ECRPD
Energy Conservation in Road Pavement Design, Maintenance and Utilisation

Road deterioration models

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With the support of:

Intelligent Energy Europe

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Preface

VTI has on commission of the EU participated in the project "Integration of the Measurement of Energy Conservation in Road Pavement Design, Maintenance and Utilisation (ECRPD)": Coordinator of the ECRPD project has been Ray Vincent at Waterford County Council, Ireland.

This study of road deterioration models constitutes one of two parts part of WP5 in the ECRPD project. The following persons at VTI have contributed in this study:

- Ulf Hammarström has been project leader for the VTI part of ECRPD and responsible for the documentation
- Nils-Gunnar Göransson, road technology advices and support for the use of the LTPP data base
- Mohammad-Reza Yahya, statistical analyzes.

Summary

Road deterioration is depending on road strength. The strength of a road construction for each type of sub grade is supposed to be a function of the thickness of especially the bound layers in the road. Used materials in the construction also are of importance for the strength. When the thickness of these layers increases the strength (SCI300) of the road is supposed to increase but also the energy use for road construction.

Decision of a new road surface is based on road surface measures like:
- Cracks
- Road roughness (IRI)
- Ruts
- Cross fall.

Energy use for road traffic will increase when these measures increase. Another measure of importance for the road traffic is the macro texture of the surface (MPD). This measure will decrease by time. When MPD decreases this will reduce rolling resistance and fuel consumption.

In order to find an optimal strength of a road construction in order to minimize energy use for construction, maintenance and for the traffic there is need for road deterioration models. To some extent existing models have been used and in other cases new models have been developed. One most important existing model is the HDM-4 model. In this model one can notice there are local calibration factors in most sub models. This must be the case also for an ECRPD model.
One important explanation variable in the models is number of passing axles on heavy vehicles. These axles are translated into 100 kilo Newton axles (N100).

The presented models have been calibrated based on the Swedish LTPP data base. In this data base selected road sections, at most over 600, have been observed from 1985 and until today.

The strength of the road is the key variable for describing deterioration of the road surface. Unfortunately a representative model for strength is most difficult to develop based on statistical data. The estimated strength functions, based on LTPP statistics, of layer thickness have low degrees of explanation. The signs of estimated parameters based on statistics in several cases indicate reduced strength with increasing thickness. The proposed model is based on recommended values for road construction.

Models used for crack estimation are split into initiation and propagation. Existing models have been recalibrated and to some extent modified. Cracks are of importance both for IRI and MPD.

Ruts are caused by deformation from heavy traffic and from studded tyre wear.

The MPD value decreases by time until the crack propagation starts.

The change of IRI by time is expressed based on type of subgrade, SCI300 and the crack index. The average increase in IRI per year for a time period of 20 years is 0.018 and 0.030 when SCI300 is equal to 100 and 200 respectively and N100 is equal to 100000 per year. For a new pavement, in LTPP, IRI is approximately equal to 1.

The structure of the model for road deterioration is year by year and lane by lane.

For motorways different deterioration is expected in different lanes in the same direction.

Road strength in most sub models is an important explanation variable but at the same time without strong connection to layer thickness in statistics. The recommended strength information on the contrary has strong connections to layer thickness.. This contradiction is not satisfying.

1 Introduction

The strength of a road construction for each type of sub grade is supposed to be a function of the thickness of the unbound and the bound layers in the road. When the thickness of these layers increase the strength of the road increases but also the energy use for road construction. Decision of a new road surface is based on road surface measures like:

- cracks
- road roughness
- ruts
- ravelling
- potholes
- cross fall.

The road user has criteria's for each such measure to decide if a new road surface needs to be performed. When the criteria are reached for any of the measures there will be a decision for a new road surface. There will also be a time gap from the criteria is reached until the repavement is done.

Another question could be criteria's for the length of road with the criteria's reached in order to take a decision for repavement. For road planning purposes in Sweden the normal length for road surface data sections is 20 m.[1] The question then would be how many such 20 m sections have to meet the criteria in order to take a decision about repavement.

There also could be different categories of actions:

- just repairs of the surface
- recycling and use of the material in the existing pavement
- a new pavement above the old
- a total new construction.

The model described below represents the last two alternatives.

The longer one waits with adding a new road surface the more energy will be used booth for the repavement and for the traffic on the road. The increased energy use for the traffic is a function of increased driving resistance when the road surface deteriorates. The question of interest is to find the repavement periods and layer thickness that minimize the total sum of energy used for the total lifetime of the road. If the total lifetime would be a function of these variables as well the complexity of the analyze would increase.

There exists at least one complete model both for road measure change by time and for the traffic effects, the HDM-4 model (Odoki and Kerali, 2000). One problem with different models is road surface measures not used or familiar for the user. A model like HDM-4 includes local adjustment factors. In order to use the model such factors have to be estimated.

In Sweden there exist models for ruts, (Göransson, 2007), and for cracks, (Wågberg, 2001). The Swedish road planning system is based on measurements (RST) each year. Based on the RST-measurements year by year individual statistical prognoses are made for individual road segments. Then there is **no** need for a prognoses model, at least not for the RST measured roads.

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[1] In Sweden the road surface on the main road network is measured on an yearly basis. For these measurements so called RST vehicles are used. The measurement equipment among other things include laser equipment.

2 Objective

The objective for this study is:

- to make use of existing knowledge in the ECRPD project about road deterioration
- to develop a model describing road strength as a function of the unbound and bound road layers
- to put together existing models for the change of cracks, roughness, ruts and MPD by time
- to develop new deterioration models when there are no acceptable existing models.

3 Method

3.1 Overview

Useful available knowledge about road deterioration was only available at VTI among ECRPD partners. The existing knowledge of ECRPD interest at VTI included mainly:

- models for cracks
- models for ruts
- the LTPP data base.

Missing model knowledge is:

- for strength (SCI300)
- for roughness (IRI)
- for macro texture (MPD).

These missing parts have to be described in model form including parameter estimation.

3.2 The LTPP data base

3.2.1 The national Swedish LTPP-programme[2]

A short description of the data base is available in (Wågberg, 2008):

" The test sections are 100 meters in length and both directions are included in the monitoring programme. The pavements consist of a hot mix asphalt concrete layer placed over an untreated granular base. The monitoring programme started in 1985 with a small amount of sections. In the end of 2000 the LTPP-programme involved over 600 test sections distributed over more than 60 sites located in the middle and south of Sweden.

The sections in the Swedish LTPP-program were selected based on the following general criteria:

- there are no intersections, ramps, stop signs or other features close to the section which influence traffic movement over the test section,
- sections locate at grade or within consistent cut or fill with the depth of cut or fill approximately constant throughout the section in order to avoid inconsistent sub grade support and drainage conditions,
- transitional areas (cut to fill, shallow fill to deep fill, etc.) were avoided,
- test sections with added or widened lanes or shoulders were not accepted."

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[2] The LTPP data base can be reached: http://www.vv.se/templates/page3_____7830.aspx

"True profiles (transverse, longitudinal) of the monitored sections have been measured using a road surface monitoring vehicles, Laser RST (Road Surface Tester). Information is processed to calculate the International Roughness Index (IRI) values for each test section. Deflection measurements have been carried out with a falling-weight deflectometer manufactured by KUAB (Konstruktion & Utveckling AB) in Sweden. The surface condition was evaluated visually on an annual basis according to the Swedish distress identification manual "Bära eller brista" (Wågberg, 2003) for the Long-Term Pavement Performance program.

Other data items collected include among other things pavement age, traffic volume and the number of equivalent single axle loads. Measured data is stored in a database located at VTI. "

The following description includes data of interest in the ECRPD study i.e. there are other data in LTPP not presented here. Each of the following sections represents one data table in LTPP.

3.2.2 Object

An object includes a number of test sections. Data used on object level:
- identification of the object: county, community, road number
- date for including the object into the LTPP program
- date for ending data collection
- climate zone (in total the objects represents 5 climate zones)

Definition of climate zones (VV, 94):
- zone 1: cold index < 300
- zone 2: cold index 300 - 600
- zone 3: cold index 600 - 900
- zone 4: cold index 900 - 1200
- zone 5: cold index 1200 -

Cold index: abs(sum(average day temperature)) for all days during a year with average temperature below zero degrees (°C).

3.2.3 Test section

Each object includes a number of test sections, in average ten. With exception for MW a test section includes two directions. The length of a test section is 100 m. Test section data:
- section identification
- object identification
- road number
- opening data for traffic on the section
- total width of driving lanes (if MW the width of one direction, for other roads the sum of two directions)
- width of road shoulder
- type of road: MW or other

- speed limit
- sub grade type: 1=sand; 2=silty sand; 3=clay; (4=peat); 5=bedrock; 6=other
- ground frost risk
- sub base thickness
- base course thickness

Sub grade type 6, other, mainly includes moraine.

3.2.4 Test section measures (repavements etc.)

For each new repavement the following data is included:
- type of measure
- type of pavement
- date for the measure
- thickness of additional pavement

In this register all repavements, also before inclusion of the object in LTPP, is documented. Also the first pavement on the new road is included.

In table 3.1 frequent surface materials are listed.

Table 3.1 Frequent types of materials in wearing courses used in Sweden

1. WEARING COURSE	Max. size for stoneaggregate [mm]	Dense-graded asphalt concrete
	8	
	11	
	16	
		Stone mastix asphalt concrete (SMA)
	8	
	11	
	16	
		Thin asphalt surface course
	8	
	11	
	16	
		Open-graded (drain) asphalt concrete
	11	
	16	
		Cold mix
		Seal coat / Slurry seal
		Single surface treatment on bounded layer
	4/8	
	8/11	
	11/16	
		Double surface treatment on bounded layer
		Single surface treatment on gravel
		Double surface treatment on gravel
2. BASECOURSE		Basecourse (bounded)
	11	
	16	
3. ROADBASE		Roadbase (bounded)
	16	
	22	
	32	
		Grouted macadam (40 or 60 mm)
	8/22	
	16/22	
4. METHODS		Heating
		Repaving
		Remixing

3.2.5 FWD/deflection

The strength of a road is expressed by the FWD measure. Data included in the data base:
- test section identification

- driving direction
- date for measurement
- FWD hit number
- d0, d200, d300, d450, d600, d900 and d1200 (μm)
- ambient temperature (°C)
- temperature in the road surface (°C)
- temperature in the middle of the bound layer (°C).

