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# ANALIZA OBČUTLJIVOSTI ZA MODEL PROPADANJA TLAKOV HDM-4

Magistrsko delo št.: 34/II.GR

# SENSITIVITY ANALYSIS OF HDM-4 PAVEMENT DETRIORATION MODELS

Graduation – Master Thesis No.: 34/II.GR

**Mentor:**
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Ljubljana, 16. 09. 2016

## PAGE FOR IMPROVEMENTS

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## BIBLIOGRAPHIC – DOCUMENTALISTIC INFORMATION AND ABSTRACT

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### Abstract:

The sensitivity of road deterioration and maintenance prediction to variation of individual input parameters, are classified according to their impact elasticity in “Highway Development and Maintenance Management Model” *HDM-4 version 2 Volume, which* was developed by World Bank.

As classification presented in the documentation is more or less qualitative the aim of this thesis is to quantify elasticity of some of the most important parameters.

In this research sensitivity analyzed of the deterioration parameters which have been already classified in *HDM-4 Volume 5 Sensitivity Class I*, is provided.

As described by Mrawire et al. (1998), there are different approaches which can be used for undertaking sensitivity analysis. The way we are following here is the Traditional Ceteris Paribus *(TCP)* method in which by changing single input parameters and holding other parameters to be unchanged, the impact elasticity will be calculated. Impact elasticity is the ratio of the percentage change of specific result by the percentage change to individual input parameters of the pavement deterioration models. (HDM-4 V5)

This study is executed by the using of the project analysis of the *HDM-4* application using *TCP* method, and then the results are used to find the impact elasticity which is used for sensitivity ranking. The parameters which are chosen from the sensitivity *class-I* for the deterioration sensitivity analysis are as follows:

- Adjusted Structural Number (*SNP)*
- Pavement Roughness
- All Structural Cracking

Each parameter was studied separately in a real road section which was chosen form the Afghanistan Rind road, Kabul – Kandahar region.

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## BIBLIOGRAFSKO – DOKUMENTACIJSKA STRAN IN IZVLEČEK

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**Ključne besede: Pločnik moč, sistem vodenja pločnik, pločnik modeli poslabšanja**

Povzetek:

Občutljivost *HDM-4* modelov propadanja vozišč je sicer že prikazana v dokumentaciji *HDM-4* paketa, a zgolj na kvalitativnem nivoju. Namen te naloge pa je, da kvantitativno ocenimo elastičnost modelov na spremembe nekaterih ključnih parametrov.

V tej nalogi sem analiziral občutljivost parametrov, ki so bili v dokumentaciji *HDM-4* modela razvrščeni v I. razred.

Kot je opisal Mrawire et al (1998), obstajajo različni pristopi, ki se lahko uporabljajo za izvedbo analize občutljivosti. V nalogi sem uporabil tradicionalni pristop “Ceteris paribus”, kjer opazujemo spremembe izhodnih rezultatov v primeru spremembe enega od vhodnih podatkov, pri čemer pa ostali ostanejo nespremenjeni.

Iz rezultatov izračunamo elastičnost kot razmerje med procentom spremembe rezultatov in procentom spremembe vhodnega podatka.

Ta študija je bila izvedena z uporabo projektne analize v paketu *HDM-4*. Parametri, ki so bili izbrani za analizo občutljivosti so naslednji:

- Prilagojeno Strukturno število *(SNP)*
- Neravnost vozišča
- Vse strukturne razpoke

Vsak parameter smo preučevali ločeno na primerih realnih cestnih odsekov ceste Kabul – Kandahar v Afganistanu.

## ACKNOWLEDGMENT

Thanks Almighty Allah for all Blessings and opportunities in all my life he gives to me.

I would like give a big appreciate and a great thankful to my parents, for all their supports and prays in all my life, especially with my studying cycles, I ask Allah to bless them, although they are not among us but their prays are still with me.

By this words I would like to appreciate and a sincerely thanks to my mentor Assoc. prof. Dr. Marijan Zura, for all his advices regarding the development of this Master Thesis and the positive approach to the works over the course of study during this study cycle, and also I thanks Assist. Dr. Darja Šemrov for her useful suggestions and cooperation.

## KEY WORDS

| | |
|---|---|
| SN | ...Structural Number |
| SNC | ...Modified structure number |
| SNP | ...Adjusted Structural Number |
| RD | ...Road Deterioration |
| WE | ...Work Effect |
| SEE | ...Social and Environment Effects |
| YAX | ...Vehicle Axles Numbers |
| ESAL | ...Equivalent Standards Axle Loads Number |
| AADT | ...Annual Average Daily Traffic |
| TCP | ...Traditional ceteris paribus HDM |
| FLH | ...Factorial Latin Hypercube |
| RUE | ...Road User Effect |
| RDWE | ...Road Deterioration Work Effect |
| NTFD | ...Number of Traffic Flow Direction |
| MMP | ...Mean Monthly Precipitation |
| CBR | ...California Bearing Ration |
| COMP | ...pavement relative compaction |
| PMS | ...Pavement Management System |
| IQL | ...Information Quality Level |

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# 1 Introduction

## 1.1 Background

Prediction of the pavement deterioration has a key role in pavement management systems.
Sensitivity analysis of the individual input parameters of pavement deterioration models have a critical role in the prediction process, because proper concentration and emphasis can be given to the most sensitivity and important parameters and less to less sensitive, by this way the loosing of time will be prevented.

In 2000 a report regarding the sensitivity of the deterioration models has been done and provide by the Trans fund New Zealand by the name of "Evaluating the Sensitivity of Parameters in Predictive Pavement Deterioration Modeling". In this report the sensitivity of Roughness and Surface Integrity Index *(SII)* to the other pavement deterioration parameters are calculated and determined by the using of the Traditional ceteris paribus *(TCP)* method and Factorial Latin Hypercube *(FLH)* method.

The sensitivity of the deterioration models has also been provided in *HDM-4 Manual Volume 5 section 4*. In this manual sensitivity analysis is conducted with both *RUE* (Road User Effect) and *RDWE* (Road Deterioration Work Effect) and the level of sensitivity is ranked in 4 classes of sensitivity (High, Moderate, Low and Negligible). For more details see table 62 in Appendix at the end of this study.

## 1.2 Research Objective

The objective of the study is to find the sensitivity of *HDM-4* Deterioration models. For this purpose the highest sensitive parameters *(Sensitivity Class I, See Table 62 in Appendix)* which were introduced by *HDM-4 Manual Volume 5 Section4*, are chosen. The following input pavement deterioration parameters were selected:

- Adjusted Structural Number *(SNP);*
- Roughness;
- All Structural Cracking;

The following parameters are the affected results of pavement deterioration models:

- Adjusted Structural Number *(SNP);*
- Pavement Roughness;
- All Structural Cracking;
- Wide Structural Cracking;
- Transvers Thermal Cracking;
- Raveled Area;
- No of Pothole;
- Edge Break;
- Mean Rut Depth;
- Rut depth Standard Deviation;
- Texture Depth;
- Skid Resistance

*TCP* method is used to find the elasticity of the individual results of deterioration models to individual inputs parameters. Input parameters were then ranked in *4 levels* as follows:

| | |
|---|---|
| Level 1 | Impact Elasticity greater than 0.5 |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 |
| Level 4 | Impact Elasticity less than 0.05 |

## 1.3 Study Approach

To meet the objectives of the research the study will go through the following tasks:

- Literature Review

The first part of this chapter will go through an over view of *HDM-4* Application, and then the chapter keep going to pavement classification, modeling approach and philosophy, the key variables affecting the deterioration, and then each deterioration models which are introduced in *HDM-4* manual will be studied and reviewed.

- Data

The chapter will go through the *HDM* models data requirements, concept of the quality level of the input data and their relation with the *HDM* models will be studied.

Then the input data of the road sections which are taken as the examples for this study will be introduced.

- Sensitivity analysis

The sensitivity of results to the chosen parameters of the pavement are determined in two cases, without maintenance and with maintenance case both in low and high traffic conditions.

# 2 Literature Review

## 2.1 The Approach of Modeling

To go through the modeling phase, there are two stages of works need to do:

- Deterioration Modeling;
- Prediction Modeling;

### 2.1.1 Deterioration modeling

Deterioration of road pavement is related to the following parameters according to *HDM-4* Manuals:

- Material properties;
- Original design;
- Method and Quality of construction;
- Traffic volume;
- Characteristics of axle load;
- Geometry of the road;
- Environment and climate of condition in which the road is located;
- Pavement history and age;
- Maintenance standards and policy;

Robinson (1998) described prediction condition methods in two classes of **Probabilisti**c and **Deterministic** methods. In probabilistic method probability function which are based on a possible condition range, is used to predict the pavement condition, while in deterministic method the mathematical functions which are used to predict the condition are based on the measured or observed distresses. (HDM-4 V6)

As deterministic method is used in *HDM* models, so here only this method is mentioned.

Deterministic Method has two classes (HDM-4 V6):

- Mechanistic model

Pavement behavior fundamental theories is used in the modeling purpose for the mechanistic deterioration model, the models are based on stress and strain knowledge, concentrated data, and rely on the parameters which are difficult to estimated and measured in the field.

- Empirical Mechanistic Model

Empirical deteriorating model is based on observed deteriorations statistical analysis.

Each of these modeling classes has their own advantages and disadvantages.

According to Paterson (1987), the relations which are include in *HDM* formulas are based on the concept of properties and behavior of layer materials and are affected by traffic and the climate factors of the road location. The advantages of these relationships are the combination of the theoretical and mechanical experimental bases with the behavior, which are observed in the studies of empirical analysis. (NDLI, 1995)

### 2.1.2 Prediction modeling

Road Deterioration can be predicted by the following two models (NDLI, 1995):

- Absolute Model
    - Conditions are presented as the function of the independent variables;
    - Need to be applied in a specific condition;
    - Less flexibility for initial condition;
- Incremental Model
    - Change in Conditions are presented as the function of the independent variables;
    - Can be applied in a variation of initial conditions;
    - More flexibility for initial condition;

Incremental model is used as the bases for *HDM* pavement deterioration models.

### 2.1.3 Distresses of Road Pavement

The pavement distresses which are modeled in *HDM-4* have been classified in table below. (HDM-4 V4 Part c)

**Table 1: Pavement Distress which are modeled in *HDM-4* (HDM-4 V4)**
**Preglednica 1: Poškodbe vozišč, ki so modelirane v *HDM-4***

| Bituminous | Concrete | Block* | Unsealed |
|---|---|---|---|
| Drainage<br>Cracking<br>Raveling<br>Potholing<br>Edge Break<br>Rutting<br>Roughness<br>Texture Depth<br>Skid Resistance | Cracking<br>Joint Spalling<br>Joint Faulting<br>Failures<br>Roughness | Rutting<br>Roughness<br>Surface Texture | Gravel loss<br>Roughness |

* Not Currently Modeled in HDM-4

## 2.2 Effect of Routine Maintenance

Pavement deterioration models and relations are affected by routine maintenance operations which are as follows (HDM-4 V6):

- Crack Sealing;
- Crack Patching;
- Surface patching;

These operations have different effect on distress parameters, which are described below:

- By crack sealing structural strength would not prevent from losing which is due to asphalt cracking, but it can prevent the water to ingress to lower layers, so it can preserve the lower layer strength.
- By crack patching in addition of preventing of water ingress, asphalt layer structural strength will restore.

- Both cracks sealing and patching could not prevent the future cracks but they will prevent to pothole development.
- Roughness effects could be reduced to half by sealing the cracks
- Raveling surface patching would not have any effect on future raveling but it can prevent the pothole development.

## 2.3 Pavement Management System

The purpose of the Pavement Management Systems development is to provide objective information to the Highways managers who can make a more consistent, cost effective, and defensible decisions related to the preservation of a pavement network. Pavement Management Systems cannot make the final decision by itself, but it can provide information of possible consequences of alternative policies. (Alkire, 2009)

There are two major levels of pavement management system decisions; Network and Project. Decisions which affect entire network is called Network Level, and these decisions involve the following ( Alkire, 2009):

- Policy for pavement Preservation;
- Priorities Identification;
- maintenance budget;
- Rehabilitation;

A comprehensive PMS includes components to assist in both network and project-level decisions (Alkire, 2009).

The schematic representation of the typical modules of a *PMS* which is shown in *figure 1* has included three phases for *PMSs* which are as follows:

- Database which contains, as minimum as data required for *PMS* analysis;
- Analysis methods to generate products useful for decision-making;
- Feedback process which uses on-going field observations, to improve the reliability of *PMS* analysis;

For an analysis method the main choices to increase the order of sophistication are (Ref. fig 1):

- Pavement condition;
- Priority assessment models;
- Network optimization models;

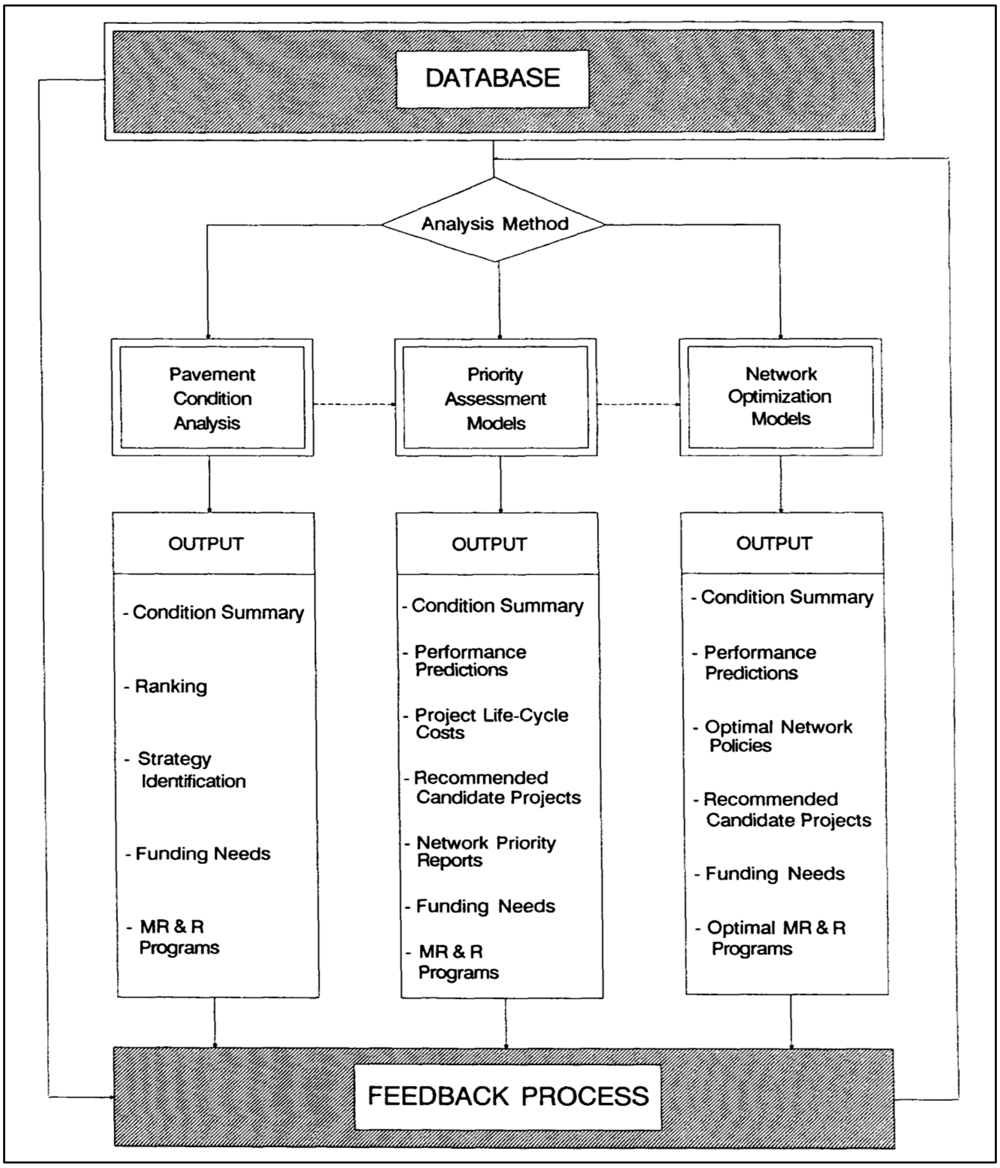


**Figure 1: A Schematic Representation of PMS Modules (Alkire, 2009)**
**Slika 1: Shema *PMD* modulov**

Both the required database and the feedback process will be affected by the choice of an analysis method. These two modules of a PMS must be designed carefully and taking into consideration current and potential future choice of the analysis method. Each of the models of PMS, which are described below, is in terms of their purpose and input-output characteristics. (Alkire, 2009)

The database is the first building block of any management system, since the analysis used and recommendations made by a management system should be based on reliable, objective, and timely (current) information. The major categories of input data essential for a *PMS* are as follows:

- Inventory;
- Information relative to pavement condition;
- Construction, maintenance and rehabilitation history;
- Traffic;
- Cost data;

It should be mentioned that, the aim of any infrastructure management system is to increase the quality of services to the users, for this reason all the standards in *PMS* are developed along according to this purpose.

