Advances in predictive maintenance planning of roads by empirical models

Konsta Mikael Sirvio
Advances in predictive maintenance planning of roads by empirical models

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**Abstract**

Roads constitute one of the most valuable asset group of a country. Road asset value is better preserved by preventive instead of corrective maintenance. Traditionally, road maintenance has been planned using mechanistic or hybrid models for estimation, prediction and optimisation. This thesis proposes a framework for road maintenance planning, where Road User Costs and Agency Costs are estimated and forecasted, road condition forecasted and future maintenance works optimised with empirical models. The concept is called predictive maintenance planning.

Various empirical methods were combined and applied in sub-tasks of road maintenance planning. The methods included Sequential Input Selection Algorithm for variable selection, k-means++ for clustering, Principal Component Analysis for dimension reduction, Markov Chains, Ordinary Least Squares regression, Radial Basis Functions and Least Squares Support Vector Regression for forecasting and Genetic Algorithms and Variable Neighbourhood Search for optimisation.

The research showed that accuracy of road condition forecasting can be increased with non-linear empirical models using collected data from the roads. The best method was Least Squares Support Vector Regression for multi-step ahead forecasting. The best applied optimisation method combined Parallel Genetic Algorithms with Variable Neighbourhood Search.

The Thesis shows that accuracy can be increased and cost saved in road maintenance by a paradigm shift from mechanistic to empirical models in road maintenance planning.

**Keywords**  Road maintenance planning, road maintenance optimisation, road deterioration, road condition forecasting, life cycle cost analysis, condition-based maintenance planning, preventive maintenance, predictive maintenance planning

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Tekijä
Konsta Mikael Sirvio

Väitöskirjan nimi
Edistysaskeleet tiestön ennustavassa kunnossapidon suunnittelussa empirisillä malleilla

Julkaisija
Perustieteiden korkeakoulu

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Tiivistelmä
Tiet muodostavat yhden arvoikkaammin julkisista omaisuuseristä. Tieomaisuuden arvo säilyy ennakoivalla kunnossapidolla korkeampana kuin korjauksen suunnitellut. Perinteisesti tiestön kunnossapitoa on suunnitellut käyttämällä mekaanisia tai hybridimalleja arviointiin, ennustamiseen ja optimointiin.

Tässä väitöskirjassa ehdotetaan viitekehystä tiestön kunnossapidon suunnittelun, jossa tienkäyttäjän ja tieviranomaisen kustannukset sekä tiestön kunto arvioidaan ja ennustetaan ja tulevaisuudessa tapahtuvat kunnossapitotoimet optimoidaan empirisillä malleilla. Käsitetään ennustavaksi kunnossapidon suunnitteluka.

Useita empirisistä menetelmiä yhdisteltiin ja sovellettiin tiestön kunnossapidon tehtävissä. Menetelmät sisälsivät peräkkäisen syötevalinnan algoritmin muuttujen valintaan, k-keskiarvot++ -menetelmän ryhmittämiseen, pääkomponenttianalyysin ulottuvuuden pientäminen, Markovin ketuja, tavaltaa pienimmän neliösumman regressiota, satiittäisperustafunktioita ja pienimmän neliön vektoritukiregressiota ennustamiseen sekä geneettisiä algoritmeja ja Variable Neighbourhood Search -menetelmää optimointiin.


Väitöskirja osoittaa, että tarkkuutta voidaan parantaa ja tiestön kunnossapidon kustannuksia pienentää muuttamalla ajatus- ja toimintamallia mekanistisista malleista empriisin tiestön kunnossapidon suunnittelussa.

Avainsanat
Tiestön kunnossapidon suunnittelut, tiestön kunnossapidon optimointi, tiestön rappeutuminen, tiestön kunnon ennustaminen, elinkaarkustannusanalyysi, kuntopohjainen kunnossapidon suunnittelu, ennaltaehkäisevä kunnossapito, ennustava kunnossapidon suunnittelu


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Helsinki, 29 August 2017
Konsta Mikael Sirvio
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<tr>
<td>AADT</td>
<td>Annual Average Daily Traffic</td>
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<tr>
<td>AC</td>
<td>Asphalt Concrete</td>
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<td>AC</td>
<td>Accident Costs</td>
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<td>ADP</td>
<td>Approximate Dynamic Programming</td>
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<tr>
<td>ADT</td>
<td>Average Daily Traffic</td>
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<td>AHP</td>
<td>Analytical Hierarchy Process</td>
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<td>ANN</td>
<td>Artificial Neural Network</td>
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<td>ARIMA</td>
<td>Autoregressive Integrated Moving Average</td>
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<td>B/C</td>
<td>Benefit-Cost Ratio</td>
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<td>BC</td>
<td>Before Christ</td>
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<td>CBM</td>
<td>Condition-Based Maintenance</td>
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<td>CM</td>
<td>Cold Mix</td>
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<td>CM</td>
<td>Corrective Maintenance</td>
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<td>CPI</td>
<td>Consumer Price Index</td>
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<td>CW</td>
<td>Carriageway</td>
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<td>DCP</td>
<td>Dynamic Cone Penetrator</td>
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<td>DBSD</td>
<td>Double Bituminous Surface Dressing</td>
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<td>DP</td>
<td>Dynamic Programming</td>
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<td>EUAC</td>
<td>Equivalent Uniform Annual Cost</td>
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<td>FSM</td>
<td>Four Step Model</td>
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<td>FTA</td>
<td>Finnish Transport Agency</td>
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<td>FWD</td>
<td>Falling Weight Deflectometer</td>
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<td>Acronym</td>
<td>Description</td>
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<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
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<td>GDP</td>
<td>Gross Domestic Product</td>
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<td>GPR</td>
<td>Ground Penetrating Radar</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>GRASP</td>
<td>Greedy Randomized Adaptive Search Procedure</td>
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<td>HRA</td>
<td>Hot Rolled Asphalt</td>
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<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
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<td>IFI</td>
<td>International Friction Index</td>
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<td>IQL</td>
<td>Information Quality Level</td>
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<td>IRI</td>
<td>International Roughness Index</td>
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<td>IRR</td>
<td>Internal Rate of Return</td>
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<tr>
<td>IT</td>
<td>Information Technology</td>
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<tr>
<td>ITS</td>
<td>Intelligent Transport System</td>
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<tr>
<td>km</td>
<td>Kilometre</td>
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<tr>
<td>KPI</td>
<td>Key Performance Indicator</td>
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<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
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<tr>
<td>LCCA</td>
<td>Life Cycle Cost Analysis</td>
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<tr>
<td>LP</td>
<td>Linear Programming</td>
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<tr>
<td>LRP</td>
<td>Location Reference Point</td>
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<tr>
<td>LRS</td>
<td>Location Referencing System</td>
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<tr>
<td>LS-SVR</td>
<td>Least Squares Support Vector Regression</td>
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<td>MC</td>
<td>Markov Chain</td>
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<td>MLP</td>
<td>Multi-Layer Perceptron</td>
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<td>mm</td>
<td>Millimetre</td>
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<td>MSE</td>
<td>Mean Square Error</td>
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<td>MUC</td>
<td>Maintenance Unit Costs</td>
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<tr>
<td>NPV</td>
<td>Net Present Value</td>
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<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
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<tr>
<td>OLS</td>
<td>Ordinary Least Squares</td>
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<tr>
<td>PA</td>
<td>Porous Asphalt</td>
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<tr>
<td>PBC</td>
<td>Performance-Based Contract</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>PBM</td>
<td>Performance-Based Maintenance</td>
</tr>
<tr>
<td>PC</td>
<td>Principal Component</td>
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<tr>
<td>PCA</td>
<td>Principal Component Analysis</td>
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<tr>
<td>PCC</td>
<td>Portland Cement Concrete</td>
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<tr>
<td>PCI</td>
<td>Pavement Condition Index</td>
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<tr>
<td>PGA</td>
<td>Parallel Genetic Algorithm</td>
</tr>
<tr>
<td>PM</td>
<td>Planned Maintenance</td>
</tr>
<tr>
<td>PMA</td>
<td>Polymer Modified Asphalt</td>
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<tr>
<td>PMS</td>
<td>Pavement Management System</td>
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<td>PPP</td>
<td>Public Private Partnership</td>
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<td>PSI</td>
<td>Present Serviceability Index</td>
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<td>QI</td>
<td>Quarter Car Index</td>
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<tr>
<td>RA</td>
<td>Road Agency</td>
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<tr>
<td>RAC</td>
<td>Road Agency Costs</td>
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<tr>
<td>RAC</td>
<td>Rubberised Asphalt Concrete</td>
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<td>RBF</td>
<td>Radial Basis Function</td>
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<td>RMS</td>
<td>Road Management System</td>
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<td>RQI</td>
<td>Ride Quality Index</td>
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<tr>
<td>RUC</td>
<td>Road User Costs</td>
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<tr>
<td>SBSD</td>
<td>Single Bituminous Surface Dressing</td>
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<tr>
<td>SISAL</td>
<td>Sequential Input Selection Algorithm</td>
</tr>
<tr>
<td>SMA</td>
<td>Stone Mastic Asphalt</td>
</tr>
<tr>
<td>SN</td>
<td>Structural Number</td>
</tr>
<tr>
<td>SUV</td>
<td>Sport Utility Vehicle</td>
</tr>
<tr>
<td>SVR</td>
<td>Support Vector Regression</td>
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<td>VNS</td>
<td>Variable Neighbourhood Search</td>
</tr>
<tr>
<td>VOC</td>
<td>Vehicle Operating Costs</td>
</tr>
<tr>
<td>VOT</td>
<td>Value of Travel Time</td>
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This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals


Author’s Contribution

Publication 1: “Spatio-Temporal Road Condition Forecasting with Markov Chains and Artificial Neural Networks”

The article introduced new methods for forecasting road condition of one time-step. The methods were jointly developed with Dr. Jaakko Hollmén. The author collected the data, carried out the experiments and wrote the article.

Publication 2: “Multi-year network level road maintenance programming by genetic algorithms and variable neighbourhood search”

Global and local optimisation strategies were applied on road maintenance planning. The author was responsible for data collection, selection of methods and preparation of the article.

Publication 3: “Forecasting road condition after maintenance works by linear methods and radial basis function networks”

Non-linear methods were applied to road condition estimation after road maintenance. The author selected the methods and carried out the experiments with the data collected from the Road Agency.

Publication 4: “Multi-Step Ahead Forecasting of Road Condition Using Least Squares Support Vector Regression”

A new method was applied in road condition forecasting with multiple time-steps. The author selected the methods, collected the data and wrote the article.

Publication 5: “Intelligent Systems in Maintenance Planning and Management”

A general framework and maintenance planning concepts with literature review on intelligent maintenance planning and optimisation of roads and vehicles were created. A practical experiment for intelligent road maintenance planning was introduced by the author.
1. Introduction

1.1 Motivation and Background

Roads are among the most valuable assets of many countries (OECD, 2001), but preservation of the assets have been partly neglected due to constrained budgets and poor asset management (PIARC, 2013). Still, road networks are vital for economic, cultural and social development of most of the countries facilitating communication and transfer of goods and people improving thus socio-economic living conditions especially in rural areas (Starkey and Hine, 2014).

Since the first man-made roads the techniques for construction and maintenance have gradually improved. Development of Information Technology (IT) has greatly facilitated planning of maintenance. Although certain criteria have always been used in selection of the target roads for maintenance the efficiency can be improved with more sophisticated methods.

Once a road is constructed there are regular maintenance costs incurring to the Road Agency (RA), which is here regarded any organisation responsible for management of a road network. The costs are usually covered by tax revenues from the public and thus road users pay for the usage of roads. In some countries, there are direct costs of the right to use the road from the road owner in terms of road tolls. Even if road tolls did not exist road users pay for the capital costs of the vehicle and operating costs such as fuel and maintenance (de Rus and Romero, 2004).

