with asphalt and sometime on rural roads with Ralumac. Sometimes in rural areas surface dressing might be used for that purpose, but it is strongly recommended not to do that (Valgeirsson, Hjartarson, Guðfinnsson, & Jóhannesson, 2003).

In other countries, concrete overlays tend to be used, due to dramatic traffic increases. In that case, the old asphalt layer acts as a base for new concrete pavement, but this approach is almost unknown in Iceland.

Concrete

Because there is limited experience with concrete pavement rehabilitation in Iceland, this section describes the most traditional rehabilitation possibilities in other countries. Naturally, concrete pavement rehabilitation options depend on local conditions and pavement deterioration but usually include:

Grinding: Different cutter settings allow a grinding machine to remove the concrete top layer. The thickness of the layer removed is usually 2-3.5 cm. The major advantage of this approach is that it is not necessary to close down the entire road during the grinding process (ACPA, 2006). The cost depends on many factors, including aggregate and PCC mix properties, average thickness of the layer removed, and smoothness requirements. The State Department of Transportation (DOT) has found that the cost of diamond grinding is generally lower than the cost of asphalt overlay (Correa & Wong, 2001).

Concrete overlays: A non-reinforced concrete overlay typical design thickness is 5-12.5 cm; it is placed on top of the existing pavement (Iowa State University, 2008). In some cases, this requires a lot of preparation, possibly even full depth repair. This usually includes patching, grinding and cleaning. Many factors have to be taken into account, such as weather conditions and the difference in temperature between old and new concrete layers, for the structure to act as whole (ACPA, 2007). Overlay´s joint type, location and width must match those of the existing concrete pavement, in order to create a monolithic structure (Iowa State University, 2008).

It is also possible to replace the damaged layer with reinforced concrete overlays, but in that case, a thin asphalt layer is required for layer separation and good preparation is essential (ACPA, 2007).

Asphalt overlays: This approach is called rehabilitation because it increases the capacity of the existing pavement. It is especially useful if there is a need to improve concrete pavement skid resistance. It requires surface preparation, usually milling and patching, and it is also very important to ensure that the concrete pavements is stable, because it might lead to new damage to the asphalt layer (National CP Tech Center, 2006a). After asphalt overlay, pavement is no longer called concrete pavement, and rehabilitation and maintenance types that are suitable for asphalt pavements should be used.

3.9. Pavement management system – RoSy

RoSy is a pavement management system supplied by the engineering firm Carl Bro of Denmark. It has been used in Iceland for several years for the maintenance of the road network, both in Reykjavík and on ICERA roads throughout the country.

The RoSy system ensures systematic road maintenance. It is possible to register all kinds of data such as signs, roadside area elements, road markings and many other kinds of data. More data can improve maintenance strategy. Roads are measured systematically and their condition registered (Grontmij Carl Bro, 2010). At the same time, the municipality decides on the desired condition for the roads, and the RoSy system then calculates where municipalities should focus their maintenance efforts.

Road classes, pavement structure classes, distress types and limits, deterioration models, traffic classes, traffic growth, equivalent standard axles, vehicle operating cost data, IRI progression models, repair products and pavement products are used in this software. Combining RoSy outputs with visual road checking provides a basis for all decisions on the maintenance of streets and roads.

The original idea to use the RoSy management system for the entire Reykjavík capital area was good, but this was never implemented. That would mean closer collaboration between municipalities, which is sometimes difficult due to different values and expectations.

Currently, RoSy does not work very well for the streets of Reykjavík. Specialist are working on the program and trying to define the best parameters for the local environment with the expectation that it will operate effectively within a few years.

RoSy might become a useful and important form of data storage. At that point, it will contain huge input (information on rehabilitation type and frequency) into LCCA models.

Information obtained in this and the previous chapter will be used for model building, which is described in the following chapter.

4. METHODS

It is clear that if the agencies that are responsible for planning, constructing, and operating the street network could use LCCA as decision supporting tool in the pavement design process, then more economical and informed decisions would be achieved.

In this project, it was decided to build a model based on LCCA methodology and test it by comparing asphalt and concrete pavements. The model will be tested using six traffic groups: 2.500, 5.000, 7.500, 10.000, 12.500, and 15.000 veh/day/lane. For each traffic group, two pavement behaviour scenarios will be built: one for asphalt pavement and one for concrete pavement. The LCCA applied here includes all costs that are involved in the manufacture and use of the product during its lifetime; it was decided to compare alternatives by using the Net Present Worth method. A more detailed description of LCCA can be found in chapter 2.

The components of LCCA were divided into two categories, agencies' costs and user costs. Agencies' costs include initial construction, rehabilitation and maintenance costs. Others costs, such as engineering design and land acquisition, were not considered. User costs such as vehicles operating costs, accident costs, discomfort costs etc. were considered equal for both pavement types. The only user cost to be considered will be travel time delay costs, because other user costs are difficult to collect and quantify at this stage of the project.

Analysis period

Experience in the US and in Iceland shows that the life of concrete pavement is often more than 20 years, while the life of asphalt pavement in Iceland is around 10 years, depending, of course, on traffic intensity (Valgeirsson, Hjartarson, Guðfinnsson, & Jóhannesson, 2003). The Federal Highway Administration (FHWA) recommends an analysis period of at least 35 years (Walls & Smith, 1998). An analysis period of 40 years was chosen for this project so that it could include at least one rehabilitation for concrete pavement, depending on the traffic level.

Discount rate

Discount rate is used to discount the future benefits and costs of projects. The higher the discount rate, the lower the net present worth of future costs will be. Thus, higher rates render initially expensive projects less profitable, while lower rates render them more so. Given the variation in the rate of discount from 4% to 8%, many projects move from being unprofitable to profitable as indicated by the present worth (NPRA, 2005b). A discount rate of 6% as a base case will be used in this study, but a sensitivity analysis will be applied for the base case by using 2, 4, 5 and 8% discount rates as well.

Traffic

The Net Present Worth is calculated for initial values of traffic volume of 2.500, 5.000, 7.500, 10.000, 12.500 and 15.000 vehicles per lane per day. An increase of one per cent on the initial AADT will be added for the 40-year analysis period for initial traffic up to and including 10.000 veh/day. For 12.500 and 15.000, a maximum of 15.000 is assumed for the number of vehicles that use one lane in one average day and when traffic has reached that volume it is assumed to remain constant after that. Figure 4-1 describes the increase in traffic for an initial volume of 10.000 vehicles a day or less.

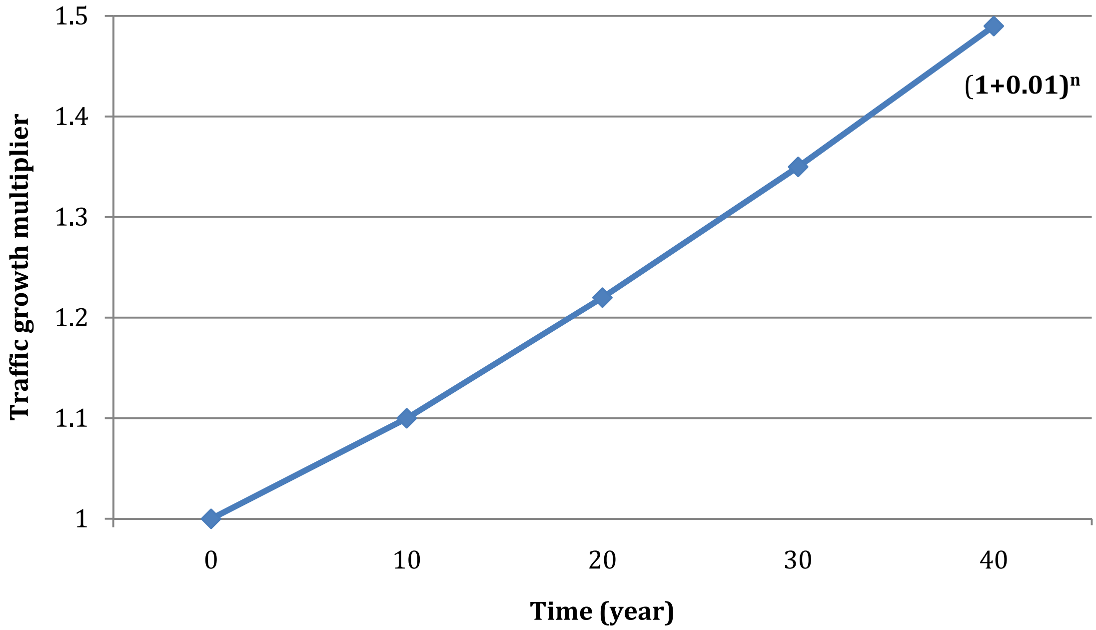

Figure 4-1: *Traffic growth over an analysis period of 40 years*

Design speed is 70 km/h; allowed rut depth is 3.5 cm. Such a rut depth on high speed roads would not be accepted, due to safety reason. For this model, it was assumed that this rut depth would not cause danger, since traffic speed is moderate.

Agencies' costs

Agencies' cost data were obtained from historical projects and interviews with specialist in each field. Unit prices of material and work are presented in appendix B. Because there is negligible experience with concrete pavements in Iceland in recent years, an uncertainty advance of 8% will be added to costs involving concrete pavements, whereas an advance of 5% is included in unit prices for asphalt pavements.

Rehabilitation

Like all structures, roads deteriorate over time. Heavy vehicles and intensive traffic are the main reasons for pavement deterioration, as well as environmental factors, as mentioned in chapter 3. Tables 4-1 and 4-2 represent resurfacing frequency based on the recommendation in the *"Viðhaldsaðferðir"* report (Valgeirsson, Hjartarson, Guðfinnsson, & Jóhannesson, 2003). Tables were recently updated by one of the authors, due to some changes in input parameters: decreased use of studded tires, less initial rut depth, according to the latest measurements results. Updated tables from the report are presented in the appendices G and H; rehabilitation frequency depends on the traffic density, traffic speed and allowed rut depth. In this project, a rut depth of 3.5 cm was used, with an initial speed of 70km/h. Maintenance frequency is adjusted to the design speed. Pavement durability decreases with increased speed.

Table 4-1: *Asphalt rehabilitation frequency, when design speed is 70km/h*

Initial AADT (veh/day/lane)	**Rehabilitation in year**
2.500	15, 30
5.000	15, 29,
7.500	11, 21, 30, 38
10.000	8, 15, 22, 28, 34
12.500	6, 12, 18, 23, 28, 33, 38
15.000	5, 10, 15, 20, 25, 30, 35

Table 4-2: *Concrete rehabilitation frequency, when design speed is 70km/h*

Initial AADT (veh/day/lane)	**Rehabilitation in year**
2.500	39
5.000	26
7.500	17, 31
10.000	13, 25, 35
12.500	11, 21, 30, 39
15.000	9, 18, 27, 36

The following rehabilitation measures were selected for use in the model.

Asphalt :

- Repave
  - Repave with 2 cm of asphalt
  - No more than twice in a row: after that, the road must be resurfaced.
- Resurface milling and overlay

- Includes milling and overlay, 4.5 cm of existing pavement is removed and replaced with a new layer.

Concrete :

Diamond grinding and concrete overlay was considered as options. Asphalt overlay could also be an option, but after asphalt overlay, the road is treated as an asphalt road. Because of that, it was decided that during the analysis period (40 years), the test case should be treated as a concrete road, but asphalt overlay could be an option later.

- Diamond grinding:
  - Remove 3.5 cm of the pavement: this way, ruts in the pavement will be removed. No more than two diamond grindings in a row.
- Concrete overlay:
  - Concrete overlay instead of the third grinding, 7 cm thickness.

User delay costs

Road works slow down traffic and increase vehicle travel time, and as a result, increase costs for road users.

Table 4-3 is based on the results from the aforementioned report on profitability of investments in road building *"Arðsemi og ávinningur af vega- og gatnaframkvæmdum"* by S. Einarsson and H. Sigþórsson (Einarsson & Sigþórsson, 2009). However, some assumptions were made: a calculation for single unit and combination unit trucks was not given in the report, due to difficulty in dividing the cost between personal cars and heavy vehicles. In this case, it was decided to use time cost during working hours for single unit and combination trucks, multiplied by the average number of people in the car:

$$C_{wh} * N = 1695 * 1.3 = 2204\ kr. \quad (2)$$

Where C_{wh} = cost during working hours; N = average number of passengers;

The calculations will use 50% single unit trucks and 50% combination trucks of the total truck number, even though, in this case, there is no difference in cost between single unit and combination trucks.

Table 4-3: *The value of travel time in kronur per hour*

Passenger cars	Trucks Single- unit and combination
1695 Kr/hour	2204 Kr/hour

Equation 3 calculates the average user delay cost due to maintenance work per one-vehicle trip. The equation calculates the extra time that one vehicle spends driving through the construction and work zone, multiplied by the vehicle's average money value, so the cost of vehicle delays can be quantified.

$$-\left(C_{pc} * \left(\left(\frac{L_{cz}}{V_0} - \frac{L_{cz}}{V_{cz}}\right) + \left(\frac{L_{wz}}{V_0} - \frac{L_{wz}}{V_{wz}}\right)\right) * \left(\frac{\%_{pc}}{100}\right)\right) + \left(C_t * \left(\left(\frac{L_{cz}}{V_0} - \frac{L_{cz}}{V_{cz}}\right) + \left(\frac{L_{wz}}{V_0} - \frac{L_{wz}}{V_{wz}}\right)\right) * \left(\frac{\%_t}{100}\right)\right) \quad (3)$$

Where L_{cz} = construction zone length; L_{wz} = work zone length; V_0 = initial speed; V_{cz} = construction zone speed; V_{wz} = work zone speed; C_{pc} = time value for passenger car; C_t = time value for combination truck; $\%_{pc}$ = percentage of passenger vehicles; $\%_t$ = percentage of trucks.

Materials:

Asphalt

Asphalt types that are available from the Höfði asphalt plant and their recommended usage is shown in Table 4-4.

Table 4-4: *Recommended asphalt type and thickness from Höfði*

Type of asphalt	AADT (veh/day/lane)	Thickness (cm)
Y 8	Less than 2.000	Less than 3,5
SMA 8	Less than 5.000	Less than 3,5
Y 11	Less than 12.000	More than 4
SMA 11	Less than 12.000	More than 4
Y 16	More than 12.000	More than 4,5
SMA 16	More than 12.000	More than 4,5

To simplify calculations, it was decided to use SMA 16 asphalt for all traffic groups.

Asphalt thickness was calculated using the Norwegian road standard (NPRA, 2005a). Detailed calculation can be found in appendix A.

Table 4-5: *Asphalt design thickness*

AADT	$H_{Asphalt}$
2.500	4+ 4.5 cm
5.000	4+ 4.5 cm
7.500	4+ 4.5 cm
10.000	4+ 4.5 cm
12.500	4+ 4.5 cm
15.000	4+ 4.5 cm

Concrete

There is not much recent experience of concrete roads in Iceland. Therefore, most recommendations are taken from foreign countries such as the USA and Norway, but discussions with local specialists were also held; consequently, it was decided to use C35 concrete for all traffic groups.

Unit costs for concrete material and placement were taken from foreign countries such as Sweden and Germany, and were adjusted to the Icelandic situation.

Adjustment method:

- Compare cost for asphalt material in Sweden, Germany and Iceland.
- The foreign concrete price is adjusted by a factor determined as Icelandic asphalt price divided by foreign asphalt price.

It should be mentioned that the unadjusted price for concrete and related work with that material is not represented in this report for reasons of competition within the industries.

Pavement thickness of 27 cm will be used for the calculations for the first (2.500 veh/day/lane) and 28 cm for the second traffic group (5.000 veh/day/lane), with one milling planned. For the third and fourth traffic groups (7.500 and 10.000 veh/day/lane), 32 cm of C35 concrete will be used, with two millings planned. For the fifth and sixth traffic groups (12.500 and 15.000 veh/day/lane), a 32 cm thickness of C35 concrete will be used, with two millings planned. It is assumed that joints in the concrete will not be damaged, and that it will not require any rehabilitation (see Table 4-6).

