UNIVERSITY OF BELGRADE
FACULTY OF CIVIL ENGINEERING

Jelena B. Ćirilović

AN INTEGRATED NETWORK-LEVEL MANAGEMENT MODEL FOR MAINTENANCE OF FLEXIBLE PAVEMENTS

Doctoral Dissertation

Belgrade, 2017

УНИВЕРЗИТЕТ У БЕОГРАДУ
ГРАЂЕВИНСКИ ФАКУЛТЕТ

Јелена Б. Ћириловић

ИНТЕГРИСАНИ МОДЕЛ УПРАВЉАЊА ОДРЖАВАЊЕМ ФЛКСИБИЛНИХ КОЛОВОЗА НА НИВОУ МЕЖЕ

Докторска Дисертација

Београд, 2017

ПОДАЦИ О МЕНТОРУ И ЧЛАНОВИМА КОМИСИЈЕ

Ментор:

В. проф. др Горан Младеновић, Универзитет у Београду, Грађевински факултет

Чланови комисије:

- др Ненад Шушић, научни саветник, Институт ИМС, Београд
- В. проф. др Горан Младеновић, Универзитет у Београду, Грађевински факултет
- Доцент др Немања Бранисављевић, Универзитет у Београду, Грађевински факултет

Датум одбране докторске дисертације: __________________________

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my mentor, Prof. Goran Mladenović for his guidance, support, help, and encouragement throughout my doctoral studies. Without his insightful suggestions, I could not have been where I am today. It has been my privilege to work with him.

I owe a special appreciation to Prof. Cesar Queiroz, a long time visiting professor at the University of Belgrade, who has always been eager to share time, thoughts and ideas regarding my research.

I have written the major part of my dissertation while visiting the research group of Prof. Athena Roumboutsos at the Aegean University in Chios, Greece, as part of the ERASMUS+ programme. Prof. Athena showed an immense understanding of my research and has given me the opportunity to be involved in the programme, which I appreciate very much.

The IMS Institute has provided me with technical and financial support for this research, and I am eternally grateful for that.

Finally, I would like to thank my colleagues at the IMS institute and the Faculty of Civil Engineering, all my friends, and my family, who each in their own way, have helped me finish this thesis.

To my family.

Thank you for teaching me to be free.

AN INTEGRATED NETWORK-LEVEL MANAGEMENT MODEL FOR MAINTENANCE OF FLEXIBLE PAVEMENTS

Abstract

In recent years, road agencies and authorities, responsible for maintaining road networks on a national level, are being faced with new challenges. In addition to their attempt to keep overall maintenance costs low while keeping their road networks in an appropriate condition, road agencies are facing even more demanding challenges as they become obliged to incorporate effects of global climate change and other environmental and social impacts into their decision making process.

Many studies and research initiatives have investigated the impact of the pavement condition on vehicle fuel consumption and maintenance costs, indicating that maintaining the pavement network at the lowest pavement roughness level would lower fuel and parts consumption, which is beneficial for the environment. Conversely, more intensive pavement maintenance activities, which are required to keep roads as smooth as possible, are accompanied with significant emissions and negative environmental impacts.

The objective of this research was to integrate and consolidate cost estimation models, cost optimization models, and environmental impacts models, in order to adequately respond to modern requirements, which include the implementation of strategies that are not only economically but also environmentally sustainable.

Optimization model applied was based on exhaustive search, and later on multi-criteria optimization with the use of Genetic Algorithms, while cost estimation models were created using regression analysis, classification trees and Artificial Neural Networks.

Developed methodology found an optimal maintenance plan for Serbian road network, a solution that is both economically and environmentally sound. However, the applied methodology can easily be applied on any other network worldwide.

Keywords

Road maintenance, asphalt pavements, maintenance strategies, optimization methods, cost estimation models, road network, carbon dioxide emissions

Research area: Civil Engineering

Specific research areas: Planning and design of roads and airports, Construction and maintenance of roads and airports

UDK: 625.765:614.718(043.3)

ИНТЕГРИСАНИ МОДЕЛ УПРАВЉАЊА ОДРЖАВАЊЕМ ФЛКСИБИЛНИХ КОЛОВОЗА НА НИВОУ МЕЖЕ

Резиме

Последњих година, предузећа која се баве одржавањем путне инфраструктуре, на државном и локалном нивоу, се суочавају са новим захтевима када је реч о одржавању путева. Поред потребе да се смање укупни трошкови одржавања путне мреже и ускладе са реалним могућностима и расположивим буџетом, и да се у исто време обезбеди одржавање путне мреже у одговарајућем и стабилном стању, предузећа која управљају путном инфраструктуром се налазе пред још захтевнијим изазовом, а то је укључивање климатских промена и утицаја на животну средину у процес одлучивања.

Многе студије и истраживачки пројекти су истраживали утицај стања коловозног застора на потрошњу горива и трошкове одржавања. Резултати показују да би одржавање коловоза, на нивоу путне мреже, на најнижем нивоу равности смањило потрошњу горива и резервних делова возила, што је такође корисно и за животну средину. С друге стране, интензивни радови одржавања, који су неопходни како би путеви били у одличном стању равности, праћени су значајним емисијама и негативним утицајем на животну средину.

Циљ овог истраживања је био да се интегришу модел процене трошкова, оптимизациони модел одржавања и модели утицаја на животну средину, како би се адекватно одговорило савременим захтевима, који укључују развој и примену стратегија које нису само економски, већ и еколошки одрживе.

Примењен оптимизациони модел је заснован на методи „exhaustive search“, а касније је примењена вишекритеријумска оптимизација са употребом генетских алгоритама, док су модели процене трошкова развијени коришћењем регресионе анализе, стабала одлучивања и вештачких неуронских мрежа.

Развијена методологија налази оптималан план одржавања путне мреже Р Србије, тј решење које је и економски и еколошки оправдано. Међутим, примењена методологија може лако да се примени на било коју другу путну мрежу широм света.

Кључне речи

Одржавање путева, асфалтни коловози, стратегије одржавања, методе оптимизације, методе процене трошкова, путна мрежа, емисије угљен диоксида

Научна област: Грађевинарство

Уже научне области: Планирање и пројектовање путева и аеродрома, Грађење и одржавање путева и аеродрома

УДК: 625.765:614.718(043.3)

Contents

List of Tables

List of Figures

Abbreviations

Chapter 1

PMS	Pavement Management Systems
CO_2	Carbon dioxide

Chapter 2

USA	United States of America
USD	United States Dollar
LCCA	Life Cycle Cost Analysis
LCA	Life Cycle Assessment
BoQ	Bill of Quantities
ECA	Europe and Central Asia
RA	Regression Analysis
ANN	Artificial Neural Network
MRA	Multiple Regression Analysis
GA	Genetic Algorithm
UK	United Kingdom
n	Number of years
k	Number of solutions
RUC	Road Users' Costs
VOC	Vehicle Operating Cost
IRI	International Roughness Index [m/km]
SNC	Modified structural number
AADT	Annual Average Daily Traffic
RE (PZP, in Serbian)	Road Enterprise (Preduzeće za puteve)
s	Road condition
s_0	Initial road condition – pavement roughness at the start of the analysis period [m/km]
s_{1i}	Roughness after maintenance treatment "i" is applied [m/km]
s_{2i}	Roughness at threshold value for maintenance treatment "i" [m/km]
t_0	Time before first maintenance treatment [years]
t_i	Time between maintenance treatments "i+1" and "i" [years]
τ	Time between maintenance treatments in a steady-state solution [years]
r	Discount rate [%]
C	Road user costs [million US$/km]
M	Road agency costs [million US$/km]
w_i	Asphalt overlay thickness [mm] of treatment "i"
G	Improvement in condition after maintenance treatment is applied [m/km]
DP	Dynamic Programming

ADP	Approximate Dynamic Programming
HDM-IV	Highway Development and Management tool
RONET	Road Network Evaluation Tool
CH_4	Methane
N_2O	Nitrous oxide
NH_3	Ammonia
SO_2	Sulfur dioxide
CO	Carbon monoxide
NMVOC	Non-methane Volatile Organic Compound
PM10	Particulate Matter (10 micrometers or less in diameter)
GHG	Greenhouse Gasses
LCA	Life Cycle Assessment
ISO	International Standard Organization
RAP	Reclaimed Asphalt Pavement
WMA	Warm Mix Asphalt
HMA	Hot Mix Asphalt
MIT	Massachusetts Institute of Technology

Chapter 3

IronMaP	Integrated Road Network Maintenance Planning Tool
GWP	Global Warming Potential
RRR	Road Rehabilitation and Reconstruction
CT	Classification Trees
AC	Asphalt Concrete
GNI	Country’s Gross National Income (per capita)
GDP	Gross Domestic Product
TICPI	Transparency International Corruption Perceptions Index
WGI	World Governance Index
WDI	World Development Indicators database
RSGFC	Road Sector Gasoline Fuel Consumption
L.O.O.	Leave One Out (method)
OLS	Ordinary Least Square
a_0	HDM-4 coefficient (value of 134)
a_1	HDM-4 coefficient (value of 0.7947)
a_2	HDM-4 coefficient (value of 0.0054)
K_{gm}	Calibration coefficient for the environment (takes value of 1)
K_{gp}	Calibration coefficient for the deterioration rate (takes value of 1)
m	Climatic factor (takes value 0.035 for Serbia)
ESSO	Number of equivalent standard axles in millions
CBR	California Bearing Ratio
M&R	Mill and Replace
b_0–b_3	RUCKS coefficients for estimating user costs
c_1’c_5	HDM4 coefficients for estimating CO_2 emission during usage phase
D_{IMPR}	Overlay thickness [mm]

Chapter 4

SR	State roads
RDB	Roads Data base
PC	Passenger car
BUS	Bus
LT	Light Truck
MT	Medium/heavy Truck
AT	Articulated Truck
t	Time
SR	State Roads

Chapter 5

μ	Measuring uncertainty
δ	derivative

CHAPTER 1: INTRODUCTION

1.1. Problem statement

In recent years, road agencies and authorities, responsible for maintaining road networks on a national level, are being faced with new challenges. In addition to their attempt to keep overall maintenance costs low while keeping their road networks in an appropriate condition, road agencies are facing even more demanding challenges as they become obliged to incorporate effects of global climate change and other environmental and social impacts into their decision making process.

Many studies and research initiatives have investigated the impact of the pavement condition on vehicle fuel consumption and maintenance costs, indicating that maintaining the pavement network at the lowest pavement roughness level would lower fuel and parts consumption, which is beneficial for the environment. On the other hand, more intensive pavement maintenance activities, which are required to keep roads as smooth as possible, are accompanied with significant emissions and negative environmental impacts.

In many countries worldwide the road agencies, as well as local municipalities, that are responsible for conscientious decision-making regarding asset management of the state road network, and local road network, have been for years faced with very limited budgets for road maintenance. Although in most western countries road networks are fully developed, in some developing countries substantial investments are still being allocated to the construction of new corridors. This puts even greater emphasis on the need to optimize road maintenance in order to achieve maximal effects in terms of road durability and users' satisfaction, but keeping the annual spending within available budgets.

In order to achieve the abovementioned objectives, *Pavement Management Systems (PMS)* imply conducting analyses and defining optimal maintenance strategies on typically three basic levels:

- Strategic analysis on the network level,
- Defining a work program for the network level, and
- Project level analysis.

A maintenance strategy consists of a certain combination of *maintenance treatments* during a certain time frame which ensures a certain level of pavement conditions and consequently, the fulfillment of transport goals.

The results of these analyses are highly dependent on the quality of input data. One of the most important input data which are needed for performing such analyses are unit costs of various maintenance works.

Naturally, among those costs, the most influential are the costs of the most demanding works (in terms of engineering complexity, time, or money); such are road rehabilitations and reconstructions (R&R). Both the underestimation and overestimation of such costs may lead to unrealistic projections of the optimal budget. Underestimations lead to additional costs for both the road agency and road users, while overestimations lead to unused financial resources which may have been used for further improvements of the road network condition (which consequently lowers road users' costs and improves their satisfaction).

At strategic and program levels, as well as during initial phases of the road rehabilitation or reconstruction project development, typically limited information is available. In those phases of analyses and preparations of the project documentation, cost prediction models, which are based on the minimum available data, are particularly important. As the project progresses with its implementation, during the development of the preliminary design and the feasibility study, more precise and detailed project-related data becomes available, and consequently, only then does it become possible to substantially increase the precision of initial estimates.

Models developed to date are neither final nor unambiguous and usually the decision on "Which of the existing models to apply?" is based on the availability of data in the particular case, i.e., the specific road maintenance project. However, during the process of the assessment of maintenance costs, various difficulties may arise. One of the biggest problems is, for example, the lack of historical data on costs in the previous period, the lack of project-specific data, a large spread of the existing data, and the application of inadequate models to estimate costs (e.g., too general or too precise).

After defining input parameters, it is necessary to define an optimal maintenance strategy at the road network level which assesses the required budget for achieving a certain network condition (i.e., *unconstrained budget scenario*) or a strategy which allows achieving the best network performance within the available budget (i.e., *constrained budget scenario*). Systems, currently in use, are not general or universally applicable, and decisions on whether it is necessary or not to apply certain maintenance treatments are in some cases even based solely on the engineering judgment.

However, in order to adequately respond to modern requirements, which include the implementation of strategies that are not only economically but also environmentally sustainable, which is in accordance with the European Union strategic goals (the European Commission Roadmap 2011), it becomes necessary to integrate and consolidate cost estimation models, cost optimization models, and environmental impacts models. Only by doing so, it becomes truly possible to evaluate costs and benefits of a certain strategy from a sound standpoint.

1.2. Research objectives

The objective of this research is to develop an integrated model for strategic planning of maintenance activities on flexible pavements, on a network level. In order to meet these requirements, it is necessary to independently develop three modules:

- The maintenance cost estimation model,
- The maintenance optimization model at the road network level, and
- The model which estimates the environmental impacts during a life cycle of a pavement.

Then, it is necessary to consolidate the three abovementioned modules to ensure the uniqueness of the final decision. It is also very important, for the decision-making process, to conduct an analysis of mutual relations, i.e., trade-offs, between possible solutions from the economic point of view and relative to environmental impacts. This can allow finding a solution which is, at the same time close to the “optimal”, but also flexible enough and adaptable to client requirements (i.e., to the requirements of the Road Agency, which is responsible for maintaining the analyzed road network).

1.3. Research hypothesis

When creating maintenance cost estimation models, the initial hypothesis was that it is possible to form a mathematical expression, using regression analysis, which uses, as input data, a set of statistically significant variables that describe:

- project-specific parameters (e.g., section length, the existence of paved shoulders, the type of terrain etc.), as well as
- country-specific parameters (e.g., economic characteristics of the state where the project was implemented, climate characteristics, the price of oil, etc.).

The goal of the optimization model is to determine the minimum of total pavement maintenance costs at the road network level and it is based on several assumptions. Pavements deteriorate over time under the influence of climatic conditions, traffic, winter maintenance and the like. Deterioration of pavements has multiple effects on:

- *road users* (fuel consumption increases whilst driving comfort decreases when driving on a road in poor condition) and
- *the environment,* through increased emissions of harmful gases caused by the slower movement of the vehicles.

In addition, the scope of required maintenance works, which are needed to put the pavement back to the required condition, increases in line with the level and the severity of pavement deterioration.

Finally, research objectives are set with the premises that the proposed integrated model improves, in various aspects, the current pavement maintenance management. The value that is added by this research is the better planning of pavement maintenance budgets over the time by identifying consequences of the application of different budget scenarios.

1.4. Scope of the study

The model developed within this study aims to assist road pavement and asset managers in reaching more sustainable decisions in terms of pavement/asset maintenance planning on a road network level. After the initial evaluation of various alternative solutions, this integrated model allows consideration of both economic and environmental effects into the decision-making process. This gives an opportunity to determine the required budget for maintaining the road network in a certain condition and/or how to keep the environmental impact under a certain threshold.

However, road network management also involves nontechnical and noneconomic motivations for decision-making such as social and political reasons. These aspects were not included in the analysis, but this can be overcome by allocating a certain percentage of the total budget for such works.

The focus of environmental impacts was put on CO_2 emissions, as one of the most influential contributors to overall gas emissions that are produced during the pavement life cycle. The emissions were considered in two manners: (i) as a quantity of CO_2 that is released into the atmosphere and (ii) as a monetary influence. The first approach provides a possibility to prioritize pavement maintenance based on two "objective" functions, one solely based on CO_2 emissions and another obtained through an economic analysis. The second approach enables the solving of the problem of finding an optimal maintenance plan through a unique optimization objective function (i.e., based on determining a maintenance plan that has a minimal total cost). However, special consideration has to be given to the sensitivity of assigning a monetary value to CO_2 emissions.

The optimization method proposed in this study is based on finding the minimal total cost including the user cost and the road agency cost. The sequential approach was used that simplifies the problem by defining a set of maintenance treatments in different thicknesses and then finding the threshold values for the application of a certain maintenance treatment. The proposed optimization routine considers a deterministic approach to the problem of finding the minimum of the objective function, meaning that the models do not account for the variability and probability of occurrence of a certain event.

The models used in this research are based on actual data, however since there is almost no historical data on the Serbian road network condition it was not possible to calibrate road deterioration models. Also, CO_2 emissions are not being closely monitored on Serbian asphalt plants and other material production facilities, so it was only possible to use data for typically used equipment from abroad.

The results of this research allow comparing network performance in terms of cost and benefits by the application of various maintenance strategies, and what are the impacts of those decisions on the total CO_2 emission during a certain time frame. It allows the monitoring of trade-offs between cost-based and environment-based objective functions, but in relation to road conditions and road class.

1.5. Research methods

Research methods used here should enable the identification of the most important findings in this field,i.e.,state-of-the-art, as well as key shortcomings in the overall knowledge of the matter,i.e., “knowledge gaps”.

In addition to general scientific methods which are primarily used for literature review and the analysis of existing knowledge, as well as for the synthesis of findings, also specific scientific methods are applied:

- Normative research:
  - The collection of previously established relevant data needed for the input dataset;
- Modeling:
  - Numerical modeling of the process of pavement deterioration,
  - Optimization model;
- Statistical Analysis:
  - Decision trees,
  - Regression analysis,
  - Neural networks.

State-of-the-art involves several topics, namely (i) cost estimation procedures, (ii) maintenance optimizations between maintenance alternatives in order to allocate the available funding, (iii) procedures of including environmental impacts in the optimization routines, and (iv) sustainable decision-making policies. Numerous case studies are also consulted in order to determine the *state-of-the-practice*.

In order to perform the optimization routine, it was necessary to previously define all the parameters of the objective function, which included pavement deterioration modeling, pavement improvement due to treatment models, CO_2 emission models during different phases of a pavement life cycle, user cost models, and road maintenance works cost estimation models. Simultaneously, several optimization methods were considered for performing analyses in terms of complexity versus generalizations. While it is preferable to develop models as precise as possible, when performing a network-level optimization routine, computational time and availability of data has to be accounted for.

Regarding cost estimations, among the most used statistical method are regression analysis and neural networks, which have been also applied in this research. However, due to the abovementioned problem of "precision versus generalization", a third method, i.e., decision trees, was also applied within this research. Only through a combination of those methods it was possible to determine the most suitable method for further analysis.

1.6. Research tasks and organization of the thesis

Research objectives are met through the completion of the following research tasks (Figure 1.2):

- Task 1: The identification of key variables that affect the value of maintenance costs will be established through a literature review and statistical analysis,
- Task 2: Collection of data on the condition of the road network and on completed road maintenance projects – a database will be used that contains over 200 international and domestic projects of road maintenance, completed in a period of 10 years and the road database of PE Roads of Serbia, on the condition of the road network,
- Task 3: Gathering information about the environmental impacts throughout the life cycle of the pavement – literature review about data on conducted measurements and models that are in use for this type of analysis,
- Task 4: Development of a statistical model for cost estimation of road maintenance. The model will be developed in accordance with the results of Task 1 and Task 2,

- Task 5: Development of an optimization model for the maintenance of pavements at the strategic level – a model will be developed based on data collected in Task 2, applying appropriate optimization techniques,
- Task 6: Assessment of the environmental impact during the life of the pavement construction – a model will be developed based on data collected in Task 2,
- Task 7: The development of an integrated model at the strategic level – a model will be developed by integrating the modules developed in Task 4, 5, and 6,
- Task 8: Testing and validation of models.

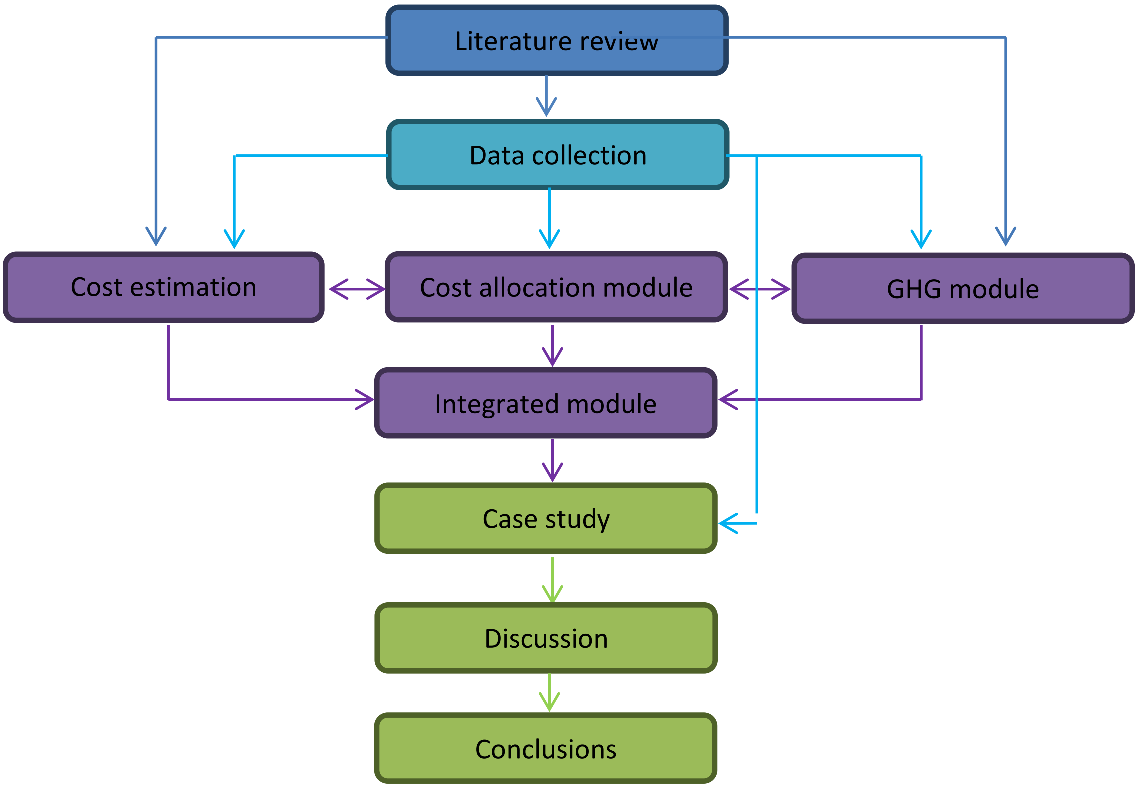


Figure 1.2 Main research tasks

The dissertation is organized in eight chapters.

Chapter 1, i.e., *Introduction*, explains the problem statement and problem formulation which are the core motivation for conducting this research, followed by the research objectives that were met through research tasks. Furthermore, a detailed presentation of the research hypothesis, upon which the research relies, was given.

Finally, the scope of this research was explained, alongside with research tasks and methods.

Chapter 2, i.e., *Literature review*, consists of three main subchapters, one concerning cost estimation modeling, second concerning pavement maintenance optimization models and software, and the third dealing with the environmental impact models during a pavement life cycle. Finally, the emphasis was put on the combined and integrated models in use for pavement network level optimizations, and in identifying knowledge gaps and research needs in all abovementioned areas.

Chapter 3consists of the section explaining the overall *methodology* applied, followed by three subchapters wherein the procedures for the development of all the relevant models have been presented. The starting point was to determine which variables and data to use, followed by defining the appropriate maintenance treatments and maintenance scenarios. Then, the optimization objective function was defined with its input parameters and restrictions. Also the routine for the integration of the three models was developed herein. *Model implementation* included the application of the developed methodology on the existing dataset. This included the application of the optimization routine, step by step, and defining all the parameters needed for the analysis, including (i) fixed parameters and (ii) parameters that can be changed and adapted for the application on a different road network. All input data are described in detail, especially the way it was collected and/or computed. The model was applied on a real network of Serbian state roads, divided into three different road classes: (i) highways, (ii) class I roads, and (ii) class II roads. Within the analysis, Serbian road standards were used, as well as Serbian regulations and recommendations, which do not preclude the application of the proposed model to any other road network after performing the appropriate changes.

Chapter 4 presents the *results* obtained using the integrated optimization model. Results show the optimal maintenance strategy, as per the criterion of minimal total cost and the criterion of minimal harmful effects on the environment. It also presents the adaptation of the optimal solutions and what consequences it has on the road network's overall condition, total cost, and the impact on the environment in terms of CO_2 emissions. The model is applied to the existing road network and is based on real data from the road database.

Chapter 5 includes *validation and sensitivity analysis, and* explains to what extent the developed integrated model depends on uncertainty of deterioration model, and how changes in the traffic growth rate and discount rate may influence overall results. A sensitivity analysis was performed for the unit cost of CO_2 emission, because it can also be a weighting factor in such an analysis. The cost estimation model was verified by applying the model on the test sample which contained data that was not used during the model development.

Chapter 6 includes the main and most important conclusions of this research, followed by a recommendation for future work and further research. This chapter also describes whether research objectives were adequately responded to, and how the research tasks were performed with special consideration for the limitations of this research.

1.7. Scientific justification of the thesis, expected results, and practical application of the results

In Serbia, for years, investment in road maintenance has been closely determined by a limited budget, where the impact on the environment has never been analyzed at the strategic level. The proposed doctoral dissertation is devoted to solving the problem of optimal planning of road network maintenance from several aspects.

On the one hand, it offers a balance between real possibilities of the Department of Roads and the available budget, and on the other hand, in the decision-making process it introduces the aspect of the users of the road network and environmental impacts. Also, the maintenance cost estimation model has significant potential for practical applications because it includes a large number of influential variables and provides a framework for comparing the current levels of maintenance costs with completed international projects.

Road maintenance is an extremely actual topic since road networks in most European countries have been fully developed, so that the maintenance of already built pavements is the key for an efficient and safe operation of the entire road network.

CHAPTER 2: PAVEMENT MAINTENANCE MANAGEMENT ON THE ROAD NETWORK LEVEL

The idea of assessing the need for road maintenance during a pavement's life cycle, arose in the 1960's, primarily in the USA. At that time, road agencies became faced with extensive and demanding road networks which were deteriorating. Additionally, each road, within a road network, deteriorates by various rates, due to different road section characteristics, such as climate conditions, quality of materials, type of pavement structure/construction, type of subsoil, and traffic loading. As the networks of public roads have been growing in the last several decades all over the world, the need for substantial investments regarding both maintenance activities on existing roads and new construction projects grew as well (Loijos et al., 2013). Consequently, the management decisions for those vast networks bear very important global environmental and economic impacts.

However, the total allocated budget for maintaining a road network is limited. Therefore the common objective for all road agencies and directorates worldwide is to optimize the total costs and benefits while making strategic-level decisions. For instance, in the USA the annual budget for maintaining pavements is 91 billion USD (ASCE, 2013). However, it was estimated that there is an annual shortfall of 170 billion USD (ASCE, 2013), since there is obvious decline in the road condition on the network level. That shortfall can be only dealt with clever maintenance planning, and focusing on maximizing the benefits while minimizing the total costs.

Transportation infrastructure management refers to *"the process of allocating a limited set of resources to a system of deteriorating facilities* "for maintenance, rehabilitation and replacement activities (Medury and Madanat, 2014). That system may include roads, bridges, tunnels, lighting, culverts, etc. Consequently, *Road Pavement Management* deals only with road pavements and tries to solve the problem of finding the optimal maintenance plan for pavements which is a process of defining the optimal timing, type, and intensity of a maintenance treatment for a road or a highway section (or network), with respect to a certain criterion.

As a result, *Pavement Management Systems (PMS)* are developed and are based on the current and historical network condition, but PMS also take into consideration future pavement conditions, during a certain time frame, in order to maximize the network condition within the available budget. Since 1970, a number of studies have been made regarding PMS which is designed to lower the life cycle cost of road pavements (Hass et al. 1994, Hudson et al. 1997, Kobayashi et al. 2008).

For that reason, *Life Cycle Cost Analysis (LCCA)* has been applied as an economic analysis and decision-making tool for pavements for over 60 years. LCCA is widely considered as key component of the infrastructure and pavement management process, for evaluating both network- and project-level decisions (Santos and Ferreira, 2013). It is a technique that evaluates economic efficiency between competing projects, including all the relevant costs during a life cycle of an investment, including construction, maintenance, usage and end of life phases.

*Life Cycle Assessment (LCA),*being a tool for evaluating environmental impacts, is considered to be a complementary method to LCCA (Santero et al., 2011a, Santero et al., 2011b), and it deals with assessing the overall environmental burdens related to all the phases of pavement or infrastructure life cycles. Using LCCA alongside LCA, allows combining pavement management objectives, and has the potential to make a positive impact on the environment and all the stakeholders involved, since the decision-makers are able to better ascertain the overall impacts of a proposed project or policy.

In Serbia, the issue of road network management has been gaining importance only after 2000. The last condition survey on the road network level was funded by a loan from the World Bank and implemented in 2008. Therefore, one can only assume the magnitude of arising problems that are a consequence of several factors:

- an extensive road network, still widening each year, maintained without the implementation of an appropriate PMS,
- all sections left to deteriorate without almost any interventions for more than 10 years (during the 1990’s),
- rare condition surveys, performed with different methods and equipment, resulting in no possibility of creating viable pavement deterioration assessments,
- limited historical data, and
- cost data based solely on BoQs and/or engineering judgment.

Therefore, the current local practice in terms of PMS is lagging behind and struggling with serious challenges, which make all the efforts in that direction essential for further growth.

2.1. Cost estimation in road construction and maintenance projects

"More accurate and transparent conceptual cost estimates have obvious technical benefits, not to mention to the public confidence that can be gained through better management of public funds"
(Molenaar 2005)

As concluded and confirmed many times in the past by numerous authors and researchers, reliable cost estimations are crucial for successful project management and to all parties involved in the construction project. However, the unit costs of road maintenance and construction works vary substantially across countries and through time (Turner and Townsend, 2012), but also in the same country, in the same year, due to various local conditions, i.e., topographical and climatic characteristics of a terrain, wage and skill levels, previous experience of construction companies, availability of materials, and price and availability of energy resources. Apart from the basic technical factors and fundamental cost drivers (i.e., cost of the land, materials, equipment and labor), the wide range of economic and institutional conditions in different countries will itself always lead to variations in the cost of infrastructure projects (Directorate of the European Commission, 2013).

Accurate cost estimations at the early stages of planning and programming road maintenance, rehabilitation, and construction are difficult to obtain (Chou, 2011), and in numerous cases, because of a lack of detailed information, on subjective judgments of experienced engineers. In a good number of cases that process is actually based on intuition and guessing (Akintoye and Fitzgerald, 2000).Such analysis may be subject to human error, and typically has a high level of variability in the results (Adeli and Wu, 1998). Major problems in developing accurate cost estimation during the conceptual phases of a project are the lack of historical and preliminary data, missing data, and high data and model uncertainties (Sodikov, 2005). As the project gains its maturity, more information becomes available, and more precise can be made estimations (Figure 2.1).

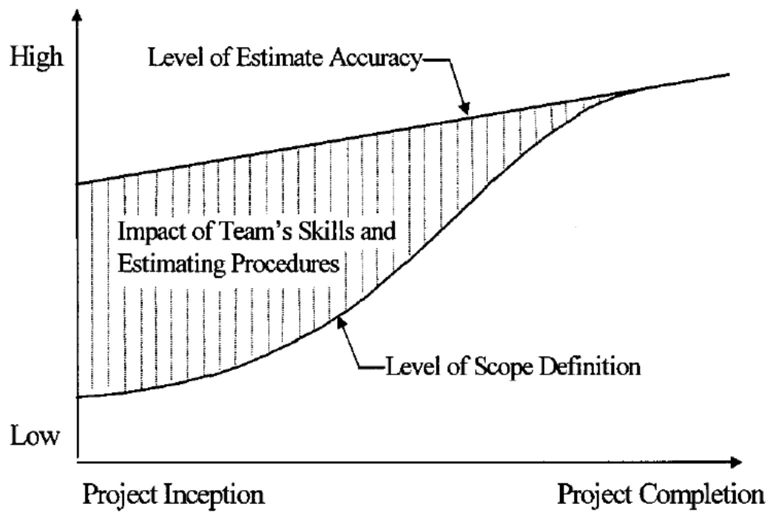


Figure 2.1 Estimate accuracy and project timeline (Picture by Trost and Oberlender, 2003)

Both over-estimations and under-estimations could lead to serious problems when implementing road works programs, especially in the case of constrained budgets. *Cost underestimations*, which are common worldwide (Flyvbjerg et al., 2002, Odeck, 2004, Chou, 2009) lead to cost and time overruns due to the lack of necessary resources, and can even lead to a construction that fails to meet its expectations (Chou 2011). Notably, cost overruns are far more often occurring than *cost under-runs* (Cantarelly et al., 2012a, Odeck, 2004, Molenaar, 2005). Flyvbjerg et al. (2002) strongly argue that cost underestimation can be drawn from political decisions, and strategic misinterpretations which all lead to the implementation of nonviable projects and wastage of resources (Odeck, 2004).

Although *cost overruns* are widespread in many construction projects, they indubitably create a significant financial risk to all the project participants, e.g., to both the contractor and the owner (Akinci and Ficher, 1998). The Directorate of the European Commission reported that even small cost overruns can cause a disruption and lead to additional financial claims. On the other hand, *cost overestimations* detain the funds that might be applied elsewhere, where they are needed more.

Flyvbjerg et al. (2002) argue that misleading cost estimations are extremely harmful, especially to financiers of an infrastructure project, but also to the users i.e., tax payers and private investors. Conversely, the total allocated budget for road construction and maintenance projects is generally fixed; the cost variation in a single project actually influences many other projects that were considered for development at the same time or within a few years. Consequently those “other” projects may be cut in scope or even canceled altogether (Molenaar, 2005) due to a cost overrun in a project.

In developed countries parametric cost estimations or estimations based on historic databases are widely used during the conceptual estimation phase (Sodikov, 2005). However, developing countries typically face difficulties in developing a database that can be used for cost estimations at the initial stages of project development. One of earliest attempts to develop such a database for developing countries was the Road Costs Knowledge System (Archondo-Callao et al.,2004; World Bank, 2016). The World Bank has recently performed two studies to establish frameworks for cross-country comparative assessments of the procurement and implementation processes of road works contracts in Sub-Saharan Africa (Alexeeva et al., 2008) and Europe and Central Asia—ECA (Alexeeva et al., 2011).

2.1.1. Variables used for developing cost estimation models

There are various methodologies and tools for unit cost estimations (Anderson et al., 2007), and numerous variables which could be explored for their significance in estimating future construction costs (Wilmot and Cheng, 2003). Chou et al. (2006)and Chou (2009)explored the idea of considering, beside the historical cost data, more unique *characteristics of projects*:

- Project length,
- Proposed main lane number,
- Lane width,
- Shoulder width,
- Project width,
- Truck percentage measured on the road,
- Average daily traffic,
- Project type,
- Designed speed for traffic of highway, and
- Whether the population on the project location is urban or rural.

Akintoye (2000) used 24 possible variables, including variables that are based on technical project characteristics (such as the complexity of the project, site constrains, tender period, market conditions, build-ability, and the location of a project), but also variables depicting the parties involved in the project (namely the clients' financial position, contractor past experience on similar projects, and the expertise of consultants).

Some recent analyses of unit costs indicate that *state-specific variables*(e.g., corruption and road development growth rate) also have an effect on costs in addition to the technical and economic variables of a project (Meduri and Annamalai, 2013). Irfan et al. (2011) established a statistical relationship between the *project duration* and the actual cost of a project, *project type* (e.g., pavement construction, rehabilitation, maintenance, traffic facility installation, and bridge construction) and *contract type* (fixed-duration and fixed-deadline) with the use of deterministic log-linear logistic modeling, as well as a probabilistic hazard-based model.

Odeck (2004)also highlighted the size of project as a significant contributor to overall cost overruns, claiming that typically, cost overruns appear predominantly among smaller projects in comparison to large-scale ones. Cantarelli et al. (2012b) emphasized the influence of geographical features. They confirmed, on the sample of more than 800 projects, that cost overrun is, indeed, a global phenomenon, and its size varies with location, i.e., developing countries are generally less resilient to cost overruns compared with Europe and North America.

2.1.2. Cost estimation through various numerical and mathematical models

Developing a cost estimation model for highway projects with the use of *Regression Analysis (RA)*and *Artificial Neural Networks (ANNs)* has been attempted by numerous authors in the past. In numerous case studies (Akintoye and Fitzgerald, 2000, Munns and Al-Haimus, 2000), it was proven that the classical approach of calculating the expected costs of a project, based only on quantities, underperforms compared with methods relying on artificial intelligence (Hegazy and Ayed, 1998, Sodikov, 2005, Kim et al., 2004b).

*Multiple Regression Analysis (MRA)*is a technique that has been used for several decades for solving similar problems (Chou et al., 2006), and it can be used as both an analytical and/or predictive technique (Skitmore and Ng, 2000, Chou, 2009). Although it is expected that ANNs provide improved cost estimates (Smith and Mason, 1997), they operate as a black box, i.e., only inputs and outputs are readable, and also require a substantial training dataset based on known cases (Bode, 1998). That is why it is usually advisable to explore MRA models first, prior to developing a model based on artificial intelligence or some other sophisticated technique.

Among the other reported advantages over traditional methods, ANNs have a trait that leads to reasonable estimations although they are not based on expert judgment or any specific rule (Adeli and Wu, 1998) and to a successful modeling of the nonlinearity in the data (Emsley et al., 2002). On the other hand, ANNs are completely data-driven models, and in cases where relationships between variables are known, can under-perform in comparison with RA models (Smith and Mason, 1997, Sonmez, 2004).

Hegazy and Ayed (1998) simulated an ANN’s algorithm in a spreadsheet program for a cost estimation model for highway projects based on data from18 projects. Emsley et al. (2002) used models based on linear regression as a benchmark for evaluating the ANNs’ models for the prediction of total construction costs, based on data from nearly 300 building projects. Kim et al. (2004b) used *Genetic Algorithms (GAs)* to determine the optimal architecture of ANNs for estimating construction costs for 530 projects concerning residential buildings constructed in Korea. Sonmez (2004) also concluded that a combination of the methods used usually improves the quality and the objectivity of the estimation.

Lowe et al. (2006) tested 41 features as potential variables in prediction models for the construction cost of buildings, based on 286 UK projects with the use of a linear RA, with the purpose to single-out the most influential cost drivers. Akintoye (2000) used a *factor analysis* to determine the main factors relevant for cost estimating practice, form a constructor point-of-view, using data on 84 UK contactors, divided into (i) very small, (ii) small, (iii) medium, and (iv) large firms.

Classification trees are also one of the techniques that may be used for determining the most important features for describing an explanatory variable (Kass, 1980). Likewise, the accuracy of the estimation depends on the availability and the quality of information, i.e., input parameters. Trost and Oberlender (2003) used factor analysis and MRA to identify factors that exhibit a significant impact on the estimation accuracy.