Travel time is another cost element that the users and the society as whole pay. Travel time is an opportunity cost of road users not being able to dedicate their time to something more productive while driving a car, which is often used in transport modelling – justifiably or not (Metz, 2008).

Accident costs are also often included in travel cost analysis as they directly affect the livelihood of the participants as well as the welfare society (Metz, 2008). Overall, it has been proved that the poorer the road condition is the higher the road user costs are (Odoki and Kerali, 2000; Amos, 2006). Relationship between the accident risk and thus the costs and road condition is not as straightforward as the several studies indicate (Pulugurtha et al., 2013 and Izquierdo et al., 2013). On the other hand, the better the road condition is the higher are the costs of the maintenance for the Road Agency as road condition deteriorates over time. Thus, road maintenance is an optimisation problem, where the overall costs to the society i.e. Road Agency costs and road user costs are minimised.
The overall optimisation problem is easy to understand and justify, but difficult to implement in optimal way due to various reasons. First, political decision-making does not always lead to optimal solutions, but compromises are made and political self-interest vanquish the common good. This is especially visible in preference of new road construction over existing road network maintenance (Wales and Wild, 2012). Another challenge is to acquire relevant information on the major aspects of the optimisation problem. These depend on the country and practice, but usually include road condition, road traffic volumes, road user costs and maintenance costs (Tapper et al., 2016).

Even if exact costs are not known approximations can be used. The next problem is finding and using the best suitable models for planning so that the optimisation problem is solved. One key aspect is the cost models that map road condition to road user costs. Ideally, the plan would be followed if the models take all the relevant aspects into consideration. In practice this is not the case due to difficulties related to the aforementioned problems. Therefore, validation of the results is yet another problem in the real-world situation.

The main research question studied in this thesis is how to increase the efficiency of road maintenance by improved maintenance planning. Maintenance planning has been studied not only concerning roads, but also other assets such as bridges (Ok et al., 2013) and railways (Bergquist and Söderholm, 2014). The same principles apply in preventive maintenance; whichever asset is in question as the maintenance needs to take place prior to the default. If maintenance planning is effective defaults are avoided. If the maintenance planning is also efficient defaults are avoided with minimum costs. The problem, however, with other asset types is to monetise the effects of deteriorating condition.

The overall maintenance planning problematics can be complex in the predictive form. The framework is divided into several phases and studied separately. Another research question is stated as what methods give the best accuracy in road condition forecasting. The third research question asks what methods can be applied for optimisation of road works minimising the costs to the society.

Due to advances in Information and Communication Technology (ICT), the bottleneck does not exist in data transmission and storage. Computing power would also be available for computations based on empirical models. One of the main problems is in getting the tested computational models from the theory to practice. The aim of the thesis is to alleviate the transition towards further optimisation of road maintenance by presenting empirical methods that are applicable to maintenance planning. The hypothesis of the research is that empirical models can increase efficiency in road maintenance.

1.2 Scope of the study

Different condition variables are collected on road networks with variable frequency and granularity i.e. the level of aggregation of zero-dimensional values of condition variables to one-dimensional average values describing a road
segment. Not all the variables are collected frequently everywhere on the road network. This study relies on existing, already collected data on the road networks and relies mainly on the two major condition variables: roughness measured by International Roughness Index (IRI) expressed by mm/m and depression along the wheelpath of a road i.e. rutting depth measured by mm that partly illustrate the surface condition (FDOT, 2015), but can give an indication of road base or drainage condition. Although these variables can also be collected on gravel roads replications of the measurements can differ greatly from each other and therefore automatic gravel road measurements is not yet widely applied. Thus, this study is limited to consider the issue of maintenance planning of paved or sealed roads although the same principles can be applied to unsealed roads once automatic measurement data is collected on them. The study is also restricted to flexible pavement types as the amount of rigid pavement in the case areas is negligible.

Overall road asset management does not include only road maintenance, but also maintenance of bridge parts, culverts, road furniture, road markings etc. Road Agencies tend to apply routine maintenance on regular basis on the road networks. This study concentrates on the maintenance works that are called periodic maintenance in the road sector including major works affecting the pavement of the roads. Maintenance of bridges is similar in principle, but more complex in practice due to multiple engineering parts deteriorating by separate patterns.

Road network maintenance planning can be divided into three parts: 1) strategic planning, 2) network level maintenance planning and 3) project level work planning (Shah at al., 2016). This study’s main focus is at network level maintenance planning, but with the same methods issues related to strategic planning can be solved. As there is a plethora of possible methods related to maintenance planning i.e. forecasting and optimisation not all of them are examined and tested. The focus in this study is in empirical methods that resort to large quantities of collected data instead of mathematical engineering models that try to grasp the essence of the phenomenon in a relatively simple mathematical formula.

1.3 Outline of the thesis

An overall framework of a road model and maintenance planning is presented in Section 2. More detailed description of road maintenance planning and optimisation is described in Section 3. Case studies with utilised methods and data as well as achieved results with discussion is given in Section 4. The study is summarised and concluded in Section 5. The five publications are presented in the end.
2. Road model

A road is “Line of communication (travelled way) using a stabilized base other than rails or air strips, primarily for the use of road motor vehicles running on their own wheels” (PIARC, 2017). Road construction is preceded by road planning that can be divided into feasibility study, preliminary engineering planning, final engineering planning and construction planning phases (FTA, 2010).

Road maintenance is required to keep roads accessible and in acceptable condition. Without any maintenance a sealed road deteriorates unusable. The service life of a road depends on the design standards, but recommended design life varies between 10 and 50 years depending on the road class (AASHTO, 1993). As road networks can be long and include roads with different characteristics efficient road maintenance cannot take place without proper maintenance planning. An overview of road maintenance planning is presented in Figure 2.1. Information is needed from the road network for the maintenance planning. There are financial constraints that restrict the scope of the plans and assumptions that define or direct the planning.

![Figure 2.1. Road maintenance planning is done with the help of collected information on the road network and the results drive the actual maintenance works.](image)

Roads enable ground transport and therefore road use is linked in wider aspects of economic and social activity. Road design standards, construction material, environment and the legal framework define the maximum legal speed and the capacity of a road. The purpose of maintenance is to preserve both the capacity and the value of road assets in an optimal way.
2.1 Road network

In asset management context, a road network means “all roads in a given area” (PIARC, 2017), or the roads in a given area that meet certain criteria (e.g. the southern region expressway network). The model of a road network consists of spatial information that is referenced to a geographic location on the earth. A road network can be described by three spatial dimensions, time and theme. The same applies to the smaller constituents of the road network: roads, links, nodes and sections.

A road consists of consecutive links that are connected with each other on nodes located at intersections of roads (Huang, 2003). Traffic remains relatively constant on every point on a link. In practice, there can be connections to road links from private property or minor roads. In such cases, a vehicle entering a link travels through the link only partially.

The roads and links can be represented as centrelines. In addition to the ending and starting points of the road link, crossings of the roads (=crossings of road centre lines) are represented as nodes. A road link starts and ends either where the road starts or ends or in the crossings of the roads.

In one-dimensional, linear Location Reference System (LRS) the links are often further divided into sections, which have a unique identifier. Road sections start from and end to permanent, clearly visible Location Reference Points (LRP) on the road.

Each point of the road network can be identified and located by using these Location Reference Points (LRP). Any collected data from the road network can then be referenced to the Location Referencing System with the road and section identifiers and distance from the closest LRP.

Required spatial accuracy and presentation model of the road network depend on the application area. Infrastructure management including maintenance planning and travel demand modelling is less sensitive to positional data accuracy than Intelligent Transport System applications (ITS), for example (Fekpe et al., 2003). Indeed, there are several other error and inaccuracy sources preventing optimal maintenance optimisation as can be later seen.

2.2 Information from the road network, usage and surroundings

The information collected from the road network depends on the objectives set for the maintenance planning. Location, geometry and material choices of roads are made already at the design and construction phase and they cannot be substantially altered at the maintenance stage as the maintenance aims at prolonging the usable time of the roads close to the designed standards. Thus, some sustainability aspects such as equity in terms of accessibility to the road network cannot be affected by road maintenance. Others, such as socio-economic efficiency and effectiveness can be affected (Asomani-Boateng et al., 2015).

It could be argued that efficiency should be the main driver for road maintenance, but the maintenance planning should minimise the objective function
of total costs to the road users and road administration (Babashamsi et al., 2016). To minimise the objective function, the input information needs to be measured or estimated.

A road as a whole and separate layers can be described by state variables. Some of the state variables remain relatively constant unless the road is reconstructed. These variables are determined during geometric design according to design standards. Actual values after construction may differ from the designed values. The design variables are called here road characteristics. Other state variables, however, change over time and can be affected by road maintenance. These are road condition variables that can describe not only the surface layer, but also the layers below.

Besides the state variables of the road itself there are state variables that describe the relation of the road to the external environment. Road use is characterised by traffic amounts describing how many vehicles travel on a road link, while maintenance costs describe how much it costs to perform a certain maintenance operation on a part of the road and road user costs reflect the total cost to a road user traveling on a certain segment with a given vehicle and speed.

### 2.2.1 Road characteristics

Road characteristics describe the permanent or at least long-lasting features of roads defined in road design. The characteristics include road width, design speed, road geometry and construction material.

Geometric design of a road can be divided into alignment, profile and cross-section. The alignment is the route of the road, defined as a series of horizontal tangents and curves. The profile is the vertical aspect of the road, including crest and sag curves, and the straight grade lines connecting them. The cross section shows the position and number of vehicle and bicycle lanes and sidewalks, along with their cross slope or banking. Cross sections also show drainage features, pavement structure and other items outside the category of geometric design (Wiegand and Stevens, 2007).

Roads typically have several separate layers when correctly designed as shown in Figure 2.2. Below all the layers is the native ground that is called subgrade. Actual road layers start with an optional sub-base course or directly with base course that are made of aggregate materials. Surface course is on the top above an optional binder course (Zheng et al., 2012).

<table>
<thead>
<tr>
<th>Surface Course</th>
<th>Binder Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Course</td>
<td>Subbase Course</td>
</tr>
<tr>
<td>Compacted Subgrade</td>
<td>Natural Subgrade</td>
</tr>
</tbody>
</table>

**Figure 2.2.** Different layers of a paved road.
Three-dimensional road alignment and profile can be described by geometric variables. Typically used variables are superelevation, curvature and slope at each cross section of the road (AASHTO, 2001).

Each pavement layer consists of different construction material. The materials depend on the location and availability of types of stones. Road surface can be either sealed or unsealed. Unsealed roads are typically classified as earth or gravel roads, while sealed roads are classified as rigid or flexible surface. Rigid surface types include jointed plain concrete pavement, jointed reinforced concrete pavement and continuously reinforced concrete pavement (Hall et al., 2001). Flexible surface types include asphalt concrete pavement and full-depth asphalt concrete pavement. Composite pavements include both rigid and flexible surface layers (Li et al., 2016). The consistence of the material in terms of composition of particle sizes and stone material affect the durability of the road.

2.2.2 Road condition

Once constructed one of the main objectives set to a road is that it would remain close to the original condition. The main idea with good condition is that a road can resist external pressure and wearing caused by traffic and weather conditions. Ideally, roads should be stiff and strong.

However, roads deteriorate over time and therefore road condition is conceptually separated from more permanent road characteristics. There are various measures that describe the condition, how deterioration has affected a road or how well the qualities (stiffness and strength) are close to the designed values (Zornberg and Gupta, 2010). Condition variables can describe any element of a pavement whether it is the visible wearing course or non-visible layers below.

The main implications of road deterioration are lower riding comfort for road users and shorter service life. There are two types of condition evaluations namely functional and structural evaluation. A functional evaluation provides information about surface condition that directly affect users’ safety and comfort, or serviceability. On the other hand, a structural evaluation provides information on whether the pavement structure is performing satisfactorily under traffic loading and ambient conditions. Functional evaluation serves for serviceability and safety functions of the pavement while structural evaluation reveals structural capacity of the pavement. Figure 2.3 summarises the main categories of pavement condition data collection.

