Design of Concrete Pavements: A Comparison between Swedish and U.S. Methods

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Abstract

The Swedish regulations for roads have now been converted into a computerised design guide that will provide engineers with the necessary, up to date, tool for the design of roads, no matter the surfacing material. The design of concrete roads is, however, based on old tables that offer little change in the concrete thickness when altering parameters like climate, traffic, and material properties. In an ongoing project a new computer-based design method for concrete roads is being developed. The aim of the project is to facilitate the design method and establish a method that treats the concrete pavement with the same ease, accuracy and safety level as current asphalt pavement design methods. In the Ph. D. project an inventory of various design methods is conducted. The project has a focus on investigating and comparing the mechanistic-based design procedure available in the United States to the current Swedish aspects of design.

Introduction

In Sweden, less than one percent of the national roads are paved with concrete (European Commission 1999). The concrete roads of the 1960's were constructed with long slab lengths on unbound road bases and had severe joint faulting problems. The unbound granular base under the slab eroded and cracks appeared as the loading capacity decreased. New attempts in the 1970's resulted in a few roads that have been performing well but have now reached a critical point where they are in need of rehabilitation. The Swedish National Road Administration (SNRA) has during the last 15 years regained interest in concrete roads because of the growing problems with rutting on heavily trafficked asphalt roads and the need for competition between different road surfacing materials (Löfsjögård 2003).

The current design method for concrete roads in Sweden herein from the investigation conducted by Petersson (Petersson 1990) in the 1990's. A thorough analysis of different design methods for concrete roads was performed and several methods for calculating traffic and temperature loads were considered. This work resulted in a new design method, later implemented in the Swedish regulations for roads. The methodology was evaluated with the design of two highways in the south of Sweden.

The modern concrete roads that have been constructed since 1990 are plain jointed concrete pavements (PJCP) on a cement bound or asphalt bound road base and the results from the follow-ups show a high reliability and an excellent long-

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term performance (Löfsjögård 2003). The Swedish model for the design of concrete roads is based on Westergaard's, by Eisenmann, improved equations. It is a design method used in several countries in Europe.

Nowadays, new computerised tools are available that can handle many more parameters in the design and make calculations instantly. Overcoming the difficulties of how to estimate traffic, variations in climate, and different material types, it would be possible to optimise and improve the accuracy in pavement design with these tools.

The Swedish regulations for roads have been converted to a computerised design guide that will provide engineers with the necessary, up to date, tool for the design of roads, no matter the surfacing material. This change in design methodology has, however, left the design of concrete pavements behind. The old tables for calculating pavement thicknesses are still used in new design, probably resulting in less optimised design.

The thicker the pavement is the less attractive it becomes and, therefore, a new more flexible design method is needed in Sweden, a method that can account for a greater variation of inputs and have a high level of reliability.

The new mechanistic-empirical design procedure, the Design Guide, that has been developed in the U.S. during the last ten years is based on mechanistic concepts but calibrated to observed data (Darter 2004, Transportation Research Board 2004). This design concept can be applied to both flexible and rigid pavements and the procedure is based on damage calculation accumulated incrementally over the entire analysis period. The mechanistic-based design procedure enables the functional properties, i.e., cracking, joint faulting and smoothness, to be evaluated throughout the pavement's designated lifetime. This is necessary when estimating the total cost of a highway construction project and makes it possible to compare different surfacing materials. The design method is more attractive both for the designers and the contractors, as both economical and practical issues become possible to analyse.

Comparing this procedure to the Swedish aspect of design many questions arise on weather it would be possible to apply some of its features on projects in Sweden. It is of course fundamental that the design procedure is validated for the actual construction site and the actual materials as well as to the type of traffic and climate that the pavement will endure. In the U.S., it has been feasible to validate the design process to a huge bank of collected data and is, therefore, in some way optimised for these specific conditions. Taking this data to a new environment and using other materials in layers beneath the concrete, the parameters for particular parts of the design can be put faulty if not examined well. It is also courageous to replace design methods that differ too much in inputs, but also in redefining design criteria. The specifications for the design are always validated to test sections and reference projects. Specifications for all sorts of structures are always improved to new materials and new construction methods but follow the same principles.

The objective of this paper is to describe the differences between the new mechanistic-empirical design procedure for plain joint concrete pavements developed in the U.S., and the current Swedish design method. The paper will highlight the Swedish aspects of design and analyse the corresponding methodology in the Design Guide. The Design Guide software has been available for evaluation through the Transportation Research Board's homepage and a limited investigation of the program has been done. The aim of this work is to investigate how new tools and new modelling techniques could be used in Sweden and how these methods are developed.

A New Design Criteria

The new design procedure for plain joint concrete pavements in the U.S. is based on mechanistic concepts. In the development of the procedure many new parameters for the design are taken into account. The intention is to predict the functional properties as joint faulting, slab transverse cracking, and smoothness (IRI) based on the site conditions. These performance parameters are considered the most important in pavement design since they directly affect the riding comfort for the people travelling on the roads. Modern methods with high capacity for calculations and reliability prediction based on observed data have made it possible to consider further parameters in the design. It is nevertheless difficult to understand exactly which parameters to investigate and how these particular parameters change over time in ever changing conditions.

The Swedish design method

For pavement design, the procedure in Sweden is similar to the methods used in many European countries (Silfwerbrand 2001). The procedure consists of the determination of the acceptable number of load applications for a selected pavement type. Taking seasonal effects into account, the Miner-Palmgren's hypothesis is used to determine the required pavement structure for each of the traffic loading and subgrade bearing capacity combinations. In the design, the diurnal combinations of thermal loads and traffic loads are critical for determining the bearing capacity of the road. For this it is necessary to calculate tensile stresses in the concrete pavement and the road base but also the vertical compressive strain on top of the subgrade. Tensile stresses in the road base are, however, often neglected for a cement bound base since it is considered cracked under the concrete pavement. The procedure is simple in a way that stresses are calculated assuming linear elastic properties of the materials. The likelihood of the method to lead to unsuitable thicknesses of the pavement is imminent since specific conditions are difficult to take into account, i.e. the true properties of the materials. It is believed that in most cases the method results in too thick pavements, taking into account the safety margins needed and the observed performance of roads constructed in Sweden.