Often, the most suited method is determined through the simultaneous application of several techniques in order to assess the applicability and precision of various methods, and a similar approach was taken by many authors in the past (Lowe et al. 2006). Consequently, Kim et al.(2004a)made a comparison of construction cost estimating models that are based on RA, ANNs, and case-based reasoning, and determined that ANNs are superior in terms of accuracy.

Similarly, Wang and Gibson(2010) investigated the relationship between pre-project planning and project success, using two techniques—ANNs and RA models—and concluded that ANNs outperform RA in terms of goodness of fit; however, RA gives valuable insights from an engineering point of view.

2.1.3. Challenges within cost estimation modeling

Based on the analyzed literature, there are many potential fields of improvement in terms of building cost estimation models, suitable for early project cost planning, i.e., strategic road maintenance planning on a network level. Unfortunately, even today, most of the cost estimation is based on the BoQ, without taking into consideration the complexity of the problem. The most important issues determined, which need to be further addressed, are the following:

- *Model choosing* and/or combining or adopting the models, since the data comes from various sources, in various units and ranges, many models have to be adopted in order to adequately handle such vast variations in data type and origin;
- The inclusion of a *wide range of potential variables* is very significant since previous experience showed that there are many drivers leading to changes in the overall costs of projects, which can be both global and local. For example, during cost estimations, it is important to keep in mind *wider implications of projects*, not just project specific variables, but to also include financial surroundings and climate, social factors, local practices, etc.

The *fluctuation of prices* on a local market may greatly affect the price of road works. Furthermore, it is very demanding to model the expected changes in cost due to sudden hits and during turbulent times (e.g., during economic or political crises), but these fluctuations may be of a great magnitude.

The tendering process itself is very important from several aspects. Tenders may be complicated, lengthy, and costly for participants leading to cost overestimations and a drop in the number of offers, or on the other hand the terms for participation may be too relaxed which can attract many incapable contractors to apply, leading to an increase in the competition and in the drop of the estimated cost of a project.

Using a significant amount of data and historical cost data is crucial, but also very challenging since that data may not be always available. However, without the adequate data sample, sufficiently detailed and covering a significant period of time, it is not possible to develop an estimate for future expectations.

To achieve the balance between *precision versus over-fitting* is a challenge in every estimation procedure. For that reason, it is necessary to conduct honest validation procedures which determine how the developed model works on “new data” (not previously used data). In order to do so, once again it is crucial to have a large data sample and to pay special attention to the validation procedure.

A ready-to-use approach is vital since cost estimations are needed constantly in road maintenance activities. However, if the prediction model requires a large set of data that is difficult to obtain, it may not be appropriate for frequent use. On the other hand, the accuracy of the model based on limited prior information may be questionable.

Leverage between data-driven i.e., self-adoptable and assumption-based models is also a great challenge. In the case of cost modeling, one must “understand” the data, since it may be driven by local or temporary conditions; therefore, the engineering (experts’) assumptions may be critical in the overall understanding of the underlying processes. However, the model needs to be self-adoptable, i.e., to lead to an increase in precision, due to past and new experience, in its domain of applicability.

2.2. Pavement maintenance optimization in terms of cost during a certain time frame

Finding the optimal pavement maintenance strategy, that includes the timing and intensity of rehabilitation treatments over the analysis period, is one of the major problems dealt with in *Pavement Management.*

Time spent on calculation holds the researchers back from searching for the “true” solution of the problem, because there is a pool of at least 20 different possible maintenance treatments that can be applied (or not) in each year of the analysis period (e.g., overlays in different thicknesses, crack sealing, micro surfacing, slurry seals, pothole patching, cold in place recycling, hot recycling, and various types of asphalt mixtures). For example, the number of solutions for a 30-year analysis period equals:

$$numberofsolutions = \binom{n}{k} = n^k = 30^{20} = 3.5 \times 10^{29} possiblesolutions \quad (eq.\ 2.1)$$

Consequently, various optimization techniques are developed that can be used for finding the “optimal” solution that is the closest to the “true” optimum, based on a certain criterion. One of the definitions of the “optimal” solution can be formulated as follows, “*Assuming that the pavement deterioration model and pavement improvement model after completion of pavement maintenance work, are known, that it is the frequency and intensity of rehabilitation works, for which the total discounted costs of society are minimal”* (Hass et al. 1994).

The total society costs are defined as the sum of the *Road Users’ Costs (RUCs)* and road maintenance costs borne by the company undertaking the road maintenance (e.g., department for transportation, government agency). Those two costs are proportional to the pavement condition, one directly and the other indirectly. More specifically, as the pavement is in worse condition, RUCs rise accordingly. On the other hand, keeping the pavement in excellent condition, which lowers RUCs, leads to a significant increase in agency costs, i.e., costs of maintenance activities. Finding the “optimal” solution, is actually a process of finding the point where the sum of the total society cost (RUC and agency cost) is minimal, as presented in Figure 2.2

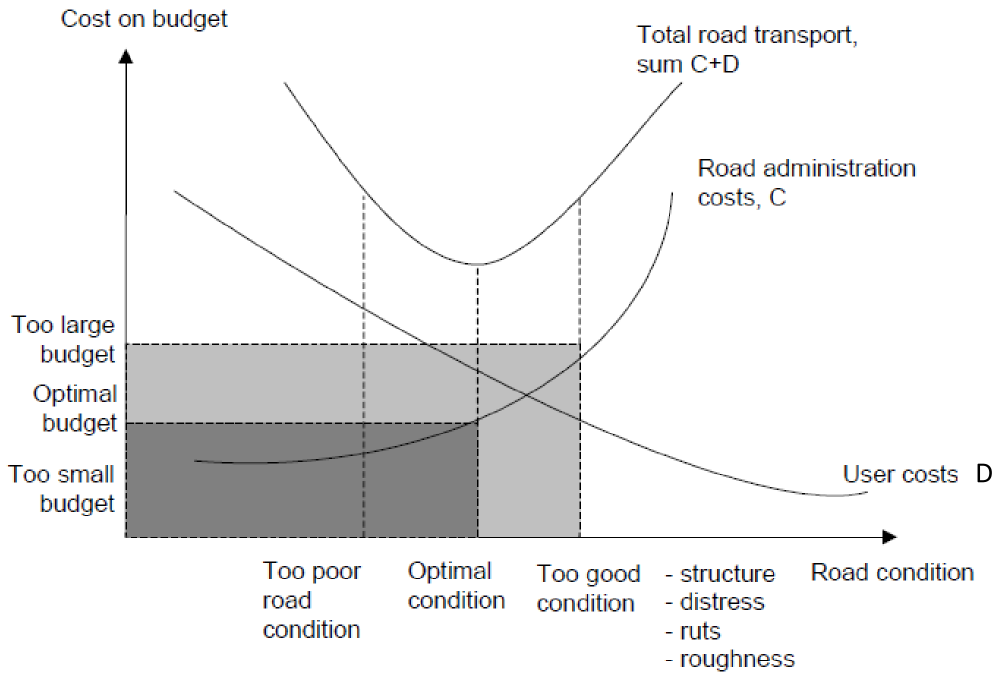


Figure 2.2 General principle behind finding the "optimal" maintenance budget (figure by AIPCR, 2000)

Gao and Zhang (2013) also confirmed, in course of their research, that when maintenance costs are high (frequent works) RUCs are decreasing, and vice versa, stating how the two costs are strongly competitive with respect to each other.

RUCs can be defined in numerous ways, but in most cases they represent the sum of

(i) *Vehicle Operating Costs – VOCs* (e.g., cost of fuel, spare parts, tires, oil, and gasoline),

(ii) Costs of time – travel delay,

(iii) Costs of accidents and injuries,

among which, the VOC and the travel delay are the two main drivers of RUCs (Gao and Zhang, 2013).

Since both RUCs and maintenance costs are related to the pavement condition, it is possible to find, for each section, an optimal pavement condition, i.e., *the threshold value* at which it becomes necessary to implement a specific type of pavement improvement in order to obtain a close-to-minimum total society cost. For example, sections experiencing low traffic volumes are not so often candidates for major improvements, because in this case, the cost of interventions may be predominant in the overall cost since the RUCs are related to low traffic volumes, and may be minor.

On the other hand, on highly trafficked sections of highway networks, there may be very high traffic levels, associated with equally high RUCs. Many previous analyses indicated that, in this case, it is more advisable to maintain the pavement in very good or good condition, because the RUCs are predominant in the total society cost. However, the traffic volume is only one of the significant parameters that can influence the choice of optimal maintenance strategy.

The system is based on *pavement deterioration models*, evaluating the condition of the pavement surface and functional characteristics of pavements, as well as the structural condition:

- Longitudinal roughness (typically expressed through IRI – International Roughness Index, expressed in units of m/km),
- Distress of pavement surface (typically expressed through the number of potholes, patching, cracking, rut depth, etc),
- Bearing capacity of the pavement structure (typically expressed through the modified structural number SNC),
- Traffic volume (expressed through AADT – Annual Average Daily Traffic), and
- Climatic conditions.

There is also a previously established and even intuitively known fact, that pavement deterioration is not a linear process, i.e., there is a theoretical point after which the rate of deterioration rapidly increases. Practically, that means that in its first years after construction (or major rehabilitation), it is possible to bring back the pavement to its initial condition using moderate maintenance work techniques. However, after the “critical” point of deterioration, bringing pavement back to its initial condition becomes considerably more costly and time consuming, i.e., this requires major rehabilitation/reconstruction works. This was illustrated in Figure 2.3, showing the pavement serviceability on the y-axis, dropping through time, affecting the increased thickness of the overlay needed for achieving the initial serviceability index.

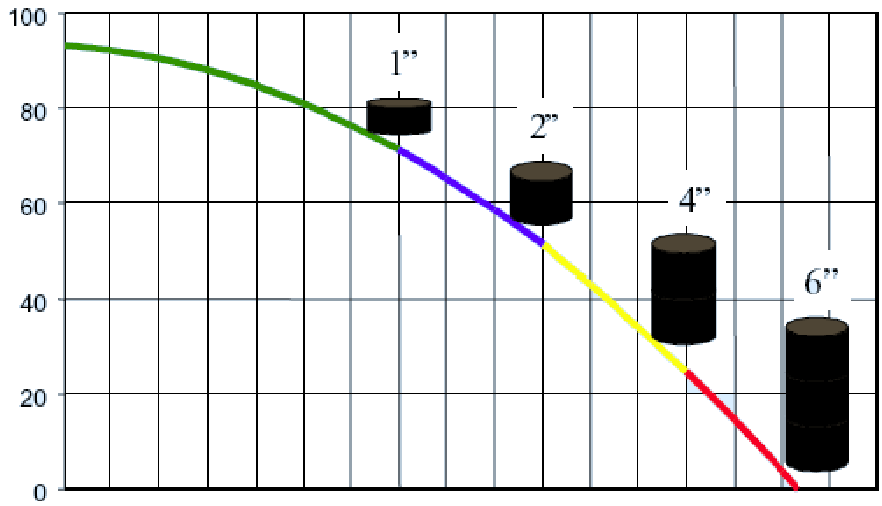


Figure 2.3 Relation of road deterioration and rate of deterioration [figure by WSDOT 1999]

Therefore, there is a point of optimality, for each pavement type, and set of characteristics, which allows keeping the road in satisfactory condition with minimal investment. From a mathematical standpoint, the potential number of solutions is almost infinite, i.e., in each year, there is a possibility to perform one of a number of possible treatments and each treatment can be applied in various thicknesses, or the choice can be made not to apply any treatment that year and let the pavement deteriorate. This combination of triggers associated with a certain type of intervention is known as *pavement maintenance scenario* or strategy (e.g., “apply asphalt overlay, 40 mm thick, whenever pavement roughness becomes higher that IRI 3.5 m/km”).

This task becomes even more complicated, if the problem expands to the network level, i.e., for each section of the road network, in each year, there are a number of possible solutions. Each section has a unique combination of various influencing characteristics; such are the terrain type, climatic conditions, traffic levels, road geometry, pavement bearing capacity, structural number, condition, and roughness.

For that reason, when it comes to performing a strategic analysis regarding the optimal maintenance plan, even supposing one uses the most up-to-date optimization routine and sophisticated computer equipment, a certain level of generalization is needed on the network level, considering the frequent lack of data.

There is also an important aspect when considering optimal maintenance plans for road pavement networks, e.g., the choice of possible maintenance techniques and local practice in terms of project design and project delivery, i.e., the quality of performed construction works.

The second important aspect of an “optimal” maintenance solution are the budget constraints. Naturally, the budget for maintenance works is constrained even in the most powerful economies. However, it may fluctuate from year to year, and also may not be balanced with regard to minimal maintenance needs for keeping the overall network in an appropriate condition. This causes many road directorates to have a problem with maintenance backlog, i.e., the scope of works that was not performed on time, leading to an overall network performance under sub-optimal conditions.

2.2.1 Mathematical interpretation of the problem of optimal maintenance

The pavement condition (e.g., pavement roughness) at any point of time, **s**, follows a saw-tooth curve as a result of pavement deterioration and the periodic application of certain types of maintenance treatments. At a time t_n, there is a pavement overlay applied in a thickness of w_n, which results in an improvement in roughness from s_{2n} to s_{1n}.

The road condition follows a saw-tooth trajectory through time, meaning that pavement deteriorates to a point when a maintenance treatment is applied (Figure 2.4). The application of the maintenance treatment is represented with an instantaneous improvement in pavement conditions (vertical line that links the s_{2i-1} threshold value and s_{1i}– the roughness after the treatment). The level of improvement depends on the intensity of the treatment which is defined as the thickness of the asphalt overlay w_n, and the pavement condition prior to the treatment s_{2n}.

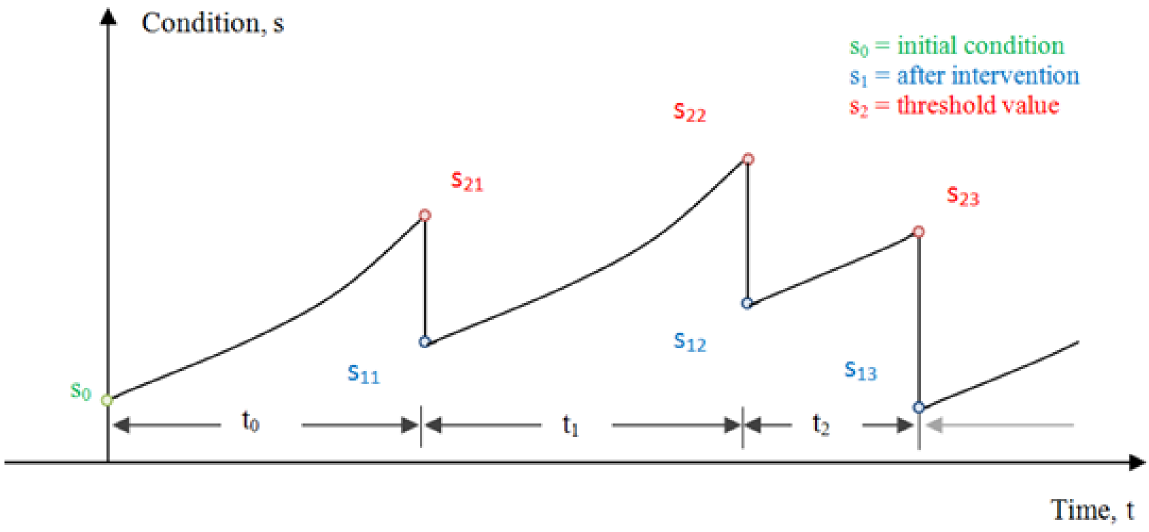


Figure2.4Model formulation – condition curve [figure by Cirilovic et al., 2014]

After application of a maintenance treatment, the pavement continues to deteriorate which is represented with a line connecting the point s_{1i} with $s_{2(i+1)}$. The goal in finding the "optimal" maintenance plan is to minimize the total society cost, discounted to the present value, during the analysis period. Total society cost represents the sum of RUCs and the cost of maintenance treatments borne by the company that manages the transport infrastructure (Road Agency costs), as shown by Equation 2.2.

$$\min J = \sum_{n=1}^{\infty} \left\{ \int_{t_{n-1}}^{t_n} C\big(s(t)\big) \times e^{-rt} \times dt + M(w_n) \times e^{-rt_n} \right\} \qquad \textit{(eq. 2.2)}$$

With the following constrains

$$\frac{ds(t)}{dt} = F(s(t)) \qquad \textit{(eq. 2.3)}$$

$$s_{2n} - s_{1n} = G(w_n, s_{2n}) \qquad \textit{(eq. 2.4)}$$

$$s(0) = s_0 \qquad \textit{(eq. 2.5)}$$

Equation 2.3 states that the rate of pavement deterioration depends only on the current pavement condition, while Equation 2.4 specifies that the reduction of roughness which is the consequences of the pavement intervention depends on the pavement condition before the intervention and the intensity of the intervention. Equation 2.5 defines the initial pavement condition.

2.2.2. Methodical approaches for road maintenance and rehabilitation cost allocation optimization

Accurately forecasting future maintenance activities continues to be a challenging task (Santero et al., 2011a), even nowadays, after many years of experience and past research. The two most common approaches are bottom-up (facility, or project level) and top-down (network level). Medury and Madanat (2014) underline how there is still a very significant gap between *top-down* system-level (i.e., network-level) approaches for solving the optimization problem in comparison with *bottom-up* facility-specific (i.e., project-level) approaches. The first generalize strategies based on budget constraints, while the former approach gives best decisions related to a specific section, but with limited or no consideration given to overall budget constraints. On the other hand, the shortfall of top-down approaches is the homogenization of sections with various characteristics (Sathaye and Madanat, 2012),primarily in terms of deterioration and cost parameters.

Historically, maintenance planning on a network level has been conducted using various techniques and methodologies, including the *worst-first approach* (Gosse et al., 2013), i.e., road sections in the worst condition are rehabilitated until the annual budget is exhausted. However, that approach had shortcomings after being applied during a longer period of time (Meneses and Ferreira, 2013). Moreover, it is very important to, when prioritizing the maintenance activities between different projects, take into consideration the importance of a road section within the road network, in order to assure a comfortable and safe transportation for a maximum number of users.

Alternatively, there are few other simple approximate methods such as best-first, or scoring. The *best-first approach* may be appropriate when the budget is very limited, and then it is possible to maintain only part of the network with available funding. In that case, the sections in good condition are considered as candidate for maintenance works, while other parts of the network with roads in worse conditions are left to deteriorate until more funds become available, focusing on the best parts of the network. The logic behind this approach is that those sections need lower investments for keeping them in good condition.

Scoring is a method which assigns a value, usually ranging from 1 to 5, or 1 to 10, to all the road sections of the road network, using a certain criterion. This allows a simplified comprehension of the overall problem, leading the managers from road authorities (e.g., investors, officials from the Ministries, and road agency managers) to more easily reach managerial decisions and prioritize without necessary knowledge of technical indicators and parameters. The whole problem is downsized to comparing indicators from a specific range. This is a technique very applicable on smaller networks, where sometimes there is no sufficient data available concerning all the technical parameters, needed for more sophisticated analyses, therefore the decisions have to be based on an engineering assessment and judgment.

Finally, *LCCA* has risen as one of the most powerful tools, when it comes to pavement management assessments (Ozbay et al., 2004). This procedure takes into account the overall life of a pavement, including construction, usage, maintenance, and end-of-life, making assessments based on both economic and engineering principles.

More generally, *the objective function* can be defined in various manners, depending on maintenance goals, policies, and objectives, and is usually defined in such a manner to find

- the minimum discounted social (agency plus user) cost (Li and Madanat, 2002) while fulfilling reliability and functionality requirements (Morcous and Lounis, 2005), or
- a minimum duration of road works (Tsunokawa and al., 2006) and lately an additional optimization criteria has been set up, and it is
- accounting information on asset value – maintaining an appropriate service life (Kobayashi et al 2008), and
- minimum greenhouse gas emissions (Lidicker et al., 2012).

Multi-objective optimizations allow combining several objective functions, each associated with an appropriate weighting factor. Herabat and Tangphaisankun (2005) applied multi objective constraint-based GA optimization on the road network in

Thailand in order to minimize VOCs while maximizing the network condition, while Wu and Flintsch (2009)presented an approach for pavement preservation programming considering minimum total preservation costs and maximum road network conditions. Meneses and Ferreira (2013) developed a Multi-Objective Decision-Aid Tool to achieve (i) minimal agency costs, (ii) minimal RUCs, and (iii) maximal residual value of pavements.

2.2.3. Computational methods for road maintenance and rehabilitation cost allocation optimization

As the cost estimation model is defined, and the relevant information about the road network is collected, it becomes possible to optimize maintenance works on the network level during a certain time frame. Numerous techniques have been used for solving the optimization problem of pavement maintenance (Harvey, 2012, Morcous and Lounis, 2005):

- Optimal control theory,
- Linear Programming,
- Non-linear (including convex) programming,
- Integer Programming,
- Dynamic programming,
- Soft computing, etc.

However, since the data quality and availability, and model complexity are very demanding, the best performing tools (and most commonly chosen by researchers) are the ones including hybrid models that combine several techniques.

Optimal control theory was introduced in Pavement Management in the early 1980s; since then, it has been employed in numerous methodologies to find the abovementioned “optimal” solution. Friesz and Fernandez (1979) set the problem of finding an optimal maintenance strategy as the problem of optimal control theory, although in their work they accepted the generalization that pavement conditions change smoothly over time. This limitation was overcome by Tsunokawa and Schofer (1994), who were using an approximation of the saw-curve, which represents the current state (condition) of the pavement, with a continuous curve that connects the midpoints of the peaks. In this way, the problem of finding the time and intensity of maintenance is replaced by the problem of finding the optimal frequency of rehabilitation, which is becoming a standard problem of optimal control theory. That was later considered as a far more realistic solution procedure since the deterioration curve is approximated with a smooth line, and maintenance activities are presented as instantaneous improvements, i.e., "jumps" in the pavement condition.

This methodology was later applied by many researchers, who improved the solution by adding other parameters to the problem. This procedure was able to produce the "optimal" solution:

- In case of a constrained budget (Ouyang and Madanat, 2006),
- For an unlimited time period (Li and Madanat, 2002);
- For a limited time period (Ouyang and Madanat, 2004) and multiple resurfacing activities with realistic pavement performance models (Ouyang and Madanat, 2006), and
- For an infinite time on a network level (Ouyang, 2007).

Recently, Rashid and Tsunokawa (2012) once again applied the trend curve optimal control model which included, besides overlays, resealing and reconstruction works, while Guet al. (2012) solved the optimization problem including also preventive maintenance for a continuous pavement condition curve and for an infinite time horizon.

Within *linear programming*, the optimization problem is solved through a linear objective function and linear boundary functions. Because of this restriction, since many problems cannot be adequately expressed linearly, it is often necessary to apply *non-linear programming*. The most used example for this methodology was done by Golabi et al.(1982) (later continued by Wang and Zaniewski, 1996) who developed the Arizona Pavement Management system that is based on continuous linear optimization that gives the minimum of expected discounted agency costs while keeping the network in an appropriate condition. *Convex programming* is a special case of nonlinear optimization with constraints, whose objective function is concave, and all the constraint-functions are convex.

The use of an *integer programming* formulation is beneficial in terms of selecting optimal maintenance treatments on a project level (Medury and Madanat, 2014). For instance, Oyang and Madanat (2004) combined a nonlinear performance model and integer decision variables in the algorithm that produced optimal rehabilitation planning for a finite horizon for a multi-facility system under budget constraints.

Dynamic programming (DP) is often applied to solve large and complex optimization problems by solving series of minor problems. Among the first attempts to solve the optimization problem of road network maintenance was the work of Abelson and Flowdew's from 1975, which used DP to solve the problem of minimizing the cost of maintaining the road network in Jamaica during a 10-year period. More recently, Gao and Zhang (2009) as well as Kuhn (2010) used Approximate Dynamic Programming (ADP) for the large networks infrastructure management optimization problem, while Medury and Madanat (2013), applied ADP to assess the impact of network-based constraints in budget allocation optimization within road infrastructure management.

Among soft computing techniques, Flintsch and Chen (2004) state as the most used within infrastructure management the three following ones: ANNs, fuzzy systems, and probabilistic reasoning (including evolutionary computing, genetic algorithms, and belief networks).

Genetic algorithms, discovered by Holland (1975) and later developed by Goldberg (1989), are based on Darwin's theory of evolution. GAs belong to a group of heuristic methods that give approximate solutions of the optimization problem, i.e., GAs find a good, but not always the optimal solution, with the advantage of significantly saving computational time. Since 1990, GAs have been used in a number of methodologies to solve more complex optimization problems (Fwa et al., 1994, Morcous and Lounis, 2005, Santos and Ferreira, 2013).

GAs are significantly different from traditional optimization methods. The search process is not based on a gradient, so the objective function needn't be differentiable or convex (Fwa et al., 1994). GA optimization begins with the development of a set of randomly selected "parent" of possible solutions. The characteristics that describe each solution are encoded in the "chromosome". A solution is reached through an iterative process that involves copying, mutations, and crossovers of the genes of chromosomes from a set of possible solutions, while choosing better solutions and removing bad solutions from the set, so that the set evolves towards an optimal solution.

Ferreira et al. (2002) demonstrated the efficacy of GAs for solving complex optimization problems at the national road network while Hegazy and Rashed (2013) applied GAs and segmentation for large-scale asset optimization. Jorge and Ferreira (2012), while determining the optimum maintenance strategy at the road network level, combinedHDM-4 pavement deterioration prediction models and a GA optimization model, which was applied to a municipality in Portugal.

2.2.4. Available software for maintenance planning on the network level

There are many tools and several software packages that deal with network level optimization problems; among the most known and used are:

1. **HDM-4** (internet ref. 1) **–** Highway Development and Management tool, developed under collaborative research of several institutions (the World Bank, MIT[1], LCPC [2], TRRL [3], UNDP [4], Governments of Kenya, Brazil, Caribbean, India, PIARC[5])one of “what-if” models that is used to predict the consequences of various maintenance options by using very sophisticated models for pavement deterioration, VOC, etc. Its optimization is based on choosing “the best” among several developed scenarios by an analyst. Since there are infinite combinations of possible treatments (i.e., maintenance scenarios) it can give only suboptimal solutions (Tsunokawa et al., 2006);

2. **RONET** (internet ref. 2) **–** Road Network Evaluation Tool**,** also developed by the World Bank, is a very useful tool especially for developing countries, since it can assess the required budget for maintaining the overall network in a certain condition, and to also asses the income from tolls and other forms of income. It has only several types of possible maintenance treatments and it relies on a great deal of generalization, which also gives more of an assessment than an optimal solution;

[1]Masachusets Institute of Technology, Boston, USA
[2] Laboratoire Central des Ponts et Chaussées, France
[3]Transport and Road Research Laboratory, UK
[4]United Nations Development Programme
[5]the World Road Association

3. **dTIMS** (internet ref. 3) is more of a platform for asset management (not just pavements, but also suitable for sewage systems for example) which allows for a proper optimization routine (based on exhaustive search or GAs). All the models and processes are user-specific, which makes it very adaptable but on the other hand, may be demanding in terms of usage;

4. **HIMS** (internet ref. 4)**–**HIMS is a relational database and analytical system software with built-in GIS. HIMS is designed for managing data for analysis with applications such as HDM-4. The HIMS analytical module (for predictive modeling and optimization) allows undertaking LCCA, asset valuation, and risk management;

5. **HERS-ST**(internet ref. 5) – Highway Economic Requirements System-State Version also performs cost-benefit analyses using "what-if" models, i.e., among defined scenarios. HERS-ST is a tool that uses engineering standards to identify highway deficiencies, and then applies economic criteria to select the most cost-effective mix of improvements for system-wide implementation. HERS-ST is designed to evaluate the implications of alternative programs and policies on the conditions, performance, and RUC levels associated with highway systems. The model will provide cost estimates for achieving economically optimal program structures, as well as predict system conditions and RUC levels resulting from a given level of investment;

6. **RealCost** (internet ref. 6)is a tool for conduction of LCCA, developed under the Federal Highway Administration, appropriate for project-level applications using both deterministic and probabilistic (Monte Carlo simulation) approaches. Costs and benefits are based on the leverage between RUCs and agency costs;

7. **MicroBENCOST** (internet ref. 7)was developed in the early 1990's through the National Cooperative Highway Research Program as a framework for performing highway user cost-benefit analyses. MicroBENCOST is designed to analyze different types of highway improvement projects on a corridor. Benefits are calculated for existing and induced traffic, as well as for diverted traffic in the presence of a competing parallel route or when a bypass project is evaluated. The benefit categories considered are user travel times, VOCs, and accidents. The cost categories considered are total initial costs, salvage (residual) value at the end of the evaluation period, and

rehabilitation and maintenance costs during the analysis period. It also uses the simple ratio between benefits and cost for a set of alternative scenarios.

2.2.5. Challenges within pavement maintenance systems

In the area of PMS there are advanced systems that are emerging constantly worldwide. These systems are based on large databases with historical condition data, and in many cases advanced optimization techniques. However, available commercial software is more general, at best leaving plenty of room for users' adaptation of the models and processes.

There are constant advances in prediction modeling in terms of costs and pavement behavior, which are particularly important in reaching realistic and custom-made solutions. Unfortunately, in most cases, cost prediction is derived solely from historical data and BoQs.

Also, it is essential to find an optimum between the generalization that is needed for network-level optimizations and the level of detail used in project-level analyses. The models have to be adopted for local conditions, but general enough to be easily applied to network level problems.

There is also a need to find a balance between optimization routines that are exhaustive, i.e., based on testing a set of usually-applied maintenance options, at different trigger levels, and optimization routines that may use a wide range of possible solutions, but converging to a local minimum which may or may not be close to the "real" optimum.

Each road network is largely defined by its country-specific context, requiring strategies in line with the local economic, political, and societal climate, introducing additional limitations and requirements. The available budget leads to budget constraints; political decisions may introduce further restrictions in the available budget as well. This requires setting realistic maintenance and quality goals, keeping in mind the overall tendency toward the "optimal" solution. Also, the available budget may not be fixed annually; therefore, fluctuations in the available budget may also be taken into consideration.

The sensitivity of the overall model is highly significant, since the analysis is conducted for a long time period, dealing with future events, during which many unexpected changes may arise. This is especially the case in assessing traffic projections which may lead to unexpected increases in traffic causing a steep deterioration in parts of the road network, or unexpected decreases in traffic, causing drops in income, e.g., collected through tolls.

A special issue arises with inherited maintenance backlog, which increases the needed resources both in terms of available funds, but also in the capacity of the local construction industry to carry out the increased amount of work. For example, Serbia experienced a cease in construction during the 1990's economic isolation influenced by difficult political times in the country, which produced a significant drop in the overall mobility and a considerable backlog since there were almost no maintenance interventions on the state network for almost 10 years.

Until recently, the optimization problem was simply denominated as the problem of finding the minimal overall cost. This implies that all the costs and benefits are monetized. This may be rather problematic, especially when expressing the value of persons' lives and injuries, the value of disturbance and/or annoyance, the value of pollution to ecosystems, etc.

Another solution is to treat all the societal costs and benefits through multi-criteria optimization, allowing for each objective to have its own weight relative to all the others. However, assigning weights to different objectives and strategic decision making is not always possible from the stand point of a road manager. For example, is the "do nothing" scenario even an option, if there is a need to respond to the needs of all users regardless of traffic volumes?

Lastly, new technologies are emerging in terms of new materials and new pavement technologies, which have to be considered, at least in the beginning, from a theoretical stand point, in order to make room for future applications.

2.3. Environmental considerations in road maintenance optimizations

"Improving the sustainability of pavements requires a better understanding of how this infrastructure impacts the natural environment."

(Loijos et al., 2013)

It was previously established that RUCs are one of the main drivers of the total societal costs related to pavements, and that they include the cost of time, VOC, and the like. However, RUC may be defined more broadly, including not just monetary, but also socio-economic and environmental aspects, such as

- the cost of noise and disturbance,
- the cost of biodiversity loses,
- the cost of greenhouse gas (GHG) emissions, and
- cultural or heritage damage.

In more narrow terms, *the environmental impacts* include emissions to air, discharges into water, and the generation of solid waste (Park et al., 2003.) and were categorized by Huang et al.(2009a) in several groups (Figure2.5):

- Global warming – determined through emissions of CO_2, CH_4, N_2O
- Stratospheric Ozone depletion
  - Acidification, determined through emissions of SO_2, NO_x, NH_3
  - Photo oxidant formation (ground level ozone or fog), determined through emissions of SO_2, NO_x, CO, CH_4, NMVOC
- Human toxicity
  - Emission to air determined through emissions of SO_2, NOx, CO, HCd, NMVOC, PM_{10}, NH_3, heavy metals
  - Emission to water determined through emissions of HCd, heavy metals
- Eco-toxicity (fresh water, marine, and terrestrial)
  - Emission to air determined through emissions of HCd, NMVOC, heavy metals
  - Emission to water determined through emissions of HCd, heavy metals
- Eutrophication determined through emissions of NO_x, NH_3, COD, Phosphate, Nitrate
- Noise
- Depletion of minerals, fossil fuels and landfill space.

All those impacts are more easily apprehended if evaluated through their damage to ecosystems and human health, and through the depletion of resources (Blankendaal et al., 2014.). For example, the impact of pollutants such asSO_2, NO_x, and CO can be judged if they are categorized into photochemical smog formation or human toxicity (Santero et al., 2011a).

Furthermore, among the vast number of environmental impacts, Huang et al. (2009a) proposed a matrix for assessing the priority (i.e., low vs. high) and reach (i.e., local, regional, or global) of each impact (shown in Figure 2.5). For example, asphalt fumes during construction might pose an occupational exposure hazard to workers in the form of respiratory problems, eye and throat irritation (Horvath and Hendrickson,1998) which is a threat to human health—a local effect of medium priority.

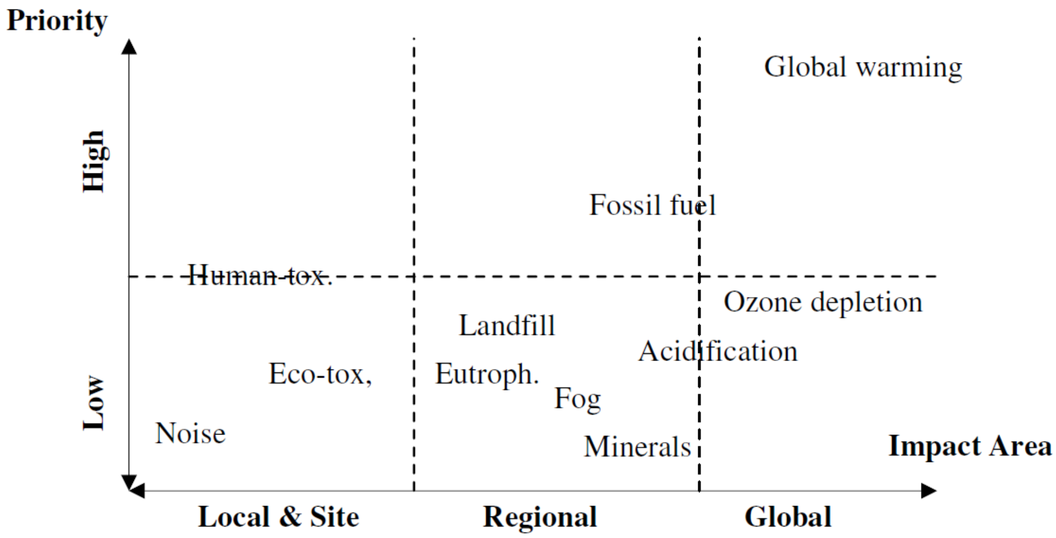


Figure 2.5 Grouping and weighting of environmental impacts [Figure by Huang et al., 2009]

From Figure 2.5 it is clearly seen that global warming has a very high global influence, which is assessed through emissions of GHGs. CO_2 emissions are the principal contributor to global warming, i.e., their emission levels often are a sufficient impact indicator (Santero et al., 2011a).

The European Union, through its legislation (European Commission White paper, 2011), has set a clear objective to reduce GHG emissions in the transport sector by 60% of the1990 levels by 2050 having in mind that the transport sector accounts for nearly 25% of all CO_2 emissions (European Commission, 2014), and the road transport mode accounts for 71.7% of the transport sector. Similarly in the USA, the *road transport* sector accounted for 83% of emissions from the transport sector and for 27% of all emissions in 2007 (Environmental Protection Agency, 2009, Loijos et al., 2013). Similar examples can be found worldwide, i.e., in the republic of Korea the transport sector accounts for 17% of total national GHG emissions, and has been considered as the second largest GHG contributor (Seo and Kim, 2013). In the USA, two of the tree top categories for CO_2 emissions result from pavements (White et al., 2010)

Those data put responsibility on road agencies to, in addition to minimizing total maintenance costs during a certain period of time, include environmental considerations into the decision making process. In the last decade, public awareness of global environmental problems such as global warming and ozone depletion has been increasing (Park et al., 2003), especially in the domain of the transport sector.

Overall GHG emissions can be lowered in three manners: (i) use energy efficient, clean cars, (ii) reduce vehicle miles traveled, and (iii) lower emissions from pavements (Wang et al., 2012). Since the assessment of environmental impacts (especially for major projects) is becoming mandatory in many countries, there is a distinctive need for research projects assigned to evaluate the environmental impact of different pavements materials, technologies, or processes over the road life cycle (Guistozzi et al., 2012).

Although environmental impacts affect greatly road users as well as neighbors and the general public, they are not so easy to include in a LCCA tool. One of the most common approaches is to monetize those influences, and then to include them into the LCCA. Pellecuel et al. (2014) even succeed to monetize the cost associated with biodiversity loss, productivity loss, building damages, and health effects, and determined a very strong relationship between pavement conditions and society costs associated with environmental impacts. However, maintaining the road network in an excellent condition is very costly and every maintenance activity leads to additional negative influences due to construction works needed for maintaining the pavement network.

“LCA provides a valuable opportunity to decrease the environmental footprint associated with the vast and essential infrastructure system”(Santero et al., 2011b).In pavement LCAs, environmental performance was usually evaluated using

- Energy consumption,
- Air pollutants (e.g., SO_2, NO_x, CO, particulate matter),
- GHGs,
- Nitrogen releases into water,
- Hazardous waste generation,
- Heavy metal releases, etc.

Energy consumption is an important issue from both a social and environmental aspect, as it is closely tied to energy security and usage of non-renewable natural resources.

2.3.1. LCA analysis

LCA is considered as the basic technique when it comes to the assessment of environmental impacts throughout the life cycle (Ekvall, 2002) and has been applied to date by a number of researchers, to various infrastructures, including highways (Park and al., 2003). LCA offers a comprehensive approach to evaluate and improve the environmental impacts of pavements (Loijos et al., 2013.)

However, series of ISO standards give guidance for the application of LCA analysis on pavements. LCA involves six pavement life cycle phases (ISO 14040:2006):

- Material extraction and production,
- Construction, maintenance and rehabilitation,
- Transportation of materials,
- Work zone traffic management/traffic delay,
- Usage, and
- End-of-life.

Material production involves the raw material extraction and initial processing, and transport to the asphalt plant and later to the construction site, as well as material manufacturing within the asphalt plant.

Pavement interacts with the environment through rolling resistance, albedo, carbonation (only in concrete pavements), lighting, and leachate.

Rolling resistance describes the vehicle energy loss due to driving on a pavement. Although it primarily depends on properties of tires, the structure and roughness of a pavement is also an important factor. Roughness only accounts for a portion of the rolling resistance, through the energy used to deform either the pavement or the tire, instead of moving the vehicle. For example, driving on a rough pavement increases the vehicle gasoline/diesel usage. However, Lepert and Brillet (2009) demonstrated that the type of pavement distress that most increases atmospheric pollution is longitudinal unevenness within a short wavelength, i.e., when road works are introduced to correct longitudinal profiles, rather than texture, the emissions benefit may be substantial.