About the measurements:
- in the right wheel track
- in the autumn after a measure
- earlier also in the spring before a measure
- measurements in five positions per wheel track (approximately 20 m between positions)
- down pressing in positions from the centre: 0; 200; 300; 450; 600; 900 and 1200 mm

3.2.6 VTI-RST

The different statistical road characteristics from RST, an average over the test section length (normally 100 m) per direction, are presented as follows:
- test section identification
- direction
- length
- Date for measurement
- IRI (left and right wheel track), wavelength 0.25 – m, unit (mm/m)
- *RMS* measures, left and right wheel track, wavelength 0.5– 30 m. unit (mm)
- *MRMS*, megatexture, wavelength 0.1– 0.5 m, unit m (mm)
- *RRMS*, rough macrotexture, wavelength 0.01– 0.1 m, unit (mm)
- *FRMS*, fine macrotexture, wavelength 0.002– 0.01 m, unit (mm)
- *MPD* (between wheel tracks and in the right track), wavelength 0.001 – 0.100 m, unit (mm)
- rut depth (left and right wheel track), unit (mm)
- rut maximum for the total width, unit (mm)
- rutSTDV (left and right wheel track), standard deviation of wheel track rut depth, unit (mm)
- hilliness, unit (%)
- crossfall, unit (%)
- curvature etc.

The measures for unevenness are measured in both wheel tracks. Further description of the RST system and the different measures can be found in (Arnberg et. al, 1991) and Swedish Road Administration (VV, 1998).

In general the texture of the road is classified in different wavelength areas as follows:
- Microtexture, wavelength - 0.0005 m
- Macrotexture, wavelength 0.0005 – 0.050 m

- megatexture. wavelength 0,050 – 0,500 m

The macrotexture are described of the RST measures: *MPD*. *FRMS; RRMS* and *MRMS*. The unevenness is described of the measures: *IRI* and *RMS measures*. *IRI* and *MRMS* have a small part of the wavelengths overlapping.

IRI data is available for the time period 1987 – 2007 in LTPP.

Rut data is available for different numbers of lazar. If one compare 17 with 11 lazar the first alternative gives a value approximately 0.3 mm bigger than the other alternative.[3]

Curvature is expressed as:

1/(R/10000)

R: radius (m)

One also adds a sign for curve direction:
- + for left turn
- - for right turn.

RST measurements are normally done during summer time with exception for test sections planned to be repaved. These are measured during the spring.
For motorways there are only RST measurements in the right lane.

3.2.8 Traffic
Available data:
- the sum of traffic in both directions
- percent heavy vehicles
- number of axels per heavy vehicle
- year of last measurement (S)
- year of the last but one measurement (T)
- percent change per year of total traffic from T to S
- percent change per year of heavy traffic from T to S

Comments about traffic data:
- there is not data for years outside the interval T - S
- for some test sections percent change values are missing
- in the data base there is no traffic data available before 1993 and after 2002.

Traffic flow values in general represents year S. If the object has left the program, traffic values will represent year T. For the interval T to S traffic is estimated by use of traffic change data in the register.

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[3] Thomas Lundberg, VTI.

Percent change per year represents compound interest

3.2.9 Cracks

Description of cracks (Wågberg, 2008):
"For analysis purpose a crack index was developed which takes into account the amount and severity level of each type of crack. The crack index is computed first by multiplying the amount of each type of crack occurring on a pavement surface by the weighing factor and by the corresponding severity level factor, respectively. Weighing factors were defined separately for each crack type (i.e. 2.0 for alligator and 1.0 for longitudinal cracking). Weighing factors for severity levels were as follows: low 1.0, moderate 1.5 and high 2.0. Subsequently all calculated distress values are summed to give the crack index. The Crack Index in this paper is based and calculated from traffic induced cracks in the wheel paths."

A wheel path has a width of 0.8-1 meter and represents what is caused by the heavy traffic. The index represents both paths in each direction i.e. a total length of 400 meter.

Cracks shorter than 1 m are assigned a length of 1m.

crackindex $(Si)= 2xKr(m)+LSpr(m)+TSpr(m)$

Kr: krackelering $=Kr_{low}(m) + 1.5 \times Kr_{average}(m) + Kr_{bad}(m)$
LSpr: cracks along the road $=LSpr_{low}(m) + 1.5 \times LSpr_{average}(m) + 2 \times LSpr_{bad}(m)$
TSpr: cracks across the road $=TSpr_{low}(nu)+ 1.5 \times TSpr_{average}(nu)+TSpr_{bad}(nu)$

Low, average and bad are defined in (Wågberg, 2003)

The reason for multiplying *Kr(m)* with 2 is that this type of damage should be twice as serious for the strength compared to *LSpr*.

The crack is supposed to be a function of heavy traffic. Because of this the cracks should be located to the wheel tracks or in the border area to the tracks.

Si-data in the register:
- Date for inspection
- Si for the left and right wheel track summarized for both directions of the road. For MW there is only inspection for one direction, the right lane only. The *Si* value for this direction has been multiplied by a factor 2"

The *Si* data in the register then is different from most other register data since it represents both driving directions of a road.[4]

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[4] In the following sections Si represents just one lane.

3.2.10 Weather conditions

Data of special interest:
- year
- average year temp (°C)
- average max temp i.e. an average of each max temperature per day (°C)
- average min temperature i.e. an average of each min temperature per day (°C)
- number of days per year with a min temperature < 0 °C
- number of days per year with a max temperature > 25 °C
- total precipitation per year
- number of days with precipitation > 0.1 mm

3.3 Measures used for analyse

3.3.1 Introduction

To a big extent the same variables as in the database have been used. In some cases other measures estimated from register data, described below, have been used. To some extent data is missing in LTPP. When such data is needed and possible to estimate, missing data has been estimated. The structure of the data base has not directly been suitable for the necessary analyzes. From the data base a new set of data has been organized suitable for analyze. One general problem in the analyze is that the number of "observations" for parameter estimation decrease with increasing number of explanatory variables.

3.3.2 Traffic

In the models there is need for both annual traffic and accumulated traffic. Accumulated traffic could be of interest both from the date for the opening of the road and from the last repavement.

Comments about traffic data:
- there should be traffic data available for the time interval T to S per test section
- for some test sections percent change values are missing i.e. traffic data is only available for year S
- if the section has left the program data is available for year T

In the data base there is no traffic data available before 1993 and after 2002. There is always traffic data available for at least one year.

For several test sections there is no percent change data available. Estimate year by year percent change values as follows:
- calculate average values for neighbouring counties
- calculate average values for the test section county
- calculate a final average as an arithmetic average of these two values

Traffic data is always missing outside year T and S. In order to estimate traffic data outside the interval T to S average national traffic change data is used, see table 3.2.

Table 3.2 Traffic change data (index) based on Swedish total national traffic.*

Year	Light	Heavy	Year	Light	Heavy
1980	0.732	0.899	1995	0.946	0.919
1981	0.726	0.895	1996	0.950	0.923
1982	0.736	0.898	1997	0.953	0.926
1983	0.748	0.904	1998	0.962	0.949
1984	0.756	0.895	1999	0.986	0.984
1985	0.782	0.897	2000	1.000	1.000
1986	0.789	0.881	2001	1.014	1.013
1987	0.838	0.914	2002	1.047	1.044
1988	0.885	0.937	2003	1.060	1.048
1989	0.933	0.965	2004	1.070	1.054
1990	0.923	0.945	2005	1.078	1.070
1991	0.933	0.920	2006	1.078	1.096
1992	0.945	0.891	2007	1.106	1.155
1993	0.925	0.873			
1994	0.935	0.896			

*Based on (Edwards et al, 1999) and statistics until 2007.

Measures of possible interest for explanation of road deterioration:
- light traffic
- heavy traffic
- axles for heavy traffic
- standardized N100 axles for heavy traffic
- weighted combinations of light and heavy traffic.

If accumulated traffic, the measure should be total accumulated traffic for selected time period. Traffic on a year level could be the traffic for a certain year or the average yearly traffic for a time period of several years.

In order to estimate a correct N100 one needs detailed local data for each test section.
The data needed, in order to estimate representative N100, for each passing heavy vehicle:
- with or without trailer
- axle arrangement for the motor vehicle and for the trailer
- type of suspension
- type of tyres
- load factor for the motor vehicle and for the trailer
- empty weight for the motor vehicle and for the trailer.

What also could be of importance is type of suspension and type of tyres: single or super single tyres. The importance of these factors is reported in (Hjort, 2008).
The LTPP information for heavy vehicles includes the amount of heavy vehicles and the average number of axis per such vehicle. VTI has estimated a correction factor in order to translate an ordinary axle to an N100 (Djärf, 1988):

Number of N100= (number of heavy vehicle axis) x 0.33

The true correction factor will vary with time and local conditions. However this single general correction factor is used as a general correction factor in this study.

Data in LTPP represent an average day. What is needed is traffic in one direction (one lane) on a year level or for a sum of years. Road surface data is in general measured in the autumn.

Traffic measures used:

total(j)= (total traffic in both direction per average day (j)) x 365/2

light(j) = total(j) x (1 – (percent heavy(j))/100)

heavy(j) = total(j) x (percent heavy(j))/100

N100(j) = heavy(j) x (average number of axels per heavy vehicle (j)) x 0.33

j: index for a year. j=1 for a year with new pavement. j=n for a year with the next repavement

sum(traf(j)) = (traf(1) + traf(2) + ...traf(j-1) + traf(j)) x (j – 1)/j

annual average(traf)$_j$:
            = traf(1), if j=1
            = sum(traf(j))/(j-1), if j>1

traf: light, heavy or N100

N100$_Y$(j)= annual average (N100)$_j$

Observe that "*annual average(traf)$_j$*" represents an annual average from the time of repavement until year *(j)*.

