Antti Ruotoistenmäki

CONDITION DATA IN ROAD MAINTENANCE MANAGEMENT

HELSINKI SCHOOL OF ECONOMICS

ACTA UNIVERSITATIS OECONOMICAE HELSINGIENSIS

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Abstract

Knowledge of the current and optimal condition of road assets is an essential part of maintenance management. This knowledge can be used as an input in the management process and also as a tool for evaluating maintenance strategies and policies. The framework for this study is thus two-fold: Firstly, how to optimally collect road condition data, based on the knowledge of its accuracy from measurements and models. And, secondly, how to present and use this information in maintenance management, where the costs and benefits of maintenance policies are evaluated.

In the maintenance management framework, specific mathematical issues inherent in data collection and analysis are raised. A basic assumption is that the properties of a road condition measurement series along the length of road can be depicted using models for autoregressive processes. It is demonstrated that even though statistical deviation from normal distribution is likely for large samples from entire networks, normal distribution for homogeneous road sections can be achieved by using the logarithmic transformation.

The accuracy of measured and modelled road condition data is estimated by the standard deviation of logarithmic indicator values. A cost-benefit analysis based on data accuracy indicates that using the current monitoring vehicles for road surface profile, measurements can be taken every other year. The optimisation model for maximisation of benefits from taking new measurements, combined with the balancing constraints is developed into a route optimisation model. As a result, the measurement budget can be allocated so as to yield maximum benefit in terms of expected length of reclassified road.

Based on factor analysis of measured road condition data, a flexible road condition classification is developed. The resulting classification is then used in the economical analysis of maintenance policies, using a simplified method that relates maintenance funding to network condition. This method is especially suitable for finding an appropriate maintenance policy when the target for condition distribution has been set elsewhere.

The major limitations of this study and suggestions for further work are related to the available data. Firstly, all lanes for all roads could be measured, instead of the current Finnish practise of measuring in one direction only on one-carriageway roads. Secondly, multivariate analysis of network level data should be repeated including cracking indicators interpreted from digital surface images and road surface texture variables calculated from the measured surface profile. Thirdly, the concept of access matrix could be incorporated as a constraint in the route optimisation model, which is expected to lead to even more effective allocation of the available measurement budget. Finally, a risk analysis framework could be applied for road condition indicators whose distributions are highly skewed to the right, even after a logarithmic transformation.

Keywords: *Road condition, maintenance management, transformation of data, accuracy, route optimisation, condition rating, policy evaluation*

Acknowledgements

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Tomi is a keen professional in statistics, as well as a specialist in quality control methods, both of which are essential for my research field. Once he was introduced into the subject of road condition assessment, Tomi has been an enthusiastic partner in my research and great fun to work with. Writing articles with him has taught me to express concisely and precisely that which I want to say. The research we have started has brought up several issues not quite unlooked-for and extremely important in my field.

Besides Tomi and Antti, Dr. Fridtjof Thomas, of Swedish National Road and Transport Research Institute (VTI), but lately enrolled in the Department of Preventive Medicine at the University of Tennessee Health Science Center in Memphis, is co-authoring one of the papers in this thesis. I first met him at a conference workshop some years ago, and his enthusiastic attitude has inspired many a fruitful philosophical discussion which forwarded my research.

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Kauklahti, Espoo

Oct 11, 2007

Antti Ruotoistenmäki

Table of Contents

PART I

PART II

Essay One

Ruotoistenmäki, A., Seppälä, T. & Kanto, A.: **Comparison of modelling and measurement accuracy of road condition data**

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Essay Two

Seppälä, T., Ruotoistenmäki, A. & Thomas, F.**: Optimal selection and routing of road surface measurements**

In *Helsinki School of Economics Working Papers, W-424, October 2007.*

Essay Three

Ruotoistenmäki, A. & Seppälä T.: **Road condition rating based on factor analysis of road condition measurements**

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Essay Four

Ruotoistenmäki, A.: **Road maintenance management system - a simplified approach**

In *Helsinki School of Economics Working Papers, W-425, October 2007.*

PART I

1 Introduction and Objectives

1.1 Motivation

Knowledge of asset condition is an essential part of asset management, both as an input to the management process, and as a tool for evaluating maintenance strategies and policies. The particular application in this context is road asset management. However, the approach and methods used in this context are generally applicable to managing any physical or intellectual assets.

The condition or serviceability of road assets can be determined from the viewpoint of the maintaining agency, road users and society at large (Finnra 2004). The agency's viewpoint is technical in that it aims at preserving and maintaining the technical condition of the assets. The road user experiences the serviceability of the road, which is, of course, related to the technical condition and his/her expectations of this service. From the society's perspective, both the agency and user's definition of condition are combined with various other objectives of transportation policies. The condition is depicted using five categories, and differences between the condition categories should be related to their observable differences in the effects to the road users, the maintaining agency, or the society at large.

The asset value of the road is related to its (physical) condition. Thus, technical and financial terms are used for the valuation of the road asset. The technical value of an asset is described by its technical or physical condition. The financial value of an asset according to a simple technical interpretation implies the construction cost of the asset. Thus, the maintenance and reconstruction costs of the asset reflect changes in the asset value. Socio-economical analysis of road maintenance, on the other hand, is based on marginal user costs due to changes in road condition to justify maintenance expenditure. Assets may also have financial value related to their use. The indirect value of a road section as a part of a transportation system enabling transit of goods and people may far exceed its construction costs.

In this thesis, I want to investigate how we can and should use condition information in road maintenance management, and how this data can be collected. My emphasis is on determining the measurable technical condition. I am mostly concerned about continuous measurements of road surface condition done at normal traffic speeds as part of the normal traffic flow. These measurements relate to the road surface profile and cracking. In addition, in some of the calculations and analyses, I also use the surface deflections, measured at discrete points along the length of the road. I also briefly describe the measurements of road surface profile in both longitudinal and transverse directions as well as cracking and deflection in the following section.

In this study, I intend to draw a sketch of how to use road condition in maintenance management, rather than the comprehensive and detailed picture presented in textbooks such as Robinson, Danielson & Snaith (1998) and Hudson, Haas & Uddin (1997). In the maintenance management framework, there is a need for considering specific mathematical issues inherent in data collection and analysis. The starting point for these investigations is that the properties of a measurement series along the length of a road section can be depicted using models for autoregressive processes (Thomas 2001). From this premise I examine the statistical properties of road condition indicators as a basis for the development of tools for data collection and analysis. More specifically, these tools are used for making inferences on the accuracy of data and decisions on data collection. Furthermore, these tools include the presentation of road condition as an input to the evaluation of maintenance policies.

The viewpoint of this study is that of one making decisions on data collection and that of the data analyser. Traditionally these have been the task of the road agency. However, as maintenance practices are being evolved, data management is increasingly outsourced to vendors whose main responsibility is to collect, store and analysis it. I draw no specific assumptions about the user, and the tools developed in this study should serve all parties.

1.2 Measurements and indicators

For readers unfamiliar with the subject, a short description about the equipment and methods for the measurement of road condition is given here. Road surface profile, both in the longitudinal and transversal directions, is measured using Road Surface Monitoring (RSM) vehicle based on laser technology. Several, usually 17, laser scanners measure transverse profile with lateral spacing of 100 to 300 mm from a total width of 3200 mm. The same laser scanners are used for measuring longitudinal profile at 16 to 64 kHz frequency, usually in the wheel paths. At 60 km/h, one to four readings per millimetre are obtained. Longitudinal profile is calculated from points maximum 100 mm apart. Thus, one point is an average of up to 100 consecutive readings[1].

Several road condition indicators are calculated from the measured surface profile. In the longitudinal direction, the International Roughness Index (*IRI*) is the most common and widely used measure. It relates the measured surface profile to road user comfort using a quarter-car model (Sayers et al 1986a, 1986b, UMTRI 2007). The unit of *IRI* is mm/m, indicating the vertical movement per distance travelled. The *IRI* is well-established and standardised, and many of the analyses in this study are demonstrated using it as an example. Surface profile with wavelengths from 0.5 to 30 meters is used in the calculation of *IRI*. Unevenness with wavelengths from 0.5 to 500 mm is used for depicting the macro and mega texture of road surface, which reflect the noise and friction properties of the road surface.

In the transversal direction, rut depth is probably the most common condition indicator. As a concept, it is also readily comprehensible to the travelling public, even though the calculated indicators are not necessarily so. The algorithms for the calculation of rut depth also vary. In this context, rut depth calculated using the

[1] The information in this paragraph applies to the equipment commonly in use in Finland. The exact amount of lasers, their lateral spacing, the measuring width and the measuring frequency may vary between countries and makes of equipment.

string algorithm[2], is used. Other indicators in the transversal direction used in this study include average ridge height, transversal unevenness and maximum deviation. Their definitions are to be found, for example, in the bidding documents for the current and new contract (Finnra 2002, 2007).

Surface cracking is interpreted automatically or semi-automatically from surface images. Several 2D and 3D techniques exist for capturing the images, including analogous or digital matrix cameras, digital line cameras, and 3D laser scanning. The cracking of road surface can be quantified in various ways that are less standardised than those for assessing the road surface roughness. Internationally, provisional bases for standards exist, such as AASHTO (2003). In 2006, network-level automated cracking measurements were commenced on the Finnish paved public road network. In this study, I use these measurements for studying the statistical properties of a new variable - Cracked Surface (*CS*, %). The *CS* indicates the amount of cracked road surface as a percentage of the total survey area divided into squares of 200 mm * 200 mm.[3] In fact, the *CS* variable is a specific case of the Unified Crack Index (*UCI*), whose block size is 125 mm (5") (Lee 1992). Other indicators relating to the degree and severity of cracking exist, but are not dealt with in this context.

Road surface deflections are measured using the Falling Weight Deflectometer (FWD), see e.g. COST336 (2000). A dynamic loading equivalent in magnitude to truck wheel load is generated by dropping a mass on a loading plate. Deflection signals under the loading plate and at several offsets from the loading plate are measured and the peak deflection is generally used in further analysis. Unlike the measurements of surface profile and cracking, deflections are obtained with measurement vehicle stopped at each measuring point.

Other existing methods for road condition assessment not dealt within this context include measuring the electrical properties of road materials and subgrade soils

[2] An imaginary string is stretched over the measured transverse profile of road, and the maximum perpendicular deviation from the string is the rut depth in mm.
[3] Starting in 2008, *CS* with 100 mm * 100 mm block size will be used.

using the ground penetrating radar (GPR) and the measurement of the continuous deflection profile. The description of GPR and its use in road asset condition surveys has been undertaken by Saarenketo (2006). The surface deflection profile is measured at highway speeds using, for example, the Traffic Speed Deflectometer, TSD (Greenwood 2007). The methods developed in this thesis are general and should be applicable to these and other measures of condition for roads and other assets.

1.3 Objectives

I argue that the statistical distribution of road condition indicators should be adequately taken into account when road condition data is used in road maintenance decision-making. From this, it follows directly that the statistical properties have to be investigated first. Tools need to be developed for maintenance management that properly address these properties.

The main objective of this thesis is to explore the use of road asset condition both as an input to the maintenance management process and in evaluating its results. This main objective is made explicit in the following five objectives:

1. To examine the distributional properties of road condition indicators.
2. To develop methods for estimating the accuracy of road asset condition based on measurements and deterioration models.
3. To develop tools for evaluating the benefit of taking new measurements.
4. To describe how road condition can be presented for strategic-level decision-making.
5. To develop simple analytical tools for assessing funding needs of road maintenance.

Each of these objectives will be achieved in this introductory section and the four separately published papers or essays contained in this thesis.

1.4 The structure of the presentation

In Section 2, I outline and describe the problem setting for obtaining and using road condition information. In Section 3, I explore and analyse the distributional properties of road condition indicators and the transformation of data. The summaries of individual papers contained in Part II of this thesis are described in Section 4. Section 5 is a conclusion, and an analysis of the limitations of this thesis as well as suggestions for further study.

2 Problem setting

As illustrated in Figure 1 below, the main focus is on road condition. Road condition can be analysed from two perspectives. The first one is about how to optimally collect reliable road condition data from measurements and models. The second aspect of this process is how to present and use this information in maintenance management, where the costs and benefits of maintenance policies are evaluated.

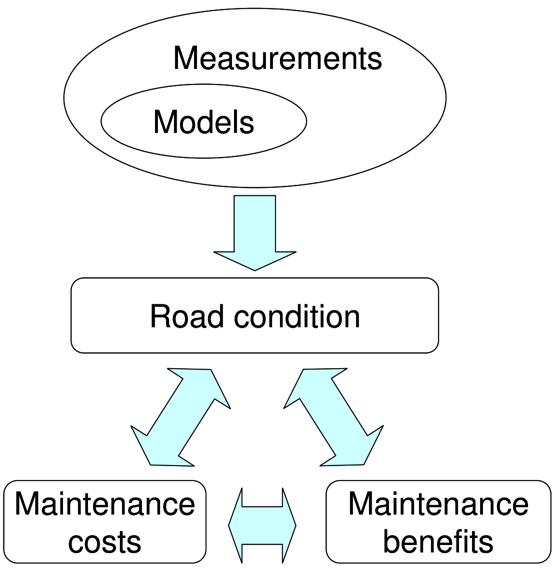

Figure 1. Problem setting with the focus on road condition, and how to collect, present and use information based on the knowledge of its accuracy.

Road surface condition can be measured and modelled. Models are usually based on previous measurements, but in their absence the models can, for example, be based on engineering judgement. Note that the word model here refers to not just formal mathematical models, but to all reasoning that is used for making inferences on road condition.

The decision on when and where to collect road condition data is directly related to the approach taken in determining road network condition. For this purpose two optional practices can be used. The entire network in question is measured or a sample that represents the condition of the entire network is taken. The first option is widely used with high-speed measurement devices of road surface profile and cracking, and the latter with other, more time-consuming measurements, such as those of surface deflections using the FWD. If the entire network is measured, usually a part of the network is measured every second or third year, with the current condition of the network being predicted from previous measurements, taking into consideration the deterioration that has taken place since then.

But how accurate is the information on road condition? How does measuring and modelling affect its accuracy? The latter question directly raises further questions such as whether existing information should be used or new data should be collected, bearing in mind the costs of doing so.

Measuring accuracy is based on the variation of repeated observations in similar conditions, while modelling accuracy is calculated from the standard deviation of model residuals. Two approaches to define the benefits of data collection are taken. First, a cost-benefit analysis that relates the measuring and modelling accuracies to losses from maintenance being performed too late or too early, results in a threshold value of excess variation between measuring and modelling.

The second approach to define the benefits of taking new measurements is in a decision-theoretical framework, where Bayesian updating is used for estimating the benefits of data collection. This approach makes use of the measures of accuracy developed in the first approach. The decision to take or not to take a new measurement in this framework depends on how likely it is that our maintenance decisions change, if new measurements are taken. The benefits of data collection are defined as the expected probability of change in decision to maintain or not to maintain a road, multiplied by the length of road. A measurement program is constructed by maximising this expected length in a route optimisation context.

Are the accuracies and benefits different when a sample of the network is measured, as compared to the situation when the entire network is measured? Often network level condition data is used for dividing the network into condition categories for further analysis and for communication purposes. Taking a sample effectively means that an additional uncertainty associated with the distribution of roads into categories is introduced. This uncertainty, depicted using a confidence interval of the share of roads in each category, may well be accepted, especially if the cost of reducing it becomes excessive compared to the gained benefits. Thus, the measures of accuracy can be applied both when a sample of the network is measured and when the entire network is measured.

An important issue needs to be raised here. Road condition information, whether measured or modelled, always contains some uncertainty. This is quite clear from a statistical viewpoint. However, even when this fact is acknowledged, its full implications are not always properly taken into account while using road condition information in maintenance management. Often the latest measurement for a road section is considered as the true value of its current condition. It could be from the previous year, but its value at the present moment may be predicted using an appropriate model. But when a new measurement becomes available, the previous one is completely disregarded as having no value. This can be a reasonable practice in a context in which the measurements are collected with zero uncertainty. With uncertainty involved in all observations, a more sustainable policy is to consider all available relevant information about the current condition of the asset, whether it is obtained from measurements or other sources and weighted based on their uncertainty.

Once the network condition has been determined, this information is presented in a usable format for the economical analysis of maintenance policies. It is a widespread practice to derive classifications of road condition from measured condition information. Road condition is commonly described on a scale from excellent to poor. The benefit of using verbal classifications is that they convert engineering terminology into the language of the travelling public. Numbers for the condition categories are widely used, e.g. 5 to 1 or 100 to 0. For the definition and calculation of the Pavement Condition Index (*PCI*) and the Present Serviceability Index (*PSI*) see e.g. Hudson, Haas & Uddin (1997), FAA (1982), Shahin & Walter (1990) and AASHO (1962).

However, a major drawback of many such classifications is that their use necessitates the collection of similar data (same variables) for the entire network. However, in practice, the condition of different roads is not comparable and it is not meaningful to calculate condition distributions. For these reasons, a flexible road condition classification is developed in this study. It is based on factor analysis of measured road condition data. This classification enables the comparison of all roads in the network under consideration.

The resulting classification is further used in the economic analysis of maintenance policies. Full socio-economical analysis that takes into account the road user benefits of various maintenance policies is a well-established practice for high-class paved roads. However, for other road assets, such as low-volume roads, whether paved or unpaved, bridges and road furniture, it is difficult or even impossible to determine user benefits from maintenance work. For this reason, it is desirable, in this context, to develop a simplified method that relates maintenance funding to network condition. This method is especially suitable for finding an appropriate maintenance policy when the targets for condition distribution have been set elsewhere.

However, a very basic question that has to be tackled first concerns the statistical properties of road condition measurement series, the knowledge of which is essential for proper development of tools for road maintenance management. This leads to the transformation of road condition measurement series, which is also the first stage of data analysis in three of the four papers of this thesis discussed in the following section.

3 Distribution and transformation of road condition data

3.1 Measurement series of road condition indicators

The measured road condition indicators may be depicted as a measurement series along the length of road. This is the approach taken and elaborated by Thomas (2001, 2003, 2004), who developed a Bayesian updating method for dividing road links into homogeneous sections based on measurement series of condition indicators. Thomas's approach is to regard the measurement series as a piecewise stationary stochastic process. Often applied to time series data from the stock market, this is an intriguing approach to analysing road condition data. Indeed, it is the very reason for performing a transformation to the measurement data in order to reach a situation where the distributional properties of data for each homogeneous section are as close to normal distribution as possible. This is due to the fact that at some point the statistical methods used for analysing road condition data usually make the assumption of normality. Possible transformations include Box-Cox (Box and Cox 1964) as a general family of transformations, and logarithmic transformation as a specific case of Box-Cox transformation.

The measurement series may be depicted as a first-order autoregressive process (AR1), see e.g. Box, Jenkins & Reinsel (1994):

$$x_t = \alpha_t + \beta_t x_{t-1} + \varepsilon_t \,, \tag{1}$$

where x_t is the observed condition X at point t, x_{t-1} is the observed condition X at a point previous to t, and a, β and ε are the process parameters. Consecutive samples in a stationary series are from the same distribution with the same (unknown) mean and they vary around that mean according to the same (unknown) standard deviation. A measurement series from a specific road link, let alone from a network, may not be taken to be from the same distribution. Instead, shorter sections may be considered as homogeneous sections, and measurements from each section may be treated as stationary.

Whether a measurement series of road condition is stationary is difficult to investigate, as most roads are measured only once in the same conditions. From a single measurement series the variance of a single observation can not be estimated. In the first paper, a method for estimating this variance, based on two or more observed measurement series at the same location, is developed.

3.2 Distribution of road condition indicators

First, the observed distributions of condition indicators were constructed and then different types of distributions were fitted to the observed distributions. The distributional properties of road condition data were studied using data sets derived from the condition database (CDB) of the Finnish Road Administration (Finnra). Surface profile, cracking and deflections measured in 2006 were selected for investigation. The reporting length is 100 meters for all condition indicators. Shorter reporting lengths are used for some of the indicators in the database. A similar analysis was carried out for selected indicators for 10-meter reporting length. The following condition indicators were considered:

- International Roughness Index (*IRI*) [mm/m]
- Rut depth (string algorithm) [mm]
- Ridge height [mm]
- Cracked surface (*CS*) [%] for the lane width, for both 100-meter and 10-meter reporting lengths[4]
- *Dd_T* = temperature corrected surface deflection [μm] d mm from the loading plate, d = 0 (under the loading plate), 200, 300, 450, 600, 900 and 1200 mm

[4] *CS*-variable is a special case of the Unified Crack Index (*UCI*) with block size 200 * mm * 200 mm. It is calculated by dividing the interpreted surface image into squares, and defined as the percentage of cracked squares over the total number of squares in the reporting area.

The distribution of observations on a homogeneous section usually has one peak and is skewed to the right. The tail of the distribution is usually well behaving, i.e. the greater the observed values are the smaller their percentage in the distribution is. The density curve decreases towards the extreme values. The values of most indicators are non-negative, but no theoretical upper limit for them exists. There is one exception, the *CS*-variable from automated pavement distress survey, which may take values between [0, 100]. Zero value represents sound pavement with no cracking, whereas the value 100 % represents the case where the entire surface is cracked. The *CS*-variables can, and indeed do, have a considerable number of zero values, especially for the parts of the lane (in, between and outside the wheel paths), and for shorter reporting lengths, such as 10 meters. In this context, however, only the *CS*-variables for the entire lane width are considered.

As an example, the distribution of *IRI* for a 100-meter reporting length is presented in Figure 2, together with the fit of log-normal distribution. The applied software (@Risk®) uses the least-squares method for fitting distribution to the observed data, which is represented by a density curve. That means the best fit is chosen for the type of distribution whose Euclidian distance from the observed distribution is the shortest of the alternative distributions. In most cases, the shapes of the distributions of road condition indicators are similar and several types of distributions are equally good for describing the observed data. Continuous distributions also describe fairly well the distributional properties of the cracking variables, whose values lie within the range [0,100].

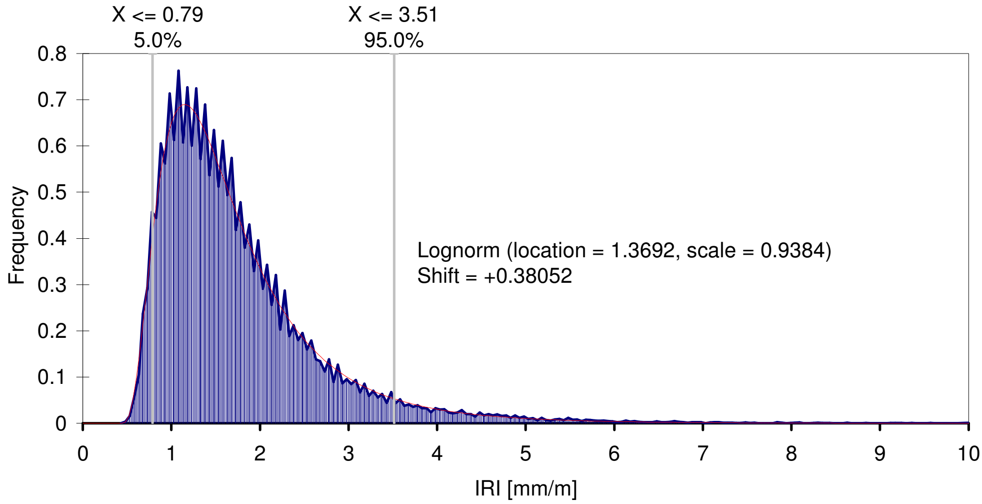

Figure 2. The distribution of IRI at 100 meter reporting length from the measurements in 2006 for the Finnish Road Administration. The fitted lognormal distribution is shown with associated parameter values.

Among the best-fit distributions for the condition indicators is the log-normal distribution. The transformation to normal distribution is a straight-forward process accomplished by simply taking the logarithms of original values for data analysis. The original values can easily be returned for the presentation of results. The many benefits of using the log-normal distribution will be discussed later.