GHG (CO_2, CH_4, N_2O) emissions

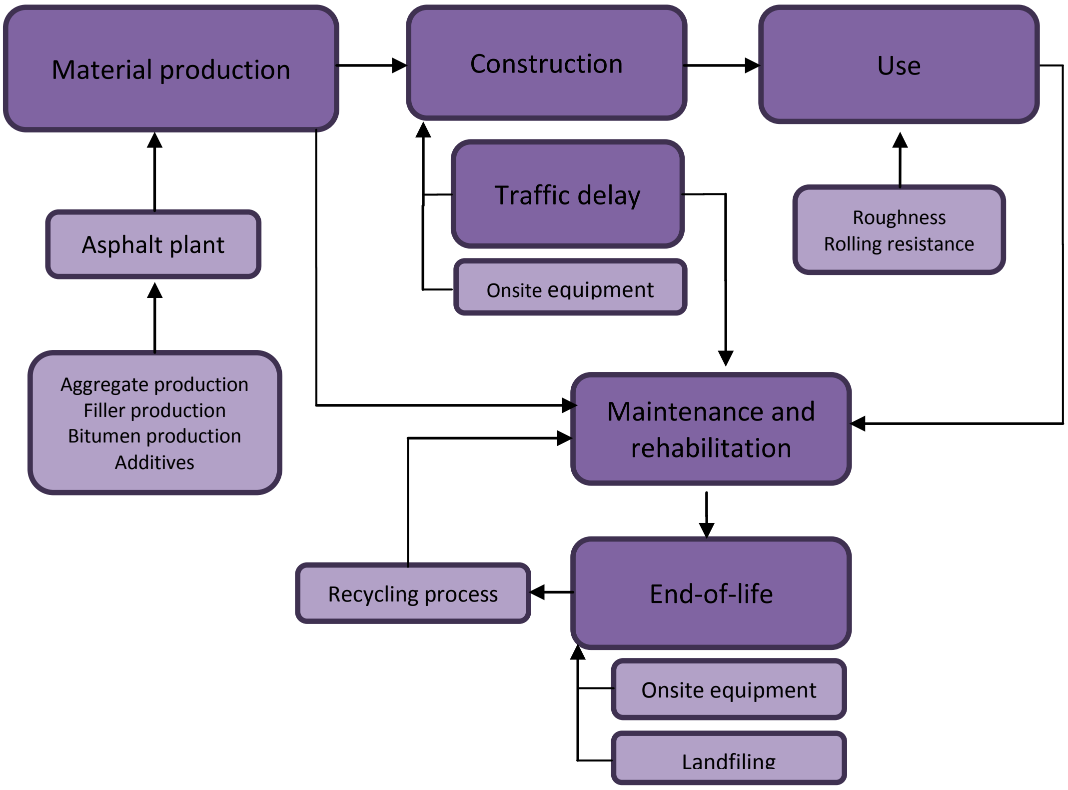


Figure 2.6 Lifecycle of a pavement

The amount of reflected radiation from the pavement is known as a surface's *albedo*, which ranges from 0 (complete absorption) to 1 (complete reflection). That means that a pavement with a higher albedo helps mitigate climate change impacts.

Electrical lighting is relevant in the pavement's life cycle only if the pavement itself affects the energy demand needed to adequately illuminate the roadway.

Leachate is any substance that poses a threat to drinking water and aqueous ecosystems, due to pavement materials leaching on aquatic toxicity. Among the usually applied maintenance treatments, the only concern may be reclaimed asphalt pavement (RAP) and asphalt sealcoats, as the RAP was exposed to vehicle exhaust, lubricating oils, gasoline, diesel fuel, and tire particles during its initial operating life.

Traffic delay is caused by the lane or road closures necessary to construct and maintain a pavement, influencing the formation of queues and associated slowdowns. In economic models it is often measured by the number of cars delayed, amount of time spent in queues, and the value of time, but should be also considered through an increase of emissions due to slower vehicle traffic.

End-of-life of a pavement can be one of three scenarios: (i) demolished and disposed on a landfill, (ii) demolished and recycled, and (iii) remaining as a lower layer in a pavement structure (Santero et al., 2011b).

Those phases represent all stages of a product's or process' life (Horvath and Hendrickson, 1998), i.e., from "cradle" to "grave" (Yu et al., 2013)The analysis involves the quantification of environmental burdens (inventory analysis), estimation of impacts on humans and nature (impact analysis), and identification of possible improvements (improvement analysis) (Horvath and Hendrickson, 1998).

Each of the phases contributes to total cost and total emissions during a life cycle. If considering LCA applied on highways, Park et al. (2003) concluded that the *material production phase* was the most significant contributor to overall GHG emissions during a 20-year analysis period, followed by the *maintenance and repair* phase, *initial construction*, and lastly the *end-of-life* phase. However Park et al.(2003) did not include in the analysis the *usage phase* and *work zone modes*.

For example, research shows that emissions decrease in a *work zone* since the roadway capacity is lower, however, emissions rates increase per vehicle because of driving at a lower speed or performing a detour (Avetysan et al., 2014). Barth and Boriboonsomsin (2008) showed that total CO_2 emissions during *traffic congestions* can be lowered up to 20% by (i) reducing congestions and allowing free-flow, (ii) reducing high free-flow speeds, and (iii) eliminating stop-and-go driving patterns. This research also proved a high correlation of CO_2 emissions to lower speeds (lower than 20 mph) and also an increase in CO_2 emissions at very high speeds (over 80 mph), i.e., even small changes in traffic speed can have a significant effect on CO_2 emissions. The same conclusion was reached by Pellecuel et al. (2014) for speeds under 40 km/h.

Weiland and Muench (2010) argued that when it comes to *material production* and *construction* phases, as the most influential ones, there are several ways to improve the ecological footprint by using Warm Mix Asphalt, WMA, (instead of Hot Mix Asphalt, HMA) and/or RAP. Blankendaal et al. (2014) also showed a reduction of environmental impacts of about 33% through the application of WMA instead of HMA.

Horvath and Hendrickson (1998) took into account sustainable development and environmental impacts when choosing the type of pavement (rigid structure with reinforced concrete or flexible structure with asphalt concrete), and concluded that asphalt pavements appear to be an environmentally better choice, primarily because of their recyclability in the disposal phase. A similar conclusion drove Kucukvar and Tatari (2012), while applying an eco-based hybrid LCA model for evaluating emissions related to continuously reinforced concrete and HMA pavements, also suggesting that the use of RAP and fly ash can significantly reduce energy consumption.

Furthermore, road traffic class and traffic foundations determine significantly the trade-offs between the abovementioned phases of a pavement’s lifecycle. Santos et al. (2014a) argue, based on the results of applying a LCA model to a case study on Portuguese roads, that on low volume roads the most dominant is the “material” phase, compared with roads with high traffic levels where the “usage” phase is by far the most prevailing. The authors also highlighted the influence of the bearing capacity of the foundations in case of high traffic volumes. The results showed lowering overall environmental impacts, since strong foundations require the construction of thinner pavements.

Similarly, Wang et al. (2012) concluded that rehabilitating a rough pavement section with high traffic volume has a great potential to reduce fuel consumption and GHG emissions. However, for sections with low traffic volumes, such interventions may not be beneficial from neither an environmental nor economic stand point. In such cases, the authors claim that construction quality and the selection of appropriate treatments and materials are very important, and determine whether there is a net positive or negative effect on emissions and energy use. However, the statement cannot be generally applied. Moreover, several authors (Wang et al., 2012, Santero et al., 2011a, 2011b, 2011c) strongly argued that comparisons between the results from various LCA studies cannot be made due to prominent distinctions in functional units, such as traffic levels, analysis periods, geographical regions, design standards, electricity mixes, production practices, maintenance schedules, and axle loadings.

Santos et al. (2014a 2014b, 2014c) discussed how the LCA methodology, although it is a very convenient method for such analyses, in pavement management is only in its “embryonic stage” for multiple reasons, including assumptions that environmentally-friendly solutions may lead to additional costs, a lack of tools and data in that area, lack of guidelines, and numerous additional sources of uncertainty. Some of the previous research also confirmed that optimization objectives based on minimizing GHG emissions may lead to more frequent maintenance activities than when the objective is based solely on cost (Yu et al., 2012). On the other hand, Gosse et al.(2013) have found that GHG emissions have been strongly coupled to economic expenditures, i.e., minimization of GHG emissions also improves the economic performance of a road network.

Jullien et al.(2012) examined the variability of environmental impacts solely in the aggregate production phase and concluded that the discrepancy shown by the results for global warming potential ranged from –15.4 to +12.9, depending on the quarry process, equipment age, and use. Loijos et al. (2013) analyzed life cycle climate impacts on the US concrete pavement network and have emphasized that the obtained results were the most sensitive to the traffic volume, varying the results up to 60%. Yu and Lu (2012) and Horvath and Hendrickson (1998) also reported a significant degree of uncertainty in results of LCA pavement analyses. Both research teams applied LCA on three types of pavements (e.g., asphaltic, cement and crack, seat and overlay), and concluded that the material production, congestion, and usage phases contribute the most in overall air pollution.

Kim et al. (2012) developed a framework for estimating GHG emissions due to asphalt pavement construction based on the material type and geometric shape of the structure and earthwork quantities, with an average estimation error of 11.2%, using an ANN and parametric calculations.

Kendall (2012) proposed a method for developing time-adjusted global warming potential which use the reference gas CO_2 (GHG gasses CO_2, CH_4, and N_2O have been converted to CO_2-equivalent today). This process can allow easy integration of GHG emissions into policy frameworks using the open-source calculation tool TAWP.

2.3.2. Model and tools for conducting LCA analyses

There is a vast number of available LCA tools and software. However, many of these are calibrated to local conditions (e.g., designed for application in certain country, based on local materials and data) or are specifically designed to assess a certain phase of a pavement's life cycle. They also differ in the level of detail, technical and data requirements, and available outputs.

One of the best known software is **SimaPro** (internet ref. 8) which is a commercial tool for LCA analysis, especially suitable for assessing the impacts during the material phase of the life cycle (Qian et al., 2013). This is not a tool customized for road and pavement applications; it has a much wider reach.

The latest version of **HDM-4** and **RUCKS**(internet ref. 9), which are designed for road and highway applications, also include environmental impacts, and may be very suitable tools for assessing environmental impacts during the usage phase.

PaLATE (internet ref. 10) is an Excel-based tool for LCA of pavements and roads. The tool takes user input for the design, initial construction, maintenance, and costs for a roadway, and provides outputs for the lifecycle environmental effects and costs. The investigated environmental effects include

- energy consumption,
- CO_2 emissions,
- NO_x emissions,
- PM_{10} emissions,
- SO_2 emissions,
- CO emissions, and
- leachate information.

MOBILE 6.2 (internet ref. 11)**,** developed by the US Environmental Protection Agency, is a complementary tool with PaLATE since it models and calculates vehicle emissions (e.g., very useful if the congestion module is to be analyzed).

NONROAD (internet ref. 12) was later replaced with **MOVES2014** (Motor Vehicle Emission Simulator)(internet ref. 13) which is a highway vehicle emission model also developed by the US Environmental Protection Agency and can calculate air pollutants, greenhouse gases, and air toxics, based on emission factors and traffic fleet composition.

Athena Pavement LCA(internet ref. 14), developed by the Athena Sustainable Materials Institute, is a free LCA-based software package that measures environmental impact of Canadian and US roadway designs in terms of materials manufacturing, roadway construction, and maintenance life cycle stages in line with ISO 14040 and ISO 14044 standards.

There are also a number of tools dealing with specific phases or issues related to LCA of pavements as presented in Table 2.1.

Table 2.1 Available LCA tools and software

Tool/Year	Acronym / Developer	Application	Open source	Internet Reference
CHANGER	Calculator for Harmonized Assessment and Normalization of Greenhouse gas Emissions for Roads/IRF	Construction, maintenance, production of materials phase	NO	15
ROAD-RES	A doctoral dissertation from the Technical University of Denmark	Pavement construction and maintenance works	NO	16
ROADEO	World Bank	Calculates GHG emissions at the planning, design, and construction phases	YES	17
asPECT	Asphalt Pavement Embodied Carbon Tool/ TRL	Calculates the embodied carbon of different types of asphalt pavement	YES	18
PE-2 (2012)	Project emission Estimator	Carbon footprint for construction and maintenance projects	YES	19
CFET (2013)	Carbon Footprint Estimation Tool for Transportation Construction Projects	Carbon footprint for construction and maintenance projects	NO	20
CMS RIPT (2011)	Transport Scotland	Overall carbon footprint for road projects	NO/Upon request	21
CAL B/C	Caltrans	Overall cost and benefits, usage and construction phases	YES	22
CEEQUAL	Civil Engineering Environmental Quality Assessment and Award Scheme	Sustainability assessment, rating and awards scheme for civil engineering	NO	23
BE2ST-in-Highways	Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways	Assessing highway construction projects	YES	24

2.3.3. Project and network level applications

LCA can have various applications in the area of pavement management, and therefore is considered as a widely used tool for determining the sustainability of various proposed solutions, e.g., use of different materials and different technologies for pavement rehabilitation and reconstruction. There are a number of research efforts, usually performed *on a project level*, dealing with a certain aspect of pavement LCA. Park et al.(2003) conducted quantitative assessments of environmental impacts on the life cycle of pavements and concluded that LCA can be used as a design tool in the pursuit of more environmentally sound alternatives. White et al.(2010) developed a customizable model for road designers and transport officials to evaluate the impact of material production and road construction of different pavement types on climate change, i.e., direct CO_2 emissions.

However, the largest number of research on the subject has been published in the last six or seven years, when there was a sudden growth of awareness about the importance of this topic. Since then, several papers have been published related to the application of LCA analyses on the project level regarding maintenance works on roads and highways (Huang and al., 2009a, Huang and al., 2009b, Lepert et al., 2009, Weiland and Muench, 2010). For example, Huang et al. (2009b) applied a LCA model to the London Heathrow Terminal 5 asphalt paving project in which natural aggregates were substituted with waste glass, bottom ash from an incinerator, and recycled asphalt pavement.

Only after a two-part critical review (Santero et al., 2011a, Santero et al., 2011b) research efforts become significantly more detailed and the range of application much wider, as the authors at MIT (Massachusetts Institute of Technology) and UC Berkeley (University of California, Berkeley) gave guidance for the state-of-practice of LCA for pavements, providing critical comments on the strengths and weaknesses of the body of work, and related knowledge gaps that required further research, i.e., the authors have developed future research directions for improving pavement LCAs especially from the aspect of decision making in a policy-setting context. They provided a separate analysis during each stage of a pavement’s life cycle, then introduced the concept of uncertainty and questioned the adequacy of the comparison and interpretation of the obtained solutions.

After that, the field of application of LCA analyses, regarding pavements, is expanding to analyses of environmental burdens related to the application of preventive maintenance (Giustozzi et al., 2012), winter maintenance (Fitch et al., 2013), maintenance works that include recycling and use of reclaimed asphalt (Santos et al., 2014b) and the like. Guistozzi et al. (2012) described a methodology for assessing the environmental impacts of preventive maintenance activities during a pavement's service life through a multi-attribute LCCA, performance and environmental analysis, without the integration of the three. A life cycle approach has also been employed in choosing between the leading and most-used winter maintenance chemicals in Virginia (USA), to reduce negative environmental impacts of these activities (Fitch et al., 2013).

Typically, LCA is applied to the project level regarding roads maintenance when a number of specific information on the project becomes available, while it is far less frequently applied during the strategic analysis and decision-making phases at the road network level (Bryce et al., 2014). Also, there are very few examples where strategic-level decision making has been combined to include both aspects: cost analysis throughout the life cycle (LCCA) and the analysis of environmental impacts (Zhang et al., 2013).

2.3.4. Integrated models

One of the first attempts at integrating LCA and LCCA analyses was performed by Zhang et al.(2008) by comparing a concrete overlay system, an HMA overlay system, and a cement composite during a 40-year life cycle accounting for all six phases of a pavement's life cycle. The integration was performed by monetizing the cost of CO_2 per t, which allowed the comparison of both emissions and total costs of the three analyzed systems.

Yu et al. (2013) used a combined LCA–LCCA, i.e., an integrated model to optimize the pavement maintenance planning while also incorporating environmental damage costs and estimating marginal damage costs of various air pollutants, also on a project level. Similarly, Qian et al. (2013) employed an LCA model alongside with an

LCCA analysis to determine the sustainability performance of different overlays (including a concrete overlay, an HMA overlay, and a cement composite overlay), but without the integration of the two modules. Zhang et al.(2010) developed an optimization model based on dynamic programming for the comparison of the aforementioned three overlay systems in terms of minimizing the total lifecycle energy consumption, GHG emission, and costs on a project level.

The developed optimization method by Zhang et al. (2013) was later applied on the road network level as well, in order to minimize total lifecycle energy consumption, GHG emission, and costs as a single objective while meeting budget constraints.

2.4. Conclusion: Identification of key knowledge gaps

"Increasing demand, shrinking financial and human recourses have made the task of maintaining the infrastructure more challenging than ever before. Infrastructure systems have gradually deteriorated with age as a result of environmental and use that in many cases significantly exceeds the design expectations. Decision makers must distribute limited resources so that infrastructure systems are maintained in the best possible condition … they may help bridge the gap between infrastructure condition and user expectations."
(Flintsch and Chen, 2004)

Prediction methods and tools regarding estimating future costs of maintenance works are constantly evolving, allowing the handling of large data samples and exploring the significance of a large number of potential variables. What remains a great challenge, even now, is to create a data sample with a large variability of data, beyond just a country context, that can serve for the creation of cost estimation models applicable to different networks.

Furthermore, variables most commonly used in cost prediction modeling are limited to BoQs and detailed project information. There is an obvious need to further explore the influence of the country-context, global economic situation, political, regulatory, and societal aspects that can even be predominant drivers of cost increases/decreases.

Advancements in cost modeling include the use of soft computing techniques, which can be superior to traditional RAs in terms of goodness of fit. However, they require the inclusion of comprehensive hypotheses and engineering assumptions in order to generate outputs that are in line with real life behavior. If not, if just applied as “black box” tools, those methods may be misleading, leading to over-fitting the data sample, but inadequate in other situations.

Similarly, the area of optimizing and planning future maintenance needs of a road network also experiences constant advancements in optimization tools and techniques. For example, the use of Gas has allowed the handling of extremely large data samples, and almost infinite numbers of combinations of possible interventions and corresponding trigger levels.

The setting of the system has to account for local practices and to be in line with realistic projections, but to be general enough, i.e., to be applicable on various networks.

However, there is also great room for improvement, especially in terms of a holistic recognition of the overall problem of “optimal” maintenance. This involves the inclusion of a wider range of costs and benefits especially in terms of societal costs. Until recently, monetary expressions of all costs were predominant in all such analyses, but the question is: “Is it possible to value all that surround us through money?” Even if so, assigning monetary values may lead to a great increase in uncertainty of the overall model.

More specifically, in recent years, there is an increase of awareness about the influence of transport systems on global warming, but also on the quality of life, life expectancy, preservation of ecosystems, and the like. This influenced the strong need to include environmental consideration into PMS.

When it comes to the assessment of emissions and the impact on the environment over a pavement’s life cycle, it is a subject that has become topical only in the last five to ten years. To date, only a few scientific teams at the world's most prestigious universities (MIT, UC Berkeley, The University of Nottingham, and others) tried to respond to a particular aspect of this problem.

There is a very limited number of attempts at solving the problem of finding the optimal maintenance plan on the network level, that include both LCA and LCCA analyses, taking into consideration environmental and monetary costs. To the authors’ knowledge, there were no previous attempts to integrate those models with cost estimation modeling, and to reach the optimum without monetizing the overall cost and benefits, and without assigning relative weights to conflicting objectives in the multi-criteria analysis.

CHAPTER 3: MODEL DEVELOPMENT

"Roughness is a key factor in assessing road performance and determining the user cost. However the road surfacing conditions including the cracking, spalling, and potholes are as well the important indexes to measure road performance. A combined road performance index may be developed in the future to more accurately measure the change of road performance over the service life."

(Gao and Zhang, 2013)

3.1. Methodology

The overall methodology of the conducted research is presented in Figure 3.1.

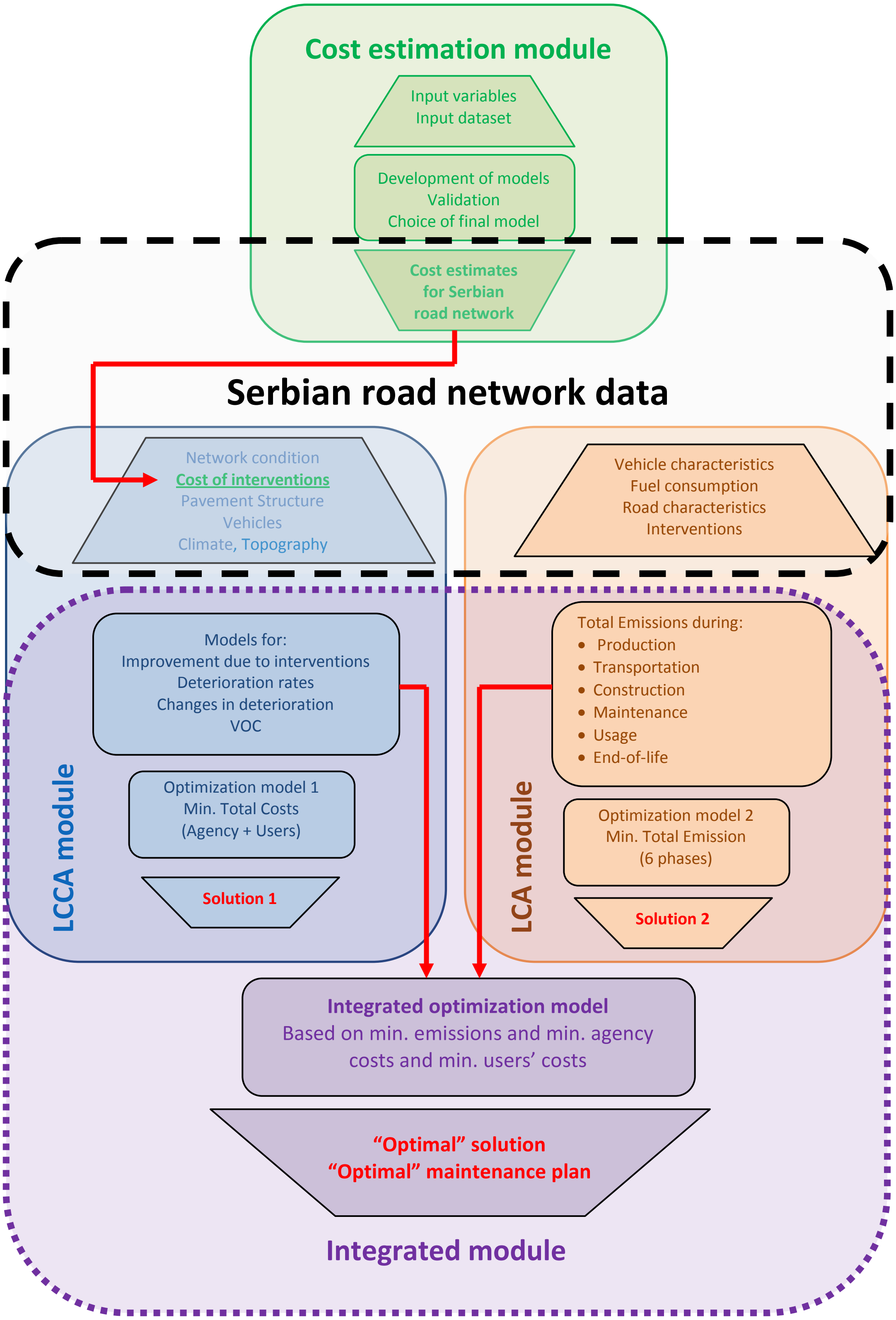


Figure 3.1 Flow chart of the integrated model

A tool named IronMaP (**I**ntegrated **Ro**ad **N**etwork **Ma**intenance **P**lanning tool) has been developed to serve the objectives of this research. The tool comprises three modules: cost estimation, cost allocation (LCCA), and environmental considerations (LCA). Finally, the integrated module combines these three modules, and produces a close-to-optimal solution in terms of future maintenance needs for a certain time period.

The input parameters considered are traffic volume and composition, length of road sections, current condition, structural number, and age, as well as the cost of maintenance, VOC, and emissions during various phases of the pavement's life (Figure 3.1). For each module, a set of maintenance treatments was used, which involved traditional but also up-to-date, high-performance maintenance treatments.

The tool then produces three different maintenance strategies, based on optimization considering a set of possible maintenance treatments applied for a wide range of possible triggers. The first scenario evaluates only the cost related to the application of a pavement maintenance treatment and corresponding VOC, for a number of different thresholds (conditions under which the specific treatment is to be applied). The second scenario uses the same routine, but taking into consideration emissions of CO_2 during the pavement's life. Finally, the third scenario assigns a monetary value to the emissions in order to reach an overall "optimal" strategy that considers agency costs, RUCs, and environmental impacts.

The optimization within the first two scenarios is based on exhaustive search, and gives an optimal solution in terms of minimizing the total CO_2 emissions as well as agency costs and RUCs, during an analysis period of 30 years, using a set of various trigger levels and a wide range of possible maintenance treatments.

The third scenario (or model) consists of applying a multi-objective optimization procedure for a wide range of unit costs of CO_2 emissions. For each unit cost, the optimal solution is determined according to the same procedure as for the previous models. However, after creating the pool of potential "optimal" solutions, the second optimization is performed, based on GAs to develop the Pareto frontier. This gives an outlook on the range of potential optimal solutions and how the unit cost of CO_2 emissions changes the "optimal" solution. The overall optimum is defined from the pavement network optimization maintenance standpoint.

Within this research, the overall Global Warming Potential (GWP), determined by CO_2 emission levels, was assessed during a period of time which included both the production of materials, transportation, construction, reclaiming and transportation to a landfill (end-of-life), and the usage phase, i.e., emissions from the vehicles driving on each road section. CO_2 emissions during the usage phase were assessed through the HDM-4 model (Odoki and Kerali, 2000, World Bank, 2016), while CO_2 emissions during maintenance activities were calculated using the PaLATE software (Horvath, 2003).

During the course of development of the analysis, other GHG emissions and environmental impacts have also been estimated (e.g., CO, NO_x, Energy and Water Consumption, PM_{10}, SO_2, CO, Hg, Pb, particulate matter). However, the calculated emissions accounted for less than 3% of the overall emissions, and for less than 0.1% of emission costs. Therefore, this paper focuses only on CO_2 emissions, while the other contributors may be added in the course of future research as more information becomes available. It is recognized, however, that there is still a great deal of uncertainty when assigning monetary value to emissions.

For the purpose of this analysis, existing road sections of the Serbian main road network were chosen for the application of the optimization model, with a total length of 10,214 km, which is equivalent to 10,808 km of a 7 m-wide road.

3.1.1. Choice of maintenance treatments

In Serbia there is very limited experience with concrete pavements, i.e., in the past 30 years there was no example of such an endeavor on the state road network. Therefore all considered treatments involve only asphaltic pavements.

Also, techniques of preventive treatments such as slurry seals or micro surfacing, are extremely rarely applied due to the insufficient experience of local contractors. That led to investors doubting the possibility of contractors achieving the required quality and durability of performed works. The application of crack sealing and pothole repairs is common on highway sections, and it serves to prolong the period between two consecutive interventions. Such treatments are used for slowing the deterioration progression, and as such were not further considered in the model, since there is not sufficient data on their effectiveness (there are no regular condition surveys on state road networks that can provide data on actual pavement deterioration rates).

Furthermore, the usage of rubberized pavements is also very limited, reclaimed asphalt is usually used only for shoulders, while there were several projects involving cold-in-place and hot-in-place recycling. However, the equipment needed for performing such works is available to only several construction companies, making the price of such works probably higher than in the case of other, more typical types of maintenance works. Furthermore, the application of cold-in-place recycling is a very project-specific decision, as it requires knowledge of the uniformity of the lower layers of the pavement structure, which is difficult to model from the network-level stand point.

Typically on the Serbian state road network, only rehabilitations involving “mill and replace” or overlays of asphalt layers are applied routinely, as well as complete road reconstructions, if needed. Therefore, the choice of treatment was set on:

- Mill and replace using HMA,
- Mill and replace using WMA,
- Mill and replace using reclaimed asphalt from old pavements.

The two later techniques are not often used in Serbia, but may be easily applied with the available equipment. Also, perpetual pavements and the application of a self-healing layer were included in the analysis, since it may be important to analyze the potential applicability of different technologies, even from a theoretical point of view.

Mill and replace HMA is the most commonly applied maintenance treatment that involves milling of the existing pavement in a certain thickness, transportation of the reclaimed pavement to the landfill, production of new asphalt at the asphalt plant, transportation from the asphalt plant, and placing and compaction of the new layer.

Use of *Mill and Replace WMA* requires the same technology as for HMA, but with the addition of a warm-mix additive to the asphalt mix, which allows lower temperatures of production and placement. Lowering the temperature of the mix is beneficial from the aspect of workers, who are in contact with asphalt fumes, and in terms of lowering energy usage in the asphalt plant. This technology is therefore potentially beneficial from an energy and environment standpoint, but is associated with additional costs for the additive used.

Recycling of pavement materials involves the use of a pavement layer that reached its end-of-life phase but, instead of being discarded on a landfill, has found its application as a part of a new asphalt pavement. It can be added to the mixture alongside virgin materials at the asphalt plant, as a substitute for a portion of aggregates and portion of bitumen, or on site, through cold-in-place or hot-in-place recycling. However, it is much easier to evaluate its composition and quality if it's added at asphalt plant. Typically, RAP can substitute for 10–40% of new materials in an asphalt mix. Its use is associated with a lower cost of raw materials, and no waste disposal, but there can be an increase of energy use due to longer mixing in the asphalt plant, and some increase in costs due to the use of additives, e.g., rejuvenators for "old" bitumen.

Self-healing asphalt pavements are applicable only as a wearing course. The mix consists of porous asphalt and metal bars or fibers that may absorb deformations caused by changes in temperature of the asphalt layer. That is why they are called "self-healing" materials. In reality, there are only several applications worldwide, strictly as experimental sections. However, this technology, although associated with significantly higher initial costs of construction, leads to a substantially significant reduction in the pavement deterioration rate, which can be beneficial if the pavement is to be analyzed through its life cycle.

A *perpetual asphalt pavement* is defined as an HMA pavement that is designed and constructed to last for 50 years or more before requiring major structural rehabilitation or reconstruction (FHWA, 2010). During its life cycle, the perpetual asphalt pavement may only need preventive (crack sealing or thin coating) and periodic maintenance (e.g., thin overlays, mill-and-replace), due to non-structural distresses. This technique involves the construction of several layers of durable asphalt mixtures, which increases the initial cost. However, this was proven to be a viable solution and has been applied usually to highly trafficked motorway sections.

.

3.2. Cost modeling

The objective of this section is to present the methodology for developing cost estimation models for asphalt concrete (AC). The development of these models was performed using a dataset containing 200 projects from the Europe and Central Asia

(ECA) region in order to apply the proposed methodology and to obtain models that could be implemented in the Serbian road network pavement maintenance optimization routine, but also in wider practice, i.e., suitable for applications in other countries.

The proposed methodology for model development consists of several steps, as illustrated in Figure 3.2. Following the development of an input dataset, an analysis of variables to be used in the models is performed based on their significance in both engineering and statistical terms. MRA, classification trees, and ANNs are used for the development of the cost estimation models. The next sections provide more details about each of these major steps.

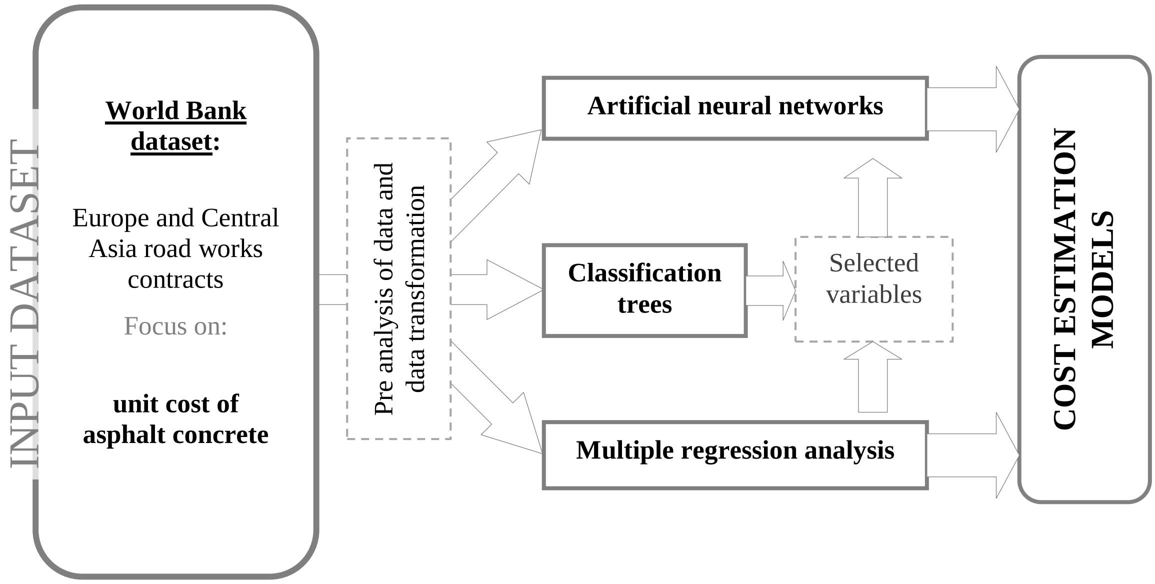


Figure 3.2 Methodology for the development of cost estimation models [adopted from Cirilovic et al. 2013]

Furthermore, cost estimation models were then used as an input for the IronMaP tool. The tool uses the derived regression model, based on outputs from ANNs, classification trees (CT) and MRA.

3.2.1. Variables tested in the models

An important aspect of the research was the selection of variables that are statistically significant for cost estimations of road rehabilitation and reconstruction (RRR) projects, which leads to improved models and a better understanding of the underlying process that generated the data (Guyon and Elisseeff, 2003). The methodology for variable selection may be more widely applicable, not only in ECA countries.

The dependent/target variable in the analysis was the unit cost of AC per cubic meter. The set of explanatory variables that were tested in the models can be divided into the three categories:

- Variables related to oil price,
- Variables that are country-specific,
- Variables that are project-specific.

A detailed list of the variables that were tested is given in Table 3.1.

It was anticipated that the costs might be lower in countries that are net oil exporters, and a dummy variable was used to test such a hypothesis. This and several other variables can be obtained in the World Bank's World Development Indicators database (WDI), which is publicly available (World Bank, 2012). Transparency International (TI) defines corruption as the abuse of entrusted power for private gain. This definition encompasses corrupt practices in both the public and private sectors. The TICPI (Transparency International Corruption Perceptions Index)ranks countries according to the perception of corruption in the public sector (Transparency International, 2011).

The country-specific variables were indications of the specific economic conditions in the country in which the road maintenance/construction project was implemented. The variables were chosen as an effort to identify possible links between the strength of a country's economy and the degree of governance and the costs of road works. Climate conditions were included in the analysis through a dummy variable which took the value 0 if the climate was mild and the value 1 if severe climate conditions were prevailing in the country (Alexeeva et al., 2008, Alexeeva et al., 2011). Depending on data availability, future research could refine this variable, for example in line with the HDM-4 environmental types, which are based on moisture classification (e.g., arid, humid), temperature classification (e.g., temperate cool, temperate freeze), and rainfall in mm/month (Odoki and Kerali, 2000).

Table 3.1Variables tested in the models [Table by Cirilovic et al. 2013]

Data group	No.	Variable	Description	Data availability
Oil price related variables	1	Crude oil price per barrel		200
	2	Diesel fuel price per liter		83
	3	Gasoline fuel price per liter		89
	4	Whether the country is a net oil exporter or importer	A dummy variable equal to 0 if the country is an oil exporter and equal to 1, otherwise.	200
Country-specific variables	5	Country's Gross National Income (GNI) per capita		200
	6	Inflation	The annual percentage change in the cost to the average consumer of acquiring a basket of goods and services that may be fixed or changed at specified intervals, such as yearly.	183
	7	Gross Domestic Product (GDP) growth rate		153
	8	Climate conditions	Dummy variable which took the value 0 if the climate was mild and the value 1 if severe climate conditions are prevailing in the country.	200
	9	Road sector gasoline fuel consumption		134
	10	Transparency International Corruption Perceptions Index (TICPI)	TICPI scores range from 0 (highly corrupt) to 10 (very clean).	194
	11	World Governance Index (WGI)	Measures the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as the 'capture' of the state by elites and private interests.	183
Project-specific variables	12	Number of bidders		166
	13	Number of foreign bidders		156
	14	Number of local bidders		156
	15	Percent of local bidders of all bidders		152
	16	Terrain type	Dummy variable that takes the value 0 if the terrain is flat and the value 1 if the terrain is hilly or mountainous.	28
	17	Expected duration of the road work project (in months)		188
	18	Length of the road works (7m-wide two lane road equivalent)		187
	19	Expected rate of work progression	Expected length of the road works to be completed in one month (km/month) calculated for the projects with a known estimation of project duration, as the average length of road works completed in one month.	174

The number of bidders was used as a proxy for the level of competition in a specific contract, the rationale being that costs would tend to be lower with a higher degree of competition. It was anticipated that performing road work on any kind of difficult terrain conditions would increase the costs. However, during the initial analysis of the dataset, it was found that the value of this variable was not available for most contracts. Using this variable in the model would then substantially reduce the size of the dataset; hence, the variable was not included in the development of the models. The expected rate of road works was calculated for projects with a known estimation of project duration, as the average length of road works completed in one month.

3.2.2. Input dataset for cost estimation

A specialized dataset was developed under a World Bank study, which covers projects in 14 countries of Europe and Central Asia: Albania, Armenia, Azerbaijan, Bosnia and Herzegovina, Bulgaria, Croatia, Estonia, Georgia, Kazakhstan, Macedonia, Poland, Romania, Serbia, and the Ukraine (Alexeeva et al., 2011).The dataset covered 200 completed or on-going road works contracts signed between 2000 and 2010 and included data on contracts above a threshold value of 1 million USD. Out of these 200 data records, 94 records were related to RRR projects. All contract amounts in local currencies were converted into USD using the exchange rate at the bid opening date (OANDA, 2012; Bank of Canada, 2012). The cost per km of road works did not include the cost of structures.

The above mentioned dataset made it possible to carry out cross-country comparisons of the costs of road works and inspired the idea of developing cost prediction models that could be used in ECA countries for strategic planning of road works at the network level. This dataset was used as a basis for developing the model. Additionally, potentially important factors that included the price of gasoline and diesel fuel per liter, inflation, road sector gasoline fuel consumption (RSGFC), perceived level of public sector corruption in the country expressed through the TICPI, and the level of local participation, expressed as the percent of local contractors compared to the total number of firms that participated in the tender, were added to the dataset.

The prices of gasoline and diesel fuel per liter were obtained for each country in the year of the bid opening. In the ECA dataset, the maintenance works were, in most cases, performed on AC pavements; thus it was expected that the price of bitumen would significantly affect the price of road works. The prices of crude oil, gasoline, and diesel are publicly available for all the countries and therefore were used as a proxy for the cost of bitumen (GTZ, 2012). RSGFC was obtained from the World Bank's World Development Indicators database (World Bank, 2012). The values of all variables were the values at the time of bidding, to the extent that it was possible to establish those values.