In 2001 (Falls.et al) had described the basic purpose of a pavement management system; as to achieve the best value possible for the available public funds and to provide safe, efficient, comfortable, and economic transportation. This concept involves all modes of transportation and is made by comparing investment alternatives at both levels of network and project, coordinating design, construction, maintenance, and evaluation activities; and using the existing practices and knowledge efficiently.

"*PMSs* were conceived in response to the shift from the design and build mode to repair and maintain mode. The nation's network of freeways and major highways was almost completed and a major responsibility of highway agencies was to preserve the huge investment in the pavements. Engineers and planners believed that a systems approach could provide more cost-effective utilization of limited resources" (Kulkarni and Miller, 2002).

Kulkarni and Miller (2002) mentioned the key *PMS* elements as follows:

- Functions;
- Data collection and management;
- Pavement performance prediction;
- Economic analysis;
- Priority evaluation;
- Optimization;
- Institutional issues;
- Information technology;

### 2.3.1 Function

They summarized the practices with regards to *PMS* in as follows:

- In the past, it was one year program;
- In Present, it is Multiyear program;
- In Future it would be Multiyear, Multi Component and Multimodal Program;

In one year program priorities were given to factors such as pavement distress, pavement age, and truck traffic. Multi Year Programs were developed on the bases of both the current and projected pavement conditions. Candidate projects are identified for each year of a multiyear planning horizon, estimated annual budgets, and the annual network performance which is projected in terms of the percentages of roadway miles in good and poor pavement conditions (Kulkarni and Miller, 2002).

It is expected that in future *PMS* generations will likely provide integrated multiyear programs for multiple components of a roadway network (such as pavements and bridges).
One can also envision *PMS* programs integrated with management systems for multimodal infrastructure facilities that include railroads, road transit, airports, and harbors (B. Kulkarni, W. Miller 2002).

### 2.3.2 Data collection and Management

This element which involves the collection and management of the data needed for *PMS* analysis is summarized as follows (Kulkarni and Miller, 2002).

Past

- Subjective Rating;
- Hard-Copy Format;
- Mainframe Program;

Present

- Equipment-measured Data;
- PC-based;
- GIS;

Future

- Greater Automation;
- GPS Referencing;
- Internet-based;

The following guidelines for data collection and management are based on experience with systems that have worked well and those that have not. (Kulkarni and Miller, 2002)

Flexible design for the database system, but develop a pragmatic plan for implementation.

- Make a clear distinction between network- and project-level data needs;
- Design the database system for easy access to all users;
- Maintain high data quality;

### 2.3.3 Pavement Performance Prediction Modeling

In the early systems predictive elements did not used, they only evaluate the current pavement conditions and the future pavement condition was implicated. In farther simple prediction models, road age was the only predictive variable. These models were based on an engineering judgment of the expected design life. (Kulkarni and Miller, 2002)

Nowadays various prediction models are used, which are based on multiple regression analysis of pavement condition, traffic loading, climate condition, pavement structural properties, and the past rate of pavement deterioration.

Kulkarni and Miller in Jun 2002 also described that the following aspects of pavement performance prediction need careful consideration in developing effective and functional prediction models:

- What to predict;
- Level at which to predict;
- Type of prediction model;
- Treatment of uncertainty;
- Static versus dynamic decision models;
- Detecting significant model departure;

#### 2.3.3.1 Economic Analysis

Economic Analysis includes various components of cost, which are related to different alternatives of rehabilitation strategies, so by an economic analysis, the least-cost strategy will be identified and chosen (Kulkarni and Miller, 2002).

In early systems only initial construction cost of rehabilitation used, in which no user costs and life-cycle costs were analyzed and calculated respectively. It is in a manner which, the present systems will analyze both agency and user costs, while all future costs are converted to their present worth, and should be assumed in a way that, the total life-cycle cost for each alternative could be obtained.

### 2.3.4 Priority evaluation

In early systems, the Weighted Index *(WI)* of pavement distress was used as the priority ranking, and Present Serviceability Index *(PSI)* which developed by *AASHTO* studies can be an example of Weighted Index *(WI)*. Nowadays, benefit-to-cost *(B/C)* ratio is used to rank the candidate projects, these benefits may be defined as user cost saving due to better pavement conditions or represent as the area under the Pavement Performance Curve. The ratio *(B/C)* has a good result while the only constraint is the total pavement rehabilitation budget; although in practice several constraints may be appropriate. For example; some may want to specify desired performance goal such as, minimum percentage of the network to be maintained in good performance level and the maximum percentage of the network allowed being in poor performance level (Kulkarni and Miller, 2002).

Bringing the network to steady state can be another constraint, in a way that the annual rehabilitation program would remain fairly uniform. In the face of such multiple constraints, a priority ranking approach based on the *B/C* ratio would not be effective.

### 2.3.5 Optimization

Optimization involve the method to identify optimal pavement rehabilitation polices; these methods are used to maximize the benefit measurements to meet the budget constraints and other policy constraints, or the specified performance goals.

In the early systems no formal optimization was used, it is in a manner that in present time optimization has a limited usage, but it is expected that in future optimization would have an extensive usage, and for the large scale projects PC-Software could be used (Kulkarni and Miller, 2002).

# 3 Overview of HDM-4

## 3.1 Introduction

As it is known, most of the Highways and road projects are constructed with a high costs and due to lack of attention to the maintenance at the right time, they will deteriorate earlier than expected.

Prioritization of projects and their maintenance at the right time not only can improve the condition of the pavement, but also it will economize the investment and optimize allocated budgets. For this purpose Highway and Highway Design and Maintenance/Management *HDM* models are developed to manage analysis and make strategy for the Road and Highway projects. The software is designed to provide Prediction of the roads' Performance, Treatment Programing of the roads, estimation of fund, budget allocation, project appraisal, studies policy impacts, and a lot of more application in special cases.

Effectiveness of the models is dependent on its ability and level of accuracy in model. Model predicts the performance of the pavement in which, pavement performance is affected by the factors such as structural design, material properties, traffic situation, methods of the construction, operation cost of the vehicle, environment condition in which the project is located and maintenance policies. These are the reasons why, calibration of software to local condition is the key factor in effectiveness of the software.

### 3.1.1 History

In 1968 for the first time by the road design studies and researches, which was done by the World Bank with the cooperation and conjunction of the Transport and Road Research Laboratory (*TRRL*) and the laboratory Central des Ponts et Chausees (*LCPC*), the first management and maintenance model was introduced. After that the word bank asks a group from Massachusetts Institute of Technology (*MIT*) to review and construct a model based on available data. The result was Highway Cost Model (*HCM*) which was produced by *MIT* (Moavenzadeh 1971, 1972). (HDM-4 V1)

After that in 1977 the British Transport and Road Research Laboratory (*TRRL*) with the cooperation of Word Bank continued their research and experiment on the deteriorations on paved and unpaved roads in developing countries, then the results of these researches and experiences was used by *TRRL* to produce the original form of the Road Transport Investment Model (*RITM*). Finally in 1976 a further development of *HCM* found by Word Bank to produce the first ever version of the Highway design and Maintenance Standards model (*HDM*), in Massachusetts Institute of Technology (*MIT*), (HDM V1).

Both of these models *RITM* and *HDM* were used at some research and wide studies projects in countries such as India and Brazil to extend the geographical scope of the models (HDM V1).

These researches continued until the further development in 1993 which lead to *RITM3* model produced by *TRRL* which was a spreadsheet, which was a more user friendly software, then in 1994 two versions of the *HDM* was developed by the Word Bank:

- HDM-Q;
  Combined effects of traffic congestion to *HDM-III* program
- HDM Manager;
  A menu-driven end was provided to *HDM-III*

### 3.1.2 Application of HDM-4

Actually there *HDM-4* can be used for three purposes:

- Project Analysis;
- Program Analysis;
- Strategy Analysis;

Each of these application areas of *HDM-4* are described briefly in bellow sections:

#### 3.1.2.1 Project analysis

In project analysis specific road projects or options for investment for short period planning could be evaluated. Analysis of specific road link or road section includes the following items:

- User-selected Treatment;
- Combination of cost and benefits;
- Section projected annually (over analyze period);

The following parameters and issues should be considered while the project analysis is used to estimate the economics and road investment engineering viability projects:

- Road Pavement Structural Performance;
- Benefits and user costs of the road;
- Life-cycle predictions of Road Deteriorations, Work Effects, and Costs;
- Comparison economically between Projects alternatives;
- Road networks preservation;
- Sensitivity analysis;

Between all these three *HDM-4* analysis options, Project Analysis, Program Analysis and Strategy Analysis, there is a key different in terms of the data requirements (more details in chapter 4)

Figure 2 shows the steps for Life Cycle Analysis in *HDM-4* models

#### 3.1.2.2 Program Analysis

In program analysis the prioritization is the aim of analysis, while all of the desired road sections should be listed as a one year or multiyear road work project under a constrained budget.

The list of the candidates of road projects, are selected as a discrete segment of road networks which are defined by homogeneous physical properties. From these candidates the selection process is according to the standards which are defined by the administration for the improvement, maintenance or development of the roads.

After the candidates of projects are identified, then the *HDM-4* application will make a comparison between the candidate’s life cycle costs in the case with maintenance or without maintenance.

The optimal association of road works options is maximized the Net Present Value (*NPV*) by life cycle analysis or multiyear analysis method for all road sections of the road network.

The main difference between the program analysis and strategy analysis is the type of road links and sections which are used. Program analysis uses individual road links and sections for analysis while strategy analysis uses a group of road sections and links according to their characteristics.

#### 3.1.2.3 Strategy Analysis

Strategy analysis is used to make a long term plan for the road projects. This type of analysis faces with the estimated cost to develop and maintain the road network under different budgets and economic conditions. It has the following typical applications (HDM-4 V1):

- Required funds for specific target;
- Prediction of road performance in different budget for a long term;
- Budget optimization;

This type of the analysis can combine different individual road sections with different user defined classes.

For example: a combination of the volume of traffic, type of pavement, and provided climate zone.

*HDM-4* then would analyzes each of these defined category in a given time period.

### 3.1.3 HDM-4 Models

*HDM-4* analysis projects by the using of these four models:

- Road Deterioration *(RD)*;

  This model will predict the deterioration of the Paved (Asphalt and Concrete) and unpaved roads.

- Work Effect *(WE)*;

  In this model the effect of the road works in a pavement condition will be simulated and the related cost will be defined.

- Road User Effect *(RUE)*;

  Vehicle Operating cost, Road Accident and Travel Time will be determined.

- Social and Environment Effects *(SEE)*;

  Vehicle Emission and Energy Consumption of the vehicle would be determined by the model.

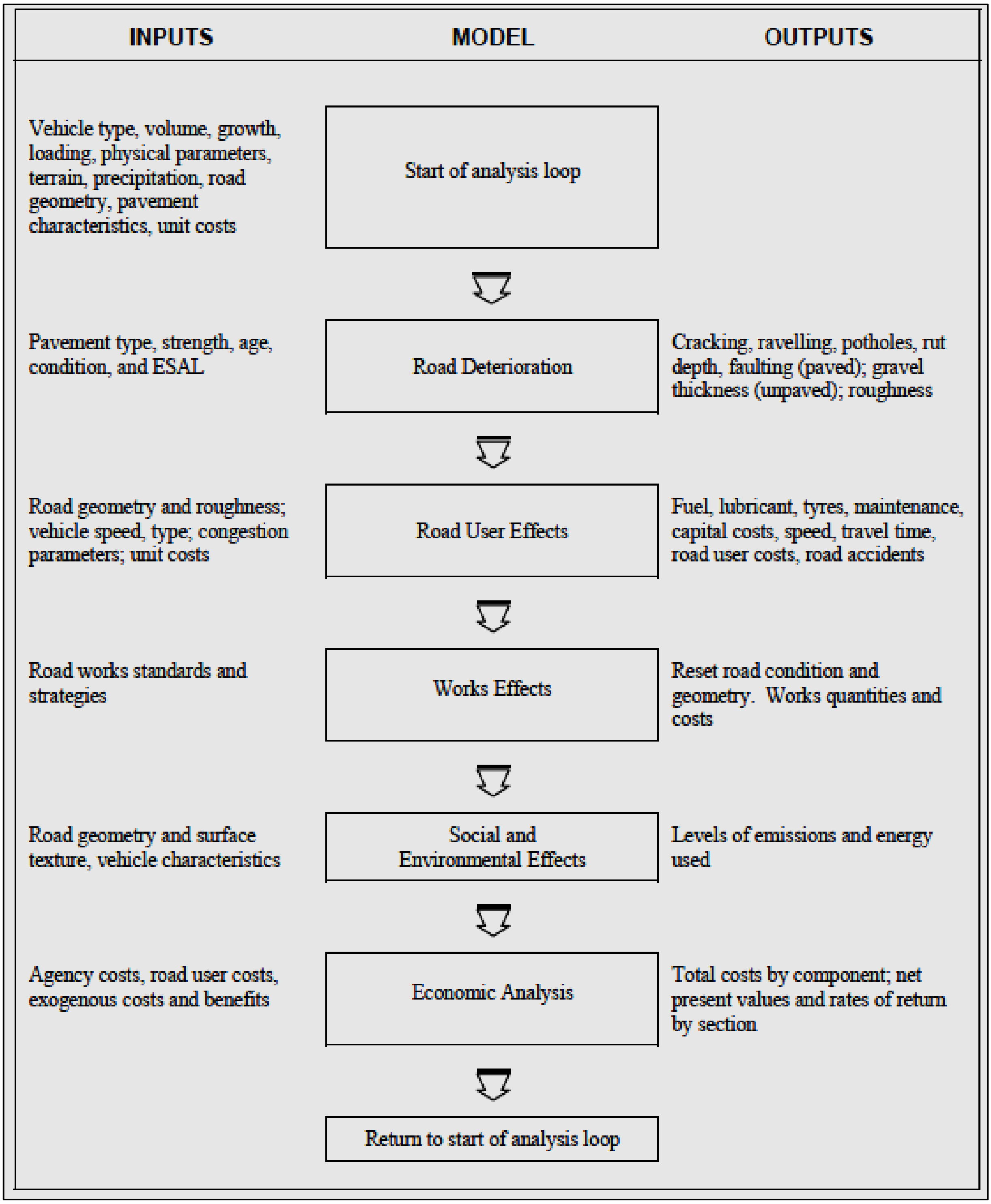


**Figure 2: Life-Cycle Analysis of *HDM-4* (HDM-4 V2)**
**Slika 2: Analiza življenjskega cikla s *HDM-4***

## 3.2 Modeling concept in HDM-4

### 3.2.1 Introduction

The models that are included in *HDM-4* to predict the annual condition of the road pavement and evaluating of the strategy of road works are separated as Road Deterioration *(RD)* and Road Work Effect *(WE).(*HDM-4 V4 Part C).

As this research is not dealing with Road Work Effect, so only the approaches of the road Deterioration models are discussed in the sections bellow.

### 3.2.2 Classification of Pavement

*HDM* models use different type of pavement classifications than it is described in the first section of this chapter, these classification are as Follows (HDM-4 V6):

#### 3.2.2.1 Surface Category

- Paved;
- Unpaved;

These categories mainly are used for a network statistics report.

#### 3.2.2.2 Surface Classes and Types

All Surface types are designed by a two-character code

1. Bituminous
   - Asphalt Mix *(AM);*
   - Surface Treatment *(ST);*
2. Concrete
   - Jointed Plain *(JP*);
   - Jointed Reinforced *(JR);*
   - Continuously Reinforced *(CR);*
3. Blocks
   - Concrete Block *(CB);*
   - Brick *(BR);*
   - Set Stone *(SS);*
4. Unsealed
   - Gravel *(GR);*
   - Earth *(EA);*
   - Sand *(SA)*

#### 3.2.2.3 Base Type

For each type of pavement there are different bases:

1. Bituminous pavement
    - Granular Base (GB);
    - Stabilized Base (SB);
    - Asphalt Base (AB);
    - Asphalt Pavement (AP);
2. Concrete Pavement
    - Granular Base (GB);
    - Stabilized Base (SB);
    - Asphalt Base (AB);
3. Block Pavement
    - Granular Base (GB);
    - Stabilized Base (SB);

#### 3.2.2.4 Pavement Type

Pavement type is given by combining of four character code, which each one represent one layer with the type of the material used.

Surface classification and surface types which are used in *HDM-4* are shown in table 2 and the key parameters of table 2 are shown in table 3 and table 4.