Dowel bars are used for load transfer across joints, as they prevent pavement damage. The US National Concrete Pavement Technology Centre recommends using dowel bars when pavement is 20 cm or thicker (ACPA, 2010). It should be noted, that poor dowel bar installation might result in future joint deterioration (National CP Tech Center, 2006b).

Typical rounded dowel bars will be used in the model, ɵ 38mm, L=450 mm, spacing 300 mm centre to centre (WSDOT, 2010).

Tie bars are used mainly for parallel slab connection.

In the model, tie bars of ɵ 12.5,L=800 mm, spacing 900 mm centre to centre will be used (WSDOT, 2010).

Tie bars will be included in the model even if it is built for only one-lane cost calculations. It is assumed that is very unlikely that only one concrete lane will be built. Therefore, the cost for tie bars and their placement will always be halved to attain the cost per lane.

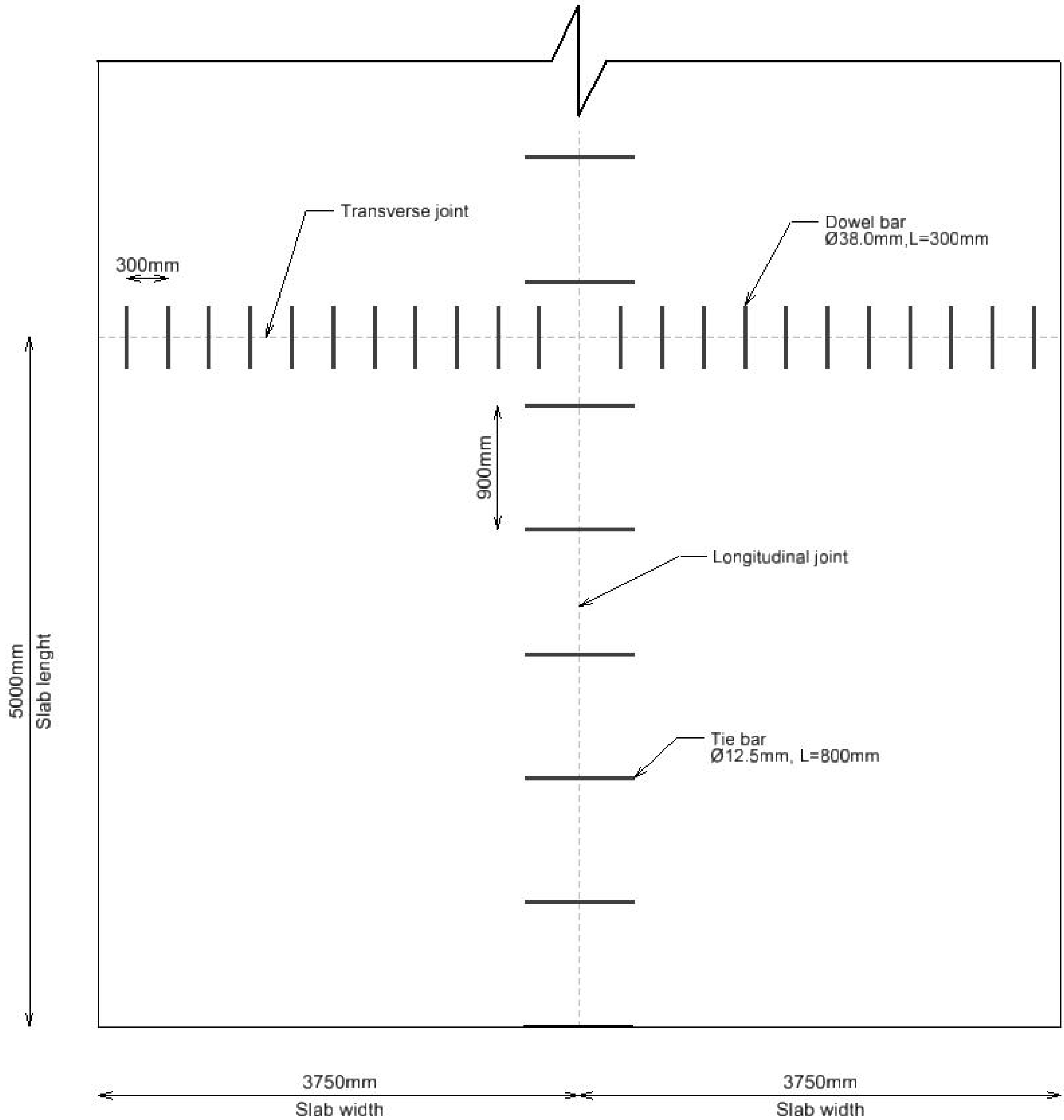

Figure 4-2: *Concrete pavement, dowel and tie bar arrangement*

Table 4-6: Design concrete thickness

AADT	$H_{Concrete}$
2.500	27 cm
5.000	28 cm
7.500	32 cm
10.000	32 cm
12.500	33 cm
15.000	33 cm

Calculation for pavement thickness selection can be found in appendix A.

Road construction

A base layer is a very important part of the bearing system, especially for asphalt pavement. Therefore, the following base thicknesses will be included for the asphalt pavement.

In Iceland, it is popular to use a crushed rock base layer, but according to the Norwegian road standard, unstabilized crushed rock is not sufficient (NPRA, 2005a). Thus, in this case, it was decided to use an Ag base layer, which is a cheap kind of asphalt concrete that might come from recycled material.

Table 4-7: Base design thickness for asphalt pavement

AADT	H base
2.500	13 cm
5.000	13 cm
7.500	14 cm
10.000	14 cm
12.500	14 cm
15.000	14 cm

Detailed calculations can be found in appendix A.

However, base thickness for concrete pavement is not as important as for asphalt pavement. Examples from the US show that very often, a base layer is not even used in road construction for low-traffic roads, so in this case, it was decided to use 5 cm of Ag.

Subbase thickness was not included in this model, since it was assumed that there would be very little difference in the thickness of these layers for asphalt and concrete; therefore, subbase thickness hardly affects comparison.

Sensitivity analysis

For sensitivity analysis, the impact of discount rate, asphalt and concrete unit prices, user delay costs and total cost changes on the results is examined. The rate of return is set to 2%, 4%, 5% and 8%, while asphalt and concrete price variations are adjusted such that the unit price is 20% and 10% less expensive and 20% and 10% more expensive. Sensitivity analysis is represented in appendix F.

5. RESULTS AND DISCUSSION

One of the foundations of asset management is that it involves a life cycle (FHWA, 2010). Decisions on investments should be considered in terms of product performance over time.

The effect of increased traffic volume on pavements, both on rural roads and urban arterials, requires further studies. The building and modernization of roads results from traffic development. This requires further studies on the selection of road pavements. Agencies seek to make more informed and comprehensive investment decisions, because pavement type selection will have a big impact on future costs and the level of service for the users. Pavement type decisions are usually based on traffic level, soil conditions, atmospheric factors and construction costs. In many cases, the initial construction cost is the main consideration; the future maintenance and rehabilitation costs may be forgotten. Not only do we need to assess the life cycle of a project: we also have to calculate the associated costs involved in order to make a LCCA of transportation infrastructure such as pavements. In the longer term, governmental agencies could save money by looking at pavement life in the long run.

Costs factors are different for each country, and for Iceland it is not easy to get an accurate estimate for all cost factors, especially for concrete pavement, due to the lack of experience with this material in the road industry. There are also uncertainties involved in estimating future costs of materials and work. It should be mentioned that material price is a very sensitive matter, which typically depends on the size of the project and its location. In this project, it was extremely difficult to predict, because project size is unknown. It was mentioned that, for example, concrete price could go down by almost 40% for very big projects. To be on the safe side, it was decided to use up-to-date material prices, as represented in manufacturers' price lists.

Having established a working LCCA model for pavements in Iceland, one hypothetical road section was tested. As was to be expected, asphalt pavement is more suitable for lower volumes of traffic, and with increased traffic, concrete pavements are more competitive. For roads with a high percentage of heavy vehicles, rigid pavement is also competitive. Test results show that when traffic is around 14.000 veh/day, asphalt and concrete are competitive, see Figure 5-1.

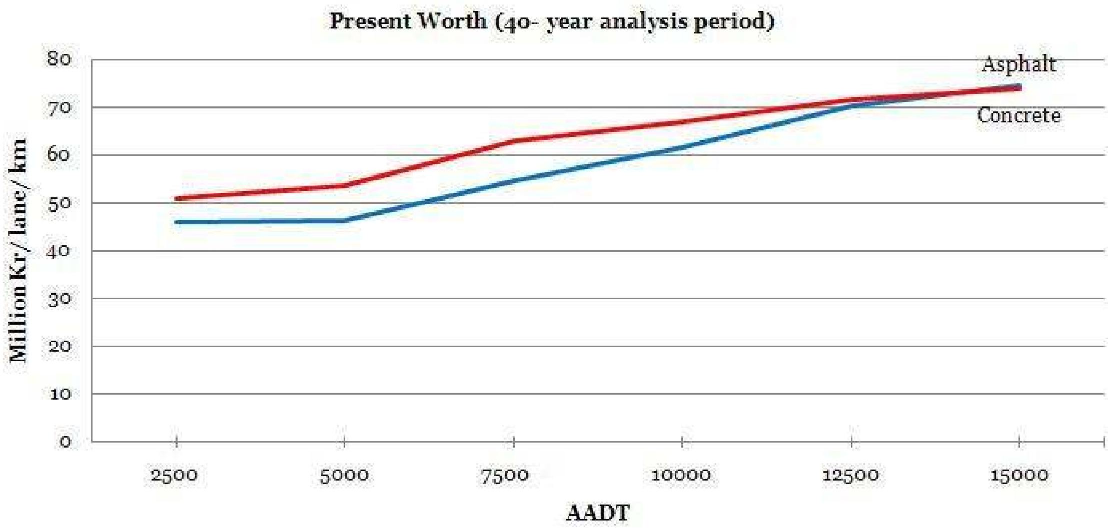

Figure 5-1: *Present worth for base case scenario (40-year analysis period)*

From the results of this study, the following can be concluded:

- Test results show that when traffic is around 14.000 veh/day/lane, then asphalt and concrete are competitive as pavement types. On roads where traffic is less than 14.000 veh/day/lane, it is still more economical to use asphalt.
- More than 40 lane/km of roads in the capital area could be suitable for concrete pavement (LUKR, 2006).
- Environmental factors might favour concrete or asphalt, although this is more likely for concrete, due to the production of dust by studded tyres.

Far from being definitive and final, this study shows, as was to be expected, that concrete pavements do have the potential to be useful on heavily trafficked Icelandic streets. However, it is very surprising how little the difference actually is between asphalt and concrete pavements if we take into account the cost over the whole design period. This could be explained by the great uncertainty involved in the calculations. For example if the decision would be based solely on the construction cost, concrete would have very little potential due to the fact that concrete construction cost is about 40% more expensive on roads with more than 10.000 veh/day/lane.

During the design period the average asphalt construction cost is 50-60 and 80% for the concrete, of total cost. Considerable part of asphalt cost is discounted through a quite high discount rate, which in this case favours asphalt pavements.

Rehabilitations that are scheduled at the end of the analysis period, have very little influence, this could explain low NPW in some cases. For example for asphalt pavements, rehabilitation on roads with traffic greater than 12.000 vet/day/lane are scheduled very often, less than 6 years apart, but these rehabilitations have very little impact at the end of the analysis period. Same with the concrete pavements on roads with low traffic, some rehabilitation activities are scheduled late, therefore have very little impact on total project cost.

However, there are a lot of uncertainties involved, especially concerning concrete pavement, due to lack of experience with this type of pavement in the country. It is very difficult to predict pavement behaviour scenario, rehabilitations types and, of course, costs. Therefore, higher uncertainty costs are used for concrete pavement in the calculations. Furthermore, fluctuations in prices for bituminous pavements are very likely too. Additionally, as mentioned before, size of the project is unknown, and prices, as rule of thumb, always depend on the project size.

A further study is obviously needed to take additional factors into account in the economic model. In addition, a further inspection of the proposed maintenance and rehabilitation scheme is needed.

Results could be different if a different discount rate was used or if unit prices were to fluctuate. Using lower rate of return could favour more expensive projects, which could move from being unprofitable to becoming profitable. Changes in the unit price or oil price would have the same effect. Therefore, sensitivity analysis was applied in this study.

Sensitivity analysis shows that the results are most sensitive to discount rate changes. When a 2% discount rate was used, the results showed that concrete becomes more economical than asphalt when AADT is 7.000, but increasing the discount rate makes concrete pavement less economical. When the discount rate is 8%, concrete is not competitive at all. Is clear that it is more efficient to use concrete for roads with traffic higher than 11.000 veh/day/lane when a rate of 4% is used.

Material price fluctuation has a very similar effect on the net present worth: if asphalt became 10 or 20% cheaper, or concrete became 10% or 20% more expensive, that would make concrete absolutely uncompetitive.

The results are least sensitive to changes in user delays costs. Changes in asphalt rehabilitation costs have a greater effect on the final results than changes in concrete rehabilitation costs. This could be explained by more frequent asphalt rehabilitation timing.

If no uncertainty cost is used, then there is very little difference in cost for traffic between 10.000 and 12.500 veh/day/lane, but for AADT higher than 12.500, it is clearly more economical to use concrete. If asphalt pavements cost 10% more than concrete, then there is very little difference for traffic lower than 10.000veh/day/lane. However, if the total cost of concrete pavement is 10% more, then asphalt is always more efficient to use.

Table 5-1: *Sensitivity to main variables*

	Low impacts	Medium impact	High impact
Discount rate			x
Asphalt price			x
Concrete price			x
Asphalt rehabilitation costs		x	
Concrete rehabilitation costs	x		
User delay costs	x		
Asphalt uncertainty costs		x	
Concrete uncertainty costs		x	

The current situation in Iceland regarding traffic and roads is described in this report, as well as the state of traffic safety in the country. As might be expected, there is a lot to be done in upgrading the rural roads. In comparison to other developed countries, the Icelandic rural road system is rather primitive, whereas the street system in the capital area is in a relatively good state. However, according to test results, concrete is not an option, since rural roads have much lower traffic. However, this case could be disputed, because too many uncertainties are involved. Furthermore, the project's location would have a significant impact on the maintenance and rehabilitation costs. Therefore, the possibility of paving rural roads with concrete should be analysed independently. The situation regarding traffic safety is relatively good, but could be improved. This is a complex issue, but better roads mean fewer crashes. By using international data, an estimate can be made on crash costs with different pavement conditions.

Other factors could also be considered, such as environmental effects and societal impacts. Sustainable pavements require consideration of environmental, economical and social indicators and this could be associated with the idea of life cycle analysis. Sustainable solutions often require major investments: hence, one has to make use of life cycle analysis. Thus, sustainability and life cycle analysis go hand in hand (Hass, Tighe, & Falls, 2005). A number of other factors that might be influential in making pavement decisions are listed below:

- Environmental issues:
    - Asphalt is produced from petroleum, which is a non-renewable natural resource.
    - On the other hand, asphalt is recyclable, but as mentioned above, recycled materials are very seldom used in road construction in Iceland.
    - Dust particles from studded tyres are produced from asphalt and concrete surfacing, and the effect of this on human health should be considered.
- Safety issues:
    - There is better skid resistance on asphalt roads. This means that concrete roads are more slippery than asphalt, and this is a very important issue given the Icelandic weather conditions
    - Concrete is lighter in colour, which means better visibility and less lightening costs.
- Other issues:
    - Concrete road construction and rehabilitation takes longer time and is more weather dependent.

Project uncertainties

Most uncertainties are due to discount rate and risk, with assumptions being made for 40 years in advance. This is a very long time period, so it is quite a complicated process; therefore, every input into the model must be well thought out. Other project uncertainties are listed below:

- The economic situation might change, which would affect discount rate and unit prices.
- Oil prices, which affect most goods prices and go hand in hand with asphalt prices, might fluctuate.
- Improved materials might be developed
- Improved maintenance and rehabilitation techniques might be developed
- Changes in societal needs and driving culture could occur: for example, perhaps public transport or cycling will become more popular and people will become less dependent on their cars.

