MODELING PERFORMANCE PREDICTION, BASED ON RUTTING AND CRACKING DATA

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Abstract
Roads are in a state of constant form of deterioration, due to factors such as climate and heavy traffic loads and are therefore constructed to have a certain lifetime before being maintained. To minimize the cost of construction and rehabilitation, robust models for predicting their performance are needed. The aim of this project is to develop prediction models for flexible pavement structures for initiation and propagation of fatigue cracks in the bound layers, and rutting for the whole structure. The models are based on observations from the Swedish Long Term Pavement Performance (LTPP) database. The intention is to use them for planning maintenance activities; as a part of a pavement management system (PMS). A statistical approach is used for the modeling where both cracking and rutting are related to traffic data, climate conditions, the subgrade characteristics as well as the pavement structure. This paper will present validated models, linking climate, environment, construction methods, material and traffic with road distress.

Keywords: performance predictions, LTPP, rut, crack, statistical modeling.

1 INTRODUCTION

The value of a society's infrastructure is difficult to measure, but the benefits of a functioning road network are easy to understand. The constant exposure to climate and repetition of heavy traffic loads results in a form of unending deterioration. Pavement structures are complex systems involving the interaction of numerous variables. Their performance due to external loading is influenced by many factors such as material properties, the environment, traffic loading and construction practices. In the past, pavement design procedures have relied mainly on empirical relationships based on long term experience, and field tests.

To minimize this cost; a Pavement Management System (PMS) can be used for managing the road network. One of the critical elements in any PMS is the link to a realistic life cycle assessment modeling of the pavement structure. The analysis and decision making process requires high quality distress prediction models; and two of the most common distresses are: rutting and cracking (Hudson et al., 1994; Holt and Grambling, 1992; Stoffels and Kargah-Ostadi, 2010).

Aim: However the models used today are obsolete, due to changes in the climate, and technical advancements in the data gathering and processing. This project intends to develop new performance prediction models for flexible pavement structures for initiation and propagation of cracks in the bound layers as well as rutting for the whole pavement.

Method The key factors in deterioration process will be identified and connected to data found in the Swedish Long Term Pavement Performance (LTPP) database. The database contains information about the original geometry of the pavement structure, traffic counting at regular intervals, climate data and regular performance measurements of various kinds. It also contains a history of overlays or upgrades conducted. This is followed by extracting, processing, and analyzing data from the LTPP-database. The models will then be developed using different types of regression techniques.

2 LONG TERM PAVEMENT PERFORMANCE and PAVEMENT MANAGEMENT SYSTEMS

The Transportation Research Board and the American Association of State Highway and Transportation Officials began a project of monitoring the deterioration of the North American highways in the early 1980s. One of the outputs was the Strategic Highway Research Program, with a focus on an LTPP-monitoring program. The ambition of this program was to prolong the life period of any pavement structure by monitoring various pavement designs and rehabilitated objects, using different types methods and materials; subjected to different loads, environments and climate.

PMS are used to store and analyze road data as a part of the infrastructure of a society. The methodology is to attain the data needed to systematically analyze and prioritize and thereafter take action needed for maintenance and planning of everything related to the road network. A PMS can be defined as *a program for improving the quality and performance of pavements, and minimizing costs through good management practices* (Smadi, 2004; Corley-Lay and Mastin, 2009).

2.1 Swedish PMS and LTPP-database

In Sweden, though, it took almost ten years before a PMS with support for planning and evaluation of the result from the road maintenance was in use. Today it can act as a Decision Support System (DSS) for budget distribution on both national and regional level. Many of the models used in the PMS are rebuilt or recalibrated for the Nordic settings. The LTPP-database contains relevant pavement information with focus on road deterioration caused by heavy traffic and exposure to climate. The Swedish National Transport Administration (STA) has given the Swedish National Road and Transport Research Institute (VTI) the assignment to collect a large number of data concerning the state of several objects in Sweden. This project started 1984 and has continued to grow ever since with time. The gathering of data is done from several objects distributed according to the map in Figure 1. Most of the road objects in the LTPP-database are concentrated toward the southern part of the country as most of the traffic is there. The objects are selected from the national road network to ensure that they are constructed according to national standards. Each object is divided into smaller, 100 m sections but the number of sections in an object varies. The performance monitoring is mainly focused on road deterioration caused by heavy traffic. The database is public accessible and has been used in various research projects for pavement performance analysis and management decisions.