3.3 Transformation of road condition measurement series

The transformation of the data is initially accomplished by using a general family of transformations, namely Box-Cox (Box and Cox 1964), and then focusing on the logarithmic transformation as a specific case of Box-Cox transformation. The Box-Cox transformation is defined using parameters λ_1 and λ_2 as:

$$y^{transformed} = \begin{cases} \dfrac{(y+\lambda_2)^{\lambda_1} - 1}{\lambda_1}, & \lambda_1 \neq 0 \\ \ln(y+\lambda_2), & \lambda_1 = 0 \end{cases}, \tag{2}$$

where $y^{transformed}$ is the transformed value, y is the original observed value and λ_1 and λ_2 are the transformation parameters ($y > -\lambda_2$). The Box-Cox set of transformations is continuous at $\lambda_1 = 0$, since

$$\frac{(y+\lambda_2)^{\lambda_1}-1}{\lambda_1} \rightarrow \ln(y+\lambda_2) \tag{3}$$

as $\lambda_1 \rightarrow 0$ (Box and Cox 1964). The Box-Cox transformation is monotonic, which implies that the original values can be returned from the transformed values unequivocally, when the transformation parameters λ_1 and λ_2 are known. Parameter λ_1 is a shape parameter and λ_2 is a scaling parameter along the x-axis. The latter ensures that all variables are strictly positive (expression $y + \lambda_2 > 0$). When $\lambda_1 \neq 0$, λ_2 also acts as a shape parameter (Box and Cox 1964).

In finding a suitable transformation for a data set, the goal is to find such values for parameters λ_1 and λ_2 which result in a situation where the distribution of transformed values $y^{transformed}$ is as close to the normal distribution as possible. This goal can be achieved e.g. by a visual examination of Quantile-Quantile (Q-Q) plots or by maximising the correlation in Q-Q plot. A series of *IRI*-measurements at 100 meter longitudinal spacing from one road section (Road 1130, section 3) is used here as an example. The values of λ_1 and λ_2 were calculated using a spreadsheet solver by maximising the correlation between the standardised transformed and standardised normal distributions. In the left hand side of the diagram (Figure 3), the plot of values of λ_1 vs. correlation is shown for one road section and in the right hand side of the diagram, the plot of values of λ_2 vs. correlation. The parameters were solved simultaneously, but the results are here presented separately for λ_1 and λ_2. It can be seen that the values $\lambda_1 = -0.2$ and $\lambda_2 = 0$ maximise the correlation in Q-Q plot for this road. However, for other roads, the parameter values may be different.

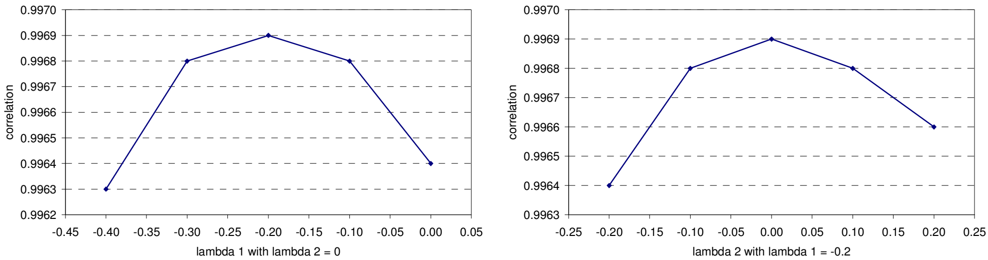

Figure 3. The values of λ_1 vs. correlation in Q-Q plot of transformed values of IRI at one road section (Road 1130, section 3) (left diagram) and the values of λ_2 vs. correlation of Q-Q plot (right diagram).

From the diagram on the left above, it can also be seen that the logarithmic transformation ($\lambda_1 = \lambda_2 = 0$) yields a correlation (0.9964), which is close to maximum correlation (0.9969). The Q-Q plot of logarithmic transformation for the same road section is shown in Figure 4, with the values of standardised normal distribution in the horizontal axis and the values of standardised transformed values in the vertical axis. It can be observed that a relatively good fit is obtained.

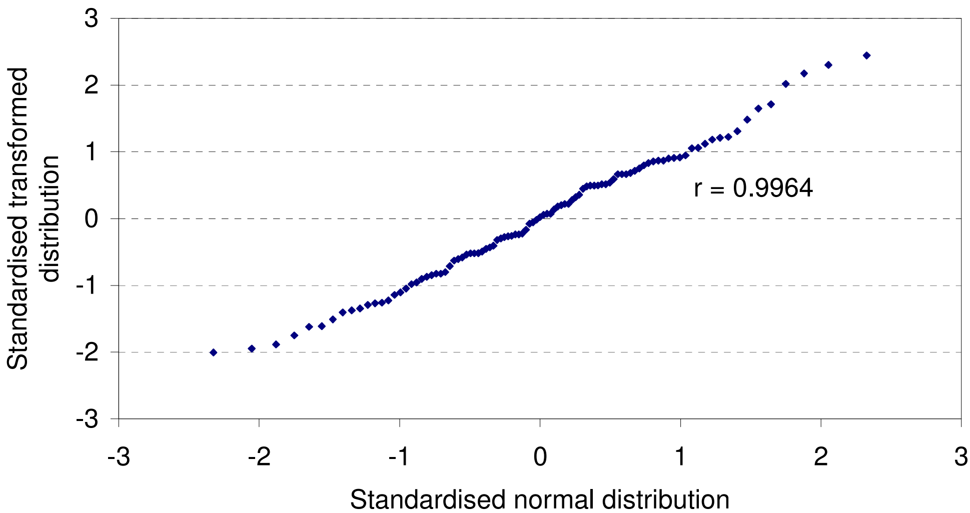

Figure 4. The Q-Q plot of log-transformed values of IRI at one road section (Road 1130, section 3, with Box-Cox transformation parameter values $\lambda_1 = \lambda_2 = 0$.

In the left hand diagram below in Figure 5, the distribution of original *IRI*-values for the same road section are shown. The resulting distribution is shown in the right hand side, when logarithmic transformation is carried out. It can be seen that the distribution of log-transformed *IRI*-values is fairly close to normal distribution.

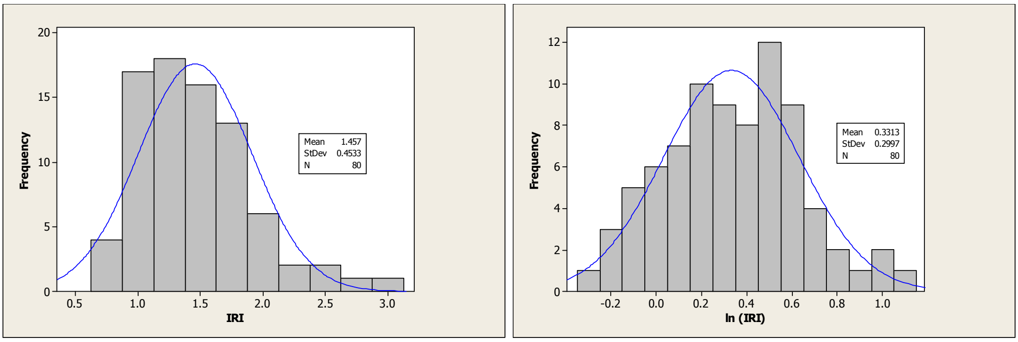

Figure 5. The distribution of original (left diagram) and log-transformed (right diagram) (Box-Cox transformation parameter values $\lambda_1 = 0$ and $\lambda_2 = 0$) values of IRI at one road section (Road 1130, section 3). Fitted normal curves are superimposed on the histograms in order to facilitate the comparison of distributions.

Several statistical tests exist for testing for the normality of distribution, and they can be applied to the transformed distribution. These include Kolmogorov-Smirnov, Shapiro-Wilk (Shapiro & Wilk 1965), Jarque-Bera (Bera & Jarque 1981) and D’Agostino-Pearson omnibus test (D'Agostino & Stephens 1986). However, road condition measurement series are typically large samples, and normality tests easily reject the null hypothesis that the data are from normal distribution, even though the actual discrepancies may be very small. A trial of Jarque-Bera test shows that log-transformed roughness data for a road link, not to mention for a road network, statistically deviates from normal distribution. Furthermore, the trial indicates that for shorter (homogenous) sections, normality may be achieved by using logarithmic transformation. This is reasonable, as the measured values from consecutive subsections of a homogeneous section are from the same distribution with common mean and variance. Instead, the measured values from a road link or a network are from several homogenous sections whose distributions (mean and variance) are different. Put together in one distribution, these values are not from one normal distribution and, therefore, normality testing rejects the null hypothesis.

3.4 Recommendations for the transformation of road condition data

When looking for a suitable method for the transformation of data, it is desirable to find one set of transformation parameters that can be applied to all data at hand. I chose to perform logarithmic transformation for the road condition data to be used in the further analysis. It is a special case of Box-Cox transformation with parameter values $\lambda_1 = \lambda_2 = 0$. This approach has several advantages. First, logarithmic transformation is easy to perform, and the original values are easily returned from the transformed values. Secondly, it enhances the validity of prediction models derived from condition data in that the transformed data fits the model assumptions better than the original data. Besides, a linear model for the transformed data can be presented as an exponential model for the original data: $\ln Y = a \ln X \Leftrightarrow Y = X^a$. Third, logarithmic transformation readily extends to relative measures of road condition accuracy, as is elaborated in the first paper. Finally, taking the logarithm of *IRI* values serves as a variance stabilising transformation. To illustrate this property, we consider the variance when multiplying the original variable X with constant a: $Var(aX) = (aX - a\mu)^2 = a^2(X-\mu)^2 = a^2 VarX$. We can see that the variance of untransformed indicator values increases in the square of constant a. Instead, the variance of log-transformed values remains unchanged when the log-transformed values are multiplied with constant a: $Var(\ln aX) = (\ln aX - \ln a\mu)^2 = (\ln a + \ln X - \ln a - \ln \mu)^2 = (\ln X - \ln \mu)^2 = Var \ln X$. The variance stabilising property enables the comparison of accuracies between different indicators with different ranges of values.

Unfortunately, the distributions of many indicators, especially surface deflections measured using the FWD are highly skewed to the right, and applying a logarithmic transformation to the measured data does not necessarily improve the situation. Road deterioration takes place when loading imposed on the road structure exceeds its capability. This is where the extreme values of condition indicators are found.

Therefore, it should be beneficial to study the tails of the distributions of condition indicators in a risk analysis framework, where different statistical distributions are used for different condition indicators.

4 Summary of individual papers

4.1 Accuracy of road condition data

Ruotoistenmäki, A., Seppälä, T. & Kanto, A., **Comparison of modelling and measurement accuracy of road condition data** *Journal of Transportation Engineering., Volume 132, Issue 9, pp. 715-721, Sept 2006.*

The condition of a road network and its deterioration rate can be estimated by using measurements and statistical models. The specific objective of this paper is to answer the following two questions: How can measuring and modelling accuracy be calculated and compared? What are the benefits of measuring the current road condition as compared to modelling? International Roughness Index (*IRI*) measurements over three years (2000 – 2002) from the condition database of the Finnish Road Administration were used. The data is stored in the database for 100-meter sections. First of all, a logarithmic transformation was applied to the measured *IRI* values. One half of the data set was used for developing linear regression models that predict the logarithmic *IRI* value in a particular year, based on the previous years' logarithmic measurements. These models were validated using the other half of the data set.

Results:

All measurement series of road condition indicators are samples of an infinite number of road conditions. They are not, therefore, 100% repeatable. An explanation for the causes of variation between repeated measurement results is that the lateral position of the measuring vehicle is a major source of variation in the measured surface profile (see e.g. Karamihas et al. 1999).

Modelling accuracy is the standard deviation of predicted logarithmic condition values, and it is estimated based on the standard deviation estimate of error (s_e) in the regression equation. The estimate of the measurement accuracy (s) from repeated measurements is the square root of average variances, weighed with the number of repeats in each section. Using logarithmic values, these measures of accuracy can be directly interpreted as percentages.

A cost-benefit analysis is done by applying the Taguchi loss function (Taguchi 1986), where the loss (L) increases according to a quadratic curve as the measured value (Y) deviates from the target (T). Deviation from the target is estimated using the measures of accuracy for measured and modelled condition data. An inequality is developed that relates the excess variation in condition data, the measurement cost and the agency and user losses due to untimely maintenance. Below threshold values for the excess variation calculated from the data, modelling the current road condition from previous measurements becomes more beneficial than taking new measurements.

4.2 Collecting road condition data

Seppälä, T., Ruotoistenmäki, A. & Thomas, F.**: Optimal selection and routing of road surface measurements** *Helsinki School of Economics Working Papers, W-424.*

The objective of this paper is to evaluate the benefits of road surface measurements, using a decision theoretical approach combined with optimisation of measurement route. An approach is used that relates the data accuracy, defined in the first paper, to the benefits of improving the knowledge of road condition according to a Bayesian updating scheme. Roads in a network are classified into four categories (No Action, Warning, Action, Must do) based on the knowledge of their true condition, θ. The likelihood of changing the classification of a road section as new information becomes available multiplied by road length is used as a benefit to be maximised in a route optimisation model.

Prior distribution of θ may be based on previous measurements, or other sources of information, such as models and engineering judgement. The likelihood function is the probability distribution of a new measurement. The predictive posterior distribution of θ is used for estimating the probability that a road section will be reclassified. Normal distribution for the prior, likelihood and the predictive posterior distributions are used, and this is achieved by the logarithmic transformation of variables. The variance of prior distribution is estimated by the squared modelling accuracy and the variance of the likelihood function is estimated by the squared measurement accuracy from the first paper, $\hat{\tau}^2 = s_e^2$ and $\hat{\sigma}^2 = s^2$.

Results

By combining the decision-theoretical framework with a route optimisation method, a measurement route can be found that yields considerably higher benefits than the current measurement policy. The benefits are defined as enhancements in the maintenance decision-making, which is operationalised as the expected length of reclassified road sections as new measurements are taken. The concept of access matrix is used for evaluating the connectivity of the optimised measurement route. As part of further development work, the incorporation of the access matrix approach as a constraint in the route optimisation model should be studied.

A simplified network is used for illustrating the calculation method, which is then extended on the network of main and regional roads of the Uusimaa Road District in Finland. The results indicate that the current measurement policy, where the main roads are measured every year and minor roads every three years, could be altered so that all lanes from all roads are measured every other year. The current practice for one-carriageway roads is to measure in one direction only. Altering the current policy has the added benefit of further improving the efficiency of data collection by reducing driving on without measuring.

4.3 Presenting road condition data

Ruotoistenmäki, A. & Seppälä T.: **Road condition rating based on factor analysis of road condition measurements** *Transport Policy, Volume 4, Issue 5, pp. 410-420, Sept 2007.*

Summarising indices are used in road maintenance management for justifying funding and fund allocation purposes. The major drawback of many of the existing condition classifications is that their use necessitates that the same information is collected from all roads in a network. The objective of this paper is to develop a flexible road condition rating model based on a factor analysis of measured road condition indicators.

Results

A total of 1441 kilometres of measurements obtained in 2003 by using the road surface monitoring vehicle (RSM) and the falling weight deflectometer (FWD) from the Finnish paved public road network were used. A two-stage (exploratory and confirmatory) factor analysis resulted in the following three correlated factors: structural factor, roughness factor and transversal unevenness factor. The factors found in this analysis - not surprisingly - are mostly the same as in previous works by Talvitie & Olsonen (1988) and Kyyrä (1992). Based on Talvitie & Olsonen, the following four condition variables have been used in the Finnish strategic-level pavement management system: International Roughness Index (*IRI*), rut depth, bearing capacity (or later bearing capacity ratio) and cracking index. Unfortunately, the cracking data from the visual survey did not yield satisfactory results, and was consequently left out of the analysis. The surface texture has opposite effects (friction, tyre wear), and inclusion of surface texture variables in the analysis is the subject of a further study.

The factor scores are calculated as the mean of the standardised values of log-transformed variables in each factor. The condition rating is then calculated as the weighted sum of the factor scores and ranges from -∞ (best) to ∞ (worst). In order to use this method in a specific road management system, the condition rating values need to be transformed into a finite scale and adjusted with the management objectives and the observed ride quality. This can be achieved, for example, by using driver panels.

Condition rating is used for evaluating maintenance policies based on their effects on the probability distribution of condition. This is the subject of the last paper in this series. It suffices here to summarise the results from the evaluation of two maintenance policies on two sub-networks: a preservation policy attempting to maintain the current condition of a network, and a preventive maintenance policy. The preventive maintenance policy, even though somewhat more expensive than the preservation policy, yields greater benefits in terms of an improved condition distribution during a five-year analysis period[5].

The presented calculation method, kept as simple as possible, also enables the analysis for those road assets where user benefits are difficult, if not impossible to determine. These include relatively low-volume paved roads, bridges and gravel roads. The selected approach is a practical tool for finding an appropriate maintenance policy when the target for condition distribution has been set elsewhere.

4.4 Using road condition data to assess maintenance funding needs

Ruotoistenmäki, A.: **Road maintenance management system - a simplified approach** *Helsinki School of Economics Working Papers, W-425.*

In order to find a sustainable maintenance policy, road asset management at strategic level seeks to answer the following questions: What is the current condition of the assets? What is the optimal condition of the assets? What are the annual funding needs and how should this funding be allocated? The objective of this last paper is to provide tools for evaluating different maintenance policies. To accomplish this objective, a probabilistic approach is applied, where the costs of maintenance works

[5] A common result is that a preventive policy is less expensive to carry out than a preservation policy. However, this result depends on the probability distribution of the condition of sub-networks.

are related to the probability distribution of the road network's condition by the estimated transition probabilities of deterioration and the effect of maintenance works. It is assumed that set policy is kept unchanged during a selected analysis period.

Alternative maintenance policies for PCC (Portland Cement Concrete) bridge assets are evaluated. The condition classification defined in a recent Finnra report (Finnra 2005a) is used, where the number of categories ranges from 5 (excellent) to 1 (poor). Deterioration and maintenance effects models for PCC bridges developed in a recent study by Äijälä & Lahdensivu (2006) are used. Maintenance cost is assigned to each condition category, and the average annual maintenance cost over the analysis period is calculated. The decision variables in the calculation method are the share of assets in each condition category that are maintained each year. The model is tested in a spreadsheet application, where the decision variables are typed on-screen, and the outcome can be evaluated instantly.

Results

Three simplified maintenance scenarios were compared over an analysis period of ten years. The first one is the current policy of bridge maintenance (Finnra 2005b). The second one is the preservation policy, whose objective is to minimise the change in condition distribution during the analysis period, and the third one is the Do Worst policy. An additional scenario, deterioration, was calculated where only routine maintenance is applied on the bridges over the ten year analysis period. The results of this analysis confirm the fact seen from the models themselves, namely that the deterioration rate according to the models is rather slow. The current policy meets the set management objectives, resulting in annual funding needs of M€ 26.4. The preservation policy, though requiring considerably higher funding (M€ 39.7), does not lead to much better condition distribution than the current policy. The Do Worst policy uses approximately the same funding (M€ 40.8), but results in the best condition distribution of the three alternatives. Thus, the conclusion is to choose between the current policy and the Do Worst policy, depending on the availability of funding.

5 Conclusions

5.1 Summary

The focus of this thesis is on the data of road network's condition, and two viewpoints to it are taken. The first is concerned with how to collect accurate data. The second perspective is the usage of road condition data in maintenance management. The main argument is that the statistical distribution of road condition indicators should be adequately taken into account when road condition data is used in road maintenance decision-making. The objectives of this thesis were thus, first, to examine the distributional properties of road condition indicators and then to develop measures of accuracy of measured and modelled road condition, evaluate the benefits of data collection, and to develop methods for classifying road condition for strategic-level analysis and for assessing maintenance funding needs.

5.2 Contribution of this study

The starting point for this study was to consider road condition measurement series on a homogeneous section as a piecewise linear stochastic process, for which mathematical models of autoregressive processes can be applied (Thomas 2001). From these investigations, the conclusion is that, even though statistical deviation from normal distribution is likely for large samples from entire networks, normal distribution for homogeneous road sections can be achieved. A study on the possible transformations, from the general family of transformations defined by Box and Cox (1964), shows that since choosing one set of transformation parameters for all data at hand is desirable, the logarithmic transformation is the most practical solution. This approach has several advantages. Firstly, it is easy to apply by simply taking the logarithms of the original values for data analysis, and return to original values for the presentation of results. It also enhances the validity of prediction models derived from condition data in that transformed data fits the model assumptions better than untransformed data. Furthermore, logarithmic transformation readily extends to a relative measure of road condition accuracy. Lastly, taking the logarithm of *IRI* values serves as a variance stabilizing transformation.

Methods were developed for assessing the accuracy of road condition data from measurements and models, and more specifically, the excess error due to modelling. Accuracy is defined as the standard deviation of measured and predicted condition indicators after logarithmic transformation has been applied. The excess error due to modelling is defined as the difference of relative accuracies of modelling and measuring.

The benefits of taking new measurements are evaluated in a cost-benefit analysis framework that utilises the Taguchi loss function. An asymmetric loss function is defined, and deviation from the target is estimated using the measuring and modelling accuracies. The excess variation due to modelling is balanced with the measurement cost and the sum of agency loss from performing maintenance work too early and the road user loss from deferred maintenance. The current measurement policy for one-carriageway roads is to measure in one direction only, whereas all lanes of two-carriageway roads are measured. Furthermore, main roads are measured every year and minor roads every three years. A practical result from this analysis is that the current policy could be altered so that all lanes from all roads are measured every other year.

The benefits of taking new measurements are assessed in a decision-theoretical framework, combined with a route optimisation method. If maintenance decisions are not changing as new measurements become available, then there is no need to measure in the first place. If, however, introducing new information affects where and which maintenance actions are carried out, then taking new measurements is clearly beneficial. The contribution of this analytical method is that the measurement budget is allocated as effectively as possible so as to enhance the decision-making process.

The linear optimisation model is developed into a route optimisation model by introducing balancing constraints that account for the fact that the number of arriving and departing arcs to and from each node in the network must be equal. The connectivity of the route is evaluated by using the access matrix, whose elements indicate the existence of connection between the nodes in the network. These two advances enable the use of an integer programming model for a route optimisation problem, where the actual routes to be measured (arcs) are selected, based on the expected benefits of new measurements that have not yet been taken.

A rating system based on factor analysis of measured condition data is developed for the presentation of road condition information. Its benefit, as compared to existing classifications, is that it can be used even when part of the information is missing from some of the sections in a road network and the calculated rating values for different road sections are similar to each other. It can also be used for deriving an existing or a new condition index. Experts who wish to apply this method have to define weights appropriate to their specific network and the objectives of the management process. Calibration with the observed ride quality may be achieved by using driver panels.

The condition rating is further used for evaluating the benefits of maintenance policies in a simplified road maintenance management system. This method, fully developed in the fourth and last paper, is based on relating the maintenance actions with the resulting condition distribution at the end of a selected analysis period. The benefits of the proposed probabilistic approach are that this method can be used when the user benefits from maintenance are difficult to determine, e.g. for low-volume roads and for bridges. This method is especially suitable for finding an appropriate maintenance policy when the target for condition distribution has been set elsewhere. It is commonly argued that in order to achieve good optimisation results, several maintenance actions have to be allowed in each condition category. From these results it can be concluded that, at least for this simplified approach, a couple of maintenance actions in each category are sufficient.

5.3 Limitations of this study

The main limitations of this study stem from the available data sets, and they can be summarised as follows:

- Data from the visual survey of road surface distress was available, but did not yield good results. Only at the last stage of the study did data from the first network-level automated interpretation of road surface images become available.
- According to the current measurement policy, one-carriageway roads are normally measured in one direction only, and maintenance decisions for both directions (lanes) are made, based on this data. The condition of lanes in different directions is correlated, but not the same.

5.4 Suggestions for further work

Further studies on the statistical properties of road condition indicators should address the following issues: The distributions of many indicators, especially surface deflections measured using the FWD are highly skewed to the right, and applying a logarithmic transformation to the measured data is not guaranteed to improve the situation. Furthermore, road deterioration takes place where the extreme values of condition indicators are found. Therefore, it should be beneficial to study the tails of the distributions in a risk analysis framework.

The concept of access matrix can be used for evaluating the connectivity of an optimised measurement route. However, as such it does not guarantee the connectivity of the route. As part of further development work, the incorporation of the access matrix approach as a constraint in the route optimisation model should be studied. This is expected to lead to even more effective allocation of the available measurement budget.