Traffic load calculations in Swedish method. In traffic estimation the heavy trucks are represented by vehicles with a total load exceeding 3,5 metric tons and a wheelbase exceeding 3.3 meters. The load from these vehicles is substituted by an equivalent single axle load (ESAL) of 100 kN. The heavy trucks are given a factor of 0.9 to 2.0 ESAL's depending on the type of pavement. Estimating the traffic, and consequently the number of load applications that the concrete slab has to withstand, it is also important to take into account the traffic wandering over the lanes, the design period, and the growth factor.

Stresses due to traffic were first calculated with Westergaard's equations, improved by Eisenmann (Eisenmann 1979). These equations are used to calculate the stresses in the centre, on the edge, and in the corner of the concrete slab. Today, stresses due to traffic are calculated with an elastic multi-layer program, GIPI (van Cauwelaert 1986). In this program, it is possible to define five layers to be calculated, each of them given properties on thickness, module of elasticity, and Poisson's ratio. Between the concrete and the bound base no bond is assumed. This is not always the case (contrarily, bond is assumed in industrial pavements) and a higher flexural stress is hereby calculated in the concrete (Silfwerbrand 2001). The design is because of this rather conservative providing additional safety to the design. Calculations have to be made for each season of the year to capture the differences in strength of the materials and the depth of frozen material with the changing temperatures. The linear elastic layer program is infinite in the horizontal plane and stresses on the edges are therefore not possible to obtain. The case of loads near the edge is either avoided by markings on the road or by thickening the edge according to a distress twice as high as the computed stresses for internal loading. The last option is more common for industrial pavements. This practice is adopted from results from analysis with the two-dimensional finite element program ILLISLAB that indicated a 100% increase of stresses when approaching the edge of the slab (Silfwerbrand 1995). The load efficiency factor between doweled joints for concrete slabs on bound bases is considered to be 100 percent.

***Traffic load calculations in U.S. Design Guide*.** The U.S. design Guide considers a broad variety of axle loads and axle configurations (Transportation Research Board 2004). The number of heavy trucks is calculated in the same manner as in Sweden but instead of one single axle, several different types of wheel loads can be modelled simultaneously. Mechanistically, this is interesting because the impact of more than one wheel on the concrete slab generates other types of distresses and damages on the pavement, e.g., top down cracking. The possibility to change anything from axle configuration to traffic distribution hour by hour is developed in a way that the traffic can be modelled with such accuracy that the main error lies within the traffic estimations. Table 1 shows the inputs for the Swedish design in comparison to the U.S. Design Guide.

Three main types of traffic related distresses for plain jointed concrete pavements are observed for analysis with the Design Guide; stresses that develop top-down cracking, bottom-up cracking, and joint faulting damage. The loads generating these distresses are identified at three critical locations on the concrete slab where the impact of the traffic loads is the most important (Transportation Research Board 2004, Darter 2001). For bottom-up cracking the critical point is situated at mid span on the edge of the slab. The same location is critical for top-down cracking but is produced by two axles acting simultaneously, developing tensile stresses on top of the slab between the axles. Faulting occurs when the loads are concentrated, and causing deflections on either side of a joint. The critical point regarding faulting is the corner of the slab.

For transverse joints, the total load transfer efficiency (LTE) includes the contribution of three major mechanisms of transfer; by concrete aggregates, by joint dowels, and by the base course (Transportation Research Board 2004).

Calibrated mechanistic based models have been developed to predict faulting, cracking, and IRI. The faulting is determined incrementally and considers the effect of previous maximum faulting, current faulting level, and differential energy. IRI depends on the initial smoothness, the change in distress, i.e., cracking and faulting, and age, subgrade type, and climate. The model predicts smoothness incrementally over the design life (Darter 2004, Transportation Research Board 2004).

Stresses due to both traffic and thermal loads are calculated with a finite element program, ISLAB2000. The procedure is explained further in the section describing thermal loads calculations.

Table 1. Comparison of design inputs for traffic calculations. The Swedish method against U.S. Design Guide

Traffic Estimation Parameters	*Sweden*	*USA*
AADTT	X	X
Monthly adjustment factors	-	X
Vehicle class distribution	-	X
Hourly truck traffic distribution	-	X
AADTT distribution by vehicle class	-	X
Traffic growth factor	X	X
Axle load distribution factor	-	X
Wheel location	-	X
Traffic wandering	-	X
Lane width	-	X
Axle spacing	-	X
Axle width	-	X
Tyre spacing	-	X
Tyre pressure	X	X
Dual tyre spacing	-	X

Discussion. The U.S. Design Guide is, compared to the Swedish design method, more sophisticated considering the amount of inputs that are taken into account, see Table 1. The Swedish method does not take more than one single axle into consideration in comparison to the different axle spectra that defines traffic loads in the Design Guide. Introducing multiples axles into the design enables to consider the effect of tensile stresses on top of the concrete slab.

The reliability in traffic estimation also has a significant effect on the traffic calculations, and the Swedish design method is sensitive to the number of ESAL's per heavy vehicle, e.g., increasing the factor from 1 to 2 equals a theoretical decrease in pavement design life from 20 to 10 years (SNRA 2003).

Thermal load calculations with Swedish method. Stresses due to thermal loads are calculated with Eisenmann's beam equation (Eisenmann 1979). The critical length L_{cr} is the decisive factor that determines the geometry of the slab. The stresses at the bottom of a simply supported concrete beam is calculated according to the following equations:

$$\sigma_{\text{temp}} = 1.2 \cdot \frac{\alpha \cdot \Delta t \cdot h \cdot E}{2 \cdot (1-\nu)} \cdot \left(\frac{L}{L_{kr}}\right)^2 \quad \text{if} \quad L \le L_{\text{cr}} \tag{1}$$

$$\sigma_{\text{temp}} = 1.2 \cdot \frac{\alpha \cdot \Delta t \cdot h \cdot E}{2 \cdot (1-\nu)} \quad \text{if} \quad L > L_{\text{cr}} \tag{2}$$

$$L_{\text{cr}} = \sqrt{\frac{4\alpha \Delta t E}{5 \cdot (1-\nu) \cdot \gamma} h} \tag{3}$$

where, α is the coefficient of thermal expansion of concrete, Δt is the temperature gradient, ν is the Poisson's ratio, E is the modulus of elasticity, h is the thickness of the beam, and γ is the dead load per unit length.