Further studies

The model requires further investigation, and could be improved by studying additional input parameters:

- Subbase thickness was not included in the model, since it was assumed that there would not be any difference in the thickness of these layers for asphalt and concrete. However, base and subbase thickness could require more detailed studies.
- Effect of studded tires on concrete strength and durability. The Norwegian road standard was used for concrete thickness design; however, the usage of studded tires in Iceland is higher than in other Scandinavian countries: therefore, further research on this subject would be beneficial.
- User costs such as vehicle operating costs, accident costs, discomfort costs etc. were considered equal for both material types, mostly due to lack of information on these parameters, which require further studies.

- Since discount rate has such a big impact on material choice, it is necessary to have more information on this factor in road projects and the construction industry.
- More pavement behaviour scenarios might be introduced into the model.

It should be emphasised that life cycle cost analysis is only a tool to assist those who make decisions concerning the selection of pavement types and not the decision itself. Moreover, this tool is not going to give an absolute answer as to which pavement to choose: rather, it helps to provide an overview of total cost during the life cycle and to give an idea of the traffic level at which concrete pavement could be considered as an option. There might be other grounds for selection than pure economic ones. Agencies might be interested in maintaining competition on the pavement market in order to avoid monopoly of one type of pavement. In addition, environmental or other considerations, such as those that have been discussed above, might outweigh economic factors.

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APPENDIX A CALCULATIONS

Paving area

Road length 1000 m; Lane width 3.75 m

Paving area= 1000 m × 3.75 m= 3750 m^2

Asphalt pavement layers thickness

For layer thickness decision, the Norwegian road standard was used (NPRA, 2005a). The procedure requires the following steps:

1. Calculate traffic loads during design period

The method is based on equivalent 10t axle loads; the formula below was used for the calculations

$$N = f * AADT - T * 365 * \left(\frac{((1+0.01*p)^n - 1)}{(0.01*p)}\right) * C * E \tag{4}$$

Where: *AADT-T* = annual average daily traffic for heavy vehicles, here is 10% of AADT; *f*= coefficient for number of lanes; f =1, for one-lane road; *p* = yearly traffic growth (%); *n* = design period (years); *C* = average number of axles per heavy vehicle; C=2.4 as recommended in standard; *E* = average equivalent factor for heavy vehicles axles, E = 0.424 for 10t axle load.

$$N_{2.500} = 1 * 250 * 365 * \left(\frac{((1 + 0.01 * 1)^{40} - 1)}{(0.01 * 1)}\right) * 2.4 * 0.424 = 4.54\, mill$$

When traffic is 2.500 veh/day then N=4.54 mill.

When traffic is 5.000 veh/day then N=9.08 mill.

When traffic is 7.500 veh/day then N=13.62 mill.

When traffic is 10.000 veh/day then N=18.16 mill.

When traffic is 12.500 veh/day then N=22.70 mill.

When traffic is 15.000 veh/day then N=27.24 mill.

2. Find load distribution factors

From Table 512.1 in the Norwegian road standard, load distribution factors for materials that are going to be used in road construction are found: see Figure A-1.

Asphalt=3.0

Bitumen base layer Ag=3.0

It is assumed that for subbase, Pukk =1.1 would be used.

a	Material-betegnelser	Bindemiddel, penetrasjonsgrad, viskositetsklasse (V)	Verdi, normal	Verdi, krakelert	Verdi, vannømfintlig materiale 8-15 % < 63 mm	>15 % < 63 mm
Vegdekker						
Varmblandet asfalt unntatt drensasfalt	Sta, Top, Ab, Agb, Ska	35/50	3,5	1,5		
		50/70-160/220	3,0	1,5		
		>250/300	2,5	1,5		
Drensasfalt	Da	Alle pen. grader	2,0	1,5		
Mykasfalt	Ma	V>6000	1,5	1,25		
		V<6000	1,25	1,25		
Myk drensasfalt	Mda	V	1,25	1,25		
Emulsjonsgrus, tett	Egt	Alle pen. grader	2,0	1,25		
		V>6000	1,5	1,25		
		V<6000	1,25	1,25		
Emulsjonsgrus drenerende	Egd	Alle pen. grader	1,75	1,25		
		V	1,25	1,25		
Asfaltskumgrus	Asg	Alle pen. grader	1,75	1,25		
		V>6000	1,5	1,25		
		V<6000	1,25	1,25		
Oljegrus	Og	VO	1,25	1,25		
Enkel/dobbel overflatebehandling	Eo/Do	Alle pen. grader	1,5	1,25		
		V	1,25	1,25		
Enkel/dobbel overflate-behandling med grus	Eog/Dog	V>6000	1,5	1,25		
		V<6000	1,25	1,25		
Gjenbruksasfalt, kaldprodusert	Gja	Alle pen. grader	1,75	1,25		
		Alle V-grader	1,5	1,25		
Bærelag						
Sementstab.matr.	Cg, Cp		2,25			
Asfaltert grus	Ag	50/70-160/220	3,0	1,5		
		250/300-330/430	2,75	1,5		
Asfaltert sand	As	Alle pen. grader	2,0	1,25		
Asfaltert pukk	Ap	Alle pen. grader	2,0			
Penetrert pukk	Pp		1,5			
Emulsjonspukk	Ep	Alle pen. grader	1,75	1,25		
		V>6000	1,5	1,25		
		V<6000	1,25	1,25		
Emulsjonsgrus/ Skumgrus	Eg/Sg		2,0 [1]	1,25		
			1,75 [2]	1,25		
			1,5 [3]	1,25		
Bitumenstabilisert grus	Bg		1,75 [2]	1,25		
			1,5 [3]	1,25		
			1,25	1,25		
Gjenbruksasfalt, kaldprodusert	Gja	Alle pen. grader	1,75	1,25		
		Alle V-grader	1,5	1,25		
Gjenbruksbetong	Gjb I		1,25			
Forkilt pukk	Fp		1,25			
Knust fjell	Fk		1,35			
Knust asfalt	Ak		1,35		0,75	0,5
Knust grus	Gk		1,25		0,75	0,5
Forsterkningslag						
Sand, grus, C_u<10			0,75		0,5	0,5
Sand, grus, C_u≥10			1,0		0,75	0,5
Pukk, kult			1,1		0,75	0,5
Sprengt stein			1,0		0,75	0,5
			0,75 [4]		0,75	0,5
Gjenbruksbetong	Gjb I		1,0			
	Gjb II		0,9			

1) Indirekte strekkstyrke > 145 kPa eller E-modul > 860 MPa (v/25 °C)
2) Indirekte strekkstyrke > 100 kPa eller E-modul > 580 MPa (v/25 °C)
3) Indirekte strekkstyrke > 60 kPa eller E-modul > 360 MPa (v/25 °C)
4) Dersom D_{maks} > 1/2 lagtykkelse

Figure A-1: *Load distribution factors for different material types (NPRA, 2005a Table 512.1)*

3. Define traffic group and other parameters using Figure A-2:

H/S/A — DIMENSJONERINGSTABELL FOR HOVED-, SAMLE- OG ADKOMSTVEGER (lagtykkelser i cm)

		TRAFIKKGRUPPE (Antall ekvivalente 10 t aksler pr. felt i dimensjoneringsperioden, N, mill.)					
		A (< 0,5)	B (0,5 - 1)	C (1 - 2)	D (2 - 3,5)	E (3,5 - 10)	F (> 10)
DEKKE 8)		Dekketype og tykkelse velges på grunnlag av ÅDT i åpningsåret, se kap. 512.12 / figur 512.2					
BÆRELAG							
Typiske materialer:		Tykkelse (cm), bærelag					
Ag		9	10	11	12	13	14
Ag over Ap		5 over 6	5 over 8	5 over 9	5 over 10	6 over 10	7 over 10
Ag over Pp		4 over 10	5 over 10	6 over 10	7 over 10	8 over 10	9 over 10
Ag over Fk		5 over 10	6 over 10	7 over 10	7 over 11	-	-
Ag over Gja 4)		6 over 5	6 over 7	6 over 9	6 over 10	-	-
Sg, Eg, Gja over Fk 4)		6 over 12	8 over 12	10 over 12	-	-	-
Fk		20	20	-	-	-	-
FORSTERKNINGSLAG PÅ							
Materialtype i grunnen:	Bæreevne gruppe	Tykkelse (cm), forsterkningslag med lastfordelingskoeffisient a = 1,0. For stamveger økes tykkelsen med 10 cm i forhold til tabellverdiene 7)					
Fjellskjæring, steinfylling, T1	1	20 9)	20 9)	20 9)	20 9)	20 9)	20 9)
Grus $C_u \geq 15$, T1	2	20 9)	20 9)	20 9)	20 9)	20	20
Grus, $C_u < 15$, T1; Sand $C_u \geq 15$, T1; Fjellskjæring, steinfylling T2	3	20	20	20	30	40	40
Sand $C_u < 15$, T1 5); Grus, sand, morene, T2	4	30	30	40	50	60	70
Grus, sand, morene, T3	5	40	50	60	60	70	80
Silt, leire, T4, $s_u \geq 50$ kPa	6	50	60	60	70	80	90
Silt, leire, T4, s_u 37,5-50 kPa	6	50	60	70	70	80	90
Silt, leire, T4, s_u 25-37,5 kPa	6	50+20 1)	60+10 1)	70	70	80	90
Silt, leire, T4, $s_u < 25$ kPa 2)	6	50+50 1)	60+40 1)	70+30 1)	70+30 1)	80+20 1)	90+10 1)
BÆRELAGSINDEKS BI_k 6)		39 3)	45 3)	50 3)	54	62	65

1) Tall med pluss foran er knyttet til anleggstekniske forhold.
2) For undergrunn av leire med s_u<25 kPa skal forsterkningslagstykkelse og sikkerhet mot grunnbrudd vurderes spesielt.
3) For N < 2 mill. kan kravet til bærelagsindeks reduseres som vist i figur 512.4 ved bruk av "myke massetyper" i slitelaget.
4) Tykkelsene forutsetter en lastfordelingskoeffisient på min. 1,75 for Sg, Eg og Gja.
5) Sand med C_u < 5 skal vurderes særskilt.
6) Definisjon av bærelagsindeks (BI_k), se vedlegg 4. Styrkeindeks (SI_k) = BI_k + forsterkningslagets tykkelse (når a=1,0).
7) For stamveger skal tykkelsen på forsterkningslaget økes med 10 cm i forhold til de tykkelser som er angitt i figuren.
8) Det henvises til kap. 512.12 for dimensjonering av vegdekket. Type og tykkelse velges på grunnlag av ÅDT i åpningsåret.
9) Dersom de øverste 20 cm av materialet i grunnen tilfredsstiller kravene til forsterkningslag, kan forsterkningslaget sløyfes.

GRUNNFORSTERKNING: Nødvendig tykkelse av grunnforsterkningslag for at dette skal kunne betraktes som undergrunn ved dimensjonering av overbygning er vist i figur 512.5.

FROSTSIKRING: Om bæreevnemessig dimensjonering ved ulike typer frostsikring, se kap. 512.13, kap. 512.4 og vedlegg 1.

***Figure A-2:** Design table for asphalt pavements (NPRA, 2005a Table 512.7)*

When traffic is 2.500 veh/day and N=4.54 mill, this road is accordingly in traffic group E. The BI_k index, according to traffic group, is 62, and base thickness is 13 cm.

BI_k is a base course index and stands for the sum of the equivalent values for all layers from the road surface and down to the layer whose load distribution factor <1.25, in this case asphalt and base course thickness, because for subbase, the load distribution coefficient is =1.1.

When traffic is 5.000 veh/day → N=9.08 mill.→ E traffic group → BIk= 62

When traffic is 7.500 veh/day → N=13.62 mill. → F traffic group → BIk= 65

When traffic is 10.000 veh/day → N=18.16 mill. → F traffic group → BIk= 65

When traffic is 12.500 veh/day → N=22.70 mill. → F traffic group → BIk= 65

When traffic is 15.000 veh/day → N=27.24 mill. → F traffic group → BIk= 65.

4. Calculate pavement thickness:

Base layer is 13 cm for E category roads, and 14 cm for F category roads: see Table A-1. Then asphalt thickness for traffic group E is:

$BI_k - (H_{base} * a_{base}) = 62-(13*3.0) = 23$

$H_{asphalt} = 23 / a_{asphalt} = 23/3 = 8$ cm

Then asphalt thickness for traffic group F is:

$BI_k - (H_{base} * a_{base}) = 65-(14*3) = 23$

$H_{asphalt} = 23 / a_{asphalt} = 23/3 = 8$ cm

Table A-1: *Design summary for asphalt pavement*

AADT	Traffic group	$H_{asphalt}$	H_{base}
2.500	E	4+ 4,5 cm	13 cm
5.000	E	4+ 4,5 cm	13 cm
7.500	F	4+ 4,5 cm	14 cm
10.000	F	4+ 4,5 cm	14 cm
12.500	F	4+ 4,5 cm	14 cm
15.000	F	4+ 4,5 cm	14 cm

Concrete pavement layer thickness

To be able to determine concrete thickness, it is first necessary to determine the K-module for all layers on which concrete is placed, which include: subgrade, subbase and base.

1. Define K- module

- The K-module for the subgrade is determined by its type. K=3 for subgrade, see Figure A-3

Undergrunn	Bæreevne-gruppe	E-modul MPa	K-modul 10^{-2} N/mm^3
Fjellskjæring, steinfylling > 2 m, T1	1	110	9
Grus, $C_u \geq 15$, T1	2	110	9
Grus, $C_u < 15$, T1	3	75	6
Fjellskjæring, steinfylling, T2	3	75	6
Sand, $C_u \geq 15$, T1	3	75	6
Sand, $C_u < 15$, T1	4	50	3
Grus, sand, morene, T2	4	50	3
Grus, sand, morene, T3	5	30	2
Leire, silt, T4	6	20	1

Figure A-3: *K-module for subgrade (NPRA, 2005a Table 513.1)*

- Define load coefficient

Load coefficient "a" was defined by using Table 513.3 in the Norwegian Road Standard: see Figure A-4.

"a" for subbase, "pukk" =1.1

"a" for base Ag=3.0, see Figure A-4.

Materialtype		E-modul MPa	Lastford.-koeff. a
Asfaltert grus	(Ag)	3000	3,0 1)
Sementstabilisert grus	(Cg)	2000	2,5 2)
Asfaltert pukk	(Ap)	1000	2,0
Penetrert pukk	(Pp)	375	1,5
Knust fjell	(Fk)	250	1,35
Knust grus	(Gk)	200	1,25
Kult, pukk		150	1,1
Sprengt stein med $D_{maks} \leq 0,5$ h		110	1,0
Forsterkningsgrus		110	1,0
Sand, sprengt stein med $D_{maks} > 0,5$ h		50	0,75

Figure A-4: *E-model and load coefficient for base and subbase (NPRA, 2005a Table 513.3)*

- Determine K- module for subbase

A subbase, 60 cm pukk is presupposed for all traffic groups. For pukk, "a" is 1.1, and as neither of the diagrams in Figure A-5 apply directly it is necessary to use to diagrams "a" =1.0 and "a" =1.25 and interpolate the results at the end.