**Table 2: Pavement Classification System of HDM-4 Models (HDM-4 V4 part C)**
**Preglednica 2: Sistem klasifikacije vozišč v HDM-4 modelih**

| Surface category | Surface class | Pavement type | Surface type | Surface material | Base type | Base material |
|---|---|---|---|---|---|---|
| Paved | Bituminous | AMGB | AM | AC, HRA, | GB | NG, CRS, WBM, etc. |
| | | AMAB | | RAC, PA, | AB | AB, EB, etc. |
| | | AMSB | | CM, etc. | SB | CS, LS, etc. |
| | | AMAP | | | AP | TNA, FDA, etc. |
| | | AMRB | | | RB | JUC, RBC, CUC, etc. |
| | | STGB | ST | SBSD, PM, | GB | NG, CRS, WBM, etc. |
| | | STAB | | DBSD, SL, | AB | AB, EB, etc. |
| | | STSB | | CAPE, etc. | SB | CS, LS, etc. |
| | | STAP | | | AP | TNA, FDA, etc. |
| | | STRB | | | RB | JUC, RBC, CUC, etc. |
| | Concrete | JPGB | JP | VC, RC, | GB | NG, CRS, WBM, etc. |
| | | JPAB | | FC, PC, | AB | AB, EB, etc. |
| | | JPSB | | etc. | SB | CS, LS, etc. |
| | | JPAP | | | AP | TNA, FDA, etc. |
| | | JPRB | | | RB | JUC, RBC, CUC, etc. |
| | | JRGB | JR | VC, | GB | NG, CRS, WBM, etc. |
| | | JRAB | | FC, etc. | AB | AB, EB, etc. |
| | | JRSB | | | SB | CS, LS, etc. |
| | | JRAP | | | AP | TNA, FDA, etc. |
| | | JRRB | | | RB | JUC, RBC, CUC, etc. |
| | | CRGB | CR | VC, | GB | NG, CRS, WBM, etc. |
| | | CRAB | | FC, etc. | AB | AB, EB, etc. |
| | | CRSB | | | SB | CS, LS, etc. |
| | | CRAP | | | AP | TNA, FDA, etc. |
| | | CRRB | | | RB | JUC, RBC, CUC, etc. |
| | Block | CBSG | CB | CB | SG | SA, NG, etc. |
| | | BRLC | BR | BR | LC | LC |
| | | SSGB | SS | SS | CG | LC, NG, etc. |
| Unpaved | Unsealed | GRUP | GR | LT, QZ, etc. | UP | |
| | | EAUP | EA | EA | | |
| | | SAUP | SA | SA | | |

**Table 3: Surface Type and Surface material Keys for Table 1 (HDM-4 V4 Part C)**
**Preglednica 3: Tip in materiali vozne površine**

| Surface type | | Surface material | |
|---|---|---|---|
| AM | Asphaltic Mix | AC | Asphalt Concrete |
| ST | Surface Treatment | HRA | Hot Rolled Asphalt |
| JR | Jointed Plain | RAC | Rubberized Asphalt Concrete |
| JR | Jointed Reinforced | PA | Porous Asphalt |
| CR | Continuously Reinforced | CM | Cold Mix ( Soft Bituminous Mix) |
| BR* | Brick | DSBD | Single Bituminous Surface Dressing |
| CB* | Concrete Block | PM | Penetration Macadam |
| SS* | Set Stone | SL | Slurry Seal |
| GR | Gravel | SBSD | Double Bituminous Surface Dressing |
| EA* | Earth | CAPE | Cape Seal |
| SA* | Sand | VC | Vibrated Concrete |
| | | RC | Rolled Concrete |
| | | FC | Fiber Concrete |
| | | PC | Porous Concrete |
| | | LT | Lateritic Concrete |
| | | QZ | Quartic Gravel |
| Note: Asterisk (*) Indicates that different types of material or construction pattern may be defined | | | |

**Table 4: Base Type and Base material Keys for Table 1 (HDM-4 V4 Part C)**
**Preglednica 4: Tipi in materiali spodnjega nosilnega sloja**

| Base type | | Base material | |
|---|---|---|---|
| GR | Granular Base | NG | Natural Gravel |
| AB | Asphalt Base | CRS | Crushed Stone |
| SB | Stabilized Base | WBM | Water Bound Macadam |
| AP | Asphalt Pavement | EB | Emulsified Base |
| RB | Rigid ( Concrete) Base | CS | Cement Stabilized |
| SG | Sand/Gravel | LS | LIME Stabilized |
| LC | Lean Concrete | TNA | Thin Asphalt Surfacing |
| CG | Concrete/Gravel | FDA | Full Depth Asphalt |
| UP | Unpaved-base types not applicable | JUC | Jointed Unbound Concrete |
| | | RBD | Reinforced Bound Concrete |
| | | CUC | Continuously Unbound Concrete |

**Note:**

Each analysis method has its own system of application classification. If the analysis is network level based on coarse data, the definition of surface class and pavement type is the minimum requirement and the default material and distress coefficient may be applied in the modeling process. In project level which needs much more level of detail data, surface and base material with the user defined coefficient of distress model might be specified. In each analysis period surface classes and pavement type might be changed. For example; if input pavement type is *AMGB* (Asphalt mix Surface with granular base), while an overlay of asphalt is applied, the pavement type then changes to *AMAP* (asphalt mix surface on asphalt pavement), (HDM-4 V6).

### 3.2.3 Deteriorations Key Variables

The following variables which have a great influence on pavement deteriorations are common in most *HDM* models. (HDM-4 V6)

- Traffic;
- Climate and environment;
- Pavement History (*Age*);
- Road Geometry;
- Characteristics of Pavement Structure;
- Properties of Material;

#### 3.2.3.1 Traffic

Traffic volume which is passing on each road section would be in two terms; Vehicle Type or Vehicle Class. They are dependent on the performed analysis (HDM-4 Volume 6).

*AADT* which comes from Annual Average Daily Traffic and represent vehicle type is formulated as follows:

$$\text{AADT} = \frac{two\ directions\ anual\ traffic}{365} \qquad 3.1$$

Beside *AADT* the following variables also needed to predict the vehicle impact on deterioration of pavement. (HDM-4 Volume 6)

- *YAX* (Vehicle Axles Numbers)
- *ESAL* (Equivalent Standards Axle Loads Number)

**a. Vehicle Axle**

The following formula represents the number of vehicle axle for each vehicle type in a specified year (HDM-4 Volume 6).

$$YAX_k = \frac{T_k(NAXLES_k)}{ELANESx10^6} \qquad 3.2$$

$$YAX = \sum_{k=1}^{k} YAX_k,$$

Where:

| | |
|---|---|
| YAX (million/lane) | Annual total No of axles for all vehicle type; |
| $T_k$ | Annual Traffic Volume for each vehicle type *K, (K = 1, 2, 3… K);* |
| $NAXLES_k$ | No of axle/vehicle type *K*; |
| ELANES | Road section effective number of lanes. |

**b. ESAL Factors**

This variable can be calculated form the following formula (HDM-4 Volume 6):

$$ESALF_k = \sum_{i=1}^{l_k} \frac{p_{ki}}{100} \sum_{j=1}^{J_k} \left(\frac{AXL_{kij}}{SAXL_j}\right)^{LE} , \qquad 3.3$$

Where:

| | |
|---|---|
| $ESALF_k$ | ESAL factors for each vehicle type $k$; |
| $l_k$ (Load Range) | No of Subgroup i of vehicle type $k$ $(i = 1, 2, 3, \ldots, l_k)$; |
| $P_{ki}$ (%) | Vehicle in Subgroup i of vehicle type $k$; |
| LE (default =4) | equivalency exponent of axle load; |
| $J_k$ | No of single axle /vehicle type $k$; |
| $AXL_{kij}$ (tons) | average load on axle j of load range I in vehicle type $k$; |
| $SAXL_j$ | axle group j Standard Single Axle Load, for dual-wheel single axle usually 8.16 tons is used for all single axles. |

It is in a way that in *HDM-4* the number of *ESAL* is *YE4*, as in Equation bellow. (HDM-4 Volume6)

$$YE4 = \sum_{k=1}^{k} \frac{T_k(ESALF_k)}{ELANESx10^6} \quad 3.4$$

Where:

| | |
|---|---|
| YE4 (million/lane) | annual total No of *ESAL* |

**c. Cumulative Traffic Loading**

This variable is calculated from the following formula (HDM-4 Volume):

$$NE4 = \sum_{y=1}^{AGE3} YE4_y \quad 3.5$$

Where:

| | |
|---|---|
| NE4 (million/lane) | Cumulative No of ESAL form the last rehabilitation (overlay) |
| $YE4_y$ (million/lane) | No of ESAL in year $y$ |
| AGE3 (years) | No of years from last rehabilitation |

**d. Light and Heavy Vehicle**

For some distresses types and for the calculation of the unsealed pavement deterioration it is required to input the parameters such as; light and heavy vehicles. Vehicles which operate Wight more than 3.5 tons are called the heavy vehicle, while the other vehicle types are light ones, these variables can be calculated from the following formula (HDM-4 Volume6).

$$QCV = \frac{ADH}{ELANES} \quad 3.6$$

Where:

| | |
|---|---|
| QCV | Heavy Commercial Vehicle/lane/day |
| ADH | Total in both direction of Average Daily Heavy Vehicle ($\geq$ 3.5 tones) |

Annual Number of equivalent light vehicle which pass over the road section is needed for the modeling of changes in depth of pavement texture, the following formula is used to calculate this parameter: (HDM-4 Volume 6)

$$\Delta NELV = 365\ [ADL + 10\ (ADH)] \tag{3.7}$$

Where:

ΔNELV No of Equivalent light vehicle passed during an analysis year
ADL Average daily light vehicle (< 3.5 tons)

During freezing seasons for pavement rutting modeling, it is needed to have the number of vehicle with standard tires. This parameter can be calculated form the following formula (HDM-4 Volume 6):

$$PASS = \frac{365(ST)(AADT_y)x10^{-5}}{NTFD} \tag{3.8}$$

Where:

| | |
|---|---|
| Pass (in thousands) | Annual No of Vehicles which is passed with studded tires (one direction) |
| ST (%) | annual number of vehicle which is passed with studded tires |
| NTFD | Number of Traffic Flow Directions |
| $AADT_y$ (Veh/day) | Annual Average Daily Traffic in the year y |

### 3.2.3.2 Climate and Environment

One of the most important factors which have a high impact on road deterioration is climate situation, in which the road has constructed. Climate situations have three parameters (HDM-4 V6).

- Temperature;
- Precipitation;
- Winter Condition;

In *HDM-4* models, Environment has five moistures and five temperatures classification, these classifications which is shown in tables below is a development of *HDM-III* (HDM-4 Volume 6)

**Table 5: Classification of moisture (HDM-4 Volume 6)**
**Preglednica 5: Klasifikacija vlažnosti**

| Moisture Classification | Description | Thornthwaite Moisture Index | Annual Perception (mm) |
|---|---|---|---|
| Arid | Very low rainfall, high evaporation | -100 to -61 | <300 |
| Semi-arid | Low rainfall | -60 to -21 | 300 to 800 |
| Sub-humid | Moderate rainfall, or strongly seasonal rainfall | -20 to +91 | 800 to 1600 |
| Humid | Moderate warm seasonal rainfall | +20 to 100 | 1500 to 3000 |
| Per-humid | High rainfall, or very wet-surface days | >100 | >2400 |

**a. Precipitation**

In road Deterioration modeling the Mean Monthly Precipitation *(MMP)* is used, which is expressed in mm/month, while it was meters/month in *HDM III* (HDM-4 Volume 6).

**b. Freezing Index**

en the air temperature is below zero Celsius (< 0° C), Freezing Index phrase as a parameter is used and it is shown by *(FI)* and expressed the cumulative effect of the intensely and duration of this phenomenon.

**Table 6: Classifications of Temperature (HDM-4 Volume 6)**
**Preglednica 6 Klasifikacija temperature**

| Temperature Classification | Description | Temperature Range (°C) |
|---|---|---|
| Tropical | Warm temperature in small range | 20 to 35 |
| Sub-tropical-hot | High day cool night temperature, hot-cold seasons | -5 to 45 |
| Sub-tropical-cool | Moderate day temperature, hot-cold season | -10 to 30 |
| Temperate-cool | Warm summer, shallow, cool winter freeze | -20 to 25 |
| Temperate-freeze | Cool summer, deep winter freeze | -40 to 20 |

Freezing Index that is expressed in terms of degree-days can be seen on a curve which shows the cumulative degree-days vs. time for a freezing season. Freezing Index *(FI*) is the difference between the highest and lowest point on this curve and can be calculated by the following formula (HDM-4 Volume 6).

$$FI = \sum_{i=1}^{ndays} abs[\min(TEMP, 0)] \qquad 3.9$$

Where:

FI (degree-days) Freezing Index
TEMP (°C) Temperature
ndays No of days in a freezing season

Freezing Index which is used in the modeling of Pavement Concrete Performance, is only required as an input data for the Temperate of temperature Zone (HDM-4 Volume 6).

***c.*** Thornthwaite moisture index *(MI)*

*MI* is defined by Last, (1996) according to the following formula (HDM-4 V4 Part C):

$$MI = I_h - 0.6 * I_a = \frac{100*SWAT-60*DWAT}{NWAT} \qquad 3.10$$

Where:

MI Thornthwaite Moisture Index
$I_h$ Humidity Index
$I_a$ Aridity Index
SWAT (mm) Water Excess
DWAT (mm) Deficiency of Water
NWAT (mm) Necessary Water

The moisture index has the capability of identifying a climate zone, if it is wet or dry, while it cannot be cleared that if a climate zone has the variations dampness or not. The free humidity of a specific zone can be identified by thornthwaite moisture index (HDM-4 V4 Part C).

#### 3.2.3.3 Pavement Age

In *HDM-4* four variables defining the pavement age are; *AGE1*, *AGE2*, *AGE3* and *AGE4*. These variables are related to the pavement surface age since a specific type of road work is carried out. These variables are described as follows (HDM-4 Volume6):

- AGE1

  It is the **preventive treatment** age, which is expressed in years since last preventive treatment such as reseal, pavement construction, overlay, or an activity.

- AGE2

  It is the **surface age**, which is expressed in years since last preventive treatment such as reseal, pavement construction, overlay, or a new activity.

- AGE3

  It is the **rehabilitation age**, which is expressed in years since last preventive treatment such as reseal, pavement construction, overlay, or a new activity.

- AGE4

  It is the **base Construction** age, which is expressed in years since last preventive treatment such as reseal, pavement construction, overlay, or a new activity in which it is included the new base construction.

#### 3.2.3.4 Characterization of Pavement Structure

To characterize a pavement structure there are several method and need deferent material and layer measurement, one way is to take a sample from each layer and calculate desired values, such as; strength, gradation, content, etc. For pavement performance modeling, usually this method is not practical; the suitable measurements are estimated by the other methods which are more accessible. In *HDM* modeling, the used characteristics of pavement structure are; Pavement strength, layer characteristics and the properties of selected layer and material. (NDLI, 1995)

**a. Pavement Strength**

Pavement strength is characterized by the following measurements:

- Modified structure number *(SNC)*

The capacity of pavement structure is quantified by the Modified Structural Number *(SNC),* in which based on *AASHTOs* structural Number concept. By the using of the following formula the portion of each layer on pavement performance can be calculated. (NDLI, 1995)

$$SN_i = a_i h_i \qquad 3.11$$

Where:

| | |
|---|---|
| $SN_i$ | structural number of the *ith* layer |
| $a_i$ | layer coefficient of the *ith* layer |
| $h_i$ (inch) | thickness of the *ith* layer, in inches |

Then by combining all measurements which is found for each layer, the overall strength of the pavement can be calculated by (NDLI 1995):

$SN = \sum_i^{n-layer} a_i h_i$ (n-layer include only the layers which are above subgrade) 3.12

As in *ASHTO* procedure portion of subgrade to pavement performance in considered by its resilient modulus, while subgrade strength is included to modified structural number *(SNC)* by considering the subgrade portion to the overall pavement Structural Number *(SN).* (NDLI, 1995)

$$SNC = 0.0394 \sum_i^{n-layer} a_i h_i + SNCG \quad 3.13$$

$SNCG = 3.51 \log_{10} CBR - 0.85(\log_{10} CBR)^2$ 1.43 For $CBR \geq 3$ and 0 for $CBR < 0$ 3.14

Where:

| | |
|---|---|
| SNC | modified structural number |
| CBR (%) | California Bearing Ratio |
| SNSG | subgrade strength contribution |

Peterson in 1987 and the some others researchers have stated that, *SNC* is derived only to a total of 700 mm thickness, it means that the layer which is beyond this amount is not included. The said that in some cases the contributions of the layers which are below 700 mm to *SNC* are included in this estimation, and from this founds, it is recommended that to thickness which exceed 700 mm an engineering judgment is should be applied to *SNC* calculation (NDLI 1995).
Relationships between Modified Structural Number (*SNC)* and Benkelman Beam Deflection (*DEF)* are provided as follows (Paterson 1987).