Factor analysis similar to the one in this study should be carried out, with data included from road surface images collected on the paved road network in Finland since 2006. From these images, the unified crack index (*UCI*) values (the variable is called cracked surface, *CS* [%]) have been taken to the condition databank of the Finnish Road Administration. In addition, the amount of different types of cracking should be calculated from these images, and included in the factor analysis. The macro and mega texture of road surface profile should be included in the factor analysis to find a satisfying interpretation, as they reflect both desirable (friction) and undesirable (noise, tyre wear) properties of road surface.

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PART II

Essay One

Ruotoistenmäki, A., Seppälä, T. & Kanto, A.

Comparison of modeling and measurement accuracy of road condition data

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Comparison of Modeling and Measurement Accuracy of Road Condition Data

Antti Ruotoistenmäki[1]; Tomi Seppälä[2]; and Antti Kanto[3]

Abstract: The condition of a road network and its deterioration rate can be estimated by using measurements and statistical models. The purpose of this paper is to provide tools for assessing the accuracy of the condition information based on measured and modeled values. In this study, International Roughness Index (IRI) measurements over 3 years (2000–2002) were used. A logarithmic transformation was applied to the measured IRI values. One half of the data set was used for developing regression models that predict road roughness. These models were validated using the other half of the data set. The comparison of the residual distribution in the logarithmic regression model and measurement accuracy in logarithmic terms facilitates direct consideration of the relative accuracies. The Taguchi loss function was applied to estimating the losses incurred when measured and modeled values were used. The decision of taking new measurements depends on the relative accuracies of the measurement and the modeling, the cost of measurement, and the losses incurred to the road users and the maintaining agency due to untimely maintenance.

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CE Database subject headings: Pavement management; Measurement; Accuracy; Regression models; Cost analysis.

Introduction and Objectives

The purpose of strategic level decision making is to justify the funding needed for road network maintenance and to allocate these funds effectively between different subnetworks and maintenance activities. The condition of the road network is an essential input in the decision-making process, and it enables the quantification of benefits derived from maintenance for both the road user and the managing agency.

Road condition, or rather its decay, is manifested in the change of the surface profile and in the cracking of the surface layer. The surface profile, usually considered as the longitudinal and transversal unevenness of the road, is measured, for example, by using a road surface monitoring vehicle equipped with laser technology. The cracking of the surface layer can be monitored visually or by high-speed data collection of digital images connected to an automated image processing facility.

Longitudinal unevenness has the greatest impact on the driving comfort and the road user costs. The most widely used measure of longitudinal unevenness is the International Roughness Index (IRI) (Sayers et al. 1986a,b; for more information on IRI see, e.g., UMTRI 2005). Several variables are calculated from the transverse profile of the road, the most obvious of them being the rut depth. The extent and severity of cracking of the surface layer can be expressed for individual types of cracking, or a combined damage index can be used. In this paper, data for longitudinal unevenness in terms of IRI (mm/m) is used to demonstrate the methodology that is also applicable to other condition variables measured and modeled for a road network.

For practical reasons, it may not be possible to measure the entire road network each year. Various performance models, which can be used for predicting road condition based on previous measurements, have been proposed (European Commission 1999; Jämsä 2000; Odoki and Kerali 2000). The main question that arises from these observations concerns the accuracy of the measured and modeled road condition information. It is known that a certain amount of variation arises from the measured condition variables and that this variation affects the estimated deterioration of the road and the accuracy of the predicted condition information.

The focus of this paper is to examine the accuracy of measured and modeled road condition information for strategic level economic analysis. The specific objective of the research is to provide answers to the following questions:

1. How can measuring and modeling accuracy be calculated and compared; and
2. When is measuring the current road condition beneficial compared to modeling?

In the following section, the data set used in the analysis, and the procedures for selecting it are outlined. This is followed by a section that describes the methodology used in the modeling and the estimation of the accuracy. The results are then tabulated and this is followed by a cost–benefit analysis. The final section of this presentation contains the summary and the conclusions of this study.

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Data

Description of Data

The data set was drawn from the road condition data base of Finnra (Finnish Road Administration). For the purposes of this study, data for roughness measurements (IRI, mm/m) was considered. The condition information stored in the Finnra data base is based on 100-m sections. For the data set used in this paper, 3 consecutive years 2000–2002 were considered. All those 100-m sections that had been measured in all 3 years 2000, 2001, and 2002 were selected for the analysis. Road sections with recorded maintenance activities occurring between any two measurements were excluded. Other criteria for excluding road sections from the analysis are described in the following subsection. Finnra's data base covers the whole network of paved public roads in Finland, which is approximately 50,000 km. Using these criteria, a data set of 65,592 observations (6,559 km) was selected.

A logarithmic transformation was first applied to the measured IRI values. The rationale for this, as will be shown later, is that the use of logarithmic values allows direct consideration of the relative accuracies of the measured and modeled values. Additionally, the assumptions of regression analysis are much better represented by using logarithmic values. The empirical distribution of the IRI values and the values of the transformed logarithmic IRI for the data from year 2002 are shown in Fig. 1. The statistics that describe the entire data set are shown in Table 1. The median (50th percentile) value increases slightly in time, which indicates deterioration of the road network. It can be noted that the standard deviation also slightly increases in time. The minimum and maximum values together with several percentile points are shown in Table 1 as well.

It is quite clear that the distribution of IRI is by no means normal. The distribution of the logarithmic IRI, however, is fairly close to normal. The writers' experience is that many road condition variables exhibit similar behavior. They are, by definition, assigned positive values only, and extremely high values are not restricted. Even if some of the high values are caused by errors, some of them depict actual road conditions. As a consequence, the resulting distributions are positively skewed like the one for IRI shown in Fig. 1(a). The skewness of the distribution is illustrated by the skewness coefficient of IRI far greater than 0 (see Table 1). The skewness values for the logarithmic IRI are approximately 0.4, and the excess kurtosis is approximately 0.2. Both values are much closer to 0 for the logarithmic values than for the untransformed values, so it is better to use the logarithmic values in the analysis.

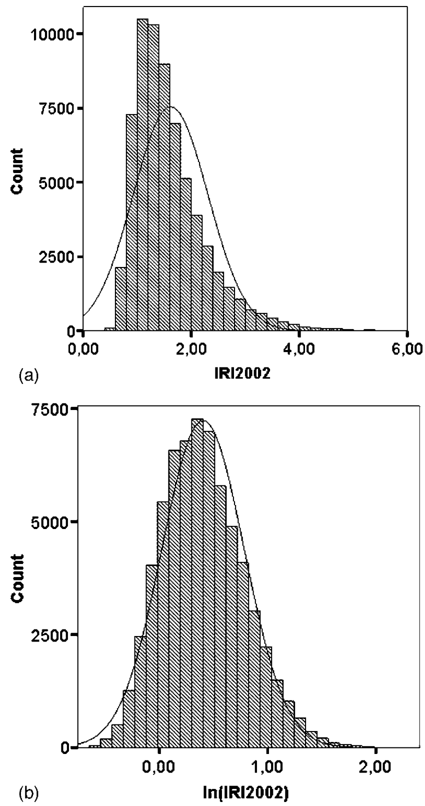

Fig. 1. Distribution of IRI (a) and natural logarithm of IRI (b) in 2002. Fitted normal curves are superimposed on histograms in order to facilitate comparison of distributions.

Variation in Data and Exclusion of Odd Observations

Roughness is measured using vehicles participating in normal traffic flow. A number of factors are known to affect the variation in the data obtained from any single year. These factors are as follows:

- The accuracy of the measurement equipment;
- The variability between different equipment of the same kind;
- The variation in the lateral position of the measurement vehicle with the same operator;
- The variation in the lateral position between the operators;
- The conditions prevailing at the time of measurement; and
- The seasonal variation of the profile.

In addition to that, variation in the data in consecutive years is caused by:

- The variation of the profile from year to year (deterioration); and
- Maintenance activities, some of which are not recorded.

Each vehicle has a certain measurement accuracy, which is described by the variation of the measured values between repeated runs along the same profile. This is due to the mechanics of the measuring apparatus, and in a statistical model, it can be considered random. A random error also exists between vehicles driving along exactly the same longitudinal profile. In practice, comparison of results from repeated runs using either the same or different vehicles in practically the same conditions (weather, etc.) is hampered by variation in the measured profile due to unavoidable lateral wander of the vehicle. The effects of different sources of variation have been studied in detail by Karamihas et al. (1999), who conclude that lateral wander is a major source of variation between roughness measurements. In this study, the effect of variation in the lateral position, both due to each operator and among several operators, is assumed to be part of the random variation.

The seasonal variation of the profile causes additional variation in the IRI values. The effect of the seasonal variation has not been quantified in this study. Seasonal variation is assumed to be negligible, and included in the general random variation, as all measurements are conducted during the nonwinter period.

Table 1. Statistics of Data Set Used in Analysis

Statistics	Variable					
	IRI2000	IRI2001	IRI2002	ln(IRI2000)	ln(IRI2001)	ln(IRI2002)
Number of observations	65,592	65,592	65,592	65,592	65,592	65,592
Mean	1.50	1.55	1.62	0.335	0.365	0.404
Standard deviation	0.615	0.656	0.693	0.366	0.373	0.380
Skewness	1.892	2.052	1.932	0.404	0.428	0.415
Excess kurtosis	7.47	9.22	7.43	0.18	0.22	0.14
Minimum	0.47	0.44	0.47	−0.755	−0.821	−0.755
1st percentile	0.67	0.69	0.70	−0.400	−0.371	−0.357
5th percentile	0.80	0.82	0.85	−0.223	−0.198	−0.163
10th percentile	0.89	0.91	0.94	−0.117	−0.094	−0.062
20th percentile	1.02	1.04	1.08	0.020	0.039	0.077
30th percentile	1.13	1.16	1.20	0.122	0.148	0.182
40th percentile	1.24	1.28	1.32	0.215	0.247	0.278
50th percentile	1.36	1.40	1.46	0.307	0.336	0.378
60th percentile	1.49	1.54	1.61	0.399	0.432	0.476
70th percentile	1.66	1.72	1.79	0.507	0.542	0.582
80th percentile	1.89	1.96	2.05	0.637	0.673	0.718
90th percentile	2.27	2.36	2.49	0.820	0.859	0.912
95th percentile	2.66	2.78	2.93	0.978	1.022	1.075
99th percentile	3.61	3.80	3.98	1.284	1.335	1.381
Maximum	9.99	11.77	11.02	2.302	2.466	2.400

Karamihas et al. (1999) also conclude that seasonal variation in measured roughness may be considerable, especially during the winter months, but that it tends to average out in network-level surveys.

Deterioration is the trend one is trying to capture using the logarithmic regression model. The other factors of variation mentioned above cause variation around this trend. In this study, variation due to these sources is considered random. Systematic variation may exist between two pieces of equipment. However, this should not be the case, since the quality assurance methodology employed in collecting the data set ensures that such cases are detected and appropriate corrective action taken.

In the data set used in this study, the contribution of each factor to the total variation cannot be explicitly determined. However, based on annual quality control measurements covering some 1–4% of the measurement program, the total variation can be quantified. In the quality control measurements done in 2001 and 2002 (Hätälä and Ruotoistenmäki 2002), a major requirement was that in 90% of the cases, the absolute value of the difference in the measured IRI value between any two measurements using different vehicles within the same year should be less than 0.5 mm/m. The deterioration of IRI between 2 years' measurements should in principle be non-negative, but in the presence of measurement errors an improvement of 0.5 mm/m in the measured IRI due to random variation could be allowed.

Previously it was noted that sections with recorded maintenance actions were excluded from the data set. However, maintenance work may actually have been carried out between any two measurements, but not recorded in the data base. This causes outliers in the data set so that a considerable decrease in the measured roughness values exists for one or several consecutive sections, even though the distribution of IRI shows that deterioration generally takes place (Fig. 1 and Table 1).

The writers wanted to eliminate the most obvious errors due to unrecorded maintenance works from the data set, and the following approach was adopted. Exclusion of single outliers, i.e., all *single* observations that show an improvement of IRI greater than 0.5 mm/m, would cause a serious truncation bias in the data, [see Fig. 2(a)]. This is undesirable and results in data that do not conform to basic requirements of regression analysis. The writers have therefore chosen to exclude only those measurements for which any *two or more* consecutive 100-m sections have a change in the measured IRI less than −0.5 mm/m between any 2 years: IRI2002−IRI2001 < −0.5, IRI2001−IRI2000 < −0.5, or IRI2002−IRI2000 < −0.5. Fig. 2(b) shows the remaining data after this operation. Obviously, the data are much less distorted by this procedure when compared to the procedure shown in Fig. 2(a).

Methods

Modeling

The form of the linear regression model that predicts the logarithmic IRI value in a particular year ($\ln Y$), based on the previous years' logarithmic measurements ($\ln X_j, j=1,2,\ldots,p$) is

$$\ln Y = \beta_0 + \beta_1 \ln X_1 + \beta_2 \ln X_2 + \ldots + \beta_k \ln X_p + \varepsilon \qquad (1)$$

where β_0=regression constant; β_j=regression coefficients of the independent variables ($j=1, 2, \ldots, p$); and ε=error term. The expected value of error $E(\varepsilon)=0$ and the variance of error is assumed constant over the range of $\ln X_j$ (i.e., homoskedastic model), but no specific distribution is assumed for ε.

In this study, the following regression models were considered:

$$\ln Y = \beta_0 + \beta_1 \ln X_2 + \varepsilon \qquad (2a)$$

$$\ln Y = \beta_0 + \beta_1 \ln X_1 + \varepsilon \qquad (2b)$$

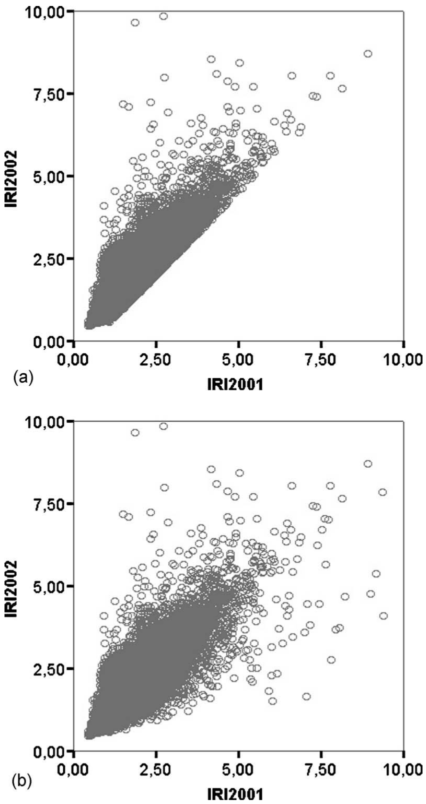

Fig. 2. Scatter plots based on data from 2001 and 2002: (a) disregarded method of excluding any single observation with IRI2002−IRI2001<−0.5; (b) adopted method of excluding observations only when measurements from two or more consecutive 100 m sections exhibit IRI2002−IRI2001<−0.5

$$\ln Y = \beta_0 + \beta_1 \ln X_1 + \beta_2 \ln X_2 + \varepsilon \quad (2c)$$

where $\ln Y$=logarithmic IRI in year 2002 and $\ln X_1$ and $\ln X_2$ are the one- and two-year-old logarithmic IRI measurements, respectively. These models were developed primarily for establishing a measure of modeling accuracy, and for this reason they were kept as simple as possible. The accuracy of other regression models with other explanatory variables can be evaluated using the methodology presented in the following subsection.

To estimate the accuracy of the forecasted values, cross-validation methods were used: The data set was randomly divided into two parts of equal size (Fig. 3). One half of the data set was used for developing regression models that predict the condition of a 100-m section in the year 2002 based on its measured condition in the years 2000, 2001, or both. The identified models were then tested using the other half of the data set, which was not used for model determination. The residuals between the measured and predicted values were calculated to determine modeling accuracy which was then compared with the accuracy of the measurement.

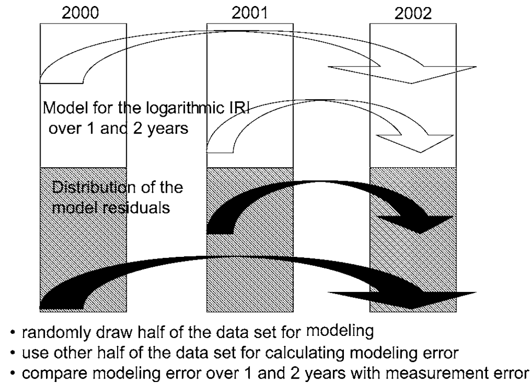

Fig. 3. Illustration of modeling and validation methodology

Calculating Modeling Accuracy

When using any of Eqs. (2*a*) and (2*b*), or (2*c*) to predict the logarithmic IRI of a 100-m section based on previous years' measurements, uncertainty is associated with each individual prediction. This uncertainty can be described by the standard deviation estimate (s_Y) of the predicted values, which in the case of one independent variable [Eqs. (2*a*) and (2*b*)] is (see, e.g., Pindyck and Rubinfeld 1997)

$$s_Y = s_e \sqrt{1 + \frac{1}{n} + \frac{(\ln x - \overline{\ln x})^2}{SS_x}} \quad (3)$$

where s_e=standard deviation estimate of the error term ε in the regression equation; n=number of observations, $\ln x$=value of the independent variable; $\overline{\ln x}$=sample mean of the independent variable, and SS_x=sum of squares of the independent variable indicating the total variation of that variable. Furthermore, $SS_x = \Sigma_{i=1}^{n}(\ln x_i - \overline{\ln x})^2$, where i indicates the observation.

In this case, the number of observations for one half of the total data set is so large (n=32,796) that both of the latter terms under the square root are close to zero. Therefore, the value of the square root is close to unity and the standard deviation of the predicted values can be estimated directly based on s_e, the standard deviation estimate of the error. The researchers found this approximation to be correct to the fourth decimal.

The standard deviation estimate of the error [s_e in Eq. (3)] is calculated from the residuals between the measured and predicted values of the logarithmic IRI in the year 2002. The residuals (e_i, $i=1,2,\ldots,n$) are calculated from the other half of the data set not used for fitting the models as follows:

$$e_i = \ln y_i - l\hat{n} y_i \quad (4)$$

where $\ln y_i$=measured logarithmic IRI value for observation i in 2002; and $l\hat{n}\, y_i$=predicted logarithmic IRI value for observation i in 2002.

In short, the accuracy of modeling is considered based on the standard deviation estimate of the predicted values [i.e., s_Y given by Eq. (3)], and is approximated by the standard deviation s_e of residuals e_i from Eq. (4). An analogous analysis is performed in the case when there are 2 independent variables [Eq. (2*c*)], i.e., when the logarithmic IRI value in the year 2002 is predicted based on the measured logarithmic IRI from both of the previous

Table 2. Accuracy of Modeling and Measuring Roughness

Accuracy			
Regression model: Dependent variable ln(IRI2002) Independent variables:			Measurement
ln(IRI2000)	ln(IRI2001)	ln(IRI2000) and ln(IRI2001)	Quality control measurements in 2002
0.168	0.156	0.147	0.118

2 years. The modeling accuracy is then compared with the standard deviation of the measured values of the logarithmic IRI, calculated as explained in the next subsection.

Calculating Measurement Accuracy

Due to the extent of the whole measurement program (approximately 30,000 km annually) several (four or five, depending on the year) measurement vehicles have been used for the production of measurement data, so that each 100-m section is measured once by one vehicle. The measurement accuracy is defined here as the standard deviation of the measured logarithmic IRI values per each 100-m section. Unfortunately, the accuracy of one measurement is not known. However, using two or more vehicles to measure the same 100-m sections, the standard deviation of a measurement can be estimated.

As part of the data-production measurement process, quality control measurements were taken using several vehicles. The same vehicles that were used for the data production measurements were also used for quality control measurements on 2,317 selected 100-m sections. In 829 of the 100-m sections, measurements were obtained from three vehicles, while in 1,488 sections they came from the use of two vehicles. Two or three measurements were then taken, once with each vehicle, from each of the 2,317 quality control sections. (Hätälä and Ruotoistenmäki 2002). In this analysis, the variance of the logarithmic IRI values using two or three vehicles was calculated for each quality control section. The variances of the logarithmic IRI are assumed to be the same for all vehicles measuring the same section, and the estimated variance of an individual measurement (s^2) is calculated as the weighted average of the variances from all sections. The estimate of the measurement accuracy is thus

$$s = \sqrt{\frac{\sum_{i=1}^{n_c}(m_i-1)s_i^2}{\sum_{i=1}^{n_c}(m_i-1)}} \tag{5}$$

where m_i=number of vehicles measuring section i; s_i^2=variance of measurements for section i; and n_c=total number of sections in control measurements. In this analysis, m_i=2 or 3 and n_c =2,317.

Results of Modeling and Measurement Accuracy

The accuracy of the different models [Eqs. (3) and (4)] and the measurement accuracy [Eq. (5)] are presented in Table 2. The results indicate that the accuracy of the predicted road condition is improved when based on the most recent measurements. Further, the availability of measurements from 2 years improves the accuracy of the predicted values. This indicates that previous measurements do have their value in estimating the current road condition. In general, the more information is available for estimating the current road condition, the more accurate the estimate is likely to be. This information may include more historical measurements and road specific data.

The standard deviation of error is increased from 0.118 when the logarithmic IRI is measured, to 0.168 when a prediction model based on 2 year old measurements is used. The logarithmic differences and the corresponding standard deviations can be interpreted as percentages. Thus, in this case, the difference is 5.0% units (0.168−0.118=0.050). Similarly, the standard deviation of error is increased to 0.156 (by 3.8% units) when a prediction model over 1 year is used and to 0.147 (by 2.9% units) when the model predicting the logarithmic IRI is based on the measured logarithmic IRI from both of the previous 2 years.

It should be noted that the modeling error includes the measurement error because modeling is also based on measurements. The difference between the reported standard deviations can be used as a measure of the excess error caused by modeling. The excess errors calculated (2.9, 3.8, and 5.0%) are significantly smaller than the actual measurement error (11.8%).

The practical consequences of these results should be evaluated by considering how the increased uncertainty in the input affects the output of the decision-making process. The benefits of the investment in the measurements should exceed the cost in order to justify the investment. The benefits may include improved accuracy of fund allocation and the use of data for other purposes such as design and quality control of procured maintenance works. The costs of wrong decisions due to the inaccuracy of the condition data could also be quantified, and used as losses or negative benefits in the analysis. The latter is the basis for the following analysis.

Cost-Benefit Analysis

Having perfect information on the road condition, proper maintenance decisions would always be made. However, all measurements and models include some error. Deviation from the true value of condition information leads to performing maintenance activities either too early or too late. The loss that occurs from variation of condition information can be quantified by using the Taguchi method (Taguchi 1986). It is generally accepted and widely used in the quality control of industrial processes, and a loss function is used for establishing a financial measure of the user dissatisfaction with a product's performance as it deviates from a target value (see e.g., Terninko 1996). In this particular application of the method, the target value is the true condition of the road, and user dissatisfaction is quantified in terms of road agency loss due to premature maintenance and additional user costs due to deferred maintenance actions. According to the Taguchi loss function, the loss (L) increases according to a quadratic curve as the measured value (Y) deviates from the target:

$$L(Y) = k(Y-T)^2 \tag{6}$$

The loss coefficient k=nominal value of loss when value Y deviates by one unit from the target value T. The Taguchi loss function can be understood as the second-order Taylor series approximation of a function (Taguchi 1986). Thus any function can be approximated using the Taguchi loss function. The intuition behind using a quadratic curve for depicting losses, rather than a linear relationship, is that the losses due to erroneous information increase with an accelerating rate as one deviates further from the target.