3.2.3. Model development – Case study for projects in the ECA region

As a starting point, MRA was selected for developing the models since it is easy to interpret and is able to capture the statistical significance of individual variables and potential mathematical relations between the variables. Those models were compared with a model obtained by ANNs.

As ANNs do not deal with missing values, it was important to select the most informative and yet most available variables, which was achieved by using classification trees as an intermediate step.

3.2.3.1. Regression models

MRA parameters can be estimated in several ways, such as ordinary least square (OLS), minimizing lack of fit, and maximum likelihood. In this analysis, the OLS regression equation was formulated as

$$y = \beta_0 + \sum_{i=1}^{p} \beta_i x_i + \varepsilon \qquad \textit{(eq. 3.1)}$$

where y is the dependent variable, x_i are independent variables, p is the number of independent variables, ε is the residual, β_i are the regression coefficients, and β_0 is a constant.

The preliminary analysis of the dataset included removing variables that had a substantial amount of missing data records, followed by performing a test of autocorrelation between the independent variables, as well as an analysis of the sign and the extent of correlation of each independent variable to the dependent variables.

For the initial model development, 18 originally selected variables were tested regarding their significance for the models. It was found out that the variables related to oil prices are highly correlated to each other, and consequently, only one of them was used in model.

In this analysis, four diagnostic methods were used for testing the dataset for outliers: analysis of the (square) residuals, standardized residuals, Cook's distance, and the Leverage matrix. The threshold value for recognizing an outlier, based on the standardized residual, was set to be ±3 standard deviations. For the Cook's distance, the "suspicious" points are the points with a significantly different value of Cook's coefficient compared with the values in the other points (a critical value of 1 was adopted), and for the Leverage distances, the critical value is calculated as $2.5 \cdot p/n$, p being the number of explanatory variables and n being the sample size. Based on the above criteria, no outliers were found, and consequently, no data points were removed from the analysis.

Before the model development, several engineering assumptions were made as the benchmark for the logical testing of the model and its results. First, it was expected that higher prices of crude oil and its derivatives would increase the price of AC, as well as severe climate and terrain conditions and the fact that the country is an oil importer.

The backward analysis method was used for the analysis of variables which should be included in the model. Models were generated as in each step of the backwards analysis one variable is to be removed from the model, i.e., the variable that has the highest p-value (because its contribution to the model is the least significant) or variable that does not comply with previously established engineering assumptions.

Two models were developed, the first one including the price of diesel fuel and gasoline at the beginning of the model development and the second one without fuel costs. As a consequence, two considerably different models were obtained, in terms of the variables selected, the number of valid data points, and the overall precision of the models (as shown in Table 3.2).

Model 1 was generated with only three variables: the price of diesel fuel per liter, the country GNI, and the WGI. These three variables were therefore considered the most significant variables when estimating the expected unit cost of AC. Model 2 was generated without the price of diesel fuel and, consequently, was derived from a larger dataset but with less accuracy.

Table 3.2Coefficients for models for unit cost of AC and corresponding model statistics

Parameter	Model 1		Model 2	
	Independent Variable	**Coefficient**	**Independent Variable**	**Coefficient**
β_0	Constant	-38.674	Constant	57.102
β_{diesel}	Diesel	0.82203		
β_{WGI}	WGI	-65.968	WGI	-68.190
β_{GNI}	GNI	0.021006	$\frac{1}{GNI^{1.67}}$	-1.0612E7
β_C			Climate	25.597
β_{oil}			$\frac{1}{OIL^{2.21}}$	-35743
$\beta_{export/import}$			Oil exporter/importer	86.433
BTICPI				
$\beta_{\%loc}$				
R^2	0.745		0.679	
Adjusted R^2	0.723		0.655	
Standard error	26.676		23.936	
F-value	33.148		29.137	
dataset size	38		75	
p-value	0.01		0.05	

Figures3.3 and 3.4 present the comparison of actual and predicted costs. The x-axis represents the actual costs, i.e., AC unit cost from the database, and the y-axis represents the calculated costs using models 1 and2.

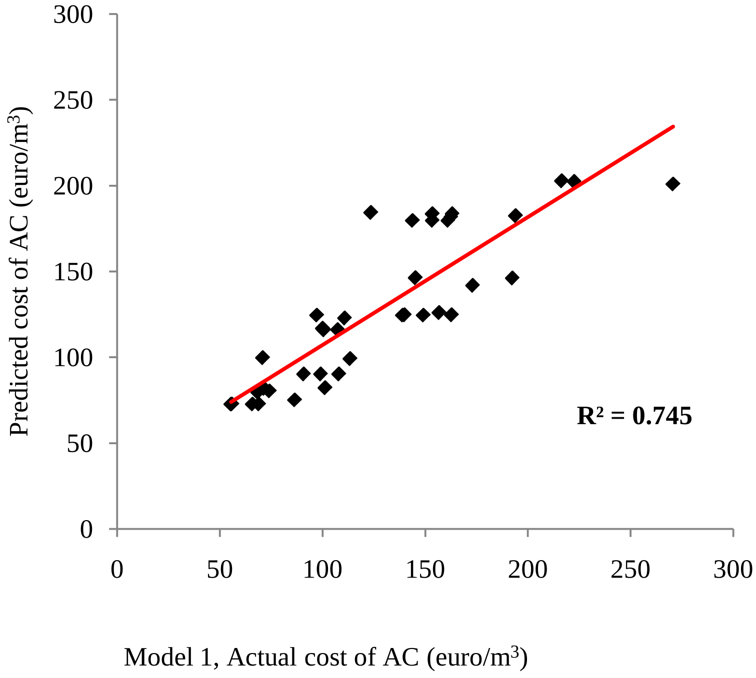


Figure 3.3 Actual vs. predicted costs per km for AC model 1

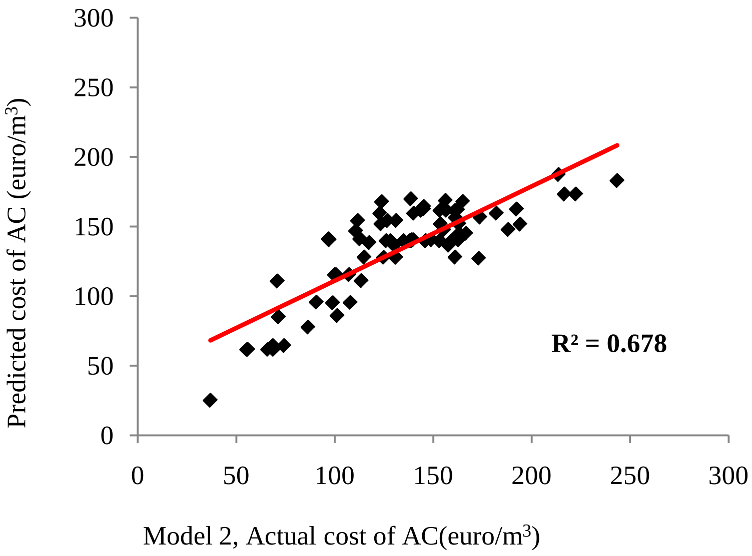


Figure 3.4 Actual vs. predicted costs per km for AC model 2

The coefficients are in accordance with the earlier established assumptions. For example, the coefficient for the variable expressing whether the country was an oil exporter was positive, meaning that cost of AC is higher in countries that have to import the bitumen.

3.2.3.2. Examination of the significance of attributes using classification trees

Since neither MRA nor ANNs could deal with the missing data, classification trees were explored as an additional prediction method in order to investigate variables which may be potentially important for the models, but were abandoned at the early phases of model development due to the incomplete dataset.

Classification trees area classification method for finding the most informative attributes for predicting independent variables. The method is proven to be robust to noisy data, and as a result it gives a set of if-then rules, easily interpreted by the user. All the variables were normalized to corresponding values in the interval [-1, 1] and later divided into subclasses, each represented with a score, as shown in Table 3.3.

Table 3.3 Classes of data according to classification trees

Value	Score
≤-0.8	5
> -0.8 and ≤-0.6	-4
> -0.6 and ≤-0.4	-3
> -0.4 and ≤-0.2	-2
> -0.2 and <0	-1
=0	0
>0 and ≤ 0.2	1
> 0.2 and ≤0.4	2
> 0.4 and ≤0.6	3
> 0.6 and ≤0.8	4
> 0.8	5

The growth of the tree was based on a greedy top-down search, which puts the most informative attribute at the root of the tree. Each of the descendant nodes then becomes a second root node, and the process of finding the most informative attribute for each node is repeated until all data records are distributed to the leaves of the tree.

Figure 3.5 and Table 3.4 present classification trees for unit costs of AC. The exhaustive CHAID (Chi-squared Automatic Interaction Detection) algorithm was used for building the trees, with a minimum of five data records in the parent nodes, and a minimum of one data point in the child nodes.

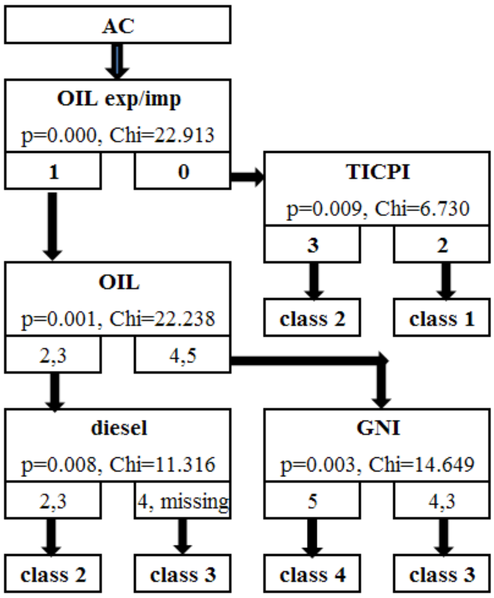


Figure 3.5 Classification tree for unit cost of AC

For defining the unit cost of AC, the variable WGI was the most informative, but since the dataset covers 86 contracts and variable WGI was divided into 11 classes (from –5 to 5), it was excluded from building the tree but was noted as a variable that is possibly very significant for estimating the unit cost of AC. Other significant variables are whether the country is an oil importer or exporter, the price of oil per barrel, the price of diesel per liter, the GNI, and the TICPI (as shown in Figure 3.5). It can be concluded that the selected variables are related to the oil price and its derivatives and to the *global features of a country's economy, but not to the project characteristics*.

The results, obtained using classification trees, are in accordance with the earlier established regression relations and engineering judgments. However, since the target variables are not evenly distributed among the classes, the models cannot adequately cover the entire range of contracts. Although they give some insight into the most important variables, the proposed method could not be used for an accurate prediction, since the size of the dataset is not sufficient for the trees to be fully developed.

3.2.3.3. Artificial neural network models

Compared with MRA, ANNs could be more practical since the input data do not have to follow a specific statistical distribution and do not require predetermination of the relationships between input and output. Moreover, ANNs are more resistant to noise and errors in datasets. Some relatively recent studies (Sodikov, 2005, Wang and Gibson, 2010) have indicated that ANNs can lead to improved solutions compared with MRA.

For performing this analysis, an open-source data mining software, WEKA, was used (Hall et al., 2009). The architecture of the network was projected to have only one hidden layer. The training of the data was performed to minimize the error in estimation, and to achieve maximal coefficient of determination. However efforts were made not to over-train the dataset by observing the coefficient of determination and the overall error of the estimation at 100, 500, 1,000, 2,000, 3,000, 5,000, 10,000, and 20,000 epochs and by performing cross validations.

To compare the ANN models with the corresponding models developed using MRA, the same validation method Leave One Out (L.O.O.) was used. For the estimation of the unit cost of AC, six variables were used (GNI, climate, TICPI, WGI, oil price, and whether the country is an oil exporter or importer), covering 78 contracts. ANNs gave a slightly better coefficient of correlation compared with MRAs, 0.747 after 950 epochs, using the same validation method. Table 3.4 provides a comparison between the models developed using MRA and ANN.

Table 3.4Comparison of cost prediction models developed using MRA and ANN

	AC		
	MRA		**ANN**
	Model 1	**Model 2**	**Model 1**
No. of projects	38	75	78
Variables	Diesel WGI GNI	WGI GNI Climate Oil price OILexp/imp	GNI Climate TICPI WGI Oil price OILexp/imp
L.O.O.R	**0.681**	**0.628**	**0.747**

It can be concluded that, for both models, the coefficient of determination was higher for the models developed using ANNs than for the models built using MRA.

Also, this analysis indicates that the chosen variables describing projects from the available dataset carry information that is relevant in estimating future costs.

3.2.4. Conclusion

This section presented the development of cost prediction models for the AC unit cost based on previously finished road contracts in Europe and Central Asia, from the World Bank database. The basic idea was to identify the most important and available parameters that influence these costs and use different techniques of MRA and ANNs for model development. As the major problem with the datasets was missing or incomplete data, classification trees were used as an intermediate step to evaluate the correctness of the selected parameters.

Two models were developed using RA. The first model was based on the price of diesel fuel, the country GNI, and the WGI. Model 2 was generated without the price of diesel fuel and consequently was derived from a larger dataset, but with less accuracy. The coefficient of determination for these models ranged from 0.679 to 0.745.

The analysis using classification trees confirmed the significance of the variables selected in the RA. The models developed using ANNs were moderately superior compared with the regression models, using approximately the same parameters, with the coefficient of determination ranging from 0.71 to 0.75.

However, although the ANNs did show an improvement in regression, in further analysis, MRA models will be included in optimization models, because of their easer applicability and comprehend-ability to the user.

3.3. Life cycle cost analysis of pavement networks

3.3.1. Basic characteristics of the analyzed network

The IronMap was developed to be able to compare the results for maximum three sub-networks. Those networks may be chosen according to traffic volumes (high volume roads, low volume roads), regions (e.g., eastern, western, central), geographical features (e.g., climate or terrain), their function in the network (inter-state, urban, local), and the like. In the case of the Serbian network, state roads are classified into the three categories by the functional class of the road in the overall network:

1. Motorways
2. State roads class I
3. State roads class II

which is the classification that was used further on.

The total length of Serbian motorways is 682.5 km (or 1,365 km of individual carriageways) which is equivalent to 1,974.53 km of a 7m-wide road. The total length of Serbian Class I state roads is 951 km which is equivalent to 1,029.66 km of a 7m-wide road. The total length of Serbian Class II state roads is 8,045 km which is equivalent to 7,220 km of a 7m-wide road. The traffic level varies in the wide range from AADT of 495 vehicles per day to 74,060 vehicles per day. Current roughness ranges from IRI = 1.59 m/km to IRI = 6.68 m/km.

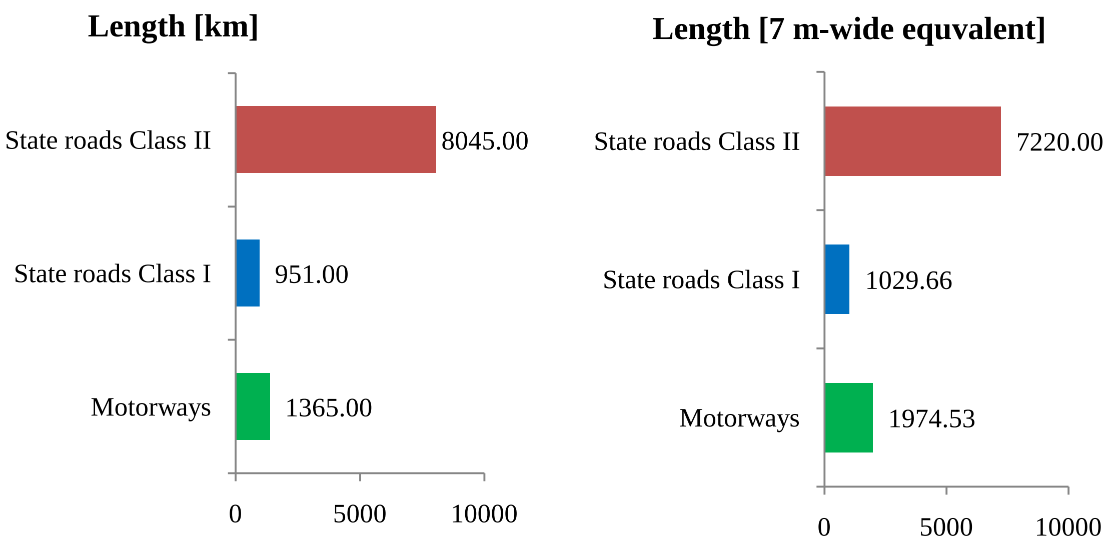


Figure 3.6 Total length of the analyzed state network

Secondly, the model allows for five condition categories: very good, good, medium, poor, and very poor condition; and five traffic levels: very high, high, moderate, low, and very low traffic level. Motorways have generally higher quality requirements than other state roads; therefore, the split by condition is different for motorways than for other roads, as shown in Table 3.5.

Table 3.5Network split by pavement condition

IRI [m/km]	Very good	Good	Medium	Poor	Very poor
Motorways	≤ 2.5	2.5–3.0	3.0–3.5	3.5–4.0	> 4.0
State roads	≤ 3.0	3.0–3.5	3.5–4.0	4.0–4.5	> 4.5

Figure 3.7 shows the network split by condition. Motorways are mostly located in flat terrain, have high traffic volumes and in general are in a good or very good condition. This split was performed in accordance to general practice in this kind of analysis and according to usual Serbian quality requirements for state roads in terms of roughness.

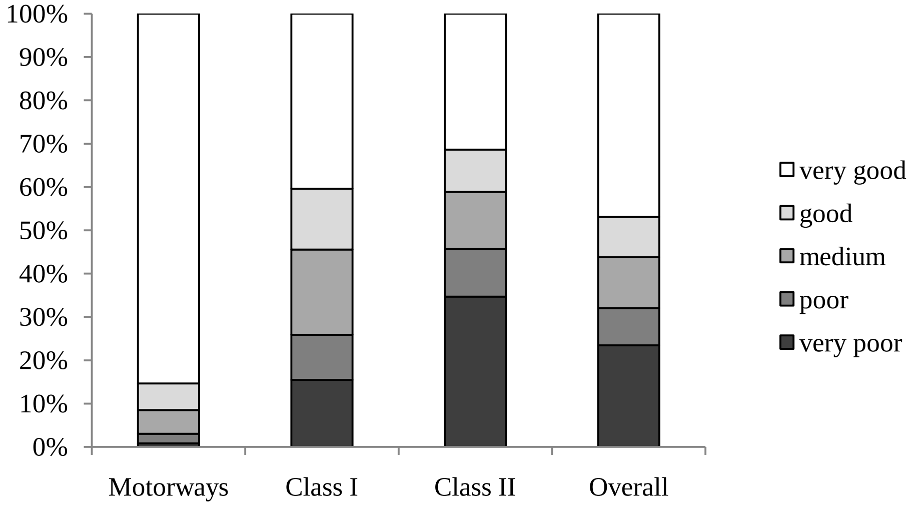


Figure 3.7 Network split by condition.

Figure 3.8 shows the network split by traffic volume. On the motorway network there were no sections with very low traffic volumes. On the other hand, state roads Class I, do not have sections with very high traffic volumes, while state roads Class II, do not have sections with either high or very high traffic volumes. This split ensured a relatively uniform split by traffic, covering a wide range of traffic levels seen on the Serbian road network.

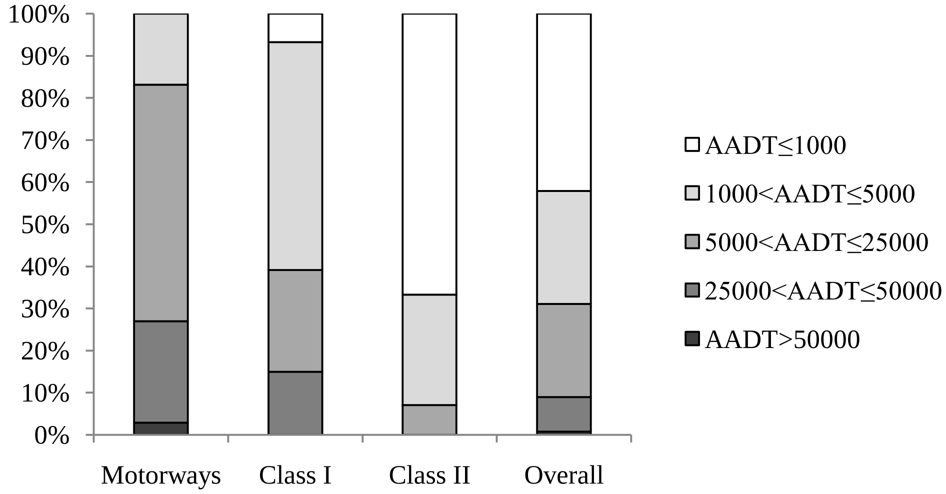


Figure 3.8 Network split by traffic.

The network was divided by road class (motorways, Class I and Class II of state roads), pavement condition (five classes from very poor to very good) and traffic level (five levels from very low to very high) into 75 virtual sections. This example was considered adequate for a qualitative and comparative analysis of the obtained results, yet the model itself can easily handle a much greater number of real sections.

3.3.2. Mathematical modeling of pavement performance

3.3.2.1. Pavement deterioration model

Deterioration of the pavement has multiple effects

- on the road users (fuel consumption increases while the driving comfort decreases when driving on a road in a poor condition, also duration of the journey prolongs when driving on a road in a poor condition), and
- on the environment through increased emissions of harmful gases caused by the slower movement of vehicles.

The IronMaP tool uses an incremental deterioration model, i.e., roughness at the end of each year, IRI(t), is calculated as the sum of the roughness at the end of the previous year, IRI(t–1), and a yearly increment in roughness (Equation 3.2).

$$IRI(t) = IRI(t-1) + \Delta IRI \qquad \textit{(eq. 3.2)}$$

The IRI increment depends on climate characteristics, traffic levels, existing pavement structural number, subgrade bearing capacity, and the current pavement surface condition. The program RONET (Archondo-Callao 2009) uses a simplified incremental deterioration model based on HDM-4, which is to a great extent in accordance to the original HDM-4 pavement deterioration model. That model was employed herein, because of its easier applicability to network-level problems in comparison with the originalHDM-4 model. The RONET model calculates the incremental change in roughness for each year of the analysis period according to the following equation:

$$\Delta IRI = K_{gp} \times (a_0 \times e^{K_{gm} \times m \times AGE} \times (1 + SNC \times a_1)^{-5} \times ESSO + a_2 \times AGE) + K_{gm} \times m \times IRI(t-1) \qquad \textit{(eq. 3.3)}$$

where, a_0, a_1 and a_2 are HDM-4 coefficients that allow calibrating the pavement strength, with default values of 134, 0.7947 and 0.0054, respectively; K_{gp} and K_{gm} are calibration factors of the roughness progression, m is the environmental factor (equal to 0.06 for Serbia, according to the procedure proposed by Archondo-Callao,2009), AGE is the number of years since the last resurfacing, ESSO is the number of equivalent standard axles (80 kN) in millions and SNC is the modified structural number. The modified structural number depends on the value of the pavement structural number and subgrade California Bearing Ratio (CBR), as shown by Equation 3.4.

$$SNC = SN + 3.51 \times \log \mathrm{CBR} - 0.85 \times (\log(CBR))^2 - 1.43 \qquad \textit{(eq. 3.4)}$$

This incremental model was used to estimate IRI annually, based on applied treatments, traffic, and aging of the pavement.

Deterioration rates for existing pavements were adjusted for local condition using calibration coefficients. This means that every virtual section deteriorated by its own deterioration rate which depends on traffic volume, strength of the structure, initial conditions, etc.

The expected rate of deterioration after an application of a certain treatment was separately considered. For example, the deterioration curve for mill and replace (M&R)treatments after the intervention was modified based on the increase in the structural number after replacing the old pavement with a new one (Figure 3.9).

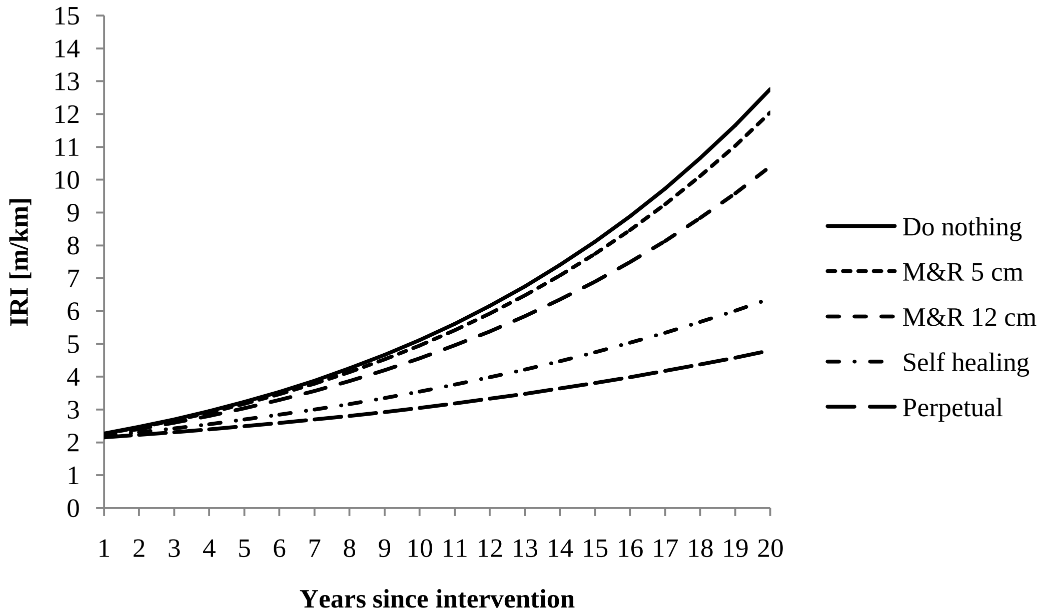


Figure 3.9 Deterioration curves for a high traffic volume section, after an intervention

Sakhaeifar et al. (2013) showed that the IRI of perpetual pavements almost does not change for the first five years. However, the application of this technology requires several maintenance activities during a pavement’s lifecycle, such as overlays and M&R of the wearing course, approximately once every 10, 15, or even 20 years (FHWA, 2010, Sakhaeifar et al., 2013, Haas et al., 2006*)*. Based on examples in the literature, a deterioration curve was modeled to assume an increase in the structural number and a slower rate of deterioration by 50% in comparison with the conventional pavement structure (as shown in Figure 3.9).

Similarly, self-healing materials also experience a retardation in roughness progression by approximately 30% (Tabakovic and Schlangen, 2015). All other maintenance strategies (RAP, WMA) have similar rates of deterioration as conventional pavements(Paterson, 1990, NCHRP 09-47A, 2014), and only a slight increase in structural number was assumed when milling the old pavement and replacing it with a new layer(s).

3.3.2.2. Pavement improvement model

The level of improvement depends on the type and intensity of the treatment, and the pavement condition prior to the treatment IRI(t–1).Following the improvement, there is also a change in the pavement deterioration rate. The models proposed to evaluate improvements due to M&R treatments, in various thicknesses, combine models proposed by Paterson (1990) and Archondo-Callao (2009).

On the Serbian road network contractors rarely manage to achieve a roughness lower than 1.5 m/km on a rehabilitated section, with better results observed on motorways. The minimal value of IRI is 1.1 m/km in the Paterson bilinear model and 2.0 m/km in the Archondo-Callao model. Therefore, slight alterations were made, as shown in Equation 3.5 (for motorways) and Equation 3.6 (for state roads), to be able to more adequately reflect the actual situation on the analyzed network and to reflect the relationship between the “previous” condition, level of improvement and the “new” condition.

$$IRI_{new} = 1.5 + 0.01 \times \max(0, IRI_{prev} - 1.0) \times \left(\max(0, (120 - D_{impr}))\right)^2 \quad \textit{(eq. 3.5)}$$

$$IRI_{new} = 2.0 + 0.01 \times \max(0, IRI_{prev} - 1.5) \times \left(\max(0, (100 - D_{impr}))\right)^2 \quad \textit{(eq. 3.6)}$$

Equations 3.5 and 3.6 also show that the reduction in roughness depends only on the maintenance treatment (overlay thickness – D_{impr} [mm]) and the condition of the pavement before the treatment.

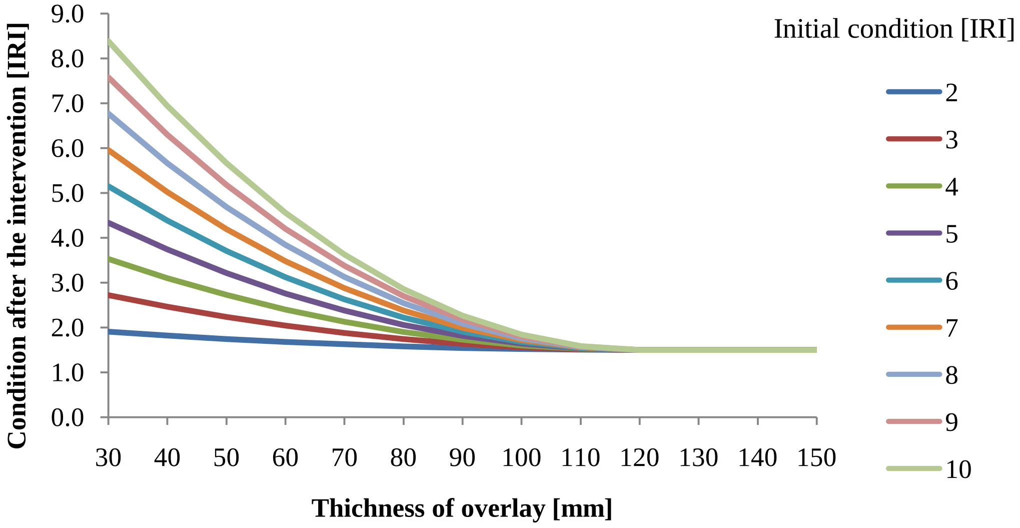


Figure 3.10 Pavement improvement modeling due to an intervention (state roads)

Based on the equations and the corresponding figure, it can be denoted that roughness converges to a minimal obtainable roughness for interventions thicker than, in case of state roads, 110 mm. Therefore, modeling the future condition after major interventions comes down to assigning a value of a minimal quality requirement defined for such type of works.

However, for thicknesses smaller that 110 mm there is a linear dependency between previous and future roughness, i.e., no matter how deteriorated the pavement is, after the intervention it will be set back to its initial roughness. However, for thinner overlays, there is a linear dependency between the roughness prior to intervention and the future roughness, after the intervention (Figure 3.11). These curves vary for state roads and for motorways (according to Equations3.5 and 3.6).

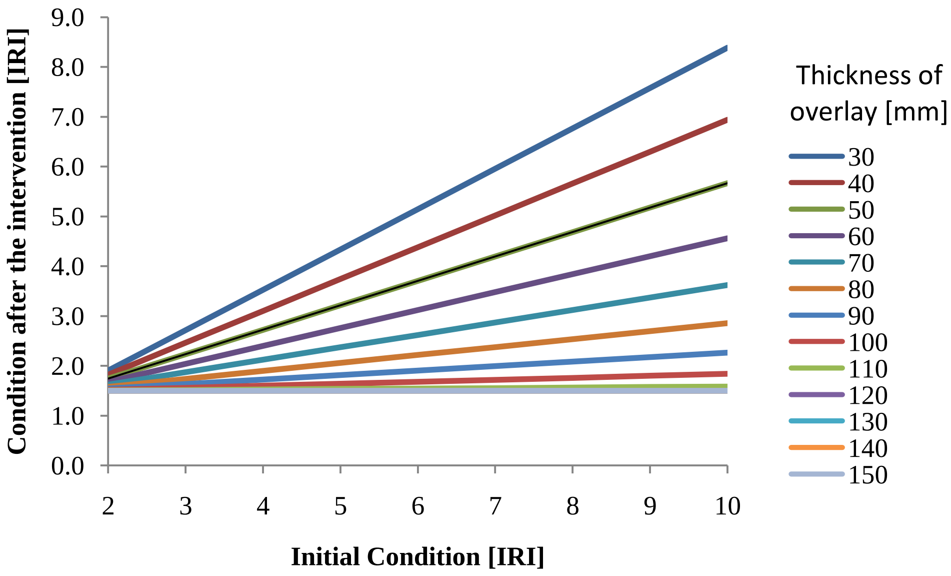


Figure 3.11 Pavement improvements functions (state roads)

This allowed extracting linear relationships for each type of overlay, and then using them in the model. For example, the equation for the pavement improvement model due to a 40 mm overlay was shown in Figure 3.12.

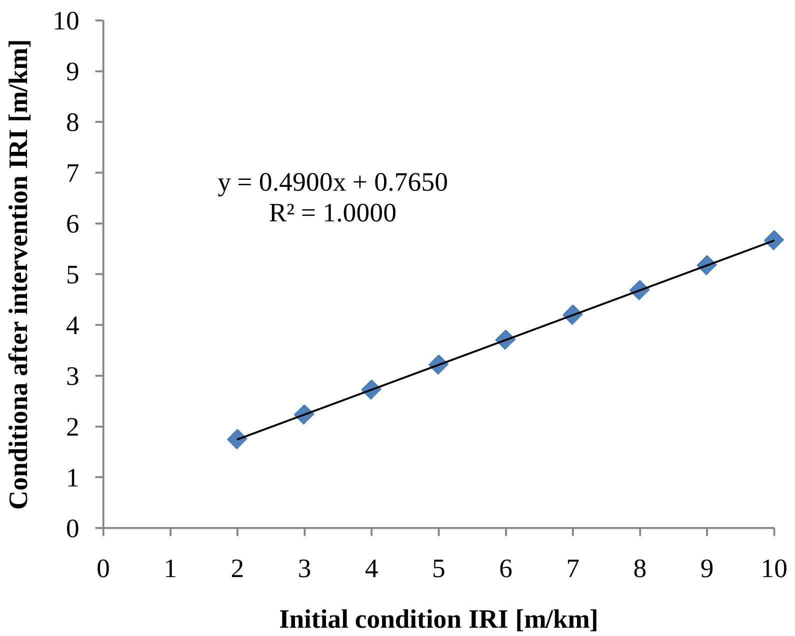


Figure 3.12 Pavement improvement modeling for a 40 mm overlay (state roads)

For example, the improvement model for state roads for a 40 mm overlay and the improvement model for motorways for a 50 mm overlay are given by Equation 3.7 and 3.8, respectively.

$$IRI(impr, 4) = 0.36 \times IRI(t-1) + 1.28 \quad \textit{(eq. 3.7)}$$

$$IRI(impr, 5) = 0.49 \times IRI(t-1) + 0.765 \quad \textit{(eq. 3.8)}$$

As seen on Figure 3.11, if the overlay thickness is higher than certain trigger value (i.e., 100 mm for state roads and 120 mm for motorways, respectively), it is assumed that the roughness of rehabilitated pavement equals the roughness of a new pavement, i.e., the initial roughness.

These equations were applied equally for recycling, WMA, and HMA since there should be no distinctive variations in the initial roughness after the application of any of those treatments. The difference between these technologies is not related to pavement quality nor durability, but mainly to the cost and emission levels. Technically, all three solutions are sound and equally applicable in any section independent of traffic levels and other characteristics.

It was assumed that the initial roughness of high-performance materials, e.g., perpetual pavements and self-healing materials is similar to that of new asphalt pavements. However, the distinct difference occurs in the substantial change in deterioration rates in comparison with more traditional technologies, as explained in the previous sub-chapter.

3.3.2.3. Usage phase and corresponding VOC models

A set of RUC models for typical local vehicle categories was developed using the RUCKS model, version 3.0 (World Bank, 2016), based on the HDM-4, road user effects equations.

The RUCs depend on the road and vehicle characteristics (Table 3.6 and Table 3.7), such as tire abrasion, consumption of motor fuel, fuel consumption (diesel or gasoline), and yearly amortization costs for a new vehicle, as well as on the traffic composition on the particular road section.

Table 3.6 Road condition – input datasheet for calculating VOC

Sub-network	Road Condition		
	Road Roughness (IRI, m/km)	Carriageway Width (m)	Surface Code (1-Paved /2-Unpaved)
Motorways	2.0	7.0	1
State roads Class I	3.5	7.0	1
State roads Class II	4.7	7.0	1

Table 3.7 Road geometry – input datasheet for calculating VOC

Sub-network	Road Geometry				
	Rise & Fall (m/km)	Number of Rise & Fall per km (#)	Horizontal Curvature (degrees/km)	Super elevation (%)	Altitude (m)
Motorways	10	2	15	2.5	0
State roads Class I	13	2	50	2.5	0
State roads Class II	15	2	75	2.5	0

Figure 3.13 presents the values of VOCs per each vehicle type that corresponds to road roughness, i.e., VOC-to-roughness sensitivity. It is clear that an increase in roughness leads to an increase in VOCs.

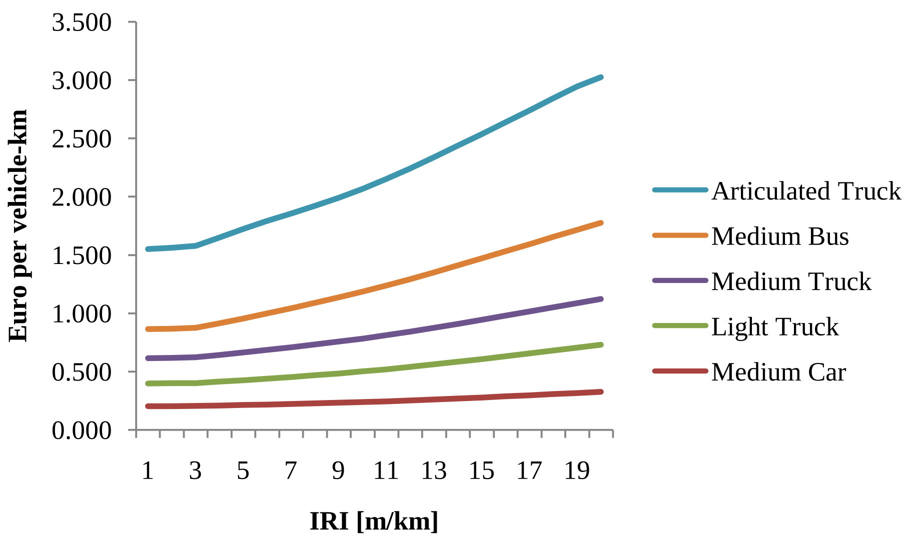


Figure 3.13 VOC Sensitivity to pavement roughness

Since the network was divided into 75 virtual sections, for each section there is a unique split between vehicle types. Because of that, RUCs were calculated for each virtual section individually, and represented by a quadratic function.

$$\text{Unit RUCs}(euro/vehicle\text{-}km) = b_0 + b_1 \cdot IRI + b_2 \cdot IRI^2 \qquad (eq.\ 3.9)$$

Figure 3.14 shows one example of fitting the data on a unit cost for various traffic levels, using Equation 3.9. The obtained coefficient of determination is higher than $R^2 = 0.999$ for all traffic levels.