| | | |
|---|---|---|
| Granular base | $SNC = 3.2\ DEF^{-0.63}$ | 3.15 |
| Cemented base | $SNC = 2.2\ DEF^{-0.63}$ | 3.16 |

- Adjusted Structural Number *(SNP)*

Adjusted Structural Number (*SNP*) has been derived from the Modified Structural Number *(SNC).*
The weighting factor which is applied by *SNP* will be reduced by increasing pavement depth to the lower layers such as sub-base and sub-grade; strength for deep pavement won't be predicted. Adjusted Structure Number is calculated by using the following formula. (HDM-4 V4)

$$SNP_s = SNBASU_s + SNSBA_s + SNSUBG_s \quad 3.17$$

$$SNBASU_s = 0.0394 \sum_{i=1}^{n} a_{is} h_i \quad 3.18$$

$$SNSUBA_s = 0.0394 \sum_{i=1}^{nm} a_{js} \left\{ \left( \frac{b_0 \exp(-b_3 z_j)}{-b_3} + \frac{b_1 \exp(-(b_2+b_3) z_j)}{(b_2+b_3)} \right) + \left( \frac{b_0 \exp(-b_3 z_{j-1})}{-b_3} + \frac{b_1 \exp(-(b_2+b_3) z_{j-1})}{(b_2+b_3)} \right) \right\} \quad 3.19$$

$$SNSUBG_s = [b_0 - b_1 exp(-b_2 z_m)][exp(-b_3 z_m)][3.51 \log_{10} CBR_s - 0.85(\log_{10} CBR_s)^2 - 1.43] \quad 3.20$$

Where:

| | |
|---|---|
| $SNP_s$ | Adjusted Structural Number |
| $SNBASU_s$ | Surface and Base Contribution |
| $SNSUBA_s$ | Sub-Base (or a selected layer) Contribution |
| $SNSUBG_s$ | Subgrade Contribution |
| DEF (mm) | Benkelman Beam Deflection *DEF* |
| n | No of Base and Surface layer *( $i = 1, 2, 3, \ldots, n$)* |
| $a_{is}$ | base or surface layer (i) coefficient (See table 9) |
| $h_i$ (mm) | base or surface layer thickness |
| m | No of Sub-Base and selected layer *( $i = 1, 2, 3, \ldots, n$)* |
| $z_i$ (mm) | depth to the bottom side of the layer j |
| z (mm) | depth measure from the sub-base top side |
| $a_{js}$ | sub-base or selected layer *(i)* coefficient (*See table 8)* |
| $b_0$, $b_1$, $b_2$, $b_3$ | Coefficients of the model *(see table 7)* |

**Note**: Denote (s) for all parameter represent the season in which the pavement is analyzed

**Table 7: Coefficient of the model (HDM-4 V4)**
**Preglednica 7 Koeficienti modela**

| Pavement type | $b_0$ | $b_1$ | $b_2$ | $b_3$ |
|---|---|---|---|---|
| All pavement types | 1.6 | 0.6 | 0.008 | 0.00207 |

**Table 8: Strength Coefficient of Pavement layers (HDM-4 V4)**
**Preglednica 8: Koeficienti nosilnosti slojev voziščne konstrukcije**

| Layer | Layer type | Condition | Coefficient |
|---|---|---|---|
| Surfacing | ST | Usually 0.2 | $a_i = 0.20$ to $0.40$ |
| | AM | $h_i < 30$ mm, low stability and cold mixes | $a_i = 0.20$ |
| | | $h_i > 30$ mm, $MR_{30} = 1500$ MPa | $a_i = 0.30$ |
| | | $h_i > 30$ mm, $MR_{30} = 2500$ MPa | $a_i = 0.40$ |
| | | $h_i > 30$ mm, $MR_{30} \geq 4000$ MPa | $a_i = 0.45$ |
| Base | GB | Default | $a_i = (29.14\ CBR - 0.1977\ CBR^2 + 0.00045\ CBR^3)\ 10^{-4}$ |
| | | CBR > 70, cemented sub-base | $a_i = 1.6\ (29.14\ CBR - 0.1977\ CBR^2 + 0.00045\ CBR^3)\ 10^{-4}$ |
| | | CBR < 60, max. axle load > 80kN | $a_i = 0$ |
| | AB, AP | Dense graded with high stiffness | $a_i = 0.32$ |
| | SB | Lime or cement | $a_i = 0.075 + 0.039\ UCS - 0.00088(UCS)^2$ |
| Sub-base | | Granular | $a_j = -0.075 + 0.184(\log_{10} CBR) - 0.0444(\log_{10} CBR)^2$ |
| | | Cemented UCS > 0.7 MPa | $a_j = 0.14$ |

Source: *Watanatada et al. (1987)*

- California Bearing Ration *CBR*

The comparative measurement of a no stabilized material is included; the sub base, granular base, and subgrade, and it is called California Bearing Ratio *CBR*. While in other hand, *CBR* is called to the percentage of resistance which is act against the penetration of a standard piston at a standard rate for a specific material. In *HDM* models *CBR* which is used in modified structural number *(SNC)*, is based on subgrade test at the in-situ moisture content situation. (NDLI, 1995)

If the *CBR* is greater than 100, it should not be used as a characteristic of stabilized material. In Table-7 several Structural Number coefficient which was found in different researches are combined by Chakrabarti and Bennett in 1994. (NDLI, 1995)

**b. Layer Properties**

The following items are other inputs that may differ in *HDM* models so it is important to note them:

- Layer Thickness

This input is mostly used for the calculation of *SNC* in a case where deflections are not known. The specification of the layers thickness is required for maintenance application characterization. It should be noted that the subgrade is assume to have infinite thickness, but the other layer are as follows: (NDLI, 1995)

- HS Thickness of the surface layer
- HB Base thickness
- HP surface plus base thickness

- Pavement Compaction Index - *COMP*

In the rut depth models this is an expository variable, COMP which is the real variable defined as the pavement compaction index is relative to standards with the percentage value. The following equation which is introduced by (Watanatada, et al., 1987) expresses this relation (NDLI, 1995):

$$COMP = \sum_{i=2}^{nlayer} RCi \frac{Hi}{\sum_{i=2,n} Hi} \qquad 3.21$$

Where:

| | |
|---|---|
| COMP | pavement relative compaction |
| $RC_i$ | in situ compaction ratio to the nominal compaction; $RC_i = min\ [1, C_i/C_{nom,\ i}]$ |
| C*i* | layer i compaction, which is defined as $DD_i/MDD_i$ |
| Hi (mm) | thickness layer |
| $DD_i$ | in situ dry density |
| $MDD_i$ | laboratory maximum dry density to the relevant Standard compaction |
| Cnom, *i* | nominal compaction, defined as $1.02 - 0.14\ Z_i$ |
| $Z_i$ (m) | bottom depth, in which $Z \leq 1$ |

**Table 9: Structural Number Strength Coefficients from Different Studies (NDLI 1995)**
**Preglednica 9: Koeficienti strukturnega števila iz različnih študij**

| Pavement Layer | Layer Strength Coefficient $a_i$ TRL (1975) | AASHTO (1993) | Paterson (1987) | CRRI (1993b) | Cenek and Patrick (1994) |
|---|---|---|---|---|---|
| *Surface Courses* | | | | | |
| Surface Treatment (ST) | | | 0.20 - 0.40 | | 0.300 |
| Surface Dressing (SSD/DSD) | 0.100 | | | | |
| Premix Carpet (PMC) | | | | 0.180 | |
| Semi-Dense Carpet (SDC), 25mm | | | | 0.250 | |
| Asphalt Mixture (cold/hot premix of low stability) | 0.200 | | 0.200 | | 0.200 |
| Asphalt Concrete (AC), 25 mm | 0.180 | | | | |
| Asphalt Concrete (AC), 40/ 25 mm | | | | 0.300 | |
| AC, MR30 – 1500 MPa | | | 0.300 | | 0.300 |
| AC, MR30 – 2500 MPa | | | 0.400 | | 0.400 |
| AC, MR30 – 4000 MPa | | | 0.500 | | 0.450 |
| Elastic Mod. at 68F, E – 100,000 psi | | 0.200 | | | |
| Elastic Mod. at 68F, E – 200,000 psi | | 0.300 | | | |
| Elastic Mod. at 68F, E – 300,000 psi | | 0.350 | | | |
| Elastic Mod. at 68F, E – 400,000 psi | | 0.425 | | | |
| *Base Courses* | | | | | |
| GB, CBR – 30% | 0.070 | 0.095 | 0.00-0.07 | | |
| GB, CBR – 50% | 0.100 | 0.110 | 0.00-0.10 | | |
| GB, CBR – 70% | 0.120 | 0.125 | 0.10-0.12 | | |
| CBR – 90% | 0.135 | 0.130 | 0.12-0.13 | | |
| CBR – 110% | 0.140 | 0.140 | 0.140 | | |
| Water Bound Macadam (WBM) | | | | 0.140 | 0.140 |
| CB, UCS – 0.7 MPa | 0.100 | 0.100 | 0.100 | | |
| CB, UCS – 2.0 MPa | 0.150 | 0.140 | 0.150 | | |
| CB, UCS – 3.5 MPa | 0.200 | 0.175 | 0.200 | | |
| CB, UCS – 5.0 MPa | 0.245 | 0.205 | 0.240 | | |
| Bituminous Base Material | | | 0.320 | | |
| Dense Bituminous Macadam/ | | | | 0.200 | |
| Built-Up Spray Grout (BUSG) | | | | 0.160 | |
| Thin Bituminous Layer, BT | | | | 0.140 | |
| AB, Marshall Stability, 200 lb | | 0.120 | | | |
| AB, Marshall Stability, 400 lb | | 0.160 | | | |
| AB, Marshall Stability, 800 lb | | 0.200 | | | |
| AB, Marshall Stability, 1200 lb | | 0.240 | | | |
| *Sub-base Courses* | | | | | |
| GB, CBR – 5% | 0.055 | 0.040 | 0.060 | | |
| GB, CBR – 15% | 0.085 | 0.090 | 0.090 | | |
| GB, CBR – 25% | 0.100 | 0.100 | 0.100 | | |
| GB, CBR – 50% | 0.120 | 0.130 | 0.120 | | |
| GB, CBR – 100% | 0.140 | 0.140 | 0.140 | | |
| Water Bound Macadam, Oversized | | | | 0.140 | |
| Brick Soling | | | | 0.120 | |
| Brick Ballast/ Aggregates | | | | 0.120 | |
| Local Gravel/ Kankar | | | | 0.100 | |
| Cemented Materials, | | | 0.140 | | |

#### 3.2.3.5 Material Properties

There are three parameter in which should be studied as the properties of bituminous material:

**a. Binder Content**

Binder content is expressed as the percentage of binder by the total mix. This content has different values for each related layer

- Wearing Course; 5 to 7.5 %
- Bituminous Base; 4.5 to 6.0 %

With the addition of binder contents in bituminous mixture the risk of deteriorations such as; rutting, bleeding, and shove will increase too. Whereas with low binder content in bituminous mixture, the pavement will be more stable, but it will be difficult in compaction. Disadvantage of lower binder content is the risk of pavement cracking (NDLI, 1995).

**b. Asphalt Viscosity**

Fundamental property of Asphalt is measured by Viscosity, and in most cases asphalts are graded by viscosity, while more often there are two ways to measure viscosity (NDLI, 1995):

| | |
|---|---|
| Capillary Tube; | How material performs at the elevated temperature which subjected to a loading, measured in Pascal-second with variable name *AVIS*. |
| Ring and Ball; | a performance of asphalt air-blown, which is defined by the temperature which the asphalt softens, so its units would be *°C*, and the variable name in *HDM-4* is *SP* |

**c. Aggregate Properties and Texture**

This is the measurement of skid resistance. In skid resistance both aggregate and surface layer characteristics have their own effects, while the effect of aggregates come from their abrasion resistance, and measurements unit would be Aggregate Abrasion Value *(AAV),* but their polishing resistance measured as Polished Stone Value *(PSV),* (NDLI, 1995).

**d. Surface Marital**

Table-10 will present the basic surface material which is used in *HDM* models. Table-12 can be a good reference for more details.

**Table 10: Surface material and their common Application for HDM-4 (NDLI 1995)**
**Preglednica 10: Materiali vozne površine in njihova običajna uporaba za HDM-4**

| Surface Material | Common Applications | Alternate Terminology | HDM-4 Designation |
|---|---|---|---|
| Asphaltic concrete | Surface layer of bituminous pavement, binder layer | Hot-Mix Asphalt, bituminous surfacing, bitumen macadam | AC |
| Hot rolled asphalt | Wearing course of surface layer | Hot-Rolled Sheet | HRA |
| Dense Bitumen Macadam | Applications requiring a high strength load carrying layer that will be covered with surface treatment | | DBM |
| Stone mastic asphalt | High stability mix used where rutting is a concern | Stone matrix asphalt | SMA |
| Porous Asphalt concrete | Reduce surface water on high volume/high speed pavements subjected to frequent rainfall | Pervious macadam, drainable asphalt concrete | PAC |
| Surface treatment | Restore skid resistance, seal surface that is beginning to crack | Single surface dressing, chip seal | SBST, DBST |
| Slurry seal | Thin surface treatment placed over fairly sound bituminous layer in order to reduce wear | | SL |
| Penetration macadam | Primarily used in labor intensive construction | Penmac | PM |

#### e. Base and Sub Base Material

The basic Base and Sub Base material type which is used in *HDM-4* Models are described in Table 11.

**Table 11: Base and Sub Base General Characteristics (NDLI 1995)**
**Preglednica 11: Splošne lastnosti spodnjega nosilnega sloja in temeljnih tal**

| **Material** | **Types of Aggregate** | **Types of Additives** |
|---|---|---|
| Granular base *(GB)* | Crushed stone, dense graded<br>Gravel, dense graded<br>Sands (sub base only)<br>Crushed stone, open-graded | None |
| Asphalt-stabilized base *(AB)* | Crushed stone Gravel | Asphalt emulsion, Cutback, or cement |
| Cement-stabilized base *(SB)* | Crushed stone Gravel | Portland cement<br>Lime<br>Lime-fly ash<br>Cement-fly ash |
| Other | Crushed slag<br>Recycled products | |

### 3.2.3.6 Road Geometry

Vertical alignment alongside with carriageway width and shoulder need to be taken in to account as a variable in deterioration of pavement.

**Table 12: Some Characteristics of Surface material used in HDM-4 Models NDLI 1995)**
**Preglednica 12: Nekaj lastnosti materialov vozne površine**

| HDM-4 Designation | Binder type | Binder Quantity[1] | Typical Additives[2] | Aggregate gradation | Aggregate top size, mm | Typical Layer Thickness, mm | Layer coefficient |
|---|---|---|---|---|---|---|---|
| AC | asphalt cement | 3 to 8 % | None | Uniform | 20 to 50 | 25 to 100 | 0.30 to 0.45 |
| HRA | asphalt cement | 5 to 9 % | None | Gap-graded | 14 to 20 | 25 to 50 | 0.20 to 0.30 |
| DBM | asphalt cement | 3 to 8 % | None | Well-graded | 20 to 40 | 25 to 100 | 0.30 to 0.45 |
| SMA | asphalt cement | 6 to 8 % | Fibers, Elastomers, Polymers | Somewhat open graded | 20 to 50 | 25 to 75 | 0.30 to 0.45 |
| PAC | asphalt cement | 3.5 to 6 % | polymer | Gap-graded | 9 to 12.5 | 10 to 14 | 0.20 to 0.30 |
| ST | cement/emulsion/ cutback | 1.6 to 2.0 L/m$^2$ 4 to 8 % | None | Single | 6 to 20 | 10 to 20 | 0.20 to 0.30 |
| SL | emulsion | 5.5 to >8 kg/m$^2$ | cement | Well-graded | 6 | 3 to 10 | 0.2 to 0.25 |
| PM | emulsion/cutback | 2.5 kg/m$^2$ | none | Gap-graded | 25 to 40 | 30 to 45 | 0.15 o 0.30 |

Notes: 1/ Typical ranges provided for information only. Actual values highly dependent upon job mix formula for AM and aggregate size for ST.

2/ Not including anti-stripping agent.