<table>
<thead>
<tr>
<th>Evaluation Type</th>
<th>Pavement Function</th>
<th>Pavement Characteristics</th>
<th>Examples of Indicators and Indexes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional Evaluation</td>
<td>Serviceability</td>
<td>Roughness</td>
<td>IRI</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PSI</td>
</tr>
<tr>
<td></td>
<td>Safety</td>
<td>Texture</td>
<td>QI</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Macrotexture</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Microtexture</td>
</tr>
</tbody>
</table>
Various condition indicators for different pavement characteristics have been developed over years. Currently, probably the most standardised variable is International Roughness Index (IRI), which describes smoothness and thus riding comfort of the road. The measure indicates how much cumulative vertical absolute movement takes place because of the roughness of the road surface on a longitudinal distance travelled (Sayers et al., 1986). IRI can be measured by several methods of which accelerometer or laser-based methods are most common. Present Serviceability Index (PSI) (Ferreira and Queiroz, 2012) and Quarter Car Index (QI) (Sayers et al., 1986) are also measuring roughness, but they are not as widely used as IRI. Figure 2.4 on the left shows a segment of a smooth road with low IRI, while on the right the road has higher IRI.

Besides roughness, texture and skid resistance concern the road surface. Indicators include macrotexture, microtexture, skid resistance coefficient and International Friction Index (IFI) (Saito et al., 2001). Road surface irregularities are divided into two scales of which macrotexture cover irregularities whose horizontal dimensions are between 0.5 and 50 mm and vertical dimensions are between 0.1 and 20 mm. In microtexture, on the other hand, horizontal dimensions are less than 0.5 mm and vertical dimensions are between 0.001 and 0.5 mm (Slimane et al., 2008).

Mechanical properties of the pavement depend mainly on the condition of sub-base and base layers that cannot be directly observed, but their performance i.e. bearing capacity i.e. stiffness can be measured by Falling Weight Deflectometers (FWD). Pavement strength can be measured by Dynamic Cone Penetrometer (DCP) (Parker et al., 1998). Resilient modulus of pavement materials (hot mix asphalt concrete, granular base, subgrade, etc.) has been used
for many years in structural pavement design. Resilient modulus is used to characterize pavement materials under loading conditions that will not result in “failure” of the pavement system.

Failure in mechanical properties of different layers of pavement can lead to pavement distress. Pavement distress visible on the flexible road surface include ravelling, weathering, rutting, alligator cracking, block cracking, thermal cracking, longitudinal cracking, slippage cracking, corrugation, shoving, bleeding, pumping, potholes, bumps, heaves, settlements and edge break (Hall et al.). Traditionally, information on these defects have been collected by visual inspection as automatic survey methods have not been available. However, recent advances in data collection and data processing have initiated research and applications on automatic Pavement Distress Inventory such as detection of cracking by image recognition (Zou et al., 2012) and rutting detection by laser-based methods (Li, 2012). Figure 2.5 shows an example with low rutting on the left side and high rutting depth on the right side.

![Figure 2.5. Roads with low rutting on the left and high rutting on the right (ODOT, 2010).](image)

### 2.2.3 Traffic

Roads are constructed for transport needs and traffic quantities usually determine design factors of roads, such as number of lanes and pavement strength. Overall traffic quantities can be further divided into traffic quantities by vehicle categories. Traffic quantities normally fluctuate over time depending on the hour, weekday and month. Traffic quantities form time-series and overall volume is often called Annual Average Daily Traffic (AADT), which is measured by a consecutive counting all the vehicles in one year on a specified link. In practice, traffic counting on certain links can last for a week to produce Average Daily Traffic (ADT), which is converted to AADT by multiplication of an adjustment factor (Gastaldi et al., 2014).

The heavier the vehicle is the more it wears out the road. Besides affecting road deterioration traffic is a main cost factor for the society as a whole. In the network level maintenance planning optimisation requires estimated traffic for the whole network. As traffic remains unchanged within a link, it should be counted on each link or the amount estimated by other means. Traffic information on the road network is used to estimate Road User Costs (RUC) affected by road condition.
2.2.4 Maintenance costs

Road maintenance require resources in the form of knowledge, capital, labour and material. Information on the future maintenance requirements can be estimated from the past maintenance treatments if the information is stored during the maintenance process. All the past maintenance works incur costs that depend on several factors such as utilised cost model and the amount of resources needed for the maintenance. Future maintenance cost estimates are often based on historical maintenance costs calculated from the past maintenance projects adjusted to the future price levels.

Since the future maintenance works are rarely identical with the past works, maintenance cost calculation can be based on unit costs. The actual maintenance costs are calculated by multiplying the unit costs with number of units. Typically, in maintenance works, units are either volume, area or length (Cutura et al., 2016). Maintenance costs can be estimated more reliably if the maintenance is implemented in-house as the cost driver information is available. In case of competitive bidding for performance-based maintenance contracts the costs are driven by the market and thus difficult to forecast.

2.2.5 Weather

High variations in temperature, alterations of the temperature between melting and freezing as well as amount of rainfall have effect on road management and road deterioration. Road weather stations can also record the temperature on the road surface besides in the air. Average air, road and ground temperatures, average of average and maximum wind speeds, wind direction, sum of rainfall and average air humidity have been included in road deterioration modelling as input variables among others as shown in Publication 1. Generally, it has been reported that bleeding takes place in hot weather and ravelling is accelerated by freezing weather (Adlinge and Gupta, 2013).

2.3 Road maintenance

There are two main approaches in road maintenance – either already occurred damage is corrected or damages are attempted to be prevented. The focus of this study is on preventive maintenance, where the maintenance works can be of periodic nature i.e. time-based or condition-based actions as introduced in Publication 5. Whichever philosophy is applied the practical maintenance works remain the same.

There are several road maintenance works that can focus on any of the road layers, shoulder or side drain. Maintenance works can be divided into routine maintenance and periodic maintenance. Rehabilitation is sometimes included part of periodic maintenance (Altamirano et al., 2007). Besides the preventive maintenance treatments emergency maintenance takes place when serious defect prevents efficient use of the road (Donnges et al., 2007).

Routine maintenance works are light maintenance works that are repeated several times per year on the same road segment. Routine maintenance works
are of small scale and simple, but widely dispersed (TRL, 1994). Routine maintenance works include works outside the surface course including vegetation control, road sign repair and drainage clearing as well as works affecting the surface course such as repair, fill and compact of potholes and ruts for paved roads of flexible pavements (Donnges et al., 2007).

Periodic maintenance, on the other hand, concerns maintenance works that are typically repeated at regular but long intervals on the same segment. The works are more expensive than routine maintenance. Periodic maintenance activities for paved roads of flexible pavement include resealing and overlay (Ibraheem and Gani, 2011).

Rigid pavement construction and therefore maintenance works differ from flexible pavements. Maintenance works include joint and crack sealing, slab stabilisation, diamond grinding, patching, dowel bar retrofitting, structural hot mix asphalt overlays and structural PCC overlays (Pereira, 2014).

Gravel road maintenance works focus mainly on the wearing course. The maintenance activities include grading, gravelling, dust control, watering, patching, dragging and ditching (Alzubaidi, 1999).

### 2.4 Assumptions for road maintenance planning

As maintenance planning period can exceed several years the time value of money for cost information should be taken into consideration by a discount factor. Discount factors do not remain constant over time and forecasting of them is difficult. A common practice is to use a fixed annual discount factor for the planning period (Worm and van Harten, 1996). Data collected over a long period reveals that the real-time value of money is only 2–4% (Babashamsi, 2016). A fixed discount factor does not distort the maintenance priorities, but can sacrifice optimal use of allocated budgets in multiannual maintenance planning.

Besides time value for money it is often assumed that the technological level remains constant in such a way that there are not new road pavement materials, major efficiency increases in road works or advances in vehicular fuel efficiency (Meneses and Ferreira, 2012).

### 2.5 Constraints for road maintenance and planning

Road maintenance planning faces constraints originating mainly from the practical issues. These constraints are mainly related to the maintenance budget, contract terms and practical arrangements of the actual maintenance.

The main constraint in road maintenance taken into consideration in maintenance planning is a budget constraint. For a public Road Authority, the budget constraint can be fixed based on road budget negotiated with the national government or have variable elements based on earmarked tax revenues (Hayashi and Morisugi, 2000). In case of Public Private Partnerships (PPP) and Performance-Based Maintenance (PBM) the private company responsible for maintenance and planning can have variable budget based on performance
or road use. In both public and private cases, the global optimum in road asset management may need to be sacrificed and a local optimum should be found within the limits of the annual budget constraints. In practice, some of the maintenance works may be scheduled to take place earlier or later than deemed optimal by planning.

Road maintenance work can be done by the staff of the Road Authority as in-house or it can be contracted out to the private sector. In case of private sector maintenance, there are two main types in contracting: traditional method-based and more recent performance-based contract (Wirahadikusumah et al., 2015).

In the traditional approach, the tasks and methods applied in maintenance are specified in advance while a performance-based contract (PBC) sets the minimum required conditions for roads, bridges and other assets without directing the contractor to specific maintenance methods leaving space for potential innovation (Fallah-Fini et al., 2012). Thus, the contractor should schedule the maintenance works in such a way that the minimum condition criteria are not violated or in opposing case, take the risk of penalty payments into consideration in maintenance planning. Selection of threshold values for maintenance works is often based on engineering judgements, but an optimisation model has been proposed (Chu and Chen, 2012).

Actual maintenance work imposes constraints to be taken into consideration in maintenance planning. At a project level the maintenance plan is more detailed than at the network level and daily operations and resource allocations are decided. Legal and practical issues restrict number of daily working hours by the maintenance teams.

### 2.6 Road maintenance planning

Road maintenance planning for corrective maintenance differs from preventive maintenance planning. Failure type and failure time could be estimated in advance. However, it has been noticed that preventive maintenance is more cost-effective and therefore road maintenance planning applies primarily for preventive maintenance approach.

In road maintenance planning, individual maintenance projects can be bundled and organised into maintenance programmes from several perspectives (Talvitie, 2000). More detailed, project-level maintenance planning covers shorter length of roads, but the plan is created in more detail concerning resource allocation and timing. When larger area and longer total road length is considered, the term “network level planning” is used. At the network level plan, the maintenance programme can cover the whole or part of the road network. The plan consists of less details on the future operations, timing and resource allocations (de la Garza et al., 2011).

Road maintenance planning can also be separated according to the time span of the plans. Long-term maintenance planning extends beyond 10 years, while medium term maintenance planning concerns shorter periods. Annual maintenance plan is done more accurately for the coming year. Individual pro-
jects can be planned separately in more details for a particular road. The basic principle has been to increase the level of detail the closer in the future the actual maintenance is.

Road maintenance planning is a mathematical optimisation problem, where the objective function should be selected according to the agent’s preferences and data, constraints and assumptions according to what has been identified from the practical maintenance operations. The next section explains the methodology in detail.
3. Methodology for road maintenance planning

Theoretically, road maintenance planning is optimal assignment of maintenance works spatially and temporally on the road network. Optimal assignment requires information explained in the previous section. The collected information is not necessarily valid in the future, where the plan extends. Therefore, the future values are forecasted. Part of the information cannot be directly collected, but it can be estimated. Estimation and forecasting applies to road condition, Road User Costs (RUC) and Maintenance Unit Costs (MUC) as presented in Figure 3.1. The publications advancing current status of modelling are presented in parentheses.