3.3.3 Road
Strength/Deflection (SCI300)
The description of *SCI300* is based on (Wågberg, 2008).
SCI300 is calculated from the measured FWD deflections as follows:

   SCI300= d$_0$-d$_{300}$

SCI300: the surface curvature index, μm

d$_0$: the surface deflection under the loading plate, μm

d$_{300}$: the surface deflection at distance 300 mm from the center of the loading plate, μm.

The distribution of *SCI300* in the LTPP data base is shown in figure 3.1.
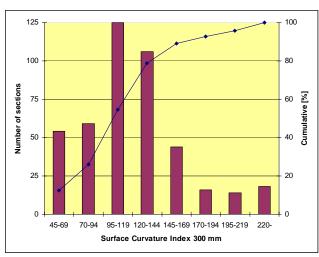
Figure 3.1. Distribution of SCI300 (Wågberg, 2008)

The *SCI300* measure was accepted in the PARIS-project.[5]
SCI300 is dependent of the temperature in the bound layers. There is a function available for describing the temperature dependence:

kd0 = 1 – (ABtemp – 20) x (0.0000975 x ABtjkl)
kd300 = 1 – (ABtemp – 20) x (0.0000517 x ABtjkl)

$SCI300t = d_0 \times kd_0 - d_{300} \times kd_{300}$

ABtemp: the temperature inside the bound layers at the deflection measurement (°C)

ABtjkl: the thickness of the bound layers (mm)

In the PARIS project all FWD measurements were adjusted to 20 °C.

In the models for *SCI300* the temperature adjusted alternative SCI300t is used. For crack initiation both alternatives are used.

There is a lack of *ABtemp* data. For such cases a function for estimation of *ABtemp* has been developed:

ABtemp = temp_surface + 0.436 x (temp_air - temp_surface)[6]

In order to add a value to temp_surface with a correct sign one would need information about the derivate of ambient temperature.

ECRPD:
- calculate *SCI300* per section with and without temperature adjustment
- use only the autumn falling weight measurements after the repavement

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[5] Performance Analysis of Road InfraStructure. EU´s fourth framework program for road transports.
[6] R^2= 0,838

- use the first value after repavement.

There is not enough data in LTPP to make calibration of the *SCI300* function for only new road constructions. For new roads a data set based on personal judgement and recommendations from NRA has been used. see appendix 1. [7] In Appendix 1 recommended *SCI300* for different type of roads with different traffic are presented. In this Appendix also recommended layer thicknesses for three different types of sub grades are presented.

The final *SCI300* values for analyze are results of one or two adjustments: missing ABtemp and correction of *d0* and *d300* to 20 °C.

Layer thickness
Unbound layers, thickness: the sum of sub base and unbound base course in the Test Section table.

Bound layers: total thickness of all bound layers in the table test section measures.

Subgrade
Separate functions for different subgrades have been estimated for: strength (*SCI300*) and for roughness.

Cracks
Si-data in LTPP is the sum of both directions and of both tracks. Data used for analyze is the crack-index/2 i.e. a value for one direction in order to correspond to traffic data in one direction.[8] For the propagation part *Sispec* is introduced. This measure represents cracks in one direction.

Roughness
There are separate *IRI* values per direction and wheel track. The model should express the average value per direction based on the two wheel tracks.

Macro texture
Per direction there are two *MPD* values available: in the right wheel track and between the tracks. An average value is calculated based on these two values.[9]

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[7] Nils-Gunnar Göransson, VTI, 2008.
[8] In (Wågberg,2001) the sum of two directions, the value in LTPP, is used. In this study the LTPP value has been divided by 2.
[9] What has been used is data from RST17.

Ruts
Per direction there are values available for the left and right wheel track. An average value per direction is calculated.

Cross fall
Crossfall is included in the road construction of two reasons:
- drainage of rain water
- reduction of the side force in horizontal curves.

For Swedish conditions the building instructions for cross fall depends on the horizontal radius of the road. When the radius increases the cross fall decreases down to a minimum value, 2.5 %. This value is reached when the radius is >2000 m

'

Other road data used without adjustments
Such data is:
- road width
- road shoulders
- speed limit.

3.3.4 Weather
Weather data is used in the same form as in the LTPP data base. One could notice that the same type of data is expressed in more than one way, for example:
- number of days with temperature below 0 °C
- average temperature of the year
- climate zone.

4 Models

4.1 Introduction

There are two main objectives, when estimating energy use, for selection of measures in road planning:
- measures used for decision about new road surface
- measures used for estimation of traffic effects.

The measures needed in the ECRPD model:
- the strength of the road construction
- cracks
- roughness
- macro texture
- ruts
- cross fall

These measures can be expected to have correlations between each other. In some cases there could be a discussion about what comes first, for example roughness or cracks. This can complicate modelling of these measures.

4.2 Strength (*SCI300*)

4.2.1 Strength in general

SCI300 has been expressed as a function of the dimensions of the bound and unbound layers in the road for different type of sub grades. The smaller *SCI300*, the higher strength in the road construction. When the bound layers increase the *SCI300* is supposed to decrease. The relation between strength and the thickness of unbound layers is not that obvious.

Looking at a new pavement, there is a question if *SCI300* only is a function of total thickness of the bound layers or if the age of underlying layers also is of importance.

SCI300 is available in LTPP with five values per test section direction, one per 20 m, with exception for MW. For MW only one direction and one lane are measured and available.

The available LTPP data is not enough to estimate a general function for *SCI300* function of layer thickness for a new road. The main focus will be on *SCI300* close after repavement.

SCI300 is depending on the temperature inside the bound layers. In the PARIS project deflection values were adjusted to 20 °C. In the PARIS project functions have been estimated with temperature adjustments to 20°C.

In HDM-4 road strength is characterised by the adjusted structural number, SNP. The adjusted structural number applies a weighting factor so that the strength for deep pavements is not over-predicted. The model for structural strength in HDM-4:
- the structural number constitutes a sum of contributions from: surfacing and base layers; the sub-base or selected fill layers and from the sub-grade
- the thickness of each base or surfacing layer

- depth parameter for the sub-base
- layer coefficient for subgrade
- pavement layer strength coefficients with a split as in table 4.1
- seasonal and drainage effects.

T*able 4.1 Structure for pavement layer strength coefficients in HDM-4.*

Layer	Layer type
Surfacing	Surface Treatment (ST)
	Asphaltic mix (AM)
Base	Granular Base (GB)
	Asphalt Base (AB); Asphalt Pavement (AP)
	Stabilised Base (SB)
Sub-base	Granular
	Cemented

4.2.2 Recommended data for new roads

There is not measured data available enough for statistical analysis of new roads. Instead **recommended values** for layer thickness and *SCI300* have been used.[10] Recommended *SCI300* values for different road types are presented in Appendix 1. In order to use the road deterioration models in ECRPD a *SCI300* value is needed. If the user is not familiar to *SCI300* a value for the road under construction might be selected based on Appendix 1. Appendix 2 includes *SCI300* values as a function of unbound and bound layer thickness for different subgrades. These recommended values should correspond to a temperature of 10-15°C.

The strength of the road before traffic exposure should be a function of at least: the type of sub grade; the thickness of the unbound layers and the thickness of the bound layers.

Different functions have been tested against these recommended values.

Tested functions:

SCI300 = a0 x exp(b1 x tub/100 + b2 x tb/100) ....(I)

SCI300 = a0 x exp((1 + b1 x tub/100) x (1 + b2 x tb/100)) ....(II)

SCI300 = a0 x exp(-(1 + b1 x tub/100) x (1 + b2 x tb/100)) ....(III)

SCI300 = a0 + b1 x tub/100 + b2 x tb/100 ....(IV)

SCI300 = a1 x (1 + b1 x tub/100) x (1 + b2 x tb/100)....(V)

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[10] Recommendations documented by Nils-Gunnar Göransson, VTI.

SCI300: the strength of the road directly after a new bound layer

tub: thickness unbound layers (mm)

*tb :*total thickness of bound layers (mm)

In table 4.2 estimated parameter values are presented.

Table 4.2 Estimated parameter values in functions for SCI300. Based on recommended data.

Function	a0	b1	b2	r^2
Gravel;	gravel/sand			
I	284.	*-0.115*	-0.457	0.99
II	106	*-1.31*	-5.38	0.99
III	225	-0.979	-2.86	0.981
IV	192	18.4	-58.0	0.998
V	190	0.109	-0.271	0.998
Sandy moraine				
I	295	*-0.0595*	-0.400	0.991
II	79.7	*0.259*	-3.99	0.989
III	136	-0.377	-0.698	0.993
IV	198	6.05	-64.7	0.998
V	22.8	*2.27*	*-0.320*	0.998
Clay				
I	342	-0.0629	-0.372	0.995
II	79.1	*0.173*	-3.97	0.99
III	111	-0.271	-0.548	0.996
IV	207	*2.00*	-61.8	0.997
V	*24.7*	*1.28*	-0.317	0.995
Bedrock				
I	162	*0.116*	-0.506	0.909
II	118	-0.658	-1.03	0.952
III	303	*-0.368*	0.455	0.928
IV	123	36.8	-40.8	0.928
V	181	*-0.0689*	-0.338	0,959

*xxx: not significant different from zero.

In Appendix 2 estimated values with function IV are presented.

4.2.3 Measured data for all test roads (LTPP) after repavement

The strength of the road is described by the first deflection measurements after repavement. Data used for analyze:
- the first FWD measurements after repavement
- total thickness of unbound layer and bound layer after repavement
- type of subgrade.

There is one separate analyze per type of sub grade:

- 1: sand
- 2: silty sand
- 3: clay
- 4: peat (not enough observations for statistical analysis)
- 5: bedrock
- 6: other (moraine etc.)