## 3.3 Philosophy of Modeling

Deterioration prediction models of bituminous pavement in *HDM-4* application have several characteristics which are as follows(HDM-4 Volume 6):

- Modeling of individual deterioration than composite ones;
- Models are structured empirical;
- There are interaction between distresses in deterioration models;

Pavement deterioration is classified as:

- Cracking;
- Surface disintegration;
- Permanent deformation;
- Longitudinal profile;
- Friction;

The factors which distress modes are dependent on are as follows:

- Pavement Strength;
- Material Properties;
- Traffic Loading;
- Environment;

The mentioned distress modes and factors are showed in the following table. (HDM-4 V6)

**Table 13: Distress Tyapes and Independent Varialbes (HDM-4 Volume 6)**
**Preglednica 13: Tipi poškodb in neodvisne spremenljivke**

| Distress Mode | Distress Type | Pavement Strength | Material Properties | Traffic Loading | Environment |
|---|---|---|---|---|---|
| Cracking | Structural | 4 | 4 | 4 | 4 |
| | Reflection | 4 | | 4 | |
| | Transverse Thermal | | 4 | | 4 |
| Disintegration | Raveling | | 4 | 4 | 4 |
| | Potholing | 4 | 4 | 4 | 4 |
| | Rutting-Surface water | | | 4 | 4 |
| | Edge Break | | 4 | 4 | 4 |
| Deformation | Rutting-Structural | 4 | 4 | 4 | 4 |
| | Rutting-Plastic flow | | 4 | 4 | 4 |
| Profile | Roughness | 4 | 4 | 4 | 4 |
| Friction | Texture depth | | 4 | 4 | |
| | Skid Resistance | | 4 | 4 | |

### 3.3.1 Interaction of deterioration models

Deterioration models are a complex mechanism; it is in a way that the distress modes are interacted by some external variables, as an example; Environment and pavement deterioration has high impacts on pavement strength, while deterioration progression is dependent on residual strength of pavement. The interaction between distresses and other variable are described in *HDM-4 Volume 6* with the following figures.

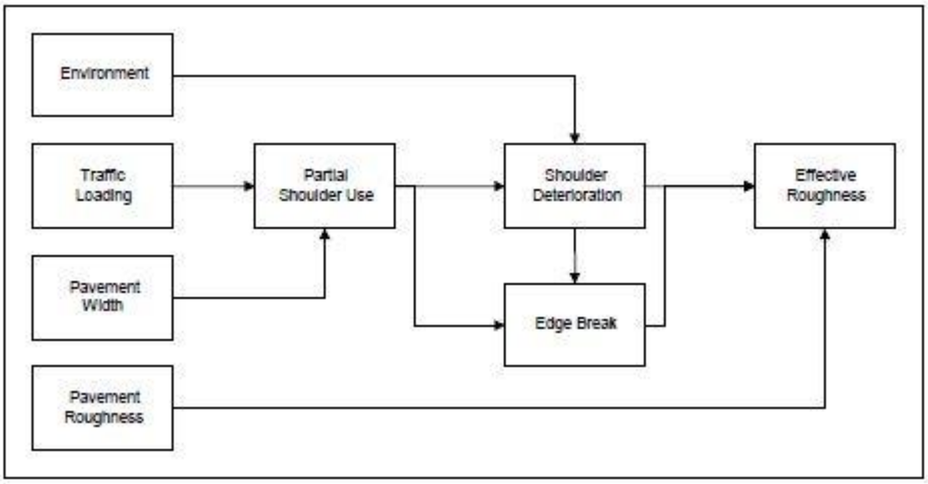


**Figure 3: Edge Beak, shoulder deterioration and effective roughness (HDM-4 V6)**
**Slika 3: Lom robov, propadanje bankin in efektivna neravnost**

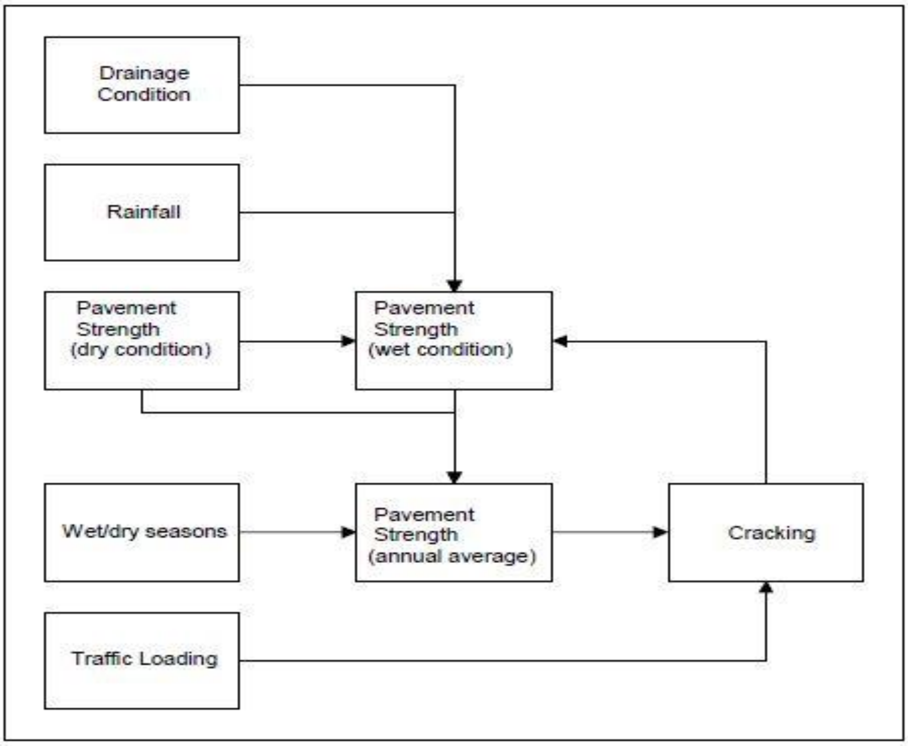


**Figure 4: Interaction between pavement strength and Structural Cracking (HDM-4 V6)**
**Slika 4: Interakcija med nosilnostjo in strukturnimi razpokami**

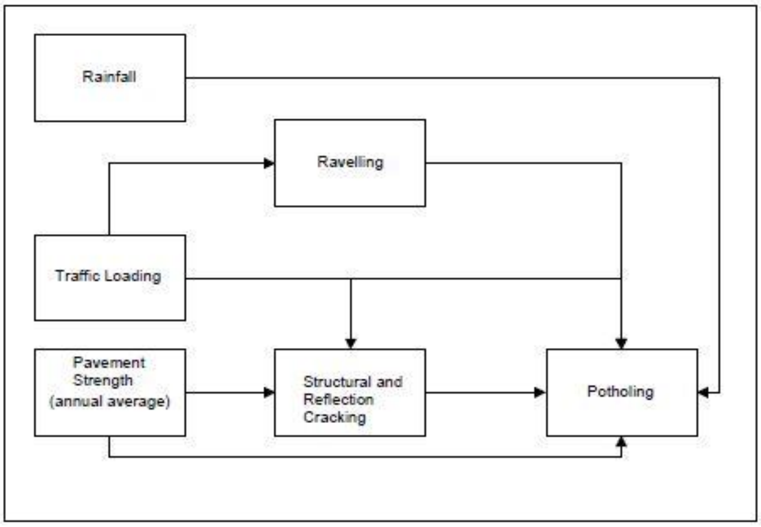


**Figure 5: Potholes vs. other parameters (HDM-4 V6)**
**Slika 5: Povezava med udarnimi jamami in ostalimi parametri**

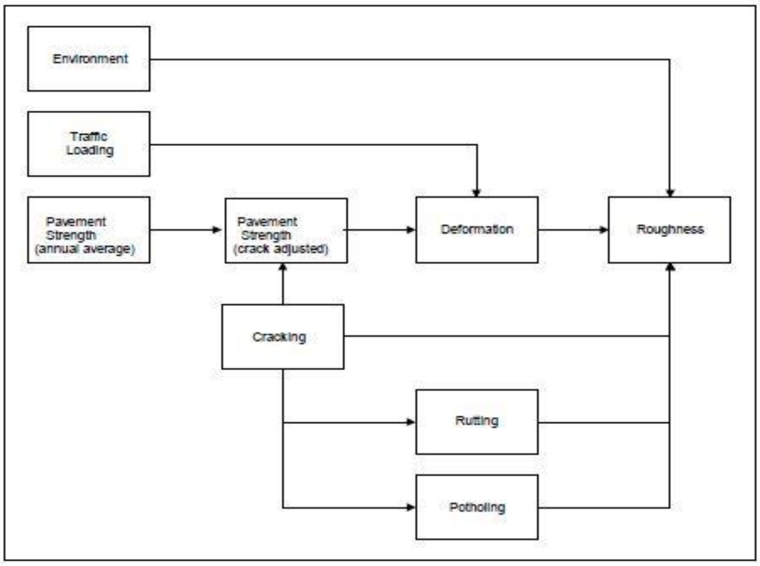


**Figure 6: Roughness vs. Other parameters (HDM-4 V6)**
**Slika 6: Povezava med neravnostjo in ostalimi parametri**

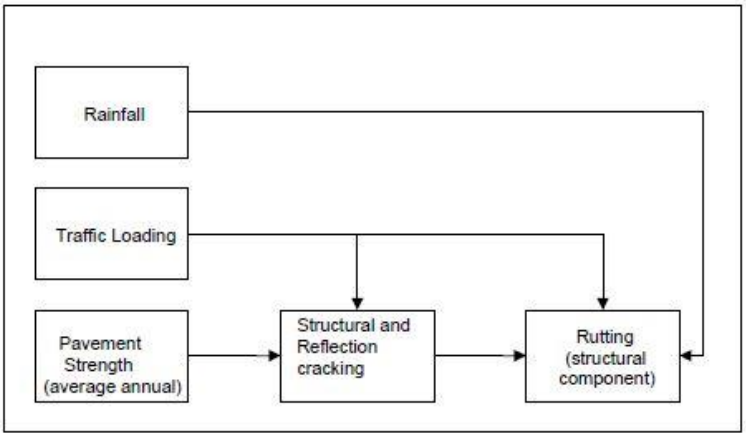


**Figure 7: Structural rutting vs. other parameters (HDM-4 V6)**
**Slika 7: Povezava med strukturnimi kolesnicami in ostalimi parametri**

### 3.3.2 Distress Initiation and progression phase

Initiation phase is called to the period which the distress is not started yet and there is zero area of distresses, but after passing the initiation phase the area gradually started to deformed and progress period started. This phenomenon is shown in the following figure (HDM-4 V6).

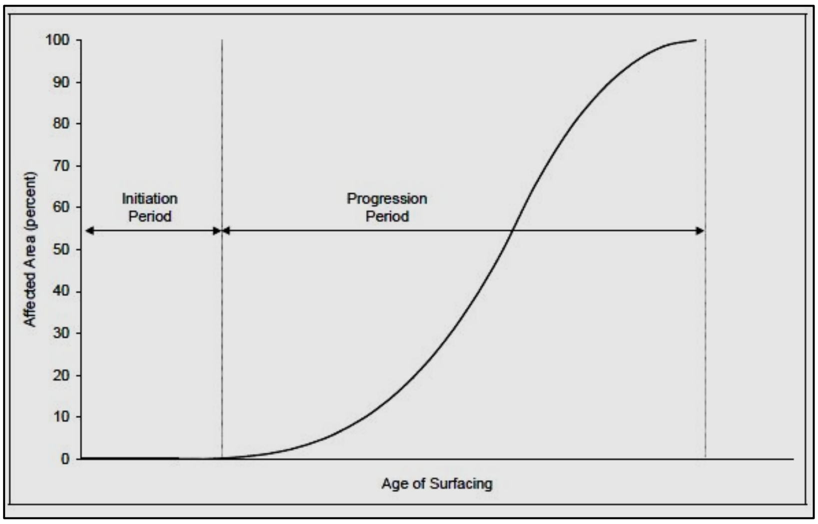


**Figure 8: initiation and Progression phases (HDM-4 V6)**
**Slika 8: Začetna in nadaljevalna faza**

The actual distress development and progression, or the function of damage of a pavement could express the pavement deterioration phenomena, but this is described by Paterson (1987); that the distress function is related to two standards; construction quality or initial condition and the final distress that is necessary to maintain and rehabilitation (NDLI, 1995).

### 3.3.3 Construction Quality

The quality of construction is one of the most important factors affected to pavement deterioration.

In *HDM-4* average level values are used to describe the construction quality and to indicate the construction defect *CDS* and *CDB* are used in deterioration models.

Another value which indicates the construction quality is *COMP* which expresses the relative compaction of the layers, to calculate the value of *COMP* there are some equations, but also the following table 12 is used to estimate the values.

As mentioned above in *HDM-4* inputs for construction defect, there are two indicators (HDM-4 V4):

- CDS Bituminous pavement surface Construction Defects;
- CDB Bituminous pavement Base Construction Defect;

High value of *CDS* means that the pavement disposed to rutting, and low value of *CDS* means that the payment deposed to cracking and raveling.

The values for *CDS* are ranging from 0.5 to 1.5 and intermediate values could be chosen by judgment. The values of *CDS* are shown in table below (HDM-4 V4):

**Table 14: Relative compaction default values (HDM-4 V4)**
**Preglednica 14: Predpostavljene vrednosti za zgoščenost**

| Compliance | Relative Compaction *COMP (%)* |
|---|---|
| Full compliance in all layers | 100 |
| Full compliance in some layers | 95 |
| Reasonable compliance in most layers | 90 |
| Poor compliance in most layers | 85 |
| HDM-4 default value | 97 |

Construction Defect Indicator *CDB* is used to evaluate the potholing, the values of the *CDB* is ranging between 0 to 1.5 while zero means no defect and 1.5 indicate several defects.

Table below shows the selection of the defects vs. *CDB* values.

**Table 15: *CDS* selection for bituminous pavement (HDM-4 V4 part C)**
**Preglednica 15: Vrednosti CDS za bitumizirane sloje**

| Surface condition | | CDS |
|---|---|---|
| Dry (*Brittle*) | Nominally about *10*% below optimal binder content | 0.5 |
| Normal | Optimal binder content | 1.0 |
| Rich (Soft) | Nominally about *10*% about design optimal binder content | 1.5 |

**Table 16: *CDB* Selection for base layer (HDM-4 v4 Part C)**
**Preglednica 16: CDB vrednosti za spodnje nosilne sloje**

| Construction defect | CDB |
|---|---|
| Poor gradation of material | 0.5 |
| Poor aggregate shape | 0.5 |
| Poor compaction | 0.5 |

## 3.4 Pavement Deterioration Models in HDM-4

### 3.4.1 Introduction

In general because of interaction among different deterioration mechanisms, pavement deterioration could be a complex action. To have an example of these interactions, road roughness can be a good example, in which it consists of several components that each one represent different distresses and these distresses have different contributions on roughness value. As cracks lead to potholes and will increase roughness, in other hand cracks allow the water to penetrate to the pavement surface and reach to lower layers, which will cause the pavement structure to be weakened. The pavement weakness also depends on materials and the drainage systems of the pavement, finally pavement weakness will lead to rutting, and it also has contribution on roughness (HDM-4 V6).

Pavement deteriorations which are included in *HDM* are classified as follows according to *HDM-4 Manual Volume 6*:

- Cracking;
- Raveling;
- Potholing;
- Edge break;
- Permanent deformation;
- Roughness;
- Pavement texture;

### 3.4.2 Cracking

#### 3.4.2.1 Introduction

Surely the most important defect in bituminous pavement is cracking, so it can be taken as the primary objective of the bituminous pavement design. However cracking has a complex modeling because there are several factors which affect its development and identification. Measurement of these factors can be done in different ways and their analyses are extremely complex, although other distresses such as rutting and pothole are not due to a single reason, but in general they have a single definition to their identification, so their measurements can be done by a single way that won’t be difficult (NDLI, 1995).

It is obvious that every kind of bituminous pavement could be cracked at a stage of its life, but it is not only the direct effect of the cracks that concern highways, indirect effects of the cracks are more critical ones, in which the strength of the layers are affected. As one of the bituminous layer functions is waterproofing, with the pavement cracking water would be able to ingress to lower layers and it will reduce the strength of the layers, and could lead to potholes (HDM-4 Volume 6).

#### 3.4.2.2 Cracking Definition

The breakage which is appear on the surface of the pavement is called cracks, according to pavement management literatures, cracking is the most important distress in bituminous pavement because in most cases it is the start point of other defects in pavement. Peterson (1987) introduces two phase for the pavement cracks, which are initiation phase and progression phase as shown in fig-9 (NDLI, 1995).

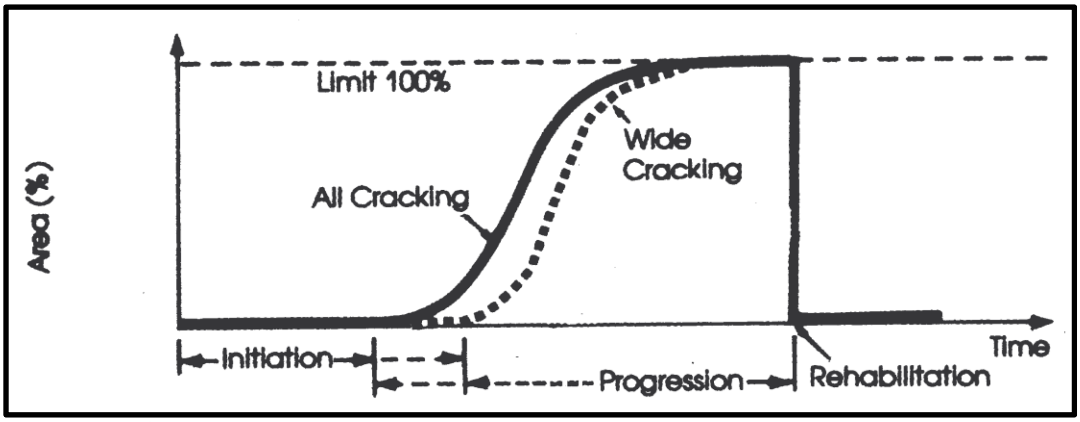


**Figure 9: Inititan and progression phase (paterson 1987)**
**Slika 9: Začetna in nadaljevalna faza**

Cracking also can be defined and classified according to their appeared pattern, and these classifications which are shown below may give us a probable cause of the cracking (NDLI, 1995).