The expected loss can be decomposed into the following two components:

$$E[L(Y)] = k\sigma^2 + k(\mu - T)^2 \tag{7}$$

where $\mu = E[Y]$=expected value of Y and σ^2=variance of Y. In the context of this study, the measured and modeled logarithmic values of the IRI are considered, and T=true logarithmic value of roughness. Because the measurement vehicles have been calibrated, the measured values are considered unbiased, i.e., they are correct in average. Similarly, the modeled values in regression analysis are unbiased. Thus, in Eq. (7), $\mu = T$. The expected loss then simplifies to

$$E[L(Y)] = k\sigma^2 \tag{8}$$

and the expected loss is proportional to the variance. Often the loss from positive and negative errors can be different. In such cases an asymmetric quadratic loss function can be used (Kackar 1985)

$$L(Y) = \begin{cases} k_1(Y-T)^2, & \text{if } Y < T \\ k_2(Y-T)^2, & \text{if } Y \geq T \end{cases} \tag{9}$$

Following similar arguments as before, and assuming a symmetric probability distribution for the errors (e.g., normal distribution), leads to the expected loss

$$E[L(Y)] = \tfrac{1}{2}k_1[\sigma^2 + (\mu - T)^2] + \tfrac{1}{2}k_2[\sigma^2 + (\mu - T)^2] \tag{10}$$

$$= \tfrac{1}{2}(k_1 + k_2)\sigma^2 \tag{11}$$

The variance σ^2 is estimated by the error variances of the measurements and the estimated models, respectively. By taking into account the cost of measurement, the expected losses resulting from each case can then be compared. The task remains to properly define the loss coefficients k_1 and k_2. The coefficient k_1 represents the case when maintenance activity is performed too early due to erroneous condition information, and the coefficient k_2 when maintenance activity should have been carried out, but is erroneously postponed. In the first case, all or part of the maintenance cost is wasted. In the latter case, excessive road user costs are incurred.

To determine the coefficients k_1 and k_2, one unit change in the logarithmic IRI is calculated. On main road networks, such as the data set used in this study, an IRI value of 1.0 [equivalent to ln(IRI)=0] would be measured immediately after maintenance activity has been performed. An IRI value of 2.7 [ln(IRI)≈1] is a maintenance threshold for such roads. Thus, the value of k_1 is defined as the cost of maintenance activity divided by its longevity, which results in the annual maintenance cost. The annual cost is calculated, because each year one is faced with the same question whether to measure or to model the condition of the road network. The additional user costs, due to deferred maintenance actions, are also calculated per annum.

For example, if the cost of repaving is €35,000/km, and its longevity is 10 years, then k_1=€3,500/km. The coefficient k_2=€17,000/km represents the additional annual user costs due to deferred maintenance for one kilometer of road with a traffic volume of 10 000 vehicles/day. The cost of measuring IRI for the data set used in this study was c=€17/km. The expected loss according to Eq. (11) and Table 2 when measured IRI is used then becomes (€/km)

$$E[L(Y)] = \tfrac{1}{2}(k_1 + k_2)s^2 + c = \tfrac{1}{2}(3{,}500 + 17{,}000) \cdot 0.118^2 + 17 = 160 \tag{12}$$

Similarly, when the model predicting the logarithmic IRI based on the measured logarithmic IRI from 2 years is used, the expected loss is €221/km. The expected loss is €249/km when a 1-year old measurement is used for predicting the current condition and €289/km when a 2-year old measurement is used. These values implicate that the road condition should be measured, rather than predicted. However, the conclusion depends on the relative accuracies of the measurement and the modeling, the cost of measurement, and the coefficients k_1 and k_2. Modeling is more profitable than measuring when the following inequality holds:

$$\tfrac{1}{2}(k_1 + k_2)s_Y^2 \leq \tfrac{1}{2}(k_1 + k_2)s^2 + c \tag{13}$$

or

$$s_Y^2 - s^2 \leq \frac{2c}{k_1 + k_2} \tag{14}$$

In Eq. (14), the terms that include costs have been reorganized to the right side of the inequality to show the maximum difference in the relative variances (i.e., squared relative accuracies) that favors the modeled values to the measured values. Thus, according to the Taguchi loss function approach, the decision to measure, or not to measure, is based on the excess variance $s_Y^2 - s^2$ caused by modeling. By keeping other terms in Eq. (14) constant, a maximum value of 0.125 (=12.5%) is found for modeling error, s_Y, which makes modeling preferable to measuring. This yields an excess error of 0.007 (=0.125−0.118), or 0.7%. Such improvement in the modeling accuracy could be achieved, e.g., by introducing other explanatory variables in the model.

Summary and Conclusions

The condition of a road network is an essential input to maintenance planning. The condition and the deterioration rate of the road network are estimated using measurements and statistical models, both of which include variation. In this paper, these effects were studied using a data set of IRI measurements from 3 years (2000–2002) drawn from the road condition data base of the Finnra (Finnish Road Administration). The measured IRI values were first transformed using logarithmic transformation. Two particular questions were addressed: How can measuring and modeling accuracy be calculated and compared? When is measuring the current road condition beneficial compared to modeling?

The main findings of this study are as follows:

1. The measurement accuracy is defined as the variation of a single measurement, and it can be quantified with the standard deviation of repeated observations using one or more vehicles in similar conditions;
2. The modeling accuracy describes the uncertainty involved with each individual prediction. This uncertainty can be described by the standard deviation estimate s_Y of the predicted values, which is approximated by the standard deviation s_e of residuals e_i in the regression model;
3. The standard deviation of the error in the logarithmic IRI value is increased by 2.9–5.0% units, when a model is used for predicting the current condition from the previous 2 years' measurements instead of measuring it. The amount

of increase in the standard deviation depends on the age of the previous measurement and the corresponding model used;

4. The modeling error includes the measurement error, and their difference is the excess error caused by modeling. This was found to be significantly smaller than the actual measurement error;
5. To develop a method for calculating the modeling accuracy, simple models that predicted roughness solely based on previous observations, were developed. The models indicate the value of historical measurements in estimating the current road condition. Generally, having more information, such as road specific data on traffic and maintenance history, would be likely to yield a better estimate of the current road condition. The accuracy of any regression model can be evaluated using the presented methodology; and
6. The Taguchi loss function was applied to estimating the losses incurred in the different cases. The decision of taking new measurements depends on the relative accuracies of the measurement and the modeling, the cost of measurement, and the losses incurred to the road users and the maintaining agency due to untimely maintenance.

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Notation

The following symbols are used in this paper:

c = cost of measurement (€/km);
$E[\cdot]$ = expected value operator;
e_i = residual of prediction for observation i;
k, k_1, k_2 = cost coefficients;
$L(Y)$ = Taguchi loss function;
$\ln X_j$ = independent variables (logarithms of measured IRI in 2000 and 2001);
$\ln x$ = measured value of independent variable $\ln X$;
$\overline{\ln x}$ = sample mean of independent variable $\ln X$;
$\ln Y$ = dependent variable (logarithm of measured IRI in 2002);
$\ln y_i$ = measured logarithmic IRI value for observation i in 2002;
$\hat{\ln}\, y_i$ = predicted logarithmic IRI value for observation i in 2002;
m_i = number of vehicles measuring section i;
n = number of observations in data set for model determination and fitting;
n_c = number of observations in control measurements;
p = number of independent variables in regression;
SS_x = sum of squares of independent variable;
s = standard deviation of measured logarithmic IRI values;
s_e = standard deviation estimate of error term in regression equation;
s_i^2 = variance of measurements for section i;
s_Y = standard deviation estimate of predicted values;
β_j = regression coefficient of independent variable X_j;
β_0 = regression constant;
ε = error term in regression equation;
μ = expected value of Y; and
σ^2 = variance of Y.

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Essay Two

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Optimal Selection and Routing of Road Surface Measurements

Abstract

The condition of the road network, collected using high-speed devices as part of normal traffic flow, is an essential input to the maintenance process at all decision-making levels. Data collection is relatively inexpensive compared to maintenance needs; yet its benefits should be evaluated and the data collection process made as effective as possible. Our objective in this paper is to evaluate the benefits of road surface measurements, using a decision theoretical approach combined with optimisation of measurement route. We develop an integer linear programming model with route constraints and an objective function that maximises the expected length of road to be reclassified using new measurements for updating the belief of road network condition. The elements of an access matrix are used for evaluating the connectivity of the optimised measurement route.

A simplified network model is used for illustrating the calculation method, which is then transferred on to the network of main and regional roads of Uusimaa Road District in Finland. The results validate the proposed method and also reveal the need for further development. For example, one-carriageway roads are normally measured in one direction only. In our example, we use the same benefits for both directions. Based on the results of this work, it can be concluded that the emphasis in the measurement policy should be shifted from measuring some roads every year to measuring all roads in both directions every other year.

Keywords: route optimisation, access matrix, measurement policy

1 Introduction and objectives

The condition of the road network is an essential input to the maintenance process at all decision-making levels. The condition is measured by using high-speed devices participating in the normal traffic flow. Relatively inexpensive, the measurements, compared to maintenance budgets, are easily taken for a large part of the road network. Yet the total expenditure on road surface measurements may be considerable. The road manager should therefore evaluate the benefits of measurements and utilise the collected information in decision-making as effectively as possible.

What are then the benefits of taking new measurements? Maintenance needs are assessed based on the condition information. This may be done by comparing the measured condition values to trigger values for classifying road sections into categories. In the absence of recent measurements, the current condition may be projected from previous measurements using statistical models. However, uncertainty is connected with both measured and modelled values, and this may result in inaccuracies in the estimated maintenance needs. The benefits may then be evaluated by assessing how much this uncertainty can be reduced by taking new measurements, resulting in more accurate assessment of maintenance needs (Ruotoistenmäki et al. 2006).

Our objective in this paper is to evaluate the benefits of road surface measurements, using a decision theoretical approach combined with optimisation of measurement route. In Section 2, the problem setting is described together with the principles of our methodical solution. In Section 3, a stylised example is presented to illustrate our calculation method. Full analysis using a test network constructed from the condition data bank of Finnish Road Administration, is presented in Section 4. Finally, the conclusions are presented in Section 5.

2 Methods

In road maintenance works programming, the decisions to be made concern which road sections are maintained and what maintenance work types are selected. In the decision-making situation, several decision criteria prevail. These are, for instance, budget constraints, scheduling the maintenance works and the condition of the road sections. In this paper, we take a closer look at the last one of these criteria - condition.

Our current belief of the network condition is based on the distribution of condition variables, such as roughness and rut depth. The distribution is composed of the condition variables for a finite number of road sections, whose condition values include uncertainty. For each individual section, the registered condition is the result of some form of averaging over a large number of measurements. For example, the rut depth attributed to a single road section is the mean value of a number of maximum rut depth measurements obtained from a larger number of transversal road surface profiles. Such an average is therefore approximately normally distributed by the central limit theorem and we therefore assume here that the condition variables for individual sections can be modelled as normally distributed random variables. This normality is conditional on the (unknown) true value for the respective road section. The discrete distribution of all conditions of the finite number of road sections is a mixture over these normal distributions. Empirically, the resulting distribution for the condition of the individual road sections in a road network under continued operation is often close to log-normal.

According to our current belief of the condition of a road section, each section is classified into one of four categories in accordance with whether that section should be included into the next maintenance program:

1. No Action.
2. Warning.
3. Action.
4. Must Do.

Normally, we have previous information on the current condition of roads. This information is, for example, based on previous measurements and knowledge of the degradation of condition from performance models and engineering experience. The value of road surface measurements lies in the fact that they cast light over the current true condition of the measured road sections.

In our particular context one is essentially interested in the resulting classification of a road section into one of the four categories from No Action to Must Do. Additional road surface measurements are therefore motivated if we would expect that the measured road sections might be reclassified based on the additional measurements. In other words, to measure a road section when we have no indication that we might change our perception of that section is of little value for the problem at hand. The value of the measurements arises from the fact that we might reclassify sections and therefore might compile a different and more appropriate maintenance program. A desirable route for a measurement vehicle is therefore a route that contains a large number of road sections which we can expect to reclassify, compared to the current classification. We formalize this approach in the following.

First, let us consider the situation where additional measurements are actually collected. Formally, we view our current belief about a road section's condition as prior information which is updated with a new observation in order to obtain the posterior distribution of the actual condition. This is illustrated as: $\text{posterior} \propto \text{likelihood} \times \text{prior}$. The likelihood follows from our knowledge of the measurement process. This posterior distribution would allow a classification of the road section that may or may not be different from the one based on the prior information (before or without additional measurements).

Now, before deciding whether to collect an additional measurement, we can evaluate the probability that the values to be measured will lead to a reclassification of that road section. We do that with the help of the *predicted* posterior density, i.e. a distribution that describes our likely posterior knowledge *before* the additional measurements are actually taken. This predictive distribution is the basis for our assessment whether it is likely that we will reclassify road sections and, consequently, whether it is worth it to actually collect these measurements.

The posterior distribution of the road condition $\pi(\theta \mid x)$ is proportional to the product of the likelihood $f(x \mid \theta)$ of the utilised statistical model and the prior distribution of the parameter, $\pi(\theta)$, i.e.

$$\pi(\theta \mid x) = \frac{f(x \mid \theta)\pi(\theta)}{\int_{\theta} f(x \mid \theta)\pi(\theta)} \propto f(x \mid \theta)\pi(\theta), \tag{1}$$

where θ indicates the actual condition for a specific road section. In our model, we utilize normal distributions for the prior and the likelihood. In that case even the resulting posterior distribution is a normal distribution that is completely specified by mean (expected) value μ and standard deviation σ.

Our current belief of the road condition is represented by the prior distribution $\pi(\theta)$, where $\theta \sim \mathrm{N}(\mu, \tau^2)$, based e.g. on a previous measurement x_{t-1}. The measurement process is assumed to produce a normally distributed measurement value so that the measured values x are correct on average, i.e. $X \sim \mathrm{N}(\theta, \sigma^2)$. The posterior distribution for θ is then (Berger 1985, p. 128)

$$\theta|x_t, x_{t\text{-}1} \sim N\left(\mu(x_t), \frac{\tau^2\sigma^2}{\tau^2+\sigma^2}\right). \tag{2}$$

Now, the measurement x_t is not yet taken, but it has the predictive density (Berger 1985, p. 95)

$$x_t|x_{t\text{-}1} \sim N\left(\mu, \tau^2+\sigma^2\right). \tag{3}$$

Thus, replacing σ^2 in Equation (2) with $\tau^2+\sigma^2$ from Equation (3) yields the following predictive posterior distribution for θ:

$$N\left(\mu, \frac{\tau^2(\tau^2+\sigma^2)}{2\tau^2+\sigma^2}\right).^{1} \tag{4}$$

This principle is illustrated in Figure 1, where the increase of θ indicates deterioration. The prior distribution of an individual road section, $\pi(\theta), \theta \sim N\left(\mu, \tau^2\right)$, is shown in the dotted curve. The predictive posterior distribution for that road section based on Equation (4) is illustrated by the solid curve. Maintenance threshold values for No Action, Warning, Action and Must Do levels are shown as vertical lines. According to the example shown in Figure 1, we classify a particular road section into Warning category based on previous condition information, because most of the probability mass of $\pi(\theta)$ falls into the associated interval for values of θ. We then calculate the probability that the road section will be classified differently by evaluating the predictive posterior distribution using the same criteria of, in this case, predictive posterior density mass for the various intervals associated with the classification. Different classification means a classification into any other class and corresponds in this particular example to the predictive posterior density mass given to all values of θ not belonging to the Warning level. This probability corresponds to the combined areas under the solid curve to the left of the leftmost vertical line

[1] Of course, once measurements are actually taken, the information should actually be updated with help of Equation (2), resulting in a true posterior distribution for θ.

between categories No Action and Warning and to the right of the vertical threshold line between categories Warning and Action.

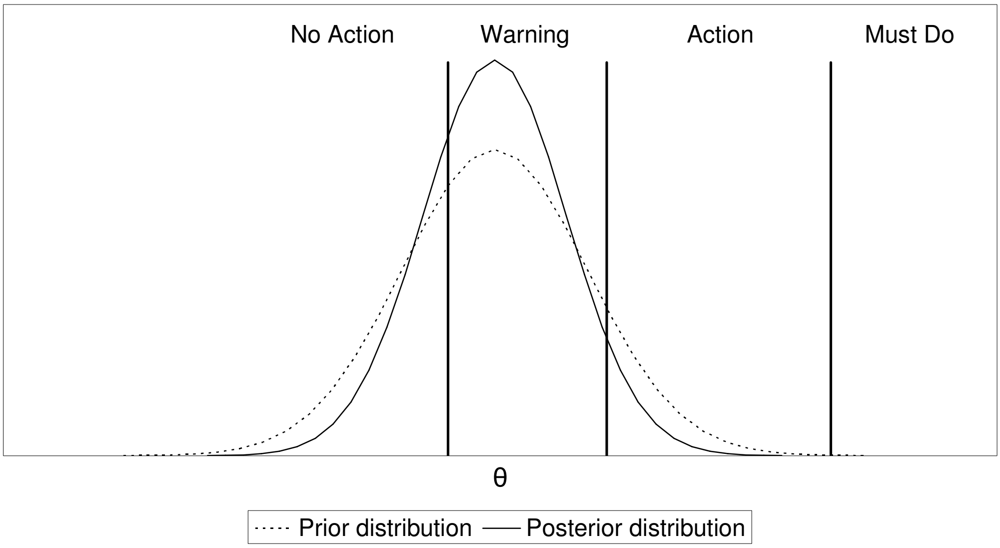

Figure 1. Evaluating whether additional measurements are likely to result in reclassification of a road section.

We determine this probability of reclassification of a section in case of additional measurements for each single section in the road network. Our aim is conditional on given resources (funding, maximum kilometres to measure, etc.), to find a route that maximises the number of sections we expect to be reclassified. This route enhances our decision-making most. Equivalently, we aim at maximising the expected length of road to be reclassified by a given measurement effort.

3 Illustration of the optimisation method

3.1 Stylised example

To give the reader a clear picture of the calculation method used, in Figure 2 we present a stylised example of a network, which is then applied to a network of in-service roads.

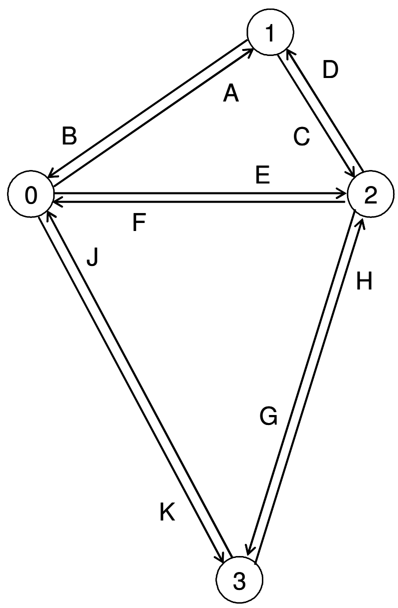

Figure 2.Network for the stylised example.

The stylised example consists of five physical sections, each one of which can be measured in two directions. This results in a total of ten sections. In our example, we use roughness in terms of the logarithm of *IRI*[2] to represent the condition θ. For each section, we have the current belief of logarithmic roughness with the associated standard deviation of 0.168 (=16.8 %) at each section. The standard deviation of the

[2] International Roughness Index (*IRI*) represents the vertical movement of passenger and vehicle per distance travelled (unit mm/m). For further explanation, the reader is referred to Sayers et al. (1986a, 1986b) and UMTRI (2007).

measured logarithmic *IRI* is assumed 0.118 (=11.8 %)[3]. The standard deviation of the conditional posterior density for the new measurement x_t from Equation (3) is then

$$\sqrt{\tau^2+\sigma^2}=\sqrt{0.168^2+0.118^2}=0.2053, \tag{5}$$

and the standard deviation of the predictive posterior distribution of condition θ, according to Equation (4) is

$$\sqrt{\frac{\tau^2\left(\tau^2+\sigma^2\right)}{2\tau^2+\sigma^2}}=\sqrt{\frac{0.168^2\left(0.168^2+0.118^2\right)}{2*0.168^2+0.118^2}}=0.130. \tag{6}$$

The classification of the sections according to *IRI*, and the associated threshold values are presented in Table 1. The threshold values of the original untransformed *IRI* values reflect those of a high-class paved road network.

Table 1. Condition classification according to IRI.

Classification	*IRI* [mm/m]	ln(*IRI*)
N = No Action	<1.5	<0.4055
W = Warning	1.5 - 2.0	0.4055 - 0.6930
A = Action	2.0 - 3.0	0.6931 - 1.0986
M = Must Do	>3.0	>1.0986

The length of sections and the expected value of the current belief of logarithmic *IRI* for each section, simulated from a normal distribution $N\sim(0.404, 0.380)$[4] are presented in Table 2, along with the current classification and the probability of reclassification. Gains from taking new measurements are defined as the product of the probability of reclassification and section length, and shown in the rightmost column in Table 2.

[3] These values are based on Ruotoistenmäki et al. (2006), who developed measures of accuracy for measured and modelled condition values. The accuracy 16.8 % of the current belief of the logarithmic *IRI* is based on the logarithmic *IRI* predicted from two year old measurements, whose accuracy is 11.8 %.

[4] These values reflect distribution of log(IRI) on a high-class paved road network, and are from the data set where the accuracy of measured and modelled condition values were verified by Ruotoistenmäki et al. (2006).

Table 2. Data for stylised example.

Section ID	From	To	Length of section [km]	Current belief, Expected value	Current classification	p [1)]	gain (g) = Length * p
A	0	1	4	0.13	N	0.016	0.062
B	1	0	4	0.49	W	0.324	1.297
C	1	2	3	0.71	A	0.459	1.378
D	2	1	3	0.58	W	0.279	0.837
E	0	2	5	0.05	N	0.003	0.017
F	2	0	5	0.62	W	0.335	1.673
G	2	3	7	0.78	A	0.260	1.820
H	3	2	7	0.03	N	0.002	0.015
J	3	0	8	0.86	A	0.130	1.037
K	0	3	8	0.62	W	0.335	2.676

1) p = Probability of reclassification for this section

The probability of reclassification p is calculated as the sum of the probabilities that the new classification is downgraded and that the new classification upgraded. For example for road section C, this probability would be calculated as

$$p = \Phi\left(\frac{0.71-0.6931}{0.130}\right) + \left(1-\Phi\left(\frac{1.0986-0.71}{0.130}\right)\right) = 0.459\,, \tag{7}$$

where Φ denotes the cumulative density of the standard normal distribution. The expected gain (expected length of reclassified road section) is the probability of reclassification multiplied by the section length, i.e. for this example 3*0.459=1.378.

In order to complete our aim to find a route that maximises the expected length of road to be reclassified using the new measurements, we need to maximise the sum of the rightmost column in Table 3, the product of section length and the probability of reclassification. Constraint in the optimisation is the funding available for measurements.

3.2 Optimisation

Let x_{ij}=1, if road section from node i to node j is to be measured, and 0 otherwise ($i = 0,\ldots,n; j = 0,\ldots,n$). Let c_{ij} and g_{ij} be the corresponding cost and gain for measuring, respectively, and let B denote the available budget. In addition, we need a balancing equation for each node that will be passed, i.e. the number of arriving and departing arcs to and from each node on the route are equal. Otherwise additional sections would have to be driven to be able to apply the optimal solution in practice. This, of course, would mean additional costs. We will also require that the measuring vehicle starts from node 0 and also finishes the route in node 0. This can be achieved by requiring that there is at least one arc leaving from node 0. The problem then becomes an integer linear programming problem with binary decision variables x_{ij} as follows (the sums are taken over all the possible routes):

$$
\begin{aligned}
& Max \quad G = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ i \neq j}}^{n} g_{ij} x_{ij} \\
& s.t. \quad \sum_{i=0}^{n} \sum_{\substack{j=0 \\ i \neq j}}^{n} c_{ij} x_{ij} \leq B \\
& \sum_{\substack{j=0 \\ i \neq j}}^{n} x_{ij} = \sum_{\substack{j=0 \\ i \neq j}}^{n} x_{ji} \quad \textit{for all nodes } i \\
& \sum_{j=1}^{n} x_{0j} \geq 1 \\
& x_{ij} \in \{0,1\} \ \textit{for all } i, j; i \neq j
\end{aligned}
\tag{8}
$$

The problem can easily be solved with specialised software, e.g. AMPL[5], which we have used to obtain the optimal solutions for the different cases in this paper. For the input values given in table 2, where cost of measurement € 43.30 / km and a budget constraint of € 1200 are presented, the optimal solution is shown in figure 3. Solving problem (8) yields the optimal solution where sections C, D, F, H and K are measured. The optimal expected length of reclassified road is 6.579 km at a cost of € 1125.8.