The gathering off the data is done both manually and automatically by the aid of an RST, and has the purpose of being a tool for constructing different types of road deterioration models for a PMS. The LTPP-database is public accessible and has been used in various research projects for pavement performance analysis and management decisions. The Swedish pavement design software "PMS Objekt" has been verified with the LTPP database.

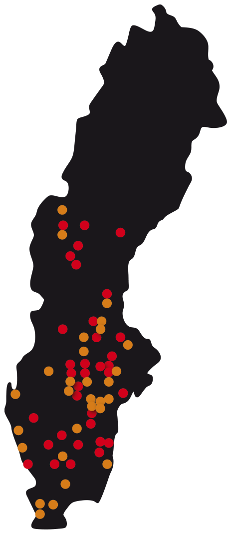

Figure 1: The geographical distributions of road objects in the Swedish LTPP database. The red dots are active objects, and the orange retired objects from data monitoring.

The database can also be used for calibrating and validating models, that requires detailed data regarding local conditions of pavement structures, bound and unbound material characterization, environmental conditions, traffic loading, and distress data, such as rutting, cracking, that stretches over the lives of pavement structures. The database is intended to have the design of a *Relational Model* and is stored in an *Microsoft Access* database (Swedish National Transport Administration, 2005; Göransson, 2009).

3 ROAD PERFORMANCE AND DISTRESS

A pavement performance can be defined as a "...a function of its relative ability to serve traffic over a period of time." (Highway Research Board, 1962). When road performance is quantified it is often described in terms of rutting and cracking. The rating is often high, medium, or low, based on a ocular inspection. In the end of the 1950 more objective measures started to appear in the literature.

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3.1 Rut measurements

The rut values in the LTPP- database are given in [mm]. The sampling is done automatically in motion, see Figure 2, this method gives small deviations each time the rut is measured, but these errors are neglected in this study. The rut depth is calculated using what is called the *"wire surface principle"*, which means that an imagined wire is stretched taut across the cross profile and the greatest deviation from this line measured at a right-angle constitutes the maximum rut depth.

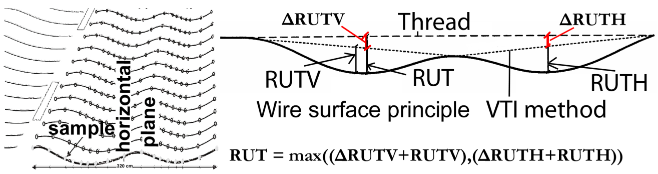


Figure 2: The method used by the RST for rut sampling.

The Figure 2 displays the rut development in [mm] measured over time for the object D-RV53-2 sections. The rut profile tends to be similar for the entire object.

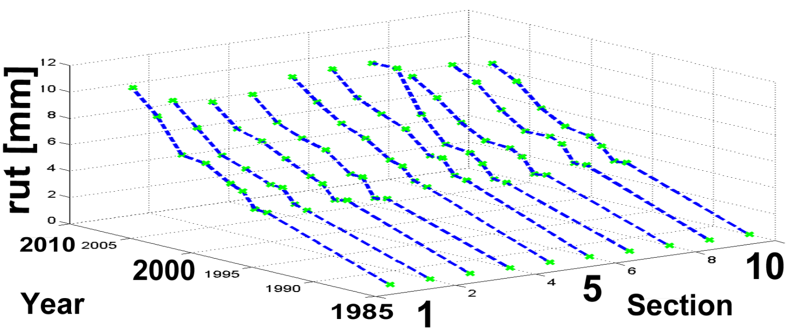


Figure 3: The rut development in [mm] measured over time for the object D-RV53:2 sections.

3.1.1 The Swedish rut model

The model used for rut, developed by Göransson N.G. (Göransson, 2009), predicts the number of accumulated standard axles allowed before a certain failure rutting depth is reached. In the model the total number of ESAL's for specific segment is given by Equation 1:

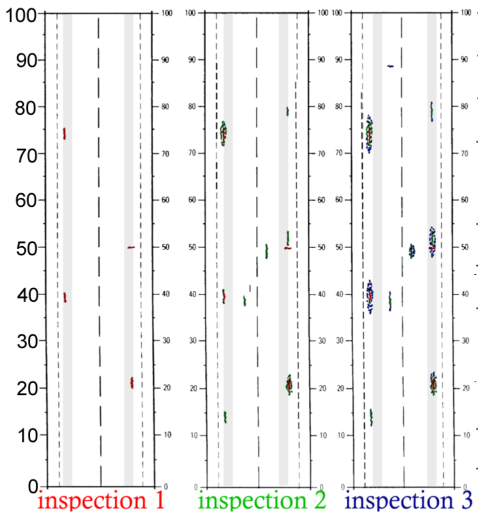
$$N_{100}^{rut} = \frac{1}{09533 * rut^{-0.0209}} * (\frac{rut}{a})^{\frac{1}{b}}, \tag{1}$$

where:

- N_{100}^{rut} is the average total annual ESALs per lane.
- rut is the total rutting in [mm] on the surface used to define failure.
- a and b are parameters estimated from FWD test as the surface curvature index SCI_{300} in [μm] measured during the fall (autumn), first time after the pavement structure is built.

3.2 Crack index measurements

A road object in the LTPP-database consists of 100 [m] sections, generally 8-13. All sections in an object are given a crack index (C_i) that describes the severity of a damage on a pavement structure calculated from a condition inspection. Each section is inspected at a regular time interval and classified with C_i. This is done manually and an example of this can be seen in Figure 4.



Inspection	1	2	3
Section	$C_i = 7$	$C_i = 46$	$C_i = 103$
1	Lc_{low} 2 [m]	Ac_{low} 6 [m]	Ac_{mean} 8 [m]
2		Lc_{low} 2 [m]	Ac_{low} 7 [m]
3		Lc_{mean} 2 [m]	Lc_{large} 3 [m]
4			Tc_{mean} 1
5		Lc_{low} 2 [m]	Lc_{mean} 4 [m]
6		Lc_{low} 3 [m]	Ac_{low} 3 [m]
7		Lc_{low} 2 [m]	Lc_{large} 3 [m]
8		Lc_{mean} 3 [m]	Ac_{mean} 6 [m]
9	Tc_{low} 1	Tc_{mean} 1	
10	Lc_{mean} 2[m]	Ac_{low} 4 [m]	Ac_{large} 5 [m]

Figure 4: Example of size and development of a crack between three different inspections of the same road that is carried out at different times. This object of 100 [m] long, which is divided into smaller 10 [m] sections.

The index increases with the level of severity and spreading, but also on the type of crack. The crack index is empirical, and based on a visual survey calculated as Equation 2:

$$C_i = 2A_c + L_c + T_c, \tag{2}$$

where:

- A_c : *Alligator cracking*; A_c *low* $[m] + 1.5 * A_c$ *average* $[m] + 2 * A_c$ *bad* $[m]$
- L_c : *Longitudinal cracks*; L_c *low* $[m] + 1.5 * L_c$ *average* $[m] + 2 * L_c$ *bad* $[m]$
- T_c : *Transversalcracks*; $T_c low\ (no) + 1.5 * T_c average\ (no) + 2 * T_c\ bad\ (no.)$

"Low", *"average"* and *"bad"* are weights defined in Bära eller Brista (Wågberg, 1991), and *"no."* stands for the number of cracks. Cracks shorter than 1 [m] are assigned a length of 1 [m]. All the sections in an object are given a C_i value, but this study uses the mean value of these as an index describing the entire object. This is described in Figure 5.

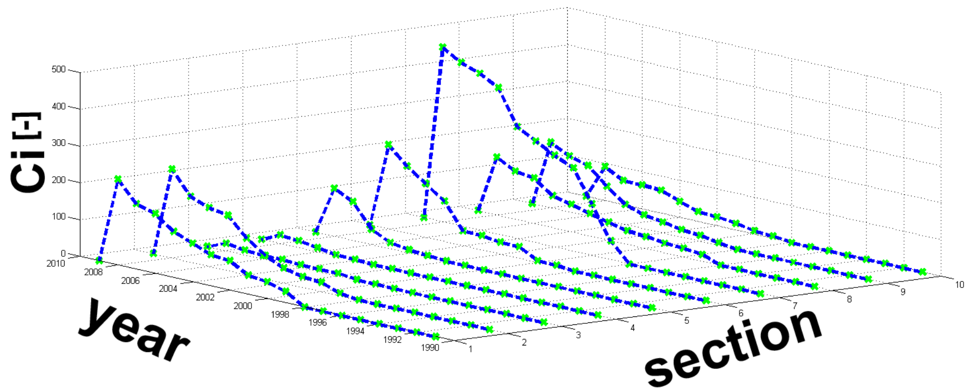


Figure 5: Crack index (C_i) for the sections in the object D-RV53-2, a maintenance was performed 2009 hence the C_i goes down to 0