For each subgrade a number of functions have been tested:

$SCI300 = a0 \times exp(b1 \times tub/100 + b2 \times tb/100)$ ....(a)

$SCI300 = a0 \times exp((1 + b1 \times tub/100) \times (1 + b2 \times tb/100))$ ....(b1)

$SCI300 = a0 + b1 \times tub/100 + b2 \times tb/100$ ....(c)

$SCI300 = a1 \times (1 + b1 \times tub/100) \times (1 + b2 \times tb/100)$....(d)

SCI300: the strength of the road directly after a new bound layer

tub: thickness of the unbound layer (mm)

tb: thickness of all bound layers (mm)

The estimated parameter values for different subgrades are presented in table 4.3

Table 4.3 SCI300, estimated parameters, after a new pavement as a function of type of sub grade, thickness (mm) of unbound layers and of bound layers.

Sub grade	Function	a0	b1 (unbound)	b2 (bound)	r^2
sand	a	198	0.137	-0.789	0.637
sand	b	50.9	0.217	-0.390	0.653
sand	c	196	17.7	-106.	0.597
sand	d	129	0.273	-0.389	0.629
silty sand	a	227	*-0.0141*	-0.224	0.083
silty sand	b	80.5	*-0.00838*	-0.240	0.082
silty sand	c	225	*-3.65*	-35.4	0.087
silty sand	d	223	*-0.015*	-0.176	0.085
clay	a	195	*-0.0203*	-0.190	0.064
clay	b	70.4	*-0.0169*	-0.219	0.058
clay	c	187	-3.78	-21.6	0.067
clay	d	*0.00006*	*-302*	*-533*	0.058
bedrock	a	117	-0.0420	*0.383*	0.106
bedrock	b	39.3	-0.0318	*0.515*	0.113
bedrock	c	118	-5.64	*4.93*	0.109
bedrock	d	102	-0.039	*0.719*	0.118
other	a	136	*-0.0152*	0.0574	0.008
other	b	49.6	*-0.0142*	0.0629	0.008
other	c	138	*-0.0214*	0.0599	0.008
other	d	137	*-0.015*	0.048	0.008

*xxx: not significant different from 0.

In general the degree of explanation is low with exception for subgrade sand. In 15 of the 20 functions at least one parameter is not significant different from zero. The only subgrade with all parameter estimations different from zero is sand. However the unbound parameter has a plus sign which not is expected. The only subgrades with minus signs booth for unbound and bound thickness are silty sand and clay.

For bedrock there is in principle no need for unbound layers. Instead unbound layers are used in order to smooth out an uneven bedrock surface. An increasing thickness of unbound layers for bedrock is then an expression for worse building conditions. The parameter however has a plus sign, even if the estimation not is significant different from zero. The bound layer parameter for bedrock is not significant different from zero. The estimated parameter for bound layer has a "wrong" sign, a plus sign.

4.2.4 Discussion and conclusion about road strength

The strength relation to the thickness of layers is not the same for recommended values and for LTPP data. The average quote between LTPP and recommended values is for sand 0.69 and for

clay 0.98. If one compare LTPP subgrade other with sand moraine the quote is 0.91. The biggest difference in levels is for sand, the sub grade with highest r^2! If recommended values would be representative for LTPP test routes when new the conclusion would be that the strength contribution of a layer is dependent of the age of the construction.

The results based on LTPP are weak. One main reason for this should be that unbound and bound layer thickness not are good enough to reach a high degree of explanation, at least not for "old" roads. There are positive correlations between bound and unbound layer thickness:
- sand: 0.51
- silty sand: 0.15
- clay: 0.37
- bedrock: 0.51
- other: 0.20

To some extent these correlations might have disturbed the estimations of parameters for *tb* and *tub*.

HDM make a difference between the last bound layer and the other: the strength contribution from each layer is not the same.

The conclusion is that the functions based on recommended values should be used. Proposed function for use:

$$SCI300 = (a0 + b1 \times tub/100 + b2 \times tb/100)xk_{SCI,sg} \ ....(IV)$$

$k_{SCI,sg}$: strength correction factor for regional and subgrade conditions. Default value will be 1, representative for Swedish conditions.

The parameters to use are presented in table 4.2.

4.3 Cracks

4.3.1 In general
Models for cracks divide the crack process into two phases: initiation and propagation or progression. The initiation phase represents a period until the first cracks appear and propagation, a period with increasing cracks. The propagation phase follows directly after the initiation period.

HDM-4 considers two types of cracking:
- structural: load and age
- transverse thermal cracking: large diurnal temperature changes or freeze/thaw conditions.

Structural cracking is split into:
- initiation of all structural cracking
- initiation of Wide structural cracking
- progression of all structural cracking
- progression of wide structural cracking

Initiation of structural cracking depends on the base: stabilised or other bases.

There are different parameter values after pavement type and surface material.

Progression of structural cracking has different parameter values after pavement type and surface material.

Transverse thermal cracking is split into:
- initiation of transverse thermal cracking
- progression of transverse thermal cracking

In all cases there is a split into original surfacing and overlays/reseals. There are different parameter values after pavement type.

Definition of initiation: "Crack initiation is said to occur when 0.5 % of the carriageway surface area is cracked.

The model in (Wågberg, 2001) divides cracking of the road surface into two parts:
- initiation: the time or the accumulated traffic until the first cracks appear
- propagation or progression: the growth of cracks (Si) by time or accumulated traffic.

In (Wågberg, 2001).there is no split of the model into different types of cracking.
Instead of separate sub models for different types of cracking the crack index used in the model is calculated based on three types of cracking:
- crackled
- along the road
- across the road.

For more details, see section 3.2.9. The observed cracks are measured (length), weighted and summarized to one crack index.

4.3.2 Initiation

Existing model (Wågberg, 2001)

The initiation phase in (Wågberg, 2001) is expressed by the function:

$sum(N100(init))_2=10^{\wedge}(7.24-0.0052xSCI300-5010000 \times (1/(SCI300 \times N100_{Y2})))$

$N100_{Y2}$: average annual number of N100, sum for both directions

$Sum(N100(init))_2$: accumulated $N100_2$ year by year until the end of initiation (=start of propagation; when $2 \times Si \geq 5$)

$SCI300$: the strength for a new pavement[11]

One problem with $N100_{Y2}$ is the systematic change in traffic by time. If the average annual traffic value is used this will be a function of the time to the next new pavement and of the change in traffic year by year.

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[11] If SCI300 has been adjusted to 20°C is not obvious.

The model is not valid for all pair of values for $N100_{Y2}$ and $SCI300$. The valid area has a limit given of the function

$SCI300= (5010000/(0.0052 \text{ x } N100_{Y2}))^{0,5}$

This function represents the value of SCI300 for the maximum of the base function i.e. the point in which the derivate of the base function is equal to zero.
The model is not valid if $SCI300$ is less than values on the curve, see figure 4.1. The need of this limit function is an expression for shortcomings in the initiation function.

.**New calibration**
 Because we were not sure if traffic data in the model (Wågberg, 2001) was for one or two road directions and if temperature corrections had been used or not recalculation was done. Resulting calibration for the sum of traffic in **both** directions:

$Sum(N100(init))_2=10^\wedge(6.81-0.00339*SCI300t-6356951 \text{ x } (1/(SCI300t \text{ x } N100_{Y2})))$ *(with correction for temperature)*

$Sum(N100(init))_2=10^\wedge(6.81-0.00407 \text{ x } SCI300-5339200 \text{ x } (1/(SCI300 \text{ x } N100_{Y2})))$ (without *correction for temperature*)

This analyze showed that the function probably was calibrated for the sum of traffic in **both** directions. If temperature correction was used or not is not obvious.

Resulting calibration with traffic (*2 x Si>=5*) in **one** direction (=new model) and **with** correction for temperature:

$Sum(N100(init))=10^\wedge(6.51-0.00339 \text{ x } SCI300t-3178478 \text{ x } (1/(SCI300t \text{ x } N100_Y)))$

The r^2 value in this estimation is 0.612.

The parameter values have also been estimated for **one** direction and **without** temperature correction of SCI300:

$Sum(N100(init))=10^\wedge(6.51-0.00407 \text{ x } SCI300-2669603 \text{ x } (1/(SCI300 \text{ x } N100_Y)))$

The r^2 value in this estimation is 0.638.The hypothesis was that r^2 would be higher with than without temperature correction. The result was on the contrary.

The limit for validity is described of the curve:

$SCI300t = (3178478/(0,00339 \text{ x } N100_Y))^{0,5}$ *(with correction for temperature)*

$SCI300t = (2669603/(0.00407 \text{ x } N100_Y))^{0.5}$ *(without correction for temperature)*

In figure 4.1 the old and the new limit curves are illustrated.
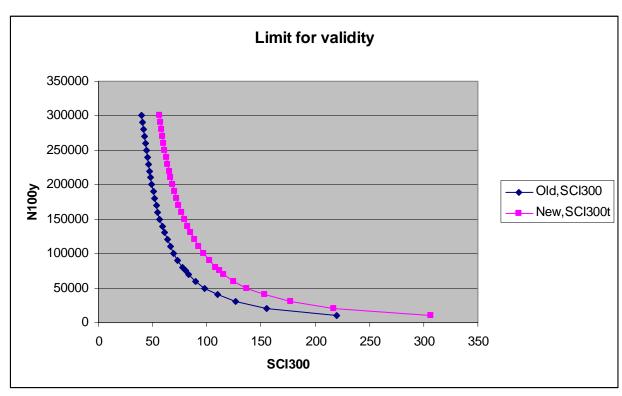
Figure 4.1 The initiation model is only valid for coordinates above the curve. The old curve is based on (Wågberg, 2001). $N100_Y$ represents traffic in one direction for both curves.[12]

The difference between the two curves in figure 4.1 is an expression for different data sets for calibration and probably temperature adjustment.
In order to handle situations with *SCI300t* and *$N100_Y$* outside the limit curve the value used for *SCI300t* is changed, increased, to the value on the curve. This change in *SCI300t* is just for the estimation of sum(N100(init)).

In figure 4.2 estimated values with the new calibrated function are presented.