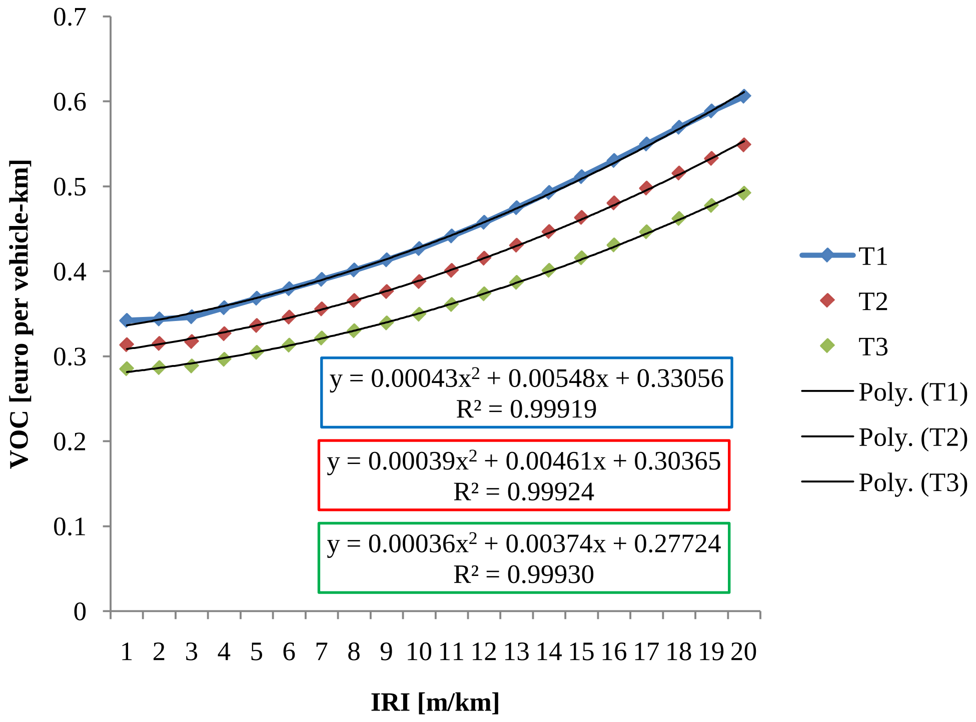


Figure 3.14 Example of the determination of VOC coefficients for SR Class II

The coefficients are calculated independently for each virtual section (as shown in Table 3.8).

Table 3.8VOC coefficients

VOC	Motorways				
	T1	T2	T3	T4	T5
a1	0.00	0.39934	0.39934	0.36452	0.24457
a2	0.00	0.00803	0.00803	0.00703	0.00269
a3	0.00	0.00052	0.00052	0.00048	0.00032
a4	0.00	0.00000	0.00000	0.00000	0.00000
VOC	**SR Class I**				
	T1	**T2**	**T3**	**T4**	**T5**
a1	0.30945	0.32027	0.30945	0.28290	0.00
a2	0.00476	0.00513	0.00476	0.00393	0.00
a3	0.00040	0.00041	0.00040	0.00037	0.00
a4	0.00000	0.00000	0.00000	0.00000	0.00
VOC	**SR Class II**				
	T1	**T2**	**T3**	**T4**	**T5**
a1	0.330560	0.303650	0.277240	0.00	0.00
a2	0.005480	0.004610	0.003740	0.00	0.00
a3	0.000430	0.000390	0.000360	0.00	0.00
a4	0.000000	0.000000	0.000000	0.00	0.00

Therefore, the VOC model is customized for each virtual section, corresponding condition, and traffic level characteristics.

3.4. Life cycle assessment on the network level

3.4.1. Usage phase and corresponding CO_2 emissions

The HDM-4 CO_2 emission calculation procedure was used to develop a model to estimate emissions from several types of vehicles, namely a medium car, light truck, medium truck, articulated truck, and medium bus (Figure 3.15).

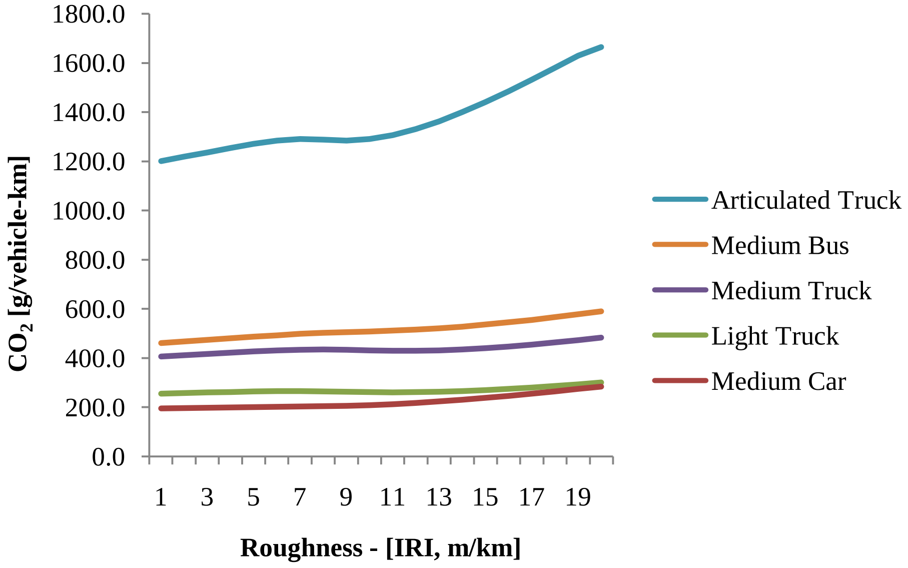


Figure 3.15 Emissions per vehicle type

Based on data simulation, which included variations in roughness, while maintaining constant all other road and vehicle parameters (such as road geometrical characteristics and vehicle mechanical properties), the relationship between roughness and CO_2 emissions for a range of road conditions is presented in Figure 3.16.

These relationships were established for each sub-network separately. This allowed creating a set of equations for each virtual section, depending on the vehicle fleet composition, driving patterns (e.g., speed), and road condition.

Figure 3.16 shows also how vehicle emissions vary according to traffic levels. The equations were developed using poly-lines of the third degree, and have a coefficient of determination R^2 close to 1 for all traffic levels (and corresponding vehicle compositions), for the whole network, which included both motorways and state roads of the first and of the second class.

$$\text{VOC } CO_2 = c_1 \cdot IRI^3 + c_2 \cdot IRI^2 + c_3 \cdot IRI + c_4 \qquad \textit{(eq. 3.10)}$$

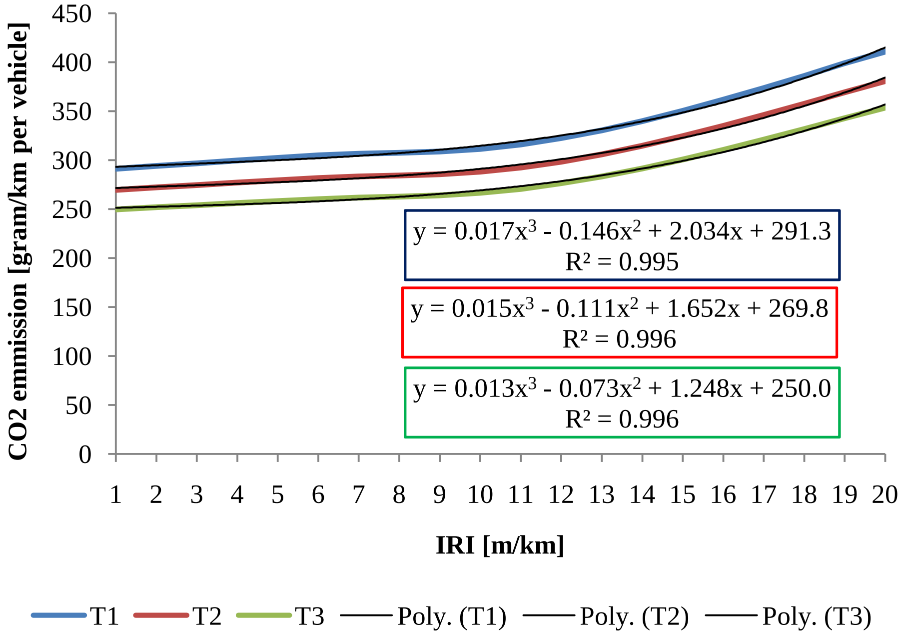


Figure 3.16 Emissions per vehicle class – SR class II

The coefficients of the CO_2 emission models are presented in Table 3.9.

Table 3.9Emissions coefficients for the usage phase

VOC, CO2	Motorways				
	T1	**T2**	**T3**	**T4**	**T5**
a_1	0.00	0.000	0.000	0.000	0.000
a_2	0.00	0.021	0.021	0.018	0.011
a_3	0.00	-0.221	-0.224	-0.166	0.018
a_4	0.00	2.988	3.003	2.451	0.682
a_5	0.00	337.400	339.800	306.800	226.100
VOC, CO2	**SR Class I**				
	T1	**T2**	**T3**	**T4**	**T5**
a_1	0.000	0.000	0.000	0.000	0.000
a_2	0.016	0.017	0.016	0.014	0.000
a_3	-0.130	-0.140	-0.124	-0.076	0.000
a_4	1.831	1.942	1.775	1.300	0.000
a_5	275.300	282.000	274.400	255.000	0.000
VOC, CO2	**SR Class II**				
	T1	**T2**	**T3**	**T4**	**T5**
a_1	0.000	0.000	0.000	0.000	0.000
a_2	0.017	0.015	0.013	0.000	0.000
a_3	-0.146	-0.111	-0.073	0.000	0.000
a_4	2.034	1.652	1.248	0.000	0.000
a_5	291.300	269.800	250.000	0.000	0.000

These coefficients allow estimating the corresponding CO_2 emissions during the usage phase of asphalt pavement's life cycle based on the projected roughness levels on a section.

3.4.2. Production, placement, end-of-life phases, and corresponding CO_2 emissions

Each treatment is associated with corresponding CO_2 emissions which involve (i) material production, (ii) material transportation, and (iii) processes which include the preparation of mixtures in the asphalt plant, laying and paving, but also the removal of old layers. That means that transportation distances include routes from borrow-pits to the asphalt plant, to the construction site, and from the site to a landfill. Emissions were estimated with the use of the PaLATE software. Input data included the volumetric composition of an asphalt mix (the ratio between bitumen and aggregate), transport distance, and equipment used for the transportation and paving of the asphalt mix.

Input parameters needed for the use of the PaLATE tool, and for calculating emissions are given in Table 3.10.

M&R WMA involves the same processes as M&R HMA, with the difference in adding WMA additives to the mix, which allows the production and placement of asphalt mixes at lower temperatures.

M&R 25% RAP involves the same processes as M&R HMA with the difference that 75% of the RAP is transported to a landfill, while 25% of it is transported from the site to the asphalt plant where it is used in the production of a new asphalt mix. That means a 25% lower consumption of raw materials. This technology also involves adding a rejuvenating agent which improves the quality of the “old” bitumen, and increases the price to some extent.

Table 3.10Input data sheet for calculation of emissions related to maintenance works

Type of maintenance		Perpetual		Self healing		RAP 25% M&R				WMA M&R				HMA M&R			
Quantities	overlay [cm]	35	25	5	4	12	10	5	4	12	10	5	4	12	10	5	4
	width [m]	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
	length [km]	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	depth [cm]	35	25	5	4	12	10	5	4	12	10	5	4	12	10	5	4
	width [ft]	22.97	22.97	22.97	22.97	22.97	22.97	22.97	22.97	22.97	22.97	22.97	22.97	22.97	22.97	22.97	22.97
	length [mile]	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
	depth [inches]	13.78	9.843	1.969	1.575	4.724	3.937	1.967	1.575	4.724	3.937	1.969	1.575	4.724	3.937	1.969	1.575
	volume [m^3]	24500	17500	3500	2800	8400	7000	3500	2800	8400	7000	3500	2800	8400	7000	3500	2800
Asphalt MIX	volume [yd^3]	32040	22890	4580	3660	10990	9160	4580	3660	10990	9160	4580	3660	10990	9160	4580	3660
	distance [mi]	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Virgin Aggregate	volume [yd^3]	32040	22890	4580	3660	8240	6870	3430	2750	10990	9160	4580	3660	10990	9160	4580	3660
	distance [mi]	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Bitumen	volume [yd^3]	1690	1200	240	190	430	360	180	140	580	480	240	190	580	480	240	190
	distance [mi]	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
RAP to plant	volume [yd^3]	0	0	0	0	2890	2410	1200	960	0	0	0	0	0	0	0	0
	distance [mi]	0	0	0	0	25	25	25	25	0	0	0	0	0	0	0	0
RAP to landfill	volume [yd^3]	14460	9640	4820	3860	8670	7230	3610	2890	11570	9640	4820	3860	11570	9640	4820	3860
	distance [mi]	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Perpetual pavements also involve the same technology as M&R HMA, but assume that the asphalt layers will be removed completely and replaced with considerably thicker asphalt pavement constructions (base layer, binder course, wearing course). The results are shown in Table 3.11.

Table 3.11 Emissions per production, transportation and end of life

Description	Motorways		SR Class I and II	
	Quantity [cm]	**t/km**	**Quantity [cm]**	**t/km**
HMA M&R	5	334	4	267
HMA M&R II	12	801	10	668
WMA M&R	5	267	4	214
WMA M&R II	12	641	10	534
Recycled 25 % M&R	5	270	4	216
Recycled 25 % M&R II	12	647	10	539
Self healing = porous + metal bars	5	434	4	347
perpetual pavement	35	2336	25	1669

The results are given for maintenance works of 1 km on a7 m-wide road equivalent.

3.5. Cost of road works

Based on the previously developed cost estimation models, the unit cost of AC was calculated with the use of a regression equation, based on the input parameters for Serbia, as shown in Table 3.12, for both Model 1 and Model 2.

Table 3.12Input parameters needed for applying cost estimation models for an AC unit price

Table CD2	Description	Abbr.	Value
Oil price related	Diesel fuel price per liter	DF	1.6
	Crude oil price per barrel	OP	80
	Oil exporter or importer	EI	1
Country-specific	World Governance Index	WGI	–0.39
	Gross National income	GNI	5,000
	TI Corruption Perception Index	TICOI	3
Project-specific	Climate	C	1
	% local bidders	LB	75
	Terrain	T	1

Models 1 and 2 give as a result a unit price of AC of 93.4 and 104.3 euro/t, respectively. Based on local experiences, the second price is more realistic, and therefore has been used further on.

Based on the unit cost of AC, the cost of a simple overlay was calculated depending purely on the quantity of materials, while the unit cost for M&R was estimated to be 5% higher than for a simple overlay (due to milling and transportation to the landfill). WMA technology means an additional increase in the unit price of 10%, also according to local experiences. The calculated cost of road works is presented in Table 3.13.

Table 3.13Cost of road works

Description	Motorways		SR Class I and II	
	Quantity [cm]	**Cost [euro]**	**Quantity [cm]**	**Cost [euro]**
HMA M&R	5	105090	4	84072
HMA M&R II	12	252216	10	210180
WMA M&R	5	115599	4	92479
WMA M&R II	12	277437	10	231198
Recycled 25 % M&R	5	110344	4	88275
Recycled 25 % M&R II	12	264826	10	220689
Self healing = porous + metal bars	5	157635	4	126108
perpetual pavement	35	735629	25	525449
Complete reconstruction	50	350000	40	300000
New construction	50	776515	40	621212

The cost of perpetual pavements was based on local prices of materials and expected bills of quantities (BoQs), as there is not much experience with perpetual pavements in Serbia. The resulting costs, which are in line with the literature (El-Hakim and Tighe, 2009,FHWA, 2010),were about 10% to 35% higher than conventional construction.

The technology of self-healing pavements is still in the early phases of its development. Therefore recommendations from the literature (FHWA, 2010) were taken as an input, which suggest that the cost of a self-healing layer is expected to be more than 30% higher in comparison with M&R of the same thickness. In Serbia there is no prior experience with this technology, and the price may be even higher than the one suggested in the literature.

CHAPTER 4: APPLICATION OF THE METHODOLOGY TO THE SERBIAN ROAD NETWORK

4.1. Input data sheets

The IronMap tool is designed to use input from Excel spreadsheets and then to import it into Matlab where the optimization is conducted and results may be obtained. Input data sheets contain all the relevant data about the network characteristics, and all the models that are needed for conducting such analyses.

There are five (5) input sheets that have to be completed in order to perform an analysis with the IronMap tool.

4.1.1. Maintenance road works

The first sheet was named “road works”, and it gives a general overview of the maintenance planning on the network level. First, it provides the opportunity to assign three sub-networks, to define their names and quality recommendations. For instance, for each sub-network it is possible to assign the required quality of maintenance work after rehabilitation and what is the minimal value of IRI (“best quality”) achieved on the sub-network.

This is actually important from the aspect of improvement functions. Although the models follow generally established relationships, it is usually needed (as described in chapter 3.3.2.2.) to adopt them to local conditions, that among other things, include general quality standards (in terms of expectations of quality) and also realistic projections about the obtainable quality, as a consequence of the experience of local contractors.

For example, as stated in the chapter 3.3.2.2, Serbian road pavement design projects (i.e., their technical conditions and requirements stated within the project documentation and contract) rarely imply a roughness lower than 2.0 for motorways and 2.5 for state roads as a quality requirement within technical conditions. However, judging from the personal experience of the author (during seven years of on-field roughness measurements for various contractors as part of the technical acceptance of rehabilitation or reconstruction projects) local contractors rarely achieve an initial roughness lower than 1.5 m/km, and that is manly on new construction projects and on motorway sections.

Furthermore, on this sheet there is a place for defining the initial threshold for the “first” intervention, as well as the “final roughness” for each sub-network. The first threshold value actually represents the lowest possible roughness trigger level, for considering the application of some kind of treatment on the pavement. This value is closely related to the timing of interventions. For example, the initial threshold should be set in such a manner to reflect the expected minimal time frame between two consequent interventions on a section. If the initial threshold value is set to “low” then the interventions may be too close to each other. The same can be applied for the “final” roughness. In case this value is too “high” this assumes a “do nothing” maintenance scenario.

Also, within this analysis, a maximal threshold was also used as a point defining “maintenance backlog”, i.e., the scope of sections needing major rehabilitation since they reached an unsatisfactory condition. This backlog was treated as a separate issue in maintenance planning, since it is obviously a residual from past under-maintenance of the network, but cannot be overcome within one year. In this analysis, maintenance backlog was calculated separately. However the optimization routine was applied regardless of the maintenance backlog.

For Serbian State Roads Class II, the initial roughness threshold was set to 3.5 m/km, while the maximal roughness threshold was 6 m/km; for Serbian state roads Class I the initial roughness threshold was set to 3 m/km, while the maximal roughness threshold was 5.5 m/km. Finally, for motorways the initial roughness threshold was set to 2.5 m/km, while the maximal roughness threshold was 5 m/km (Table 4.1).

Table 4.1 Range of trigger levels

Triggers	**IRI**	
	min	**max**
Expressways	*2.5*	*5*
SR Class I	*3*	*5.5*
SR Class II	*3.5*	*6*

The bottom part of the “road works” input sheet defines consequences to roughness after applying certain intervention. Major interventions require only the required value of roughness after an intervention (often stated within project documentation and quality requirements), while overlays and related interventions follow the Paterson bilinear model, and require setting a dependence between the overlay thickness, roughness at the trigger level, before the treatment, and the corresponding roughness after the application of a maintenance treatment (as described in chapter 3.3.2.2).

4.1.2. Traffic input data sheet

The second input sheet is closely related to traffic. It allows dividing the network into five sub-networks according to traffic levels (from T1 to T5, as shown in chapter 3.3.1.), and furthermore five sub-networks according to roughness (from very good to very poor, as shown in chapter 3.3.1.).

Also, there is a value for axle loading for each vehicle type (Table 4.2), as well as projected traffic growth rates for each vehicle type and for each of the main three sub-networks separately.

Table 4.2 Axle loading per vehicle type

Axle loading	**Vehicle type**				
	PC	**BUS**	**LT**	**MT**	**AT**
	0	1.37	0.2	0.65	3.25

Note: PC: passenger car; LT: light truck; MT: medium truck; AT: articulated truck

Since for this analysis, the traffic levels were used from the year of the last data input into the Serbian road database (2008), it was not relevant to obtain more realistic traffic projections, so a traffic rate of 3% was used for the entire vehicle fleet on the overall network.

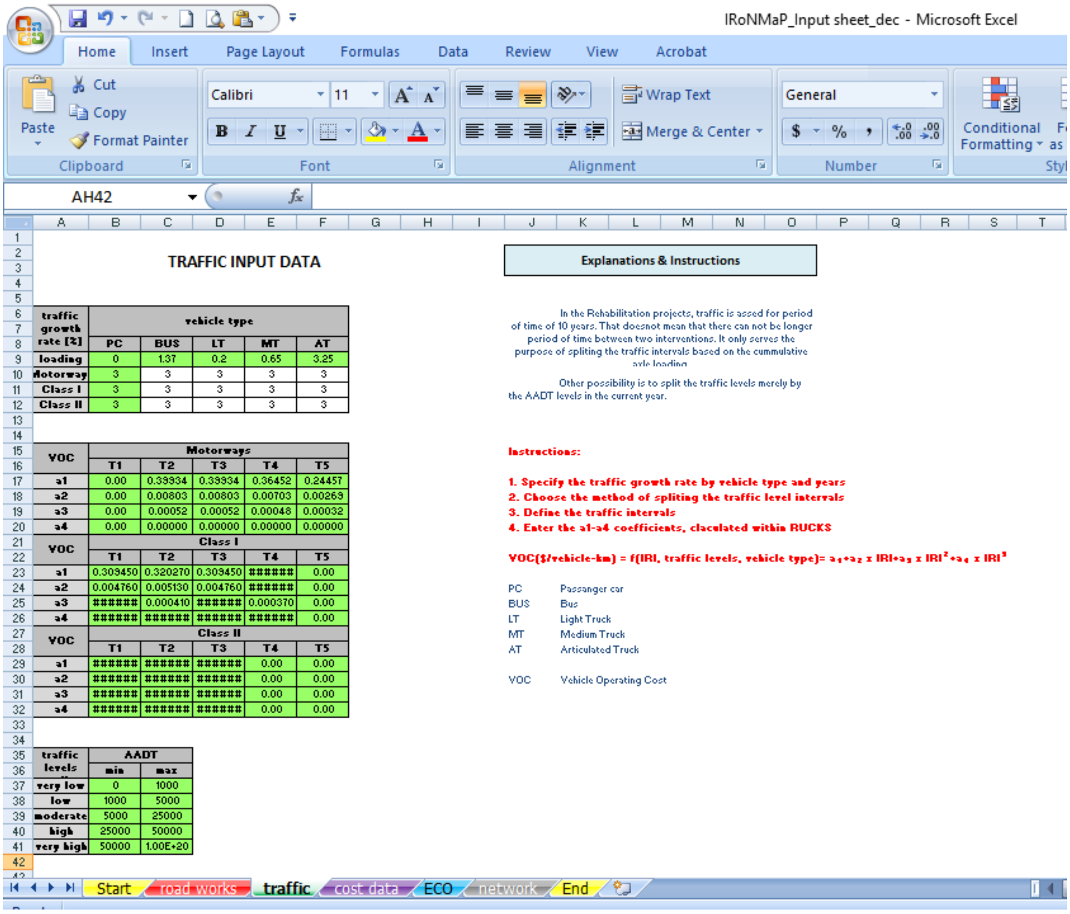


Figure 4.1 Traffic input sheet

Lastly, this sheet also contains VOC coefficients for each traffic level and sub-networks. These coefficients are from an empirical relation, i.e., polynomial equation, that establishes the relationship between the pavement roughness and corresponding RUCs (as shown in chapter 3.3.2.3.), in line with HDM-4 models.

4.1.3. Cost input data sheet

In this input sheet it is necessary to first define a discount rate. The discount rate is applied annually, and it is related to assessing future expenditures. The discount rate is the rate that is calculated each year in banks for money that is available but not in use and refers to the interest rate used in discounted cash flow analyses to determine the present value of future cash flows, by the Equation 4.1.

$$COST_{year\ t}^{disc} = \frac{COST}{\left(1+\frac{r}{100}\right)^{t}} \qquad (eq.\ 4.1)$$

Usually, the discount rate is defined in a country-specific context, and for Serbia in such analyses it is usually assessed to be 8%.

Secondly, this sheet allows the user to define the cost for each maintenance treatment according to local prices. However, if the data is not available, within this sheet there is an integrated cost estimation model, developed for countries of ECA region (chapter 3.5.) which estimates the unit cost of road works based on regression equations. Input parameters needed for such analyses are

- diesel fuel price per liter,
- crude oil price per barrel,
- whether the country is an oil exporter or importer (if importer=1, if exporter=0),
- WGI,
- GNI,
- TICPI,
- climate (if the climate is mild=0, if it is severe= 1),
- percentage of local bidders (estimation based on the development of the local contracting industry, 0–100), and
- terrain (if the terrain is flat=0, if it is mountainous= 1).

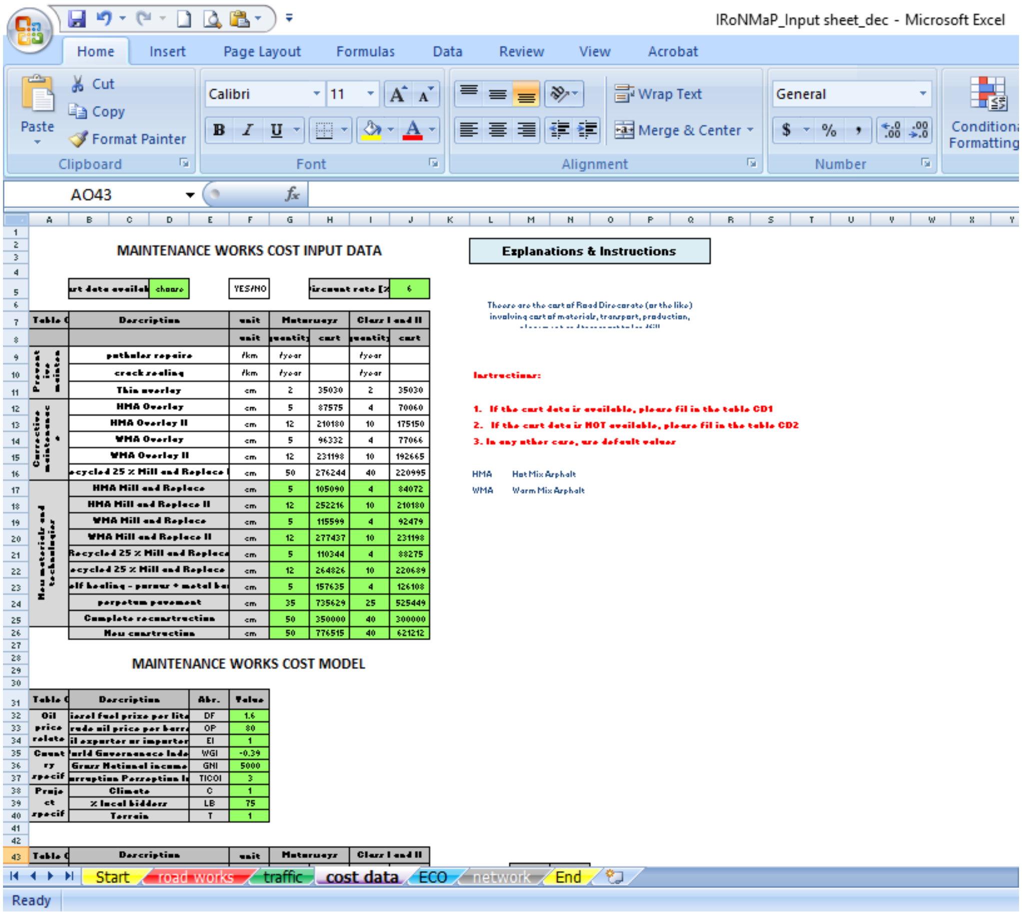


Figure 4.2 Cost data sheet

Based on these input parameters, usually readily available in open databases, the tool calculates the unit cost of AC, and the corresponding cost of maintenance treatments. The user may check the obtained results through a RA, and to adopt them if in line with local prices.

4.1.4. Environmental cost input data sheet

This sheet contains all the relevant information for assessing environmental impacts (related to CO_2 emissions) during all the phases of a pavement's life cycle.

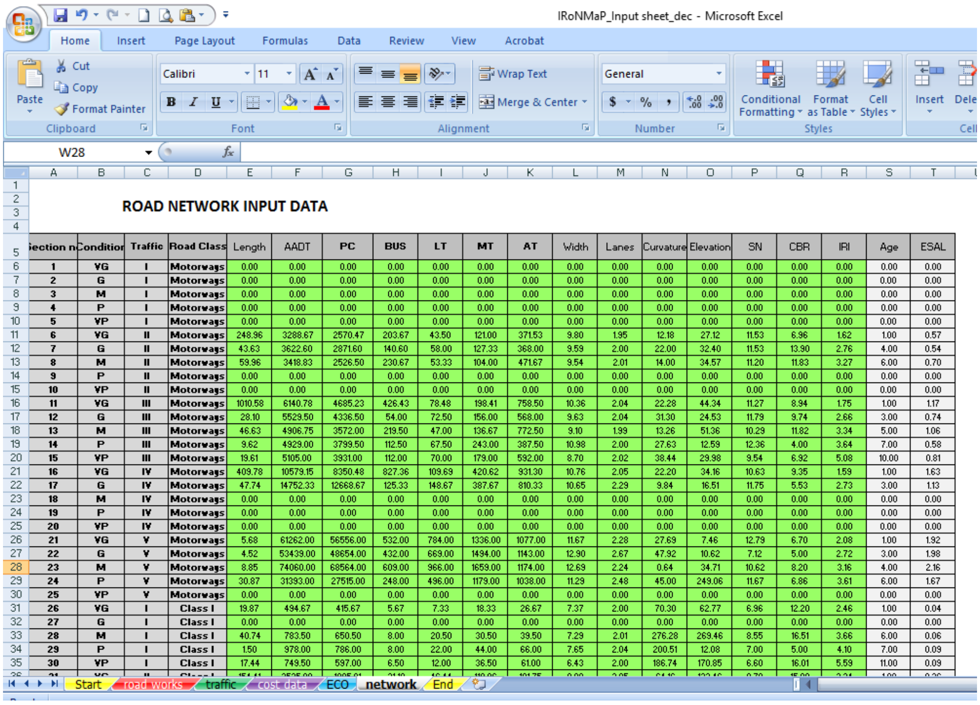
Emissions during the usage phase of a pavement are represented with a series of coefficients, that provide a relationship between the pavement condition (i.e., roughness) and CO_2 emissions, for each combination of traffic levels (and corresponding vehicle fleet composition) separately for all three sub-networks. These coefficients are calculated using the HDM4 RUCKS tool, and presented in chapter 3.4.1.

The second table of this input sheet contains input parameters in terms of CO_2 emissions related to the application of certain maintenance treatments. Overall emissions are calculated as a sum of emissions during material production and transportation, during mixing of the asphalt at an asphalt plant, followed by the transportation of the mix and laying down of the new pavement. Also, almost all treatments involve M&R of the pavement existing layers with new layer(s); therefore, the “end-of-life” phase, which involves milling the existing pavement and transportation to the asphalt plant for recycling, or to a landfill, was also calculated.

In this analysis, the PaLATE software was used for assessing emissions for all the phases of a pavement’s life cycle, except the usage phase. Results for the Serbian state road network were given in chapter 3.4.2.

4.1.5. Network input data sheet

The network input data sheet contains all the relevant details about the sections of the network. For this analysis, an artificial network was used, divided into 75 virtual sections. This approach allowed easier comparison, and set focus on the methodology. However, this does not restrict the application of the tool to wider networks and a greater number of sections.


ROAD NETWORK INPUT DATA

Section n	Condition	Traffic	Road Class	Length	AADT	PC	BUS	LT	MT	AT	Width	Lanes	Curvature	Elevation	SN	CBR	IRI	Age	ESAL
1	VG	I	Motorways	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	G	I	Motorways	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	M	I	Motorways	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	P	I	Motorways	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	VP	I	Motorways	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	VG	II	Motorways	248.96	3288.67	2570.47	203.67	43.50	121.00	371.53	9.80	1.95	12.18	27.12	11.53	6.96	1.62	1.00	0.57
7	G	II	Motorways	43.63	3622.60	2871.60	140.60	58.00	127.33	368.00	9.59	2.00	22.00	32.40	11.53	13.90	2.76	4.00	0.54
8	M	II	Motorways	59.96	3418.83	2526.50	230.67	53.33	104.00	471.67	9.54	2.01	14.00	34.57	11.20	11.83	3.27	6.00	0.70
9	P	II	Motorways	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	VP	II	Motorways	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	VG	III	Motorways	1010.58	6140.78	4685.23	426.43	78.48	198.41	758.50	10.36	2.04	22.28	44.34	11.27	8.94	1.75	1.00	1.17
12	G	III	Motorways	28.10	5529.50	4336.50	54.00	72.50	156.00	568.00	9.63	2.04	31.30	24.53	11.79	9.74	2.66	3.00	0.74
13	M	III	Motorways	46.63	4906.75	3572.00	219.50	47.00	136.67	772.50	9.10	1.99	13.26	51.36	10.29	11.82	3.34	5.00	1.06
14	P	III	Motorways	9.62	4929.00	3799.50	112.50	67.50	243.00	387.50	10.98	2.00	27.63	12.59	12.36	4.00	3.64	7.00	0.58
15	VP	III	Motorways	19.61	5105.00	3931.00	112.00	70.00	179.00	592.00	8.70	2.02	38.44	29.98	9.54	6.92	5.08	10.00	0.81
16	VG	IV	Motorways	409.78	10579.15	8350.48	827.36	109.69	420.62	931.30	10.76	2.05	22.20	34.16	10.63	9.35	1.59	1.00	1.63
17	G	IV	Motorways	47.74	14752.33	12668.67	125.33	148.67	387.67	810.33	10.65	2.29	9.84	16.51	11.75	5.53	2.73	3.00	1.13
18	M	IV	Motorways	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	P	IV	Motorways	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	VP	IV	Motorways	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	VG	V	Motorways	5.68	61262.00	56556.00	532.00	784.00	1336.00	1077.00	11.67	2.28	27.69	7.46	12.79	6.70	2.08	1.00	1.92
22	G	V	Motorways	4.52	53439.00	48654.00	432.00	669.00	1494.00	1143.00	12.90	2.67	47.92	10.62	7.12	5.00	2.72	3.00	1.98
23	M	V	Motorways	8.85	74060.00	68564.00	609.00	966.00	1659.00	1174.00	12.69	2.24	0.64	34.71	10.62	8.20	3.16	4.00	2.16
24	P	V	Motorways	30.87	31393.00	27515.00	248.00	496.00	1179.00	1038.00	11.29	2.48	45.00	249.06	11.67	6.86	3.61	6.00	1.67
25	VP	V	Motorways	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	VG	I	Class I	19.87	494.67	415.67	5.67	7.33	18.33	26.67	7.37	2.00	70.30	62.77	6.96	12.20	2.46	1.00	0.04
27	G	I	Class I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
28	M	I	Class I	40.74	783.50	650.50	8.00	20.50	30.50	39.50	7.29	2.01	276.28	269.46	8.55	16.51	3.66	6.00	0.06
29	P	I	Class I	1.50	978.00	786.00	8.00	22.00	44.00	66.00	7.65	2.04	200.51	12.08	7.00	5.00	4.10	7.00	0.09
30	VP	I	Class I	17.44	749.50	597.00	6.50	12.00	36.50	61.00	6.43	2.00	186.74	170.85	6.60	16.01	5.59	11.00	0.09

Figure 4.3 Network data sheet

The overall optimization calculation time, on a regular personal computer is a matter of fragments of a second for this network; therefore, there should be no problem in expanding the number of sections.

The set of data needed for performing the analysis includes

- the road class,
- section length,
- section width,
- AADT,
- the traffic fleet composition (PC, BUS, LT, MV, AT),
- the number of lanes,
- horizontal curvature,
- rise and fall ,
- the structural number,
- CBR,
- IRI,
- pavement age, and
- ESSO.

4.2. Rules of optimization

As previously stated, the initial optimization procedure was based on an exhaustive search. In other words, for a set of threshold levels (conditions when the specific treatments are to be applied), every section has been tested for each possible type of maintenance treatment (including the “do nothing” scenario) each year. The objective function is a simple minimum of total costs, and when the minimum is reached, an optimal scenario is produced which suggests the maintenance plan for each section in terms of the type of maintenance treatments and their timings for application.

The first scenario evaluates only the cost related to the application of a pavement maintenance treatment and corresponding VOCs, for a number of different thresholds. The second scenario uses the same routine, but taking into consideration CO_2emissions during the pavement’s life, irrelevant to any other costs (e.g., RUC, agency cost). Finally, the third scenario assigns a monetary value to the emissions in order to reach the overall “optimal” strategy that considers the agency cost, RUC and environmental impacts.

The optimization within the first two scenarios is based on an exhaustive search, and gives an optimal solution in terms of minimizing the total CO_2 emissions as well as agency and user costs, during the analysis period of 30 years, using a set of various trigger levels and a wide range of possible maintenance treatments. This procedure also allows setting very clear boundaries of the optimization problem. Namely, the total cost is expected to be lower when applying scenario “one”, higher when applying scenario “two”, and vice versa; emissions are lower for scenario “two” and higher for scenario “one”. Any integrated solution has costs and overall emissions actually in the range set by scenarios “one” and “two”, as borderline cases (Figure 4.4).

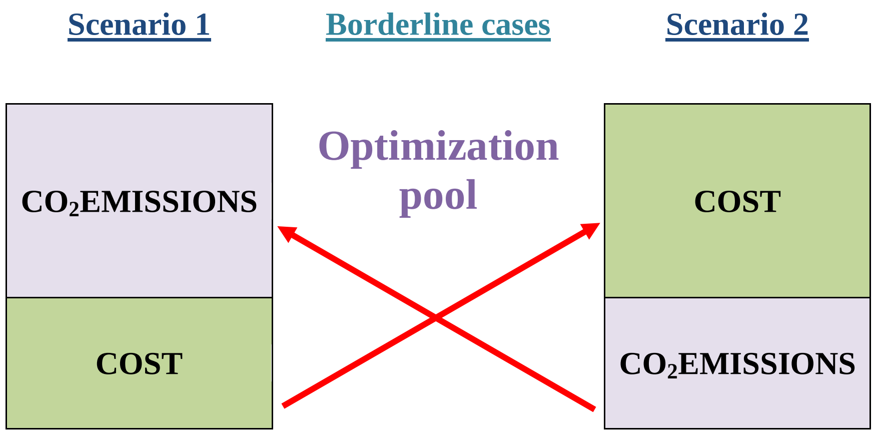


Figure 4.4 Comparison of expected results from scenarios “one” and “two”

However, in order to combine the two confronting objectives, it is necessary to translate them to the same denominator, i.e., cost. But, there is a considerable challenge to assigning a correct monetary value for environmental cost and treat it as any other cost. Assigning any value means putting a certain weight to emissions in the overall result (if the value is too low, total costs are going to be determinant in the overall optimization, and vice versa, if the value of the unit cost of emissions tends toward infinity, the optimization will mainly be focused on minimizing the overall emission levels regardless of the total cost).

For that reason, the third scenario (or model) consists of applying a multi-objective optimization procedure for a wide range of unit costs of CO_2 emissions. For each unit cost, the optimal solution is determined according to the same procedure as for the previous models. However, after creating the pool of potential “optimal” solutions, a second optimization is performed, based on GAs, to develop the Pareto frontier. This gives an outlook on the range of potential optimal solutions and how the unit cost of CO_2 emissions changes the “optimal” solution. The overall optimum is defined from the pavement network optimization maintenance standpoint.

4.3. Optimal Scenario “One”

After the application of the IronMaP procedure, Optimal Scenario “One” suggests using the interventions that have the lowest cost (e.g., M&R in various thicknesses),keeping the overall motorway network in very good and good conditions, as presented in Figure 4.5.