3.2.1 The Swedish crack models

The C_i is divided into: *initiation phase* and *propagation phase*, $5 > C_i \geq 5$. In the crack propagation model developed by Wågberg L.G. (Wågberg, 2007), the accumulated heavy traffic loading is represented by equivalent standard axle loading ESALs repetitions. The total number of ESALs for specific section, N_{100}^{Cr}, is given as the sum of the standard axle repetitions for crack initiations and for crack propagation respectively up to failure. Presented in Equation 3:

$$N_{100}^{Cr} = N_{100}^{Crini} + N_{100}^{Crpropa}. \tag{3}$$

Where the number of axle repetitions for crack initiations is given by Equation 4 and for propagation by Equation 5.

$$N_{100}^{Cr_{ini}} = 10^{7.24-0.0052*SCI_{300}-5010000*\frac{1}{SCI_{300}*N_{100}^{Y}}} \quad and \quad (4) \qquad N_{100}^{Cr_{propa}} = \frac{195*10^5}{4.39+\frac{7.1*10^6}{N_{100}^{Cr_{ini}}}}. \quad (5)$$

Where:

- N_{100}^{Y} is the average annual ESALs per lane.
- SCI_{300} is the surface curvature index in [m] based on a FWD measurements, carried out at a temperature of 20^{o}C on the structure recently construction.

4 MODEL FACTORS

The models in this study have the intention of only to be valid for objects that are of *"virginal"* form. The models are developed under the assumption that the all the objects used had no cracks and rut depth is zero when no measured data was available. The models are to be used in the maintenance planning phase for roads in cold climate regions. The data in the LTPP-database chosen to represent the input factors are:

- Traffic, represented with N_{100} (ESALs).
- Climate represented by:
  - mean annual temperature, MAT, in [^{o}C] measured over a time period of 30 years.
  - mean precipitation in [mm] over a time period of 30 years.
- Aging, in the meaning of years from construction date.
- Pavement Structure represented with M_R.
- The present C_i value.
- Subgrade represented with SCI_{300}.

The SCI_{300}, from FWD measurements, and M_r, the modulus of resistance, value should be the value measured one or two years after construction, or estimated from the measure nearest in time, and those values are to be used during the entire prediction time. In the following section are the results from the models presented, the data is plotted against time in years from which the object was opened for traffic.

4.1 Crack Index Models

The structures of the models for cracking are for initiation given as Equation 6:

$$C_{i_i} = \beta_1 + \beta_2 x_1 + \beta_3 x_2 + \beta_4 x_3 + \beta_4 x_5 + \beta_6 x_5 + \beta_7 x_6 + \varepsilon_i, \quad (6)$$

if the calculated $C_{i_i} < 0$, then the C_{i_i} is replaced by 0.
Where:

- $\beta_1, ..., \beta_7$ are the model parameters.

- x_1 the SCI_{300} value
- x_2 the M_r value
- x_3 the N_{100} value
- x_4 the precipitation value
- x_5 the temperature value
- x_6 the age, in number of years

- ε_i is an independent random variable, with the expectation value = 0 and variance = σ^2

The test result for all the objects, used in this project, is shown in Figure 6.

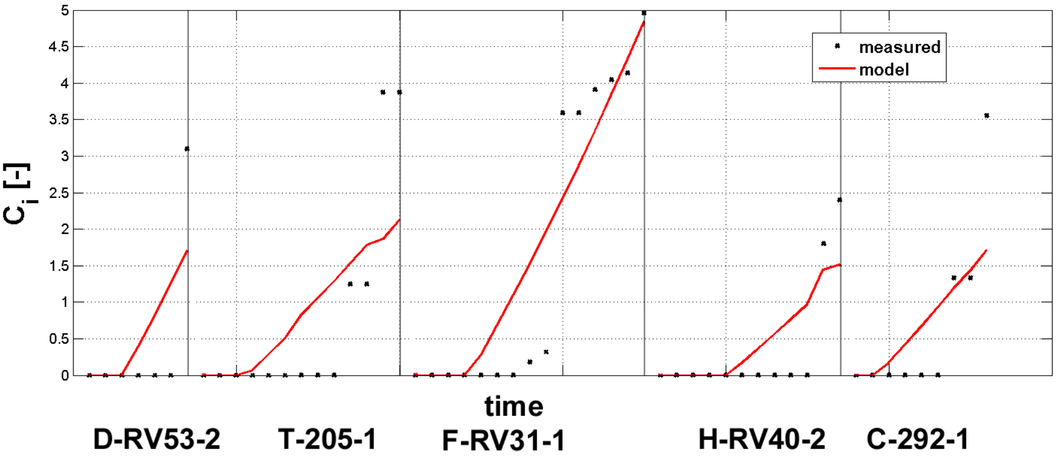


Figure 6: A plot that shows the result for all the objects used. The black dots are the measured data, and the red line is estimated. The C_i is measured as a function of time.