- Network cracking (related to fatigue);
- Line cracking (related to temperature);
- Irregular Cracking (pavement age);

### 3.4.2.3 Measurement of Cracking

Actually cracking measurement in general could involve two steps, the first one might be the cracks measuring and the next one recoding and data collection which in most cases it is done by automated machines. There are several cracks measurement methods which are used in all over the world, but there would be no accepted standards in data collection and reporting steps, some of these methods may need the observers' judgment over the crack causes (HDM-4 V6).

Paterson (1994) defines the cracking characteristics in five attributes:

| | |
|---|---|
| • Extent ($m^2$ or % total pavement area ); | Cracking Area |
| • Severity (m or crack classes); | crack width |
| • Intensity ($m/m^2$); | Length of Cracks/Area or cracking spacing |
| • Pattern | identifies the type of the cracks (e.g. block) |
| • Location; | pavement parts which are cracked (e.g. wheel path) |

From the above mentioned attributes, Extent, Severity, and Pattern are the most considerable ones which in many procedure of distresses identification are used, such as *HDM-III* models (Paterson 1987), the procedure of pavement condition Index *(PCI)* by Shahin, et al, 1977 and *SHRP* Long Term Pavement Performance *LTPP* (SHRP1993), (HDM-4 Volume 6).

#### 3.4.2.4 Mechanism of Cracking

Cracks mechanisms are described in many sources, Paterson (1987) introduce cracks mechanism and interaction, which in most cases is one of the sources for the *HDM* Manual. The cracking mechanisms which are described in *HDM-4 Volume 6* are shown in table 18.

These cracks mechanism have different patterns, in some cases they are the same for some cracks. The patterns which are seen by any observer may be the result of different distresses and cracking mechanism, it is not easy to describe cracking only according the observed pattern but it can give an initial judgment, these patterns with the related mechanism are shown in table 17.

**Table 17: Cracks mechanism and their pattern (HDM-4 Volume 6)**
**Preglednica 17: Mehanizem razpok in njihovi vzorci**

| Crack Mechanism | Crack Pattern | | | | | |
|---|---|---|---|---|---|---|
| | Crocodile | Block | Map | Transverse | Longitudinal | Irregular |
| Fatigue | √ | | | | | |
| Ageing | | | √ | | | |
| Reflection | √ | √ | √ | √ | √ | √ |
| Thermal | | | | √ | √ | |
| Shrinkage | | √ | | √ | √ | |
| Shear | | | | | √ | |

**Table 18: Cracking Mechanism in HDM-4 Model**
**Preglednica 18: Mehanizem razpok v HDM-4 modelih**

| Cracking Mechanism | Description |
|---|---|
| Fatigue | • Has the most attention (in terms of mechanistic modeling)<br>• Basis for design method for many pavements<br>• Has a crocodile pattern in wheel path<br>• Related to material properties, pavement structure and traffic loading |
| Age Cracking | • Caused by change of bituminous binder properties as bidder stiffening<br>• Has a irregular pattern<br>• Affects the pavement whole area |
| Reelection Cracking | • Is the new surface cracks in which the very close underlay is cracked<br>• Reflection rate is depends on<br>❖ new surface thickness<br>❖ traffic loading<br>❖ climate change<br>❖ surface condition and strength of old pavement<br>❖ overlay material<br>• solution is to remove the completely old layer, or apply a very thick overlay |
| Thermal | • Its causes are like age cracking by binder stiffening and change in temperature<br>• Common in continental climate<br>• Has a spaced transvers pattern |
| Shrinkage | • This mechanism is a form of reflection cracks<br>• Propagated from the base through the surface<br>• Occur in bases which stabilized by cement or lime<br>• Has transvers, block and longitudinal patter |
| Shear | • Cause by under layer shear failure<br>• due to :<br>❖ poor shoulder support<br>❖ drainage<br>❖ embankment settlement<br>• has a longitudinal patter |

### 3.4.3 HDM-4 Crack Modeling

According to *HDM-4 Manual Volume 4 part C* there are two types of cracks which are included in *HDM-4* models:

- Structural Cracking;

This type of cracking is happened because of associated of Over loading and age or environment situation of the road.

- Transverse Thermal Cracking;

This type of cracking is mostly happen because of change in temperature during day and night or in the situation of the freezing and thaw.

Each of these cracking types has their own relations and functions for the purpose of predicting initiation time and the progression rate. These relations and function have the variable which are indicates the pavement defect; they are described in section 3.3.3.

#### 3.4.3.1 Structural Cracking

*HDM-4 volume 6* described the models of structural cracking in two types as;

- All Structural Cracking;
- Wide Structural Cracking;

The following Relation and function of these two types of modes are based on Paterson (1987), (HDM-4 V4 Part C).

**a. All Structural Cracking Initiation Phase**

When 0.5% surface of the carriageway is cracked, it is said to be the initiation phase of the cracking, according to *HDM-4 manual Volume 4*, All Structural Cracking dependents to type of base layer of the pavement, so the relations with the base types are as follows:

- For Stabilized bases;

If *HSOLD = 0* which the original surface of the pavement

Then the relation would be as follows (HDM-4 V4):

$$ICA = K_{cia}\{CDS^2 a_0 exp[a_1 HSE + a_2 \log_e CMOD + a_3 \log_e DEF + a_4 (YE4)(DEF)]\}$$

If *HSOLD > 0* which is mean that the pavement is overlaid

$$ICA = K_{cia}\left\{CDS^2 \left[(0.8KA + 0.2KW)(0 + 0.1HSE) + (1 - KA)(1 - KW)a_0 * exp[a_1 HSE + a_2 \log_e CMOD + a_3 \log_e DEF + a_4 (YE4)(DEF)]\right] + CRT\right\} \quad 3.22$$

- For all other kinds of the bases;

If *HSOLD = 0* which the original surface of the pavement

Then the relation would be as follows (HDM-4 V4):

$$ICA = K_{cia}\left\{CDS^2 a_0 exp\left[a_1 SNP + a_2\left(\frac{YE4}{SNP^2}\right)\right] + CRT\right\} \quad 3.23$$

If *HSOLD > 0* which is mean that the pavement is overlaid there are two types of relations:

- For any kind of surface material except *CM, SL, CAPE*;

$$ICA = K_{cia}\left\{CDS^2\ \left[MAX\left(a_0 exp\left[a_1 SNP + a_2\left(\frac{YE4}{SNP^2}\right)\right] * MAX\left(1 - \frac{PCRW}{a_3}, 0\right), a_4 HSNEW\right)\right] + CRT\right\} \quad 3.24$$

- For *CM*, *SL*, and *CAPE* surface material;

$$ICA = K_{cia}\left\{CDS^2\ \left[MAX\left(a_0 exp\left[a_1 SNP + a_2\left(\frac{YE4}{SNP^2}\right)\right] * MAX\left(1 - \frac{PCRA}{a_3}, 0\right), a_4\right)\right] + CRT\right\} \quad 3.25$$

Where:

| | |
|---|---|
| ICA (years) | Initiation time for All Structural Cracking |
| DEF (mm) | Deflection for the two wheel paths in as the mean of Benkelman beam |
| CMOD (GPa) | Soil Cement Resilient modulus for most soils 0 to 30 *GPa* |
| HSNEW (mm) | the new surface thickness |
| HSOLD (mm) | the old total thickness |
| PCRW (%) | Wide Cracking Area before overlay (calculated as the % of the total area of Carriageway |
| PCRA (%) | Cracking Area before overlay (calculated as the % of the total carriageway area) |
| KW | *MIN [0.05 MAX (PCRW – 10, 0), 1]* |
| KA | *MIN [0.05 MAX (PCRA – 10, 0), 1]* |
| HSE | *MIN [100, HSNEW + (1-KW) HSOLD]* |
| $K_{cia}$ | Initiation calibration factor for All Structural Cracking |
| CRT (years) | Delay of cracking because of maintenance |

The value of coefficient; $a_0$ through $a_4$ are introduced as default in table 19.

**Table 19: Default values for All Structural Cracking Coefficients (HDM-4 V4)**
**Preglednica 19: Predpostavljene vrednosti za koeficiente struturnih razpok**

| Pavement type | Surface material | HSOLD value | Equ$^n$ | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ |
|---|---|---|---|---|---|---|---|---|
| AMGB | All | 0 | 5.3 | 4.21 | 0.14 | -17.1 | | |
| | All except CM | > 0 | 5.4 | 4.21 | 0.14 | -17.1 | 30 | 0.025 |
| | CM | > 0 | 5.5 | 13.2 | 0 | -20.7 | 20 | 1.4 |
| AMAB | All | 0 | 5.3 | 4.21 | 0.14 | -17.1 | | |
| | | > 0 | 5.4 | 4.21 | 0.14 | -17.1 | 30 | 0.025 |
| AMAP | All | > 0 | 5.4 | 4.21 | 0.14 | -17.1 | 30 | 0.025 |
| AMSB | All | 0 | 5.1 | 1.12 | 0.035 | 0.371 | -0.418 | -2.87 |
| | | > 0 | 5.2 | 1.12 | 0.035 | 0.371 | -0.418 | -2.87 |
| STGB | All | 0 | 5.3 | 13.2 | 0 | -20.7 | | |
| | All except SL, CAPE | > 0 | 5.4 | 13.2 | 0 | -20.7 | 20 | 0.22 |
| | SL, CAPE | > 0 | 5.5 | 13.2 | 0 | -20.7 | 20 | 1.4 |
| STAB | All | 0 | 5.3 | 13.2 | 0 | -20.7 | | |
| | All except SL, CAPE | > 0 | 5.4 | 4.21 | 0.14 | -17.1 | 20 | 0.12 |
| | SL, CAPE | > 0 | 5.4 | 4.21 | 0.14 | -17.1 | 30 | 0.025 |
| STAP | All | > 0 | 5.4 | 4.21 | 0.14 | -17.1 | 20 | 0.12 |
| STSB | All | 0 | 5.1 | 1.12 | 0.035 | 0.371 | -0.418 | -2.87 |
| | | > 0 | 5.2 | 1.12 | 0.035 | 0.371 | -0.418 | -2.87 |

### b. Wide Structural Cracking Initiation phase

The initiation phase for wide structural cracking can be calculated with the following formula (HDM-4 V4):

$$ICW = K_{ciw} MAX[(a_0 + a_1 ICA), a_2 ICA] \qquad 3.26$$

The value of coefficient; $a_0$ through $a_4$ are introduced as default in table 10.

Where:

| | |
|---|---|
| ICW (years) | Wide Cracking initiation time |
| $K_{ciw}$ | Initiation calibration factor for Wide Cracking |

The value of coefficient; $a_0$ through $a_4$ are introduced as default in table 20.

**Table 20: Default values for Wide Structural Cracking Coefficients (HDM-4 V4)**
**Preglednica 20: Predpostavljene vrednosti koeficientov širokih strukturnih razpok**

| Pavement type | Surface material | HSOLD value | $a_0$ | $a_1$ | $a_2$ |
|---|---|---|---|---|---|
| AMGB | All | 0 | 2.46 | 0.93 | 0 |
| | All except CM | > 0 | 2.04 | 0.98 | 0 |
| | CM | > 0 | 0.70 | 1.65 | 0 |
| AMAB | All | 0 | 2.46 | 0.93 | 0 |
| | | > 0 | 2.04 | 0.98 | 0 |
| AMAP | All | > 0 | 2.04 | 0.98 | 0 |
| AMSB | All | 0 | 1.46 | 0.98 | 0 |
| | | > 0 | 0 | 1.78 | 0 |
| STGB | All | 0 | 2.66 | 0.88 | 1.16 |
| | All except SL, CAPE | > 0 | 1.85 | 1.00 | 0 |
| | SL, CAPE | > 0 | 0.70 | 1.65 | 0 |
| STAB | All | 0 | 2.66 | 0.88 | 1.16 |
| | All except SL, CAPE | > 0 | 1.85 | 1.00 | 0 |
| | SL, CAPE | > 0 | 2.04 | 0.98 | 0 |
| STAP | All | > 0 | 1.85 | 1.00 | 0 |
| STSB | All | 0 | 1.46 | 0.98 | 0 |
| | | > 0 | 0 | 1.78 | 0 |

### c. All Structural Cracking Progression phase

The progression phase of the All Structural Cranking is expressing with the following equation (HDM-4 V4):

$$dACA = K_{cpa}\left[\frac{CRP}{CDS}\right] Z_a\left[(Z_a a_0 a_1 \delta t_a + SCA^{a1})^{1/a1} - SCA\right] \qquad 3.27$$

The progression will begin in two cases:

$\delta t_a > 0$

$ACA_a > 0$

As the follows:

If $ACA_a > 0$ then $\delta t_a = 0$ in any other cases $\delta t_a = MAX\ \{0, MIN\ [(AGE2 - ICA), 1]\}$

If $ACA_a > 50$ then $ZA = -1$ in any other cases $ZA = 1$

$ACA_a = MAX\ (ACA_a, 0.5)$

$$SCA = MIN\ [ACA_a, (100 - ACA_a)] \qquad 3.28$$

In the cases of $Y = [Z_a\, a_0\, a_1\, \delta t_a + SCA^{a1}]$

If $Y < 0$ then $dACA = K_{cpa}\left[\frac{CRP}{CDS}\right] Z_a[100 - SCA]$ 3.29

If $Y \geq 0$ then $dACA = K_{cpa}\left[\frac{CRP}{CDS}\right] Z_a\left[Y^{1/a1} - SCA\right]$ 3.30

If $ACAa \leq 50$ and $ACA_a + dACA > 50$

Then $dACA = K_{cpa}\left[\frac{CRP}{CDS}\right] Z_a\left[100 - {C_1}^{1/a1} - ACA_a\right]$ 3.31

In the case of $C_1 = MAX\{[2(50^{a1}) - SCA^{a1} - a_0 a_1 \delta t_a], 0\}$ 3.32

Where:

| | |
|---|---|
| dACA (%) | Incremental Change of All Structural Cracking Area (during the year of analysis) |
| $ACA_a$ | All Structural Cracking Area (start of the year of analysis) |
| $\delta t_a$ | the analysis year fraction |
| ICA (years) | All Structural Cracking Time to Initiation |
| $K_{cpa}$ | Progression Calibration factor |
| CRP | the progression cracking delay because of proper treatment (*CRP = 1- 0.12 CRT*) |

The default values for the coefficients $a_0$ and $a_1$ are given in the table 21.