The climate is characterised by temperature and sunshine and is described by the magnitude and length of the thermal gradients. In Sweden an extreme gradient of 60°C/m has been chosen for 5 percent of the year, and 40°C/m for 20 percent. During the rest of the year, a thermal gradient of 0°C/m is assumed. These values, originated from field studies in Germany, were modified for Swedish conditions by Petersson (Petersson 1990) for the new Swedish specifications of the 1990's.

Thermal load calculations with the U.S. Design Guide. In the Design Guide, the thermal loads in the concrete slab are calculated with a two-dimensional finite element program, ISLAB2000. The temperature variations in the Design Guide are treated by computerised means where the daily variations are assembled through weather station data, obtained from the National Climatic Data Centre database. (Transportation Research Board 2004)

The climatic information is given by providing the pavement location (longitude and latitude) and the elevation. It is recommended that the data be chosen from several weather stations to compensate for missing data in any one of the weather stations. The hourly inputs contain air temperature, precipitation, wind speed, percentage sunshine, and ambient relative humidity. Inputs provided from site such as seasonal or constant water table depth give the climate model sufficient information to monthly recalculate material properties over the entire design period.

The temperatures directly affect the concrete slab properties with transient hourly negative and positive nonlinear temperature differences between top and bottom, caused by solar radiation and computed using the Enhanced Integrated Climate Module (EICM). The temperature and other climate properties also have an indirect affect on the slab by changing the subgrade properties, i.e., subgrade strength and stiffness.

The analysis requires several input parameters described in Table 2. The structural model for stress computations only considers the concrete slab and the base course. For all layers beneath these two layers a dynamic k-value (psi/in) is assigned through calculations with a linear elastic layer program. In this program, a Falling Weight Deflectometer (FWD) load is simulated. The computed deflection that is produced by the FWD is then used to backcalculate the appropriate k-value. The k-value is recalculated for every month to reflect changes in material properties due to climate changes and is used directly for computations of stresses and deflections. (Transportation Research Board 2004)

To enable rapid solutions neural networks (NN) have been developed based on results from ISLAB2000. This approach is needed to deal with the large numbers of calculations that are required (Transportation Research Board 2004).

The thermal loads are calculated from a temperature profile of 11 point through the slab. The thermal gradients are generated from input data on temperatures in these points, creating nonlinear gradients.

Table 2. Parameters considered for calculation of distresses in the concrete slab. Comparison between the Swedish method and the U.S. Design Guide.

Parameter		*Sweden*	*USA*
Material Properties	Thickness	X	X
	Modulus of elasticity	X	X
	Coefficient of thermal expansion	X	X
	Unit weight	X	X
	Subgrade properties	X	X
Loads	Nonlinear temperature gradient	-	Hourly input
	Linear temperature gradient	X	-
	Axle type, weight, and position	Single axle	Several combinations
Design features	Interface conditions	Bond/no bond	X
	Joint spacing	X	Variable
	Lane width	X	Variable
	LTE - base layer	} 100%	X
	LTE - dowels		X
	LTE - aggregate interlock		X
	Shoulder type	-	X

Discussion. Eisenmann’s equation, used in the Swedish method, is based on the assumption that the thermal gradient is linear and the chosen gradients are all positive, i.e., during daytime conditions. Negative gradients are not considered in the design since they are less significant and are counterbalanced by the traffic loads. The Design Guide, on the other hand, automatically computes hourly variations of both positive and negative nonlinear gradients.

Farhang investigated how the stresses are calculated and compared Eisenmann’s beam equation to results obtained by ISLAB2000 (Farhang 2004). The results showed that Eisenmann’s method produces almost twice as high stresses assuming linear, positive gradients. Farhang also showed that by introducing a nonlinear positive temperature gradient (based on measurements) the tensile stresses are reduced further.

Damage from stresses and fatigue

The concrete slab is, as mentioned above, affected by both thermal and traffic loads. These loads act simultaneously with different magnitudes, hour by hour. The loads produce stresses in the concrete and eventually, after sufficiently many repetitions, cause fatigue damage.

Fatigue damage analysis for concrete in Sweden. The number of allowable load applications for each thickness under each part of the year is calculated with *Tepfers* fatigue equation (Tepfers 1979)

$$\frac{\sigma_{\max}}{f_{\mathrm{ct}}} = 1 - 0.0685 \cdot \left(1 - \frac{\sigma_{\min}}{\sigma_{\max}}\right) \cdot \log N \,. \tag{5}$$

The number of allowable load applications are also calculated with respect to the deformation in the subgrade according to:

$$N = \frac{8.06 \cdot 10^{-8}}{\varepsilon_Z^4} \tag{6}$$

where, N is the number of load applications, $\sigma_{\min}$ is the minimum stress, i.e. temperature stress, $\sigma_{\max}$ is the maximum stress, i.e., the traffic and thermal stress superimposed, f_{ct} is the concrete flexural strength, and ε_{Z} is the vertical compressive strain on top of the subgrade. The stresses are only calculated in the bottom of the slab.

The accumulated fatigue damage that a certain pavement can resist is calculated with Miners-Palmgren’s damage hypothesis for flexural stresses in the concrete pavement, horizontal tensile strains in the base course or the vertical compressive strain of the subgrade. The accumulated damage is computed by summing fatigue damage incurred during each of the 6 seasons of the year due to both traffic and thermal loads.

The accumulated damage is calculated with the following equation:

$$\sum_{i=1}^{n} \frac{\alpha_{\mathrm{i}} \cdot N_i}{N_{\mathrm{i,allow}}} \leq 1 \tag{7}$$

where, α_i is the percentage of time in which damage i occurs, N_{i} is the total number of loads corresponding to damage i, and $N_{\mathrm{i,allow}}$ is the number of allowable loads corresponding to damage i.