The R^2 value ranges for the individual objects [0.51,0.87].

4.2 Propagation

The propagation model is given by Equation 7:

$$C_{i_p} = \frac{\beta_1 x_3^2 + \beta_2 x_4 + \beta_3 x_5 + \beta_4 x_6^2 + \beta_5 x_7}{(x_1 + x_2)} + \varepsilon_p, \tag{7}$$

if the calculated $C_{i_p} < 5$, then C_{i_p} is replaced by 5. Where:

- C_{i_p} is the predicted C_i.
- $\beta_1, \ldots, \beta_5$ are the model parameters.
- x_1 and x_2 are the M_r and SCI_{300} constants
- $x_3, \ldots, x_6$ variables are the same as in the C_{i_i} model.
- x_7 the present C_i value.
- ε_p is an independent random variable with the expectation value = 0 and variance = σ^2.

The result is shown in Figure 7.

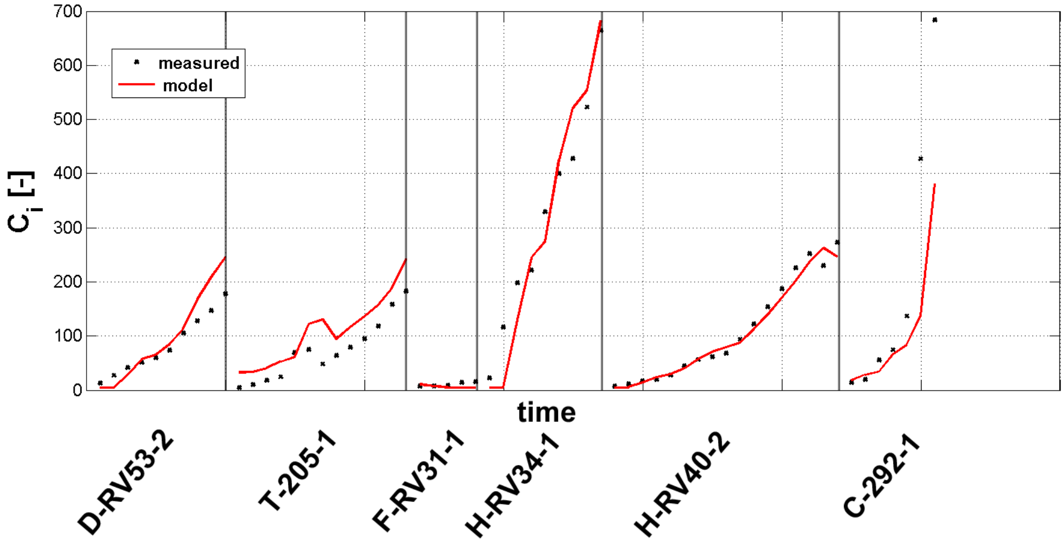


Figure 7: A plot that shows the result for all the objects used. The black dots are the measured data, and the red line is estimated. The C_i is measured as a function of time.

The R^2 values ranges from [0.52,0.97].

5 RUT MODEL

The rut model is given by Equation 8, as:

$$rut = \beta_1 + \beta_2 x_1 + \beta_3 x_2 + \beta_4 x_3 + \beta_5 x_4 + \beta_6 x_5 + \beta_7 x_6 + \varepsilon_{rut}, \tag{8}$$

if the calculated rut < 0, then rut = 0. where:

- rut is the predicted rut in $[mm]$.
- $\beta_1, \ldots, \beta_6$ are the model parameters.
- $x_1, \ldots, x_6$ variables are the same as in the C_i models.
- ε_{rut} is an independent random variable with the expectation value = 0 and variance = σ^2

The model was created using data from five different objects, and the test results from two of those are shown in Figure 8.