[5] www.ampl.com

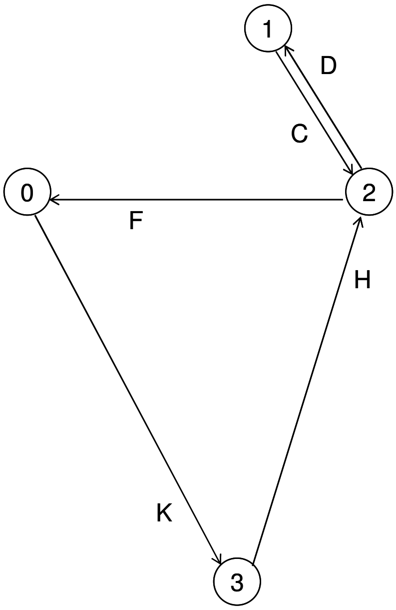

Figure 3. Solution of equation (8) for the input values given in table 2, cost of measurement € 43.30 / km and a budget constraint of € 1200. Sections C, D, F, H and K are measured. The optimal expected length of reclassified road is 6.579 km with a cost of € 1125.8.

Clearly, the solution is consistent, i.e. it is connected so that one vehicle can be used for driving all sections selected for measurement in the optimisation process. The balancing constraint of equation (8) ensures that the number of departing and arriving arches match at each node. However, this property does not guarantee the consistency of the route.

3.3 Access matrix

But how do we ensure the consistency of the route? One obvious solution is to use several vehicles, but then again the route of each individual vehicle has to be connected. Otherwise more sections have to be driven through to unite the route and this would be a violation of the budget constraint used in the optimisation. For practical purposes, slight deviation from the budget constraint may well be a feasible solution, and on small networks, the consistency of the route is easy to check on a map. However, on large networks, an analytical model is desirable for securing the consistency of an optimised route within the budget limits.

We developed a mathematical approach for detecting the consistency of the optimised route, based on the concept of *access matrix*. The elements of an access matrix **A** indicate whether a connection between two nodes exists. The value of an element $a_{ij} = 1$, if a connection between nodes i and j exists, otherwise $a_{ij} = 0$. The diagonal elements of $\mathbf{A} \equiv 0$, indicating that one cannot return to a departing node when driving along one arc only. Furthermore, the upper triangular matrix and the lower triangular matrix are mirror images of each other around the diagonal, i.e. if a connection from node i to node j exists, also a connection from node j to node i exists[6]. The elements of the sum matrix

$$\sum_{i=1}^{n} A^i = A^1 + A^2 + ... + A^n \qquad (9)$$

indicate the number of alternative routes from node i to node j in the network of n nodes when a maximum of n arcs are driven. In this case, the diagonal elements of $A \neq 0$, which means one can return to departure node after driving a maximum of n arcs.

Likewise, the sum of matrices, according to equation (9), indicates the number of alternative routes from node i to node j in an optimised solution. If an element = 0 on a row i or column i for a node i that is on the route, then that node is not connected to one or more of the other nodes $j \neq i$ on the route. More precisely, a node i for which $a_{ij} = 0$ $(i \neq j)$, is not connected with node j. However, if a node i is not on the route, all elements of that row i and column i equal 0, and it can be ignored.

[6] Actually, this need not be the case. One-way streets exist, for which $a_{ij} \neq a_{ji}$. In this case, our method can be applied as such, even though our examples represent cases for which $a_{ij} = a_{ji}$.

In order to check the consistency of an optimised route, the equation (9) is applied to the access matrix of that solution, and the sum matrix is analysed. An example is shown in Table 3, where the access matrix of the original stylised example is shown in the left pane and the access matrix of the solution in Figure 3 in the right pane.

Table 3.   Access matrix of the original stylised example (left pane) and a consistent solution (right pane).

	Original access matrix = A (Figure 2)				A consistent solution (Figure 3)			
	To				To			
From	Node 0:	Node 1:	Node 2:	Node 3:	Node 0:	Node 1:	Node 2:	Node 3:
Node 0:	0	1	1	1	0	0	0	1
Node 1:	1	0	1	0	0	0	1	0
Node 2:	1	1	0	1	1	1	0	0
Node 3:	1	0	1	0	0	0	1	0
	$A^1 + A^2 + A^3 + A^4$				$A^1 + A^2 + A^3 + A^4$			
	To				To			
From	Node 0:	Node 1:	Node 2:	Node 3:	Node 0:	Node 1:	Node 2:	Node 3:
Node 0:	22	16	22	16	1	1	2	2
Node 1:	16	14	16	14	2	2	3	1
Node 2:	22	16	22	16	3	3	3	2
Node 3:	16	14	16	14	2	2	3	1

From Table 3, we can see that both in the original network and in the consistent solution, when driving n arcs, a number of routes from a node to any other node (including the departing node), can be made. This is obvious from figure 3, but for large networks, a visual examination of an optimised solution may be cumbersome. Furthermore, the method presented here can be programmed as a part of an optimisation application.

3.4 Driving or measuring?

In practice it is possible to turn the measurement apparatus off so that driving along the sections can be less costly. In this way we can choose the sections most beneficial for measuring. We can then drive but not measure other routes so that the measurement route remains consistent.

We will assume that the cost of driving without measurement on a given section from node *i* to node *j* is estimated as d_{ij}. Let x_{ij}=1, if road section from node *i* to node *j* is being measured, and 0 otherwise; as before. In addition, we need another binary variable y_{ij}=1, if road section from node *i* to node *j* is being used for travelling without measuring, and 0 otherwise. With this modification the model is as follows:

$$
\begin{aligned}
&Max \quad G = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ i \neq j}}^{n} g_{ij} x_{ij} \\
&s.t. \quad \sum_{i=0}^{n} \sum_{\substack{j=0 \\ i \neq j}}^{n} \left(c_{ij} x_{ij} + d_{ij} y_{ij} \right) \leq B \\
&\sum_{\substack{j=0 \\ i \neq j}}^{n} \left(x_{ij} + y_{ij} \right) = \sum_{\substack{j=0 \\ i \neq j}}^{n} \left(x_{ji} + y_{ji} \right) \; for\ all\ nodes\ i \\
&\sum_{j=1}^{n} \left(x_{0j} + y_{0j} \right) \geq 1 \\
&x_{ij} + y_{ij} \leq 1 \; for\ all\ i, j; i \neq j \\
&x_{ij} \in \{0,1\} \; for\ all\ i, j; i \neq j
\end{aligned}
\tag{10}
$$

We introduce a new constraint that means that each section can either be measured or travelled on only. A reasonable estimate for the travelling cost is a fixed percentage of the measurement cost per kilometre. Using the same numerical data as before and assuming the travelling cost to be 20 % of the measurement cost, the optimisation problem was solved. The optimal solution is shown in Figure 4. The dashed lines on sections A, D and H indicate travelling without measuring. The measured sections are B, C, F and K. The total expected length of reclassified road is 7.024 km, which is more than in our previous solution (6.579) but the cost is less (€ 987.24 instead of € 1125.8).

The access matrix can similarly be used for checking the consistency of the optimised measurement route. We are only interested in whether the route is connected, not which routes are measured, or which ones are driven on only. Thus, we set all elements a_{ij} = 1 that are either driven or measured. From Figure 4 and Table 4 we see that the route is consistent. This makes this approach a feasible one in a real road measuring problem. It should be noted that if travelling cost equals measurement cost, the equation (10) is reduced back to equation (8).

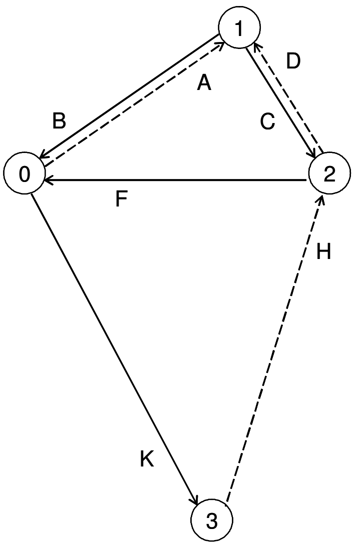

Figure 4. Solution when route constraints are considered and driving without measuring has a lower cost than measuring. Sections B, C, F and K are measured, A, D and H driven on only. The optimal expected length of reclassified road is 7.024 km with a cost of € 987.24.

Table 4. Access matrix of a consistent solution shown in Figure 4.

	A consistent solution (Figure 6)			
	To			
From	Node 0:	Node 1:	Node 2:	Node 3:
Node 0:	0	1	0	1
Node 1:	1	0	1	0
Node 2:	1	1	0	0
Node 3:	0	0	1	0
	$A^1 + A^2 + A^3 + A^4$			
	To			
From	Node 0:	Node 1:	Node 2:	Node 3:
Node 0:	6	6	6	4
Node 1:	8	8	6	4
Node 2:	8	8	6	4
Node 3:	4	4	4	2

4 Validation of the optimisation method

4.1 Test network

In the previous section, we developed a decision theoretical framework combined with a route optimisation method for assessing the benefits of road surface measurements. We also illustrated our method on a stylised network. For its further validation, we now present a calculation example using data from an in-service road network. The network consists of the main and regional roads of Uusimaa Road District in Finland. The road network also embraces Helsinki, the capital city of Finland.

In the condition data bank (CDB) of the Finnish Road Administration (Finnra), the road network is divided into management sections with an average length of approximately 5 kilometres. We divided our network into sections by placing nodes at management section change points in the CDB. The resulting network, shown in Figure 5, consists of a total of 289 nodes and 700 arcs. The total length of the network is 2 952.3 kilometres. Helsinki is located in the middle of the southern coast of the Uusimaa District, and main roads radially start from there or surround the capital as rings.

All routes can be driven in both directions and two routes in opposite directions exist between every two nodes, as in the stylised example shown in Figure 2. This enables us to complete a drivable measurement route. In addition, even though the road condition in the opposite directions is correlated, it is different, and the expected gains should be different for the different directions.

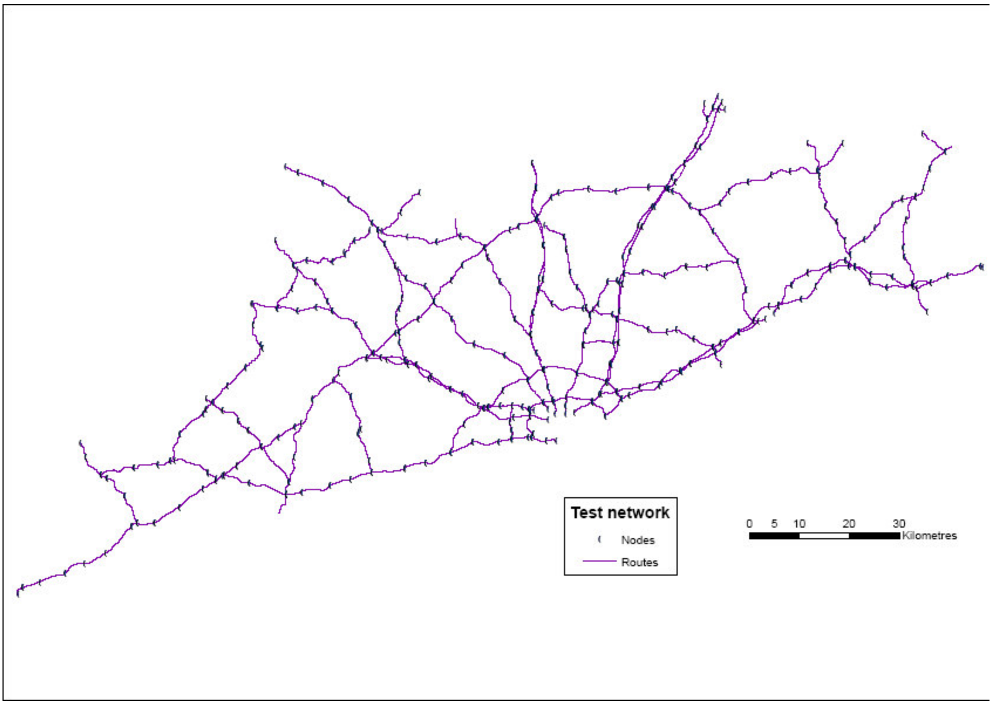

Figure 5. Test network of main and regional roads of Uusimaa road district in Finland.

Data is stored in the CDB in 100-meter sections. We extracted roughness measurements (*IRI*) from 2003 to 2006 for this network and calculated the expected benefits of taking new measurements for each 100-meter section. We then calculated the gain for each route as the average of gains from 100-meter sections, and multiplied it with route length to produce gains for maximisation according to Equation (10). The current measurement policy is to measure one-carriageway roads in one direction only, whereas for two-carriageway roads all lanes in both directions are measured. For two-carriageway roads, we used the actual measurements to derive gains in both directions separately, but for one-carriageway roads, we used the same gain from measurement in one direction for both directions.

4.2 Measures of accuracy

For the stylised example in the previous section, we used the measures of accuracy as defined by Ruotoistenmäki et al. (2006) to calculate the standard deviation of the conditional posterior density for the new measurement and the standard deviation of the predictive posterior distribution of condition according to equations (5) and (6). These measures of accuracy are based on equipment not in use any more. Instead, we developed new measures of accuracy using data from current measurement vehicles and a similar procedure as used by Ruotoistenmäki et al. (2006). These measures are based on data collected from our sample network from 2003 to 2006. These accuracies, presented in Table 5, are considerably better than the previous ones.

Table 5. Measuring and modelling accuracy from data collected between 2003 and 2006 using the method developed by Ruotoistenmäki et al. (2006).

		Accuracy	Eq (11)	
Measured		6.1%	0.0042	is the right hand side
Modelled using data from previous measurements	1+2+3 yrs	7.2%	0.0014	are the left hand sides
	1+2 yrs	7.3%	0.0016	
	1+3 yrs	7.3%	0.0017	
	1 yr	7.8%	0.0024	
	2+3 yrs	9.2%	0.0047	
	2 yr	9.7%	0.0058	
	3 yr	11.7%	0.0100	

Ruotoistenmäki et al. (2006) developed the following inequality to calculate the maximum excess variance for which it is more beneficial to use a model than to take a new measurement in order to assess the current road condition:

$$s_Y^2 - s^2 \leq \frac{2c}{k_1 + k_2} \tag{11}$$

Here s_Y^2 is the variance associated with modelled values, s^2 is the variance associated with measured values, c is the measurement cost and k_1 and k_2 are loss coefficients for agency and user losses due to untimely maintenance. The values from Equation 11 are shown in the rightmost column in Table 5. From these values it can be concluded that if a road is measured in the previous year, it is more beneficial to model the current condition of the road from previous measurements than to measure it again this year. If no data is available from the preceding year, it is more beneficial to measure than to use a model. According to this calculation, the roads should be measured every other year.

4.3 Updating knowledge of road condition

For each 100-meter section, we have the current belief of the logarithmic roughness from the CDB, with the associated standard deviation of 0.078 (=7.8 %), 0.097 and 0.117 for one, two and three year old measurements, respectively. Data from four years enables modelling based on up to three year old measurements. Thus, we estimated the standard deviation based on four year old measurements at 0.130 and based on measurements older than that at 0.140. The standard deviation of the measured logarithmic *IRI* is 0.061 (=6.1 %). The standard deviation of the conditional posterior density for the new measurement $x_t|x_{t-1}$ for one-year old measurements from Equation (3) is now

$$\sqrt{\tau^2 + \sigma^2} = \sqrt{0.078^2 + 0.061^2} = 0.099\,, \tag{12}$$

and the standard deviation of the predictive posterior distribution of the condition θ, according to Equation (4) is

$$\sqrt{\frac{\tau^2(\tau^2 + \sigma^2)}{2\tau^2 + \sigma^2}} = \sqrt{\frac{0.078^2(0.078^2 + 0.061^2)}{2*0.078^2 + 0.061^2}} = 0.061\,. \tag{13}$$

The classification of the sections according to *IRI*, and the associated threshold values are the same as before, and are presented in Table 1. One-carriageway roads are measured in one direction only, and in that case, the same value for gain is used for both sections in different directions between the same nodes. For two-carriageway roads, actual measured values are used for determining gains for the different directions separately.

4.4 Budget limit

We used the following procedure for selecting the budget limit for optimisation: As was concluded from the values of Equation (11) in Table 5, a section should be measured only if it was not measured in the previous year. A total of 705 km out of 2 950 km meet this criteria, and the expected length of reclassified road is 70.9 km, which means the average probability of reclassification of one km of road is 70.9 / 705 = 0.1. These roads are shown in Figure 6 where it can be seen that they are mainly located in the low-volume part of the network. This is due to the current measurement policy, where main roads are measured every year and minor roads every three years. The measurement cost of these roads is 705 km * 43.3 €/km = 30 521 €. This cost does not change if the sections' locations on the network change. Consequently, we set the budget limit at this lump sum. The question then is whether we can gain greater benefit for the same measurement budget by using our optimisation model.

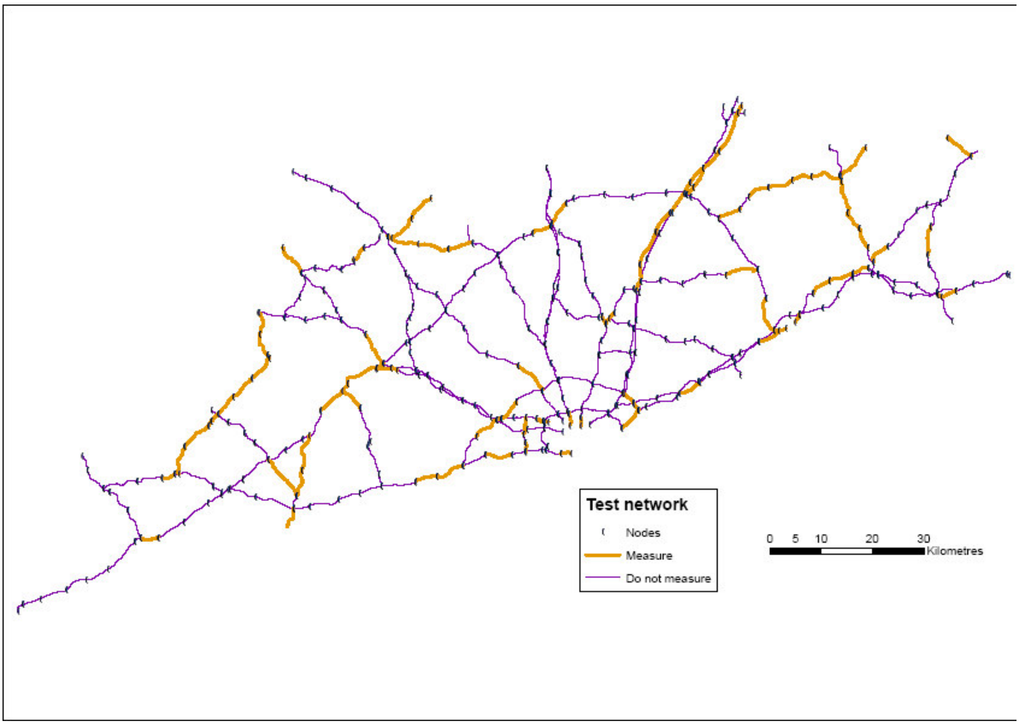

Figure 6. Measurement program of main and regional roads of Uusimaa Road District in Finland, based on accuracy of existing condition information.

4.5 Results

Optimisation was done using the AMPL[7] software. The solution is shown in Figure 7. Interestingly enough, all sections except two that are driven are also measured. The budget limit is € 30 521, and the budget used is € 30 468, which results in a measurement program of 703.7 km. The expected length of the roads in the optimised measurement program, which is the value of objective function in Equation (10), is 102.3 km. This gain is 44 % higher than the gain from measurement route that complies with the current measurement policy shown in Figure 6. The average probability of reclassification of one km of road in the optimised solution is 102.3 / 703.7 = 0.145. From Figure 7 it can also be seen that the optimised solution is concentrated in the low-volume part of the network. This is the part of the network where deterioration of roads in terms of roughness is greatest and where the expected benefits of taking new measurements are highest.

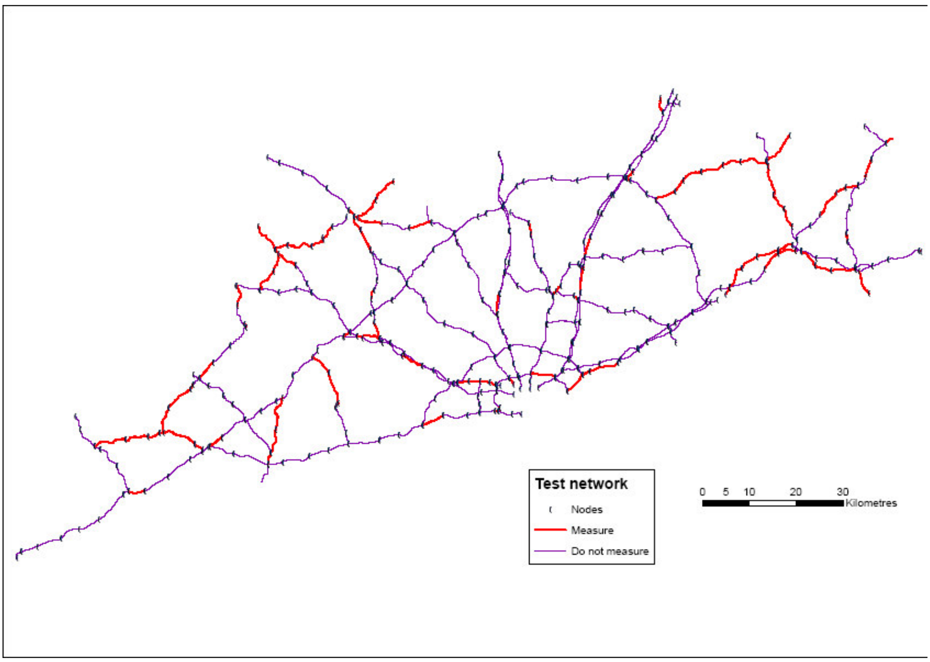

Figure 7. Optimised solution for roughness measurements on main and regional roads of Uusimaa Road District in Finland.

[7] www.ampl.com

From Figure 7 it can also be observed that the optimised measurement route is not connected. If the visual assessment of connectivity had not been possible, it could have been checked by applying Equation (9). Indeed, we calculated the sum of access matrices after first removing empty rows from the access matrix to reduce the required number of matrix multiplications to 178, which is the number of routes measured or driven in the optimised solution. Naturally, the sum of access matrices reveals the same fact as the map - that the route is not connected. This is due to one shortcoming of our example, namely that one-carriageway roads are measured in one direction only. We used the same expected gain for both directions. This implies that in the optimised solution, for most measured arcs, both directions are measured, and the balancing constraints for all nodes are satisfied even when the route is not connected.

The next problem is how to find a solution where the measurement route is connected. One solution might be to incorporate the access matrix as a constraint to the optimisation model presented in Equation (10). This, however, is proposed for further inquiry. At this moment, we can conclude that the current measurement policy could be altered so that both directions are measured on all roads. This can be done by reallocating the prevailing measurement budget because, in the light of our results, some of the roads now measured every year, could be measured every other year. Shifting the current policy has the added benefit of further improving the efficiency of data collection by reducing driving on without measuring.

5 Conclusions

Decision-makers concerned with road maintenance activities face the question about which road sections to measure as input to the maintenance management process. In this context it is important to predict the likelihood of each section to be reclassified as in need or not of maintenance. We apply a Bayesian analysis for developing the idea of gain from measurement as the expected length of reclassified road after measurement activities. This is then used as the objective function in an integer linear programming problem to maximise the expected gain.

We develop the linear optimisation model into a route optimisation model by introducing balancing constraints for each node in the network. The connectivity of an optimised solution is evaluated by using an access matrix, whose elements indicate the existence of connection between the nodes in the network. These two advances enable the use of an integer programming model for a route optimisation problem, where the actual routes to be measured (arcs) are selected based on the expected benefits of new measurements not yet taken. In this way the measurement budget is allocated as effectively as possible so as to enhance our decision-making process.

A simple stylised example, which shows the relevant aspects of our optimal selection and routing method was presented and applied to a more complicated real-life network. A cost-benefit analysis of measuring and modelling accuracies reveals the interesting result that if a road is measured in the previous year, it is more beneficial to model the current condition of the road from previous measurements than to measure it again this year. If no data is available from the preceding year, it is more beneficial to measure than to use a model. According to this calculation, the roads should be measured every other year.