Damage analysis in the Design Guide. The Design Guide contains prediction models for calculating joint faulting, slab transverse cracking, and IRI. The models are calibrated with data from JPCP sections in the field.

The maximum bending stresses and bending strength are used to compute the number of allowable axle load applications and aggregate interlock wear due to each wheel load for each time increment using the fatigue relationship (Darter 2004, Transportation Research Board 2004):

$$\log\left(N_{i,j,k,l,m,n}\right) = C_1 \cdot \left(\frac{MR_i}{\sigma_{i,j,k,l,m,n}}\right)^{C_2} - 1 \tag{10}$$

where, MR_{i} is the modulus of rupture at age i for concrete, $N_{\mathrm{i,j,...}}$ is the allowable number of loads applications at specified condition, $\sigma_{\mathrm{i,j,k,...}}$ is the applied stress at specified condition, and C_1 and C_2 are calibration constants.

The fatigue damage, for all traffic load increments over the design period is calculated in the same way as in Sweden with Miner-Palmgren's hypothesis. The fatigue is calculated both on the top and bottom of the slab and the conversion to physical pavement distress, i.e., bottom-up and top-down transverse cracking, is related to observed cracking in the field through calibration.

Comparing Swedish and U.S. Design through a Case Study

In a trial to analyse the Design Guide, a section of a Swedish road is evaluated with the program. The particular section is a highway north of Stockholm, Sweden, that will be constructed as a plain jointed concrete pavement in 2006.

The following calculations with the Design Guide are not exact because no laboratory testing for this purpose have been done prior to this investigation. Many of the needed parameters are not directly considered in Swedish design and calculations are due to these reasons made on a level 3 basis; with a minimum of inputs. Materials parameters are, for instance, chosen from recommended values in the Guide. Traffic distribution by vehicle class and axle load values are also taken directly from the Guide.

The objective is to evaluate the impact of some of the parameters in the design of new concrete pavements. The inputs are changed one by one and the effect in performance at the end of the design life is evaluated. Different improvements may affect performance on faulting but have less effect on the cracking ability. It is beneficial to know what parameters are the most significant in the design and know under which circumstances they are valid, i.e., different climate or traffic conditions.

It is also essential to scrutinize the most important parameters and develop new criteria to be able to judge performance in future Swedish design.

General Information. The highway, E4 Uppsala, is situated north of Stockholm. A 23 km long section will consist of a plain joint concrete pavement with 2 lanes in each direction. Traffic is estimated to 12 500 AADT from which 17% are heavy vehicles, i.e., vehicles exceeding 3,5 metric tons. Construction starts in July 2006 and the highway will open to traffic in October 2007.

Material Data. The pavement (Figure 1) consists of a wear layer of concrete, a bound base of asphalt, two subbase courses of compacted unbound materials, and a subbase of crushed gravel. The subgrade consists of a typical Swedish, low strength and silty, material.

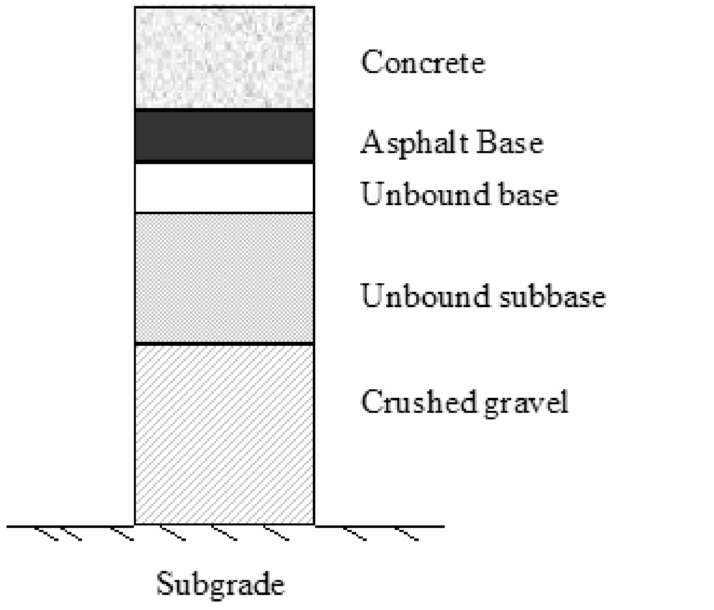

Figure 1. Pavement system according to the Swedish specifications.

Climate conditions. For each climate zone, the number of accumulated negative degrees per day is given. The site is situated in climate zone 2 in Sweden and the climate properties are given for six seasons, see Table 4, with a corresponding number of days, see Table 5. For climate zone 2, 300-600 accumulated negative degrees Celsius per day is estimated. This means, for instance, that 300 negative degrees per day equals 60 days with an average day temperature of –5ºC. The maximal frost depth is 2.0 meters.

Traffic Data. The Average Annual Daily Traffic (AADT) for one lane, in one direction, is estimated to 12 500 vehicles of which 17 % are heavy trucks. Traffic is also estimated to increase annually with a growth factor of 2.6%. This value is not really reliable considering a design life of 40 years but should be accounted for over the first 15-20 years.

Design with the Swedish method

Material data. The pavements system is from start chosen from a standard design. Properties, e.g., elastic modulus and Poisson's ratio for the different layers and different seasons, are retrieved from the Swedish specifications (SNRA 2004), see Table 3.

Traditionally, concrete pavements for highways are constructed with concrete with a flexural strength of 6 MPa and an elastic modulus of 36 000 MPa.

Traffic loads. For the design of this road section a factor of 2.45 standard axles per heavy vehicle and a growth factor over 40 years of 2.6 % is estimated. The total number of estimated ESAL's are shown in Table 3.

Table 3. Traffic calculation for E4 Uppsala

AADT	12500
Percent of trucks, *A*	17 %
Number of axles per truck, *B*	2,45
Traffic growth, *n*	2.6 % (compound)
Design life, years	40
Number of ESAL's, N_{ekv}	134 million

The traffic stresses are calculated for a 100 kN standard axle with a tyre pressure of 0.8 MPa. The stresses induced by this axle are computed with an elastic multi-layer program and no bond between the concrete and the road base is assumed. The load transfer efficiency is considered to be 100 percent in dowelled joints between two slabs on bound bases. The calculations are based on a slab with 5 m joint distance.