Forecasted Road User Costs and Maintenance Unit Costs depend not only on the collected information, but also on the results of forecasted road condition. Assigned maintenance works improve road condition on the assigned locations lowering thus future RUC. Depending on the maintenance costs model, the future MUC can also be affected. Therefore, maintenance optimisation, estimation and forecasting should not be done in isolation, but in parallel.
3.1 Modelling philosophies

Reality is complex. Systems used are simplified but the essential qualities should be captured in a model. There are two main approaches to create a model with the predefined objectives:

1. Mechanistic model
2. Empirical model

Mechanistic models are based on theory of the system behaviour trying to encapsulate the causality in analytical mathematical equations (Bretó et al., 2009). Empirical models, on the other hand, are based on quantified observations made on the system and relationship and causality is set by information theoretic inference between quantified measurements (Hendry, 2011). A combination of mechanistic and empirical elements is called hybrid models. Hybrid semi-parametric models are model structures that combine parametric and nonparametric submodels (von Stosch et al., 2014).

Modelling can also be categorised to descriptive, predictive and explanatory modelling. Descriptive modelling describe the behaviour of the system by values of state variables and possible relationship and causality between them. The objective of predictive modelling is to estimate observation values in the future for the selected state variables of the system. Explanatory modelling uses statistical methods and empirical data for testing causal hypotheses about theoretical constructs (Shmueli, 2010). Another modelling or analytics category has been introduced more recently. Prescriptive modelling uses the information to get the best course of action in each situation (Delen and Demirkan, 2013).

The actual models can be either deterministic or probabilistic (stochastic). Deterministic models claim that the future state remains the same with the given input variables, while the output of probabilistic models varies with the same input variables (Bertin, 2012).

Empirical, mechanistic and hybrid models of stochastic and deterministic nature have been applied in road maintenance planning, but the importance of empirical models is rising due to development of survey and data processing methodologies and due to the complexity of the phenomenon. Stochastic modelling is common with empirical and heuristic models introducing probability distributions to output instead of single values.

Road maintenance planning can use predictive, descriptive, explanatory and prescriptive modelling techniques. In the presented framework, the focus is at predictive and prescriptive modelling. Predictive modelling is used in forecasting the road condition between and after maintenance works, while the optimisation gives the best computer-aided plan belonging thus to prescriptive modelling.
3.2 Data for road maintenance planning

Various types of data can be collected and stored from the road network as explained in Section 2. Human-based visual condition assessment and traffic counting is being replaced by automatic data collection methodology. Whichever data collection method is used the same basic principles prevail. First, it is selected what data is collected. Secondly, the data collection methods are decided and thirdly, the aggregation level should be decided for the collected 1-dimensional line data, 2-dimensional area data or 3-dimensional volume data.

The aggregation level is in theory based on Information Quality Levels (IQL) and required level of detail for decision-making. Four levels of IQL were identified in road management in the first IQL study, where level one represents most comprehensive level of detail and such data is used mainly at the project level. Level 4, on the other hand, is the minimum detail needed for generating basic statistics of the road network. Aggregation level of 2-dimensional road data typically ranges between 3-100 metres (Paterson and Scullion, 1990), which applies to IRI and rutting used in this study. Slightly evolved and currently mostly used IQL concept with one additional level is presented in Figure 3.2.

![Figure 3.2. Information Quality Levels (Bennett et al., 2007).](image)

For IRI a common aggregation level is 100 metres (Forslöf and Jones, 2015). In the case of Finland, the data is stored in the databases that are thematically separated. Road database consists of information on road characteristics and Road condition database consists of road condition information such as IRI (Marttinen, 2015). Each country has separate data collection procedures and information systems with varying length of history. A common practice is to store network level road data in relational databases arranged by Location Referencing System (LRS) (Dueker and Butler, 2000). Our case studies in Publications 1, 2-5 resorted to the data collected in Finland and in Publication
2 data was collected in Pakistan. In case of Finland there is a long history in the data and more variables are collected than in Pakistan, where the case data has no history.

As in Finland IRI is a standardised and widely used measure that is repeatedly collected based on sensor technology on the same roads, it was used as an example in Publications 1-5. IRI has been aggregated as averages of 100-metre long road segments, but less aggregated 10-metre long averages were used in Publication 1. Rutting measurements are also machine-based, usually collected simultaneously with IRI and therefore those were used in Publications 1-4.

Bearing capacity measurements are currently 0-dimensional, not necessarily covering most of the network and not repeated with the same frequency as the previous two variables and therefore it was not used as an example. Visual condition assessments are prone to errors and they have not been used in empirical forecasting models. However, they are used in mechanistic forecasting models and empirical optimisation model in Publication 2. Traffic quantities were used both in road condition forecasting in Publication 1 and 3 as well as in maintenance optimisation in Publication 2. Road weather was used only in Publication 1.

### 3.3 Road condition forecasting

#### 3.3.1 Road condition between maintenance works

The mechanistic models in road condition forecasting are based on fundamental theories of pavement behaviour described by mathematical equations, while empirical models are less structured based on collected, historical data on the pavement. Combined mechanistic–empirical approach has structured analytical equations describing pavement behaviour. The equations are adjusted to different conditions by calibration parameters that bring the empirical element into the models (Cao and Kim, 2016). A theoretical example of analytical model and motivation for many maintenance planning studies is presented in Figure 3.3.
Deterioration of a road is a complex phenomenon, where the material of the road and the road as a whole experience deformation due to aging process and external factors such as pressure on the surface caused by traffic and environmental aspects including temperature changes and rain. Construction material, method and quality of the both affect the deterioration process. Deterioration can be measured by condition variables introduced in Section 2.1. The actual deterioration is described by a deterioration model, which is a predictive model forecasting the road condition described by the selected condition variables.

Markov Chains have been popular for a probabilistic empirical model, where road condition is the state variable and stochastic state transitions are described by state transition probabilities (Pulugurta et al., 2009). Markov Chains were selected as a starting point for a case study for Finland presented in Publication 1 since they are intuitive and resemble used mechanical models in such a way that the deterioration process has no memory beyond the current condition. Adequate data quantities to create the Markov Chains were ensured by clustering the available data of the road network (not only the case roads) assuming thus similar conditions within a cluster. The Markov Chains outperformed Artificial Neural Networks (ANN), while it has been reported that for urban roads and Pavement Condition Index (PCI) ANN outperformed other methods (Kirbas and Karasahin, 2016).

Figure 3.4 indicates development of International Roughness Index for four 100–metre long road segments in Finland between 2006 and 2014. Only routine maintenance activities have been performed on the road during the period according to the road condition register. Rutting seems to increase almost in a linear way, while IRI develops in a distinct manner for all the four segments. An interesting aspect is that road segments seem to improve during certain years for consecutive segments. This seems to happen in several segments unlike analytical models suggest.
3.3.2 Estimation of road condition after maintenance

It is an intuitive expectation that road surface condition would be relatively constant after periodic maintenance works. It has been reported that a reconstruction or thick overlay will reset roughness to the level of a new pavement, typically 2 m/km IRI or less (Harvey, 2012). Another set of deterministic and mechanistic models take into consideration the type of work, user-definable parameter, past IRI value and other past condition variable values (Odoki and Kerali, 2000). Maintenance effectiveness was studied and the term 'Performance Jump' was used for road condition after maintenance. The study introduced analytical models applied to present serviceability index (Labi et al., 2003).

The actual IRI values depend on factors such as pavement material, work method and quality of the work. Network level road condition surveys follow often a pre-defined schedule and therefore time lapse between the resurfacing and condition survey cause variance in the results. It was noticed in Publication 3 that the Mean Square Error (MSE) was approximately 0.3 mm/m for IRI and 4.3 mm for rutting using Radial Basis Functions (RBF) covering the whole road network of Finland and 54 explanatory variables. Currently used methods result in MSE figures of 0.8 mm/km for IRI and 14.2 mm for rutting. The results indicate that road condition is far from constant after road maintenance and non-linear methods improve accuracy in estimating the condition. Prioritisation of the explanatory variables also reveal that traffic vol-
Volume is not the most significant factor explaining road condition after maintenance works.

Another study concerning the Finnish road network reveals a similar phenomenon that resurfacing works do not necessarily restore the road into constant and smooth condition (Virtala, 1998).

### 3.4 Road User Cost estimation and forecasting

Total Road User Costs (RUC) on the road network are a function of traffic volume and unit road user costs per travelled distance of each vehicle. Total road user costs cannot be directly measured as not all the road users are tracked, but they can be estimated by Equation 3.1.

\[
RUC = \sum_{i=1}^{V} \sum_{j=1}^{L} v_{ij} l_j RuC_v(v, w, r), \tag{3.1}
\]

where \( V \) indicates the number of vehicle categories, \( L \) the number of road links on the network, \( v_{ij} \) the number of vehicles in each vehicle category and link, \( l_j \) the lengths of links and \( RuC_v(v, w, r) \) the unit Road User Costs for each vehicle category as a function of vehicle characteristics (v), weather (w) as well as road characteristics and conditions (r).

#### 3.4.1 Traffic estimation

Due to high number of links on national road networks traffic counters are not installed on all the links. Therefore, traffic volumes should be estimated on the links missing traffic information. In a traditional method traffic on the missing links is modelled by the Four Step Model (FSM). The model consists of the following phases:

1. Trip generation
2. Trip distribution
3. Mode choice
4. Route choice

Spatial model area is divided into trip generation units that have travel demand functions. The generated trips have both spatial and temporal distributions. Selected transport mode depends on the spatial unit as well as on the trip distribution. Selected route is expected to be shortest route on the network (McNally, 2007).

Traffic volumes are assigned to a road link by summing the number of vehicles in each category between each origin and destination that traverse the link (Smith et al., 2014). An important aspect is to fit the origin-destination traffic volumes of the FSM in the actual counted traffic volumes on the road network (Chen et al., 2007).

Recent advances in mobile phone penetration rate and availability of integrated Global Positioning System (GPS) chips on the mobile phones have allowed traffic estimation using the GPS data (D’Andrea and Marcelloni, 2017).
Smartphone GPS data itself does not reveal vehicle classes, but an estimation of overall traffic. GPS data from known vehicles gives the vehicle class, but it can also be estimated from accelerations and decelerations as was done for trucks and passenger cars (Sun and Ban, 2013). Another potential future method for traffic data collection and vehicle classification from the whole network is based on Unmanned Aerial Aircraft systems (Barmpounakins et al., 2016).

3.4.2 Traffic forecasting

Traffic volumes can be forecasted with time-series models (Kyte, 1993). However, short-term traffic forecasting on a single road has shifted from statistical univariate Autoregressive Integrated Moving Average (ARIMA) models to multivariate ARIMA models (Pavlyuk, 2017). Neural Network methods have also been applied including Radial Basis Functions (Zhu et al., 2014). Another kind of ANN applied in short-term traffic forecasting is Multilayer Perceptron (MLP) ANN, which has been compared with methods based on ordinary linear regression (Ratrout and Gazder, 2014).

In maintenance planning, however, the main interest is in longer term traffic forecasting at a network level. Link-based traffic volume forecasting by linear or non-linear regression models i.e. trend-line analyses should take into consideration possible changes in land use as well as capacity and geometry changes (Smith et al., 2014). One bottom-up approach is to use a variation of the FSM and forecast the steps separately (Odeck, 2013). Annual Average Daily Traffic forecasts can also be forecasted using past AADT values and exogenous variables, which was done using MLP ANN (Ratrout et al., 2014).

3.4.3 Estimation of unit road user costs

Road User Costs (RUC) include all the monetary costs due to the road travel. They can be further divided into three main components that are Vehicle Operating Costs (VOC), value of travel time (VOT) and accident costs (AC) (Zhu and Ahmad, 2008). VOC include costs related to the vehicle i.e. fuel, tyres, maintenance, repairs and depreciation (Barnes and Langworthy, 2003). Time costs are estimates of time value for road users and cargo. Accident cost components include medical costs, production loss, human costs, property damage and administrative costs (Wijnen and Stipdonk, 2016). Figure 3.5 summarises the Road User Cost components.
Vehicle Operating Costs are reported to be the main determinant of RUC (Curtayne et al., 1987) and these are dominated by fuel costs. Fuel consumption can be explained by several factors and models. ARFCOM approach identifies tractive forces, accessories, internal engine friction affecting total power consumption and with engine fuel efficiency factor lead to estimated fuel consumption as shown in Figure 3.6 (Bennett and Greenwood, 2001). Fuel costs is reported to constitute 19% - 78% of the VOC depending on the model and vehicle type (Santos et al., 2011).