**Table 21: Default values for all and Wide Structural Cracking Coefficients (HDM-4 V4)**
**Preglednica 21: Predpostavljene vrednosti koeficientov za vse in široke strukturne razpoke**

| Pavement type | Surface material | HSOLD value | All cracking | | Wide cracking | |
|---|---|---|---|---|---|---|
| | | | $a_0$ | $a_1$ | $a_0$ | $a_1$ |
| AMGB | All | 0 | 1.84 | 0.45 | 2.94 | 0.56 |
| | All except CM | > 0 | 1.07 | 0.28 | 2.58 | 0.45 |
| | CM | > 0 | 2.41 | 0.34 | 3.40 | 0.35 |
| AMAB | All | 0 | 1.84 | 0.45 | 2.94 | 0.56 |
| | | > 0 | 1.07 | 0.28 | 2.58 | 0.45 |
| AMAP | All | > 0 | 1.07 | 0.28 | 2.58 | 0.45 |
| AMSB | All | 0 | 2.13 | 0.35 | 3.67 | 0.38 |
| | | > 0 | 2.13 | 0.35 | 3.67 | 0.38 |
| STGB | All | 0 | 1.76 | 0.32 | 2.50 | 0.25 |
| | | > 0 | 2.41 | 0.34 | 3.40 | 0.35 |
| STAB | All | 0 | 1.76 | 0.32 | 2.50 | 0.25 |
| | All except SL, CAPE | > 0 | 2.41 | 0.34 | 3.40 | 0.35 |
| | SL, CAPE | > 0 | 1.07 | 0.28 | 2.58 | 0.45 |
| STAP | All | > 0 | 2.41 | 0.34 | 3.40 | 0.35 |
| STSB | All | 0 | 2.13 | 0.35 | 3.67 | 0.38 |
| | | > 0 | 2.41 | 0.34 | 3.40 | 0.35 |

### d. Wide Structural Cracking Progression Phase

To model Wide Structural Cracking the following equations and relations are used (HDM-4 V4):

$$dACW = K_{cpw}\left[\frac{CRP}{CDS}\right]Z_w\left[(Z_w a_0 a_1 \delta t_w + SCW^{a1})^{1/a1} - SCW\right] \qquad 3.33$$

Or in other case

$dACW = MIN\ [ACA_a + dACA - ACW_a\ ,\ dACW]$

The progression will begin in two cases:

$\Delta t_w > 0$

$ACW_a > 0$

As the follows:

If $ACW_a > 0$ then $\delta t_w = 1$

In any other cases $\delta tw_a = MAX\ \{0, MIN\ [(AGE2 - ICW), 1]\}$ 3.34

All Structural Cracking ACA is a bound for wide structural cracking beginning, in a way that Wide Structural Cracking won't begin until the area of ACA is exceeding 5%, as can be see:

$\delta t_w = 0$ If $ACA_a \leq 5$ and $ACW_a \leq 0.5$ and $\delta t_w \geq 0$

IF $ACW_a \geq 50$ then $Z_w = -1$ in any other case $Z_w = 1$

So $ACW_a = MAX\ (ACW_a\ ,\ 0.5)$ $SCW = MIN\ [ACW_a\ ,\ (100 - ACW_a)]$

In the cases of $Y = [Z_w\, a_0\, a_1\, \delta t_w + SCW^{a1}]$

If $Y < 0$

$$dACW = K_{cpw}\left[\frac{CRP}{CDS}\right]\mathrm{MIN}\ [(ACA_a + dACA - ACW_a)\ (100 - ACW_a)] \qquad 3.36$$

If $Y > 0$

$$dACW = K_{cpw}\left[\frac{CRP}{CDS}\right]\mathrm{MIN}\ [(ACA_a + dACA - ACW_a),\ Z_w\ (Y^{1/a1} - SCW)] \qquad 3.37$$

If $ACW_a \leq 50$ and $ACW_a + dACW > 50$

$$dACW = K_{cpw}\left[\frac{CRP}{CDS}\right]\mathrm{MIN}\ [(ACA_a + dACA - ACW_a),\ (100 - C_1^{1/a1}\ ACW_a)] \qquad 3.38$$

In the case that $C_1 = MAX\ \{[2\ (50a1) - SCW^{a1} - a_0\, a_1\, \delta t_w],\ 0\}$

Where:

| | |
|---|---|
| dACW (%) | Incremental Change of Wide Structural Cracking Area (during the year of analysis) |
| $ACW_a$ | Wide Structural Cracking Area (start of the year of analysis) |
| $\delta t_w$ | the analysis year fraction |
| ICW (years) | Wide Structural Cracking Time to Initiation |
| $K_{cpw}$ | Progression Calibration factor |
| CRP | the progression cracking delay because of proper treatment (*CRP = 1- 0.12 CRT*) |

The default values for the coefficients $a_0$ and $a_1$ are given in the table 21.

#### 3.4.3.2 Transverse Thermal Cracking

This type of cracking is caused by the temperature changing or thermal cycling, and in most cases its pattern is perpendicular to the road centerline.

In *MEPDG* Transverse Thermal Cracking is calculated as meter per kilometer, while in *HDM-4* it is modeled as the number of cracks per kilometer (ASHTO 2008).

The coefficient *CCT* is used to predict the initiation time of thermal cracking in different climate zones which was described in table-5. The proposed values of *CCT* are given in table 23. While the thermal cracking maximum number is expressed in *($NCT_{eq}$)* and the time which these cracking are reached from initiation is expressed in *($T_{eq}$)*.

Proposed values for these two variables are shown in table 22. (HDM-4 V4 Part c)

**Table 22: Default values proposed for $NCT_{eq}$ and $T_{eq}$ (HDM-4 V4)**
**Preglednica 22: Predpostavljene vrednosti za NCT in T**

| Model parameter | Tropical | Sub-tropical hot | Sub-tropical cool | Temperature cool | Temperature freeze |
|---|---|---|---|---|---|
| $NCT_{eq}$ | 0 | 100 | 0 | 0 | 20 |
| $T_{eq}$ | 50 | 7 | 50 | 50 | 7 |

**Table 23: Default values proposed for *CCT* (HDM-4 V4)**
**Preglednica 23: Predpostavljene vrednosti za CCT**

| Model parameter | Tropical | Sub-tropical hot | Sub-tropical cool | Temperature cool | Temperature freeze |
|---|---|---|---|---|---|
| Arid | 100 | 5 | 100 | 100 | 2 |
| Semi-arid | 100 | 8 | 100 | 100 | 2 |
| Sub-humid | 100 | 100 | 100 | 100 | 1 |
| Humid | 100 | 100 | 100 | 100 | 1 |
| Per-humid | 100 | 100 | 100 | | |

**a. Initiation phase of Transvers Thermal Cracking**

The initiation time of this type of cracking can be expressed in two cases (HDM-4 V4):

- If $HSOLD = 0$ (means that the surface is original)

$$ICT = K_{cit}\ MAX\ [a_0, (CDS)\ (CCT)] \qquad 3.39$$

- If $HSOLD > 0$ (means that the surface is overlaid)

$$ICT = K_{cit}\ MAX\ [a_0, CDS\ (CCT + a_1 + a_2\ HSNEW)] \qquad 3.40$$

**b. Progression phase of Transverse Thermal Cracking**

Transverse Thermal Cracking progression phase begins when the values of $\delta t_T > 0$, so the following relation can be used to estimate the progression rate (HDM-4 V4):

If $ACT_a > 0$ $\delta t_T = 1$

In any other case $\delta t_T = MAX\ \{0, MIN\ [AGE2 – ICT), 1]\}$ 3.41

- If $HSOLD = 0$ (means that the surface is original)

$$dNCT = K_{cpt}\left[\frac{1}{CDS}\right] MAX\left\{0, MIN\left[\left(NCT_{eq} - NCT_a\right), \left(\frac{2NCT_{eq}(AGE3 - ICT - 0.5}{(T_{eq})^2}\right)\right]\right\}\delta t_T \qquad 3.42$$

- If $HSOLD > 0$ (means that the surface is overlaid)

$$dNCT = K_{cpt}\left[\frac{1}{CDS}\right] MIN\left\{\left(NCT_{eq} - NCT_a\right), MAX\left[MIn\left(a_0 PNCT, \left(PNCT - NCT_a\right)\right), (P), 0\right]\right\}\delta t_T \qquad 3.43$$

$$p = \frac{2NCT_{eq}(AGE3 - ICT - 0.5}{\left(T_{eq}\right)^2} \qquad 3.44$$

It is assumed that the Transverse Thermal Cracking is covering the carriageway full width, so to calculate the area of the cracking the following formula can be used (HDM-4 V4):

$$dACT = \frac{dNCT}{20} \qquad 3.45$$

Where:

| | |
|---|---|
| ICT (years) | Initiation time of the cracking |
| dNCT ( No / km) | incremental Change of No of Cracking ( in analysis year) |
| dACT (%) | Incremental Change in Are of cracking (according to total carriageway) |
| CCT | Thermal Cracking Coefficient |
| PNCT (No /km) | No of Cracking (before pavement overlaid) |
| $NCT_a$ (No/km) | No of reflected thermal Cracking (at the beginning of analysis year) |
| $NCT_{eq}$(No/km) | Maximum No of thermal Cracking |
| $T_{eq}$(years) | the time when the cracking from the initiation reach to maximum No |
| $K_{cit}$ | Initiation Calibration Factor |
| $K_{cpt}$ | Progression Calibration Factor |

Default values for coefficient of $a_0$ to $a_2$ for initiation and $a_3$ for progression are given in the table 24 (HDM-4 V4 Part C).

**Table 24: Default values of Transverse Thermal Cracking Coefficient (HDM-4 V4)**
**Preglednica 24: Predpostavljene vrednosti koeficientov za prečne temperaturne razpoke**

| Pavement type | Initiation | | | Progression |
|---|---|---|---|---|
| | $a_0$ | $a_1$ | $a_2$ | $a_3$ |
| All pavement types except STGB and STSB | 1.0 | -1.0 | 0.02 | 0.25 |
| STGB and STSB | 100 | -1.0 | 0.02 | 0.25 |

### 3.4.3.3 Cracking Total Areas

Alongside of the models which were introduced in last sections to predict the areas and the time of All and wide structural cracking and also the models which were introduced to predict the area and time of Transverse Thermal Cracking, some others models could be used in many cases to predict the area of cracking. These models are introduced in the following sections (HDM-4 V4).

**a. Index Cracking Area**

According to Paterson (1987) Index Cracking Area is a weighted average of All and Wide Structural Cracking, which could be estimated by the following formula (HDM-4 V4):

$ACX = 0.62\ ACA + 0.39\ ACW$

Where:

| | |
|---|---|
| *ACX (%)* | Indexed Cracking Area (according to total carriageway) |
| *ACA (%)* | All Cracking Area (according to total carriageway) |
| *ACX (%)* | Wide Cracking Area (according to total carriageway) |

**b. Cracking Total Area**

By combining of their Structural cracking and Transverse Thermal Cracking, the cracking total area could be calculated by the following formula (HDM-4 V4):

$$ACRA = ACA + ACT \qquad 3.46$$

Where:

| | |
|---|---|
| *ACRA (%)* | Total Cracking Area (according to total carriageway) |
| *ACA (%)* | All Cracking Area (according to total carriageway) |
| *ACT (%)* | Transverse Thermal Cracking Area (according to total carriageway) |

### 3.4.4 Raveling

The process of losing surface material due to insufficient adhesion between aggregate and asphalt cement or poor construction quality through weathering and traffic abrasion is called Raveling.

As the parameters such as; construction methods and quality, specifications and standards, and available material have the most impact on raveling, so this type of deterioration varies different countries. (HDM-4 V4)

#### a. Initiation phase

Construction Defects Indicator *CDS* which is introduced in section 3.3.3 is used as a variable in relations of availing modes. The initiation model of raveling is based on relations, which introduced by Paterson (1987), instead of original Construction Quality *(CQ)* he used *CDS* as a variable.

Raveling is said to begin when the *0.5 %* of the road carriageway area is raveled, the following relation expresses the raveling imitation phase (HDM-4 V4):

$$IRI = K_{vi}\ CDS^2\ a_0\ RRF\ exp\ (a_1\ YAX) \qquad 3.47$$

Where:

IRV (years) Initiation time of raveling

YAX (million/lane) No of axle in a the year of analysis

$K_{vi}$ Calibration factor

RRF factor of raveling delay due to treatment

The default values of coefficients $a_0$ and $a_1$ are given in table 25.

**Table 25: Default value of coefficients for initiation model of raveling**
**Preglednica 25: Predpostavljene vrednosti koeficientov za začetek luščenja**

| Surface type | Surface material | $a_0$ | $a_1$ |
|---|---|---|---|
| AM | All except CM | 10.0 | 0.0 |
| | CM | 8.0 | -0.156 |
| ST | All except, CAPE | 10.0 | 0.0 |
| | SL, CAPE | 12.0 | 0.0 |

#### b. Progression Phase

Progression rate of raveling deterioration is calculated by the relations and equation which are proposed by Paterson (1987) but the traffic variables are introduced by Riley (1999).

The following equations and relations are used to estimate the progression of raveling (HDM-4 V4):

$$dARV = \left[\frac{K_{vp}}{RRF}\right]\left[\frac{1}{CDS^2}\right]\left[(Z(a_0 + a_1 YAX)a_2\ \delta t_v + SRV^{a2})^{1/a2} - SRV\right]Z \qquad 3.48$$

The raveling progression is said to be started, according to two cases:

$ARV_a > 0$ or $\delta t_v > 0$

It is while:

If $ARV_a > 0$ $\delta t_v = 1$ in any other case $\delta t_v = MAX\ \{0, MIN\ [(AGE - -IRV), 1]\}$

If $ARV_s \geq 50$ $Z = -1$ in any other case $Z = 1$

$ARV_a = MAX\ \{ARV_{a,}\ 0.5\}$

$SRV = MIN\ [ARV_a, (100 - ARV_a)]$

$YAX = MIN\ [MIN\ (YAX, 1), 0.1]$

$Y = [(a_0 + a_1\ YAX)\ a_2\ Z\ \delta t_v + SRV^{a2})]$

If $Y < 0$ $dARV = \left[\frac{K_{vp}}{RRF}\right]\left[\frac{1}{CDS^2}\right][100 - ARV]$

If $Y \geq 0$ $dARV = \left[\frac{K_{vp}}{RRF}\right]\left[\frac{1}{CDS^2}\right]\left[Y^{1/a2} - SRV\right]Z$

If $ARV_a \leq 50$ and $ARV_a\ dARV > 50$

Then the relation will be

$$dARV = \left[\frac{K_{vp}}{RRF}\right]\left[\frac{1}{CDS^2}\right]\left[100 - {c_1}^{1/a2} - ARV_a\right]Z \quad 3.49$$

$$C_1 = MAX\ \{[2(50^{a2}) - SRV^{a2} - (a_0 + a_1\ YAX)\ a_2\ Z\ \delta t_v)], 0\} \quad 3.50$$

Where:

| | |
|---|---|
| dARV (%) | Raveling area change in the analysis year (according to area of carriageway) |
| $ARV_a$ (%) | Raveling area at the beginning) according to area of carriageway) |
| $\delta t_v$ | Analysis Fraction for the analysis year |
| AGE2 | Age of pavements surface from the last seal |
| $K_{vp}$ | Calibration factor |
| IRV (years) | Initiation time of raveling |

The suggested default values for coefficients $a_0$, $a_1$, and $a_2$ are given in table 26

**Table 26: Default values for coefficients of progression model of raveling (HSDM-4 V4)**
**Preglednica 26: Predpostavljene vrednosti koeficientov napredovanja luščenja**

| Pavement type | $a_0$ | $a_1$ | $a_2$ |
|---|---|---|---|
| All pavement types | 0.3 | 1.5 | 0.352 |

### 3.4.5 Potholing

In most cases potholes occurred because of in adequate drainage, with the lack of enough strength in one or more layers of the pavements and also fatigue cracking with the existence of the water.
Potholes usually developed on roads with thin *HMA* surfaces (25 to 50 mm)) and rarely occur on roads with (100 mm) or deeper *HMA* surfaces. (Roberts et al., 1996)
Cracking and raveling are the start points for the potholing defects; Construction defect indicator *CDB* for base is used as a variable in the modeling of potholes. The unite of expression of potholes is (No of pothole with the area of 0.1 m2), which for each pothole unite volume is assumed to be 10 liter, so in this case the pothole depth would be 100 mm. Progression and initiation models are modified with the relations and equations which are given in the NDLI (1995) and (Riley 1996 b). (HDM-4 V4)

**a. Initiation Phase**

Time initiation of potholing which is due to wide structural cracking and Raveling can be modeled with the following equations (HDM-4 V4).

Potholing initiation phase due to Wide Structural cracking can happen only with the following condition, and is expressed with the equation 3.51.

*ACWa > ACWpi*

Where:

| | |
|---|---|
| ACWa | Wide structural cracking (beginning of analysis year) |
| ACWpi | wide structural cracking % initiated potholes (user defined, default = 20 %) |

$$IPT_c = K_{pic} * a_0 \left[\frac{(1+a_1 HS)}{(1+a_2 CDB)(1+a_3 YAX)(1+a_4 MMP)}\right] \quad 3.51$$

Where:

| | |
|---|---|
| $IPT_c$ (year) | Time difference between wide structural cracking and potholes initiation phase, |
| HS (mm) | bituminous surface total thickness |
| MMP (mm/month) | mean monthly perception |
| $K_{pic}$ | Calibration factor |

Potholing initiation phase due to raveling can happen only with the following condition, and is expressed with the equation 3.52.

$ARV_a > ARV_{pi}$

| | |
|---|---|
| $ARV_a$ | Raveling (beginning of analysis year) |
| $ARV_{pi}$ | Raveling percentage initiated potholes (user defined, default = 30 %) |

$$IPT_r = K_{pir} * a_0 \left[\frac{(1+a_1 HS)}{(1+a_2 CDB)(1+a_3 YAX)(1+a_4 MMP)}\right] \quad 3.52$$

Where:

$IPT_r$ Time difference between raveling and potholes initiation phase
$K_{pir}$ Calibration factor

Default values of the coefficients *($a_0$ to $a_4$)* for the pothole initiation phase are given in the table below:

**Table 27: Default values of pothole initiation phase coefficients (DM-4 V4)**
**Preglednica 27: Predpostavljene vrednosti koeficientov začetne faze nastajanja udarnih jam**

| Cause of pothole initiation | Pavement type | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ |
|---|---|---|---|---|---|---|
| Cracking | AMGB, STGB | 2.0 | 0.05 | 1.0 | 0.5 | 0.01 |
| | All except GB bases | 3.0 | 0.05 | 1.0 | 0.5 | 0.01 |
| Raveling | AMGB, STGB | 2.0 | 0.05 | 1.0 | 0.5 | 0.01 |
| | All except GB bases | 3.0 | 0.05 | 1.0 | 0.5 | 0.01 |

**b. Progression phase**

As these three distresses (*cracking, raveling, and potholes enlargement*) are the causes for the potholes, so the rate of incremental increase to the number of potholes is given with the following equation (HDM-4 V4):

$$dNPT_i = K_{pp} a_0 (ADOS_i)(PEFF_i)\left(\frac{ELANES}{2}\right)\left[\frac{(1+a_1 CDB)(1+a_2 YAX)(1+a_3 MMP)}{(1+a_4 HS)}\right] \quad 3.53$$

In the table below the bound and conditions of the pothole progression from the three distresses which are mentioned above are shown.