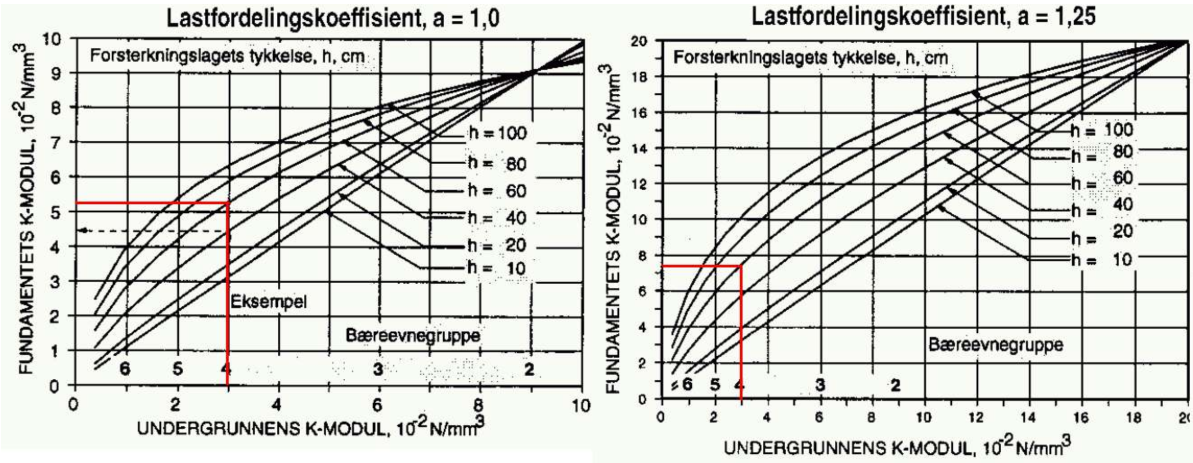


Figure A-5: *K-module for subbase (NPRA, 2005a Table 513.4)*

When diagram a=1.0 is used → K=5.2

When diagram a=1.25 is used → K=7.5

After interpolation for a=1.1, K=6.12

- Determine K-module for base

To be on the safe side, it was decided to use a 5cm Ag base, as this kind of base is a very fine and strong platform for concrete pavement. As "a" is 3, as in the case of "Ag", the diagram in Figure A-6 can be applied directly.

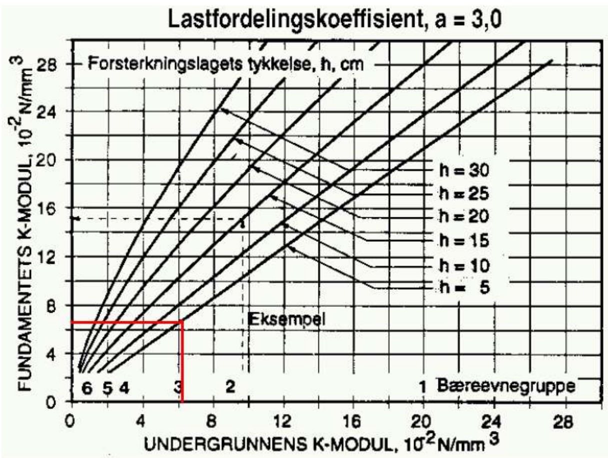


Figure A-6: *K-module for base (NPRA, 2005a Table 513.4)*

We can see that K- module for base layer is equal to 6,7.

1. Define slab thickness

Figure A-7 in The Norwegian Road Standard was used regarding concrete layer thickness.

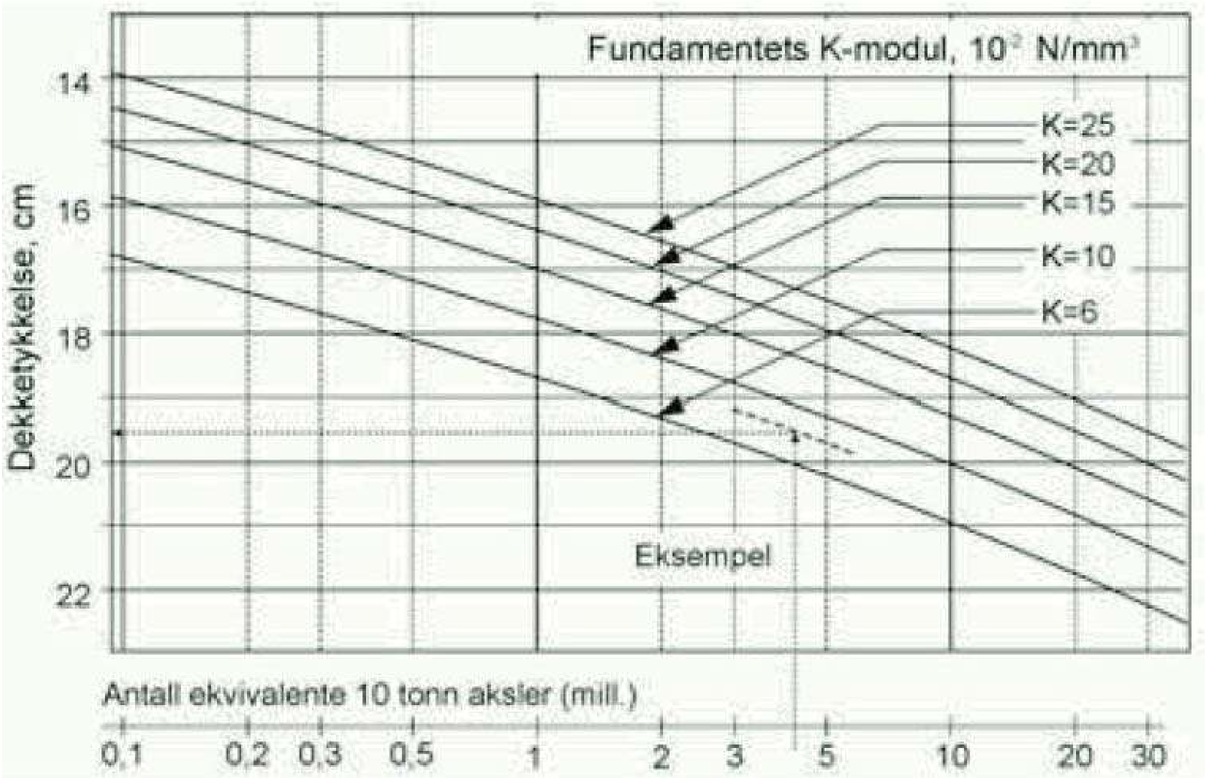


Figure A-7: *Concrete B35 thickness (NPRA, 2005a Table 513.5)*

The traffic loads calculated earlier for the asphalt pavement and K- module 6.2 will be used.

Extra thickness will be added, depending on the number of planned diamond grinding operations during the pavement design life, with an additional 3.5 cm due to the maximum rut depth. It is assumed that 3.5 cm of material will be removed during each grinding.

When traffic is 2.500 veh/day → N=4.54 mill. → $H_{concrete}$=20 cm→ adjusted to 27 cm (due to one grinding planned and maximum rut depth)

When traffic is 5.000 veh/day → N=9.08 mill. → $H_{concrete}$=21 cm→ adjusted to 28 cm (due to one grinding planned and maximum rut depth)

When traffic is 7.500 veh/day → N=13.62 mill. → $H_{concrete}$=21.5 cm→ adjusted to 32 cm (due to two grindings planned and maximum rut depth)

When traffic is 10.000 veh/day → N=18.16 mill. → $H_{concrete}$=21.5 cm→ adjusted to 32 cm (due to two grindings planned and maximum rut depth)

When traffic is 12.500 veh/day → N=22.70 mill. → $H_{concrete}$=22 cm→ adjusted to 33 cm (due to two grindings planned and maximum rut depth)

When traffic is 15.000 veh/day → N=27.24 mill. → $H_{concrete}$=22 cm→ adjusted to 33 cm (due to two grindings planned and maximum rut depth)

We can see that traffic does not have much impact on concrete thickness design, although the effect of studded tires will be substantial with increased traffic: therefore it was necessary to increase pavement thickness. Extra thickness was added depending on the number of planned diamond grinding operations during the pavement design life. It is assumed that 3.5 cm of material will be removed during each grinding.

Table A-2: *Design summary for concrete pavement*

AADT	N	$H_{cocnrete}$
2.500	5.54 mill.	27 cm
5.000	9.08 mill.	28 cm
7.500	13.62 mill.	32 cm
10.000	18.16 mill.	32 cm
12.500	22.70 mill.	33 cm
15.000	27.24 mill.	33 cm

Number of dowel bars

Slab length 5m; Road length 1000m; Lane width 3.75 m; Dowel bar spacing c/c 0.3 m.

((3.75/0.3)+1)*((1000/5)-1)= 2687

Number of tie bars

Road length 1000 m; Tie bar spacing c/c 0.9 m.

(1000/0.9) +1 = 1112

Joint lengths:

Transversal joints

Slab length 5 m; Road length 1000m; Road width 3.75 m.

3.75*((1000/5)-1) = 746 m

Longitudinal joints

Road length 1000 m= longitudinal joint length.

In this case, longitudinal joint length and number of tie bars will be halved because they belong to two lanes, and this model calculates only the cost for a single lane.

User delay cost

For the user cost calculation, formula 3 will be used, as presented in chapter 4. User cost is calculated for a single vehicle.

$$-\left(C_{pc} * \left(\left(\frac{L_{cz}}{V_0} - \frac{L_{cz}}{V_{cz}}\right) + \left(\frac{L_{wz}}{V_0} - \frac{L_{wz}}{V_{wz}}\right)\right) * \left(\frac{\%_{pc}}{100}\right)\right) + \left(C_t * \left(\left(\frac{L_{cz}}{V_0} - \frac{L_{cz}}{V_{cz}}\right) + \left(\frac{L_{wz}}{V_0} - \frac{L_{wz}}{V_{wz}}\right)\right) * \left(\frac{\%_t}{100}\right)\right) \quad (3)$$

Where L_{cz} = construction zone length; L_{wz} = work zone length; V_0 = initial speed; V_{cz} = construction zone speed; V_{wz} = work zone speed; C_{pc} = time value for passenger car; C_t = time value for combination truck; $\%_{pc}$ = percentage of passenger vehicles; $\%_t$ = percentage of trucks.

$$-\left(1695 * \left(\left(\frac{0.7}{70} - \frac{0.7}{50}\right) + \left(\frac{0.3}{70} - \frac{0.3}{30}\right)\right) * \left(\frac{90}{100}\right)\right) + \left(2204 * \left(\left(\frac{0.7}{70} - \frac{0.7}{50}\right) + \left(\frac{0.3}{70} - \frac{0.3}{30}\right)\right) * \left(\frac{10}{100}\right)\right) = 16.96 \text{ kr/veh}$$

APPENDIX B INPUT DATA

Table B-1: *Input parameters for calculation*

Input parameters	
Traffic Growth Factor	1%
Passenger vehicles	90%
Heavy vehicles	10%
Discount rate	6%
Unidentified asphalt cost	5%
Unidentified concrete cost	8%
Design life (years)	40
Length of the lane (m)	1000
Width of the lane (m)	3.75
Number of lanes	1
Width of the shoulders (m)	0
Number of shoulders	0
Max AADT per one lane	15000

Spacing between dowel bars (m)	0.3
Spacing between tie bars (m)	0.9
Concrete slab length (m)	5

AADT (veh/day)
2500
5000
7500
10000
12500
15000

Table B-2: *Agencies' costs for asphalt and concrete pavement*

Asphalt U16	38480	kr/m3
Asphalt SMA 16	52000	kr/m3
Asphalt Y11	44200	kr/m3
Ag base	28600	kr/m3
Concrete C35	30000	kr/m3
Steel	250	kr/kg
Dowel bar, Ø38mm, L=450mm	1000	kr/pc
Tie bar, Ø12.5mm, L=800mm	700	kr/pc
Asphalt placement	30%	
Ag base placement	30%	
Concrete placement	15%	
Concrete overlay	15%	
Saw and seal joints	700	kr/m
Asphalt milling	1500	kr/m2
Repave	2000	kr/m2
Diamond grinding	2500	kr/m2
Concrete milling before overlay	1500	kr/m2

Table B-3: *Inputs for user costs*

User costs	
Average value of the time for the passenger car (kr/h)	1695
Average value of the time for the single unit truck (kr/h)	2204
Average value of the time for the combination truck (kr/h)	2204
Initial speed (km/h)	70
Construction zone speed (km/h)	50
Work zone speed (km/h)	30
Percentage of the traffic affected by the construction	100%
Work zone length (km)	0.3
Construction zone length (km)	0.7
User delay costs (kr/veh)	16.96

Table B-4: *Annual Average Daily Traffic development*

Year	1st category	2nd category	3rd category	4th category	5th category	6th category
0	2500	5000	7500	10000	12500	15000
1	2525	5050	7575	10100	12625	15000
2	2550	5101	7651	10201	12751	15000
3	2576	5152	7727	10303	12879	15000
4	2602	5203	7805	10406	13008	15000
5	2628	5255	7883	10510	13138	15000
6	2654	5308	7961	10615	13269	15000
7	2680	5361	8041	10721	13402	15000
8	2707	5414	8121	10829	13536	15000
9	2734	5468	8203	10937	13671	15000
10	2762	5523	8285	11046	13808	15000
11	2789	5578	8368	11157	13946	15000
12	2817	5634	8451	11268	14085	15000
13	2845	5690	8536	11381	14226	15000
14	2874	5747	8621	11495	14368	15000
15	2902	5805	8707	11610	14512	15000
16	2931	5863	8794	11726	14657	15000
17	2961	5922	8882	11843	14804	15000
18	2990	5981	8971	11961	14952	15000
19	3020	6041	9061	12081	15000	15000
20	3050	6101	9151	12202	15000	15000
21	3081	6162	9243	12324	15000	15000
22	3112	6224	9335	12447	15000	15000
23	3143	6286	9429	12572	15000	15000
24	3174	6349	9523	12697	15000	15000
25	3206	6412	9618	12824	15000	15000
26	3238	6476	9714	12953	15000	15000
27	3271	6541	9812	13082	15000	15000
28	3303	6606	9910	13213	15000	15000
29	3336	6673	10009	13345	15000	15000
30	3370	6739	10109	13478	15000	15000
31	3403	6807	10210	13613	15000	15000
32	3437	6875	10312	13749	15000	15000
33	3472	6943	10415	13887	15000	15000
34	3506	7013	10519	14026	15000	15000
35	3542	7083	10625	14166	15000	15000
36	3577	7154	10731	14308	15000	15000
37	3613	7225	10838	14451	15000	15000
38	3649	7298	10946	14595	15000	15000
39	3685	7371	11056	14741	15000	15000
40	3722	7444	11166	14889	15000	15000

APPENDIX C RESULTS: ASPHALT PAVEMENT

Table C-1: *Asphalt pavement with $AADT_0$= 2.500 veh/day/lane with a 40-year analysis period*

Year	Item Description		QTY	Unit		Unit cost		Total costs	Present Value
0	Ag base	13 cm	3,750	m2	*	3718.00	=	13,942,500 kr.	13,942,500 kr.
0	Ag base placement	13 cm	3,750	m2	*	1115.40	=	4,182,750 kr.	4,182,750 kr.
0	Asphalt U16	4 cm	3,750	m2	*	1539.20	=	5,772,000 kr.	5,772,000 kr.
0	Asphalt placement	4 cm	3,750	m2	*	461.76	=	1,731,600 kr.	1,731,600 kr.
0	Asphalt SMA 16	4.5 cm	3,750	m2	*	2340.00	=	8,775,000 kr.	8,775,000 kr.
0	Asphalt placement	4.5 cm	3,750	m2	*	702.00	=	2,632,500 kr.	2,632,500 kr.
15	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	3,129,488 kr.
15	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	1,627,334 kr.
15	User delay costs (kr/veh)		2,902	veh	*	16.96	=	49,226 kr.	20,540 kr.
30	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	1,305,826 kr.
30	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	679,030 kr.
30	User delay costs (kr/veh)		3,370	veh	*	16.96	=	57,149 kr.	9,950 kr.
						SUBTOTAL		59,942,725 kr.	43,808,518 kr.
	Uncertainness		5%					2,997,136 kr.	2,190,426 kr.
						TOTAL		**62,939,861 kr.**	**45,998,943 kr.**

Table C-2: *Asphalt pavement with $AADT_0$= 5.000 veh/day/lane with a 40-year analysis period*