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[12] For the old curve $N100_Y$ is multiplied by 2 when using the function for two directions.
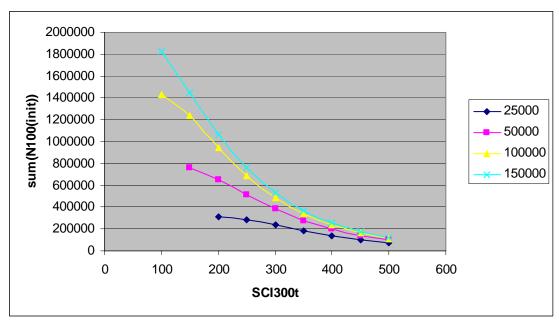
Figure 4.2 Length of initiation phase as a function of SCI300t per N100$_Y$.

In the calibration *2 x Si(init) = 18* as an average.

4.3.3 Propagation

Existing model

Principal model for crack propagation based on (Wågberg, 2001):

Y = a + b x X

a: 2 x Si(init), the value at the end of the initiation phase.

Y: crack index

b: parameter equal to propagation speed

X: sum(N100(prop))$_2$, traffic in both directions from the end of the initiation phase

In the development of the model the importance of different variables on *b* was examined. No effects could be demonstrated for:
- *SCI300*
- *N100(j)$_{Y2}$*
- Cold index
- *Si* before the last repavement.

One variable of importance for *b* was the relation between *2 x Si* and *sum(N100(init))$_2$* since the last repavement:

$b = 4,39 + 1.42 \times SR_0$

$SR_0 = 2 \times Si(init)/(sum(N100(init))_2 / 10^6)$

$Sum(N100(init))_2$: the observed sum of $N100_2$ until $2 \times Si \geq 5$

Resulting function for propagation (Erlingsson, 2008) based on Wågberg:

$Sum(N100(prop))_2 = (2 \times Si(prop)) \times 10^6/(4.39 + (2 \times Si(init)) \times 1.42 \times 10^6 / (sum(N100(init))_2))$

$2 \times Si(init)$: ≥ 5. the observed value (sum for both directions of the road)

$Sum(N00(init))_2$: is the observed value in parallel to the observed $2 \times Si(init)$ value.

For each test section there was separate parameter estimations. One hypothesis was that the parameter values should be correlated to some conditions. Any correlation of importance was not able to prove.

In order to use this function one needs to know $2 \times Si(init)$. This value need to be observed for each route. One alternative could be to use the limit value 5 as a general value. This would be a deviation from (Wågberg, 2001).

New models
The propagation function, to some extent also in principal adjusted, has been recalibrated. Select all observations with $2 \times Si \geq 5$ and a demand there also shall be observations $2 \times Si < 5$ before per test route.

Principles in existing models followed:
For each observation calculate:

$Sispec = ((Si(j) - Si(init)))/(Sum(N100(j)-Sum(N100(init)))$

This *Sispec* corresponds to the *b* value for progression speed above.

Compile for each new road pavement:
- one initiation value, *SRn*
- a number of *Sispec*

Each *Sispec* represents one observation of Si in the propagation phase.

There are two alternatives for SRn:
- $SRna = Si(init)/sum(N100(init))$
- $SRnb = 1/(sum(N100(init)))$

Tested functions:

$b = c + d \times SRna ...(a)$

$b = c + d \times SRnb ...(b)$

b = c x exp(d x SRna)...(c)

b = c x exp(d x SRnb)...(d)

Si = Si(init) + (Sum(N100(j))-Sum(N100(init))) x b

As a rough estimation, underestimation, one can exchange *(≥2.5)* to *2.5*. A more representative method would be to estimate *(≥2.5)* as an average value of observed Si(init). The average value for Si(init) x 2 in data is 18.

Resulting parameter estimations are presented in table 4.4.

Table 4.4 Estimated parameters in functions for propagation.

Function	c	d	r^2
a	0.000112	2.17	0.154
b	0.0000991	22.2	0.109
c	0.000178	2 798.0	0.069
d	0.000155	50 333	0.071

Alternative model principle:
Instead of estimating a propagation speed the accumulated propagation is expressed by:

Si(j) – Si(init) = (93.0 x ((Sum(n100(j) – Sum(N100(init))/10^6) -22.2 x ((Sum(N100(j)-Sum(N100(init))/10^6)^2) x (1 + 0.116/(Sum(N100(init)/10^6))

The r^2 value for the estimation is 0.355.

In figure 4.3 examples on additional Si during propagation are presented for different initiation periods (250000, 500000 and 1000000 N100)
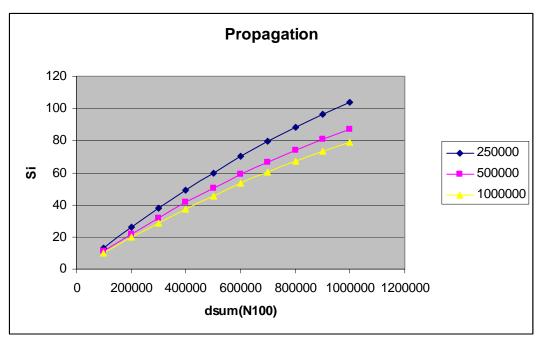
Figure 4.3 Additional Si during propagation for different initiation intervals – 250000, 500000 and 1000000 - as a function of accumulated traffic during propagation.
(dsum(N100)=sum(N100(j))-sum(N100(init)))

4.3.4 Discussion and conclusions about cracks

The main alternative for analyze has been to use *SCI300t*, the alternative with temperature adjustment to 20°C. The test of using the strength value without temperature adjustment gave for initiation a higher degree of explanation compared to the adjusted alternative. Possible explanations for such a result:

- the adjustment functions are not representative
- the temperature function for missing ABtemp values is not representative
- not adjusted values could be more representative for local conditions, temperature differences between different test routes in the LTPP data base.

Initiation

Proposed function for estimation of the length of the initiation phase:
Sum(N100(init))=(10^(6.51-0.00339 x SCI300t-3178478 x (1/(SCI300t x N100$_Y$)))) x k$_{init}$

k_{init} : initiation correction factor for regional conditions. Default value will be 1, equal to Swedish conditions.

This function has weaknesses in that sense that the function increases with decreasing SCI300 until one value and after that decreases with decreasing SCI300 i.e. the function is concave. The function increases with increasing N100$_Y$. In order to handle this problem one limit function has been presented by Wågberg.

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If
SCI300t < (3178478/(0.00339 x N100$_Y$))$^{0.5}$, then SCI300t:= (3178478/(0.00339 x N100$_Y$))$^{0.5}$

<u>Propagation</u>

Si(j) = Si(init) + (93.0 x ((Sum(n100(j) – Sum(N100(init))/10^6) -22.2 x ((Sum(N100(j)-Sum(N100(init))/10^6)^2) x (1 + 0.116/(Sum(N100(init)/10^6)) x k$_{prop}$

Si(init) = 9 (the value from the LTPP calibration)

k$_{prop}$: propagation correction factor for regional conditions. Default value will be 1, equal to Swedish conditions.

The proposed value for *Si(init)* is the average value received in LTPP when selecting the first observation with *2 x S(i)>5*.

4.4 Ruts

4.4.1 HDM-4
The model for ruts includes four components:
- initial densification
- structural deformation
- plastic deformation
- wear from studded tyres.

The initial densification is a function of:
- N100
- beam deflection
- structural number of pavement
- relative compaction.

There are two groups of pavement type parameters for initial densification[13]:
- AMGB; AMAB; AMSB; STGB; STAB; STSB
- AMAP; STAP.

There are two types of structural deformation: without cracking and after cracking.

The plastic deformation is a function of:
- construction defects
- N100
- speed of heavy vehicles
- total thickness of bituminous surfacing.

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[13] (Surface type/base type); AM: Asphaltic Mix; ST: Surface Treatment; GB: Granular Base; AB: Asphalt Base; SB: Stabilised Base; AP: Asphalt Pavement.

There are different sets of parameter values for: asphaltic mix (AM) and surface treatment (ST).

A surface wear model is applied for traffic with studded tyres. The model is a function of:
- annual number of vehicle passes with studded tyres
- average traffic speed
- salted or unsalted road
- road width.

4.4.2 VTI

A model for ruts is documented in (Göransson, 2007)[14]:

rut_d(j)= 10^((log10(0.9533 x sum(N100(j))) x a^(1/b)))/((1/b)+0.0209))

a=0.0001579 x SCI300+0.03432

b=0.0005695 x SCI300+0.2965

rut_d(j): rut depth from deformation *(mm)*[15]

SCI300 (μm)[16]

The model is valid per road lane. For roads with one lane per direction the conditions in most cases should be equal in both directions. For motorways the traffic conditions especially could be expected to be different between different lanes per direction.
The reason for not using temperature adjustment of SCI300 is that all measurements have been done at approximately the same temperature. If the model will be used for other temperature conditions than 10°C there is a question about the representativity of the model.
In figure 4.4 the resulting rut functions are presented for different SCI300.

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[14] Based on RST Trut_0 with 11 lazar.
[15] Trut_0 (3,2 m) RST
[16] Not adjusted for temperature.
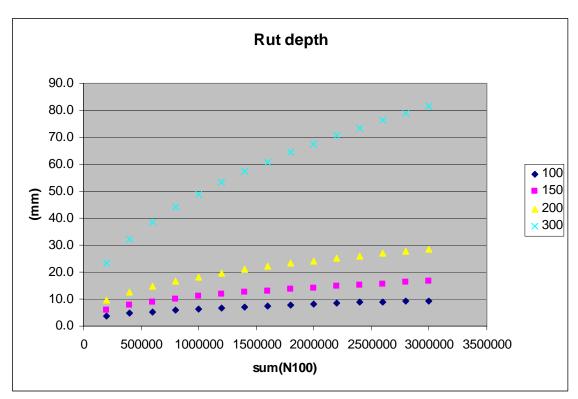
Figure 4.4 Ruts as a function of accumulated number of equivalent standard axles and SCI300.