Thermal loads. The pavement is affected by a positive thermal gradient of 40°C/m under 20 % of the year and 60°C/m under 5 % (SNRA 2004). These gradients take place under the summer period. Thermal stresses are calculated with Eisenmann's beam model, Eq. 1-3.

Table 4. Material and climate data (SNRA 2004). (Note: 200 mm = 7.9 in, 36 GPa = 5.2 Mpsi)

Materials	*Thick-ness [mm]*	*Modulus of elasticity [MPa] for each season 1-6*						*Poisson's ratio*
		1	*2*	*3*	*4*	*5*	*6*	
Concrete	200	36 000	36 000	36 000	36 000	36 000	36 000	0.2
Asphalt base	100	11500	10000	9000	8500	2500	8000	0.4
Unbound base	80	1000	150	300	450	450	450	0.35
Unbound subbase	220	450	450	450	450	450	450	0.35
Crushed rock	850	1000	1000	70	85	100	100	0.35
Subgrade		1000	1000	10	20	45	45	0.35

Table 5. The year is divided into season with a corresponding number of days.

Climate period					
1	*2*	*3*	*4*	*5*	*6*
Winter 80 days	*Freeze-thaw 10 days*	*Spring thaw 31 days*	*Spring 15 days*	*Summer 153 days*	*Autumn 76 days*

Results. The limitation for the pavement system, is the vertical compressive strain of the subgrade, see Table 6. The requirement for traffic class 7, i.e., traffic exceeding $19 \cdot 10^6$ standard axles, is nevertheless fulfilled. The thickness of the pavement structure is satisfactory against frost heave.

Table 6. Number of permissible axle loads for the pavement system calculated with the Swedish method. The subgrade is the weakest component in the system.

Pavement layer	*Allowable ESAL's*
Concrete	$2.65 \cdot 10^{12}$
Asphalt base	$7.93 \cdot 10^{8}$
Subgrade	$\mathbf{2.28 \cdot 10^{8}}$

Evaluation of the Design Guide

Materials. The materials for the structure are chosen to correspond to the actual material properties in the Swedish specifications. The Design Guide is most accurate after affecting thorough analysis of the materials in the laboratory. Because of this, the input values for the unbound materials are, without exception, chosen from the default values provided by the Guide. The common rule for the choice of elastic modulus, or corresponding strength properties, is that the deeper under the slab the material is situated, the lower the modulus. No stress-dependent properties are accounted for and the climate model is restrained from altering the modulus over the months, i.e., specified modulus values are given for each month.

Traffic. The Design Guide inputs for traffic is the number of AADT and the number of heavy vehicles. These parameters are computed in the same way as in the Swedish method. The inputs concerning the traffic are then chosen through the help of default values recommended in the guide as showed in Table 7.

Table 7. Inputs for traffic calculation in the Design Guide.

Parameter	*Input*
Operational Speed	60 mph (100 km/h)
Volume Adjustment factors	Default, 100% for all vehicle classes
Vehicle class distribution	TTC 8 "High percentage of single-trailer truck with some single-unit trucks."
Hourly truck traffic distribution	Default, maximum of 6% per hour around noon
Traffic growth	2.6% (compound)
Axle load distribution factors	Default, level 3
Mean wheel location	18 in (457 mm)
Traffic wander std deviation	10
Number of axles per Truck	Default for single-, tandem-, tridem-, and quad axles
Axle Configuration	Default

***Climate*.** The New York climate was chosen to represent the climate of this particular design because it is well defined and does not bring too extreme temperature variations to the calculations.

***Design features – Structure*.** The dowels, the slab size, and the joint spacing are the constructive features that have been altered in the design, see Table 8. Case 4 corresponds to Swedish practice regarding these features.

Table 8. Five different design features analysed with the Design Guide.
(Note: 5.0 m = 16.4 in. 25 mm = 1 in.)

	Case 0	Case 1	Case 2	Case 3	Case 4
Joint spacing	5.0 m	4.6 m	4.6 m	4.6 m	5.0 m
Dowel diameter	25 mm	25 mm	38 mm	38 mm	25 mm
Slab width	3.7 m	3.7 m	3.7 m	4.3 m	4.3 m

***Results*.** The results show that the design features, e.g., joint design and edge support, have significant importance in crack development and damage accumulation under the design period.

The most effective parameters to avoid premature cracking, faulting and rapid damage accumulation is done by the use of widened slabs, decreased joint spacing, increased dowel diameter, increased thickness of the concrete slab, and higher strength of the concrete. The faulting is also affected by the capability of erosion of the base and how the slab shoulder is tied to the adjoining pavement. (Darter 2004, Transportation Research Board 2004)

The first model, Case 0, with the same parameters for joint spacing and dowel diameter as in Swedish practise shows the most damage. The slab width is, however, the same as the lane width, contrarily to Swedish practice where the slab is more or less square with a maximum width of 4.5 m. Because of the fact that the properties are not correct regarding materials we only consider this model as the basic model, the model from where we evaluate the following ones.

The model in Case 1 has shorter joint spacing. The percentage of cracking is decreased and illustrated by decreased bottom-up and top-down cracking. The LTE is about the same as for Case 0.

In Case 2, the joint spacing is shorter, the dowel diameter is enlarged, and the slab width is increased. In this case, the LTE is not affected at all over the entire design period, see Figure 2.

Shortening the joint spacing, increasing dowel diameter, and widening the slab yields the best result in comparison to the basic model. This is done in Case 3. Bottom-up cracking is significantly decreased.

In Case 4, the basic model is simply modified by a widened slab. The result shows on a significant improvement in cracking development. Faulting is, however, considerably increased after 20 years as shown in Figure 6 and the LTE is, consequentially reduced, see Figure 2.

The main results from this limited study show that faulting is significantly depending on the dowel size, and that both top-down and bottom-up cracking can be controlled by slab size. The bottom-up cracking is more dependent of the width of the slab. IRI and LTE can be related to cracking and faulting and are, consequently, dependent of the same parameters, see Figure 6 and Figure 7.