Year	Item Description		QTY	Unit		Unit cost		Total costs	Present Value
0	Ag base	13 cm	3,750	m2	*	3718.00	=	13,942,500 kr.	13,942,500 kr.
0	Ag base placement	13 cm	3,750	m2	*	1115.40	=	4,182,750 kr.	4,182,750 kr.
0	Asphalt U16	4 cm	3,750	m2	*	1539.20	=	5,772,000 kr.	5,772,000 kr.
0	Asphalt placement	4 cm	3,750	m2	*	461.76	=	1,731,600 kr.	1,731,600 kr.
0	Asphalt SMA 16	4.5 cm	3,750	m2	*	2340.00	=	8,775,000 kr.	8,775,000 kr.
0	Asphalt placement	4.5 cm	3,750	m2	*	702.00	=	2,632,500 kr.	2,632,500 kr.
15	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	3,129,488 kr.
15	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	1,627,334 kr.
15	User delay costs (kr/veh)		5,805	veh	*	16.96	=	98,451 kr.	41,080 kr.
29	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	1,384,176 kr.
29	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	719,771 kr.
29	User delay costs (kr/veh)		6,673	veh	*	16.96	=	113,167 kr.	20,886 kr.
						SUBTOTAL		60,047,968 kr.	43,959,084 kr.
	Uncertainness		5%					3002398.412	2197954.225
						TOTAL		**63,050,367 kr.**	**46,157,039 kr.**

Table C-3: *Asphalt pavement with $AADT_0$= 7.500 veh/day/lane with a 40-year analysis period*

Year	Item Description		QTY	Unit		Unit cost		Total costs	Present Value
0	Ag base	14 cm	3,750	m2	*	4004.00	=	15,015,000 kr.	15,015,000 kr.
0	Ag base placement	14 cm	3,750	m2	*	1201.20	=	4,504,500 kr.	4,504,500 kr.
0	Asphalt U16	4 cm	3,750	m2	*	1539.20	=	5,772,000 kr.	5,772,000 kr.
0	Asphalt placement	4 cm	3,750	m2	*	461.76	=	1,731,600 kr.	1,731,600 kr.
0	Asphalt SMA 16	4.5 cm	3,750	m2	*	2340.00	=	8,775,000 kr.	8,775,000 kr.
0	Asphalt placement	4.5 cm	3,750	m2	*	702.00	=	2,632,500 kr.	2,632,500 kr.
11	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	3,950,906 kr.
11	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	2,054,471 kr.
11	User delay costs (kr/veh)		8,368	veh	*	16.96	=	141,914 kr.	74,759 kr.
21	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	2,206,166 kr.
21	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	1,147,206 kr.
21	User delay costs (kr/veh)		9,243	veh	*	16.96	=	156,762 kr.	46,112 kr.
30	Asphalt milling		3,750	m2	*	1500.00	=	5,625,000 kr.	979,369 kr.
30	Asphalt SMA 16	4 cm	3,750	m2	*	2080.00	=	7,800,000 kr.	1,358,059 kr.
30	Asphalt placement	4 cm	3,750	m2	*	624.00	=	2,340,000 kr.	407,418 kr.
30	User delay costs (kr/veh)		10,109	veh	*	16.96	=	171,448 kr.	29,851 kr.
38	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	819,291 kr.
38	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	426,032 kr.
38	User delay costs (kr/veh)		10,946	veh	*	16.96	=	185,654 kr.	20,281 kr.
						SUBTOTAL		89,051,378 kr.	51,950,521 kr.
	Uncertainness		5%					4,452,569 kr.	2,597,526 kr.
						TOTAL		**93,503,947 kr.**	**54,548,047 kr.**

***Table C-4:** Asphalt pavement with $AADT_0$= 10.000 veh/day/lane with a 40-year analysis period*

Year	Item Description		QTY	Unit		Unit cost		Total costs	Present Value
0	Ag base	14 cm	3,750	m2	*	4004.00	=	15,015,000 kr.	15,015,000 kr.
0	Ag base placement	14 cm	3,750	m2	*	1201.20	=	4,504,500 kr.	4,504,500 kr.
0	Asphalt U16	4 cm	3,750	m2	*	1539.20	=	5,772,000 kr.	5,772,000 kr.
0	Asphalt placement	4 cm	3,750	m2	*	461.76	=	1,731,600 kr.	1,731,600 kr.
0	Asphalt SMA 16	4.5 cm	3,750	m2	*	2340.00	=	8,775,000 kr.	8,775,000 kr.
0	Asphalt placement	4.5 cm	3,750	m2	*	702.00	=	2,632,500 kr.	2,632,500 kr.
8	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	4,705,593 kr.
8	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	2,446,908 kr.
8	User delay costs (kr/veh)		10,829	veh	*	16.96	=	183,654 kr.	115,227 kr.
15	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	3,129,488 kr.
15	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	1,627,334 kr.
15	User delay costs (kr/veh)		11,500	veh	*	16.96	=	195,042 kr.	81,384 kr.
22	Asphalt milling		3,750	m2	*	1500.00	=	5,625,000 kr.	1,560,966 kr.
22	Asphalt SMA 16	4 cm	3,750	m2	*	2080.00	=	7,800,000 kr.	2,164,540 kr.
22	Asphalt placement	4 cm	3,750	m2	*	624.00	=	2,340,000 kr.	649,362 kr.
22	User delay costs (kr/veh)		12,447	veh	*	16.96	=	211,106 kr.	58,583 kr.
28	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	1,467,226 kr.
28	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	762,958 kr.
28	User delay costs (kr/veh)		13,213	veh	*	16.96	=	224,093 kr.	43,839 kr.
34	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	1,034,336 kr.
34	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	537,855 kr.
34	User delay costs (kr/veh)		14,026	veh	*	16.96	=	237,879 kr.	32,806 kr.
						SUBTOTAL		100,847,375 kr.	58,849,006 kr.
	Uncertainness		5%					5,042,369 kr.	2,942,450 kr.
						TOTAL		**105,889,744 kr.**	**61,791,456 kr.**

Table C-5: *Asphalt pavement with $AADT_0$= 12.500 veh/day/lane with a 40-year analysis period*

Year	Item Description		QTY	Unit		Unit cost		Total costs	Present Value
0	Ag base	14 cm	3,750	m2	*	4004.00	=	15,015,000 kr.	15,015,000 kr.
0	Ag base placement	14 cm	3,750	m2	*	1201.20	=	4,504,500 kr.	4,504,500 kr.
0	Asphalt U16	4 cm	3,750	m2	*	1539.20	=	5,772,000 kr.	5,772,000 kr.
0	Asphalt placement	4 cm	3,750	m2	*	461.76	=	1,731,600 kr.	1,731,600 kr.
0	Asphalt SMA 16	4.5 cm	3,750	m2	*	2340.00	=	8,775,000 kr.	8,775,000 kr.
0	Asphalt placement	4.5 cm	3,750	m2	*	702.00	=	2,632,500 kr.	2,632,500 kr.
6	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	5,287,204 kr.
6	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	2,749,346 kr.
6	User delay costs (kr/veh)		13,269	veh	*	16.96	=	225,045 kr.	158,648 kr.
12	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	3,727,270 kr.
12	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	1,938,181 kr.
12	User delay costs (kr/veh)		14,085	veh	*	16.96	=	238,889 kr.	118,721 kr.
18	Asphalt milling		3,750	m2	*	1500.00	=	5,625,000 kr.	1,970,684 kr.
18	Asphalt SMA 16	4 cm	3,750	m2	*	2080.00	=	7,800,000 kr.	2,732,682 kr.
18	Asphalt placement	4 cm	3,750	m2	*	624.00	=	2,340,000 kr.	819,804 kr.
18	User delay costs (kr/veh)		14,952	veh	*	16.96	=	253,586 kr.	88,842 kr.
23	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	1,963,479 kr.
23	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	1,021,009 kr.
23	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	66,602 kr.
28	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	1,467,226 kr.
28	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	762,958 kr.
28	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	49,769 kr.
33	Asphalt milling		3,750	m2	*	1500.00	=	5,625,000 kr.	822,298 kr.
33	Asphalt SMA 16	4 cm	3,750	m2	*	2080.00	=	7,800,000 kr.	1,140,253 kr.
33	Asphalt placement	4 cm	3,750	m2	*	624.00	=	2,340,000 kr.	342,076 kr.
33	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	37,190 kr.
38	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	819,291 kr.
38	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	426,032 kr.
38	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	27,791 kr.
						SUBTOTAL		128,695,730 kr.	66,967,954 kr.
	Uncertainness		5%					6,434,786 kr.	3,348,398 kr.
						TOTAL		**135,130,516 kr.**	**70,316,351 kr.**

Table C-6: *Asphalt pavement with $AADT_0$= 15.000 veh/day/lane with a 40-year analysis period*

Year	Item Description		QTY	Unit		Unit cost		Total costs	Present Value
0	Ag base	14 cm	3,750	m2	*	4004.00	=	15,015,000 kr.	15,015,000 kr.
0	Ag base placement	14 cm	3,750	m2	*	1201.20	=	4,504,500 kr.	4,504,500 kr.
0	Asphalt U16	4 cm	3,750	m2	*	1539.20	=	5,772,000 kr.	5,772,000 kr.
0	Asphalt placement	4 cm	3,750	m2	*	461.76	=	1,731,600 kr.	1,731,600 kr.
0	Asphalt SMA 16	4.5 cm	3,750	m2	*	2340.00	=	8,775,000 kr.	8,775,000 kr.
0	Asphalt placement	4.5 cm	3,750	m2	*	702.00	=	2,632,500 kr.	2,632,500 kr.
5	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	5,604,436 kr.
5	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	2,914,307 kr.
5	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	190,104 kr.
10	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	4,187,961 kr.
10	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	2,177,740 kr.
10	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	142,057 kr.
15	Asphalt milling		3,750	m2	*	1500.00	=	5,625,000 kr.	2,347,116 kr.
15	Asphalt SMA 16	4 cm	3,750	m2	*	2080.00	=	7,800,000 kr.	3,254,667 kr.
15	Asphalt placement	4 cm	3,750	m2	*	624.00	=	2,340,000 kr.	976,400 kr.
15	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	106,153 kr.
20	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	2,338,535 kr.
20	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	1,216,038 kr.
20	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	79,324 kr.
25	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	1,747,490 kr.
25	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	908,695 kr.
25	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	59,275 kr.
30	Asphalt milling		3,750	m2	*	1500.00	=	5,625,000 kr.	979,369 kr.
30	Asphalt SMA 16	4 cm	3,750	m2	*	2080.00	=	7,800,000 kr.	1,358,059 kr.
30	Asphalt placement	4 cm	3,750	m2	*	624.00	=	2,340,000 kr.	407,418 kr.
30	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	44,294 kr.
35	Repave		3,750	m2	*	2000.00	=	7,500,000 kr.	975,789 kr.
35	Asphalt SMA 16	2 cm	3,750	m2	*	1040.00	=	3,900,000 kr.	507,410 kr.
35	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	33,099 kr.
						SUBTOTAL		128,741,418 kr.	70,986,339 kr.
	Uncertainness		5%					6,437,071 kr.	3,549,317 kr.
						TOTAL		**135,178,489 kr.**	**74,535,656 kr.**

APPENDIX D RESULTS: CONCRETE PAVEMENT

Table D-1: *Concrete pavement with $AADT_0$= 2.500 veh/day/lane with a 40-year analysis period*

Year	Item Description		QTY	Unit		Unit cost		Total costs	Present Value
0	Ag base	5 cm	3,750	m2	*	1430.00	=	5,362,500 kr.	5,362,500 kr.
0	Ag base placement	5 cm	3,750	m2	*	429.00	=	1,608,750 kr.	1,608,750 kr.
0	Concrete C35	27 cm	3,750	m2	*	8100.00	=	30,375,000 kr.	30,375,000 kr.
0	Concrete placement	27 cm	3,750	m2	*	1215.00	=	4,556,250 kr.	4,556,250 kr.
0	Dowel bar, ø38mm, L=450mm		2,687	pc	*	1000.00	=	2,686,500 kr.	2,686,500 kr.
0	Tie bar, ø12.5mm, L=800mm		1,112	pc	*	700.00	=	778,478 kr.	778,478 kr.
0	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	872,375 kr.
39	Diamond grinding		3,750	m2	*	2500.00	=	9,375,000 kr.	966,145 kr.
39	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	89,903 kr.
39	User delay costs (kr/veh)		3,685	veh	*	16.96	=	62,503 kr.	6,441 kr.
						SUBTOTAL		56,549,731 kr.	47,302,343 kr.
	Uncertainness		**8%**					4,523,978 kr.	3,784,187 kr.
						TOTAL		**61,073,710 kr.**	**51,086,530 kr.**

Table D-2: *Concrete pavement with $AADT_0$= 5.000 veh/day/lane with a 40-year analysis period*

Year	Item Description		QTY	Unit		Unit cost		Total costs	Present Value
0	Ag base	5 cm	3,750	m2	*	1430.00	=	5,362,500 kr.	5,362,500 kr.
0	Ag base placement	5 cm	3,750	m2	*	429.00	=	1,608,750 kr.	1,608,750 kr.
0	Concrete C35	28 cm	3,750	m2	*	8400.00	=	31,500,000 kr.	31,500,000 kr.
0	Concrete placement	28 cm	3,750	m2	*	1260.00	=	4,725,000 kr.	4,725,000 kr.
0	Dowel bar, ø38mm, L=450mm		2,687	pc	*	1000.00	=	2,686,500 kr.	2,686,500 kr.
0	Tie bar, ø12.5mm, L=800mm		1,112	pc	*	700.00	=	778,478 kr.	778,478 kr.
0	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	872,375 kr.
26	Diamond grinding		3,750	m2	*	2500.00	=	9,375,000 kr.	2,060,719 kr.
26	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	191,757 kr.
26	User delay costs (kr/veh)		6,476	veh	*	16.96	=	109,839 kr.	24,144 kr.
						SUBTOTAL		57,890,817 kr.	49,810,222 kr.
	Uncertainness		**8%**					4,631,265 kr.	3,984,818 kr.
						TOTAL		**62,522,082 kr.**	**53,795,040 kr.**

Table D-3: *Concrete pavement with $AADT_0$= 7.500 veh/day/lane with a 40-year analysis period*

Year	Item Description		QTY	Unit		Unit cost		Total costs	Present Value
0	Ag base	5 cm	3,750	m2	*	1430.00	=	5,362,500 kr.	5,362,500 kr.
0	Ag base placement	5 cm	3,750	m2	*	429.00	=	1,608,750 kr.	1,608,750 kr.
0	Concrete C35	32 cm	3,750	m2	*	9600.00	=	36,000,000 kr.	36,000,000 kr.
0	Concrete placement	32 cm	3,750	m2	*	1440.00	=	5,400,000 kr.	5,400,000 kr.
0	Dowel bar, ø38mm, L=450mm		2,687	pc	*	1000.00	=	2,686,500 kr.	2,686,500 kr.
0	Tie bar, ø12.5mm, L=800mm		1,112	pc	*	700.00	=	778,478 kr.	778,478 kr.
0	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	872,375 kr.
17	Diamond grinding		3,750	m2	*	2500.00	=	9,375,000 kr.	3,481,541 kr.
17	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	323,969 kr.
17	User delay costs (kr/veh)		8,882	veh	*	16.96	=	150,645 kr.	55,944 kr.
31	Diamond grinding		3,750	m2	*	2500.00	=	9,375,000 kr.	1,539,889 kr.
31	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	143,292 kr.
31	User delay costs (kr/veh)		10,210	veh	*	16.96	=	173,163 kr.	28,443 kr.
						SUBTOTAL		73,527,160 kr.	58,281,681 kr.
	Uncertainness		**8%**					5,882,173 kr.	4,662,534 kr.
						TOTAL		**79,409,333 kr.**	**62,944,216 kr.**

Table D-4: *Concrete pavement with $AADT_0$= 10.000 veh/day/lane with a 40-year analysis period*