The rut depth will also increase as a function of number of passing vehicles equipped with studded tyres. A more detailed model describing this type of wear is documented in (Jacobson and Wågberg, 2007). This can also be expressed as an increase in rut depth per passing vehicle with studded tyres:[17]

rut_st(j) = sum(light(j)) x (r_st/100) x (Nw/12) x wst

rut_st(j): total additional rut depth from light vehicles with studded tyres from the new pavement until the j:th year after repavement.

r_st: percent of light vehicles with studded tyres during winter months *(%)*

Nw: number of winter months per year

wst=2.3E-06 (mm/veh), light vehicle specific rut wear

If the proportion of vehicles with studded tyres is 62 % the additional rut depth per year would be like in table 4.5.

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[17] Information from Nils-Gunnar Göransson, VTI (2008).

Table 4.5 Additional rut depth (mm) from studded tyres per year.*

Veh/day	Winter months per year				
	2	3	4	5	6
1000	0.09	0.13	0.18	0.22	0.26
2000	0.18	0.26	0.35	0.44	0.53
3000	0.26	0.40	0.53	0.66	0.79
4000	0.35	0.53	0.70	0.88	1.06
5000	0.44	0.66	0.88	1.10	1.32

*Proportion of studded tyres: 62 % during winter months.

For the left lane(s), right hand traffic, in motorways probably other conditions than ruts will constitute base for decision about new pavement.

4.4.3 Discussion and conclusion about ruts

The deformation part model of ruts has been calibrated to SCI300 values measured at an ABtemp of approximately 10°C. If this temperature was a true traffic N100 weighted average for the year per test route and if the deformation function was linear to SCI300 the function should be representative. None of these demands are fulfilled. Despite these weaknesses there is a high degree of explanation (r^2=0,808) for the estimated function. If the estimated function was representative for an ABtemp of 10°C and if the temperature adjustment functions in section 3.3.3 were representative it would be possible to develop a deformation function including ABtemp.

The total rut depth is estimated as the sum of the *N100* deformation and the wear of studded tyres:

rut(j) = rut_d(j) x k_{rutd} + rut_st(j) x k_{rutst}....(mm)

rut_d(j)= 10^((log10(0.9533 x sum(N100(j))) x a^(1/b)))/((1/b)+0.0209))

a=0.0001579 x SCI300+0.03432

b=0.0005695 x SCI300+0.2965

rut_st(j) = sum(light(j)) x (r_st/100) x (Nw/12) x 2.3E-06

k_{rutd}: deformation correction factor for regional conditions. Default value will be 1, which will be representative for Swedish conditions.

k_{rutst}: studded tyre wear correction factor for regional conditions. Default value will be 1, which will be representative for Swedish conditions.

4.5 MPD

4.5.1 HDM-4

Comments based on HDM-4:
- MPD is expressed as a function of NELV (=light vehicles + 10 x (heavy vehicles))
- HDM-4 distinguish deterioration parameter values after surface type and surface material

Comments in general about a MPD model:
- the MPD value for a new road surface could be expected being a function of the maximum size of the stone material and of the distribution of stone sizes in the material.
- one hypotheses is that that MPD could increase when the crack propagation phase is reached
- one hypotheses is that the reduction in MPD for the same stone size depends of the pavement construction
- one hypotheses is that the change by time is depending of the lane and shoulder width
- one hypothesis is that vehicle speed influence change by time.

4.5.2 New model

In order to analyze, the empirical data has been grouped after <u>pavement class</u>. One analyze per such class has been performed.

Tested models[18]:

$MPD(j) = a0 + (a1 \times (sum(N100(j)) + a2 \times (sum(N100(j))^2) \times (1 + a4 \times (90\text{-speed limit}) + a5 \times (3,5 - (lane\ width))) + a3 \times Si \ ...(a)$

$MPD(j) = a0 \times exp(a1 \times ((1 + a4 \times (90\text{-speed limit})) \times (sum(N100(j)))) + a3 \times Si \ ....(b)$

$MPD(j) = a0 \times exp((1 + a4 \times (90\text{-speed limit}) + a5 \times (3.5 - (lane\ width))) \times (a1 \times (sum(light) + a12 \times sum(N100)))) + a3 \times Si \ ....(c)$

$MPD(j) = a0 + (a11 \times sum(light) + a12 \times sum(N100)_j) \times (1 + a4 \times (90\text{-speed limit}) + a5 \times (3.5 - (lane\ width))) + a3 \times Si \ ....(d)$

$MPD(j) = a0 \times exp(a1 \times (sum(N100(j)/100000))) + a3 \times Si \ ....(e)$

Si: crack index per lane

Lane width: 0.5 x (value in table "Sträcka")

---

[18] For calibration values for RST 17 have been used. There are MPD values from the right wheel track and from between the tracks. An average value of these two has been used for calibration.

The correlation between *sum(light)* and *sum(N100)* was too high for a meaningful analysis including booth. The resulting parameter values in function (e) for different type of materials are presented in table 4.6.

Table 4.6 Estimated parameter values for function (e): MPD(j)= a0 x exp(a1 x (sum(N100(j))/100000) + a3 x (Si_j) *

Surface type**	a0	a1	a3	r
ABS16	1.2586	-0.0044	*-0.0005*	0.059
ABT16	0.6039	-0.0253	0.0013	0.177
Y1B16	1.1216	-0.0218	*0.0003*	0.095
ABT12	0.5659	-0.0600	0.0033	0.656
Y1B12	0.9904	*0.0069*	0.0010	0.139
AG32	0.7360	-0.0155	*0.0004*	0.008

*xxx: not significant different from zero;**ABS: Stone mastix asphalt concrete; ABT: Dense-graded asphalt concrete; Y1B: Single surface treatment on bounded layer; AG: Roadbase (bounded); Y2B: Double surface treatment on bounded layer; Seal coat; the final number is the maximum diameter size of the stones.

In figure 4.4 the results in table 4.6 have been illustrated. The additional effect from road surface cracking is illustrated in figure 4.5.
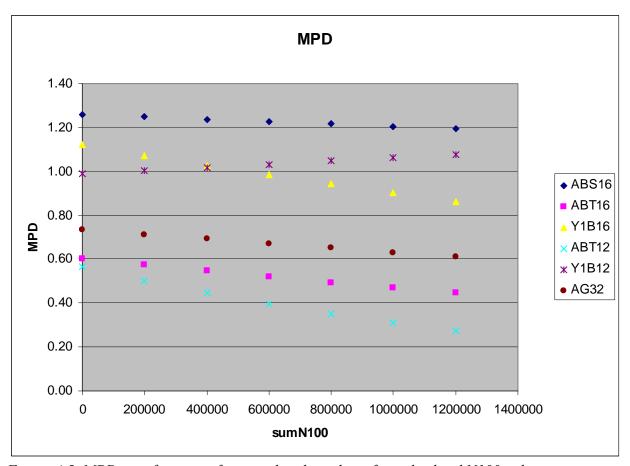
Figure 4.5 MPD as a function of accumulated number of standardized N100 axles.
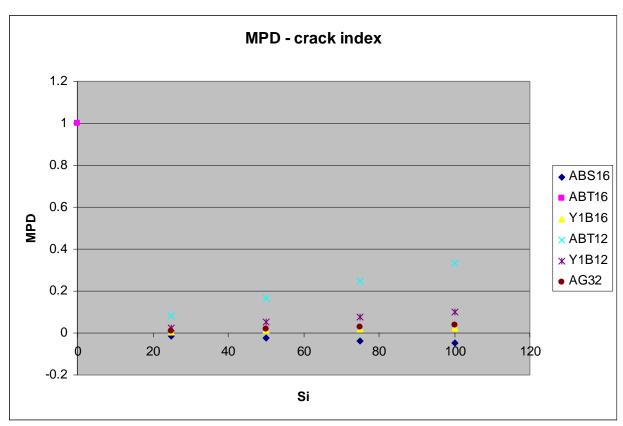
Figure 4.6 Additional MPD effect from road surface cracking.

The total MPD effect constitutes the sum of MPD in figure 4.5 and 4.6.

4.5.3 Discussion and conclusion about MPD

The degrees of explanation are low with exception for ABT12. Probably the degree could be increased with more representative traffic data per test route. Another possibility to improve the degree of explanation could be to consider wear from studded tyres.

The model to use in ECRPD should be:

MPD(j)= (a0 x exp(a1 x (sum(N100(j))/100000) + a3 x (Si$_j$)) x k$_{MPD}$

k$_{MPD}$: calibration factor for regional conditions. Default value will be 1, equal to Swedish conditions.

The parameter values to use are presented in table 4.6.

4.6 Roughness

4.6.1 Models

IRI is in HDM-4 described as an incremental change year by year. The total change by year is the sum of contributions, increments, from:
- structure
- cracking
- rutting
- potholing
- environment.

The *structural* increment is a function of:
- cracking
- thickness of most recent surfacing
- total thickness of underlying surfacing layers
- pavement age since last overlay
- annual number of *N100*

The *cracking* incremental change is just a function of the incremental change in total cracking during the analysis year.

The *rutting* contribution to IRI is just a function of the incremental change in rutting standard deviation.

The *potholing* contribution is a function of:
- carriageway width
- annual average daily traffic
- incremental change in number of potholes
- number of potholes at the start of the analysis year.

The *environmental* contribution is a function of time and calibration factors.

In HDM-4 there is no direct split of the model after road data, but since the structural increment is a function of structural number there will be an indirect split after table 4.1. Also cracks are used as explanatory variable in HDM-4. For cracks there is a split after base, pavement type and surface material.

Initiation of wide structural cracking has different parameter values after pavement type and surface material.

The basic idea for a model is increasing strength with increasing thickness of the unbound and bound layers respectively. This should be valid in most cases but with some exceptions like:
- subgrade sand: in principle there is no need for the unbound layers. They include approximately the same materials as in the subgrade
- subgrade bedrock: in principle no need for unbound layers. The use of unbound materials is for unevenness in the subgrade.

4.6.2 New model

Two groups of functions have been adjusted to LTPP data: one corresponding to the HDM-4 model and one after own ideas. For booth alternatives separate analyzes have been performed per sub grade type (5 classes) and basic function.