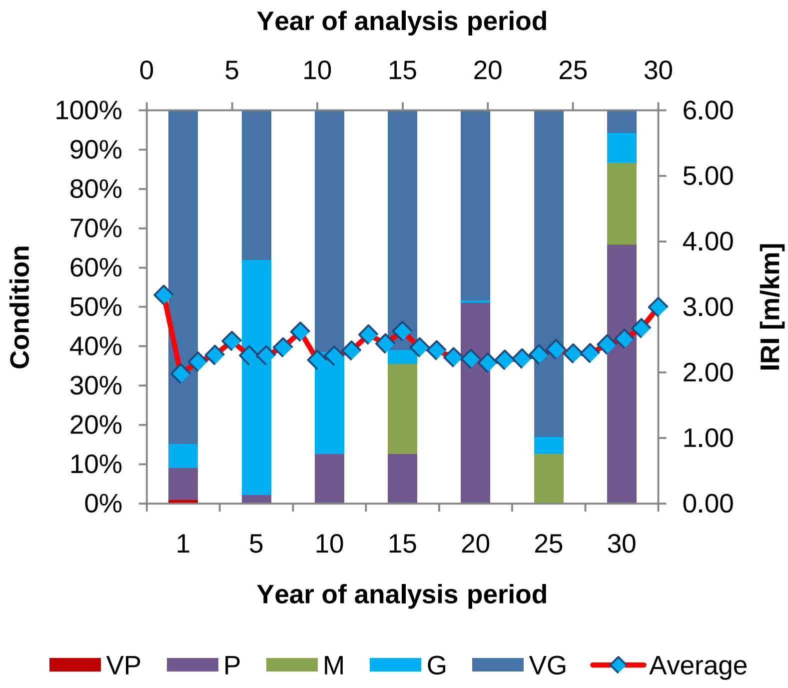


Figure 4.5 Optimal Scenario “one”, network condition for motorways

There is one exception to that conclusion, and that is the increase in sections in medium and poor conditions between years 15 and 20. The reason behind that is the application of perpetual pavements and thick M&R as maintenance treatments at higher thresholds, on the virtual sections of very significant lengths, as presented in Table 4.3.

The reason for this is purely mathematical, since both of those two sections were in excellent condition in the first year of the analysis period. Plus, those were sections with moderate traffic, therefore major rehabilitation, such as the application of a perpetual pavement, would happen in later years of the analysis period, as the condition tended towards higher threshold values. However, this means that economically, motorway sections in very good condition may be good candidates for perpetual pavements, but in order to make more realistic conclusions, it is necessary to divide these lengthy virtual sections into several sub-sections. Since this scenario served only to establish borderline conditions, that step was not included in further analysis.

Table 4.3 Optimal Scenario “one”, solution catalogue for motorways

Traffic Level	Initial Condition	Length	Trigger	Intervention
II	VG	248.96	5	HMA M&R thick
	G	43.63	3.8	HMA M&R thick
	M	59.96	2.7	HMA M&R thin
III	VG	1010.58	3.6	HMA M&R thick
	G	28.10	2.6	HMA M&R thin
	M	46.63	2.5	HMA M&R thin
	P	9.62	2.7	HMA M&R thin
	VP	19.61	2.5	HMA M&R thin
IV	VG	409.78	3.3	Perpetual
	G	47.74	2.6	HMA M&R thick
V	VG	5.68	2.5	HMA M&R thick
	G	4.52	2.5	HMA M&R thick
	M	8.85	2.6	HMA M&R thick
	P	30.87	2.7	HMA M&R thick

Suggested interventions on almost all sections involved the application of HMA M&R in one or two layers at very low threshold values. Intervals for interventions were 5–7 years, for thin overlays and 7–10 years for thick overlays, respectively. Notably, threshold values were highly dependent on traffic levels, as well as on the thickness of maintenance treatments. For example, sections with low traffic volume had threshold values 2.7–5.0 m/km, and required the application of thin and thick overlays, while sections with very high traffic volumes had threshold values 2.5–2.7 m/km, and required the application of thick overlays.

Similar to motorways, the optimal scenario “one” kept the state road Class I network in very good and good conditions throughout the analysis period (Figure 4.6). A distinctive feature is the fact that there were significant parts of the network in very poor condition (more than 20%) at the beginning of the analysis period, which was found to be an under-optimal solution, and a sign of under-maintaining the network, since the optimal scenario kept this percentage throughout the analysis period under 1%.

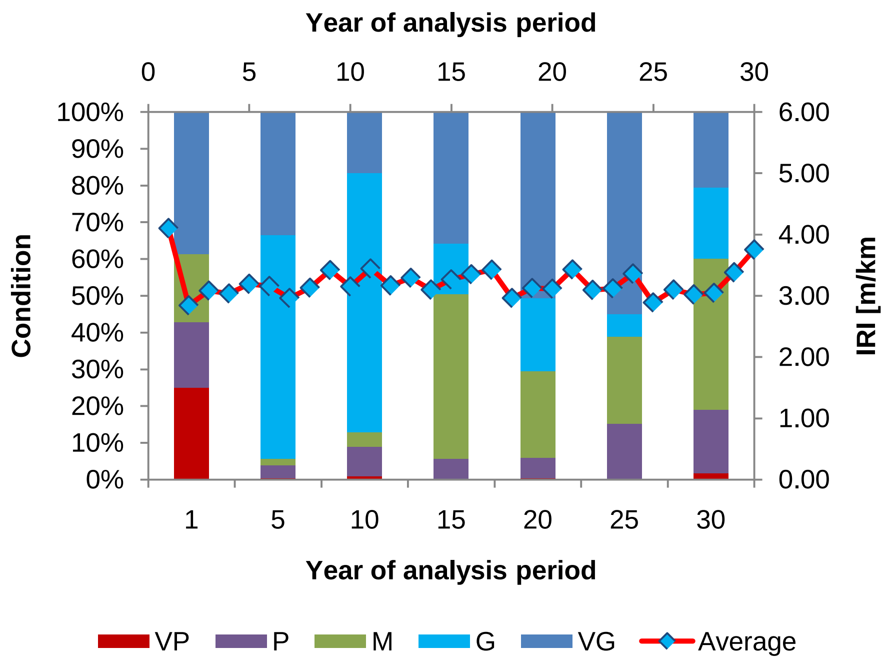


Figure 4.6 Optimal Scenario "one", network condition for SR Class I

Suggested interventions on almost all sections involved the application of HMA M&R in one or two layers at various threshold values. Intervals for interventions were 6–9 years, for thin overlays and 10–12 years for thick overlays, respectively. Furthermore, one section was a candidate for perpetual pavements, also in a very good initial condition and with moderate traffic levels (as in the case of the motorways sub-network).

Notably, threshold values were highly dependent on the traffic level, as well as the thickness of maintenance treatments. For example, sections with a low traffic volume had threshold values 4.8–5.4 m/km, and required only the application of thin overlays, while sections with very high traffic volumes had threshold values 3.1–3.4 m/km, and required the application of both thin and thick overlays.

Table 4.4 Optimal Scenario “one”, solution catalogue for SR Class I

Traffic Level	Initial Condition	Length	Trigger	Intervention
I	**VG**	19.87	5.4	HMA M&R thin
	M	40.74	5.3	HMA M&R thin
	P	1.50	4.8	HMA M&R thin
	VP	17.44	4.8	HMA M&R thin
II	**VG**	154.41	3.8	HMA M&R thin
	G	70.73	4.4	HMA M&R thin
	M	100.34	3.5	HMA M&R thin
	P	87.97	3.7	HMA M&R thin
	VP	136.94	3.6	HMA M&R thin
III	**VG**	180.72	4.1	Perpetual
	G	47.00	4.1	HMA M&R thick
	M	22.76	3.2	HMA M&R thin
	VP	4.36	3.1	HMA M&R thin
IV	**VG**	43.01	3.3	HMA M&R thick
	G	30.25	3.1	HMA M&R thick
	M	45.10	3.1	HMA M&R thin
	P	14.17	3.1	HMA M&R thin
	VP	11.49	3.3	HMA M&R thick

The optimal scenario “one” kept the state road network Class II generally in medium and poor conditions throughout the analysis period, unlike the case of motorways and state roads Class I (Figure 4.7). In this case, a major part of the network was in very poor condition (more than 60%). However, conditions improved during the analysis period but not drastically, as the optimal scenario for the state road network Class II involved relatively moderate maintenance works.

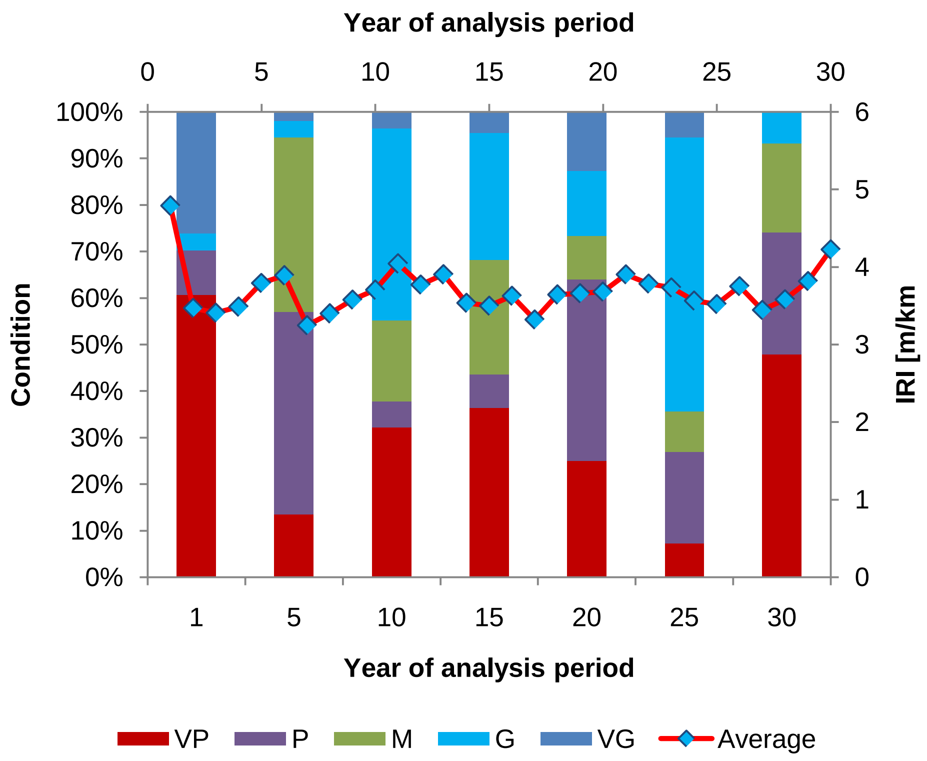


Figure 4.7 Optimal Scenario “one”, network condition for SR Class II

Suggested interventions on almost all sections involved the application of thin HMA M&R overlays at relatively high threshold values. Intervals for interventions were 7–9 years, for thin overlays. One section was a candidate for self-healing materials, and the proposed IRI threshold was 5.7 m/km, assuming the application of only one intervention in the 30-year period, since the section was already in excellent condition. This was a section with extremely low traffic volume, but in excellent condition, and further retardation of the deteriorations almost led to the “do nothing” scenario.

Once again, threshold values were highly dependent on traffic levels, e.g., sections with low traffic volumes had threshold values 5.2–6.0 m/km, while sections with very high traffic volumes had threshold values 3.6–4.3 m/km.

Table 4.5 Optimal Scenario "one", solution catalogue for SR Class II

Traffic Level	Initial Condition	Length	Trigger	Intervention
I	**VG**	1227.34	5.7	self healing
	G	397.59	5.6	HMA M&R thin
	M	579.41	6	HMA M&R thin
	P	519.51	5.7	HMA M&R thin
	VP	2224.73	5.2	HMA M&R thin
II	**VG**	654.68	4.3	HMA M&R thin
	G	187.86	4.2	HMA M&R thin
	M	328.03	3.9	HMA M&R thin
	P	224.21	3.8	HMA M&R thin
	VP	401.91	4.1	HMA M&R thin
III	**VG**	257.18	4.3	HMA M&R thick
	G	82.96	4.3	HMA M&R thick
	M	25.86	3.6	HMA M&R thin
	P	47.12	3.6	HMA M&R thin
	VP	51.32	4.1	HMA M&R thick

The associated discounted costs of interventions are shown in Figure 4.8. It can be seen that once again the use of perpetual pavements influenced a non-uniform distribution of costs, since it's a major intervention, applied rarely.

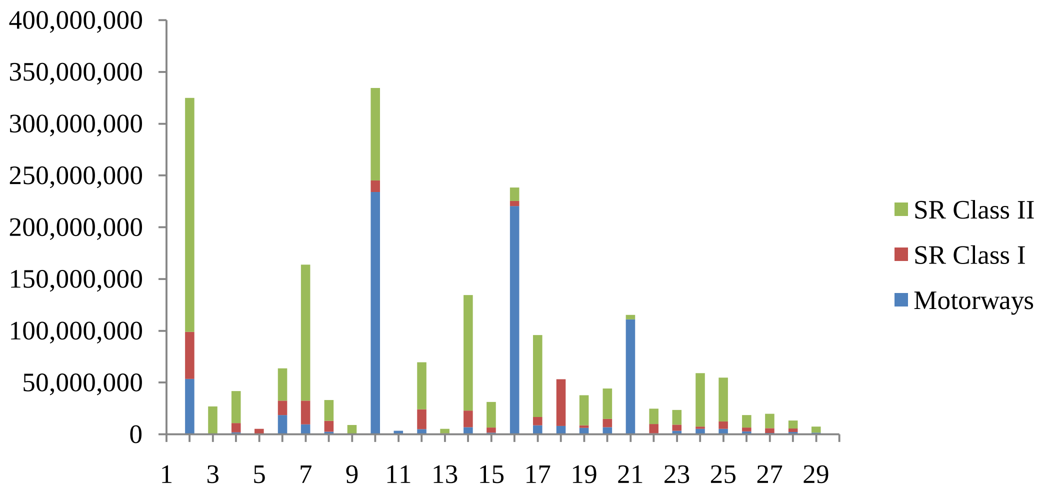


Figure 4.8 Optimal maintenance plan for scenario "one"–optimization based on agency and user costs

The related discounted VOCs were Euro 2,293 million/year in the 30-year period, or in total Euro 68,789 million, for an average network condition of 3.12m/km throughout the analysis period. Total agency costs were Euro 1,891 million or Euro 63 million/year. Associated emissions of CO_2 were 1,383 million t or 46 million t/year.

The proposed plan lowers the overall user cost, keeping the network in very good condition. However, this is an inconvenient solution from the aspect of reoccurring interventions that are associated with emissions, but also with additional delays due to detours, alongside with an increase in the probability of occurrence of accidents in work zones. This influence was not modeled within this analysis because of a low income in Serbia (e.g., 361 Euro per month in January 2016, Statistical Office of The Republic of Serbia, 2016). However, it may be easily added for application to other networks.

4.4. Optimal Scenario “Two”

The second scenario, whose optimization procedure is based on finding minimal total emissions, regardless of the associated cost, produced totally opposite maintenance plans. Since the overall emissions are influenced by the construction and maintenance phases of a pavement’s life cycle, the “optimal” plan minimizes total emissions by increasing threshold values. The optimal scenario “two” proposes using road maintenance interventions with the lowest emissions while keeping the motorway network in average condition, as presented in Figure 4.9.

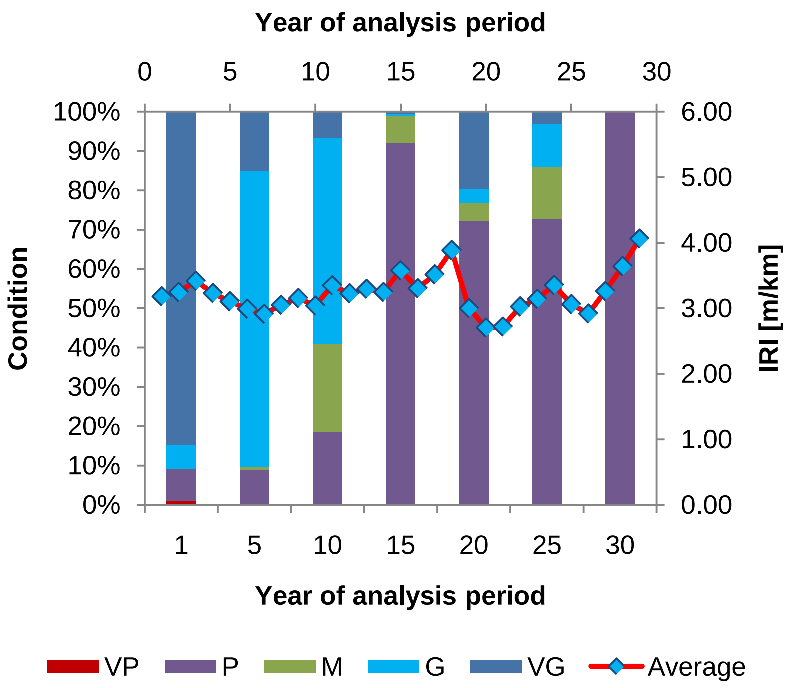


Figure 4.9 Optimal Scenario “two”, network condition for motorways

Suggested interventions on all sections involved the application of WMA M&R at very high threshold values. Intervals for interventions were 9–14 years, for thick overlays and 6–7 years for thin overlays, respectively.

Table 4.6 Optimal scenario “two”, solution catalogue for motorways

Traffic Level	Initial Condition	Length	Trigger	Intervention
II	**VG**	248.96	5	WMA M&R thick
	G	43.63	4	WMA M&R thin
	M	59.96	4.4	WMA M&R thin
III	**VG**	1010.58	3.9	WMA M&R thin
	G	28.1	4	WMA M&R thin
	M	46.63	4.7	WMA M&R thick
	P	9.62	4.2	WMA M&R thin
	VP	19.61	4.6	WMA M&R thin
IV	**VG**	409.78	4.6	WMA M&R thin
	G	47.74	4.1	WMA M&R thick
V	**VG**	5.68	3.9	WMA M&R thick
	G	4.52	4.4	WMA M&R thick
	M	8.85	3.9	WMA M&R thick
	P	30.87	4.9	WMA M&R thick

The optimal scenario “two” kept the state road Class I network in average condition throughout the analysis period (Figure 4.10). At the beginning of the analysis period, more than 25% of the analyzed network was in poor condition, which was unacceptable according to optimal scenario “two” where, throughout the analysis period, this percentage did not exceed 5%.

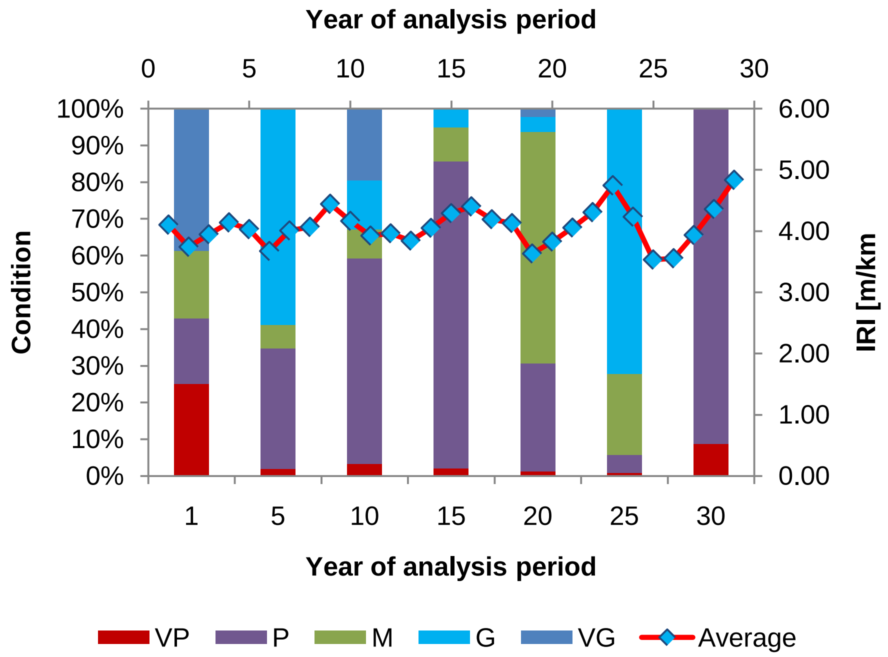


Figure 4.10 Optimal Scenario “two”, network condition for SR Class I

However, as mentioned before, threshold values for the application of certain maintenance treatments are relatively high for all sections, i.e.,4.5–5.4 m/km. Suggested interventions involved the application of WMAM&R in one layer. Intervals for interventions were 7–9 years, and 13 years for one section with thick M&R.

Table 4.7 Optimal scenario “two”, solution catalogue for SR Class I

Traffic Level	Initial Condition	Length	Trigger	Intervention
I	**VG**	19.87	5.4	WMA M&R thin
	M	40.74	5	WMA M&R thin
	P	1.5	4.5	WMA M&R thin
	VP	17.44	4.7	WMA M&R thin
II	**VG**	154.41	4.5	WMA M&R thin
	G	70.73	5.4	WMA M&R thin
	M	100.34	5.3	WMA M&R thin
	P	87.97	5.2	WMA M&R thin
	VP	136.94	5.5	WMA M&R thin
III	**VG**	180.72	5.1	WMA M&R thin
	G	47	4.8	WMA M&R thin
	M	22.76	5.4	WMA M&R thick
	VP	4.36	4.5	WMA M&R thin
IV	**VG**	43.01	5.2	WMA M&R thin
	G	30.25	4.8	WMA M&R thin
	M	45.1	5.4	WMA M&R thin
	P	14.17	5.4	WMA M&R thin
	VP	11.49	5.1	WMA M&R thin

Optimal scenario “two” kept the state road network Class II generally in medium/poor condition throughout the analysis period (Figure 4.11). In this case, a major part of the network was in very poor condition (more than 60%) at the beginning of the analysis period.

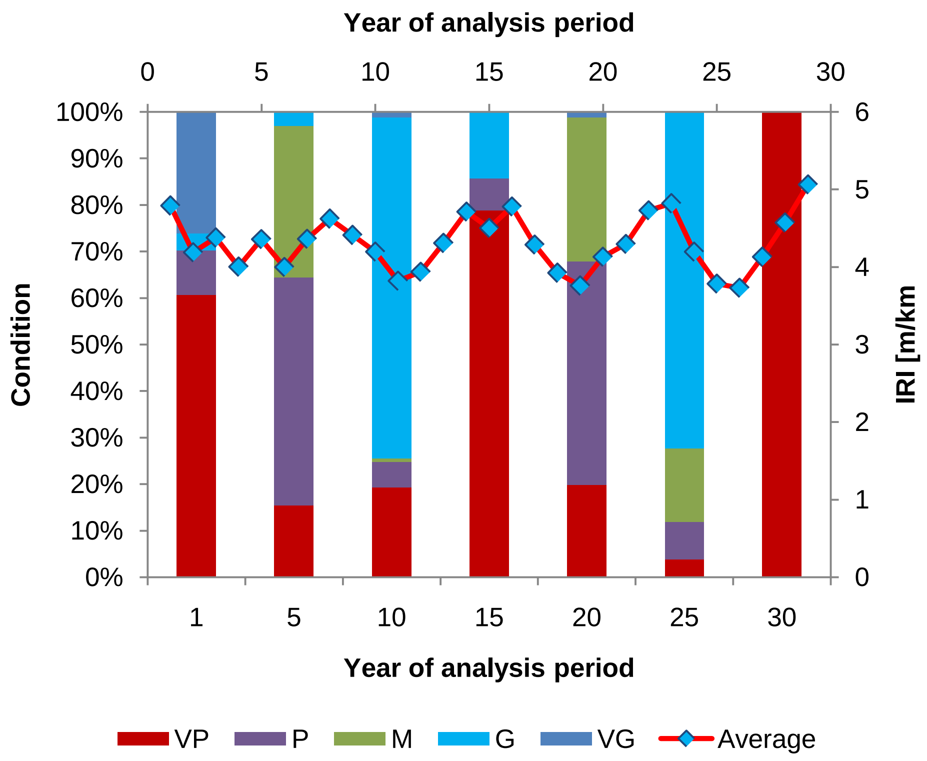


Figure 4.11 Optimal Scenario “two”, network condition for SR Class II

Suggested interventions on all traffic volume sections involved the application of thin WMAM&R overlays at high threshold values (4.6–6.0 m/km). This being the maximal possible threshold value suggests that these sections are prioritized as “do minimal maintenance” sections as seen in the Table 4.8. Intervals for interventions were 7–9 years.

Table 4.8 Optimal scenario "two", solution catalogue for SR Class II

Traffic Level	Initial Condition	Length	Trigger	Intervention
I	VG	1227.34	4.6	WMA M&R thin
	G	397.59	5.3	WMA M&R thin
	M	579.41	6	WMA M&R thin
	P	519.51	5	WMA M&R thin
	VP	2224.73	5.2	WMA M&R thin
II	VG	654.68	5.1	WMA M&R thin
	G	187.86	4.9	WMA M&R thin
	M	328.03	5.7	WMA M&R thin
	P	224.21	5.8	WMA M&R thin
	VP	401.91	5.8	WMA M&R thin
III	VG	257.18	5.4	WMA M&R thin
	G	82.96	5.7	WMA M&R thick
	M	25.86	5.1	WMA M&R thin
	P	47.12	5.4	WMA M&R thin
	VP	51.32	5.8	WMA M&R thin

The associated discounted costs of interventions are shown in Figure 4.12.

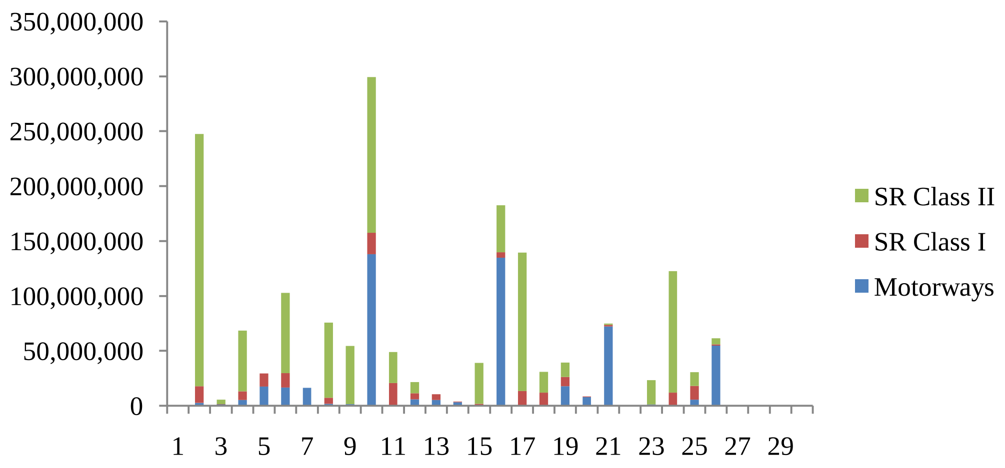


Figure 4.12 Optimal plan for scenario "two"–optimization based on emissions

The related discounted VOC were 2,333 million Euro /year in the 30-year period, or in total 70,004 million Euro, for an average network condition of 3.92 m/km throughout the analysis period. Total agency costs were 2,333 million Euro or 53 million Euro /year. Associated emissions of CO_2 were 1,337 million t or 44 million t/year.

This scenario lowers emissions; however, there is a significant increase in the average roughness and corresponding VOCs, but also the use of more costly maintenance treatments at higher thresholds.

4.5. Integrated "Optimal" Solution

The analysis showed that (i) the optimization based only on agency costs and RUCs results in higher overall emissions and (ii) the optimization based solely on minimizing emissions, during a certain period of time, leads to an increase in road network roughness and the application of more costly maintenance intervention treatments than traditional maintenance treatments. In order to combine the two objectives, i.e., minimal cost and minimal emissions, a monetary value (or some other kind of weighting factor) has to be assigned to emissions. If this unit cost is too low, the solution would be inclined to the "cost" model rather than "emissions" model and vice versa.

Therefore, the key uncertainty, of an integrated optimization model, lies in the unit cost of CO_2emissions. A simulation of various costs of CO_2/t was applied to find the most appropriate policy for optimal maintenance planning at the network level. Literature suggests a wide range of potential prices, from USD0.01362/t to USD150 /t (Knittel and Sandler, 2014). One of the most recent World Bank policy papers stated the optimal unit cost for 1 t of CO_2 in pavement maintenance optimization procedures to be USD30–80 (World Bank, 2014).

Figure 4.13 shows a representation of the abovementioned sensitivity of overall costs to the change of price of CO_2 emissions for costs 1–550 euro, with 5 euro increments. Each point is a combination of optimal maintenance treatments that minimize the overall cost, at the network level, during the 30-year analysis period.

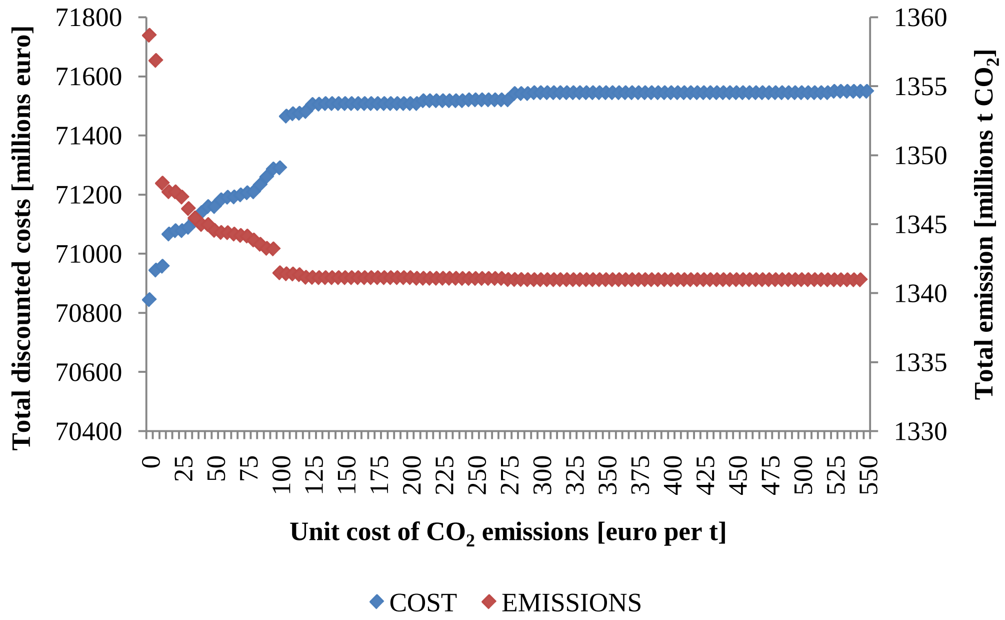


Figure 4.13 Sensitivity of the integrated optimal solution to the unit cost of CO_2

When the cost of CO_2 emissions is “0”, the total costs have a minimal value, but emissions reach a maximal level. However, when the unit cost of CO_2emissions per t is higher than 150 euro/t, the optimal integrated solution produces results that resemble the solution of scenario “two”, i.e., lower emission levels with higher user and agency costs.

That means that the “optimal” integrated solution should be looked for in the [0, 150] interval (shown in Figure 4.14) for the cost of CO_2/t in order to reach an overall optimum that serves both objectives, i.e., lowering cost and emissions simultaneously.

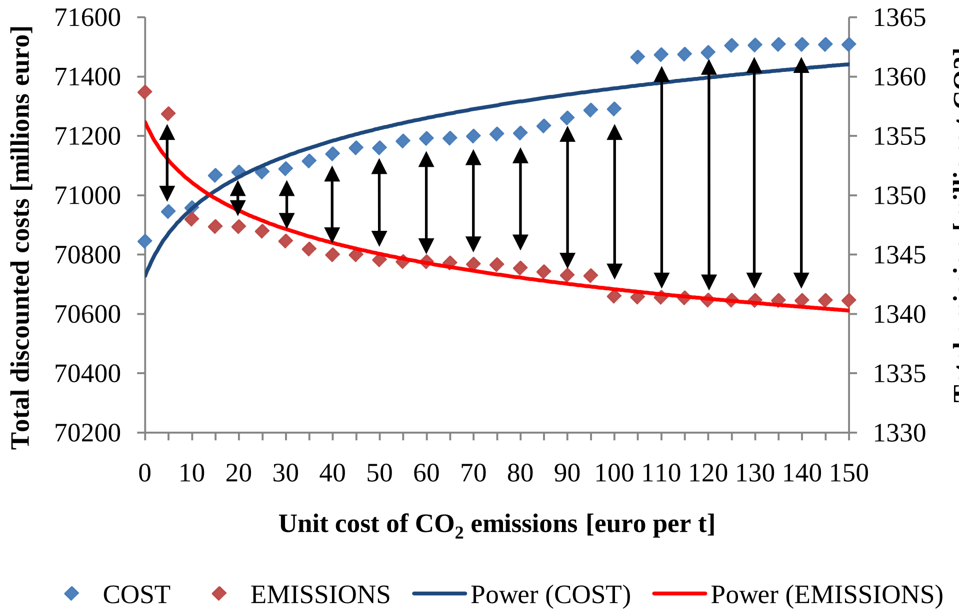


Figure 4.14 Sensitivity of the integrated optimal solution to the unit cost of CO_2 emission

Each value of the unit cost is applied for finding an optimal integrated scenario, and for each solution, average normalized network triggers were calculated and presented in Figure 4.15. The figure also graphically illustrates the domain where the optimal integrated solution may be located.

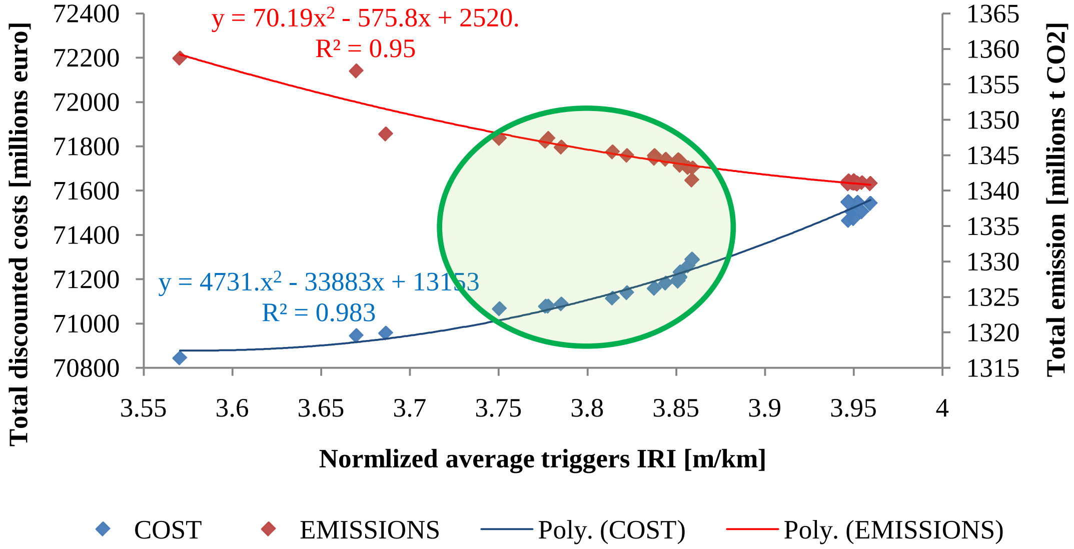


Figure 4.15 Sensitivity of the integrated optimal solution to the cost of CO_2 emissions

However, in order to find an optimal overall solution numerically, in the next step, these two curves (i.e., dependence of the overall cost and emissions on the CO_2 unit price) were fitted to functions, using the Gaussian and power transformations, with the adjusted R^2 above 0.96.

For the sensitivity of CO_2 to overall cost, the Gaussian transformation (Equation 4.1) was used for fitting the data, with coefficients that were calculated and presented in equation 4.2.

Goodness of fit was estimated based on the value of R^2 which is 0.9731, adjusted R^2 0.9667, and standard error RMSE 31.19.

$$f(x) = \frac{a_1}{\frac{1}{e^{\left(\frac{x-b_1}{c_1}\right)^2}}} + \frac{a_2}{\frac{1}{e^{\left(\frac{x-b_2}{c_2}\right)^2}}} \qquad \textit{(eq. 4.1)}$$

$$f(x) = \frac{30920}{\frac{1}{e^{\left(\frac{x-231.1}{141.1}\right)^2}}} + \frac{69050}{\frac{1}{e^{\left(\frac{x+19.98}{291.6}\right)^2}}} \qquad \textit{(eq. 4.2)}$$

The estimated curve is presented on Figure 4.16.

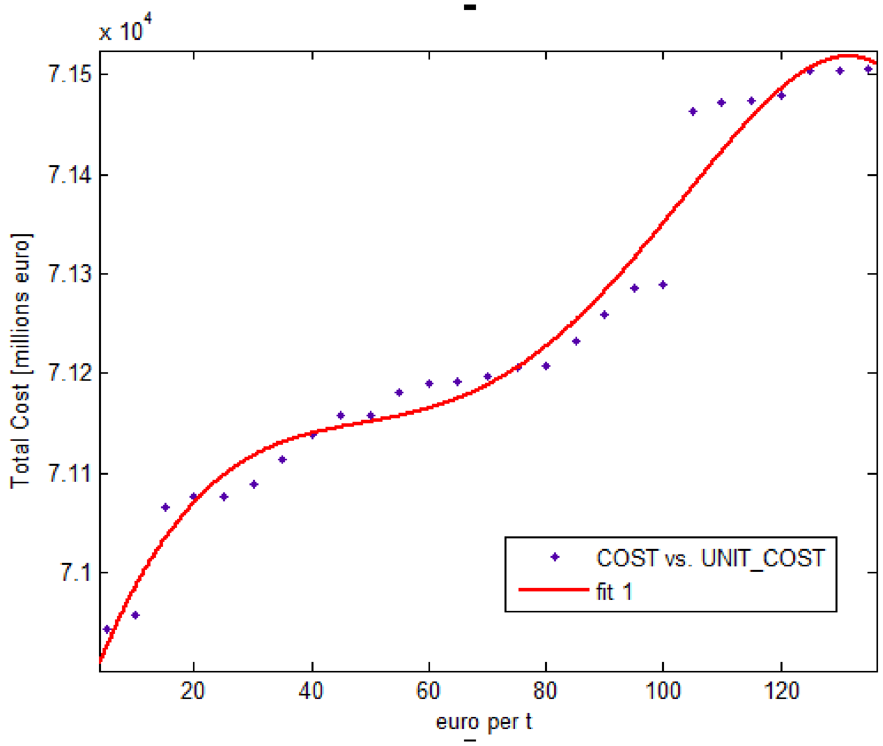


Figure 4.16 Dependence of the overall cost on the unit cost of CO_2 emissions

Similarly, the dependence of total emissions, in various optimal scenarios, on the unit cost of CO_2 was fitted using a power function (Equation 4.3) and coefficients were calculated to fit the model with the value of $R^2$of 0.9603, adjusted R^2 0.9566, and standard error RMSE 0.4443.

$$f(x) = a \times x^b + c \quad \textit{(eq. 4.3)}$$

$$f(x) = -0.3301 \times x^{0.6742} + 1350 \quad \textit{(eq. 4.4)}$$

The model is also presented on Figure 4.17.