Year	Item Description		QTY	Unit		Unit cost		Total costs	Present Value
0	Ag base	5 cm	3,750	m2	*	1430.00	=	5,362,500 kr.	5,362,500 kr.
0	Ag base placement	5 cm	3,750	m2	*	429.00	=	1,608,750 kr.	1,608,750 kr.
0	Concrete C35	32 cm	3,750	m2	*	9600.00	=	36,000,000 kr.	36,000,000 kr.
0	Concrete placement	32 cm	3,750	m2	*	1440.00	=	5,400,000 kr.	5,400,000 kr.
0	Dowel bar, ø38mm, L=450mm		2,687	pc	*	1000.00	=	2,686,500 kr.	2,686,500 kr.
0	Tie bar, ø12.5mm, L=800mm		1,112	pc	*	700.00	=	778,478 kr.	778,478 kr.
0	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	872,375 kr.
13	Diamond grinding		3,750	m2	*	2500.00	=	9,375,000 kr.	4,395,366 kr.
13	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	409,003 kr.
13	User delay costs (kr/veh)		11,381	veh	*	16.96	=	193,023 kr.	90,497 kr.
25	Diamond grinding		3,750	m2	*	2500.00	=	9,375,000 kr.	2,184,362 kr.
25	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	203,262 kr.
25	User delay costs (kr/veh)		12,824	veh	*	16.96	=	217,503 kr.	50,678 kr.
35	Concrete milling before overlay		3,750	m2	*	1500.00	=	5,625,000 kr.	731,842 kr.
35	Concrete C35	7 cm	3,750	m2	*	2100.00	=	7,875,000 kr.	1,024,579 kr.
35	Concrete overlay	7 cm	3,750	m2	*	315.00	=	1,181,250 kr.	153,687 kr.
35	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	113,501 kr.
35	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	33,099 kr.
						SUBTOTAL		89,421,906 kr.	62,098,478 kr.
	Uncertainness		**8%**					7,153,752 kr.	4,967,878 kr.
						TOTAL		**96,575,658 kr.**	**67,066,356 kr.**

Table D-5: *Concrete pavement with $AADT_0$= 12.500 veh/day/lane with a 40-year analysis period*

Year	Item Description		QTY	Unit		Unit cost		Total costs	Present Value
0	Ag base	5 cm	3,750	m2	*	1430.00	=	5,362,500 kr.	5,362,500 kr.
0	Ag base placement	5 cm	3,750	m2	*	429.00	=	1,608,750 kr.	1,608,750 kr.
0	Concrete C35	33 cm	3,750	m2	*	9900.00	=	37,125,000 kr.	37,125,000 kr.
0	Concrete placement	33 cm	3,750	m2	*	1485.00	=	5,568,750 kr.	5,568,750 kr.
0	Dowel bar, ø38mm, L=450mm		2,687	pc	*	1000.00	=	2,686,500 kr.	2,686,500 kr.
0	Tie bar, ø12.5mm, L=800mm		1,112	pc	*	700.00	=	778,478 kr.	778,478 kr.
0	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	872,375 kr.
11	Diamond grinding		3,750	m2	*	2500.00	=	9,375,000 kr.	4,938,633 kr.
11	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	459,556 kr.
11	User delay costs (kr/veh)		13,946	veh	*	16.96	=	236,524 kr.	124,598 kr.
21	Diamond grinding		3,750	m2	*	2500.00	=	9,375,000 kr.	2,757,707 kr.
21	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	256,614 kr.
21	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	74,834 kr.
30	Concrete milling before overlay		3,750	m2	*	1500.00	=	5,625,000 kr.	979,369 kr.
30	Concrete C35	7 cm	3,750	m2	*	2100.00	=	7,875,000 kr.	1,371,117 kr.
30	Concrete overlay	7 cm	3,750	m2	*	315.00	=	1,181,250 kr.	205,668 kr.
30	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	151,889 kr.
30	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	44,294 kr.
39	Diamond grinding		3,750	m2	*	2500.00	=	9,375,000 kr.	966,145 kr.
39	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	89,903 kr.
39	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	26,218 kr.
						SUBTOTAL		101,297,835 kr.	66,448,899 kr.
	Uncertainness		**8%**					8,103,827 kr.	5,315,912 kr.
						TOTAL		**109,401,661 kr.**	**71,764,810 kr.**

Table D-6: *Concrete pavement with AADT$_0$= 15.000 veh/day/lane with a 40-year analysis period*

Year	Item Description		QTY	Unit		Unit cost		Total costs	Present Value
0	Ag base	5 cm	3,750	m2	*	1430.00	=	5,362,500 kr.	5,362,500 kr.
0	Ag base placement	5 cm	3,750	m2	*	429.00	=	1,608,750 kr.	1,608,750 kr.
0	Concrete C35	33 cm	3,750	m2	*	9900.00	=	37,125,000 kr.	37,125,000 kr.
0	Concrete placement	33 cm	3,750	m2	*	1485.00	=	5,568,750 kr.	5,568,750 kr.
0	Dowel bar, ø38mm, L=450mm		2,687	pc	*	1000.00	=	2,686,500 kr.	2,686,500 kr.
0	Tie bar, ø12.5mm, L=800mm		1,112	pc	*	700.00	=	778,478 kr.	778,478 kr.
0	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	872,375 kr.
9	Diamond grinding		3,750	m2	*	2500.00	=	9,375,000 kr.	5,549,048 kr.
9	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	516,357 kr.
9	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	150,580 kr.
18	Diamond grinding		3,750	m2	*	2500.00	=	9,375,000 kr.	3,284,473 kr.
18	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	305,631 kr.
18	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	89,128 kr.
27	Concrete milling before overlay		3,750	m2	*	1500.00	=	5,625,000 kr.	1,166,445 kr.
27	Concrete C35	7 cm	3,750	m2	*	2100.00	=	7,875,000 kr.	1,633,023 kr.
27	Concrete overlay	7 cm	3,750	m2	*	315.00	=	1,181,250 kr.	244,953 kr.
27	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	180,903 kr.
27	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	52,755 kr.
36	Diamond grinding		3,750	m2	*	2500.00	=	9,375,000 kr.	1,150,695 kr.
36	Saw and seal joints		1,246	m	*	700.00	=	872,375 kr.	107,076 kr.
36	User delay costs (kr/veh)		15,000	veh	*	16.96	=	254,403 kr.	31,226 kr.
						SUBTOTAL		101,315,713 kr.	68,464,646 kr.
	Uncertainness		**8%**					8,105,257 kr.	5,477,172 kr.
						TOTAL		**109,420,970 kr.**	**73,941,818 kr.**

APPENDIX E COST COMPARISON

Table E-1: *Asphalt and concrete pavement cost comparison with* $AADT_0$*= 2.500 veh/day/lane*

Alternative	Construction	Maintenance	User delay	Total	Difference	Rank
Alternative 1: asphalt	37,036,350 kr.	6,741,677 kr.	30,490 kr.	45,998,943 kr.	1.000	**1**
Alternative 2: concrete	46,239,853 kr.	1,056,049 kr.	6,441 kr.	51,086,530 kr.	1.111	**2**

Table E-2: *Asphalt and concrete pavement cost comparison with* $AADT_0$*= 5.000 veh/day/lane*

Alternative	Construction	Maintenance	User delay	Total	Difference	Rank
Alternative 1: asphalt	37,036,350 kr.	6,860,769 kr.	61,966 kr.	46,157,039 kr.	1.000	**1**
Alternative 2: concrete	47,533,603 kr.	2,252,476 kr.	24,144 kr.	53,795,040 kr.	1.165	**2**

Table E-3: *Asphalt and concrete pavement cost comparison with* $AADT_0$*= 7.500 veh/day/lane*

Alternative	Construction	Maintenance	User delay	Total	Difference	Rank
Alternative 1: asphalt	38,430,600 kr.	13,348,918 kr.	171,003 kr.	54,548,047 kr.	1.000	**1**
Alternative 2: concrete	52,708,603 kr.	5,488,691 kr.	84,387 kr.	62,944,216 kr.	1.154	**2**

Table E-4: *Asphalt and concrete pavement cost comparison with* $AADT_0$*= 10.000 veh/day/lane*

Alternative	Construction	Maintenance	User delay	Total	Difference	Rank
Alternative 1: asphalt	38,430,600 kr.	20,086,566 kr.	331,840 kr.	61,791,456 kr.	1.000	**1**
Alternative 2: concrete	52,708,603 kr.	9,215,601 kr.	174,273 kr.	67,066,356 kr.	1.085	**2**

Table E-5: *Asphalt and concrete pavement cost comparison with* $AADT_0$*= 12.500 veh/day/lane*

Alternative	Construction	Maintenance	User delay	Total	Difference	Rank
Alternative 1: asphalt	38,430,600 kr.	27,989,792 kr.	547,562 kr.	70,316,351 kr.	1.000	**1**
Alternative 2: concrete	54,002,353 kr.	12,176,602 kr.	269,943 kr.	71,764,810 kr.	1.021	**2**

Table E-6: *Asphalt and concrete pavement cost comparison with* $AADT_0$*= 15.000 veh/day/lane*

Alternative	Construction	Maintenance	User delay	Total	Difference	Rank
Alternative 1: asphalt	38,430,600 kr.	31,901,431 kr.	654,307 kr.	74,535,656 kr.	1.008	**2**
Alternative 2: concrete	54,002,353 kr.	14,138,604 kr.	323,689 kr.	73,941,818 kr.	1.000	**1**

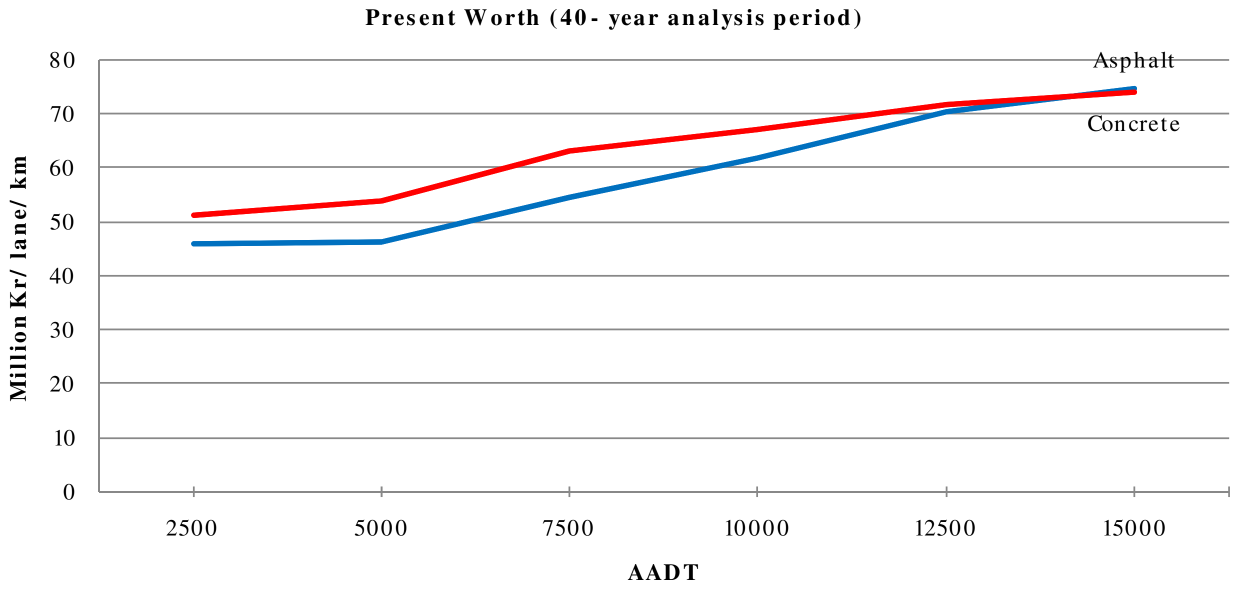
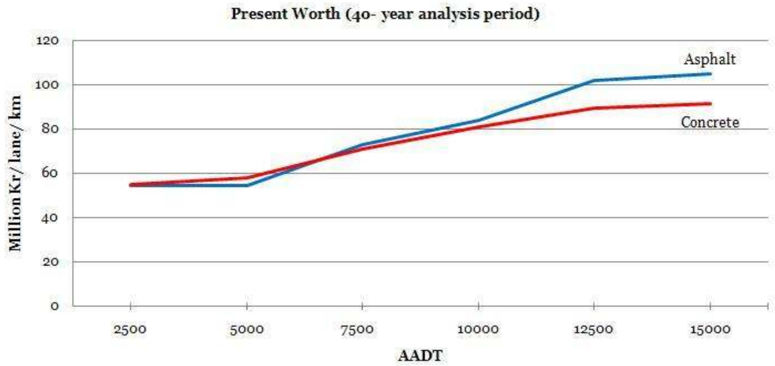
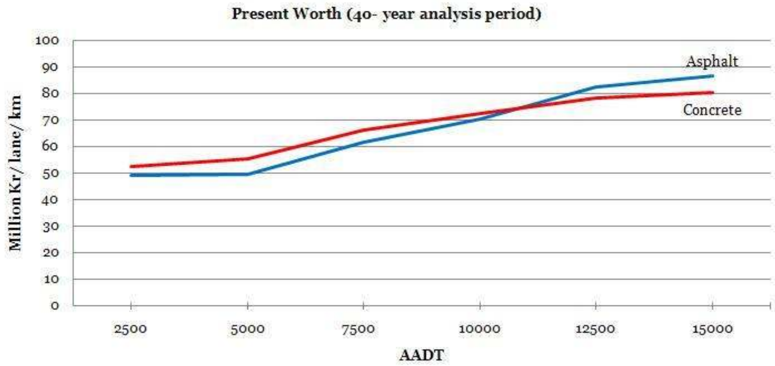


Figure E-1: *Present Worth for asphalt and concrete pavement for 40 years analysis period, break even when AADT is around 14000 veh/day/lane*

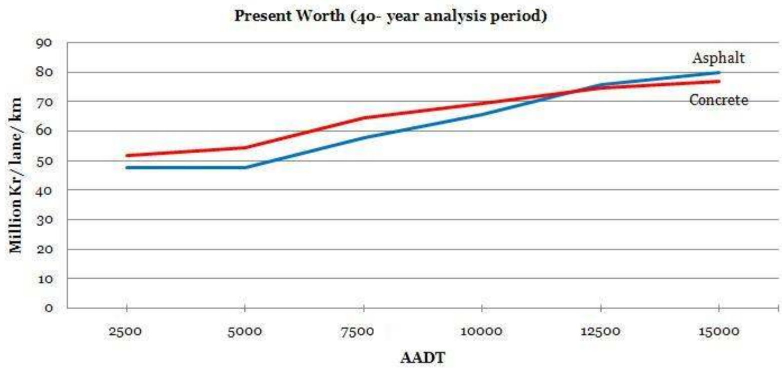
APPENDIX F SENSITIVITY ANALYSIS



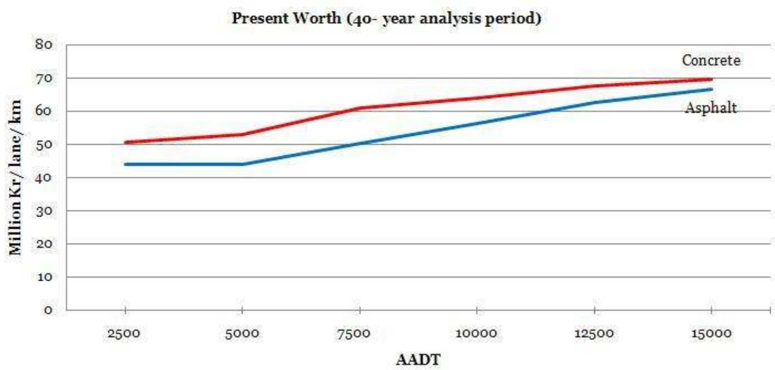
Discount rate 2%



Discount rate 4%

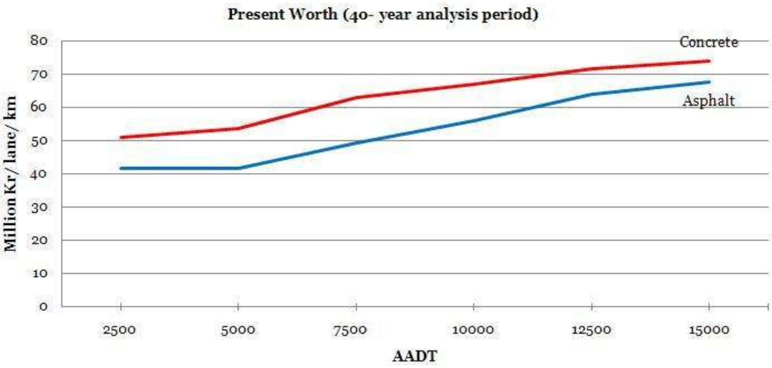


Discount rate 5%

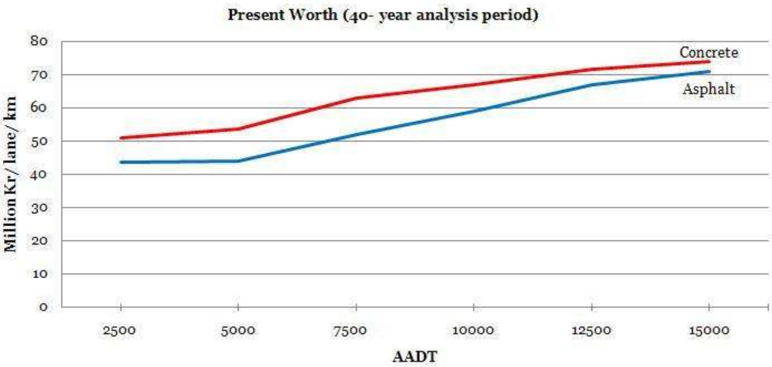


Discount rate 8%

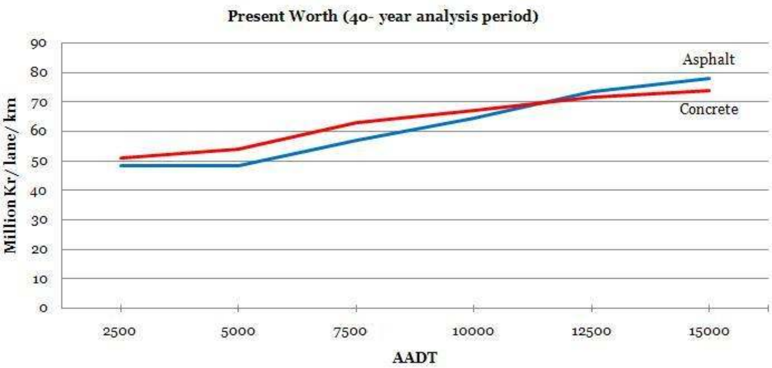
Figure F-1: *Sensitivity to change in discount rate*