The major limitations of our study relate to the available data, which has been collected mostly in one direction only. We therefore used the same expected gain from new measurements to be taken for both directions. This results in a situation where in the optimised solution most arcs that are measured are measured in both directions. The condition of lanes in different directions is correlated, but certainly not equal. Measuring in both directions would allow us to evaluate the expected gains of an optimised measurement program more realistically. This can be done by reallocating the prevailing measurement budget because, in the light of our results, some of the roads now measured every year, could be measured every other year.

Unfortunately, the resulting optimal solution could possess the property of non-connectivity, i.e. there is no connection from some nodes to other nodes on the selected route. This can happen despite the balancing condition of the number of incoming arcs equalling the number of leaving arcs. The access matrix concept provides a tool for checking the consistency of the route, and it can also be possibly incorporated as a constraint in our optimisation model. This is something that could be done at a later stage of the development work.

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Essay Three

Ruotoistenmäki, A. & Seppälä, T.

Road condition rating based on factor analysis of road condition measurements

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Road condition rating based on factor analysis of road condition measurements

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Abstract

Summarising indices of road condition are used in road maintenance management for aggregating the vast amount of data and for communication purposes. In this paper, a road condition rating based on factor analysis of measured road condition variables is developed to calculate values for an existing or a new condition index. Three factors were extracted from road surface profile and deflection measurements: structural factor, roughness factor and transversal unevenness factor. Factor scores are calculated as the mean of the standardised values of log-transformed variables in each factor. Condition rating, calculated as the weighted sum of the factor scores, is used for maintenance policy evaluation.

Keywords: Strategic level; Decision making; Road maintenance; Road condition; Summarising indices; Factor analysis; Policy evaluation

1. Introduction and objectives

Many road agencies collect a large number of road condition variables from their network into their databases. The different variables indicate various aspects of road condition. For example, the longitudinal and transversal surface profiles are most often measured using the road surface monitoring (RSM) vehicle based on laser technology. The different surface distresses are monitored visually or using automated image collection and interpretation techniques. The properties of the road structure and the subgrade can be deduced from surface deflections measured using the falling weight deflectometer (FWD) and measurements done using the ground penetrating radar (GPR). For strategic-level decision-making in road maintenance management, the condition of the road network has to be described using indicators that summarise the vast information obtained from measurements (Hudson et al., 1997).

The most famous and widely used summarising indices include the pavement condition index (PCI) and the present serviceability index (PSI). The PCI of a road in excellent condition is 100, and the severity and extent of various defects reduce the PCI to a minimum of 0 (Hudson et al., 1997; FAA, 1982; Shahin and Walter, 1990). The PSI reflects the user rating of ride quality on a scale from 5 (excellent) to 0 (poor), and it is estimated from the measured condition variables using regression equations (AASHO, 1962). For example, in the German road management system, a rating based on the measured condition variables is calculated as a weighted overall index ranging from 1 (excellent) to 5 (poor) (see e.g. Elchlepp and Heller, 2004).

However, in the Finnish road maintenance management context, overall indices of road condition have rarely been used. This may partly be due to unfamiliarity with such indices within the Finnish road community. A classification of infrastructure condition into five categories from 5 (excellent) to 1 (poor) is proposed in a recent Finnish study (Finnra, 2005), where a standardised level-of-service scale for the condition of the road assets based on the measured condition indicators is presented.

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The problem with many of the existing practices for deriving summarising condition index values is that they require identical information from all roads in consideration. The objective of this paper is to present a flexible condition rating system for presenting the overall condition of a road network and comparing different roads and sub-networks, based on a number of measured road condition variables. The objective is also to introduce a tool for using road network condition as an input to strategic-level decision-making. These objectives are achieved by means of factor analysis that considers the various aspects of road condition and combines them into an overall condition rating. This rating is further used as an input to a simplified evaluation method of maintenance policies. This method relates the various maintenance policies to their resulting condition distributions during a selected analysis period. Although the specific application presented here is road maintenance management, the proposed method is suitable for assessing the overall condition of any asset based on a number of observed variables.

The benefit from using the proposed condition rating is that, once calibrated, it can be used for estimating index values from road condition measurements for an existing or a new condition index. Furthermore, any number of condition variables available from a road can be used for calculating this rating. The resulting indices from two roads are also directly comparable, even when different condition variables have been measured on different roads.

The principles of the analysis method and the results are explained in Section 2 of this paper. The calculation of a condition rating based on the factor analysis is explained in Section 3 and the selection of the data set used in this study is described in Section 4 of this paper. The results are discussed and the use of the proposed method is then illustrated in Section 5. The derived condition rating system is applied to maintenance policy evaluation which is presented in Section 6. The main findings and limitations of the study together with recommendations for implementation of the results are summarised in Section 7.

2. Factor analysis of road condition data

2.1. Approach and short review on previous studies

Factor analysis is a multivariate data analysis method, which summarises the vast information conveyed by a large number of observed variables. The factors—less in number than the original variables—describe the more general properties of the object of research, in this case the road. These properties are latent, i.e. they are usually not directly measurable. For example, the structural capacity of the road cannot be directly measured. Instead, surface deflections, measured using the FWD, are taken to describe the structural capacity of the road. In this paper, the calculation method has been explained to the extent that it gives the reader an understanding of the results. For a complete explanation of the method, the reader is referred to textbooks such as Cureton and D'Agostino (1983), or Hair et al. (1998).

Factor analysis has been applied to road condition measurements at least by Hajek and Haas (1987), Talvitie and Olsonen (1988), Ramaswamy and McNeil (1991) and Kyyrä (1992). Hajek and Haas use cracking data from Ontario, with 15 pavement surface distress types aggregated to five general dimensions of surface cracking using factor analysis techniques. Unfortunately, as will be further discussed in Section 4, the cracking variables from visual survey could not be clearly interpreted in this study, neither as a distinct factor nor as part of any other of the derived factors.

Talvitie and Olsonen used factor analysis to find general dimensions of road condition for use in a network-level pavement management system. Based on their work, four condition indicators have traditionally been used by the Finnish Road Administration (Finnra): International Roughness Index (IRI), rut depth, bearing capacity (or later bearing capacity ratio) and cracking index. Kyyrä found the same factors that describe road condition, except that for bearing capacity, she derived two factors: bearing capacity of the road structure, and that of the subgrade.

Ramaswamy and McNeil derive one- and two-factor models from the measured rut depth, slope variance and cracking variables and compare the results with the PSI. The difference of this work to that of Ramaswamy's and McNeil's—and other previous works referred to in this section—is that the factors are derived separately, so that the measured condition variables are each included to only one factor. Furthermore, the results of the factor analysis are used for establishing a condition rating, whose use in evaluating alternative maintenance policies is demonstrated in Section 6.

2.2. Measurement model

The measurement model gives factor loadings that relate the factors with the original variables according to:

$$x_i = \sum_{j=1}^{k} \lambda_{ij} F_j = \lambda_{i1} F_1 + \lambda_{i2} F_2 + \cdots + \lambda_{ik} F_k, \quad i = 1, 2, \ldots, n, \tag{1}$$

where x_i refers to original variable i, λ_{ij} is the loading of the variable i on factor j, F_j is factor j, n is the number of original variables and k is the number of factors, with $k < n$.

First, an exploratory factor analysis (starting with correlation matrix using principal component factoring) was carried out to unveil the factors in the data set. Three factors with eigenvalue greater than one were extracted and a Varimax rotation was applied. Eigenvalue describes the amount of variation in the original data that a factor explains, and values greater than one imply that a factor explains the variation in the original data better than an original variable in average. The derived factors are rotated in the variable space in order to find a solution where the original variables have high loadings on the factors. Varimax rotation aims at a result where each of the original variables has a high loading on exactly one factor. The resulting factors are orthogonal, which means that they are uncorrelated. The factors can be interpreted and named based on the variables with high loadings on the factors. For example, if the variables calculated from the longitudinal profile load on the same factor, this factor can be interpreted as a roughness factor.

The analysis was continued with a confirmatory factor analysis, where the factors found in the exploratory analysis were extracted, one at a time, from the data set using only the variables chosen to represent that factor. In this method, no rotation is necessary, as maximum loadings on each factor are immediately found. The resulting measurement models from the confirmatory analysis with the final factor loadings are shown in Table 1, where names are given to the factors, based on the variables included in each factor.

Mäenpää et al. (2006) use an approach related to the one used in this paper for analysing the behaviour of internet bank customers. They found distinct dimensions in the behaviour of more hedonic and less hedonic consumers. The results can be applied when developing internet banking services to key target groups of customers. In parallel, this approach allows consideration of distinct aspects of road condition separately. The results from the confirmatory analysis are further used in developing the condition rating.

Table 1
Measurement models with the corresponding factor loadings

Factor	Variables[a]	Factor loadings
1. Structural factor	D0_T = temperature-corrected deflection under the loading plate	0.860
	D20_T = temperature-corrected deflection 200 mm from the loading plate	0.942
	D30_T = temperature-corrected deflection 300 mm from the loading plate	0.982
	D45_T = temperature-corrected deflection 450 mm from the loading plate	0.993
	D60_T = temperature-corrected deflection 600 mm from the loading plate	0.982
	D90_T = temperature-corrected deflection 900 mm from the loading plate	0.939
	D120_T = temperature-corrected deflection 1200 mm from the loading plate	0.883
2. Roughness factor	IRI	0.972
	Root mean square (RMS) of the surface profile with 0.5–1 m wave length, outer wheel path	0.821
	RMS 1–3 m wave length, outer wheel path	0.944
	RMS 3–10 m wave length, outer wheel path	0.924
	RMS 10–30 m wave length, outer wheel path	0.655
3. Transversal unevenness factor	Rut depth	0.957
	Average of transversal unevenness	0.930
	Average of ridge value	0.819
	Average of maximum deviation	0.708

[a]All the variables have been transformed using logarithmic transformation.

Table 2
Correlations between factors

	1. Structural factor	2. Roughness factor	3. Transversal unevenness factor
1. Structural factor			
2. Roughness factor	0.160		
3. Transversal unevenness factor	0.146	0.630	

A logarithmic transformation was applied to the variables, as will be further discussed in Section 4, where the data set used in this study is described.

It is seen, that the factors have meaningful and coherent interpretations. All the deflections, measured using the FWD, have high loadings on one factor, which is thus named structural factor. The IRI and the various root mean squares (RMS) in the wavelength area used for calculating the IRI have high loadings on one factor named roughness factor.

The variables describing the transversal profile of the road have high loadings on one factor named transversal unevenness factor. The variables are rut depth, average ridge height, transversal unevenness and maximum deviation. On the main roads in Finland, the major deterioration mechanism is rutting of bituminous layers due to heavy traffic and studded tyres. On minor roads, the transversal profile is distorted due to deterioration of both the road structure and the subgrade. This is seen in increased values of ridge height, transversal unevenness and maximum deviation.

Unlike the original Varimax rotated factors, the final factors are correlated with each other; the correlations are shown in Table 2. The correlations are fairly small, except for the one between roughness factor and transversal unevenness factor. A closer look at the correlations between the logarithmic transformations of the original variables revealed that several of the variables in the roughness and transversal unevenness factors have fairly high correlations with each other. This is natural, since especially minor roads with distorted transversal profile also have high roughness values. It is also worth noting that this correlation of 0.63 implies a value of coefficient of determination of 0.4 (R^2), which is fairly high, but is usually not considered to show strong explanatory power. The two factors can thus be considered separately.

2.3. Calculating factor scores

The factor scores η_j of the factors F_j can be used as new variables in further analysis, and they are calculated from the values of the original variables using least-squares estimation:

$$\eta_j = \sum_{i=1}^{n} \beta_{ij} x_i = \beta_{1j} x_1 + \beta_{2j} x_2 + \cdots + \beta_{nj} x_n, \quad j = 1, 2, \ldots, k, \tag{2}$$

where β_{ij} is the least-square estimator of the weight of the factor j on variable i; β_{ij} is set to 0, if variable i is not included in factor j. Kyyrä (1992) developed equations for calculating factor scores from measured condition variables. They are, however, rather complex for practical use. Also, the exact values of factor weights vary between data sets. For using the measured road condition as the basis for a condition rating, a simplified approach was to be found for the calculation of factor scores.

As can be seen from the values in Table 1, most of the factor loadings from Eq. (1) within each factor are fairly close to each other. It can be shown that in such a case, the coefficients β_{ij} in Eq. (2) can be approximated as the mean of the standardised variables in factor j; this implies that the coefficients within one factor are approximately equal, i.e.

$$\beta_{ij} = \frac{1}{n_j}, \tag{3}$$

where n_j is the number of variables in factor j. Thus, all the variables in one factor have equal importance when determining that factor score, and bring their share of information of the corresponding factor score. If some variables are not available, the factor scores can still be calculated from the remaining variables by adjusting the number of factors n_j in Eq. (3). It is desirable to use as many variables as possible: the more variables there are, the more reliable are the estimates of the road asset condition.

3. Road condition rating

In this study, a condition rating was constituted by assigning relative weights to each of the factors. The factor scores were first calculated from the original variables using Eqs. (2) and (3), and then the condition rating (CR) was calculated as the weighted sum of the factor scores from

$$CR = \sum_{j=1}^{k} w_j \eta_j, \tag{4}$$

where w_j is the relative weight of the factor j, η_j is the factor score for factor j and k is the number of factors.

The original variables, x_i, have different scales. To allow for the comparison and summation of the different variables, the standardised values of the log-transformed variables, z_i, are calculated using

$$z_i = \frac{x_i - \bar{x}_i}{s_i}, \tag{5}$$

where $\bar{x}_i$ is the sample mean of log-transformed variable i and s_i is the sample standard deviation of log-transformed variable i.

The condition rating assigns each road section a single value which describes the overall condition of that section. The variables included in the analysis are such that the greater the value of the variable, the worse is the road condition. Therefore, the greater the value of the condition rating, the worse the road condition. There are no theoretical limits to rating values, thus the scale extends from ∞ (poor) to $-\infty$ (excellent). For practical purposes, the rating values need to be transformed into a finite scale, and depending on the application, divided into categories.

The relative weights of the factors, w_j, can be defined, for example, based on expert opinions, which is a common approach. Another alternative would be to use information of the factor eigenvalues, as a higher eigenvalue refers to a factor with a larger share of the total variance of the road condition. It is beyond the scope of this study to define a condition index for any specific road administration. For this reason, equal weights have been assigned to all factors in order to demonstrate the use of the factors in a condition rating. The relative weights are scaled to sum to unity. Any administration wishing to employ this method has to define weights appropriate to its specific network and the objectives of the management process.

4. Description of the data set

A data set was drawn from the road condition database of the Finnra. The condition data in the database is stored in 100-m sections. The database covers the whole network of paved public roads in Finland, with a road length of approximately 50,000 km. The condition measurements done in 2003 were used for this analysis. A total of 33,685 lane-km of measurements using the RSM vehicle were done, yielding variables on the longitudinal and the transversal profile of the road. Surface deflections were measured with the FWD on 4042 km of road using 100 m longitudinal spacing. The purpose of this study was to find dimensions of road condition based on various condition variables. Therefore, those road sections, where both RSM and FWD measurements were done in 2003, in total 1411.6 km, were selected for the analysis, resulting in 14,416 observations.

The main roads are measured using the RSM vehicle every year, whereas the secondary roads are measured every 1–3 years. The FWD measurements were at that time generally done in the year following maintenance work. The RSM and FWD measurements were done between June and September. The FWD measurements are concentrated on the low-volume part of the network, thus the distribution of traffic in the data set used in this analysis is somewhat different from that of the whole network. Yet, a comparison of distributions of IRI and deflection between the data set and the latest measurement from the whole network revealed no substantial differences. The data set used in this study can thus be taken as representative of the Finnish paved road network.

A visual examination of the distributions of the original variables reveals that they are not normally distributed. The logarithmic transformations of most variables follow normal distribution more closely than the original values. This is illustrated by the distribution of IRI-values and the values of the natural logarithm of IRI in the data set, as shown in Fig. 1. The statistics (mean, Standard deviation, skewness, excess kurtosis, minimum and maximum values and a number of percentile points) of all variables used in the analysis, after logarithmic transformation, are shown in Table 3.

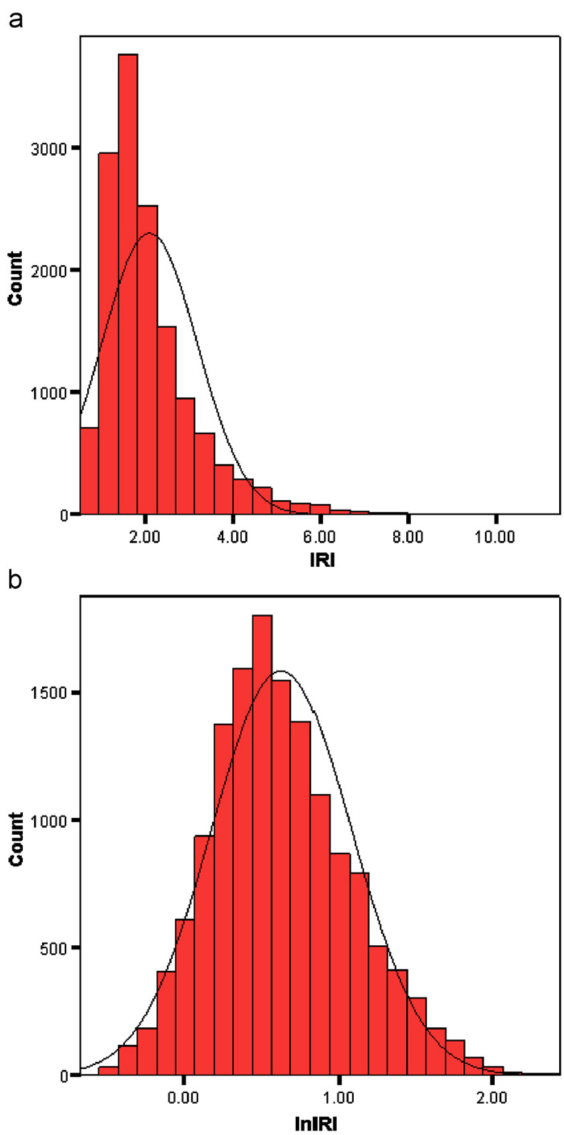

Fig. 1. Distribution of IRI (a) and the natural logarithm of IRI (b) in the data set. Fitted normal curves are superimposed on the histograms in order to facilitate comparison of the distributions.

It is clearly seen, that the distribution of IRI is not normal, whereas the distribution of the logarithmic IRI is fairly close to normal. Most road condition variables are, by definition, assigned positive values only, and extremely high values are not restricted. As a consequence, the resulting distributions are right-skewed like the one for IRI shown in Fig. 1a. The skewness of the distribution is also illustrated by the skewness coefficient deviating from 0. The skewness coefficient of the original IRI values is 1.974, whereas the skewness coefficient for the logarithmic IRI values is 0.417. This together with excess kurtosis close to 0 for the logarithmic IRI values indicates that the log-transformed values follow the normal distribution more closely than the original values, as can be seen in Fig. 1b. Unfortunately, for many of the log-transformed deflection values, especially those at 300, 450 and 600 mm from the loading plate, the excess kurtosis values deviate from 0 (see Table 3). However, the distribution of condition variables is closer to the normal distribution after the logarithmic transformation than without the transformation.

In addition, the logarithmic transformation is among the simplest transformations applicable to most road condition variables. Its use also facilitates the consideration of the measuring accuracy, defined by Ruotoistenmäki et al. (2006) as the variation of repeated log-transformed observations. It is the authors' conclusion to treat road condition variables as log-normally distributed for the purpose of deriving a condition classification based on the results of the factor analysis.

Certain longitudinal surface profile variables and variables from visual distress survey were excluded from the analysis. The RMS of the longitudinal profile of the road with wavelengths less than 500 mm correlate well with variables describing the road surface texture. However, the surface texture variables reflect both desirable and undesirable properties of the road surface. Unevenness with short wavelength provides sufficient friction for safe ride, but in the same time it is the cause of noise and tyre wear (Chavet et al., 1987). Therefore, longitudinal unevenness with wavelength less than 500 mm is not used for determining the condition rating in this study. However, the inclusion of surface texture variables in the condition classification should be further investigated.

Road surface distresses indicate problems in the road structure or subgrade, and should therefore be of interest in a condition classification. Data on surface distress has indeed been collected at network level using visual survey. However, when the distress variables retained in the database were included in the data set used in this analysis, no satisfactory interpretation could be found. The distress variables had loadings on several factors instead of one factor that could be called a distress factor. The loadings on other factors together with road surface profile and deflection variables could not be given logical

Table 3
Statistics of the data set used in the analysis[a]

	Rut depth	IRI	Max. deviation	Transversal unevenness	Ridge height	RMS 0.5–1 m	RMS 1–3 m	RMS 3–10 m
N	14416	14416	2199	14416	14365	14415	14416	14416
Mean	1.548	0.632	1.472	2.219	1.880	−1.474	−0.914	−0.088
Std. Deviation	0.633	0.452	1.012	0.863	0.705	0.570	0.633	0.583
Skewness	0.108	0.417	−1.321	−0.578	−0.535	−0.231	−0.017	0.161
Excess kurtosis	−0.492	0.097	1.875	−0.395	1.075	0.748	0.510	−0.042
Minimum	−0.511	−0.673	−2.303	−0.693	−2.303	−4.605	−3.912	−2.207
Percentiles: 1	0.182	−0.301	−2.303	0.095	0.000	−2.996	−2.506	−1.347
5	0.531	−0.051	−0.511	0.588	0.693	−2.408	−1.897	−1.022
10	0.742	0.086	0.095	0.993	0.993	−2.207	−1.661	−0.821
20	0.993	0.255	0.788	1.435	1.308	−1.897	−1.386	−0.580
30	1.163	0.378	1.163	1.775	1.548	−1.715	−1.238	−0.400
40	1.335	0.482	1.482	2.092	1.758	−1.609	−1.079	−0.248
50	1.504	0.588	1.723	2.389	1.946	−1.470	−0.942	−0.117
60	1.686	0.698	1.946	2.610	2.104	−1.347	−0.799	0.030
70	1.902	0.833	2.140	2.815	2.282	−1.204	−0.616	0.191
80	2.152	1.004	2.282	3.001	2.477	−0.994	−0.386	0.405
90	2.416	1.247	2.468	3.211	2.728	−0.755	−0.073	0.693
95	2.588	1.456	2.595	3.367	2.939	−0.545	0.166	0.916
99	2.929	1.800	2.856	3.602	3.319	−0.174	0.592	1.302
Maximum	3.846	2.439	3.453	4.151	3.987	0.663	1.297	2.307

	RMS 10–30 m	D0_T	D20_T	D30_T	D45_T	D60_T	D90_T	D120_T
N	14416	14416	14416	14416	14416	14416	14416	13942
Mean	1.548	6.275	5.895	5.603	5.256	4.974	4.480	1.788
Std. Deviation	0.453	0.378	0.409	0.445	0.518	0.593	0.753	0.758
Skewness	0.346	0.007	0.147	−0.032	−0.594	−0.894	−1.287	−0.279
Excess kurtosis	0.957	0.851	1.450	2.559	5.791	5.900	5.436	0.299
Minimum	−0.446	4.710	2.708	1.386	0.000	0.000	0.000	0.000
Percentiles: 1	0.554	5.314	4.905	4.511	3.912	3.296	1.946	0.000
5	0.837	5.645	5.236	4.898	4.431	4.007	3.219	0.000
10	0.990	5.802	5.412	5.088	4.663	4.290	3.611	0.693
20	1.179	5.986	5.583	5.278	4.905	4.585	4.025	1.099
30	1.314	6.105	5.700	5.398	5.043	4.754	4.248	1.386
40	1.421	6.198	5.796	5.497	5.159	4.883	4.407	1.609
50	1.530	6.280	5.889	5.591	5.257	4.997	4.543	1.792
60	1.641	6.361	5.976	5.684	5.361	5.106	4.682	1.946
70	1.761	6.449	6.071	5.790	5.472	5.231	4.820	2.197
80	1.910	6.560	6.192	5.924	5.620	5.389	4.997	2.398
90	2.121	6.731	6.397	6.146	5.866	5.652	5.298	2.708
95	2.307	6.896	6.586	6.353	6.100	5.903	5.580	2.996
99	2.728	7.242	6.994	6.791	6.558	6.363	6.080	3.526
Maximum	4.426	7.944	8.809	7.662	7.488	7.309	6.965	4.263

[a]All the variables have been transformed using logarithmic transformation.

interpretation either. This may be due to large variation in the distress data from visual survey. Also, the identification of the types of distress may contribute to this effect, e.g. one investigator classifies certain distress as alligator cracking while another classifies it as several longitudinal cracks. It is the authors' anticipation that when distress data with less variation is obtained using automated image collection and interpretation techniques, the inclusion of distress data in the factor analysis and subsequent condition classification will become more meaningful.