Road User Costs form the basis of positive impacts attained by proper road maintenance as they are dependent on the road condition. The better the road condition is the higher can be the vehicle speed reducing thus time costs. Reductions in tyre, vehicle depreciation and maintenance costs are also expected. Vehicle Operating Costs can constitute over 50% of the total RUC (Santos et al., 2010). There is a plethora of research results that consistently show an
increase in the RUC with the decrease of road condition (Robbins and Tran, 2015). The effect is more drastic when earthen and paved or gravel and paved roads are compared. An early research revealed 40% difference in VOC in the former and 20% difference in the latter case (de Weille, 1966). VOC approximations are often used for various IRI threshold values such as cost adjustment multiplier increase by 25% when IRI increases from 1.2 m/km to 27 m/km (Barnes and Langworthy, 2003). Research also shows an increase in number of accidents (Chan et al., 2008) or their severity index (Li et al., 2013) due to poor road condition.

It can be argued that road crashes cause long-term, negative, effects on the rest of the society that cannot be easily monetised. There are more direct effects on the rest of the society from the road use. From the negative perspective, environmental impacts include vehicle emissions, detrimental residue substances from the road maintenance and noise (van Essen et al., 2011). Road construction often causes major negative impacts on the environment and aesthetics. On the other hand, increased accessibility in developing countries is claimed to have positive effect on economic growth and poverty reduction. The effect is often indirect, where increased connectivity provides increased labour opportunities in and outside the agricultural sector (Gachassin et al., 2010).

Constituents of road user costs can be estimated either by mechanistic, empirical or hybrid models. Mechanistic models are better in the sense that developments in vehicle technology can be better taken into consideration (Bennett and Greenwood, 2001). On the other hand, it is argued against mechanistic and hybrid models that they don’t produce as accurate results (Chatti and Zaabar, 2012). HDM-4 hybrid model (Odoki and Kerai, 2000) is widely used in maintenance planning and it was also used in Publication 2.

Hybrid and mechanistic models are often used in practice as they have been integrated in Pavement Management Systems (PMS) (Qin and Cutler, 2013). Practical use of empirical models would require extensive data collection on the VOC and most important affecting factors and making the data available for maintenance planners.

### 3.4.4 Forecasting of unit road user costs

Road user costs are forecasted in maintenance planning, where future maintenance treatments are prioritised and selected under a constrained budget. The main factors affecting future unit road user costs are the unit cost components of Road User Costs affected by fuel price and road condition as well as technical performance of vehicles.

According to the current practice, the unit road costs are not usually forecasted in maintenance planning, but the current costs are used. Forecasting individual cost components is laboursome, error-prone and the gains are questionable. Isotemporal prioritisation of the projects would not change as the unit RUC remain constant on the whole network. However, impacts in aniso-temporal prioritisation and work scheduling would be expected in multi-year maintenance planning.
3.5 Estimation and forecasting of maintenance unit costs

Road Agency Costs (RAC) of road maintenance is often divided into recurrent and capital costs (Onyango et al., 2015). The costs can be further divided into direct and indirect costs. On the other hand, the costs are either variable, i.e., changing with the level of output, or fixed, i.e., independent of the maintenance quantity (Kockelman et al., 2013).

As maintenance costs depend on the characteristics of the maintenance project as well as on the price levels of cost factors a popular method has been identification and estimation of unit costs for maintenance works (Talvitie, 2000). Unit cost estimation has been usually based on historical cost accounting, where the future unit costs are derived from the historical unit costs corrected by estimated future cost indicators (Heike, 2006). Thus, the total maintenance costs of a maintenance project can be presented by Equation 3.2.

\[ C_M = C_F + C_V^i Q, \quad (3.2) \]

Where \( C_V^i \) represent the unit variable cost and \( Q \) the production quantity. Therefore, the total variable costs of a project are given by \( C_V^i Q \) and fixed costs by \( C_F \). Maintenance costs, \( C_M \) are a sum of fixed and variable costs. Cost estimation depends on the maintenance model. If maintenance is outsourced to the private sector the detailed cost information is usually not public (Heike, 2006), but the costs can be estimated by regression models, where historical projects are divided into homogeneous groups (by maintenance method and pavement type, for example) and the total costs of each group are explained by the number of units such as maintenance work area. The problem with the estimation is expected high variance in case the variance of number of units is high since the fixed costs are included in the total costs (Moen and Serpell, 2015). For German motorway renewals, it was noticed substantial economies of scale depending on the project size using an estimated translog production model (Heike, 2006).

In case the maintenance is done by the public road authority detailed cost information may be available. In this case, the cost factors are based on accounting figures, but the challenge is allocation of indirect costs to the particular maintenance works. Also, public sector has been accused of lower productivity and efficiency due to lack of competition, which may thus increase unit costs compared to private sector works as was proved in case of road construction (Talvitie and Sikow, 1992).

The main maintenance cost factors are labour, machine, material and capital costs (Talvitie and Sikow, 1992). There are both fixed and variable elements included in labour, machine and capital cost factors for each maintenance work independent of the length of the work. When a project starts, the machines need to be transported to the site, which takes time for both the machines and personnel. Also, there might be a minimum rental duration if they are not owned by the executor of the maintenance work. As capital is tied to the machines and labour costs fixed capital costs also exist. Usually the main costs are variable by nature if project lengths are optimised. For increased
planning accuracy, fixed costs should be separated from the variable costs. The longer the road project the lower are fixed unit costs. Suggested overall cost function in analytical, but simplified form for estimation is presented in Equation 3.3.

\[ C_M = C_F^L + C_F^M + C_F^C + C_V^L \times Q^L + C_V^M Q^MC + C_V^M Q^MT + C_V^C Q^C, \]  

(3.3)  

Where subscript \( F \) stands for fixed costs and \( V \) for variable costs. Variable \( C \) represents total costs for fixed costs and unit costs for variable costs. Superscript \( L \) stands for labour, \( MT \) for material, \( MC \) for machines and \( C \) for capital. The variable \( Q \) represents quantities depending on the project size. The fixed costs are expected to remain fixed irrespective of project size, but not necessarily with respect to the project distance from the base (or previous project). Materials, machines and people need to be transported to the project site, which can be far away and therefore the fixed costs include those setup costs. Unavailability costs for road users during the maintenance depend on the traffic volumes, but they are assumed to be negligible between two consecutive years.

The main input factors affecting costs of a single maintenance work include work method that affect the number of employees and equipment and thus the required skills, labour hours, equipment types and utilisation time. Maintenance work and work method types also define the required material. Material quantities and work time are mainly affected by the maintenance length, road width and layer thicknesses. Capital costs depend on not only project size and interest rate for the organisation and for the project, but also on the contract terms and management as how the cash flow is affected depending on the contractual matters and scheduling project phases. Economies of scale exist in road projects i.e. marginal costs are lower than average variable costs (Talvitie and Sikh, 1992). The organisation actually executing the maintenance should utilise the cost models in road maintenance optimisation.

As maintenance planning can cover several years, future maintenance costs should be estimated instead of using present costs. Each cost factor depends on other aspects. A general method is to use cost indexes or inflation rate that are approximations of cost level change (Moretti et al., 2017). In terms of material costs, the driving factor is oil price since most of the roads are based on asphalt that is extracted from petroleum. For example, in Poland, bitumen price increased approximately 50% in 5-6 years (Senderski, 2014). Labour and machine costs have closely followed Consumer Price Index (CPI) in Sweden (Mirzadeh et al., 2014). Capital costs depend on the overall economic and political situation and they vary not only between countries, but also between companies. The fundamental and difficult problem of forecasting the future was raised as a key problem for low usage of life cycle costing for the building and construction industry (Wennström, 2014 FROM 1991).

In practice, transport planners often fall into planning fallacy, where stakeholders tend to focus on specific components of the project instead of comparing to similar projects in the past (Salling and Leleur, 2015). When past cost
information is examined the variability in the maintenance unit costs can be taken into consideration by a probability distribution (Adams, 2011). The stochastic nature of the costs can then be taken into consideration in maintenance planning by selection of probability that the budget remains under the budget constraints (Piyatrapoomi and Kumar, 2004).

Technological development can reduce the costs and change maintenance methods. The development can be fast in developing countries, but it is difficult to incorporate it in long-term maintenance planning. Figure 3.7 gives an example of mean unit costs per kilometre of road maintenance in low and middle income countries (Collier et al., 2016).

![Maintenance Costs (US$ / km)](image)

**Figure 3.7.** Mean maintenance unit costs in US dollars per kilometre.

### 3.6 Road maintenance optimisation

#### 3.6.1 Objectives and constraints

Ideally, the aim is to achieve maximum output in terms of quantity and quality with minimum input. The output can be measured by the quantity of maintenance units (such as maintained road length) according to accepted quality level. The input, on the other hand, can be measured by each factor such as labour, material, capital and machines. In practice, the input factors can be converted to financial terms i.e. costs.

Since maintenance planning covers several years of future operations maintenance plans need to take temporal aspect into consideration besides spatial element. An important aspect is to combine road segments together for a maintenance work of same type for the same time to minimise fixed maintenance unit costs.
In case the public sector is responsible for performing road network maintenance, the incentive is often not just to minimise life cycle costs of the network maintenance, but to minimise the overall costs to the society. In such a case road user costs play a significant role. They can constitute 96% of the total costs (Meneses and Ferreira, 2013). Better road condition lowers road user costs since Vehicle Operating Costs (VOC) and time costs are lower (Tarefder, 2015). If the private sector maintains the roads, the incentive is to maximise the profits, which means to minimise the costs, while still fulfilling the requirements set by the public sector.

In case of the society the cost-based target function to be optimised can be combined from the agency costs and road user costs. On the other hand, the target function can be made multi-objective. This makes sense especially if the objectives cannot easily be commensurated. This is the case for example with costs, performance and environmental factors (Yu et al., 2015).

Long-term performance-based maintenance contracts include condition criteria that the contractor should meet. In such a case, a logical target function is overall maintenance costs during the contract period with the condition criteria as constraints (Tamin et al., 2011).

Mathematical problem formulation depends on the objectives and constraints. A theoretical efficiency-based objective function for optimised predictive maintenance is presented in Publication 5. A viable option is to maximise Net Present Value (NPV) of the maintenance projects to the society for the whole period under examination, which was presented in Publication 2. Other economic indices have also been optimised including the internal rate of return (IRR), equivalent uniform annual cost (EUAC) and benefit-cost ratio (B/C) (Wennström, 2014).

### 3.6.2 Maintenance triggering

Poor road condition not only increases the Road User Costs, but is expected to increase the deterioration speed and therefore increases the future maintenance costs as more expensive maintenance treatment would be needed. However, quantitative studies on reduction in the future deterioration rates due to road maintenance are scarce (Qiao et al., 2015).

In a corrective maintenance strategy, a failure or malfunctioning of the system gives rise to the initiation of maintenance. In the case of structural road surface deterioration, any violation of a quality norm can be considered as a failure and an initiating event for maintenance can be the end of technical lifetime of the asphalt (Worm and van Harten, 1996).

In condition-based preventative maintenance strategy a maintenance work can be triggered when a pavement condition index or combination of indices reach or are forecasted to reach threshold values depending whether corrective or preventive maintenance philosophy is applied (Qiao et al., 2015). IRI, cracking area and total damaged area have been used as intervention criteria without optimisation of the threshold values (Shah et al., 2016).