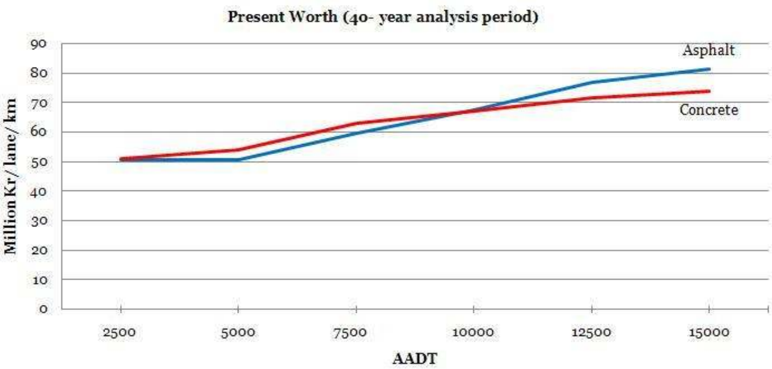
20% less expensive



10% less expensive

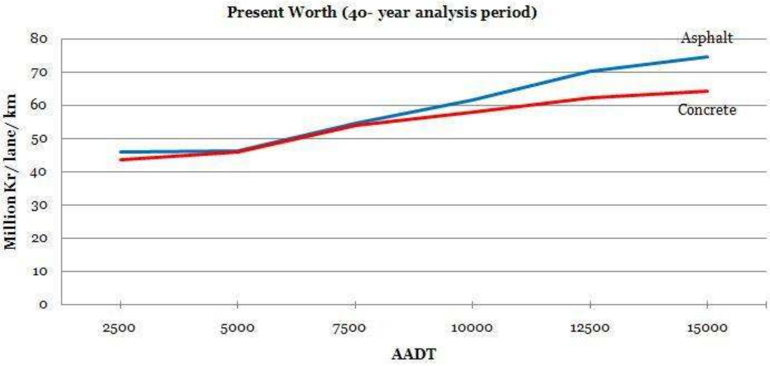


10% more expensive

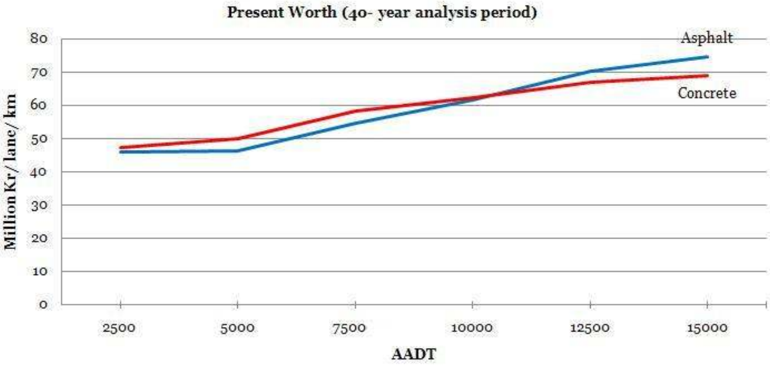


20% more expensive

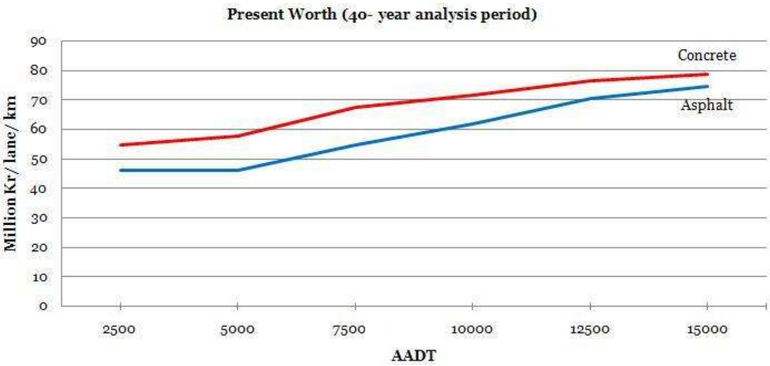
Figure F-2: *Sensitivity to change in asphalt price*



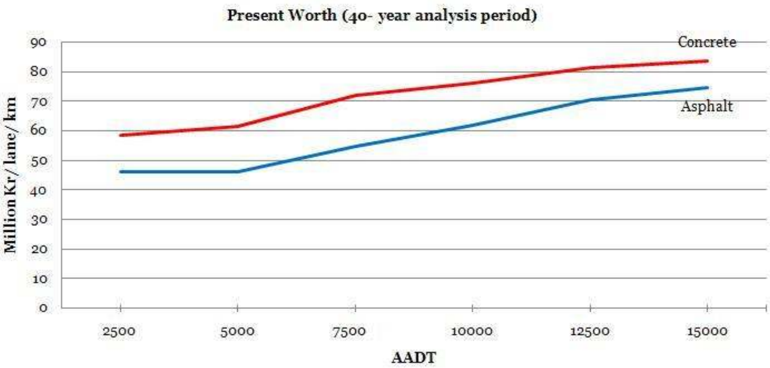
20% less expensive



10% less expensive

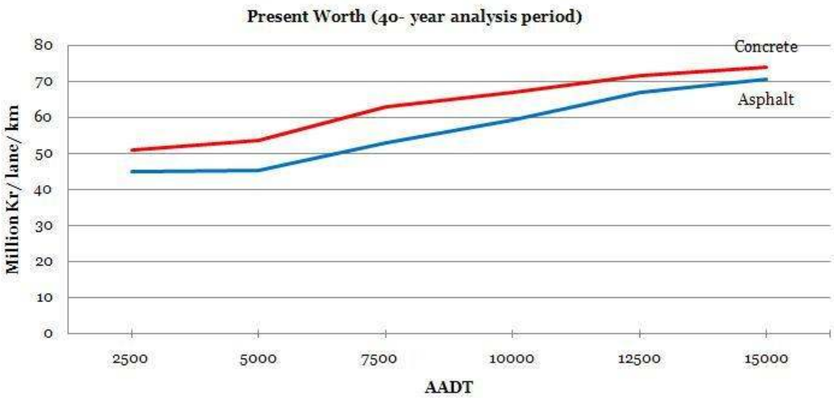


10% more expensive

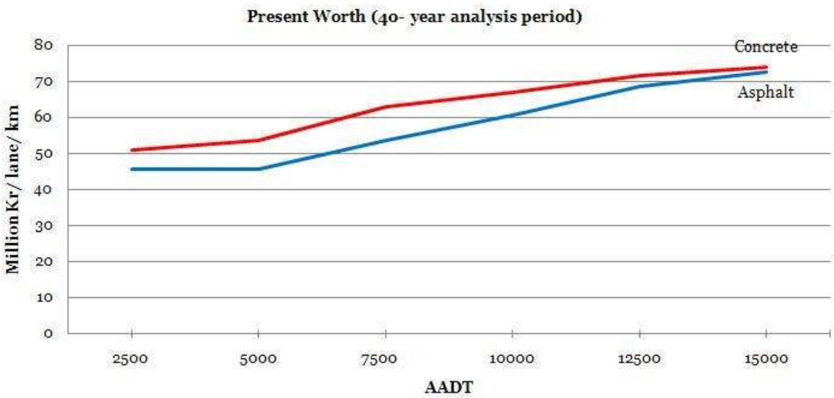


20% more expensive

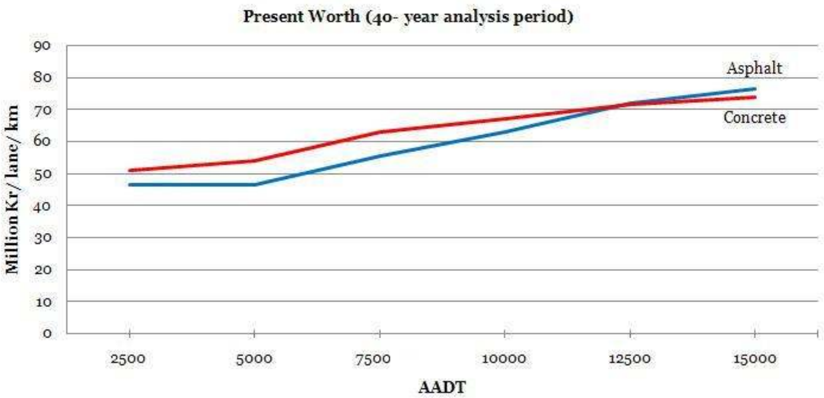
Figure F-3: *Sensitivity to change in concrete price*



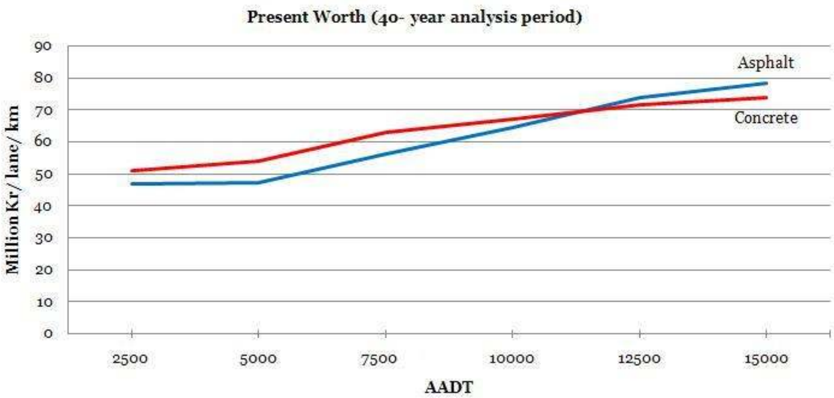
20% less expensive



10% less expensive

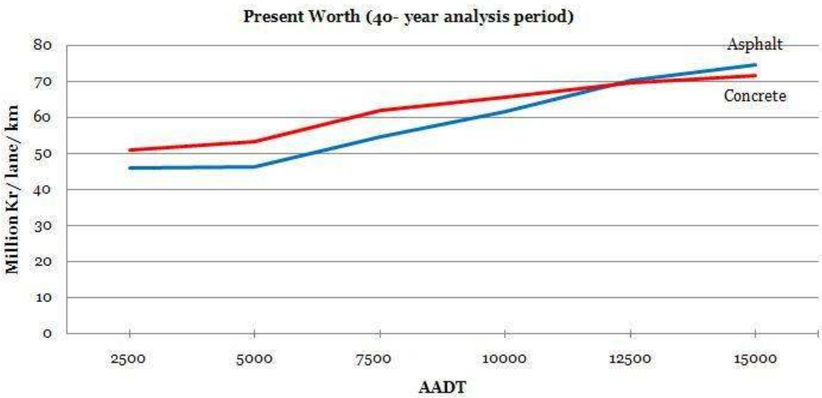


10% more expensive

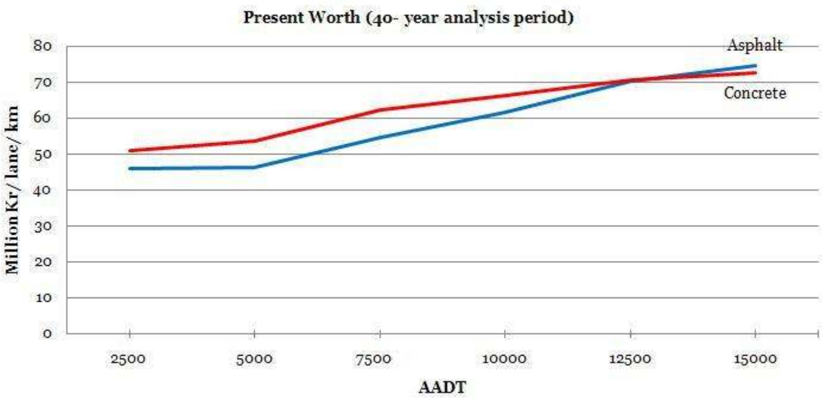


20% more expensive

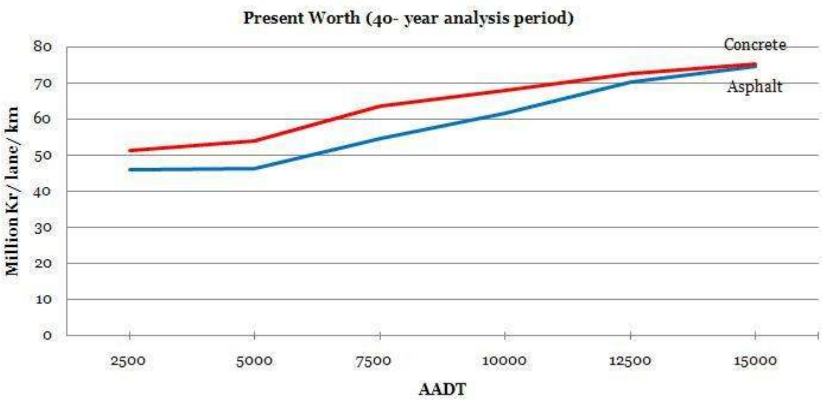
Figure F-4: *Sensitivity to change in asphalt rehabilitation prices*