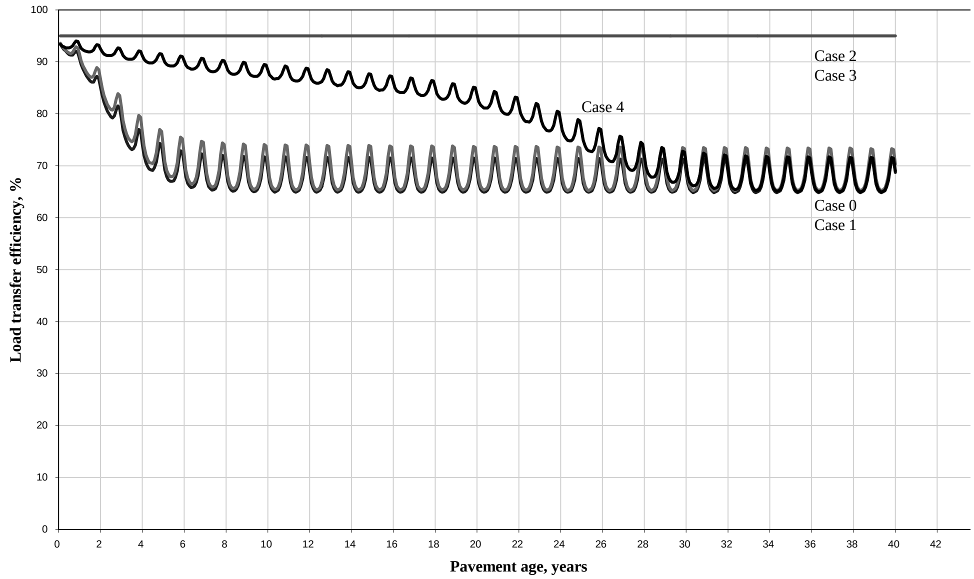

Figure 2. Load transfer efficiency during design life for cases 0-4. Cases 2 and 3 show the beneficial influence of enlarged dowel diameter.

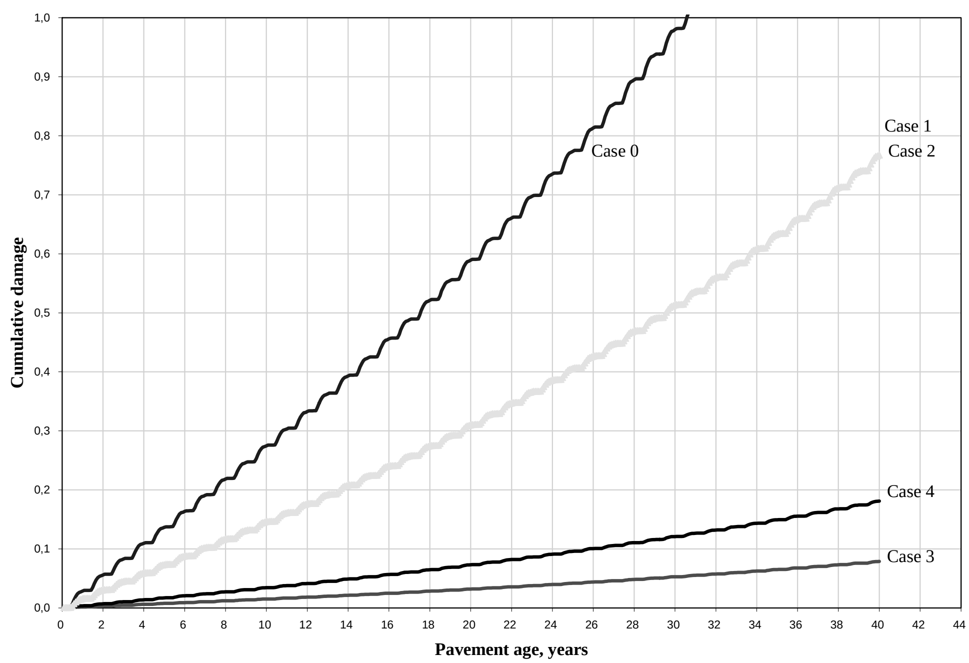

Figure 3. Bottom-up cracking over the design life for cases 0-4. Case 3 and case 4 show the efficiency of widened slabs to avoid bottom-up cracking.

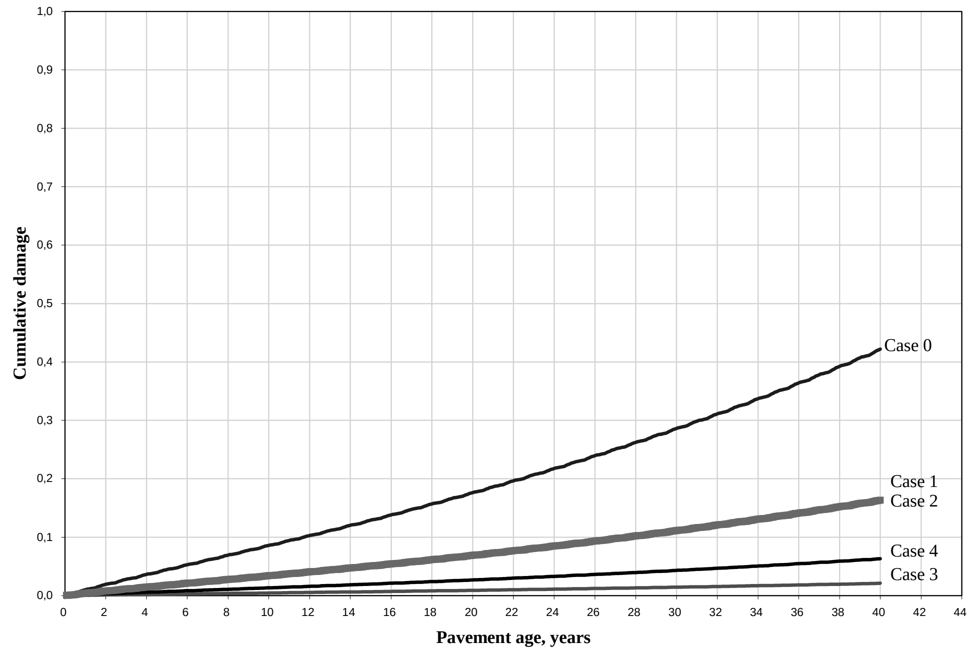

Figure 4. Top-down cracking over the design life for Cases 0-4. Cases 3 and 4 show the efficiency of widened slabs in the development of top-down cracking. Case 1 and 2 have shorter joint spacing compared to Case 0.