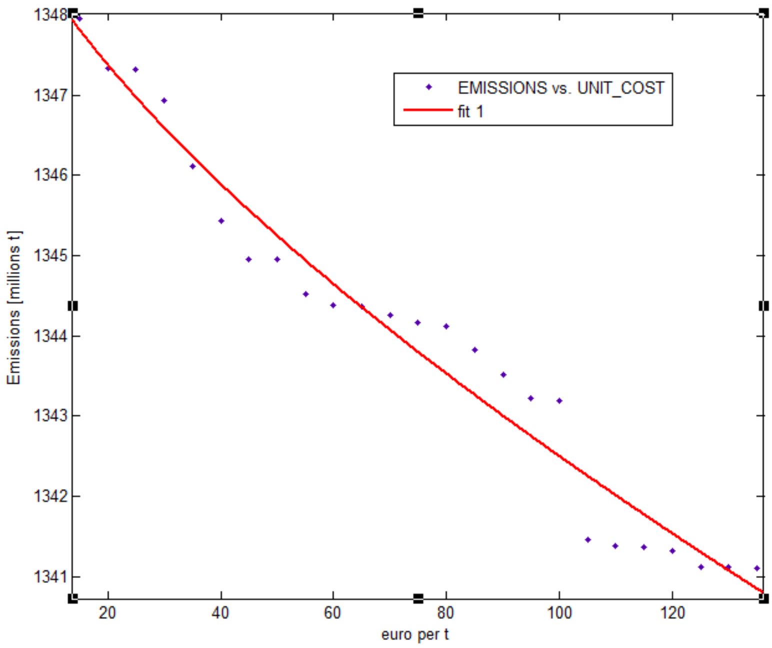


Figure 4.17Dependence of total emissions on the unit cost of CO_2 emissions

A multi-objective optimization, based on GAs, was performed in order to find a balance between the two objectives, and an improved maintenance strategy.

The Pareto frontier, as shown in Figure 4.18, represents the set of “optimal” solutions which provides a clearer outlook on the trade-off between the two solutions based on costs and CO_2 emissions, as a relative distance between the solutions.

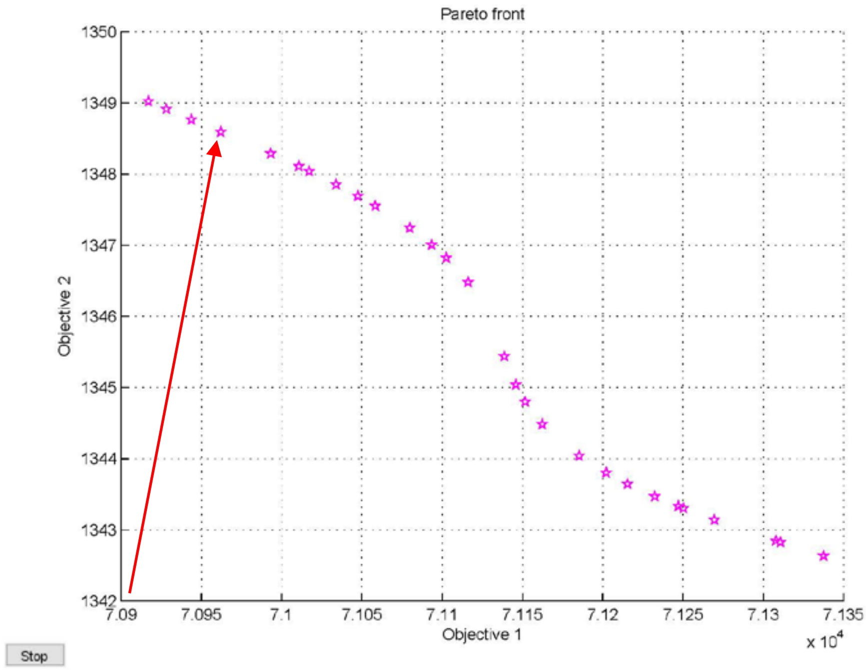


Figure 4.18Pareto frontier for the two objectives

The optimization determined the “optimal” point at the price of $CO_2$of 14.047Euro/ton, which accounts for 71,017 million Euro of both user and agency costs, and 1,348 million tons of emissions. This is the point where both curves in Figure 4.15(?) have steep slopes, and both objectives were taken into account.

The integrated solution includes more environment-friendly treatments, i.e., use of RAP at higher threshold values, leading to an increased time between pavement maintenance interventions and a lower GHG footprint.

Table 4.9 Solution catalogue for the integrated optimal solution

	Traffic	Condition	Threshold	Intervention type
Motorways	II	VG	5	25% RAP M&R thick
		G	3.8	25% RAP M&R thick
		M	4.2	25% RAP M&R thick
	III	VG	3.6	25% RAP M&R thick
		G	3.9	25% RAP M&R thick
		M	4.7	25% RAP M&R thick
		P	2.7	25% RAP M&R thin
		VP	3.4	25% RAP M&R thick
	IV	VG	4	25% RAP M&R thick
		G	3.1	25% RAP M&R thick
	V	VG	2.5	25% RAP M&R thick
		G	2.8	25% RAP M&R thick
		M	2.6	25% RAP M&R thick
		P	3.5	25% RAP M&R thick
SR Class I	I	VG	5.4	25% RAP M&R thin
		M	5.3	25% RAP M&R thin
		P	4.8	25% RAP M&R thin
		VP	4.8	25% RAP M&R thin
	II	VG	4.5	25% RAP M&R thin
		G	5.4	25% RAP M&R thin
		M	5.1	25% RAP M&R thick
		P	5.2	25% RAP M&R thin
		VP	4.3	25% RAP M&R thin
	III	VG	3.9	25% RAP M&R thick
		G	5.4	25% RAP M&R thick
		M	5.3	25% RAP M&R thick
		VP	3.5	25% RAP M&R thin
	IV	VG	4.1	25% RAP M&R thick
		G	3.7	25% RAP M&R thick
		M	3.8	25% RAP M&R thick
		P	3.8	25% RAP M&R thick
		VP	4	25% RAP M&R thick
SR Class II	I	VG	4.7	25% RAP M&R thin
		G	5.6	25% RAP M&R thin
		M	6	25% RAP M&R thin
		P	5.7	25% RAP M&R thin
		VP	5.2	25% RAP M&R thin
	II	VG	5.1	25% RAP M&R thin
		G	4.9	25% RAP M&R thin
		M	5.2	25% RAP M&R thick
		P	4.6	25% RAP M&R thin
		VP	5.8	25% RAP M&R thin
	III	VG	4.3	25% RAP M&R thick
		G	5.5	25% RAP M&R thick
		M	4.9	25% RAP M&R thick
		P	4.3	25% RAP M&R thin
		VP	4.1	25% RAP M&R thick

CHAPTER 5 VALIDATION AND SENSITIVITY

Network level optimizations of pavement maintenance are, by default, linked ‘to a certain level of generalization, estimation, and issue of missing data records. Since the integrated model developed herein actually consists of several models, it was necessary to explore the sensitivity of each model in particular, followed by comparing the developed integrated model to other recognized tools that may serve the same purpose.

Having that in mind, it was necessary to verify

- the validation method for cost estimation modeling,
- explore deterioration uncertainty and uncertainty regarding roughness measurements,
- the sensitivity of the LCCA model to the traffic growth rate,
- the sensitivity of the LCCA model to the discount rate, and
- the sensitivity of integrated models to the unit cost of CO_2 emissions.

5.1. Validation regarding cost modeling

Validation was one important part of the development procedure for each cost estimation model as the models are based on a limited dataset. In order to produce models that can be generally applied, it is necessary to develop a validation procedure that involves building models on a limited dataset (i.e., training sample) and verification of the generated model on a totally independent dataset (i.e., test sample). Data records from the independent set have to be excluded completely from the initial model development. Only by following such a procedure, it is possible to gain insight into how the model can perform on “new data”.

Several authors emphasize the importance of a cross-validation methodology, especially with complex data such as those from various contracts (Adeli and Wu, 1998). This allows finding optimal models in terms of precision versus over-fitting (the model should as precisely as possible fit the dataset – “precision”, but also to be able to be applicable to independent data, i.e., not “over-fitted” to the existing dataset). Such procedures were applied for all cost estimation techniques used in this research: RA, classification trees and ANNs.

As a validation method, a tenfold cross-validation was applied for classification trees. This means that nine-tenths of the dataset was used for training (model generation), and the remaining one-tenth was used for model validation. This process was repeated ten times, always with a different nine-tenths of data for model generation and corresponding one-tenth of data for model validation. That means that all the data was at some point used for both training and validation. The statistics of the resulting classification tree were calculated as the average value from the 10iterations.

Since the dataset was relatively small, splitting the dataset between training and validation samples might possibly cause additional errors in the prediction models. Therefore, for RAs (MRA and ANNs) the leave one out (L.O.O.) method was used, which is actually an n-cross validation, meaning that the computation goes through n iterations, leaving one data point out of the training sample each time. L.O.O. statistics were used for calculating the L.O.O. coefficient of determination, which can be interpreted as one additional representation of the applicability of the models in future use on entirely new datasets.

Table 5.1 L.O.O. statistic for AC cost estimation models

Parameter	Model 1	Model 2
R^2	0.745	0.679
Adjusted R^2	0.723	0.655
L.O.O. R^2	0.681	0.628

Results of L.O.O. statistics show than the model is generally applicable, with a slightly lower precision on other datasets.

For classification trees, a tenfold cross-validation was performed, and it was shown that the classifications according to the proposed models were correct in up to 77.9% of contracts/data records for AC, as shown in Table 5.2.

Table 5.2 Classification tree for unit cost of AC

	Predicted values, AC						Correct
	scores	1	2	3	4	5	(%)
Observed values	**1**	3	0	1	0	0	75.0
	2	2	14	7	0	0	60.9
	3	0	1	47	0	0	97.9
	4	0	0	4	3	0	42.9
	5	0	0	3	1	0	0.0
Total number of correctly classified contracts (%)							**77.9**

In case of ANNs, the L.O.O. method was used for model development, and the L.O.O. coefficient of determination was 0.765, which also suggests that the model is applicable to other data.

5.2. Deterioration model uncertainty

After cost estimation models, the deterioration rate and progression, expressed through the roughness development, are one very important cause of uncertainty in the model.

Since the deterioration model is incremental, the overall uncertainty of the deterioration model is actually the uncertainty related to roughness measurements, uncertainty that is a consequence of generalization, and uncertainty related to estimations of age, ESSO, and SNC.

The calculation procedure for model uncertainty is given by the following set of equations.

$$\mu(IRI_t) = \mu(IRI_{t-1}) + \mu(\Delta IRI) \qquad \textit{(eq. 5.1)}$$

$$\mu(\Delta IRI) = \mu(K_{gp} \times (a_0 \times e^{K_{gm} \times m \times AGE} \times (1 + SNC \times a_1)^{-5} \times ESSO + a_2 \times AGE) + K_{gm} \times m \times IRI(t-1)) \qquad \textit{(eq. 5.2)}$$

Equations 5.1 and 5.2 are expressions for the deterioration model used in all the models within this research. Uncertainty can be calculated by assessing uncertainty related to each variable and the corresponding derivative (Equation 5.3).

$$\mu(\Delta IRI) = \sqrt{\left(\frac{\partial(\Delta IRI)}{\partial\, AGE} \times \mu(AGE)\right)^2 + \left(\frac{\partial(\Delta IRI)}{\partial ESSO} \times \mu(ESSO)\right)^2 + \left(\frac{\partial(\Delta IRI)}{\partial\, SNC} \times \mu(SNC)\right)^2} \qquad \textit{(eq. 5.3)}$$

In the next step it is necessary to calculate each derivative, namely δAGE, δESSO, and δSNC (Equations 5.4–5.7).

$$\frac{\partial(\Delta IRI)}{\partial\, AGE} = \frac{\partial(K_{gp} \times (a_0 \times e^{K_{gm} \times m \times AGE} \times (1 + SNC \times a_1)^{-5} \times ESSO + a_2 \times AGE))}{\partial AGE}$$

(eq. 5.4)

$$\frac{\partial(\Delta IRI)}{\partial\, AGE} = K_{gp} \times (\frac{a_0 \times K_{gm} \times ESSO \times m \times e^{(K_{gm} \times m \times AGE)}}{(1 + SNC \times a_1)^5} + a_2)$$

(eq. 5.5)

$$\frac{\partial(\Delta IRI)}{\partial\, SNC} = \frac{-5 \times a_0 \times a_1 \times ESSO \times K_{gp} \times e^{(K_{gm} \times m \times AGE)}}{(1 + SNC \times a_1)^6}$$

(eq. 5.6)

$$\frac{\partial(\Delta IRI)}{\partial\, ESSO} = \frac{K_{gp} \times a_0 \times e^{(K_{gm} \times m \times AGE)}}{(1 + SNC \times a_1)^6}$$

(eq. 5.7)

Then, it is needed to assess the individual uncertainty for each variable. This can be very difficult since there isn’t sufficient data about the variations in assessment. For instance, the age of the pavement should be correct data (except if it is for some reason a miss-typed number). However, in case the variable “AGE” is missing from the input dataset, the error of estimation needed for further calculations probably equals several years. Therefore, the uncertainty related to AGE is given by Equation 5.8, under the assumption that assessments follow a triangular distribution (a common case when engineering assessment is needed). In case of ESSO, measurements are also accurate, but the error may occur due to adopting homogeneous sections, therefore uncertainty is linked to the standard deviation of actual traffic levels within the traffic level class. The same can be applied for the variable SNC.

$$\mu(AGE) = \frac{2}{\sqrt{3}}$$ *(eq. 5.8)*

$$\mu(ESSO) = SD_{ESSO}(per\ virtual\ section)$$ *(eq. 5.9)*

$$\mu(SNC) = SD_{SNC}(per\ virtual\ section) \qquad (eq.\ 5.10)$$

$$\mu(IRI_{t-1}) = SD_{IRI}(per\ virtual\ section) \qquad (eq.\ 5.11)$$

Now, all the parameters are known and the uncertainty for the deterioration curve may be calculated based on Equation 5.2. Table 5.3 gives an example of such calculations for several virtual sections, with various traffic volumes and different initial condition.

Table 5.3 Calculation on deterioration increment uncertainty on various sections

	virtual section 26	**virtual section 38**	**virtual section 23**	**virtual section 16**	**virtual section 51**
traffic level	I	III	V	IV	I
condition	I	III	III	I	I
a_0	134	134	134	134	134
a_1	0.7947	0.7947	0.7947	0.7947	0.7947
a_2	0.0054	0.0054	0.0054	0.0054	0.0054
m	0.035	0.035	0.035	0.035	0.035
K_{gm}	1	1	1	1	1
K_{gp}	1	1	1	1	1
AGE (years)	1	5	4	1	1
SNC	6.96	7.32	10.62	10.63	7.79
ESSO	0.04	0.45	2.16	1.63	0.09
IRI_{t-1} (m/km)	2.46	3.7	3.16	1.59	2.75
δ AGE	0.00542	0.00557	0.00556	0.00551	0.00542
δ SNC	–0.00028	–0.00284	–0.00187	–0.00126	–0.00036
δ ESSO	0.00179	0.00159	0.00022	0.00020	0.00100
μ AGE	1.155	1.155	1.155	1.155	1.155
μ SNC	2.360	0.280	0.000	2.500	1.880
μ ESSO	0.013	0.053	0.000	0.255	0.063
Δ IRI (m/km)	0.09	0.16	0.14	0.06	0.10
U (Δ IRI)	0.00629	0.00648	0.00641	0.00710	0.00630
Result	0.09±0.006	0.16±0.007	0.14±0.006	0.06±0.007	0.10±0.006

Part of the deterioration uncertainty that is related to generalization, i.e., use of virtual sections instead of real section of the network, is presented in Table 5.2. Results show that this uncertainty does not affect the result, since the trigger levels for interventions are set to IRI one tenth of m/km, and the order of magnitude of this uncertainty is 0.01 m.

As stated before, the other possible increment in uncertainty is related to IRI measurements, $\mu(IRI\,(t-1))$, as seen in Equation 5.1. This value depends on the measuring device and equipment used.

5.3. Sensitivity to traffic growth rate

Traffic sensitivity is one of common uncertainties in network-level strategic analyses. In order to evaluate the influence of the change of the traffic growth rate on the optimal maintenance strategy, the results, obtained with the use of optimal scenario “one”, were compared for traffic growth rates of 5%, 3%, and0%.

The results were given in Tables 5.4 and 5.5.

Results show that an increase in the traffic growth rate of2% (from 3% to 5%) led to the use of heavier maintenance treatments for three sections. However, for both scenarios threshold values for the application of certain interventions were very comparable.

Table 5.4 Sensitivity to traffic growth rate – results

	Average Condition [IRI, m/km]	**Agency Cost [million Euro]**	**User Costs [million Euro]**	**Total costs [million Euro]**	**CO_2 Emissions [million t]**
0%	3.14	1809.75	68721.11	70530.86	1373.437
3%	**3.12**	**1891.45**	**68789.12**	**70680.57**	**1382.906**
5%	3.15	2026.91	68778.14	70805.05	1404.083

A change in total cost by applying a 5% instead of a 3% traffic growth rate leads to an increase in total costs of0.2%. The change in overall emissions is higher and it equals (for the same case) +1.5%.

Heavier traffic levels lead to an increase in the rate of road deterioration, which also affects the frequency of maintenance treatments, which all leads to an increase in agency costs. However, this change equals 0.1% for a change in the traffic growth rate of 2% (from 3% to 5%).

Similarly the change in total cost by applying a 0% instead of a 3% traffic growth rate leads to a decrease in total costs of0.2%. The change in overall emissions equals (for the same case) –0.7%. In this case, the threshold for interventions is slightly lower than in the base scenario, due to the retardation of pavement deterioration progression which is a consequence of lower traffic.

Table 5.5 Sensitivity to the traffic growth rate

	Traffic Level	Initial Cond.	0%		3%		5%	
			IRI (m/km) threshold	Treatment	IRI (m/km)threshold	Intervention	IRI (m/km)threshold	Intervention
Motorways	II	VG	4.7	M&R thick	5	M&R thick	3.6	M&R thick
		G	2.6	M&R thin	3.8	M&R thick	3.9	M&R thick
		M	2.7	M&R thin	2.7	M&R thin	2.7	M&R thin
	III	VG	3.4	M&R thick	**3.6**	**M&R thick**	**3.8**	**perpetual**
		G	2.6	M&R thin	2.6	M&R thin	2.5	M&R thin
		M	2.5	M&R thin	2.5	M&R thin	2.5	M&R thin
		P	2.5	M&R thin	2.7	M&R thin	2.6	M&R thin
		VP	2.5	M&R thin	3.3	M&R thick	3.3	M&R thick
	IV	VG	3.2	perpetual	3.3	perpetual	3.5	perpetual
		G	2.5	M&R thick	2.6	M&R thick	2.7	M&R thick
	V	VG	2.5	M&R thick	2.5	M&R thick	2.5	M&R thick
		G	2.5	M&R thick	2.5	M&R thick	2.5	M&R thick
		M	2.5	M&R thick	2.6	M&R thick	2.5	M&R thick
		P	2.7	M&R thick	2.7	M&R thick	2.5	M&R thick
SR Class I	I	VG	5.4	M&R thin	**5.4**	**M&R thin**	**5.5**	**self-healing**
		M	5.3	M&R thin	5.3	M&R thin	5.3	M&R thin
		P	5.3	M&R thin	4.8	M&R thin	5.2	M&R thin
		VP	5.5	M&R thin	5	M&R thin	5.1	M&R thin
	II	VG	3.5	M&R thin	3.8	M&R thin	4.2	M&R thin
		G	4.1	M&R thin	4.4	M&R thin	4	M&R thin
		M	3.3	M&R thin	3.5	M&R thin	3.6	M&R thin
		P	3.8	M&R thin	3.7	M&R thin	3.9	M&R thin
		VP	3.2	M&R thin	3.6	M&R thin	3.4	M&R thin
	III	VG	4.1	perpetual	4.1	perpetual	4.2	perpetual
		G	3.1	M&R thin	4.1	M&R thick	4.5	M&R thick
		M	3.5	M&R thin	3.2	M&R thin	3.1	M&R thin
		VP	3	M&R thin	3.1	M&R thin	3.2	M&R thin
	IV	VG	3.2	M&R thick	3.3	M&R thick	3.5	M&R thick
		G	3	M&R thick	3.1	M&R thick	3.2	M&R thick
		M	3	M&R thin	3.1	M&R thin	3	M&R thin
		P	3	M&R thin	3.1	M&R thin	3	M&R thin
		VP	**3**	**M&R thin**	**3.3**	**M&R thick**	3.5	M&R thick
SR Class II	I	VG	**6**	**M&R thin**	**5.7**	**self-healing**	5.8	self healing
		G	5.6	M&R thin	5.6	M&R thin	5.6	M&R thin
		M	5.6	M&R thin	6	M&R thin	6	M&R thin
		P	5.7	M&R thin	5.7	M&R thin	5.7	M&R thin
		VP	5.2	M&R thin	5.9	M&R thin	6	M&R thin
	II	VG	4.8	M&R thin	4.3	M&R thin	4.4	M&R thin
		G	3.7	M&R thin	4.2	M&R thin	4.3	M&R thin
		M	4	M&R thin	**3.9**	**M&R thin**	**5.6**	**M&R thick**
		P	3.9	M&R thin	3.8	M&R thin	4.1	M&R thin
		VP	4.6	M&R thin	5.2	M&R thick	5.3	M&R thick
	III	VG	3.6	M&R thin	4.3	M&R thick	4.6	M&R thick
		G	3.7	M&R thin	4.3	M&R thick	4.3	M&R thick
		M	3.8	M&R thin	3.6	M&R thin	3.5	M&R thin
		P	3.8	M&R thin	3.6	M&R thin	3.5	M&R thin
		VP	3.7	M&R thin	4.1	M&R thick	4.4	M&R thick

5.4. Sensitivity to discount rate

The discount rate is commonly used in strategic analyses to evaluate future expenditures, and compare them to current prices. However, deterioration rates, prescribed on the national level, by the National Bank of Serbia have changed significantly in the past several years. Prior to 2015, the value of the discount rate was higher than 8% for years; but at the end of 2016 it was set at 4%. Therefore, the possible change in the discount rate was evaluated by applying discounts rates of 4%, 6%, and 8% and comparing results of the optimization model, i.e., optimal maintenance strategy.

The results were given in Tables 5.6 and 5.7.

Results show that an increase in the discount rate of2% (from 6% to 8%) led to the use of different maintenance treatments for 5 sections, but with no distinct pattern whether this change requires heavier or more moderate interventions. However, for both scenarios threshold values for the application of certain interventions were very similar.

Table 5.6 Sensitivity to discount rate – results

	Average Condition [IRI, m/km]	**Agency Cost [million Euro]**	**User Costs [million Euro]**	**Total costs [million Euro]**	**CO_2 Emissions [million t]**
4%	3.07	2531.78	86178.79	88710.57	1384.49
6%	**3.12**	**1891.448**	**68789.12**	**70680.57**	**1382.91**
8%	3.17	1436.60	56409.43	57846.03	1397.76

Although the change in agency costs, user costs, and total costs are evident, because of the application of different discount rates for the 30-year analysis period, overall emissions and average network conditions were very similar for all scenarios.

The change in overall emissions, when applying a 4%, instead of a 6% discount rate, equals +0.1%.

Similarly the change in overall emissions during the30-year analysis period by applying an 8% discount rate, instead of 6%,ledto an increase of 1.1%, due to the use of slightly higher threshold values for interventions.

Table 5.7 Sensitivity to discount rate

	Traffic Level	Initial Cond.	4%		6%		8%	
			IRI (m/km)threshold	**Intervention**	**IRI (m/km)threshold**	**Intervention**	**IRI (m/km)threshold**	**Intervention**
Motorways	**II**	**VG**	3.3	M&R thick	**5**	**M&R thick**	**5**	**perpetual**
		G	3.8	M&R thick	3.8	M&R thick	3.8	M&R thick
		M	2.7	M&R thin	2.7	M&R thin	2.7	M&R thin
	III	**VG**	3.6	M&R thick	**3.6**	**M&R thick**	**4.1**	**perpetual**
		G	2.6	M&R thin	2.6	M&R thin	2.6	M&R thin
		M	3.4	M&R thick	2.5	M&R thin	2.5	M&R thin
		P	2.7	M&R thin	2.7	M&R thin	2.5	M&R thin
		VP	3.1	M&R thick	3.3	M&R thick	3.3	M&R thick
	IV	**VG**	3.3	perpetual	3.3	perpetual	3.5	perpetual
		G	2.6	M&R thick	2.6	M&R thick	2.6	M&R thick
	V	**VG**	2.5	M&R thick	2.5	M&R thick	2.5	M&R thick
		G	2.5	M&R thick	2.5	M&R thick	2.5	M&R thick
		M	2.6	M&R thick	2.6	M&R thick	2.6	M&R thick
		P	2.7	M&R thick	2.7	M&R thick	2.7	M&R thick
SR Class I	**I**	**VG**	5.4	M&R thin	5.4	M&R thin	5.4	M&R thin
		M	5	M&R thin	5.3	M&R thin	5.3	M&R thin
		P	4.8	M&R thin	4.8	M&R thin	5.2	M&R thin
		VP	5	M&R thin	5	M&R thin	5.5	M&R thin
	II	**VG**	3.8	M&R thin	**3.8**	**M&R thin**	**4.9**	**self-healing**
		G	4.4	M&R thin	4.4	M&R thin	4.4	M&R thin
		M	**5.3**	**M&R thick**	**3.5**	**M&R thin**	3.5	M&R thin
		P	3.7	M&R thin	3.7	M&R thin	3.7	M&R thin
		VP	3.6	M&R thin	3.6	M&R thin	3.6	M&R thin
	III	**VG**	3.8	perpetual	4.1	perpetual	4.3	perpetual
		G	4.1	M&R thick	4.1	M&R thick	4.1	M&R thick
		M	**4.1**	**M&R thick**	**3.2**	**M&R thin**	3.2	M&R thin
		VP	3.1	M&R thin	3.1	M&R thin	3.1	M&R thin
	IV	**VG**	3.3	M&R thick	3.3	M&R thick	3.3	M&R thick
		G	3	M&R thick	3.1	M&R thick	3.1	M&R thick
		M	**3.2**	**M&R thick**	**3.1**	**M&R thin**	3	M&R thin
		P	**3.9**	**M&R thick**	**3.1**	**M&R thin**	3	M&R thin
		VP	3.2	M&R thick	**3.3**	**M&R thick**	**3**	**M&R thin**
SR Class II	**I**	**VG**	4.7	M&R thin	5.7	self healing	5.7	self healing
		G	5.3	M&R thin	5.6	M&R thin	5.6	M&R thin
		M	6	M&R thin	6	M&R thin	6	M&R thin
		P	5.3	M&R thin	5.7	M&R thin	5.9	M&R thin
		VP	5.9	M&R thin	5.9	M&R thin	5.9	M&R thin
	II	**VG**	4.2	M&R thin	4.3	M&R thin	4.3	M&R thin
		G	**4.8**	**M&R thick**	**4.2**	**M&R thin**	4.2	M&R thin
		M	**5.2**	**M&R thick**	**3.9**	**M&R thin**	4.1	M&R thin
		P	**5.4**	**M&R thick**	**3.8**	**M&R thin**	4	M&R thin
		VP	4.8	M&R thick	**5.2**	**M&R thick**	**4.9**	**M&R thin**
	III	**VG**	4.3	M&R thick	**4.3**	**M&R thick**	**3.8**	**M&R thin**
		G	4.1	M&R thick	4.3	M&R thick	4.3	M&R thick
		M	3.6	M&R thin	3.6	M&R thin	3.6	M&R thin
		P	3.6	M&R thin	3.6	M&R thin	3.6	M&R thin
		VP	4	M&R thick	4.1	M&R thick	4.1	M&R thick

5.5. Sensitivity to cost of CO_2

The unit cost of CO_2 emissions [euro/t] is an important variable in the integrated model. The integrated model searches for minimal total costs that comprise user costs, agency costs, and costs related to CO_2 emissions. For that reason, the unit cost of CO_2emissions plays an important role and gives weight to environmental factors in the overall costs.

As previously stated in Chapter 4.4, and as seen in Table 5.8, an increase in the unit cost of emissions led to optimal scenarios that had lower emissions, higher total cost, and worse average network conditions, and vice versa.

However, small changes in the unit cost of CO_2 emissions did not influence the final solution significantly. More precisely, a change in unit cost from 20 Euro/t to 30 Euro/t led to an increase in total cost of 0.2 % and a decrease in overall emissions during the 30-year analysis period by 0.7%.

Table 5.8 Sensitivity to the unit cost of CO_2 emissions –results

Euro/t	**Average Condition [IRI, m/km]**	**Agency Cost [million Euro]**	**User Costs [million Euro]**	**Total Cost [million Euro]**	**CO_2 Emissions [million t]**
10	3.32	2010.29	68946.30	70956.58	1356.84
20	3.45	1896.22	69180.58	71076.80	1347.33
30	3.49	1884.67	69203.31	71087.97	1346.94
50	3.66	1828.66	69329.67	71158.33	1344.95
75	3.72	1818.39	69386.62	71205.01	1344.16
100	3.77	1877.81	69411.57	71289.38	1343.19

Similarly, a change in unit cost from 20 Euro/t to 30 Euro/t led to an increase in total costs of 0.02 % and a decrease in overall emissions, during the 30-year analysis period by 0.03%.

Table 5.9 Sensitivity to the unit cost of CO_2 emissions

	Traffic Level	**Initial Cond.**	**10 euro/t**		**20 euro/t**		**30 euro/t**	
			IRI (m/km)threshold	**Treatment**	**IRI (m/km)threshold**	**Intervention**	**IRI (m/km)threshold**	**Intervention**
Motorways	**II**	**VG**	5	RAP M&R thick	5	RAP M&R thick	5	RAP M&R thick
		G	3.8	RAP M&R thick	3.8	RAP M&R thick	3.8	RAP M&R thick
		M	4.2	RAP M&R thick	4.2	RAP M&R thick	4.2	RAP M&R thick
	III	**VG**	3.6	RAP M&R thick	3.6	RAP M&R thick	3.6	RAP M&R thick
		G	3.9	RAP M&R thick	3.9	RAP M&R thick	3.9	RAP M&R thick
		M	4.7	RAP M&R thick	4.7	RAP M&R thick	4.7	RAP M&R thick
		P	**2.7**	**RAP M&R thin**	**4.2**	**RAP M&R thick**	4.2	RAP M&R thick
		VP	3.4	RAP M&R thick	3.4	RAP M&R thick	3.4	RAP M&R thick
	IV	**VG**	**3.3**	**perpetual**	**4**	**RAP M&R thick**	4	RAP M&R thick
		G	3.1	RAP M&R thick	3.1	RAP M&R thick	3.1	RAP M&R thick
	V	**VG**	2.5	RAP M&R thick	2.5	RAP M&R thick	2.5	RAP M&R thick
		G	2.8	RAP M&R thick	3.1	RAP M&R thick	3.1	RAP M&R thick
		M	2.6	RAP M&R thick	2.6	RAP M&R thick	2.6	RAP M&R thick
		P	2.7	RAP M&R thick	3.5	RAP M&R thick	3.5	RAP M&R thick
SR Class I	**I**	**VG**	5.4	RAP M&R thin	5.4	RAP M&R thin	5.4	RAP M&R thin
		M	5.3	RAP M&R thin	5.3	RAP M&R thin	5.3	RAP M&R thin
		P	4.8	RAP M&R thin	4.8	RAP M&R thin	4.8	RAP M&R thin
		VP	4.8	RAP M&R thin	4.8	RAP M&R thin	4.8	RAP M&R thin
	II	**VG**	4.5	RAP M&R thin	4.5	RAP M&R thin	4.5	RAP M&R thin
		G	4.4	RAP M&R thin	5.4	RAP M&R thin	5.4	RAP M&R thin
		M	**5.1**	**RAP M&R thick**	**5.3**	**RAP M&R thin**	5.3	RAP M&R thin
		P	5.2	RAP M&R thin	5.2	RAP M&R thin	5.2	RAP M&R thin
		VP	4.3	RAP M&R thin	4.3	RAP M&R thin	4.3	RAP M&R thin
	III	**VG**	3.9	RAP M&R thick	3.9	RAP M&R thick	3.9	RAP M&R thick
		G	5.4	RAP M&R thick	5.4	RAP M&R thick	5.4	RAP M&R thick
		M	5.3	RAP M&R thick	5.3	RAP M&R thick	5.3	RAP M&R thick
		VP	3.5	RAP M&R thin	3.5	RAP M&R thin	3.5	RAP M&R thin
	IV	**VG**	4.1	RAP M&R thick	4.1	RAP M&R thick	4.1	RAP M&R thick
		G	3.7	RAP M&R thick	3.7	RAP M&R thick	3.7	RAP M&R thick
		M	3.8	RAP M&R thick	3.8	RAP M&R thick	5.1	RAP M&R thick
		P	3.8	RAP M&R thick	3.8	RAP M&R thick	3.8	RAP M&R thick
		VP	4	RAP M&R thick	4	RAP M&R thick	4	RAP M&R thick

SR Class II	I	**VG**	**5.7**	**self-healing**	**4.7**	**RAP M&R thin**	4.7	RAP M&R thin
		G	5.6	RAP M&R thin	5.6	RAP M&R thin	5.6	RAP M&R thin
		M	6	RAP M&R thin	6	RAP M&R thin	6	RAP M&R thin
		P	5.7	RAP M&R thin	5.7	RAP M&R thin	5.7	RAP M&R thin
		VP	5.2	RAP M&R thin	5.2	RAP M&R thin	5.2	RAP M&R thin
	II	**VG**	5.1	RAP M&R thin	5.1	RAP M&R thin	5.1	RAP M&R thin
		G	4.9	RAP M&R thin	4.9	RAP M&R thin	4.9	RAP M&R thin
		M	**5.2**	**RAP M&R thick**	**5.7**	**RAP M&R thin**	5.7	RAP M&R thin
		P	4.6	RAP M&R thin	5.8	RAP M&R thin	5.8	RAP M&R thin
		VP	4.6	RAP M&R thin	5.8	RAP M&R thin	5.8	RAP M&R thin
	III	**VG**	4.3	RAP M&R thick	4.4	RAP M&R thin	4.4	RAP M&R thin
		G	5.5	RAP M&R thick	5.5	RAP M&R thick	5.5	RAP M&R thick
		M	4.9	RAP M&R thick	4.9	RAP M&R thick	4.9	RAP M&R thick
		P	3.6	RAP M&R thin	**4.3**	**RAP M&R thin**	**5.3**	**RAP M&R thick**
		VP	4.1	RAP M&R thick	**4.1**	**RAP M&R thick**	**4.7**	**RAP M&R thin**

CHAPTER 6 – SUMMARY CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary

The objectives of this research were met through the completion of previously established research tasks.

Task 1, i.e., identification of key variables that affect the value of maintenance costs, was established in Chapter 3.2.1through a literature review which indicated the variables that are commonly used in such analyses. In Chapter 3.2.3 a statistical analysis was performed over a sample of 200 road maintenance projects, which included testing the significance of 20 potential variables. Some of the variables such as governance indicator, corruption index, country being an oil exporter or importer, are new in such analyses. This allowed creating models that are new and improved in comparison with existing knowledge.

Task 2, i.e., data collection, included collecting data on the condition of the road network and on completed road maintenance projects. The road database of PE Roads of Serbia was used for applying the developed models to an existing network. For developing cost estimation models, a database was used that contains over 200 international and domestic projects of road maintenance, completed in the last 10 years. This data was broadened with information on the TICPI from the Transparency International database, the WGI from the World Bank Global Indicators database, crude oil prices and whether the country is an oil exporter or importer, from the World Bank Global Indicators database, and climate and terrain from various country-specific sources including country profiles and maps.

Task 3, i.e., gathering information about environmental impacts throughout the life cycle of the pavement, was conducted through a literature review for data on conducted measurements and models that are in use for this type of analysis. For that purpose, several tools and models were considered, before choosing the model used in this research. These tools have been presented in Chapter 2.3.2.

Task 4, i.e., development of a statistical model for the cost estimation of road maintenance, was performed in Chapter 3.2.3. Two models were developed for estimating the price of AC using MRA. Those models were then compared with models obtained using ANNs and CT.

Fulfillment of Task 5, i.e., development of an optimization model for the maintenance of pavements at the strategic level, was demonstrated in Chapter 4.3. Within this research three solutions for the optimization model were presented, one based on cost (according to Task 5), second dealing with optimizing CO_2 emissions (responding to Task 6), and finally an integrated model (in line with requirements from Task 7). The environmental assessment included all phases of a pavement's life cycle. The resulting strategic analysis provided a solution catalogue (type and intensity of interventions, per section, for each year of the analysis period).

Finally, Task 8 involved testing and validating the models, which was performed by a sensitivity analysis, varying potentially influential parameters of the models. Chapter 5.2 also presents an analysis of uncertainty related to the pavement deterioration model, which is one of the fundamental models in pavement maintenance optimization procedures.

Performing those tasks allowed fulfilling the main research objective, i.e., to develop an integrated model for the strategic planning of maintenance activities, on flexible pavements, and on a network level. This was complemented with the analysis of mutual trade-offs between possible solutions from an economic and environmental aspect, which allowed finding a solution which is both economically and environmentally sound.

6.2. Limitations

The integrated model allows integrating both economical and environmental considerations into the decision-making process, while taking into account only unconstrained budget options. However, in reality, the available annual budget for road maintenance works may be much lower than the one proposed by the optimal scenario. Furthermore, in case of an unconstrained budget, annual spending may vary significantly from year to year, which is unrealistic from the standpoint of road authorities, i.e., in reality the maintenance budget allocated for road maintenance is typically fixed and unchangeable from year to year.

However, the use of an unconstrained budget gives an opportunity to determine the required budget for maintaining the road network in a certain condition and/or how to keep emissions under a certain threshold. It allows a more in-depth analysis of multiple drivers of the road network condition, requirements, and performance.

Mathematically, only small changes in the calculation of the optimal scenario may lead to obtaining the solution in a restricted budget situation. More precisely, if the total sum of road works is already spent, all remaining sections requiring interventions become candidate section but for the following year. In that case, the length of virtual sections has to be reasonably moderate, and such a procedure would lead to lower prioritization of low volume sections and for more demanding (in terms of cost) maintenance treatments.

In this analysis the length of virtual sections was, in some cases, considerable, since there were only 75 virtual sections. Hence, it is not realistic to apply the optimization procedure in case of a restricted budget.

The limited number of virtual sections is also one of the limitations of the model, although the model itself is easily adoptable for use on a much greater number of virtual sections. However, the current calculation time is approximately 3 minutes a personal computer, which was adequate for investigating and developing multiple models. In practical applications, computers used have considerably improved performances, and calculation time may last for hours. However, the number of sections does not affect the methodology for developing conclusions.

The proposed optimization routine considers a deterministic approach to the problem of finding the minimum of the objective function, meaning that the models do not account for the variability and probability of occurrence of a certain event (e.g., variations in quality of construction works were not taken into account nor was the uncertainty regarding pavement deterioration curves, traffic forecast, composition, etc.).

Road network management involves, beside technical, also nontechnical and noneconomic motivations for decision-making such as social and political reasons. For example, in order to preserve cultural heritage and/or boost local tourism, certain low-volume roads (roads leading to historical or cultural landmarks and touristic resorts) may be considered for pavement R&R works, although, due to low traffic levels, from an economical (or even environmental) aspect those sections would not be candidates for rehabilitation works.

Similarly, because of political decisions, some sections can become included into maintenance plans solely for the reason of addressing the needs of local communities or expectations of the general public, unrelated to technical evaluations.

These aspects were not included in the analysis, but this limitation can be bypassed by adopting a certain percentage of the total budget and allocating it for such works (e.g., 10–20% of the total budget). This issue in not related to Serbia alone, but generally, a part of the budget may be allocated for satisfying wider social needs (and/or for political decisions).