Optimisation of threshold values was conducted in a study that had fog sealing and milling+overlay maintenance treatments using IRI as a criterion and
reconstruction dependent on pavement age. The difference for IRI threshold values was surprisingly low being at maximum 1.07 m/km (Chu and Chen, 2012). In another study, it was proved that threshold-based maintenance is more beneficial to the society compared to maintenance planning strategy without thresholds and variable threshold values between planning years give better results (Chu and Li, 2013). In one of the few studies the increased maintenance needs with deferred maintenance were taken into consideration when thresholds were optimised. Using mainly analytical methods, hastened and deferred maintenance was showed to lead to higher maintenance expenses (Khurshid, 2010). It has been estimated that one year change in resurfacing can make a difference of 14%-20% in chip seal and 4%-8% for asphalt pavements in project costs (Luhr et al., 2015).

3.6.3 Homogenisation

Even a single road does not deteriorate homogeneously or share the same characteristics or traffic. Therefore, same periodic maintenance work is not applied to the entire road. Roads should be divided into homogeneous enough segments, where the same maintenance work is executed. Economies of scale exist in road projects and cost models determine the overall maintenance costs as demonstrated in Section 3.5. Thus, the optimisation problem would need to take the production cost model into consideration as the fixed costs can be too high for short projects, but not necessarily so if short projects are close to each other i.e. on the same road.

It was proved that under certain circumstances depending on the traffic volume, for example, it is justified to apply junction-to-junction maintenance strategy (Dekker et al., 1998). However, in a typical approach the homogeneous sections are selected without optimisation, but using expert opinions (Lee and Yoo, 2008). The expert opinion can be set as numerical variation in the target variables causing a new homogeneous section (Hiep, 2009). Also, statistical methods have been used and certain percentiles selected (Oliveira et al., 2007). Several possible variables can be used for section homogenisation such as road name, road class, climate zone, speed-flow type, traffic flow pattern, surface class, surface materials, traffic volume and roughness (Hiep, 2009).

With the presented empirical models applied for each 100-metre long road segment each segment has individual deterioration model and therefore section homogenisation done today may not apply in the future. Therefore, there should be several section homogenisations for each year for the duration of the entire planning horizon. In case maintenance decisions are based on condition threshold values a homogeneous section at a given year should include the segments that have reached the threshold values as well as those segments that would reach the threshold values soon only if the production cost model indicates that the project size for the year after would remain too short resulting at discounted cash flows of road user costs deducted by maintenance costs to be lower, which is still unresearched area.
3.6.4 Solution methods

Even if the road maintenance optimisation problem can be formulated analytically, it needs to be solved by empirical meta-heuristic methods that make few assumptions about the problem to be solved. The two main strategies are application of global (population) and local search algorithms as explained in Publication 5. An important differentiating factor between different solution strategies as well as with problem formulation is the level of uncertainty. In deterministic case the solution remains always the same with the same parameters and input values while in stochastic case the solution is every time different leading to probabilistic distribution.

Both analytical and empirical methods have been applied in road maintenance optimisation both to single roads and larger network. A hybrid Greedy Randomized Adaptive Search Procedure (GRASP) that first constructs initial feasible solutions followed by an iterative process in which all the possible alternatives are analysed and ranked based on a greedy function. The algorithm was applied to an 810-km long road network (Torres-Machi et al., 2017). A Genetic Algorithm (GA) –based solution was applied to a single road maintenance multi-objective optimisation (Yu et al., 2015). A Tabu Search algorithm for the network level maintenance optimisation has been applied (Chu and Chen, 2012). A Linear Programming (LP) optimisation method was applied to 500 lane-miles (de la Garza et al., 2011). Another analytical method, Dynamic Programming (DP) was applied to a fictional case study and single road (Yu et al., 2013). Analytical Hierarchy Process (AHP) combined with fuzzy logic is one of the methods applied to 131 road sections (Moazami et al., 2011). Local and population optimisation methods can also be combined as was done using parallel Genetic Algorithms and Variable Neighbourhood Search in Publication 2.

The past researched has focused on relatively simple cases and it is yet to be researched how multi-year network level maintenance optimisation can be best solved using empirical models and multiple years of survey data having road deterioration, threshold optimisation, section homogenisation, cost function estimation and cost forecasting integrated.

3.7 Summary of modelling status

Overall, road maintenance planning resorts mainly on expert knowledge and mechanistic or hybrid models as summarised in Table 3.1. The main restriction using empirical models is a need of collected data on the circumstances similar to the application area. Therefore, pure empirical models are not applicable in case of new pavement material or maintenance method unless data from existing material and method is used, which may produce lower accuracy. However, the same problem applies to mechanistic models since the material or method may not give accurate results with the models created for the existing materials and methods.
Table 3.1. Summary of modelling areas in road maintenance planning.

<table>
<thead>
<tr>
<th>Problem area</th>
<th>Current status</th>
<th>Contributions</th>
<th>Restrictions for empirical modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition forecasting between maintenance works</td>
<td>Mechanistic or hybrid models are mostly utilised, but many empirical models have been applied</td>
<td>Publication 1: Data fusion with non-linear methods were applied&lt;br&gt;Publication 4: Multiple time-steps ahead forecasting at the network level with non-linear methods were applied</td>
<td>• Pavement material and maintenance method status quo assumed&lt;br&gt;• Historical data of the whole condition and pavement material range preferred</td>
</tr>
<tr>
<td>Condition forecasting after maintenance works</td>
<td>Very few applications of empirical models</td>
<td>Publication 3: Network level non-linear methods with variable selection was applied</td>
<td>• Maintenance method status quo assumed&lt;br&gt;• Results may vary by maintenance teams</td>
</tr>
<tr>
<td>Estimation of Vehicle Operating Costs</td>
<td>Mechanistic or hybrid models are mostly utilised</td>
<td>Publication 2: Standard HDM-4 approximation was used</td>
<td>• Results depend on multiple factors such as car make, model, weight, weather, road geometry and condition&lt;br&gt;• Extensive data collection should take place for reliable mapping of the dependency of VOC on road condition</td>
</tr>
<tr>
<td>Estimation of Maintenance Costs</td>
<td>Based mainly on empirical knowledge or very simple models</td>
<td>Publication 2: Expert opinions were used</td>
<td>• Maintenance cost models should be created</td>
</tr>
<tr>
<td>Estimation of traffic volumes</td>
<td>Analytical models</td>
<td>Publications 1-5: Road Agency data and estimations were used</td>
<td>• Reliability of empirical models has not been tested</td>
</tr>
<tr>
<td>Traffic volume forecasting</td>
<td>Mostly general growth factor used, but also analytical and empirical models</td>
<td>Publication 2: A growth rate by an expert opinion was used</td>
<td>• Sectionwise long-term forecasting with empirical models not tested for accuracy</td>
</tr>
<tr>
<td>Optimisation of maintenance planning</td>
<td>Empirical models are widely used</td>
<td>Publication 2: Local and global search algorithms were combined&lt;br&gt;Publication 5: Genetic Algorithms were applied</td>
<td>• Network level, long-term optimisation is computationally intensive and mostly local optima can be reached</td>
</tr>
</tbody>
</table>
4. Case Studies

4.1 Motivation

A large cost saving potential exists in road maintenance by using more accurate planning methods. The topic has been widely researched, but the viewpoint has often been a concise sub-problem or application of existing models. The presented case studies, however, aim to provide knowledge on how empirical models can be applied in predictive road maintenance planning. The case studies have a limitation of not providing advances in all the modelling aspects regarded as relevant in Section 3. Some aspects such as estimation of Vehicle Operation Costs by empirical models has a large scope by itself. However, the presented cases with predictive and prescriptive models are believed to form the core of predictive maintenance planning procedure.

The predictive part of the procedure is mainly covered in Publications 1, 3 and 4. The first problem of predicting road condition for one time-step ahead is presented in Publication 1. The case study concerns roads that have not been assigned any maintenance treatment (besides possible routine maintenance) during the period under examination.

Publication 3 shows a similar case by forecasting of one time-step ahead, but after a maintenance treatment. The publication also introduces a relatively new variable selection method to select the most relevant variables of the case data set. Publication 4, on the other hand, addresses a similar problem as in Publication 1, but in case of one, multiple time-steps were involved in forecasting and road condition forecasting was applied on the entire road network of which data was available. The forecasting ideas are illustrated in Figure 4.1. The x-axis represents the time dimension. Information from the past divided into different categories is used for the forecasting. More accurate description of the data used in each article is presented in the next section.
Optimisation of the road maintenance problem was addressed in Publication 2 with real data collected in Southern Pakistan. Publication 5 synthesises road maintenance planning and optimisation problematics. Overall, the publications present a framework that can be applied to predictive maintenance planning. If the application area is rich with data in terms of several variables that potentially have a relationship with road deterioration, variable selection and dimensionality reduction techniques can be applied as shown in Publications 1, 3 and 4. In case of previous mechanistic or mechanistic-empirical models, only a small part of the measured data has been taken into the modelling process. When a time-series with several measurements exists, it is possible to forecast further in the future with higher accuracy using empirical methods. This allows more accurate maintenance planning and budgeting. This saves total costs to the society.

### 4.2 Data

Table 4.1 summarises the utilised data in each publication. Besides the listed variables, various method-dependent parameters (Genetic Algorithm mutation rate, Genetic Algorithm population size) and general factors (traffic growth, discount rate) were used. Variables are here categorised as characteristics, condition, ambient and maintenance. Ambient variables include road use.
Data from different sources was combined before the analysis so that variable values from different 1-dimensional data sets match each other concerning road number, carriageway number, section number, lane number and
chainage from the section start. 0-dimensional weather data in Publication 1 is taken to cover each road segment from the closest weather station. In Publication 1, input variables for forecasting also covered a spatial element as not only the historical values of the forecasted segment, but ten neighbouring segments (five from each side) were taken into consideration. In the multi-step ahead forecasting case of Publication 4, road segments without reported maintenance treatments during the period were taken into consideration. Separate data sets were created depending on the number of condition surveys i.e. time steps in question.

4.3 Methods

The methods can be categorised in various ways. In this thesis the methods are divided into descriptive, predictive and prescriptive methods. Further, the methods can be divided into deterministic and stochastic ones. A summary of the methods used in each publication categorised by the mentioned two dimensions is presented in Table 4.2.

<table>
<thead>
<tr>
<th>Method category (Stochastic or Deterministic)</th>
<th>Descriptive</th>
<th>Predictive</th>
<th>Prescriptive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Publication 1</strong></td>
<td>PCA</td>
<td>FTA92</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>k-means++</td>
<td>FTA05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Markov Chains</td>
<td>MLP ANN</td>
<td></td>
</tr>
<tr>
<td><strong>Publication 2</strong></td>
<td>-</td>
<td>Linear estimates</td>
<td>VNS GA PGA</td>
</tr>
<tr>
<td><strong>Publication 3</strong></td>
<td>SISAL</td>
<td>FTA05</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OLS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RBF ANN</td>
<td></td>
</tr>
<tr>
<td><strong>Publication 4</strong></td>
<td>k-means++</td>
<td>FTA05</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OLS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RBF ANN</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LS-SVR</td>
<td></td>
</tr>
<tr>
<td><strong>Publication 5</strong></td>
<td>-</td>
<td>Linear estimates</td>
<td>GA</td>
</tr>
</tbody>
</table>

The descriptive methods of the thesis are used for three purposes: reduction of dimensionality, determination of the model parameters and variable selection. Principal Component Analysis is used in dimensionality reduction by selecting the first 32 principal components instead of 404 original variables. In case of k-means++, clustering the data serves the purpose of determining the model parameters as 10-fold cross-validation with training and validation was applied for each cluster separately for predictive modelling. Sequential Input
Selection Algorithm (Tikka and Hollmén, 2008) was applied to identification of the most significant variables for road condition prediction after road maintenance.