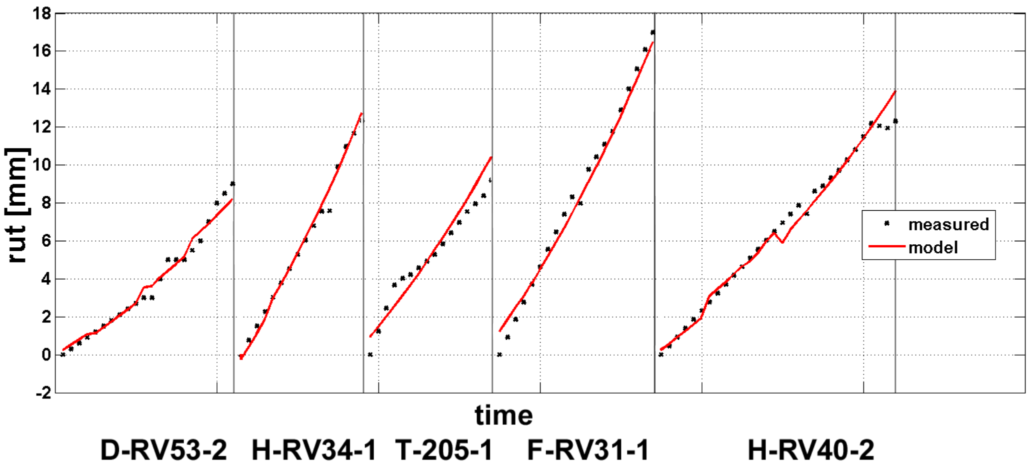


Figure 8: A plot that shows the result for all the objects used. The black dots are the measured data, and the red line is estimated. The rut is measured as a function of time.

The R^2 values ranges between [0.96,0.99].

6 RECOMMENDATION

The recommendations from this project are the models with the β-coefficients presented here:

$$\beta_{\mathbf{C_{i_i}}} = \begin{bmatrix} 5.52 \\ -0.004 \\ 0.002 \\ 5.07 \\ -0.007 \\ -0.31 \\ 0.06 \end{bmatrix} \qquad \beta_{\mathbf{C_{i_p}}} = \begin{bmatrix} -5.84e-10 \\ 14.20 \\ -2090.35 \\ -4.88 \\ 382.12 \end{bmatrix} \qquad \beta_{\mathbf{r}} = \begin{bmatrix} 22.88 \\ -0.003 \\ 0.01 \\ 9.3e-006 \\ -0.01 \\ -2.58 \\ 0.07 \end{bmatrix}$$

6.1 Variance

The variance for the models is estimated as: $s^2 = \frac{SS_{RES}}{n-k-1}$, where:

- SS_{RES} - The variation in the result that the models was not able to predict.
- n - the number of observed data.
- k - number of explanation factors.

The C_i models gives for the initiation model a s^2 = 0.86, and for propagation 0.89. For the rut model the s^2 is 2.5163e-018.

6.2 Sensitivity Analysis & Validation

All the data in the Swedish LTPP-database are of course measured on a finite number of occasions that are meant to be representative for a longer time period, but some measurement are more sensitive for errors them others, sensitivity tests were performed on each model and the results are:

- C_{i_i} model: M_r and SCI_{300} are the most sensitive factors for errors.
- C_{i_p} model: no factor seems to be more sensitive then the others.
- *rut* model: no factor seems to be more sensitive then the others.

When it comes to validation the low number of samples can only give indications. The models created has been validated on objects W-RV80-1 and Z-E45-4.

W-RV80-1 The R^2 is for the predicted C_i 0.95, and rut 0.99, but the number of available samples is very low.

Z-E45-4 The R^2 is 0.89 for the rut, but not defined for the C_i. The number of available samples is also here very low.

7 CONCLUSION & DISCUSSION

Prediction models have been developed based on observation from the Swedish LTPP-database, with the intended of aiding planning of maintenance as a part off a PMS. The models seem to be able to predict performance adequately; however they need further testing and calibration before they can be used. To increase the models reliability more larger data sets are needed. The plan for the gathering of data needs to be changed before a proper validation can be conducted. That may result in restructuring of the models.

A large part of the road network in Sweden consists of roads designed according to older standards giving some variation in pavement thickness and support layer material. This can cause problems when evaluating the performance models, and calibration of the factor parameters is needed before they are applied. The validation can only give indications due to the small set of data and the high number of factors. The precision in the numerical data given from the LTPP-database can be discussed, however that is not an aim for this article.

These new models will allow the Swedish National Transport Administration to prudently manage the road network, in a cost effective manner.

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