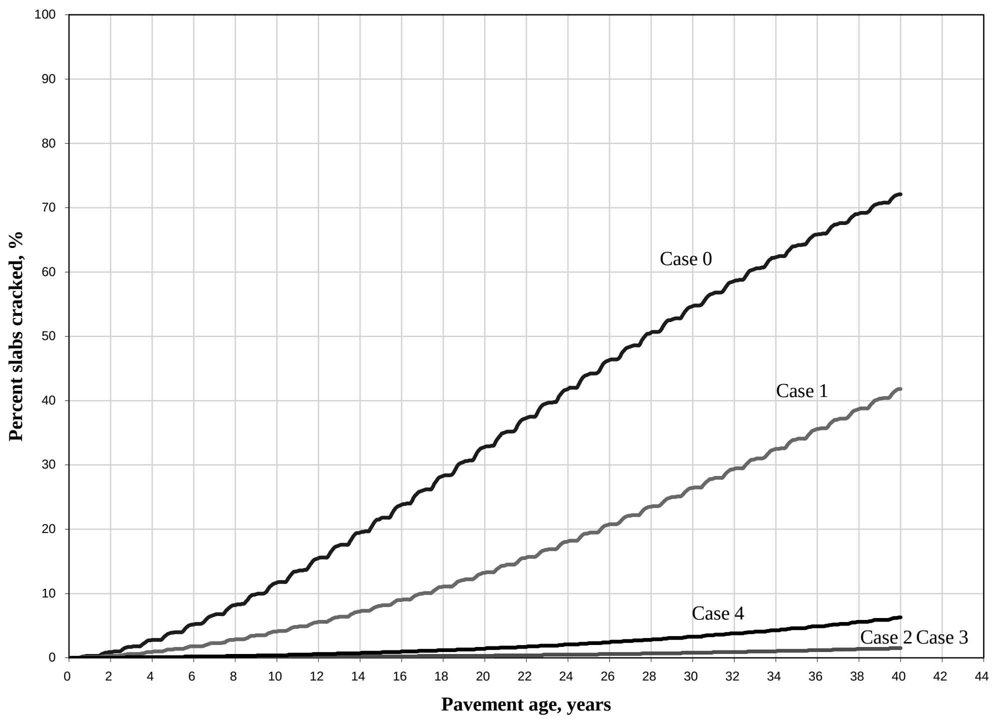

Figure 5. Cases 0-4. Predicted slabs cracked over the design life, considering the effect from both bottom-up and top-down cracking. The damage is predicted on a 50% reliability level.

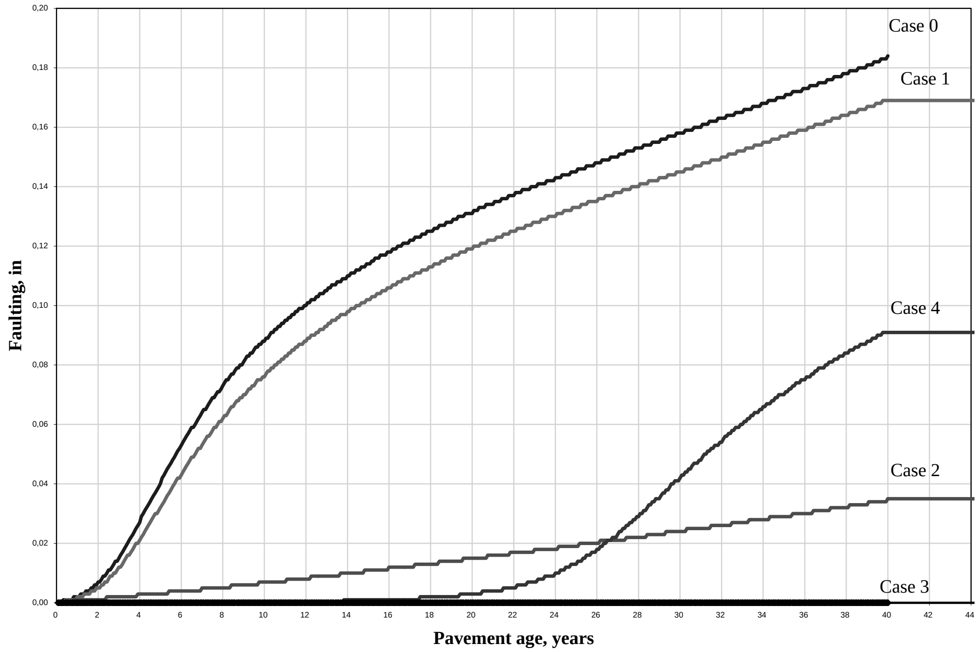

Figure 6. Faulting development over the design life for cases 0-4. The most effective parameters are dowel diameter and joint spacing.