The simplest predictive methods are linear estimates derived from expert opinions and Pavement Management System HDM-4. Other simple and deterministic methods FTA92 and FTA05 refer to the methods Finnish Transport Agency in 1992 and 2005. The former methods were linear and the latter have non-linear components. Markov Chains are stochastic processes, but applied to prediction in this thesis. Another category of methods belong to artificial neural networks of which Radial Basis Functions are the simplest and Multi-Layer Perceptron neural networks more complicated ones. Regression models was another class of methods, where Ordinary Least Squares regression method is the simplest and Least Squares Support Vector Regression the most complex originating from the classification family of Support Vector Machines. Even if the predictive model is deterministic, 10-fold cross-validation introduces stochastic element in the process.

Variable Neighbourhood Search can be implemented in stochastic, deterministic or mixed form. In this thesis a stochastic implementation was made with three neighbourhood variations, which was combined with other stochastic prescriptive methods, genetic algorithms and parallel genetic algorithms. These are global search methods unlike Variable Neighbourhood Search.

The main focus of the thesis has been on hybrid methods, i.e. combining several methods to improve the results. Prescriptive methods have been combined within the same category while different types of predictive methods have been combined together, but also with descriptive methods. A short technical introduction to the methods are given in the subsequent sections.

4.3.1 Descriptive methods

The main idea of clustering is to group the observations similar to each other in the same cluster while having longer distance between separate clusters. In case of k-means, the number of clusters is selected beforehand and the algorithm is initialised by selecting the cluster centre points by random selection of k observations from the data set or assigning the cluster number randomly to each observation. Each data point is assigned to one of the clusters so that the within-cluster sum of squares is minimised (Hartigan and Wong, 1979). The initialisation procedure is improved in k-means++ by selecting only the first cluster centre randomly while the remaining ones are selected with probability proportional to the squared distance to the closest cluster centre (Arthur and Vassilvitskii, 2007).

Principal Component Analysis (PCA) transforms linearly the existing observations to new variables called Principal Components. The original observations are usually linearly correlated, while the Principal Components are linearly uncorrelated. The Principal Components are ordered by a decreasing amount of variance and the dimensionality reduction is based on selection of k Principal Components carrying n % of the information of the observations (Haykin, 1999).
The last descriptive method concerns variable selection. In Sequential Input Selection Algorithm (SISAL), the least significant variables are consecutively deleted from the list of input variables by using the ratio of the estimate for the parameter mean \((m_i)\) divided by the estimate for the standard deviation \((\sigma_i)\) being an approximation of signal-to-noise ratio. The lower the value the less significant the variable is considered. The list of all input variables is gone through excluding input variables one by one and the final model is selected according to two criteria: the sparsity and prediction accuracy. An ideal model includes only part of the input variables without compromising the prediction accuracy (Tikka and Hollmén, 2008).

Figure 4.2 illustrates the utilised descriptive methods in a simplified two-dimensional form.

![Figure 4.2](image)

Figure 4.2. Summary of descriptive methods in two-dimensional simplification. In the leftmost picture three cluster centre points and observations are illustrated, where k-means++ attempts to minimise within-cluster sum of squares be correct cluster assignment for each observation. In the middle picture, observations by two dimensions X and Y are transformed to Principal Components PC1 and PC2. In the rightmost picture, variable significance is estimated by a ratio of absolute value of mean and standard deviation.

### 4.3.2 Predictive methods

The predictive methods included Markov Chains, Multilayer Perceptron (MLP) artificial neural network, Ordinary Least Squares (OLS), Radial Basis Functions (RBF) and Least Squares Support Vector Regression (LS-SVR).

Markov chains can be used to depict a dynamic system where the state of the system changes dynamically in time and thus the system becomes a chain of stochastic variables in time. To be called Markov Chains the random variables must satisfy the Markov property that the current state depends only on the previous state of the system. Both the state space and time parameter can be either discrete or continuous (Norris, 1997).

Multilayer Perceptron (MLP) artificial neural networks are computational methods to model complex relationships between inputs and outputs of a system. The network consists of \(k\) layers of neurons that are the basic computational units. Neurons of the first hidden layer gets inputs \(x\) weighted by \(w\) as their inputs. Each neuron in a layer is associated with a function \(f\) that is used
in calculating the output of the neuron. Typically, the non-linear functions are hyperbolic tangent or logistic. MLP neural networks require supervised training so that the weight vectors are calculated by minimising the error term between the given output and network generated output with given inputs and calculated weights (Haykin, 1999).

RBF network is an artificial neural network using radial basis functions as activation functions. The output of a RBF network is a linear combination of radial basis functions of the inputs and parameters. Values of radial basis functions depend on the distance from the centre point (Broomhead and Lowe, 1988).

In SVR, the input is mapped onto \( m \)-dimensional feature space using a non-linear mapping and then a linear model is constructed in the feature space. In the Least Squares version of SVR, the model is optimized by solving a linear system of equations instead of a quadratic problem (Rubio et al., 2011).

Figure 4.3 illustrates Markov Chains, Artificial Neural Networks (both MLP and RBF) as well as Support Vector Regression.

```
Figure 4.3. Summary of predictive methods in two-dimensional simplification. The picture on the left shows states S1, S2, S3 and Sn of a system, which can change to another state with a probability \( p_{ij} \). The middle picture shows an example of an artificial neural network comprising of input data \( x_i \), input layer, hidden layer, output layer, output \( y_i \) and weights \( w_i \) and \( w_{jk} \) between the layers. The picture on the right shows observations as dots, regression line in the middle and epsilon boundaries in both sides.
```

4.3.3 Prescriptive methods

The prescriptive (optimisation) methods included Genetic Algorithms (GA), Parallel Genetic Algorithms (PGA) and Variable Neighbourhood Search (VNS).

In Genetic Algorithms, the initial population is first selected out of which the fittest genomes are chosen for recombination. The resulted offspring is susceptible to mutation. The possibly mutated offspring is placed back in the population and the whole process is iterated until the stopping criterion is met (Holland, 1975).

In the parallel version of the genetic algorithm several populations co-exist without extensive reciprocal interference. However, to enhance the genetic source, genomes are transferred (migrated) between populations and it can happen to all existing populations or just one (Muhlenbein et al., 1991).

Variable Neighbourhood Search (VNS) is a local search method, where several different neighbourhoods are defined in the algorithm. In the search pro-
cess, neighbouring instances are changed systematically according to the various neighbourhoods (Mladenovic and Hansen, 1997).

Figure 4.4 gives an illustration of the Genetic Algorithms and Variable Neighbourhood Search.

![Figure 4.4](image)

**Figure 4.4.** Summary of prescriptive methods in two-dimensional simplification. On the left, the initial population is selected for Genetic Algorithm (1) out of which the fittest genomes (2) are chosen for recombination (3). The resulted offspring is susceptible to mutation (4). The possibly mutated offspring is placed back in the population and the whole process is iterated until the stopping criterion is met. On the right, the solution is improved by altering the solution space with the neighbourhood space.

### 4.4 Results

Figure 4.5 gives a summary of the one timestep ahead forecasting accuracy in Publications 1, 3 and 4. The methods are given on the horizontal axis, IRI Mean Square Error on the primary vertical axis and Rutting Mean Square Error on the secondary vertical axis. The chart combines road condition forecasting without maintenance treatment (18 first) and road condition forecasting after maintenance treatment (3 last). The average was calculated of the case roads of Publication 1.

The results show the best performance of Least Squares Support Vector Regression for both IRI and rutting forecasting with a comparable error at the training phase of Multilayer Perceptron Artificial Neural Networks. Validation error of MLP remains relatively low, but when a new timestep is introduced for testing phase, the accuracy worsens especially for rutting indicating overfitting. Non-linear methods outperform the linear ones except for the problematic parts of the MLP. Optimisation of the ANN structure could improve the results. However, LS-SVR is more straightforward with fewer parameter choices. Clustering of the data before application of Markov Chains (MC) does not seem to affect the results much in case of IRI prediction. The error seems to be larger for the road condition prediction after maintenance that is interesting as traditionally road condition is regarded to be more or less constant after a maintenance treatment. Certainly some variation in the condition measure is introduced by the time lag between the maintenance and the first condition survey after the maintenance treatment.
In case of multiple time steps, forecasting error increases with the number of forecasted time steps for the methods introduced in Publication 4 shown in Figure 4.6, where the horizontal axis represents the time-steps. One of the reasons for the error increase can be a decrease in the sample size for training the models. In multi-step ahead recurrent prediction, the previous predictions are used as inputs possibly accumulating errors.

![Figure 4.5](image1.png)

**Figure 4.5.** Forecasting errors of International Roughness Index on the primary vertical axis and Rutting on the secondary vertical axis for one timestep ahead. The last three represent forecasting after maintenance and others forecasting without maintenance treatment.

![Figure 4.6](image2.png)

**Figure 4.6.** Forecasting errors of International Roughness Index and Rutting in a network-level multi-step ahead case, where the horizontal axis represents the time step. Support
The findings of Publications 1, 2 and 4 suggest a combination of various methods in network-level road condition forecasting should be used depending on the data availability. These are summarised in Table 4.3. If historical data is available only for a single or a few roads there may not be enough training data and therefore hybrid methods may be most usable. If there is no historical data available for a single road, the network it belongs to or from similar conditions, mechanistic methods should be applied. When historical data exist for the forecasted road and its network, direct Support Vector Regression approach would be suitable to as many time-steps ahead as there is historical data available. Recurrent empirical methods should be used for longer forecasts. When datasets from other networks are used, the conditions should be similar and the same input variables ensured.

**Table 4.3. Applicability of empirical methods for road forecasting.**

<table>
<thead>
<tr>
<th>Road data history</th>
<th>Road network data history</th>
<th>History data from similar conditions</th>
<th>Method up to history length</th>
<th>Method beyond history length</th>
</tr>
</thead>
<tbody>
<tr>
<td>X time steps</td>
<td>None</td>
<td>None</td>
<td>Direct Support Vector Regression or Hybrid methods</td>
<td>Recurrent empirical methods or Hybrid methods</td>
</tr>
<tr>
<td>X time steps</td>
<td>X time steps</td>
<td>Any</td>
<td>Direct Support Vector Regression</td>
<td>Recurrent empirical methods</td>
</tr>
<tr>
<td>None</td>
<td>X time steps</td>
<td>Any</td>
<td>Direct Support Vector Regression</td>
<td>Recurrent empirical methods</td>
</tr>
<tr>
<td>None</td>
<td>None</td>
<td>X time steps</td>
<td>Direct Support Vector Regression</td>
<td>Recurrent empirical methods</td>
</tr>
<tr>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Mechanistic methods</td>
<td></td>
</tr>
</tbody>
</table>

### 4.5 Significance of the research

Publication 1 presents the first reported research known to the author that forecasts road condition for each 10-metre long segment taking into consideration not only the data from the given segment, but also from the neighbouring ones and combines various existing data sets including road characteristics, condition, road use and road weather. It is also the first known article, where Principal Component Analysis is combined with Multi-Layer Perceptron artificial neural networks as well as k-means++ clustering with Markov Chains applied to road condition forecasting.

Publication 2 is the first known article, where road maintenance planning is applied to provincial road network of Sindh province of Pakistan using real data collected from the road network. It is the first article that combines global and local search optimisation methods, Variable Neighbourhood Search, Genetic Algorithms and Parallel Genetic Algorithms.

Publication 3 is the first known article forecasting road condition after maintenance treatment for the public road network of Finland. The article is
also the first one applying Sequential Input Selection Algorithm and Radial Basis Functions to road condition forecasting after maintenance.

Publication 4 is the first article using empirical models for multi-step ahead road condition forecasting problem at the network level. It is also the first known article, where Least Squares Support Vector Regression is applied to road condition forecasting.

Publication 5 is the first known article that introduces the main road maintenance philosophies in analytical form.