An "HDM-4" alternative

$dIRI(i) = a0 + a1 \times p(i) + a2 \times fr(i)/100 + a3 \times dSi(i) + a4 \times IRI(i-1) + a5 \times ((N100(j-1) + N100(j))/2)/1000000 + a6 \times SCI300.......(4.6.a)$

$p(i) = ((\ precipitation(i-1)) + (\ precipitation(i)))/2$

$fr(i) = ((number\ of\ days\ with\ min\ temp<0\ C(i-1)) + (number\ of\ days\ with\ a\ min\ temp<0\ C(i)))/2$

$dIRI(i)$: the change in *IRI* from the *i-1:th* to the *i:th* year after repavement

IRI(i): IRI at the *i:th* year

Si(i): crack index the *i:th* year after a road measure

i = 1,.. (dIRI(1) represents the deterioration during the first year after a new pavement)

The results from the parameter estimation are presented in table 4.7.

Table 4.7 *Additional roughness per year (HDM-4 alternative)*

Sub grade	a0	a1	a2	a3	a4	a5	a6	r²
Sand	-0.208	0.000082	0.0577	-0.001048	-0.002302	0.002621	0.000627	0.105
Silty sand	-0.0342	0.000041	0.00754	0.002624	0.003723	-0.034055	0.000064	0.028
Clay	-0.0503	0.000054	-0.00364	0.001258	0.025105	0.021123	0.000041	0.084
Bedrock	0.115	-0.000069	-0.0408	0.000035	-0.002494	0.009666	0.000113	0.054
Other	0.00313	-0.000010	-0.0110	0.000924	0.042367	0.007771	-0.000005	0.176
All	-0.0426	0.000028	0.00227	0.000840	0.027170	0.010042	0.000087	0.074

* There is an error in used traffic data for parameter estimation causing a "marginal" error in estimated paramer values.

The r^2 values for the functions are low. If this function is going to be used one needs a starting value *IRI(1)* in order to estimate the total *IRI(i)* value:

IRI(i) = IRI(1) + dIRI(2) +....+dIRI(i)

<u>Total IRI change by time</u>
An alternative to additional roughness per year *dIRI* is a function giving total *IRI(i)* directly:

IRI(i) = a00 + sum(N100(i))/1000000 x (a0 + a1 x medel_p(i) + a2 x medel_fr(i) + a6 x SCI300) + a3 x Si(i)........(4.6.b)

IRI(i) = a00 +(i) x (a0 + a1 x medel_p(i) + a2 x medel_fr(i) + a6 x SCI300) + a3 x Si(i).....(4.6.c)

IRIMedel = b0 + (i) x (a0 + a1 x Medelp + a2 x Medelfr) x (1 + a6 x SCI300start) + a3 x Si......(4.6.d)

medel_p(i): average precipitation from the repavement until year (i).

medel_fr(i): average number of days per year with min temp<0 C from the repavement until year (i).

i = 1,...   (i = 1 for the year of measure)

The best alternative for total IRI is function (4.6.c). In table 4.8 estimated parameter values are presented.

Table 4.8 Estimated parameter values for function (4.6.c)

Sub grade	a00	a0	a1	a2	a3	a6	r²
1	1.06	*-.0149*	*-.0000245*	.000242	*.0000447*	.00172	0.238
2	1.02	-.242	.000127	.000389	.000639	.0325	0.257
3	.895	-.139	.0000672	.000972	.000113	*-.000328*	0.200
5	.856	-.326	.000288	.00128	*.000123*	.00120	0.225
6	1.06	-.0444	-.0000893	.000660	.000117	.00193	0.368
All	1.03	*-.0132*	-.0000736	.000460	.0000712	.000972	0,174

*1=sand; 2=silty sand; 3=clay; (4=peat); 5=bedrock; 6=other; cursive: not significant different from zero.

In the development of an IRI-function there have been tests of including variables like speed limit and road width. The parameter estimations for these variables have not been significant different from zero.

Additional accumulated IRI change by time
Proposed function:

$$dIRI(t) = (t) (a + b \times SCI300t) + c \times (Si(i+t) – S(i))$$

dIRI(t): additional accumulated *IRI* for a time period *t*.

S(i): crack index at the start of the time period *t*. In most data cases *i* should be equal to zero i.e. the time for a new pavement.

In table 4.9 estimated parameters are presented.

Table 4.9. Estimated parameter values for function: dIRI(t) = (t) (a + b x SCI300t) + c x (Si(i+t) – S(i))

Sub grade	a	b	c	r²
Sand	-0.0224	0.000408	*0.0000353*	0.45
Silty sand	-0.0161	0.000244	0.000324	0.442
Clay	*-0.00287*	0.00021796	0.000328	0.352
Bedrock	*0.00740*	*-0.0000273*	0.000722	0.449
Other	0.0199	*0.000000262*	0.000331	0.483
All	0.0053	0.000113	0.000331	0.377

* cursive: not significant different from zero.

In figure 4.7 and 4.8 the IRI increase by time is demonstrated for SCI300t equal to 100 and to 200.
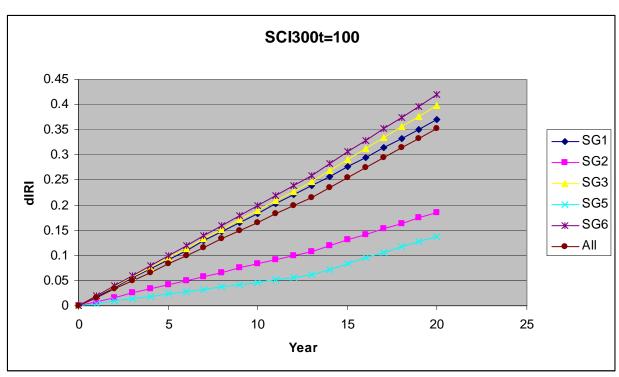
Figure 4.7 The IRI increase by time for SCI300t=100 and N100$_Y$=100000.
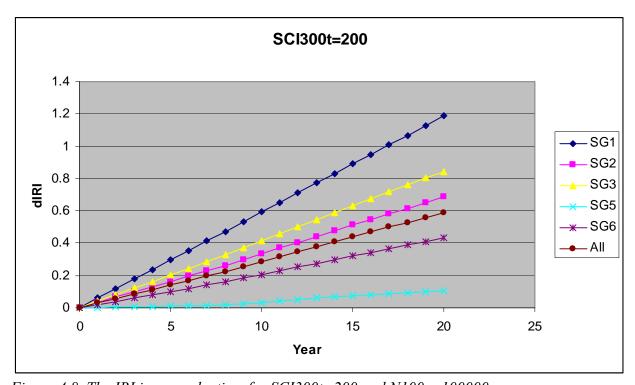
Figure 4.8 The IRI increase by time for SCI300t=200 and N100$_Y$=100000.

4.6.3 Discussion and conclusion about IRI

The proposed function to use:

$$dIRI(t) = (t) (a + b \times SCI300t) + c \times (Si(i+t) - S(i)) \times k$$

$$IRI(t) = IRI(0) + dIRI(t)$$

k_{IRI}: regional calibration factor, Default value is 1, which will be representative for Swedish conditions.

$IRI(0)$: the roughness for the new pavement. Default value will be 1, which will be representative for Swedish conditions.

There are different parameter values for different subgrades, see table 4.9.

4.7 Crossfall
The LTPP data has been used for correlation analysis, see table 4.10.

Table 4.10 Correlation analysis for crossfall and other variables.

Variable	Correlation with crossfall
Penecitration	0.096
Ambient temperature	-0.051
Cracks	-0.020
IRI	-0.005
N100	-0.013
Speed limit	-0.013
Road width	-0.184
Road shoulder width	0.064

Based on these correlations the conclusion was that it would not be meaningful to try developing a model for prediction of cross fall.

5 Discussion
The HDM-4 model is in most cases more complex than the one proposed in this study. In order to use HDM-4 together with the LTPP data base one needs to include structural number. Probably it would be possible to estimate structural number from *SCI300*. Such a transformation demands a data set with structural number and *SCI300* in parallel.
The HDM-4 model can not be used directly, one needs a local calibration. The ECRPD-model is designed as a general model but could need local adjustments as well.

The LTPP data base constitutes of test routes representing Swedish typical road construction. One draw back with such a limited selection could be that the variation in construction per set of condition could be too small in order to develop general representative models for deterioration. For the ECRPD objectives there is need for a representative model valid for a wide range of bound and unbound base coarse thicknesses. If the variation range in LTPP is good enough is not obvious.

Traffic data, especially *N100*, should be important variables in order to describe deterioration by time. Unfortunately the lack of these data is considerable in LTPP. Missing data has been estimated by statistical methods with unknown accuracy. For local representative *N100* one needs more information than number of heavy vehicles and average number of axis per heavy vehicle. Such data has not been available. Instead one general transformation factor, *0.33*, from axles on heavy vehicles to N100 has been used.

The strength in the road construction is a base for road deterioration. In order to estimate representative deterioration there must be a representative estimation of the strength. The strength of a road construction is a function of the thickness of different layers and of what materials used. The energy used for road construction is a function of the same variables. This estimation of strength then is of highest interest for ECRPD. One big problem then is to estimate representative strength values as a function of road construction, demonstrated in section 4.2.

FWD values in LTPP are measured in the right wheel track. One question could be if there are systematic differences between the right and the left wheel track. The cross fall of roads could result in a systematic difference in deterioration by time. For new pavements there should not be any systematic difference. Booth wheel tracks are included in the *Si* estimation.

FWD data has been adjusted for road temperature to represent 20 °C. There are different adjustment functions for different positions of the falling weight. It is not obvious why different positions should have different adjustment functions. The function for estimating missing temperature data inside the bound layers contributes to increase the data set for calibration of strength functions but also a contribution to deviation. One could notice that the use of SCI300 without temperature correction gave higher r^2 for initiation compared to the use of temperature adjusted SCI300t.

In the analyze SCI300 has been adjusted to 20°C. An alternative could be to adjust SCI300 after the temperature conditions per test route. This type of adjustment could then also be used between countries with different temperature conditions.