5. Condition classification

Calculating the condition rating of a road section is demonstrated using the data set where the factors were extracted from. The factor scores are calculated from the standardised values of condition variables, and the condition rating value is calculated as a weighted sum of the factor scores. In this case, equal weight is given to all factors, and the resulting condition distribution is shown in Fig. 2a. Smaller values represent better condition, as explained in Section 3. In Fig. 2b, the condition rating has been divided into five categories, each one standard deviation wide, and the x-axis values as group midpoints. In road maintenance management applications, the condition rating values need to be adjusted with the management objectives and the observed ride quality. This can be achieved, for example, using driver panels.

In the absence of some of the measurements on some of the road sections in the network, a condition rating value can still be calculated for all sections of the network using the existing measurement data, and the calculated rating values from different road sections are comparable. In case some of the factors are completely left out from the calculation of a condition rating for a road section, the weight of that factor has to be divided among the remaining factors so that their weights sum to unity (the w_j's in Eq. 4).

This is illustrated in Fig. 3, where the best category is assigned a value of 5, whereas the worst category is assigned a value of 1, and 3 represents average condition. The scaling from 1 (poor) to 5 (excellent) is consistent with the condition classification used by the Finnish Road Administration (Finnra, 2005). The dark columns indicate the situation where all available variables are used for calculating the condition category, as in Fig. 2. The white columns indicate the situation where some of the variables are missing for some of the road sections as follows: for approximately one-third of roads in the database condition category was calculated only based on the roughness factor, and the associated variables. For another one-third of roads, the condition category was calculated based on the roughness and transversal unevenness factors, and the associated variables. The condition category for the last one-third of roads was calculated from all available variables. Entire roads were selected into each group, in order to retain the autocorrelation structure in the original data set. Roughly, the same number of 100-m sections from all road classes and geographical locations were selected into all three groups.

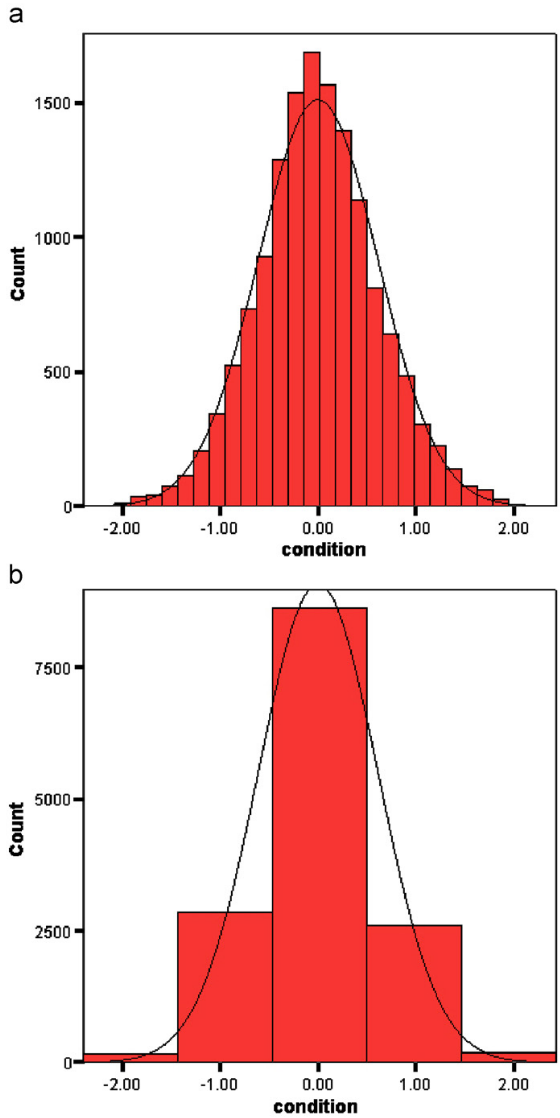

Fig. 2. Example of the condition rating distribution (a) and condition categories (b) based on the data used in factor analysis. Smaller values represent better condition. Fitted normal curves are superimposed on the histograms in order to facilitate comparison of the distributions.

From Fig. 3 it is seen that when more information is used for determining the condition category of the 100-m sections, the distribution of condition categories is centred so that the number of sections in average condition (category 3) increases, whereas the number of sections in all other categories decreases. Furthermore, the category improves or worsens for roughly the same amount of

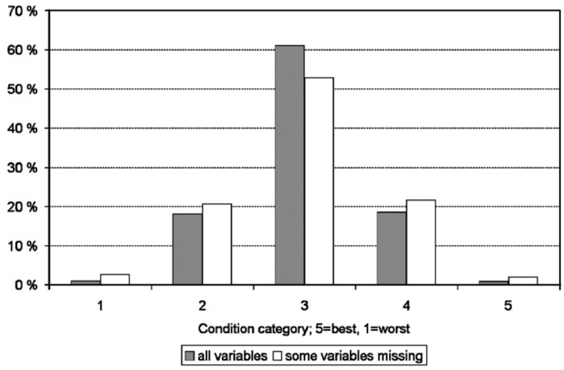

Fig. 3. Example of calculating the condition category based on different variables from different roads. In the white columns, for roughly one-third of roads only variables from the longitudinal profile are used, for another one-third of roads variables from the longitudinal and transversal profile are used, and for the last one-third, all variables, including the measured deflections are used.

sections. In a large data set, averaging across a large number of variables tends to decrease the variance of a summarising index, which consists of two parts—one due to the variances of the original variables and other due to the covariances (correlations in the case of standardised variables) between the original variables. As the number of variables increases, the first part approaches 0, whereas the latter part approaches the average pair-wise covariance (correlation) between the variables.

In this paper, a fixed section length of 100 m is used, because that is how the Finnra's road database is organised. Other fixed lengths can naturally be used, and the condition rating can be calculated for sections with varying lengths as well. Condition ratings for sections with equal length are directly comparable. For many widely used condition variables, such as the IRI and rut depth, the reporting length affects the variation in that variable. Therefore, in the case of sections that vary in length, an adjustment to account for the different variation needs to be made when calculating the condition rating. However, the approach is not further elaborated in this context.

6. Policy evaluation

Finding the optimal condition distribution of the road assets and the annual funding needs for reaching this optimal condition are the goals of road maintenance management at strategic level. The condition classification developed in the previous sections is here used as an input to a simplified policy evaluation method which relates the maintenance expenditure of various policies to benefits defined by the resulting condition distributions over a selected analysis period. The method is fully elaborated in Ruotoistenmäki (2007), and used here for illustration purposes.

The probability distribution of road network's condition categories in year t is represented by vector X_t. Markovian transition probability matrix P is used for multiplying the condition distribution in year t to find the condition distribution in the following year $t+1$ (see e.g. Heyman and Sobel, 1982):

$$X_{t+1} = P^{\mathrm{T}} X_t, \tag{6}$$

where T denotes the transpose of a matrix. The transition probability matrix P is divided into two parts—the first indicating the effect of maintenance works, and the latter the deterioration. The elements of the transition probability matrix are calculated as follows:

$$P_{ij} = a_{i,t} M_{ij} + (1 - a_{i,t}) D_{ij}, \tag{7}$$

where M_{ij} is the element of the maintenance effect matrix indicating the transition probabilities due to maintenance, D_{ij} the element of the deterioration matrix indicating the transition probabilities due to deterioration, and $a_{i,t}$ is the share of road assets in category i that are maintained in year t ($0 \leqslant a_{i,t} \leqslant 1$). Furthermore, it is assumed that a policy is kept unchanged during the analysis period, thus $a_{i,t}$ is constant for all years t in each condition category i. The elements of the deterioration matrix D_{ij} and maintenance effects matrix M_{ij} indicate the proportion of 100-m sections that move from category i in year t to category j in year $t+1$. The elements of the deterioration matrix were estimated from the data set used in this study; the squared difference between the predicted and the observed distributions of condition category and age were minimised in a spreadsheet application. The maintenance effects matrix was constructed based on experience.

The distributions are derived from the 100-m data, which is the shortest section length in this data set, therefore the predicted deterioration is that of the 100-m sections. Condition categories could be calculated for longer road sections than 100 m, but that would decrease the variability of the condition between the sections, and the knowledge of the localised road conditions would be more uncertain.

Maintenance cost is assigned to each condition category, and the total maintenance cost in year t is calculated as

$$C_t = N \sum_{i=1}^{m} x_{i,t} a_{i,t} c_{i,t}, \tag{8}$$

where N is the extent of the network, m the number of condition categories, $x_{i,t}$ the share of roads in condition category i in year t and $c_{i,t}$ is the maintenance cost in condition category i in year t. The decision variables in the calculation method are the elements $a_{i,t}$ in Eqs. (7) and (8). The model was tested in a spreadsheet application, where the decision variables are typed on-screen, and the outcome can be evaluated instantly.

The time frame for the analysis can be selected freely, but it is not reasonable to increase the length of the period too much, as the uncertainty in the analysis increases, thus making the results less useful. The length of a planning period for a road agency is typically 5 years, which is also used in this analysis. Eq. (6) is applied five times from year t to year $t+5$, and the resulting condition distribution X_{t+5} is used for the comparison of maintenance policies. The average maintenance cost over the analysis period is calculated.

Two policies are compared, preserving the current condition (Alt 0) and a preventive maintenance policy (Alt 1). Both policies are considered for two traffic categories separately, average daily traffic (ADT) > 500 vehicles per day and ADT ⩽ 500 vehicles per day. Dividing the original network of 1441 km at ADT = 500 vehicles per day results in two sub-networks of fairly equal size (638 and 803 km), whose results are combined for the comparison of policies.

The preservation policy is achieved by minimising the sum of squared differences between the initial condition distribution and the condition distributions in each year of the analysis period. This is done using spreadsheet optimisation tools and results in a solution where part of the roads in the two worst categories is maintained. The preventive policy is one where additionally some of the roads in the best three condition categories are maintained. This policy prevents the condition distribution of road network from deteriorating too fast and reduces maintenance needs, as maintenance is less expensive in good condition than in poor condition.

The resulting maintenance budgets (annual sum from the two sub-networks averaged over the 5-year analysis period) are M€ 2.91 for preserving the current condition and M€ 3.45 for the preventive maintenance policy. Thus, the cost of the preventive maintenance policy is 19% higher than that of the preservation policy. A common result is that a preventive policy is less expensive to carry out than a preserving policy. However, this result depends on the probability distribution of the condition of the sub-networks.

Fortunately enough, in favour of the preventive policy, also the benefits are higher, as is clearly seen from the resulting condition distributions at the end of the 5-year analysis period shown in Fig. 4, where the condition distributions of the two sub-networks are combined into one distribution.

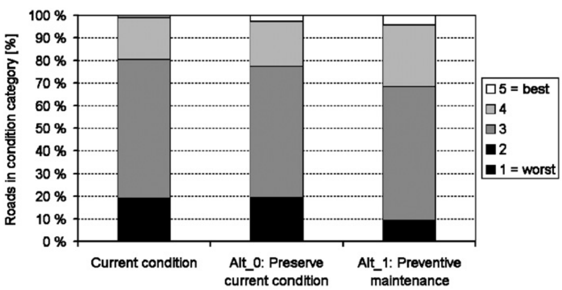

Fig. 4. Current condition and condition at the end of 5-year planning period for alternative maintenance policies.

It is difficult to directly determine how much higher the benefits are when they are defined as the improvement of the condition distribution. The road user benefits from the improved condition could be calculated, as is a common practice in full socio-economic cost–benefit analysis of road maintenance. However, the presented calculation method is kept as simple as possible. This enables the analysis also for those road assets where the user benefits are difficult, if not impossible to determine, such as relatively low-volume paved roads like the data set of this study, bridges and gravel roads. The selected approach is a practical tool for finding an appropriate maintenance policy especially when target for condition distribution has been set elsewhere.

It is seen that differences in distributions between the current condition and the preservation policy exist. This is most likely due to the simplifications in the model; for example, if different values were assigned for the decision variables $a_{i,t}$ in different years of the analysis period, the spreadsheet optimisation technique might find a solution with a closer match of the initial condition distribution and the resulting condition distribution at the end of the analysis period. However, the original purpose of this method is to simplify analysis from full optimisation; thus the approach is kept as simple as possible.

From the resulting values of the decision variables of $a_{i,t}$ from this simple analysis it can also be concluded that the average time between maintenance works is 14 years for the preventive maintenance policy, but more than 25 years for the alternative of preserving the current condition. Thus, the preventive maintenance policy better represents a sustainable maintenance policy of the compared two alternatives.

7. Conclusions

In this study, three distinct factors describing road condition were extracted from a data set of 14,416 observations of 100-m road sections with road surface profile and deflection measurements: structural factor, roughness factor and transversal unevenness factor. The factors are essentially the same as found in previous studies of Talvitie and Olsonen (1988) and Kyyrä (1992), except that the data on road surface cracking did not yield satisfactory results in this analysis.

A road condition rating is calculated as a weighted sum of factor scores. This rating can be calibrated for estimating an existing or a new road condition index, which is used for describing the overall condition of a road network and as an input to the strategic-level decision-making in road maintenance management.

The main conclusions and expected benefits of this study are:

- The proposed condition rating is easily applicable for estimating condition index values from the available road condition variables. The factor scores are calculated as the average of the standardised variables in each factor. In this way, the structural factor, for example, can be calculated from any number of measured deflections, and a different number of measured deflections for different road sections.

- In the absence of the deflection or surface profile measurements, a condition rating value can be calculated using the existing measurements, and the calculated rating values for different road sections are still comparable with each other.
- The condition rating can be used for evaluating the benefits of maintenance policies in a management system. This is demonstrated by using a simple model that relates the budgets of various policies to their resulting condition distribution defined by this rating. The results emphasise the benefits of a preventive maintenance policy.

General conclusions include:

- The log-transformed values of the variables follow the normal distribution more closely than the original variables.
- The reporting lengths of the variables, such as the IRI and rut depth, affect the amount of variation in that variable. In this paper, a fixed section length of 100 m is used. If sections that vary in length are to be used, an adjustment to account for the different variation will have to be developed for the calculation of the condition rating.

The limitations of this study, for consideration in further work, are:

- Variables describing surface texture are not included in the current analysis since they reflect both desirable (friction) and undesirable properties (noise and tyre wear) of the road surface. However, it is recommended that their inclusion in the condition rating be further studied.
- Possibly due to large variation in the results from visual survey, the distress variables did not yield satisfactory interpretation in the factor analysis. Therefore, they were left out of the final analysis. Data with improved accuracy, e.g. from automated distress survey, should enable the inclusion of distress data in the factor analysis and the subsequent condition rating.

The recommendations for implementation of the results of this study are:

- If the database of the network under consideration contains variables not included in this study, factor analysis using all the available variables should be run to find the relevant factors that describe the different aspects of road condition. An optimal number of variables and factors ought to be found that conveys all relevant information from the road network into the summarising index.
- Appropriate weights for the different factors are to be defined, based on the properties of the network under consideration and the objectives of the management process.
- The condition rating values need to be adjusted with the observed ride quality and management objectives, e.g. using driver panels.

Acknowledgements

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Essay Four

Ruotoistenmäki, A.

Road maintenance management system - a simplified approach

Abstract

In order to find a sustainable maintenance policy, road asset management at strategic level seeks to answer the following questions: What is the current condition of the assets? What is the optimal condition of the assets? What are the annual funding needs and how should this funding be allocated?

The objective of this paper is to provide simple tools for evaluating different maintenance policies. To accomplish this objective, an approach is used whereby the costs of maintenance works are related to the probability distribution of road network's condition by estimated transition probabilities of deterioration and the effect of maintenance works. The decision variables in the calculation method are the amount of maintenance in each condition category during a selected analysis period. The benefit of the proposed method is that it can be used for analysing maintenance of assets where user benefits are undefined and full socio-economic optimisation of maintenance funding needs is not possible.

I use the network of PCC (Portland Cement Concrete) bridges as an example to illustrate the developed calculation method. For strategic level management purposes in the Finnish Road Administration (Finnra), the condition of the road assets is presented using a five-step condition classification, ranging from excellent (5) to very poor (1). Average annual maintenance cost over a ten-year analysis period is calculated to compare three alternative maintenance policies: Current Policy, Preservation Policy and a Do Worst Policy. The results of this analysis confirm the fact seen from the models themselves, namely that the deterioration rate according to the models is rather slow. This, together with the superior condition effects of reconstruction makes the Do Worst Policy superior to all other alternative policies. The results may, however, be different for other networks and models.

Keywords: bridges, maintenance, policy evaluation, probabilistic models

Acknowledgements

The idea for this paper was inspired by the work of Mr. Vesa Männistö of Pöyry Infra Oy presented at the 2nd European Pavement and Asset Management Conference in March 2004 in Berlin. I sincerely thank Mr. Männistö for continually supporting this work. This research has been done in conjunction with the projects in the Asset Management Research Programme (VOH) of the Finnish Road Administration (Finnra). The continuing support from my employers has also, in its part, enabled me to complete this paper.

1 Introduction and objectives

Road asset management at strategic level addresses the following questions: What is the current condition of the assets? What is the optimal condition of the assets? What are the annual funding needs and how should this funding be allocated? A road manager should be able to answer these very basic questions in order to carry out a sustainable maintenance policy.

For strategic level management purposes, the condition of the assets is presented in summarised form (see e.g. Hudson et al 1997). I use the condition classification defined in a recent Finnra report (Finnra 2005a), where the condition categories for bridges are defined on the basis of visual inspection of defects in the bridges' main structural parts. The number of categories in this classification scheme is five. The value 5 represents excellent condition, whereas the value 1 represents poor condition.

The main question is: Should the emphasis of maintenance be placed on assets in poor condition, or should some of the maintenance works be targeted at that part of the network in relatively good condition? The first approach is commonly described as a Do Worst Policy and the latter one is described as a preventive maintenance policy. My objective in this paper is to provide tools for evaluating the different maintenance policies. I do this by applying a probabilistic approach that uses the costs of maintenance works and the transition probabilities of network condition distribution due to deterioration and maintenance works.

In Section 2, I describe the problem setting, and in Section 3, I develop the necessary assessment tools. I then evaluate the alternative maintenance policies using these tools in Section 4, and discuss the results in Section 5. Finally, I draw the conclusions of this study in Section 6.

2 Problem setting

The basic assumption I use in this paper is the stochastic nature of road asset deterioration. This assumption requires the selection of a probabilistic-based approach for analysis. Justification of this approach has already been made by several road asset management developers (e.g. Golabi et al. 1982), and, as a result, I will not further discuss it in this context. Instead, I first shortly discuss some of the research questions in the probabilistic framework. These are, mainly, the problem of defining losses for certain sub-networks and the issue of the number of allowable maintenance actions in each condition state.

Linear optimisation methods are often used for minimising the sum of maintenance costs and losses due to deterioration of the road assets. Usually the considered losses are additional user costs caused by deterioration. Additional user costs due to maintenance works causing lane closures or detours may be also be considered as part of maintenance costs. The road assets may be divided into sub-networks and a few condition indicators are divided into several categories. The condition of a sub-network can thus be described using a distribution of assets into condition states, i.e. the combination of variables and their categories. The decision variables in the optimisation model are the amount of assets to be maintained in each sub-network and condition category.

The approach to minimising the socio-economic costs of maintenance is illustrated in Figure 1. Better condition means less maintenance costs. A minimum of total socio-economic costs, which is the sum of maintenance and user costs, is the optimal solution for maintenance funding level.

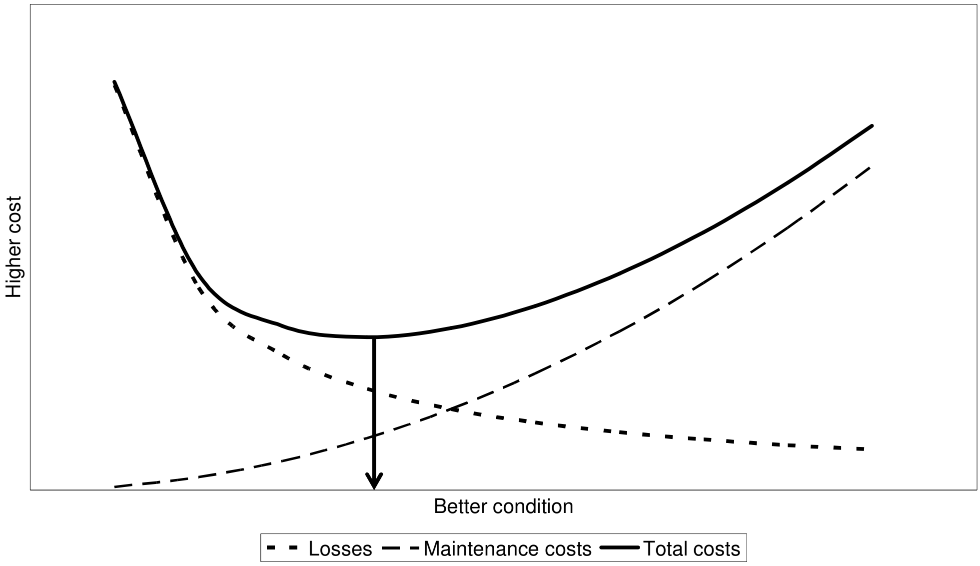

Figure 1. Principle of socio-economical analysis of road asset management. The optimal funding levels are found as the minimum of the total costs, which is the sum of maintenance costs and losses due to untimely maintenance.

The drawback of this approach is that losses may be difficult to determine, which makes the results from such analysis implausible. In such a case, optimisation is reduced to merely finding the minimum maintenance cost that satisfies other constraints set for e.g. condition. This is especially the case for sub-networks with low traffic volumes, and bridges. Nevertheless, these sub-networks form a major part of road assets. To address this problem, I develop a method that considers maintenance costs and the effect of maintenance on road asset condition.

In a probabilistic optimisation framework, it is often thought that in order to achieve good results, several alternative maintenance work types are needed in each condition state. However, this has not been shown to improve the optimisation results. In practice, road asset condition dictates the appropriate maintenance action, and the question becomes one of choosing the optimal maintenance schedule. Therefore, I have chosen to limit the number of allowable maintenance actions in each condition state. This is also the approach taken by Äijälä and Lahdensivu (2006), who developed models for deterioration and maintenance costs and condition effects for bridge assets. I use their models to illustrate the method developed herein.

In this paper, I want to take a simplified approach to assessing the funding needs for road asset maintenance. Simplifying the analysis increases the inaccuracy of results. However, in large populations errors tend to even out, and the results are correct on average. At network level the interest is not in individual roads or bridges whose condition predictions may contain large errors in this approach. I have developed tools for quick analysis based on few inputs that can be estimated by practitioners. These tools can be further developed to increase the accuracy of the results, if needed.

My aim is to evaluate the outcome of different maintenance policies. I operationalise this aim by calculating the change in the probability distribution of condition during a planning period for a defined set of policies. I use the network of Portland Cement Concrete (PCC) bridges to illustrate the calculating method. New probabilistic models for bridges have recently been developed in this area by Äijälä & Lahdensivu (2006). Another purpose of selecting the network of PCC bridges for analysis is to provide a test bench for the new models. This method can readily be extended to other road assets, where full socio-economic analysis of management policies has not been possible.

3 Calculation method

The probability distribution of road network into condition categories in year t is represented by vector X_t. The change in condition distribution is represented by using the Markovian transition probability matrix P, which is used for multiplying the condition distribution in year t to find the condition distribution in the following year $t+1$ (see e.g. Heyman & Sobel 1982):

$$X_{t+1} = P^T X_t \,. \tag{1}$$

where ^{T} denotes the transpose of a matrix. The elements P_{ij} of P represent the transition probabilities, where i refers to the condition category in year t and j refers to the condition category in year $t+1$. Part of the network is maintained annually, and part of the network is left to deteriorate. Therefore, the transition probability matrix is divided into two parts, the first indicating the effect of maintenance works, and the latter the deterioration[1]. The elements of the transition probability matrix are calculated as follows:

$$P_{ij} = a_{i,t} M_{ij} + (1 - a_{i,t}) D_{ij} \,, \tag{2}$$

where M_{ij} is the element of the maintenance effect matrix indicating the transition probabilities due to maintenance, D_{ij} the element of the deterioration matrix, and $a_{i,t}$ is the share of road assets in category i that are maintained in year t ($0 \leq a_{i,t} \leq 1$). The decision variables in the calculation method are the elements $a_{i,t}$.