The research shows that empirical methods allow increased accuracy in road maintenance planning. The real value of the increased accuracy is not materialised unless the methods are put into practice. If so done, there is potential for direct cost savings. In case the cost models reflect the reality, the quantity of accuracy increase in prescriptive models give directly the cost savings if the created maintenance plan is followed. Accuracy increase in predictive models does not map directly to the same cost savings as the phenomena are highly non-linear.

The research shows part of the methodology that should be applied in the coming years and decades for road maintenance planning as data collection, quantity of available data and computing power capacity increase.

4.6 Discussion

4.6.1 Empirical versus Mechanistic models

Theories in science try to explain the phenomena with causes and consequences. A natural and comprehensible method is to search for natural laws that can be described by mathematical formula, which has also been done in road deterioration modelling. The formula attempt to encompass all the relevant variables. Validation of the formula can be done when the effect of all the other variables is minimised. When complexity between the output and several possible input variables is increased, the formula may not apply anymore inducing error between the reality and output of a model. This is very much the case in social sciences, but also in engineering sciences, where all the affecting factors cannot be controlled and therefore an interplay between the environment and construction material cause variations from the idealised models. Mechanistic parametrised hybrid models can try to explain this interplay and road deterioration, for example, but more accurate results can be achieved with empirical models.

The ideal of absolute truth driven by mathematical and physical sciences has probably influenced engineering science with road maintenance planning and given the past status of information collection, storage and computation, it has been practical to use mechanistic models. Data driven computational models have entered in many fields of science and gradually civil engineering, physical asset maintenance including roads benefit the advanced in information technology. However, there are some potential conflicts of interest. First, a strong
tradition of mechanistic and hybrid modelling exists with established software tools. Secondly, due to political motivations, scientific approach for optimisation of public investments is not fully applied and results are not fully respected. Private asset owners, however, should have more motivation to preserve the asset value and optimise the costs.

The focus in the past research has been mainly on using mechanistic models in road condition forecasting and empirical models have not been compared at the network level. The study reveals a clear indication that empirical, non-linear methods give more accurate results.

There are further challenges in applying empirical models in the road sector. There is not research attention driving the change and focusing at finding and combining the best models. There should be focus not only on finding the models, but also the circumstances when the models can be applied taken into consideration possible medium- and long-term changes in road construction and maintenance technology, possible changes in materials, vehicles and data collection methodology. Important, concrete development steps can be taken by Road Agencies, where one crucial action is to follow open data movement and to provide all the collected survey data openly available to the public. Openly available road sector data from several countries and years would facilitate training the models based on supervised learning.

4.6.2 Most important modelling aspects

In case of the total road sector costs (including social and environmental externalities) to the society the whole lifecycle should be taken into consideration including land planning. From the road user perspective, an important question is not only the variable costs of motorised transport, but also the capital costs incurring from vehicle ownership.

Location of activities along the road network and requirements for travel can be changed partly by land planning. Also, concepts of Mobility as a Service (MaaS) can change the travel behaviour and costs to the road users that reflect in road maintenance optimisation first in the capital costs and later in time costs if congestion is relieved. Current models do not distinguish between individual road users and possible mobility operators. It can be argued that the effect is negligible to the road maintenance since MaaS concept is mostly applied first in urban context on the street network.

Savings in Vehicle Operating Costs and possible accelerated deterioration of roads are the clearest benefits to the society in the road maintenance optimisation model. There is no argument against savings in VOC with better roads. There is also wide acceptance that preventive maintenance saves costs. There are neither strong efforts, nor applied empirical models nor publicly available data for VOC modelling especially when the past research has shown wide variation between road condition and VOC relation.

With the current technology, it is relatively cheap and straightforward to install a vehicle tracking system that transmits the GPS-based location. It is slightly more complicated to have accurate fuel consumption sensor in the same device. Although this is not in a mass market and not something yet for
private vehicle owners, it is still feasible for private companies interested in optimising the logistic costs. The collected time-stamped and spatially identified fuel consumption data should be fused with weather, road geometry, weight, vehicle, tyre pressure, traffic conditions and use of auxiliary systems as well as motor type, condition as well as driving behaviour data to cover the main constituents in vehicle fuel efficiency (Zacharos and Fontaras, 2016).

Fuel consumption of a medium car is reported to increase by 4% when IRI increases from 1 m/km to 5 m/km (Greene et al., 2013). It is estimated that 37 430 million vehicle-kilometres were travelled in Finnish roads in 2015 (FTA, 2016). With average fuel consumption of 10 litres per 100 kilometres and with average fuel price of 1.5 euros per litre the annual VOC increase would be around 225 million euros if the hypothetical good network condition dropped to fair condition. A rough estimate for other constituents of RUC apart from the VOC is 58% (FTA b, 2013). A rough estimate for annual RUC increase due to deterioration is 50 million euros if average IRI deterioration is 10%. At the Agency Cost side, periodic maintenance of roads is estimated to be around 200 million euros in Finland in 2017 (FTA a, 2013). Thus, the effect of preventive maintenance on saving the costs of not needing heavier maintenance treatments should be annually at least 150 million euros.

As Finnish Transport Agency is applying region-wise performance-based maintenance contracts, the agency cannot optimise the benefit-cost ratio, but it can be done by private contractors on the networks under their responsibility. An important question is the optimisation of the target condition values for the performance-based contracts by road agencies. The private companies should also be interested in the maintenance production cost model for more improved optimisation and cost savings. Since major road maintenance is nowadays mainly contracted out in most countries, scientific literature on empirical road maintenance cost models are mainly lacking.

Two road networks (Finland and Pakistan) were selected in the research as spatio-temporal extent were different. It was shown that empirical models could be used for forecasting when historical data is available. In case of lack of history, empirical optimisation models can be combined with mechanistic forecasting models.

4.6.3 Limitations

The research introduces an overall strategy for road maintenance planning with advances in empirical modelling. The general framework can be applied not only for roads, but other infrastructures requiring maintenance. The specific methods and models, however, need to be created for each area of application. The main limitation of the research is that it does not give accurate enough maintenance and Road User Cost models although they are required in the overall framework. On the other hand, estimations can be used, which is an everyday practice in road asset management.

Another major limitation is that the whole maintenance planning cycle was not tested with the developed models within a limited region. The main missing part is actual validation of the strategy. This, however, is difficult to
achieve since it would have required a road authority to follow new methods under research instead of their operational systems and current practices.

The research data was mainly from Finland and limited to two condition variables. This poses some problems. First, condition variables are developed over time and it is not known whether the same deterioration models would be as applicable. Secondly, empirical deterioration models developed in the research require historical, quantitative survey data. This limits currently the applicability on many developing countries as road data collection is either obsolete or limited. However, it is expected that the derived empirical methods can be well applied to other conditions since training of the methods is based on the actual data from the location of interest.

The research is concentrated on periodic maintenance activities on sealed roads concerning only the surface course and condition of flexible pavements. In terms of gravel roads there are not yet reliable automatic data collection for gravel road specific condition variables and therefore the deterioration models are not applicable. In terms of rigid (concrete) pavements there are also other condition variables and different maintenance treatments. Therefore, the general strategy is applicable, deterioration models and methods partly applicable and maintenance optimisation methods partly applicable for other pavement types. In case, other pavement types, other pavement courses or other condition variables are used and research put into practice, reliable data, cost models and intervention criteria would be required.
5. Summary and Conclusions

5.1 Summary and Conclusions

The thesis described the overall framework of predictive road maintenance planning of roads with empirical models and described the future paradigm for road maintenance optimisation. The work showed the difference between a simple preventive maintenance planning and predictive maintenance planning, where the future conditions are predicted before the actual optimisation. There were also several advances in application of non-linear methods in large-scale road maintenance planning.

Computational data-driven empirical methods were applied to both types of road condition forecasting as well as to road maintenance optimisation. Most of the data was collected in Finland and concerned the Finnish public road network. The study included a case without history data and thus mechanistic models and expert opinions were combined with heuristic optimisation. It was discussed that in such situations empirical models could also be applied if collected data was available from other countries.

The research revealed that the existing methods for road condition forecasting works between maintenance works are mainly mechanistic or hybrid models that lack prediction accuracy. Our research showed that the accuracy can be significantly improved by taking fuller advantage of the collected data and non-linear methods (Publications 1, 3 and 4). It was also shown that direct multi-step ahead condition forecasting is possible and give reasonable results when historical data is available (Publication 4). It was shown that clustering of the input data and variable selection in combination with non-linear empirical models can be successfully utilised in road condition forecasting (Publications 1, 3 and 4). The research also revealed that non-linear empirical methods give better accuracy in road condition forecasting after maintenance works (Publication 3).

Another significant contribution of the thesis is that the study introduced optimisation philosophies in analytical form and methods used in road maintenance planning (Publication 5). A combination of local and global search optimisation methods was utilised and it was shown that these give results that are closer to the global optimum (Publication 2). It was concluded that the current practice and current research does not yet fully encapsulate the whole complexity of maintenance planning in the utilised models.

The purpose of the study was to facilitate two paradigm shifts in the maintenance planning and especially in road maintenance planning. The first para-
digm shift is from corrective maintenance to preventive maintenance and there from time-based preventive maintenance to predictive or condition-based preventive maintenance. Time-based preventive maintenance is already widely used, but condition-based preventive maintenance combined with optimisation has still space for improvement and practical implementation. Even the widely-established concept and word ‘periodic maintenance’ in the road maintenance proves the point.

Another paradigm shift concerns wider utilisation of empirical models in maintenance planning. Data is easier to collect, store, share and compute due to technological progress, which make empirical models a viable option. The advantages would include more accurate results and maintenance work scheduling resulting thus cost savings and improved road condition with the same budget constraints.

Although road maintenance planning would benefit from fast development of empirical methods (machine learning algorithms), there are hindrances as the current Pavement Management Systems are fixed and closed. A greater vision for road maintenance planning has a global road asset database that could be used for creation of empirical models for developing countries as well as more open and accessible Pavement Management and maintenance planning systems, where the actual models can be changed or updated.

5.2 Future Work

Useful future work has two avenues: implementation of the findings in practice and identified new research areas. In the practical implementation, some of the utilised empirical models will be incorporated in a Road Management System (RMS) based on Cloud computing enabling thus access to road data from multiple road networks. The RMS would integrate data management, reporting and maintenance planning functionalities.

In case of future research, several avenues can be identified. To improve overall accuracy of the strategy more research should be dedicated on maintenance cost modelling with a specific goal to reduce variance in the modelled unit maintenance costs. The variance could be reduced by introducing new features and non-linear regression models and separation of fixed and variable costs if possible. The main challenge here is to find historical, reliable cost information on maintenance projects.

Another major improvement would be detailed research on Road User Costs and publication of the collected data and not just the analytical models. Recent developments in car electronics would facilitate the research experiment as fuel consumption could be detected and communicated through the CAN-bus and further transmitted to a remote server by an external telematics device. Impact of car make, model, condition and load weight could be eliminated, driving behaviour could be detected by an accelerometer in the telematics device, road geometry and surface condition and pavement data taken from external data source usually owned by the road authorities. Once installed in several vehicles the operating costs for data collection would be low. In the
data analysis phase an important aspect would be creation of empirical regression models with correct features for driving behaviour affecting fuel consumption and correct matching of data from different sources not to forget to collect other VOC besides fuel.

The maintenance planning strategy with forecasting and optimisation models could be further integrated in a framework applicable in real-life decision-making. An important research topic for such a framework would be how to use the same framework in different conditions, where the quantity and quality of collected data vary. This could be addressed by application of transfer learning.

As non-linear methods proved to be promising in terms of road condition forecasting it would be beneficial to generate new features from the existing data and try to improve forecasting accuracies. Also, application of the same methods for other countries and condition variables would be an interesting study.

Another important research aspect is to combine the full optimisation model with the forecasting methods in such a way that road maintenance cost model is implemented considering fixed and variable costs.

Perhaps the most important and interesting research question concerns validation of the maintenance strategy and models in such a way that the developed models are applied, suggested actions put into implementation and impacts measured.


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References