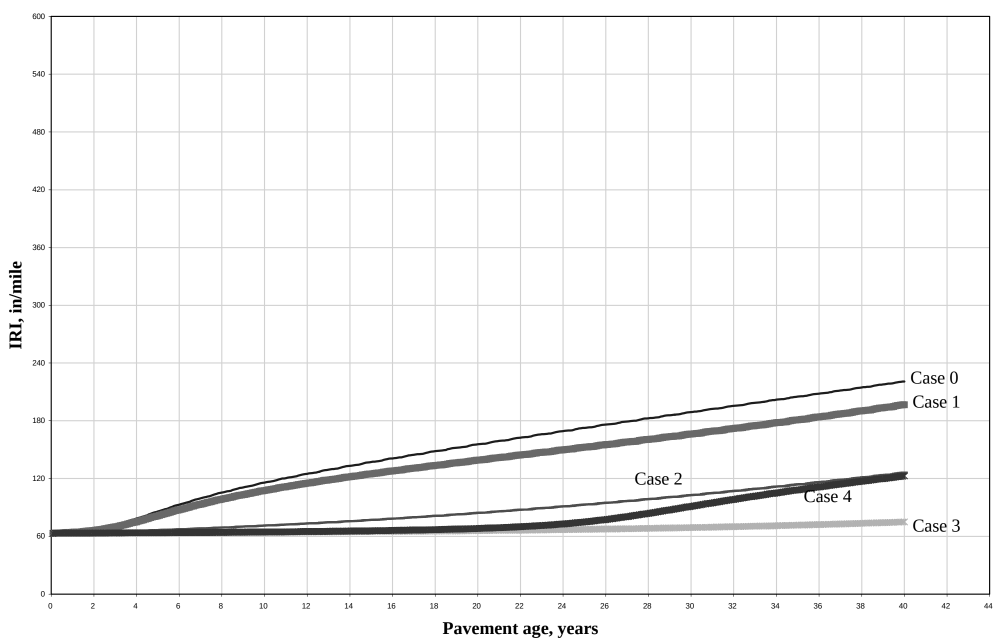

Figure 7. IRI growth for cases 0-4. Similarly to faulting, the IRI is controlled by dowel diameter and joint spacing.

Discussion and Conclusions

The design of concrete pavements in Sweden is based on specifications established in the 1990's. The procedure offers little change when altering parameters like climate, traffic, and material properties. In a first step towards the development of a new and more flexible method, an inventory of the U.S. Design Guide has been conducted. This paper focuses on the differences in traffic and thermal load calculations, as well as design criteria and damage analysis. Apart from the direct comparison of defined parts of the design procedure, a quantitative study of a highway project in Sweden has been performed with both methods.

The Swedish method considers distresses in the concrete slab, the bound base course, and the subgrade. The study shows, for instance, that the subgrade is decisive for the design. In the U.S. Design Guide the distresses in the pavement itself, i.e., cracking, smoothness, and joint faulting, are decisive in the design

The Swedish method accounts for bottom-up cracking and calculations with the Design Guide show that bottom-up cracking is critical in the design. Nonetheless, both top-down cracking and the load transfer efficiency contributes to the over all performance. The Design Guide is flexible in such a way that, by changing parameters for joint design, it can demonstrate how cracking or faulting can be decreased.

A level of damage of approximate 50%, can in the Swedish method, in this particular case study, be formulated in the subgrade after 40 years, i.e., by dividing the total number of ESAL's with the allowable number ESAL's calculated for the subgrade. The U.S. Design Guide reveals instead, on a 50% reliability level, a predicted 5 % damage in the concrete slab (Figure 5).

The level of distress used as design criteria in the U.S. Design Guide is to a certain extent dependent on the type of road that is designed. The designer establishes the allowable limit of cracking and expresses the criteria in terms of percentage of cracked slabs, percentage of LTE, or inches of faulting.

The calculations performed with the Design Guide are not accurate for the reason that the many input parameters, especially for materials in the subbase and subgrade, have not been evaluated regarding U.S. standards. Most inputs are taken directly from the recommended values provided by the Guide, i.e., level 3 model with the least possible inputs. The aim is, however, to model the Swedish pavement system and investigate in how to interpret the results.

The criteria for road construction in Sweden are different in that manner that it is difficult to put a number on the effective, accumulated damage. In the method, the safety margins are achieved by underestimating mechanistic properties.

The performance criteria must, nevertheless, be measurable in terms of relating percentages of distress to established criteria in preceding methods. Cracking is for instance, in Sweden, related to the flexural strength of concrete beams. The safety lies within the assumption that a slab is more resistant to stresses than a beam due to bi-axial load bearing, and that the stresses are calculated for the characteristic strength of the material, i.e., 28-days flexural strength (Silfwerbrand 1995, SNRA 2004).

The performance criteria in the Design Guide are developed with the intention that designers can decide what level of performance is acceptable for the actual design. The design can be weighed to the cost, i.e., using existent or available materials, chose simpler joint design features etc.. The modelling example considered in this paper could, for instance, be further improved by varying materials in the pavement system or choosing a stronger base course. The way of proceeding to achieve the best possible pavement depends much on the resources available and the engineering experience. The U.S. design procedure is different to methods applied in Sweden. Attempting to adopt a similar method requires new procedures to determine specific environmental effects, integrating new material characterisation methods, and assembling data for regional calibration of damage models.

Calibration data for a mechanistic based design, similar to the data used for the U.S. Design Guide, is for Swedish conditions very limited since less than 1 % of the national roads consist of concrete pavements but many of the necessary tools to establish a new methodology in Sweden are already at hand. Climate data are, as an example, collected continuously for weather predictions and could be retrieved and applied in the same way as in the U.S. Design Guide.

New methods to estimate traffic are also being developed in Sweden. Here, information on actual loads and actual axle configurations that are trafficking the roads in Sweden are being assembled. Traffic is divided in traffic classes in the same manner as in the Design Guide and these results will be applicable in future design (SNRA 2002). Material properties in Sweden originate from FWD tests conducted by the Swedish National Road and Transport Research Institute. Typical values for elastic modulus for different materials have been established in accordance with the SNRA. New methods to estimate nonlinear material behaviour will have to be utilised to get necessary information for pavement design if a more optimised method is chosen.

Further Research

This Ph.D. project is a part in the development of a new design method for concrete roads in Sweden.

The project will involve further investigation in international methods for design of concrete pavements and especially a deeper understanding of the methodology applied in the U.S. Design Guide. Further analysis of the Design Guide will include a profound examination of the material characterisation methods, an analysis of the calibration procedure, and an evaluation of the procedure in Swedish conditions.

Furthermore, laboratory tests on concrete and lean concrete will be conducted in order to verify and analyse the existing fatigue criteria in Sweden, and parameters for climate affects will also be analysed within this project.

Together with the Swedish National Road and Transport Research Institute and the Swedish National Road Administration a new computer-based design method for concrete pavements will be chosen, modified for Swedish conditions, and implemented in a computerised design guide.

Acknowledgment

The financial support provided by Cementa AB, the Royal Institute of Technology, and the Swedish Agency for Innovation Systems is gratefully acknowledged.

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