In the parameter estimations for crack initiation and propagation a limit has been defined as an index for both directions ≥ 5. For observations> 5, sum in both directions, data could have been adjusted to represent the limit value 5. Such an adjustment of sum(N100(init)) could be done by interpolation. For motorways the crack index only is observed in the lane to the right (for right hand traffic).

In the analyze MPD is an average of the right track and between the tracks. Other road surface measures, IRI, represent an average of the tracks only. If these models will be used as input to rolling resistance models this should be of importance.
MPD is described as a function of surface material and N100. For ruts a studded tyre effect on the road surface is stated. In order to be stringent there should be an MPD effect of studded tyre as well.

The IRI model estimated is based on sub base grouping of data. One alternative would be to split data after different type of pavements and surface material as well. Instead of the used split of roughness after five types of subgrades the use of two classes, like in HDM-4, could be enough.

The use of the model for motorways is a complication. The models are based on data for the right lane. In order to make estimations for the left lane, this must be done separately. As a simplified role the time interval between new pavements for the left lane on motorways approximately is twice the period length of the right lane.

6 Final model

The final model should include:
- strength, *SCI300*
- cracking, initiation and propagation
- ruts
- macrotextur, *MPD*
- roughness, *IRI.*

Road surface conditions need to be described **year by year** from the year of new pavement. The conditions are per lane. A normal situation should be a systematic change in traffic per year.

Strength, *SCI300t*
Input data:
- subgrade
- unbound layer thickness, mm
- bound layer thickness, mm

An alternative is that the user gives *SCI300t* directly as input.

Output data: *SCI300t* for a new pavement.
The proposed model is described in section 4.2.4.

Cracking
Initiation. Input data:
- *N100* per year and lane
- *SCI300t* for a new pavement

Just for initiation the selected SCI300t might be replaced if the value is below the limit curve value.

Output data:
- Limit curve for the validity of the initiation model
- Accumulated number of N100 until the start of propagation, *sum(N100(init))*.

Propagation. Input data:
- *Sum(N100(init))*
- *N100* per year and direction

Output data: *Si* per year. This value is the sum of *Si(init)* and additional *Si* during propagation.
The proposed model is described in section 4.3.4.

Ruts
Input data:
- *SCI300*
- *sum(N100(j))*, sum of *N100* year by year from new pavement until year (j)
- *sum(light(j))*
- number of months per year with studded tyres
- percentage of light vehicles with studded tyres

Output data: rut depth year by year and lane by lane after the pavement was new.
The proposed model is described in section 4.4.3.

Macrotexture, *MPD*
Input data:
- surface type
- *sum(N100(j))*, sum of N100 year by year from new pavement until year (j)
- crack index year by year.

Output data: MPD year by year and lane by lane from the new pavement.
The proposed model is described in section 4.5.3.

Roughness, IRI
Input data:
- sub grade
- SCI300t
- crack index year by year from the last repavement.

Output data: IRI year by year and lane by lane.
The proposed model is described in section 4.6.3.

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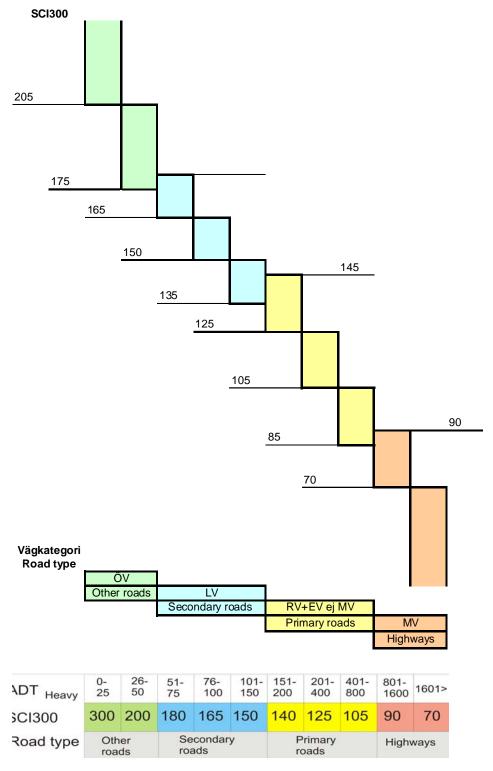
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Appendix 1: Recommended road strength (SCI300) for different type of roads

Source.[19]

SCI300

205

175

165

150

135

125

105

145

85

70

90

Vägkategori
Road type

ÖV
Other roads

LV
Secondary roads

RV+EV ej MV
Primary roads

MV
Highways

ADT $_{Heavy}$	0-25	26-50	51-75	76-100	101-150	151-200	201-400	401-800	801-1600	1601>
SCI300	300	200	180	165	150	140	125	105	90	70
Road type	Other roads		Secondary roads			Primary roads			Highways	

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[19] Nils-Gunnar Göransson, VTI, 2008.

Appendix 2: Recommended bound and unbound layer thickness for SCI300

Table 1 Recommended bound and unbound layer thickness for SCI300. Subgrade: Gravel, sandy gravel

tb	tub				
		100	**120**	**140**	**160**
40		188	191	195	**199**
50		182	185	**189**	193
60		176	180	**183**	187
70		170	**174**	177	181
80		164	**168**	172	175
90		158	**162**	166	170
100		153	**156**	160	164
110		147	**151**	154	158
120		141	**145**	148	152
130		135	**139**	143	146
140		129	**133**	137	140
150		124	**127**	131	135
160		118	**122**	125	129
170		112	**116**	119	123
180		106	**110**	114	117
190		100	**104**	108	111
200		95	**98**	102	106
210		89	**92**	96	100
220		83	**87**	90	94
230		77	**81**	85	88

Extra bold type: cells with available calibration data.

Table 2 Recommended bound and unbound layer thickness for SCI300. Subgrade: Sandy moraine

tb	tub									
		300	325	350	**375**	400	425	450	475	500	525
40		190	192	193	195	196	**198**	199	201	202	204
50		184	185	187	188	**190**	191	193	194	196	197
60		177	179	180	182	**183**	185	186	188	189	191
70		171	172	174	**175**	177	178	180	181	183	185
80		164	166	167	**169**	170	172	173	175	177	178
90		158	159	161	162	**164**	166	167	169	170	172
100		151	153	155	156	**158**	159	161	162	164	165
110		145	147	148	150	**151**	153	154	156	157	159
120		139	140	142	143	**145**	146	148	149	151	152
130		132	134	135	137	138	**140**	141	143	144	146
140		126	127	129	130	132	**133**	135	136	138	139
150		119	121	122	124	125	**127**	128	130	131	133
160		113	114	116	117	119	120	**122**	123	125	126
170		106	108	109	111	112	114	**115**	117	118	120
180		100	101	103	104	106	107	109	**110**	112	113
190		93	95	96	98	99	101	102	**104**	105	107
200		87	88	90	91	93	94	96	97	**99**	100
210		80	82	83	85	86	88	89	91	**92**	94
220		74	75	77	78	80	81	83	84	86	**87**
230		67	69	70	72	73	75	76	78	79	**81**

Table 3 Recommended bound and unbound layer thickness for SCI300. Subgrade: Clay

tb (mm)	tub (mm) **625**	**650**	**675**	**700**	**725**	**750**	**775**	**800**	**825**	**850**	**875**
40	195	**195**	196	196	197	197	198	198	199	199	200
50	188	**189**	189	190	190	191	191	192	192	193	193
60	**182**	183	183	184	184	185	185	186	186	187	187
70	**176**	177	177	178	178	179	179	180	180	181	181
80	**170**	170	171	171	172	172	173	173	174	174	175
90	164	**164**	165	165	166	166	167	167	168	168	169
100	157	**158**	158	159	159	160	160	161	161	162	162
110	151	**152**	152	153	153	154	154	155	155	156	156
120	145	**146**	146	147	147	148	148	149	149	150	150
130	139	139	**140**	140	141	141	142	142	143	143	144
140	133	133	134	**134**	135	135	136	136	137	137	138
150	127	127	128	**128**	129	129	130	130	131	131	132
160	120	121	121	**122**	122	123	123	124	124	125	125
170	114	115	115	**116**	116	117	117	118	118	119	119
180	108	109	109	110	**110**	111	111	112	112	113	113
190	102	102	103	103	104	**104**	105	105	106	106	107
200	96	96	97	97	98	98	**99**	**99**	100	100	101
210	89	90	90	91	91	92	92	**93**	**93**	94	94
220	83	84	84	85	85	86	86	87	**87**	**88**	88
230	77	78	78	79	79	80	80	81	81	82	**82**

Table 4 Recommended bound and unbound layer thickness for SCI300. Subgrade: Bedrock

tb (mm)	tub (mm) 20	35	50	65	80	95	110	125	140	155	170
40	114	120	125	131	136	142	**147**	**153**	158	164	169
50	110	116	121	127	132	**138**	143	149	154	160	165
60	106	112	117	123	128	**134**	139	145	150	156	161
70	102	107	113	119	124	**130**	135	141	146	152	157
80	98	103	109	114	**120**	125	131	137	142	148	153
90	94	99	105	110	**116**	121	127	132	138	144	149
100	90	95	101	106	**112**	117	123	128	134	139	145
110	86	91	97	**102**	108	113	119	124	130	135	141
120	82	87	93	**98**	104	109	115	120	126	131	137
130	77	83	89	**94**	100	105	111	116	122	127	133
140	73	79	84	**90**	95	101	107	112	118	123	129
150	69	75	80	**86**	91	97	102	108	114	119	125
160	65	71	76	**82**	87	93	98	104	109	115	120
170	61	67	72	**78**	83	89	94	100	105	111	116
180	57	63	68	**74**	79	85	90	96	101	107	112
190	53	59	**64**	70	75	81	86	92	97	103	108
200	49	**54**	**60**	65	71	77	82	88	93	99	104
210	45	**50**	56	61	67	72	78	84	89	95	100
220	41	**46**	52	57	63	68	74	79	85	90	96
230	**37**	42	48	53	59	64	70	75	81	86	92