According to the model, road assets either stay in the initial category or deteriorate to the next poor category, but are not allowed to skip a condition category in one year. Thus, only those elements in the deterioration matrix for which $j = i$ or $j = i+1$ are non-zero. Moreover, the road assets in the worst category stay in that category unless they are maintained. In contrast, the road assets that are maintained are distributed over all categories that are better than the initial category. All elements in the maintenance effect matrix, for which $j \leq i$ (the lower triangular matrix) may be non-zero.

[1] Even though the maintenance works are ideally aimed at the poor sections, in practice some sections in all condition categories are maintained as part of longer maintenance sections. The selected approach to consider the transition probabilities based on the probabilities of deterioration and maintenance effects applies both to the ideal situation and in practice.

This calculation method does not specify the number of condition categories. An user of this method has to only be able to define the categories so that (s)he can calculate the current condition of the assets, and derive the transition probability matrices for the maintenance effects (M_{ij}) and deterioration (D_{ij}). In this context, I use the five-step classification for the condition of the road assets as defined by the Finnish Road Administration (Finnra 2005a). The maintenance effect matrix and the deterioration matrix can be developed from road data banks or in lack of such data, estimated by experience. In this study, I use the recently developed models (Äijälä & Lahdensivu 2006) for deterioration and maintenance effects of concrete bridges using the Finnra's 5-step classification.

The poorer the road asset condition is, the higher the maintenance cost. Maintenance cost is assigned to each condition category, and the total maintenance cost in year *t* is calculated as

$$C_t = N \sum_{i=1}^{m} x_{i,t} a_{i,t} c_{i,t} \,, \qquad (3)$$

where N is the extent of the network, m is the number of condition categories, $x_{i,t}$ is the share of roads in condition category i in year t, $a_{i,t}$ is as defined in Eq. (2) and $c_{i,t}$ is the maintenance cost in condition category i in year t. The average annual maintenance cost during a selected analysis period is then calculated.

The length of the analysis period can be selected freely, but it is not reasonable to increase the length of the period too much, as the uncertainty in the analysis increases, which makes the results less usable. Bridges are a fairly long-lasting part of road assets, designed typically to last 50 to 100 years of service. In this analysis, I have chosen ten years as the length of the analysis period. Equation (1) is applied 9 times from year t to year $t+9$, and the resulting condition distribution X_{t+9} is used for the comparison of maintenance policies.

Furthermore, it is assumed that a policy is kept unchanged during the analysis period, therefore $a_{i,t}$ is constant for all years t for a condition category i. A more realistic approach would be to let $a_{i,t}$ for a condition category vary from year to year. However, as the original purpose of this method is to evaluate maintenance policies in a rather straight-forward manner, I have kept the approach as simple as possible.

In this method, the funding needs are assessed and the different maintenance policies evaluated solely based on maintenance costs and transition probabilities. This approach makes it possible to also evaluate losses and benefits from different maintenance policies. The losses in year t can be calculated in parallel with the maintenance costs from

$$L_t = N \sum_{i=1}^{m} x_{i,t} L_{i,t} , \tag{4}$$

where $L_{i,t}$ are the losses in condition category i on year t. On paved roads, typically, additional user costs due to road deterioration and maintenance work zones are used as losses in the analysis. For other road assets, losses may be defined in a different manner, e.g. as detours resulting from load restrictions for bridges in poor condition or low-volume roads during spring thaw period. These losses can be monetised as losses of time and additional driving costs to be used in the analysis. However, losses are not considered in the maintenance policy evaluation of concrete bridges that I present in the following section.

4 Alternative maintenance policies

I evaluate the outcome of different maintenance policies for concrete bridges on the Finnish public road network, using the method presented in the previous section. Portland Cement Concrete (PCC) bridges form a major part (80%) of the total surface area of bridges managed by the Finnish Road Administration. They are divided into five sub-networks, depending on whether they are continuous, located in salted roads or not, or made of pre-stressed concrete. The bridge condition is defined by a five-step classification (Finnra 2005a). In the two best categories, routine maintenance is sufficient, whereas in the worst category, the bridge should already have been maintained, and reconstruction may be needed. The optimal time for maintenance is when the bridge is in the second to worst condition category.

I use the recently developed models (Äijälä & Lahdensivu 2006) for deterioration and maintenance effects of concrete bridges using the Finnra's 5-step classification system. The deterioration model for discontinuous PCC bridges on salted roads is shown as an example in Table 1. All the models are shown in Appendix 1. The models are read from left (condition in year *t*) and up (condition in year *t+1*). From the models it can be concluded that:

- The deterioration rate according to the models is fairly slow, especially in condition category 3 (fair), where only 2 % of bridge deck m^2 deteriorate to category 4 (poor) in one year and 98 % stay in category 3. According to Äijälä & Lahdensivu (2006), the models are on the safe side (deterioration is faster than the actual observations), but realistic.
- Reconstruction is targeted at the two worst categories and it always restores condition to category 1, whereas rehabilitation allowed in worst three condition categories improves condition usually only to the second best category. These properties of the models contribute to the success of a Do Worst Policy, as will be seen later.

Table 1. Deterioration model for discontinuous PCC bridges on salted roads (Äijälä & Lahdensivu 2006).

Condition in year *t*	Condition in year *t+1* 5	4	3	2	1
5	0.85	0.15	0	0	0
4	0	0.965	0.035	0	0
3	0	0	0.98	0.02	0
2	0	0	0	0.94	0.06
1	0	0	0	0	1

The following three simplified scenarios were generated:

- **Alt 1** Current policy of bridge maintenance, documented in (Finnra 2005b): At the first stage, the deterioration of bridge assets is halted. At the second stage, the maintenance backlog is gradually decreased. Objectives are set for the amount of bridges in condition categories 'poor' (4 %) and 'very poor' (1 %) in the year 2010.
- **Alt 2** Preservation policy, whose objective is to minimise the change in condition distribution compared to the initial distribution during the analysis period.
- **Alt 3** A Do Worst Policy: Almost all bridges in the two worst condition categories are maintained, but a small percentage of bridges are left to deteriorate. In addition, 10 % of the bridges in category 3 ('fair') are maintained.

These three scenarios were generated using a spreadsheet application and a ten-year analysis period was selected. In the spreadsheet application, the decision variables are typed in and the on-screen result can be evaluated instantly. Spreadsheet optimisation tools are used in the analysis of **Alt 1** and **Alt 2** for minimising the difference between the initial condition distribution and the condition distribution each year in the ten-year analysis period (2006 – 2015). This minimisation is done for each of the five sub-networks separately, and the combined condition distribution is calculated for all sub-networks. In **Alt 1**, the best three best condition categories are considered in the optimisation, whereas the amount of bridges in the worst two condition categories is constrained in the optimisation so that it meets the objectives set for the year 2010. In **Alt 2**, all condition categories are considered.

Bridge deterioration was calculated by only applying routine maintenance on the bridges over the analysis period. According to the models (Äijälä & Lahdensivu 2006), routine maintenance does not improve the condition distribution. This scenario is referred to as **Alt 0**, and it is estimated for two reasons: First, maintenance policies presented above include routine maintenance, whose part of the annual costs is revealed in this way. Secondly, this alternative is used for evaluating the validity of the deterioration models. The result of this analysis for discontinuous PCC bridges on salted roads is shown as an example in Figure 2. It is seen that the deterioration rate using these models in this calculation method is fairly slow, as was concluded from the models themselves (Table 1 and Appendix 1).

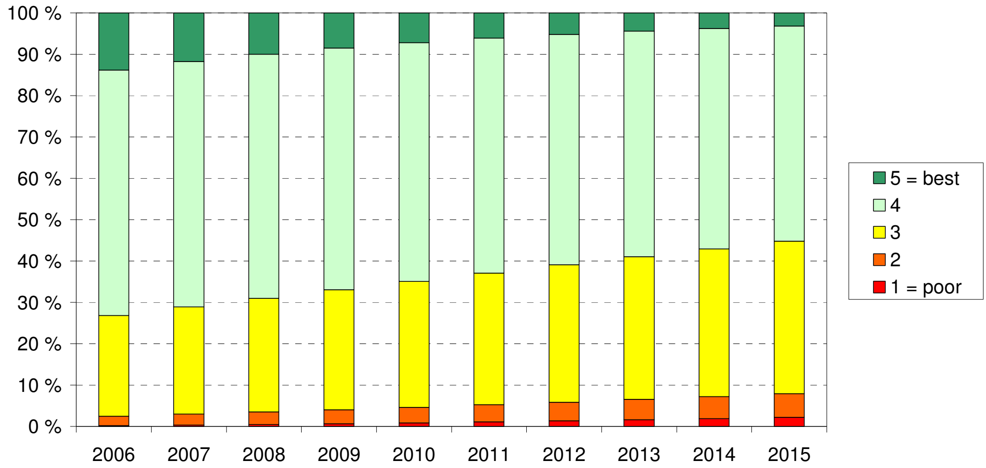

Figure 2. Result from analysis of deterioration model during the 10-year analysis period. Discontinuous PCC bridges on salted roads are used as an example.

The alternative maintenance works are rehabilitation and reconstruction of the bridge. For bridges not rehabilitated or reconstructed, routine maintenance is applied. Thus, equation (2) is extended to:

$$P_{ij} = a_{ireh,t}\mathrm{Reh}_{ij} + a_{irec,t}\mathrm{Rec}_{ij} + (1 - a_{ireh,t} - a_{irec,t})D_{ij}, \quad (5)$$

where $a_{ireh,t}$ refers to the share of bridge deck-m² rehabilitated each year, and $a_{irec,t}$ to the share of bridge deck-m² reconstructed each year. Reh_{ij} and Rec_{ij} represent the elements of maintenance effects matrices for rehabilitation and reconstruction, respectively. For the rest of the bridge assets only routine maintenance is applied that year, but it is not considered to affect deterioration.

The results of this analysis are presented in Figure 2. The average annual maintenance costs over the ten-year analysis period for the alternative policies Alt 1, Alt 2 and Alt 3, are M€ 25.5, M€ 39.7 and M€ 40.8, respectively. In Figure 3, the condition distribution at the beginning and the end of the analysis period is shown for deterioration and the three alternative policies. The Alt 0, where the bridges are left to deteriorate, indicates the costs of routine maintenance, which is M€ 7.6.

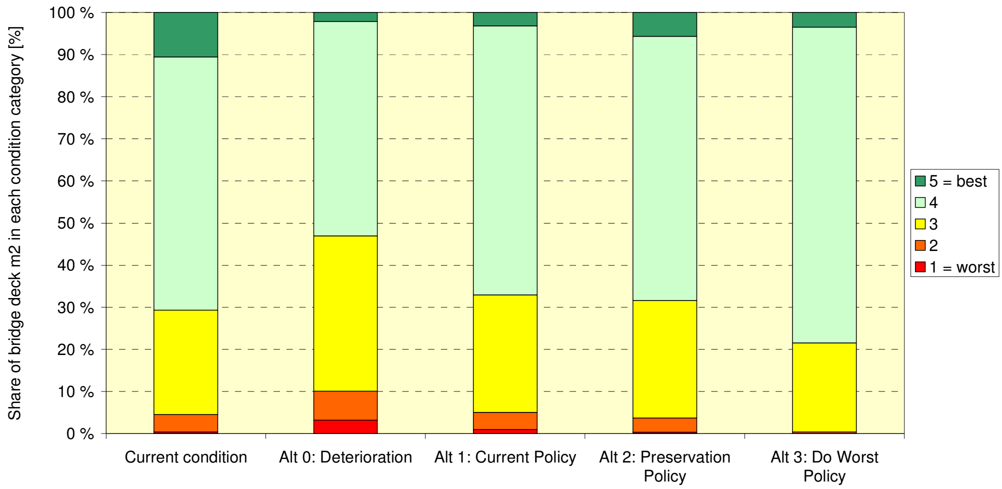

Figure 3. Current condition and condition at the end of the ten-year analysis period with alternative maintenance policies.

5 Discussion

A common result, presented in textbooks, and expected by the author, is that a preventive maintenance policy is superior to other alternatives, especially to a Do Worst Policy. A Do Worst Policy is one where maintenance is concentrated on the parts of assets that have reached (or passed) a maintenance threshold. A preventive maintenance policy, on the contrary, is one where part of maintenance works are carried out before a threshold in technical condition is reached. This is done, because maintenance in an earlier phase of deterioration is less expensive to carry out and it increases the life time of assets and lowers the life cycle costs of maintenance.

The case for preventive maintenance is based on the assumption that the asset condition first deteriorates fairly slowly, and then the rate of deterioration starts to increase before a breakdown in condition. However, as can be seen from Figure 2, the deterioration rate according to the models used here is rather slow. According to the models (Äijälä & Lahdensivu 2006) and the classification (Finnra 2005a) used here the transition probabilities from category 2 (poor) to 1 (very poor) are in the range of 0.94 to 0.96. Recalling that according to the condition classification, category 2 is optimal for maintenance work to be carried out and category 1 is considered 'too late' or even 'shameful', these deterioration models can be considered rather conservative. Accordingly, a feasible solution in favour of a preventive maintenance policy could not be found, and is therefore not presented explicitly.

Furthermore, according to the maintenance effects models (Äijälä & Lahdensivu 2006) rehabilitation allowed in worst three condition categories improves condition usually only to the second best category. Instead, the condition of all reconstructed bridges improves to the best condition category. Reconstruction is allowed only in the worst two categories, and its considerably higher cost seems rather irrelevant as compared to its superior effects to condition. It may be noted that the perceptions of words like 'poor', 'too late' or 'shameful' vary between individuals and organisations. Keeping in mind the relatively high standard of maintenance on the Finnish bridge network, these models may well be considered reliable. Neither is the case for preventive maintenance, supported by a large number of studies, refuted by these results.

The Current Policy (Alt 1) meets the objectives set in (Finnra 2005b), resulting in annual funding need of M€ 25.5. The difference between the initial condition distribution and condition distribution each year in the ten-year analysis period (2006 – 2015) for the three best condition categories is minimised using spreadsheet optimisation tools. In addition, the amount of bridges in the worst two condition categories is constrained in the optimisation so that it meets the objectives in year 2010. This results in 2 – 7 % of the bridge deck-m^2 in the worst three condition categories being rehabilitated. In addition, a fixed amount of 5 % of bridge deck-m^2 in the category 'very poor' is set for reconstruction.

The Preservation Policy (Alt 2), though requiring considerably higher funding (M€ 39.7), does not lead to much better condition distribution than the current one. This is due to the fact that the optimisation model tries to preserve the current condition distribution by minimising the difference between condition distributions at each year of the analysis period and the initial condition, but does not consider a budget constraint in the process. Indeed, introducing a budget constraint, e.g. that maximum funding is the same as in current policy, leads to worse condition distribution at the end of the 10-year analysis period than either the current policy or the initial distribution. Furthermore, referring to the above-discussion on models for deterioration and maintenance effects, the spreadsheet solver used for optimisation reaches a minimum value for the objective function by letting the bridges deteriorate and reconstructing them in the worst two categories. The required funding to do so is high.

The Do Worst Policy (Alt 3) uses approximately same amount of funding (M€ 40.8) as the Preventive Policy (Alt 2), but results in what is clearly the best condition distribution of the considered alternatives. In this policy, reconstruction is assigned to most bridges (>90 %) in the worst condition category and rehabilitation to most bridges in the second to worst condition category. Additionally, 10 % of bridges in the category 'fair' are rehabilitated.

It is possible to reconsider these results by altering the types of maintenance works allowed in different condition categories. This, however, would also require a revision to the set of models. Instead, the results of this study are considered as one test bench for the models developed by Äijälä & Lahdensivu (2006). My conclusion is that these models are conservative but realistic. The maintenance decision, depending on available funds, is to choose a position between the Current Policy (Alt 1) and the Do Worst Policy (Alt 3). In other words, funding should be raised, if possible.

6 Summary and conclusions

Maintenance policy evaluation seeks answers to the following questions: What is the current condition of the road assets? What is the optimal condition of the assets? What are the annual funding needs? In this paper, a simple model is developed that relates the budgets of the alternative policies to their resulting condition distribution at the end of the analysis period by applying a probabilistic approach. The current condition, distributed in categories, is used for multiplying the Markovian transition probability matrix, which is calculated from the deterioration matrix and the maintenance effects matrices.

The method is illustrated using data and models from the PCC bridges, which form the major part of the bridge assets on the Finnish public road network. The results confirm the implications of Äijälä & Lahdensivu's study (2006), that the deterioration according to the models is fairly slow. The Current Policy meets the defined management objectives. Compared to the Current Policy, the Preservation Policy and the Do Worst Policy have to raise 60 percent of their funding needs. The Do Worst Policy leads to clearly the best condition distribution at the end of the analysis period, whereas the Preservation Policy or the Current Policy does not produce any better results.

Preventive maintenance, where part of assets are maintained before reaching a maintenance threshold, is widely considered the most effective and inexpensive policy. However, these results do not seem to endorse this view. The fairly slow deterioration rate and maintenance effects according to the models developed in (Äijälä & Lahdensivu 2006) result in a solution where it is most effective to reconstruct bridges in poorest condition and rehabilitate bridges that have passed maintenance threshold. Keeping in mind the relatively high standard of maintenance, however, these results are not contrary to the widely endorsed case for preventive maintenance. The choice then should be (depending on available funding) between the Current Policy and the Do Worst Policy. It should be concluded that the selected approach is a practical tool for finding an appropriate maintenance policy when the target for condition distribution has been set elsewhere.

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7 Appendices

Appendix 1. Deterioration and maintenance effects models for Portland Cement Concrete (PCC) bridges according to Äijälä & Lahdensivu (2006).

Discontinuous PCC bridges on salted roads

Total bridge deck area 517 742 m2

Current condition

Category	5	4	3	2	1
% in each category	13.8 %	59.3 %	24.3 %	2.3 %	0.2 %

Deterioration model

Transition probability matrix

Condition in year *t*	Condition in year *t+1* 5	4	3	2	1
5	0.85	0.15	0	0	0
4	0	0.965	0.035	0	0
3	0	0	0.98	0.02	0
2	0	0	0	0.94	0.06
1	0	0	0	0	1

Maintenance effects models

Rehabilitation

Condition	Condition in year *t+1*				
in year *t*	5	4	3	2	1
5	1.00	0.00	0.00	0.00	0.00
4	0.00	1.00	0.00	0.00	0.00
3	0.10	0.90	0.00	0.00	0.00
2	0.00	0.90	0.10	0.00	0.00
1	0.00	0.70	0.30	0.00	0.00

Reconstruction

Condition	Condition in year *t+1*				
in year *t*	5	4	3	2	1
5	1.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	1.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	1.0000	0.0000	0.0000
2	1.0000	0.0000	0.0000	0.0000	0.0000
1	1.0000	0.0000	0.0000	0.0000	0.0000

Cost models

Cost €/m2

Condition category	**Maintenance action** Routine maint.	**Rehab**	**Reconst**
5	3		
4	3		
3	3	350	
2	3	450	1300
1		500	1300

Continuous PCC bridges on salted roads

Total bridge deck area 831 070 m2

Current condition

Category	5	4	3	2	1
% in each category	8.0 %	57.0 %	27.0 %	6.0 %	1.0 %

Deterioration model

Transition probability matrix

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	0.85	0.15	0	0	0
4	0	0.965	0.035	0	0
3	0	0	0.98	0.02	0
2	0	0	0	0.94	0.06
1	0	0	0	0	1

Maintenance effects models

Rehabilitation

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	1.00	0.00	0.00	0.00	0.00
4	0.00	1.00	0.00	0.00	0.00
3	0.10	0.90	0.00	0.00	0.00
2	0.00	0.85	0.15	0.00	0.00
1	0.00	0.70	0.30	0.00	0.00

Reconstruction

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	1.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	1.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	1.0000	0.0000	0.0000
2	1.0000	0.0000	0.0000	0.0000	0.0000
1	1.0000	0.0000	0.0000	0.0000	0.0000

Cost models

Cost €/m2

Condition category	**Maintenance action**		
	Routine maint.	**Rehab**	**Reconst**
5	3		
4	3		
3	3	350	
2	3	450	1300
1		650	1300

PCC bridges on unsalted roads

Total bridge deck area 890 600 m2

Current condition

Category	5	4	3	2	1
% in each category	6.0 %	61.0 %	28.0 %	5.0 %	0.0 %

Deterioration model

Transition probability matrix

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	0.86	0.14	0	0	0
4	0	0.975	0.025	0	0
3	0	0	0.985	0.015	0
2	0	0	0	0.96	0.04
1	0	0	0	0	1

Maintenance effects models

Rehabilitation

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	1.00	0.00	0.00	0.00	0.00
4	0.00	1.00	0.00	0.00	0.00
3	0.10	0.90	0.00	0.00	0.00
2	0.00	0.90	0.10	0.00	0.00
1	0.00	0.70	0.30	0.00	0.00

Reconstruction

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	1.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	1.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	1.0000	0.0000	0.0000
2	1.0000	0.0000	0.0000	0.0000	0.0000
1	1.0000	0.0000	0.0000	0.0000	0.0000

Cost models

Condition category	Cost €/m2 **Maintenance action** **Routine maint.**	**Rehab**	**Reconst**
5	2		
4	2		
3	2	300	
2	2	400	1300
1		450	1300

Prestressed PCC bridges on salted roads

Total bridge deck area 515 963 m2

Current condition

Category	5	4	3	2	1
% in each category	15.4 %	60.2 %	21.1 %	2.9 %	0.4 %

Deterioration model

Transition probability matrix

Condition in year *t*	Condition in year *t+1* 5	4	3	2	1
5	0.85	0.15	0	0	0
4	0	0.965	0.035	0	0
3	0	0	0.98	0.02	0
2	0	0	0	0.94	0.06
1	0	0	0	0	1

Maintenance effects models

Rehabilitation

Condition in year *t*	Condition in year *t+1* 5	4	3	2	1
5	1.00	0.00	0.00	0.00	0.00
4	0.00	1.00	0.00	0.00	0.00
3	0.10	0.90	0.00	0.00	0.00
2	0.00	0.90	0.10	0.00	0.00
1	0.00	0.70	0.30	0.00	0.00

Reconstruction

Condition in year *t*	Condition in year *t+1* 5	4	3	2	1
5	1.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	1.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	1.0000	0.0000	0.0000
2	1.0000	0.0000	0.0000	0.0000	0.0000
1	1.0000	0.0000	0.0000	0.0000	0.0000

Cost models

Condition category	Cost €/m2 **Maintenance action** **Routine maint.**	**Rehab**	**Reconst**
5	3		
4	3		
3	3	350	
2	3	450	1300
1		750	1300

Prestressed PCC bridges on unsalted roads

Total bridge deck area 192 800 m2

Current condition

Category	5	4	3	2	1
% in each category	20.6 %	68.8 %	10.5 %	0.1 %	0.0 %

Deterioration model

Transition probability matrix

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	0.86	0.14	0	0	0
4	0	0.975	0.025	0	0
3	0	0	0.985	0.015	0
2	0	0	0	0.96	0.04
1	0	0	0	0	1

Maintenance effects models

Rehabilitation

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	1.00	0.00	0.00	0.00	0.00
4	0.00	1.00	0.00	0.00	0.00
3	0.10	0.90	0.00	0.00	0.00
2	0.00	0.90	0.10	0.00	0.00
1	0.00	0.70	0.30	0.00	0.00

Reconstruction

Condition in year *t*	Condition in year *t+1*				
	5	4	3	2	1
5	1.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	1.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	1.0000	0.0000	0.0000
2	1.0000	0.0000	0.0000	0.0000	0.0000
1	1.0000	0.0000	0.0000	0.0000	0.0000

Cost models

Cost €/m2

Condition category	**Maintenance action**		
	Routine maint.	**Rehab**	**Reconst**
5	2		
4	2		
3	2	350	
2	2	450	1300
1		650	1300

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