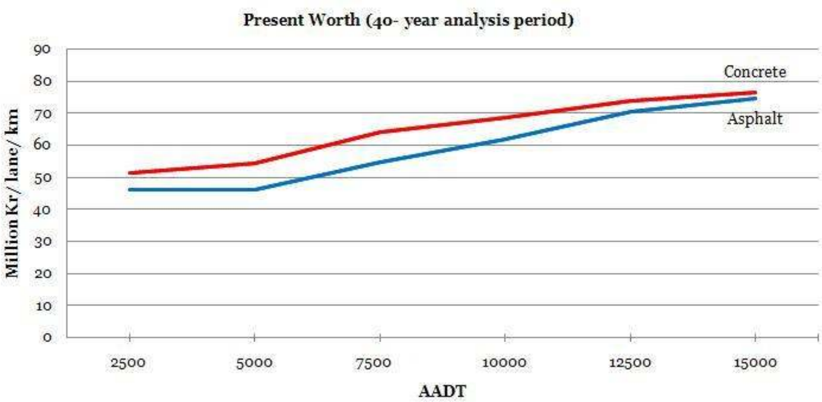
20% less expensive



10% less expensive

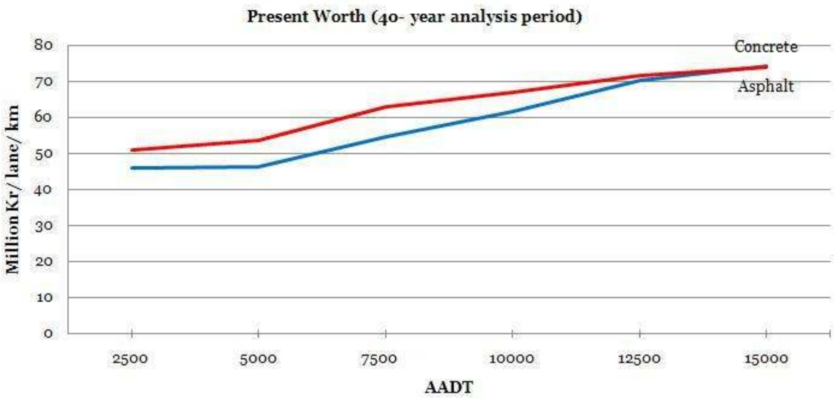


10% more expensive

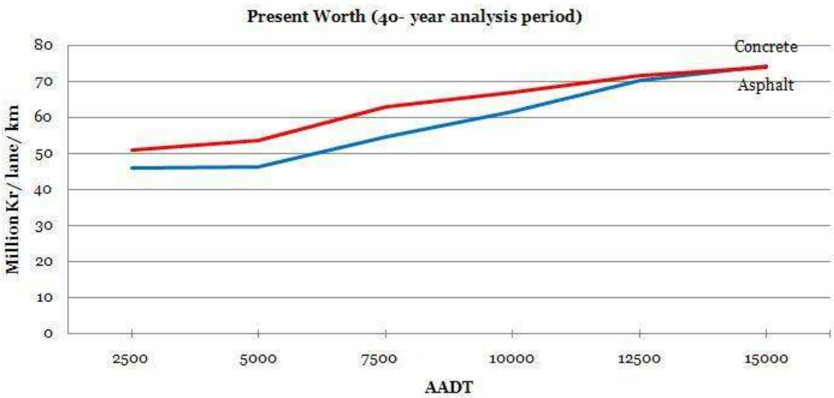


20% more expensive

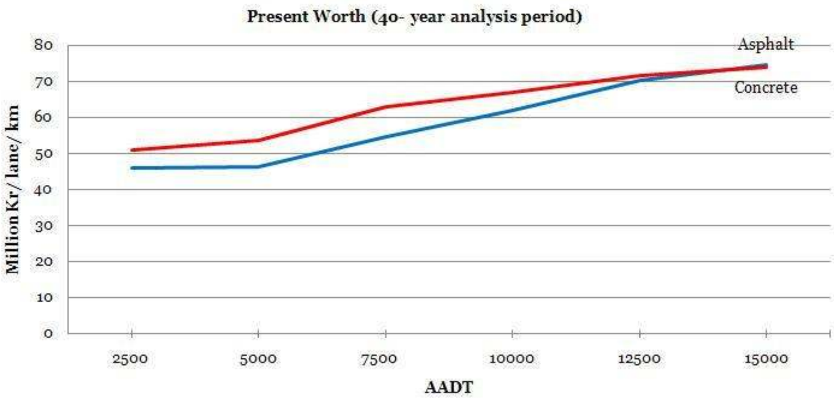
Figure F-5: *Sensitivity to change in concrete rehabilitation prices*



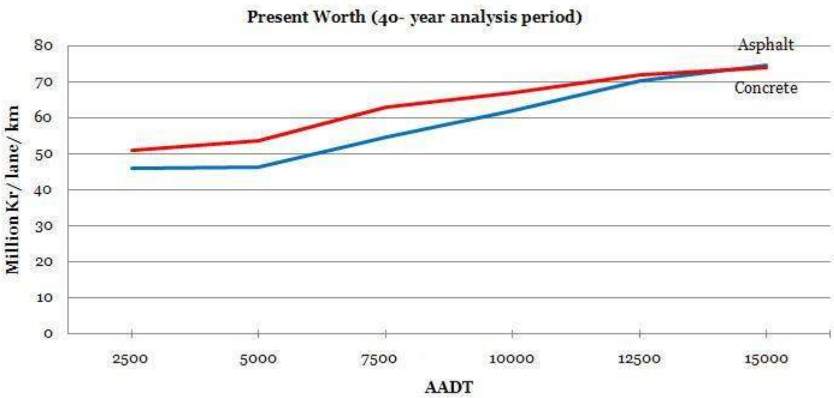
20% less expensive



10% less expensive

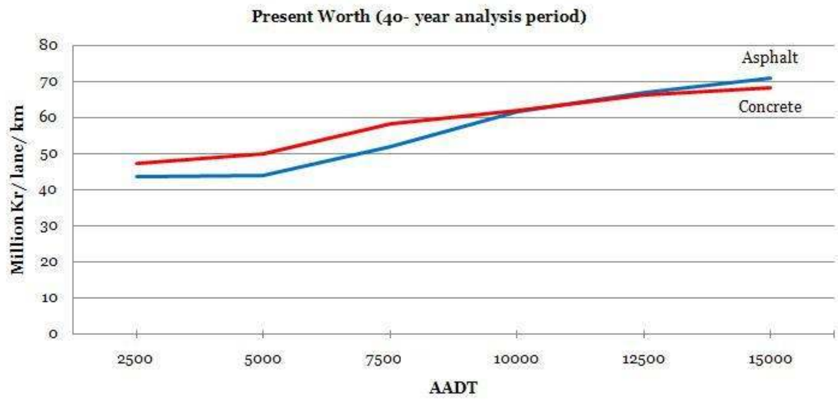


10% more expensive



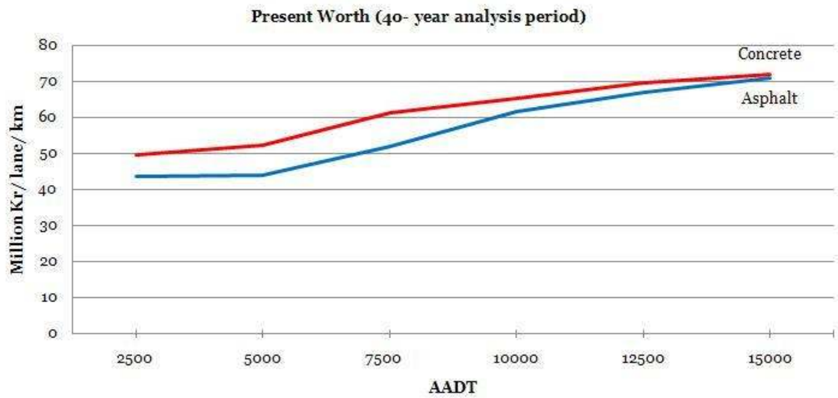
20% more expensive

Figure F-6: *Sensitivity to change in user delay costs*



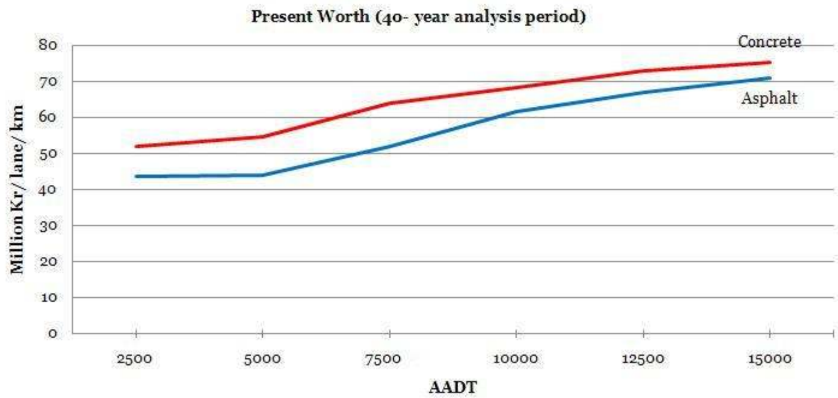
Asphalt, Uncertainty costs 0%

Concrete, Uncertainty costs 0%



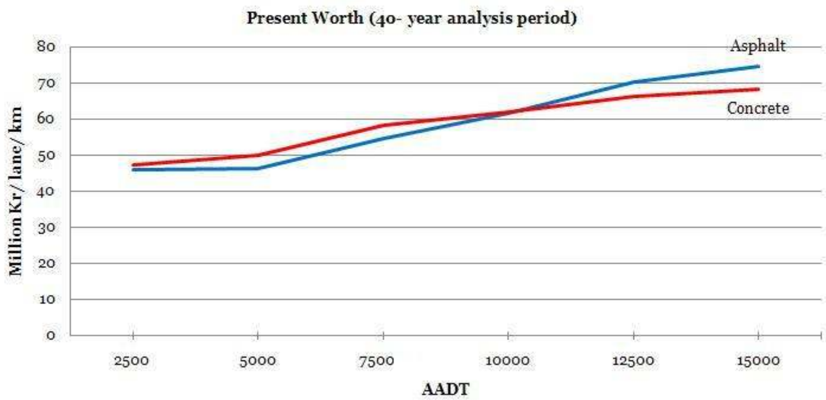
Asphalt, Uncertainty costs 0%

Concrete, Uncertainty costs 5%



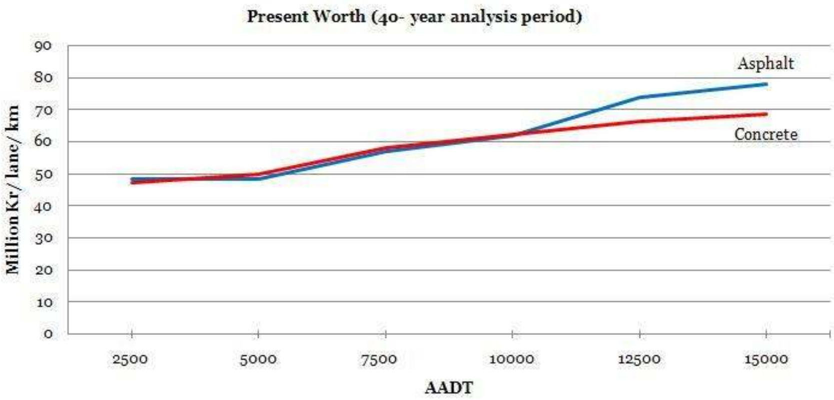
Asphalt, Uncertainty costs 0%

Concrete, Uncertainty costs 10%



Asphalt, Uncertainty costs 5%

Concrete, Uncertainty costs 0%



Asphalt, Uncertainty costs 10%

Concrete, Uncertainty costs 0%

Figure F-7: *Sensitivity to change in total costs*

APPENDIX G RECOMMENDED ASPHALT REHABILITATION FREQUENCY

ENDINGARÁÆTLUN
TÖFLURNAR SÝNA ÁÆTLAÐA ENDINGU Í ÁRUM

SLITLAG: **SMA 16**
KVARNARTALA: **7**

Forsendur:

Umferðarhraði, km/klst:	60
Byrjunarhjólför, mm:	3
Kvarnartala:	7
SPS við 60 km/klst	27
Hjólfarsdýpkun pr. SPS pr. jafngildi, mm:	0.1
Hluti bíla á negldum hjólbörðum:	0.2
Hrörnunarmark, ár:	15

Forsendur:

Umferðarhraði, km/klst:	70
Byrjunarhjólför, mm:	3
Kvarnartala:	7
SPS við 70 km/klst	27
Hjólfarsdýpkun pr. SPS pr. jafngildi, mm:	0.1
Hluti bíla á negldum hjólbörðum:	0.2
Hrörnunarmark, ár:	15

UMFERÐARHRAÐI: 60 KM/KLST

UMFERÐ,	LEYFÐ HJÓLFÖR, MM					
ÁDU	20	25	30	35	40	45
2,000	15	15	15	15	15	15
4,000	15	15	15	15	15	15
6,000	14	15	15	15	15	15
8,000	11	14	15	15	15	15
10,000	9	11	14	15	15	15
12,000	7	9	11	14	15	15
14,000	6	8	10	12	13	15
16,000	5	7	9	10	12	13
18,000	5	6	8	9	10	12
20,000	4	6	7	8	9	11
22,000	4	5	6	7	9	10
24,000	4	5	6	7	8	9
26,000	3	4	5	6	7	8
28,000	3	4	5	6	7	8
30,000	3	4	5	5	6	7

UMFERÐARHRAÐI: 70 KM/KLST

UMFERÐ,	LEYFÐ HJÓLFÖR, MM					
ÁDU	20	25	30	35	40	45
2,000	15	15	15	15	15	15
4,000	15	15	15	15	15	15
6,000	14	15	15	15	15	15
8,000	11	14	15	15	15	15
10,000	9	11	14	15	15	15
12,000	7	9	11	14	15	15
14,000	6	8	10	12	13	15
16,000	5	7	9	10	12	13
18,000	5	6	8	9	10	12
20,000	4	6	7	8	9	11
22,000	4	5	6	7	9	10
24,000	4	5	6	7	8	9
26,000	3	4	5	6	7	8
28,000	3	4	5	6	7	8
30,000	3	4	5	5	6	7

APPENDIX H RECOMMENDED CONCRETE REHABILITATION FREQUENCY

ENDINGARÁÆTLUN
TÖFLURNAR SÝNA ÁÆTLAÐA ENDINGU Í ÁRUM

SLITLAG: **STEYPA 50 MPa**
KVARNARTALA: **7**

Forsendur:

Umferðarhraði, km/klst:	60
Byrjunarhjólför, mm:	3.0
Kvarnartala:	7
SPS við 60 km/klst	14
Hjólfarsdýpkun pr. SPS pr. jafngildi, mm:	0.1
Hluti bíla á negldum hjólbörðum:	0.2
Hrörnunarmark, ár:	40

Forsendur:

Umferðarhraði, km/klst:	70
Byrjunarhjólför, mm:	3.0
Kvarnartala:	7
SPS við 70 km/klst	17
Hjólfarsdýpkun pr. SPS pr. jafngildi, mm:	0.1
Hluti bíla á negldum hjólbörðum:	0.2
Hrörnunarmark, ár:	40

UMFERÐARHRAÐI: 60 KM/KLST

UMFERÐ, ÁDU	LEYFÐ HJÓLFÖR, MM 20	25	30	35	40	45
2,000	40	40	40	40	40	40
4,000	40	40	40	40	40	40
6,000	28	36	40	40	40	40
8,000	21	27	33	39	40	40
10,000	17	22	26	31	36	40
12,000	14	18	22	26	30	34
14,000	12	15	19	22	26	29
16,000	10	13	17	20	23	26
18,000	9	12	15	17	20	23
20,000	8	11	13	16	18	21
22,000	8	10	12	14	16	19
24,000	7	9	11	13	15	17
26,000	6	8	10	12	14	16
28,000	6	8	9	11	13	15
30,000	6	7	9	10	12	14

UMFERÐARHRAÐI: 70 KM/KLST

UMFERÐ, ÁDU	LEYFÐ HJÓLFÖR, MM 20	25	30	35	40	45
2,000	40	40	40	40	40	40
4,000	34	40	40	40	40	40
6,000	23	30	36	40	40	40
8,000	17	22	27	32	37	40
10,000	14	18	22	26	30	34
12,000	11	15	18	21	25	28
14,000	10	13	16	18	21	24
16,000	9	11	14	16	19	21
18,000	8	10	12	14	17	19
20,000	7	9	11	13	15	17
22,000	6	8	10	12	14	15
24,000	6	7	9	11	12	14
26,000	5	7	8	10	11	13
28,000	5	6	8	9	11	12
30,000	5	6	7	9	10	11

APPENDIX I CALCULATION MODEL - CD