6.3. Conclusions

Testing a large set of variables, when building cost prediction models, was very adequate since a number of variables did not show any significant correlation to the cost of asphalt concrete. For example, number of bidders and size of the project and other project-specific variables were not determinant when estimating unit cost of AC on a specific project. What seems to have a very significant influence to the price of AC is country-specific context, including climate, oil resources, and governance indicators such are corruption and nepotism.

Furthermore, use of various regression techniques, on the same sample of projects, served to confirm above-mentioned conclusions, i.e. significance of the chosen variables in the cost estimation model was confirmed through use of classification threes, regression analysis and artificial neural networks.

Application of the developed regression models to Serbian data served to test the adequacy of the model, but also as input parameter to the further analysis.

Applied optimization model was based on the exhaustive search, i.e. finding minimal total cost (sum of road agency and road user cost) for 30 years of maintenance activities on a road network. Second optimization model was developed to find minimal total CO_2 emissions that are consequence of road users, and maintenance activities for the same30 years period. Outputs of those two optimization routines were different in several aspects:

- Type of treatments (e.g. recycling or not)
- Intensity of treatments (e.g. overlay thicknesses)

- Reoccurrence of treatments (e.g. every 7 years or every 12 years)
- Average network condition (good, poor, etc).

Optimization based only on cost tends to application of thinner treatments, on smaller time intervals, which keeps the overall network in good condition. Since the treatments are chosen solely by minimal cost, use of eco-friendly techniques in typically avoided. The suggested maintenance treatments largely differ between the “optimal” solutions according to the analyzed scenarios. The analysis showed that perpetual pavements may be a viable option for heavily trafficked sections that are currently in very good condition, because the first intervention was planned after some time, and this treatment keeps the pavement in excellent condition for a long period until the next maintenance treatment. Similarly, in this case, the application of WMA or recycling, from the sole aspect of agency and users’ costs, can be viable options if the costs of their application were comparable with the cost of conventional asphalt treatments.

Network split on the virtual homogeneous sections allowed easier interpretation of the obtained results regarding the influence of traffic levels and section initial condition. This showed that threshold values were highly dependent on the traffic level, as well as the thickness of maintenance treatments. For example, for higher traffic levels, user cost and vehicle emissions are predominant components and therefore the optimization results advised the application of more intensive treatments and keeping the roughness levels as low as possible. Opposite to that, low volume sections were candidates for very moderate interventions, i.e. thin overlay at very high threshold values.

However, second optimization routine, where the “goal” function was based solely on reducing total CO_2 emissions, produced significantly different optimal maintenance plan for 30 years period. In this plan, interventions are generally applied more moderately, which corresponds with higher threshold values, and thicker layers. However, all interventions included application of WMA additive since it reduces CO_2 emissions. Similarly, as in previous scenario, produced “optimal” solution is highly dependent on traffic volumes, in the similar manner. At low traffic levels, the CO_2 emissions in the “maintenance phase” are predominant compared with the “operational phase” and the vast production of the required asphalt materials cannot be justified by the lower emissions in the operational phase.

Overall, scenario “two” produces solution with lower CO_2 emissions, but at the cost of higher cost of interventions (use of additives) and having the whole network in substantially worse condition in comparison to the scenario “one”.

Finally, application of integrated models created maintenance plan which can serve both objectives, i.e. keeping maintenance spending and total emissions as low as possible, but having the whole network throughout the analysis period in a satisfactory condition.

Validation was one important part of the development procedure of the entire system, especially for cost estimation models. Only by following such a procedure, where the data records from the independent set have to be excluded completely from the initial model development, it is possible to gain insight into how the model can perform on “new data”.

A tenfold cross-validation was applied as a validation method for classification trees, meaning that all the data was at some point used for both training and validation. For RAs (MRA and ANNs) the leave one out (L.O.O.) method was used, which is actually an n-cross validation. Results of L.O.O. statistics show than the model is generally applicable i.e. can be used on entirely new datasets.

Special consideration was also given to the extent of uncertainty of the deterioration model, since this is one of the fundamental models in pavement management optimization. Results show that deterioration uncertainty does not affect the result, since the trigger levels for interventions are set to IRI one tenth of m/km, and the order of magnitude of this uncertainty is 0.01 m.

Similarly the sensitivity analysis applied to the final, integrated model, conducted by changing several important parameters, lead to similar conclusions:

- The decrease in traffic growth rate from 3% to 0% led to decrease in total cost of 0.2% and decrease in total emissions of 0.7%
- The decrease in discount rate from 6% to 4% led to increase in overall emissions of +0.1% during the 30-year analysis period. Similarly increase in discount rate from 6% to 8% led to increase in overall emissions of + 1.1%, due to the use of slightly higher threshold values for interventions.

- A change in unit cost of CO_2 emissions from 20 Euro/t to 30 Euro/t led to an increase in total cost of 0.2 % and a decrease in overall emissions during the 30-year analysis period by 0.7%.

6.4. Research contribution

There is a very limited number of attempts at solving the problem of finding the optimal maintenance plan on the network level, that include both LCA and LCCA analyses, taking into consideration environmental and monetary costs. To the authors' knowledge, there were no previous attempts to integrate those models with cost estimation modeling, and to reach the optimum without monetizing the overall cost and benefits.

One of important research contributions was the use of large sample of real data (200 projects) for building cost estimation models. The data sample consisted of projects developed in ECA countries in period of 10 years related to road infrastructure.

Also important aspect of building cost estimation models was testing a number of potentially significant variables. Those variables included project related information, but also country specific context which was proven to be very important for building cost estimations models. More specifically, Gross national income, climate, availability of oil derivates, levels of corruption and nepotism, are the variables rarely used in such analysis. However, those variables showed significant influence on the cost of road works. This cost estimation model is especially useful for early stages of project development, and for strategic pavement maintenance analysis on the network level, because they allow developing more reliable maintenance strategies with minimal data available.

Within this research several maintenance strategies were tested, including eco-friendly technologies such are WMA and use of RAP. Also, perpetual pavements and self-healing materials were used as potential maintenance treatments. These technologies have not been much considered previously in Serbia. However, herein they were tested for their applicability in the future from the theoretical standpoint.

Developed methodology showed consequences of different principles in decision-making regarding road maintenance, and what are the implications of such decisions. Methodology also served for finding a balance between confronting interests (e.g. lowering cost vs. eco-awareness) in pavement maintenance programs by using holistic approach to the overall problem.

The final solution was obtained through a combination of the use of an exhaustive search for the two confronting objectives and the use of genetic algorithms for multi-criteria analysis. In this methodology, monetizing of CO_2 emissions was avoided, by finding minimal relative distance between the two confronting objectives, using, genetic-algorithm based, multi-criteria analysis. This procedure serves the expectations of road users, road agency, and finally the environment.

Finally, the optimization model was developed for case of Serbian road network but can be easily adopted for any other network.

6.5. Future research

In the optimization model real data was used, from the Serbian Road Data Base. However, these data is obsolete, and should be updated with new measurements, when they become available. Same can be applied to the improvement models. There was no available data about roughness levels “just before” and “just after” the reconstruction on a sufficient number of sections. Therefore it was not possible to adequately calibrate the improvement models. Such procedure should be applied when adequate data becomes available.

However, future development of the model will include several aspects. First, the model can include greater number of possible treatments. For example, preventive treatments can be included in the analysis since they can affect retardation of the pavement deterioration curve. This can be especially important for highways, and high-traffic volume sections. Also, there is a possibility to apply constrains to road agency yearly budget for maintenance. Since, the focus of this research was on integration of various objectives in the optimization routine, in the first step, non constrained budget was applied. However, the model can easily be modified, to include constrained budget option as well.

The case study was presented on a fictive network consisting on relatively small number of homogeneous sections. However, the model itself can be easily adopted for use on a greater number of sections.

Finally, instead of deterministic models that have been applied in this research, use of probabilistic models can be valuable alternative for the next step.

REFERENCES

1. Abelson, P.W., Flowerdew, D.J. (1975). “Models for economic evaluation of road maintenance” *Journal of transport economy and policy*, <http://www.bath.ac.uk/e-journals/jtep/pdf/Volume_1X_No_2_93-114.pdf> (28.10.2016.)

2. Adeli, H., Wu, M. (1998). “Regularization Neural Network for Construction Cost Estimation.” ASCE Journal of Construction Engineering an Management, 124 (1), 18–24.

3. Akinci, B., Fischer, M. (1998). “Factors Affecting Contractors’ Risk of Cost Overburden.” Journal of Management Engineering, 14 (1), 67–76.

4. Akintoye, A. (2000). “Analysis of factors influencing project cost estimating practice.” Construction Management and Economics, 18(1), 77–89.

5. Akintoye, A., Fitzgerald, E. (2000). “A survey of current cost estimating practices in the UK.” Construction Management and Economics, 18(2), 161–172.

6. Alexeeva, V., Padam G., and Queiroz C. (2008). “Monitoring Road Works Contracts and Unit Costs for Enhanced Governance in Sub-Saharan Africa.” Transport paper TP-21, The World Bank Group, Washington D.C.

7. Alexeeva, V., Queiroz C., and Ishihara S. (2011). “Monitoring Road Works Contracts and Unit Costs for Enhanced Governance in Europe and Central Asia.” Transport paper TP-33, The World Bank Group, Washington D.C.

8. American Society of Civil Engineering (ASCE)(2013). Report Card 2013 Grades. <http://www.infrastructurereportcard.org/road-infrastructure/> (28.10.2016).

9. Anderson, S., Molenaar, K., Schexnayder, C. (2007). “Guidance for Cost Estimation and Management for Highway Projects During Planning, Programming, and Preconstruction.” NCHRP Report 574. Washington, DC: National Cooperative Highway Research Program, Transportation Research Board

10. Archondo-Callao, R. (2009). “Ronet User Guide.”The World Bank, Washington D.C.

11. Archondo-Callao, R., Nogales, A., Bhandari, A. (2004). ”Road Costs Knowledge System (ROCKS).” Proceeding of the 6th International Conference on Managing Pavements, Brisbane, Queensland, Australia

12. Barth, M., Boriboonsomsin, K. (2008). "Real-World CO2 Impacts of Traffic Congestion." TRB 2008 annual meeting CD-ROM

13. Blankendaal, T., Schuur, P., Voordijk, H., (2014). "Reducing the environmental impact of concrete and asphalt: a scenario approach." Journal of Cleaner Production, 66 (1), 27–36.

14. Bode, J. (1998). "Neural networks for cost estimation." Cost Engineering, Vol. 40 (1), 25–30.

15. Bryce, J., Katicha, S., Flintsch, G., Sivaneswaran, N., Santos, J. (2014). "Probabilistic Lifecycle Assessment as A Network- Level Evaluation Tool For The Use And Maintenance Phases Of Pavements". TRB 2014 Annual Meeting, paper no. 14-4639

16. Cantarelli, C.C., Flyvbjerg, B., Buhl, S.L. (2012a). "Geographical variation in project cost performance: the Netherlands versus worldwide." Journal of Transport Geography, Vol. 24, 324–331.

17. Cantarelli, C.C., Molin, E.J.E., van Wee, B., and Flyvbjerg, B. (2012b). "Characteristics of cost overruns for Dutch transport infrastructure projects and the importance of the decision to build and project phases." Transport Policy, Vol. 22, 49–56.

18. Chou, J.S. (2009). "Generalized linear model-based expert system for estimating the cost of transportation projects." Expert Systems with Applications, 36(3), 4253–4267.

19. Chou, J.S. (2011). "Cost simulation in an item-based project involving construction engineering and management." International Journal of Project Management, 29(6), 706–717.

20. Chou, J.S., Peng, M., Persad, K.R., O'Connor, J.T. (2006). "Quantity-Based Approach to Preliminary Cost Estimates for Highway Projects." Transportation Research Record: Journal of the Transportation Research Board, No. 1946, Transportation Research Board of the National Academies, Washington D.C., 22 – 30.

21. Cirilovic, J., Mladenovic, G., Queiroz, C. (2014)."Project level pavement management optimization procedure combining optimal control theory and HDM-4 models" Transport Research Arena 2014, Paris <https://trid.trb.org/view.aspx?id=1320172> (28.10.2016.)

22. Cirilovic, J., Vajdic, N., Mladenovic, G., Queiroz, C. (2013). “Developing Cost Estimation Models for Road Rehabilitation and Reconstruction: Case Study of Projects in Europe and Central Asia.” Journal of Construction Engineering and Management, DOI:10.1061/(ASCE)CO.1943-7862.0000817

23. Comité AIPCR de la Gestion des Routes (C6) (2000). Programmation Et Preparation Des Budgets Du Reseau Routier Présentation Des Budgets Aux Décideurs, <http://www.piarc.org/en/order-library/3770-en-Planning%20-%20Budgeting%20on%20Road%20Network%20Level%20-%20Presentation%20of%20Budgets%20for%20Decision-Makers.htm> (28.10.2016.)

24. Directorate of the European Commission, DG XVI, Understanding and Monitoring the Cost-Determining Factors of Infrastructure Projects, <http://ec.europa.eu/regional_policy/sources/docgener/evaluation/pdf/5_full_en.pdf> (Mar. 25, 2013).

25. Ekvall, T. (2002). “Cleaner production tools: LCA and beyond.“ Journal of Cleaner Production; 10(5): 403–406.

26. El-Hakim, M. Y., Tighe, S. L. (2012). “Sustainability of Perpetual Pavement Designs: A Canadian Prospective.” Proceedings of 2012 Transportation Research Board Annual Meeting of National Academies, D.C. Washington, USA.

27. Emsley, M.W., Lowe, D.J., Duff, A.R., Harding, A., Hickson, A. (2002). “Data modeling and the application of a neural network approach to the prediction of total construction costs.” Construction Management and Economics, 20(6), 465–472.

28. Environmental Protection Agency,(2009). Transport energy and CO_2, <https://www.iea.org/publications/freepublications/publication/transport2009.pdf>(28.10.2016.)

29. European Commission (EC), (2011). White Paper. Roadmap to a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System.<http://ec.europa.eu/transport/themes/strategies/doc/2011_white_paper/white_paper_com(2011)_144_en.pdf>(July 29, 2016)

30. European Commission (EC), (2014). EU transport in figures 2014– statistical pocketbook. Luxembourg: publications Office of the European Union. <http://ec.europa.eu/transport/facts-fundings/statistics/doc/2014/pocketbook2014.pdf >(July 29, 2016)

31. Ferreira, A., Antunes, A., Picado-Santos, L. (2002). "Probabilistic Segment-linked Pavement Management Optimization Model." J. Transp. Eng.,128, 6, pp. 568-577.

32. Fitch M, G., Smith, J., Clarens, A. (2013). “Environmental life-cycle assessment of winter maintenance treatments for roadways. “ ASCE Journal of Transportation Engineering, 139 (2), pp. 138–146

33. Flintsch, G.W., Chen, C. (2004). “Soft Computing Applications in Infrastructure Management.” Journal of Infrastructure Systems, 10(4), pp. 157–166.

34. Flyvbjerg, B.H., Holm, M.S., Buhl, S. (2002). “Underestimating costs in public works projects, error or lie.” Journal of the American Planning Association, 68(3), pp. 279-292.

35. Friesz, T.L., Enrique Fernandez, J. (1979). “A Model of Optimal Transport Maintenance with Demand Responsiveness. “ Transportation Research Part B: Methodological, Vol. 13(4), pp. 317-339.

36. Gao, H., Zhang, X. (2013). “A Markov-Based Road Maintenance Optimization Model Considering User Costs.“ Computer-Aided Civil and Infrastructure Engineering, 28, pp. 451–464

37. Gao, L., Zhang, Z. (2009). “Approximate dynamic programming approach to network-level budget planning and allocation for pavement infrastructure.“ Transportation Research Board 88th Annual Meeting. Number 09-2344.

38. German Technical Cooperation GTZ, Eschborn, Germany.“International Fuel Prices 2010/2011.”<https://www.giz.de/expertise/downloads/giz2012-en-ifp2010.pdf>(29.07.2016.)

39. Giustozzi, F., Crispino, M., Flintsch, G. (2012). “Multi-attribute life cycle assessment of preventive maintenance treatments on road pavements for achieving environmental sustainability.“ International Journal of Life Cycle Assessment, pp. 409-419.

40. Golabi, K., Kulkarni, R. B., Way, G. B. (1982). “A statewide pavement management system.“ Interfaces, 12(6), pp. 5-21.

41. Goldberg, D.E. (1989). Genetic Algorithms in Search, Optimization and Machine Learning. Addison-Wesley.

42. Gosse, C., Smith, B., Clarens, A. (2013). "Environmentally Preferable Pavement Management Systems." J. Infrastruct. Syst., 10.1061/(ASCE)IS.1943-555X.0000118, pp. 315-325.

43. Gu, W., Ouyang, Y., Madanat, S. (2012). “Joint optimization of pavement maintenance and resurfacing planning.“ Transportation Research Part B: Methodological, 46(4), pp. 511-519.

44. Guyon, I., Elisseeff, A. (2003). “An introduction to variable and feature selection.” Journal of machine learning research, Vol. 3, pp. 1157-1182.

45. Haas, R., Tighe, S. L and Falls L. C. (2006). “Determining Return on Long-Life Pavement Investments”. *Transportation Research Record: Journal of the Transportation Research Board, No. 1974,* Transportation Research Board of the National Academies, Washington, D.C., pp. 10–17.

46. Avetisyan, H. G., Miller-Hooks, E., Melanta, S., Qi, B. (2014). “Effects of vehicle technologies, traffic volume changes, incidents and work zones on greenhouse gas emissions production”. Transportation Research Part D, 26,pp.10–19.

47. Hall, M., Frank, E., Holmes, G., Pfahringer, B., Reutemann, P. and Witten, I.H.(2009). “The WEKA Data Mining Software: An Update.”SIGKDD Explorations, Vol. 11, Issue 1, pp.11 – 18.

48. Harvey, M.O. (2012). Optimizing Road Maintenance, Discussion Paper No. 2012-12, Paris: OECD, International Transport Forum.

49. Hass, R., Hudson, W.R., Zaniewski, J.P. (1994). Modern Pavement Management. Krieger Publishing, Melbourne, Fla

50. Hegazy, T., Ayed, A. (1998). “Neural Network Model for Parametric Cost Estimation of Highway Projects.” ASCE Journal of Construction Engineering an Management, 124(3), pp. 210–218.

51. Hegazy, T., Rashedi R. (2013). “Large-Scale Asset Renewal Optimization Using Genetic Algorithms plus Segmentation.“ Journal of Computing in Civil Engineering, Vol. 27, No. 4

52. Herabat, P., Tangphaisankun, A. (2005). “Multi-Objective Optimization Model using Constraint-Based Genetic Algorithms for Thailand Pavement Management“. Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp. 1137 – 1152.

53. Holland, J.H. (1975). Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence. Ann Arbor: The U. of Michigan Press, 183.

54. Horvath, A. & Hendrickson, C. Comparison of the Environ-mental Implications of Asphalt and Steel-Reinforced Concrete Pavements. Proceedings of the 1998 TRB Transportation Re-search Board Annual Meeting of National Academies, D.C. Washington, USA.

55. Horvath, A. (2003). A life cycle environmental and economic assessment of using 34 recycled materials for asphalt pavements. Technical Report, University of California, 35 Berkley, <http://www.uctc.net/research/papers/683.pdf >(July 29, 2016)

56. Huang, Y., Bird, R., Bell, M. (2009b). “A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation.“ Transport Research Part D; Transport and Environment, 14 (3), pp. 197–204.

57. Huang, Y., Bird, R., Heidrich, O. (2009a). “Development of a life cycle assessment tool for construction and maintenance of asphalt pavements.“ Journal of Cleaner Production, No 17 (2), pp. 283-296.

58. Huang, Y., Spray, A., Parry, T. (2013). “Sensitivity analysis of methodological choices in road pavement LCA.“ International Journal of Life Cycle Assessment, vol. 18, pp. 93–101.

59. Hudson, W.R., Hass, R., Uddin, W. (1997). Infrastructure Management: Integrating Design, Construction, Maintenance, Rehabilitation and Renovation. McGraw-Hill, New York.

60. Irfan, M., Khurshid, M. B., Anastasopoulos, P., Labi, S., Moavenzadeh, F. (2011). “Planning-stage estimation of highway project duration on the basis of anticipated project cost, project type, and contract type.” International Journal of Project Management, 29(1), pp. 78–92.

61. ISO 14040:2006, Environmental management -Life cycle assessment - Principles and framework
<http://www.iso.org/iso/catalogue_detail?csnumber=37456>(July 29, 2016)

62. Jorge, D., Ferreira, A. (2012). "Road network pavement maintenance optimization using the HDM-4 pavement performance prediction models", International Journal of Pavement Engineering Vol. 13, No. 1, pp. 39–51.

63. Jullien, A., Proust, C., Martaud, T., Rayssac, E., Ropert, C. (2012). "Variability in the environmental impacts of aggregate production." Resources, Conservation and Recycling, vol. 62, pp. 1–13.

64. Kass, G.V. (1980). "An exploratory technique for investigating large quantities of categorical data." Applied Statistics 29(2), pp. 119-127.

65. Kendall, A. (2012). "Time-adjusted global warming potentials for LCA and carbon footprints. " International Journal of Life Cycle Assessment, 17 (8), pp. 1042–1049.

66. Kim, B., Lee, H., Park, H., Kim, H. (2012). "Framework for estimating greenhouse gas emissions due to asphalt pavement construction." ASCE Journal of Construction Engineering and Management, 138 (11), pp. 1312–1321.

67. Kim, G.H., An, S.H., Kang, K.I. (2004a). "Comparison of construction cost estimating models based on regression analysis, neural networks, and case-based reasoning." Building and Environment, 39(10), pp. 1235-1242.

68. Kim, G.H., Yoon, J.E., An, S.H., Cho, H.H., Kang, K.I. (2004b). "Neural network model incorporating a genetic algorithm in estimating construction costs." Building and Environment, 39(11), pp. 1333-1340.

69. Knittel, C.R,. Sandler, R. (2011). "Cleaning the bathwater with the baby: The health co-benefits of carbon pricing in transportation (No. w17390)." National Bureau of Economic Research.

70. Kobayashi, K., Ejiri, R., Do, M. (2008). "Pavement Management Accounting System", Journal of Infrastructure Systems, Vol. 14, No. 2

71. Kucukvar, M., Tatari, O. (2012). "Ecologically based hybrid life cycle analysis of continuously reinforced concrete and hot-mix asphalt pavements." Transportation Research Part D: Transport and Environment, 17 (1), pp. 86–90.

72. Kuhn, K. D. (2010). "Network-Level Infrastructure Management Using Approximate Dynamic Programming." Journal of Infrastructure Systems,doi.16:103-111.

73. Lepert P, Brillet F. (2009). “The overall effects of road works on global warming gas emissions.“ Transportation Research Part D: Transport and Environment, 14 (8), pp. 576–584.

74. Li, Y., Madanat, S. (2002). “A steady state solution for the optimal pavement resurfacing problem.“ Transportation Research Part A: Policy and Practice, 36(6), pp. 525-535.

75. Lidicker, J., Sathaye, N., Madanat, S., Horvath, A. (2013). "Pavement Resurfacing Policy for Minimization of Life-Cycle Costs and Greenhouse Gas Emissions." J. Infrastruct. Syst., 10.1061/(ASCE)IS.1943-555X.0000114, pp. 129-137.

76. Loijos A., Santero N., Ochsendorf J. (2013). “Life cycle climate impacts of the US concrete pavement network. “ Resources, Conservation and Recycling, vol. 72, pp. 76–83.

77. Lowe, D., Emsley, M., Harding, A. (2006). “Predicting Construction Cost Using Multiple Regression Techniques.” ASCE Journal of Construction Engineering an Management, 132(7), pp. 750–758.

78. Meduri, S.S., Annamalai, T.R. (2013). “Unit Costs of Public and PPP Road Projects: Evidence from India.” Journal of Construction Engineering an Management, 139(1), pp. 35-43.

79. Medury, A., Madanat, S. (2013). “Incorporating network considerations into pavement management systems: A case for approximate dynamic programming.“ Transportation Research Part C: Emerging technologies, 33, pp. 134-150.

80. Medury, A., Madanat, S. (2014). “Simultaneous Network Optimization Approach for Pavement Management Systems.“ Journal of Infrastructure Systems, DOI:10.1061/(ASCE)IS.1943-555X.0000149.

81. Meneses S., Ferreira A. (2013). “Pavement maintenance programming considering two objectives: maintenance costs and user costs.“ International Journal of Pavement Engineering, Vol. 14, No. 2, pp. 206–221.

82. Molenaar, K.R. (2005). “Programmatic Cost Risk Analysis for Highway Megaprojects.” ASCE Journal of Construction Engineering an Management, 131(3), pp. 343–353.

83. Morcous, G., Lounis, Z. (2005). “Maintenance optimization of infrastructure networks using genetic algorithms.“ Automation in Construction, 14(1), pp. 129-142.

84. Munns, A.K., Al-Haimus, K.M. (2000) “Estimating using cost significant global cost models.” Construction Management and Economics, 18(5), pp. 585–585.

85. Odeck, J. (2004). “Cost overruns in road construction—what are their sizes and determinants?” Transport Policy, 11(1), pp. 43–53.

86. Odoki, J.B., Kerali, H.G.R. (2000). “Analytical Framework and Model Descriptions.” The Highway Development and Management Series, Vol. 4, The World Road Association PIARC/AIPCR, Paris, France.

87. Ouyang, Y. (2007). “Pavement Resurfacing Planning for Highway Networks: Parametric Policy Iteration Approach. “ Journal of Infrastructure Systems., 13(1), pp. 65-71

88. Ouyang, Y., Madanat, S. (2004). “Optimal scheduling of rehabilitation activities for multiple pavement facilities: exact and approximate solutions“ Transportation Research Part A: Policy and Practice, 38(5), pp. 347-365.

89. Ouyang, Y., Madanat, S. (2006). “An analytical solution for the finite-horizon pavement resurfacing planning problem“, Transportation Research Part B: Methodological, 40(9), pp. 767–778.

90. Ozbay, K., Neville, D. J., Parker, A., Hussain, S. (2004). “Life Cycle Cost Analysis: State-of-the-Practice vs. State-of-the-Art”, TRB Annual Meeting CD-ROM

91. Park, K., Hwang, Y., Seo, S., Seo, H. (2003). “Quantitative Assessment of Environmental Impacts on Life Cycle of Highways. “ ASCE Journal of Construction Engineering and Management, pp. 25-31.

92. Paterson, W. D. O. (1990). “Quantifying the effectiveness of pavement maintenance and rehabilitation”. In Proceedings, 6th REAAA Conf., Kuala Lumpur, Malaysia, p.14.

93. Pellecuer, L., Assaf, G.J., St-Jacques, M. (2014). “Influence of Pavement Condition on Environmental Costs.“ ASCE Journal of Transportation Engineering, DOI: 10.1061/(ASCE)TE.1943-5436.0000721

94. Engineering Properties and Field Performance of Warm Mix Asphalt Technologies. (2014). Project No. NCHRP 09-47A, National Cooperative Highway Research Program Transportation Research Board of the National Academies

95. Qian, S.Z., Li, V.C., Zhang, H., Keoleian, G.A. (2013). "Life cycle analysis of pavement overlays made with Engineered Cementitious Composites. " Cement and, Concrete Composites, 35 (1), pp. 78–88.

96. Rashid, M.M., Tsunokawa, K. (2012)."Trend curve optimal control model for optimizing pavement maintenance strategies consisting of various treatments". Computer-Aided Civil and Infrastructure Engineering, 27(3), pp. 155–169.

97. Reger, D., Madanat, S., and Horvath, A. (2014). "Economically and environmentally informed policy for road resurfacing: tradeoffs between costs and greenhouse gas emissions". *Proceedings of 2014 Transportation Research Board Annual Meeting of National Academies*, D.C. Washington, USA.

98. Advanced High-Performance Materials For Highway Applications, (2010). Report No. Fhwa-Hif-10-002, *the Federal Highway Administration (FHWA)*

99. Sakhaeifar, M. S., Brown, E. R., Tran, N., and Dean J. (2013). "Evaluation of Lang-Lasting Perpetual Asphalt Pavement with Life-Cycle Cast Analysis". *Transportation Research Record: of the Transportation Research Board, No. 2368*, Transportation Research Board of the National Academies, Washington, D.C., pp. 3-11.

100. Santero, N., Masanet, E., Horvath, A. (2011a). "Life-cycle assessment of pavements. Part I: Critical review. "Resources, Conservation and Recycling, pp. 801-809.

101. Santero, N., Masanet, E., Horvath, A. (2011b). "Life-cycle assessment of pavements Part II: Filling the research gaps. " Resources, Conservation and Recycling, pp. 810-818.

102. Santero, N.J., Harvey, J., Horvath, A. (2011c). "Environmental policy for long-life pavements. " Transport Research D: Transport and Environment, volume 16 (2), pp. 129–136.

103. Santos, J., Bryce, J., Flintsch, G., Ferreira, A., Diefenderfer, B. (2014b). "A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices, " Structure and Infrastructure Engineering: Maintenance,

Management, Life-Cycle Design and Performance, DOI: 10.1080/15732479.2014.945095

104. Santos, J., Ferreira, A. (2013). "Life-cycle cost analysis system for pavement management at project level. " International Journal of Pavement Engineering, 14 (1), pp. 71–84.

105. Santos, J., Ferreira, A., Flintsch, G. (2014c). "A life cycle assessment model for pavement management: road pavement construction and management in Portugal, " International Journal of Pavement Engineering, Available from http://dx.doi.org/10.1080/10298436.2014.942862

106. Santos, J., Ferreira, A., Flintsch, G., (2014a). "A life cycle assessment model for pavement management: methodology and computational framework." International Journal of Pavement Engineering, Accepted for publication. http://dx.doi.org/10.1080/10298436.2014.942861

107. Sathaye, N., Madanat, S. (2012). "A bottom-up optimal pavement resurfacing solution approach for large-scale networks." Transportation Research Part B: Methodological, 46(4), pp. 520-528.

108. Seo, Y., Kim, S. M. (2013). "Estimation of materials-induced CO2 emission from road construction in Korea. " Renewable and Sustainable Energy Reviews, 26, pp. 625–631.

109. Skitmore, R.M., Ng, S.T. (2003). "Forecast models for actual construction time and cost." Building and Environment, 38(8), pp. 1075-1083.

110. Smith, A.E., Mason, A.K. (1997). "Cost estimation predictive modeling: regression versus neural network." The Engineering Economist, 42(2), pp. 137–161.

111. Social Value of Carbon in project appraisal, Guidance note on social value of carbon in project appraisal. (2014) the World Bank Group

112. Sodikov, J. (2005). "Cost Estimation of Highway Projects in Developing Countries: Artificial Neural Network Approach." Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp. 1036-1047.

113. Sonmez, R. (2004). "Conceptual cost estimation of building projects with regression analysis and neural networks." Canadian Journal of Civil Engineering, 31(4), pp. 677-683.

114. Fwa, T. F., Tan, C. Y., Chan, W. T. J. (1994).“Road-Maintenance Planning Using Genetic Algorithms”. Transp. Engineering, 120, pp. 710-722.

115. Tabakovic, A., Schlangen, E. (2015). Self-Healing Technology for Asphalt Pavements, *Materials and Environment*, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

116. Transparency International.“Corruption Perception Index, 2011”.Available at http://www.transparency.org/research/cpi/overview Accessed 25.09.2016.

117. Trost, S. M. and Oberlender, G. D. (2003). “Predicting Accuracy of Early Cost Estimates Using Factor Analysis and Multivariate Regression.” ASCE Journal of Construction Engineering an Management 129(2), pp. 198–204.

118. Tsunokawa, K.,Van Hiep, D., Ul-Islam, R. (2006). “True Optimization of Pavement Maintenance Options with What-If Models.” Computer-Aided Civil and Infrastructure Engineering, 21(3), pp. 193-204.

119. Tsunokawa, K., Schofer, J. L. (1994). “Trend curve optimal control model for highway pavement maintenance: Case study and evaluation.“ Transportation Research Part A: Policy and Practice, 28 (2), pp. 151-166.

120. Turner and Townsend (2012). International construction cost survey, <http://www.turnerandtownsend.com/construction-cost-2012/_16803.html> (Mar. 20, 2013).

121. Wang, K. C. P., Zaniewski, J. P. (1996). “20/30 Hindsight: The New Pavement Optimization in the Arizona State Highway Network.“ Interfaces, 26 (3), 77-89.

122. Wang, T., Lee, I. S., Kendall, A., Harvey, J., Lee, E. B. E., Kim, C. (2012). “Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance.“ Journal of Cleaner Production, 33, pp. 86-96.

123. Wang, Y. R., Gibson, G.E. (2010). “A Study of Preproject Planning and Project Success Using ANNs and Regression Models.” Automation in Construction, Vol. 19, pp. 341 - 346.

124. Weiland, C., Muench, S.T. (2010). "Life Cycle Assessment of Interstate Highway Pavement Reconstruction Options in Seattle". Washington TRB 2010 Annual Meeting CD-ROM

125. White, P., Golden, J.S., Biligiri, K.P., Kaloush, K. (2010). "Modeling climate change impacts of pavement production and construction." Resources Conservation Recycling, 54 (11), pp. 776–782.

126. Wilmot, C. G., Cheng, G. (2003). "Estimating Future Highway Construction Costs." ASCE Journal of Construction Engineering and Management, 129 (3), pp. 272–279.

127. World Bank (2011). Road User Costs Knowledge System (RUCKS),<http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTTRANSPORT/EXTROADSHIGHWAYS/0,,contentMDK:20483189~menuPK:1097394~pagePK:148956~piPK:216618~theSitePK:338661,00.html> (July 29, 2016)

128. World Bank (2016). Road User Costs Knowledge System (RUCKS),<http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTTRANSPOR31T/EXTROADSHIGHWAYS/0,,contentMDK:20483189~menuPK:1097394~pagePK:14832 956~piPK:216618~theSitePK:338661,00.html> (July 29, 2016)

129. Wsdot 1999 Washington State Highway Pavements Trends, Conditions, And Strategic Plan

130. Wu, Z., Flintsch, G.W. (2009). "Pavement Preservation Optimization Considering Multiple Objectives and Budget Variability." ASCE Journal of Transportation Engineering, Vol. 135, No. 5

131. Yu, B., Lu, Q. (2012). "Life cycle assessment of pavement: methodology and case study." Transportation Research Part D: Transport and Environment, 17 (5), pp. 380–388.

132. Yu, B., Lu, Q., Xu, J. (2013). "An improved pavement maintenance optimization methodology: Integrating LCA and LCCA." Transportation Research Part A, 55, pp. 1–11

133. Zhang, H., Keoleian, G. A., Lepech, M. D., Kendall, A. (2010). "Life-Cycle Optimization of Pavement Overlay Systems. " Journal of Infrastructure Systems, Vol. 16, No. 4

134. Zhang, H., Keoleian, G.A., Lepech, M.D. (2008). “An integrated life cycle assessment and life cycle analysis model for pavement overlay systems. “ Life-Cycle Civil Engineering, http://web.stanford.edu/~mlepech/pubs/ialcce.lcamodel.08.pdf (July 29, 2016)

135. Zhang, H., Keoleian, G.A., Lepech, M.D. (2013). “Network-Level Pavement Asset Management System Integrated with Life-Cycle Analysis and Life-Cycle Optimization.” Journal of Infrastructure Systems,19, pp. 99-107.

Internet references

(Links to tools, databases and software, all accessed 28.10.2016.)

1. HDM-4, http://www.hdmglobal.com/
2. RONET, https://www.ssatp.org/en/page/road-network-evaluation-tools-ronet
3. dTIMS, http://www.deighton.com/dtims/
4. HIMS, https://romdas.com/software/hims
5. HERS-ST Highway Economic Requirements System http://www.fhwa.dot.gov/infrastructure/asstmgmt/hersindex.cfm
6. Real Cost tool, https://www.fhwa.dot.gov/infrastructure/asstmgmt/rc2100.cfm
7. MicroBensCost, http://bca.transportationeconomics.org/models/microbencost
8. SimaPro, http://www.simapro.co.uk/aboutsimapro.html
9. PaLate, http://www.ce.berkeley.edu/~horvath/palate.html
10. M6, https://www3.epa.gov/otaq/m6.htm
11. MOtor Vehicle Emission Simulator (MOVES), https://www3.epa.gov/otaq/models/moves/
12. Athena LCA, http://www.athenasmi.org/
13. Changer, http://www.irfnet.ch/files-upload/pdf-files/ghgbrochureweb.pdf
14. ROAD-RES, http://www.vegvesen.no/_attachment/110628/binary/192907

15. WB toolkit, Greenhouse Gas Emissions Mitigation in Road Construction and Rehabilitation http://siteresources.worldbank.org/INTEAPASTAE/Resources/GHG-ExecSummary.pdf

16. Aspect,http://www.trl.co.uk/solutions/asset-management/decision-support-tools/aspect-asphalt-pavement-embodied-carbon-tool/

17. PE-2 http://www.construction.mtu.edu/cass_reports/webpage/estimator.html

18. Carbon Management System, Transport Scotland, http://www.transport.gov.scot/environment/carbon-management-system

19. Cal-B/C model http://www.dot.ca.gov/hq/tpp/offices/eab/LCBC_Analysis_Model.html

20. Ceequal tool, http://www.ceequal.com/

21. BE2ST-in-Highways tool, http://rmrc.wisc.edu/be2st-in-highways/

22. Bank of Canada "10-year currency converter." www.bankofcanada.ca/rates/exchange/10-year-converter/

23. OANDA, Historical Exchange Rates, https://www.oanda.com/solutions-for-business/historical-rates/main.html .

24. Statistical Office of The Republic of Serbia, Salaries and wages per employee in the Republic of Serbia, http://webrzs.stat.gov.rs/WebSite/public/PublicationView.aspx?pKey=41&pLevel=1&pubType=2&pubKey=3689

25. World Bank, WDI-database (World Development Indicators). http://data.worldbank.org/indicator

BIOGRAFIJA AUTORA

Јелена Ћириловић је рођена 05. јула 1983. године у Београду, где похађа основну школу и гимназију. Грађевински факултет завршава 2009. године. Носилац је награда „Вук Караџић" за основно и средње образовање као и награде „Јованка Ђуран", за најбољи дипломски рад у области Коловозних конструкција.

Након завршених основних академских студија, Јелена се запошљава у Интитуту ИМС, где ради као одговорни пројектант коловозних конструкција. Током рада у Институту, усавршава се и у области контроле квалитета материјала, лабораторијских испитивања асфалта и битумена, теренских испитивања коловозних конструкција, као и на пословима надзора при извођењу и реконструкцији објеката.

Докторске студије уписује 2010. године. Као студент докторских студија, учествовала је на неколико међународних пројеката:

- Пројекат BENEFIT финансиран од стране Европске комисије, у оквиу позива HORIZON 2020. Пројекат се бави испитивањем алтернативних начина финансирања инфраструктурних пројеката),
- пројекат ISABELA финансиран од стране CEDR-а, Европског удржења путних управа, а ради се о интеграцији социјалних аспеката у моделе управљања одржавањем путева
- пројекат InteMat4PMS финансиран од стране ERANET ROAD joint research programme, а тиче се моделирања пропадања у системима за управљање путевима
- и неколико других пројеката.

У току 2016. године проводи 4 месеца на Универзитету Aegean, на Хиосу, у Грчкој, у оквиру ERASMUS програма. У том периоду ради на завршним извештајима BENEFIT пројекта, на изради неколико истраживачких радова за часописе, као и на завршетку своје докторске дисертације.

Аутор и коаутор је три рада на SCI листи, као и већех броја радова у домаћим часописима, на међународним и домаћим конференцијама. Говори енглески и француски језик.