**Table 28: bonds of pothole progression from raveling, cracking, and pothole enlargement (HDM-4 V4)**
**Preglednica 28: Mejne vrednosti nastanka udarnih jam iz luščenja in razpok**

| Cause of Pothole Progression | Begins when | If at Start of 1st year analysis |
|---|---|---|
| Wide Cracking | AGE2 > ICW +IPT<br>$ACW_a > ACW_{pi}$ | $ACW_a = 0$ |
| Raveling | AGE2 > IRV +IPT<br>$ARV_a > ARV_{pi}$ | $ARV_a = 0$ |
| Wide Cracking | $ACW_a > ACW_{pi}$ | $0 < ACW_a \leq ACW_{pi}$ |
| Raveling | $ARV_a > ARV_{pi}$ | $0 < ARV_a \leq ARV_{pi}$ |
| Wide Cracking | immediately | $ACW_a > ACW_{pi}$ |
| Raveling | immediately | $ARV_a > ARV_{pi}$ |
| Enlargement | Start | $NPT_a$ |
| Note : if $ARV_a < ARV_{pi}$ during the analysis period, potholing still begins from raveling because the area of raveling revert to other defect areas | | |

From the following formula the annual increase in total number of the *potholes/kilometer* from the mentioned distresses can be calculated by the following formula (HDM-4 V4):

$$dNPT = \sum_{i=1}^{3} dNPT_i \qquad 3.54$$

Where:

| | |
|---|---|
| $dNPT_i$ | Addition No of Potholes/Km |
| $ADIS_i$ | Percentage of each three distress type (and the No of Existing potholes) |
| $PEFF_i$ | Patching Policy Factor |
| ELANES | Road Section Effective lane number |
| $K_{pp}$ | Calibration Factor |

Denoted *(i)* referrer to the three types of the distress in which the pothole progression begins. Default values of the coefficients *($a_0$ to $a_4$)* for the pothole progression phase are given in the table below:

**Table 29: for the Pothole Progression Default Values of the Coefficient (HDM-4 V4)**
**Preglednica 29: Predpostavljene vrednosti koeficientov širjenja udarnih jam**

| Cause of pothole progression | Pavement type | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ |
|---|---|---|---|---|---|---|
| Cracking | AMGB, STGB | 2.0 | 0.05 | 1.0 | 0.5 | 0.01 |
| | All except GB bases | 3.0 | 0.05 | 1.0 | 0.5 | 0.01 |
| Raveling | AMGB, STGB | 2.0 | 0.05 | 1.0 | 0.5 | 0.01 |
| | All except GB bases | 3.0 | 0.05 | 1.0 | 0.5 | 0.01 |
| Enlargement | AMGB, STGB | 0.07 | 1.0 | 10 | 0.005 | 0.08 |
| | All except GB bases | 0.035 | 1.0 | 10 | 0.005 | 0.08 |

- The Factor of Patching Policy

The patching factor work as a correction factor is used in modified pothole progression model. (HDM-4 V4)

$$PEFF_i = 1 - \frac{Ppt}{100}(1 - TLF_i) \qquad 3.55$$

Where:

| | |
|---|---|
| $PEFF_i$ | Patching Policy Factor |
| Ppt | % of pothole to patch ($0 < Ppt \leq 100$) |
| $TLF_i$ | pothole patching frequency effects o ($0 < TLF_i \leq 1$) |

In a case with no patching performance to the road section then the default value for the $PEFF_i$ is 1 and *TLFi* is calculated with the following equation (HDM-4 V4):

$$TLF_i = a_0 + (1 - a_0)\left(\frac{Fpat}{365}\right)^{a1} \qquad 3.56$$

Where:

Fpat (day) Pothole patching interval

The default value of coefficients $a_0$ and $a_1$ for $TLF_i$ is given in the following table:

**Table 30: Default Values for Coefficients *TLF<sub></sub>*$_i$ (HDM-4 V4)**
**Preglednica 30: Predpostavljene vrednosti koeficientov $TLF_i$**

| Cause of potholing progression | $a_0$ | $a_1$ |
|---|---|---|
| Cracking & Raveling | 0.2 | 1.5 |
| Enlargement | 0 | 1.5 |

In the table below some calculated values for $TLF_i$ are given according to the patching intervals:

**Table 31: $TLF_i$ Tabulated Values (HDM-4 V4)**
**Preglednica 31: vrednosti $TLF_i$**

| | | $TLF_i$ | |
|---|---|---|---|
| **Number of patching campaigns per year** | **Pothole patching interval** | **Cracking & Raveling** | **Enlargement** |
| 24 | 2 weeks | 0.21 | 0.01 |
| 12 | 1 months | 0.22 | 0.02 |
| 6 | 2 months | 0.25 | 0.07 |
| 4 | 3 months | 0.30 | 0.12 |
| 3 | 4 months | 0.35 | 0.19 |
| 2 | 6 months | 0.48 | 0.35 |
| 1 | 12 months | 1.00 | 1.00 |

### 3.4.6 Edge-Break

The cracks and breaks which occur at the edge of the pavement due to shear failure and attrition which are due to surface or base material loss of the pavement edge is called Edge- Break.

It is mostly happened to the road with unpaved shoulders or narrow width.

Edge break can be predicted with the following models (HDM-4 V4):

$$dVEB = K_{eb} a_0 PSH (AADT)^2 ESTEP (S)^{a1} \left[a_2 + \frac{MMP}{1000}\right] 10^{-6} \quad 3.57$$

And:

$$PSH = MAX\left\{MIN\left[MAX\left(a_3 + a_4 CW \frac{CW_{max} - CW}{a_5}\right), 1\right], 0\right\} \quad 3.58$$

Where:

dVEB ($m^3$/km) Edge Material Annual Loss
PSH Vehicle driven on Shoulder (Time Proportion)
ESTEP (mm) Pavement to shoulder, elevation difference (Default = 10 mm)
S (km/h) Traffic Speed (Average)
CW (m) Width of Carriageway

| | |
|---|---|
| $CW_{max}$ (m) | Maximum of *CW* for the edge break occurrence (Default = 7.2 m, not more than 7.5 meter) |
| $K_{eb}$ | Calibration Factor |

The default value of coefficients $a_0$ and $a_5$ for the Edge-Break is given in the following table:

**Table 32: Default values of Coefficient for Edge-Break Model (HDM-4 V4)**
**Preglednica 32: Predpostavljene vrednosti koeficientov modela za lom robov**

| Pavement type | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ |
|---|---|---|---|---|---|---|
| AMGB | 50 | -1 | 0.2 | 2.65 | -0.425 | 10 |
| AMAB, AMSB, AMAP | 25 | -1 | 0.2 | 2.65 | -0.425 | 10 |
| STGB | 75 | -1 | 0.2 | 2.65 | -0.425 | 10 |
| STAB, STSB, STAP | 50 | -1 | 0.2 | 2.65 | -0.425 | 10 |

### 3.4.7 Rut Depth

Surface deformation can be a result of the weakness in one or more layers due to Traffic movement after the road opening lateral movement of the pavements layers can lead to rutting; sometimes the width of the rut can be the sign of pavement failure.
The modeling of the rut depth is performed, when the surface distresses such as Cracking, Raveling, Potholing and Edge-braking, has been calculated at the end of the analysis year and is based on four components (HDM-4 V4):

- Initial Densification;
- Structural Deformation;
- Plastic Deformation;
- Surface Wear;

#### a. Initial Densification

This component of the rut depth is dependent to the relative compaction pavement layers (COMP which is shown in table-14), the model is as follows (HDM-4 V4):

$$RDO = K_{rid}\left[a_0(YE410^6)^{(a_1+a_2DEF)}SNP^{a_3}COMP^{a_4}\right] \qquad 3.59$$

Where:

| | |
|---|---|
| RDO (mm) | Rutting because of Initial Densification |
| YE4 (million/lase) | No of Equivalent Standard Axle in a year |
| DEF (mm) | Benkelman Beam Deflection |
| SNP | Adjusted Structural Number |
| COMP | Relative Compact (Table 12) |
| $K_{rid}$ | Calibration Factor |

Initial Densification is applied when *AGE4 = 0*, it can be apply only to the new construction, for more information see section 3.2.3.3.

The default value of initial densification coefficients $a_0$ and $a_4$ for the model is given in the following table

**Table 33: Default Values of the Coefficient of Initial Densification (HDM-4 V4)**
**Preglednica 33: Predpostavljene vrednosti koeficientov začetnega zgoščanja**

| Pavement type | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ |
|---|---|---|---|---|---|---|
| AMGB, AMAB, AMSB, STGB, STAB | 51740 | 0.09 | 0.0384 | -0.502 | -2.30 | 10 |
| AMAP, STAP | 0 | 0 | 0 | 0 | 0 | 0 |

**b. Structural Deformation**

This component of the rut depth is calculated in two cases (HDM-4 V4):

- Structural Deformation with no cracking distresses

$$\Delta RDST_{uc} = K_{rst}(a_0 SNP^{a1} YE4^{a2} COMP^{a3}) \tag{3.60}$$

- Structural Deformation with Cracking

$$\Delta RDST_{crk} = K_{rst}(a_0\ SNP^{a1}\ YE4^{a2}\ MMP^{a3} ACX_a^{a4}) \tag{3.61}$$

To find the total Structural Deformation the following conditions are

If $ACRA = 0$ then $\Delta RDST = \Delta RDST_{uc}$

If $ACRA > 0$ then $\Delta RDST = \Delta RDST_{uc} + \Delta RDST_{crk}$

Where:

| | |
|---|---|
| ΔRDST (mm) | Structural Deformation (Total Incremental increase in analysis year) |
| $\Delta RDST_{uc}$ | Incremental rutting (with no cracks) |
| $\Delta RDST_{uc}$ | Incremental rutting (after cracks) |
| $ACX_a$(%) | Indexed Cracking Area (start of the analysis year) |
| $K_{rst}$ | Calibration Factor |

The default value of Structural deformation coefficients $a_0$ to $a_4$ for the model is given in the following table.

**Table 34: Default Values of the Coefficient of structural Deformation (HDM-4 V4)**
**Preglednica 34 Predpostavljene vrednosti koeficientov za strukturne deformacije**

| | Pavement type | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ |
|---|---|---|---|---|---|---|
| Without cracking | All pavement types | 44950 | -1.14 | 0.11 | -2.3 | |
| After cracking | All pavement types | 0.0000248 | -0.84 | 0.14 | 1.07 | 1.11 |

### c. Plastic Deformation

To have the prediction of the plastic deformation, the following model is used. This model includes *CDS* as a variable, that indicates whether the surface material prone to plastic deformation. (HDM-4 V4):

$$\Delta RDPD = K_{rpd} a_0\ CDS^{a1} YE4\ Sh^{a2} [MIN(HS, HSLIM)]^{a3} \qquad 3.62$$

Where:

ΔRDPD (mm) Plastic Deformation (incremental increase in analysis year)
Sh (million/lane) Heavy vehicle speed (in case of no heavy vehicle, V= 80 km/h)
HS (mm) bituminous surface total thickness
HSLIM thickness in which plastic flow effects (default = 100 mm)
$K_{rpd}$ Calibration Factor

The default value of Plastic deformation coefficients $a_0$ and $a_3$ for the model is given in the following table:

**Table 35: Default values for coefficients of plastic deformation mode (HDM-4 V4)**
**Preglednica 35: Predpostavljene vrednosti koeficientov za plastična deformacija**

| Surface type | $a_0$ | $a_1$ | $a_2$ | $a_3$ |
|---|---|---|---|---|
| AM | 0.3 | 3.27 | -0.78 | 0.71 |
| ST | 0.0 | 3.27 | -0.78 | 0.71 |

### d. Surface Wearing

In the environment where the vehicles are used studded tires, a model which is introduced by Djarf in 1995 is applied to find the incremental increase in rut depth, because of the usage of these kinds of tires (HDM-4 V4):

$$RDW = K_{rsw}[a_0 PASS^{a1} W^{a2} S^{a3} SALT^{a4}] \qquad 3.63$$

Where:

ΔRDW (mm) Ruth depth (Incremental Increase in analysis year)
PASS (1000s) No of studded tires vehicle pass in a year
S (km/h) Average speed of Traffic
SALT Salted and unsalted variable (Slated = 2 , Unsalted = 1)

W (mm) Road Width
$K_{rsw}$ Calibration Factor

The default values of Surface wearing model coefficients $a_0$ to $a_4$ are given in the following table.

**Table 36: Default Values for the coefficients of Surface Wearing model (HDM-4 V4)**
**Preglednica 36: Predpostavljene vrednosti koeficientov modela obrabe površine**

| Pavement type | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ |
|---|---|---|---|---|---|
| All pavement types | 0.0000248 | 1.0 | -0.46 | 1.22 | 0.32 |

### e. Total Rut Depth

Total Rut depth can be calculated in according to the given times, and each model could be calculated according to these times, the incremental increase in total Rut depth are calculated with the following models (HDM-4 V4):

- In the case when $AGE4 \leq 4$

$$\Delta RDM = RDO + \Delta RDPD + \Delta RDW \tag{3.64}$$

- In any other cases total Rut depth can be calculated as follows:

$$\Delta RDM = \Delta RDST + \Delta RDPD + \Delta RDW \tag{3.65}$$

Bu the total Rut depth in both wheel paths in any given time can be calculated as follows:

$$RDM_b = MIN\ [(RDM_a + \Delta RDM),\ 100] \tag{3.66}$$

Where:

ΔRDM (mm) both wheel path Total Rut Depth (Incremental Increase in analysis year)
RDO (mm) Initial Densification Rutting (in analysis year)
ΔRDST (mm) Structural Deformation (Incremental Increase in analysis year)
ΔRDPD (mm) Plastic Deformation (Incremental Increase in analysis year)
ΔRDW (mm) Studded tire wear (Incremental Increase in analysis year)
$RDM_b$ the mean of total Rut depth (end of analysis year)
$RDM_a$ the mean of total Rut depth (start of analysis year)

### f. Ruth Depth Standard Deviation

This parameter can be calculated with the following model, and is used in with the roughness model (HDM-4 V4):

$$RDS_b = RDS_a + \Delta RDS \tag{3.67}$$

And

$$\Delta RDS = K_{rds}\ max\ [a_0,\ a_1 - a_2\ (RDM_b)]\ \Delta RDM \tag{3.68}$$

Where:

| | | |
|---|---|---|
| $RDS_b$ (mm) | Standard Deviation Rut Depth | (end of analysis year) |
| $RDS_a$ (mm) | Standard Deviation Rut Depth | (start of analysis year) |
| $\Delta RDS$ (mm) | Standard Deviation Rut Depth | (Incremental Change in analysis year) |
| $K_{rds}$ | Calibration Factor | |

The default values of Rut Depth model coefficients $a_0$ to $a_2$ are given in the following table.

**Table 37: Default Values for the coefficients of Rut Depth Standard Deviation (HDM-4 V4)**
**Preglednica 37: Predpostavljene vrednosti koeficientov za globino kolesnic**

| $a_0$ | $a_1$ | $a_2$ |
|---|---|---|
| 0.2 | 0.65 | 0.03 |

Standard deviation of rut depth at the beginning of the analysis year can be calculated from the deviation of the last year as follows (HDM-4 V4):

$RDS_a = RDS_0$ or by default the model *is* $(RDS_a = 0.35RDM_0 - 0.0015RDM^2{}_0)$

Where:

$RDM_0$ Rut Depth Mean (supplied by user at the beginning of analysis year)

### 3.4.8 Roughness

The model which is used to predict the roughness consists of the following distress and component, and the sum of these components modeled the total incremental roughness of the pavement:

- Structural
- Cracking
- Rutting
- Potholing
- Environment

The following sections describe all these components according to *HDM-4 Manual Volume 4.*

**a. Structural**

The following relations and equations are used to calculate the incremental changes in roughness due to structural deterioration during the analysis year (HDM-4 V4):

$$\Delta RI_s = K_{gs}\, a_0 \exp\,(m\, K_{gm}\, AGE3)\,(1+SNPK_b)^{-5}\, YE4 \quad 3.69$$

$$SNPK_b = MAX\,[(SNP_a - dsnok),\, 1.5] \quad 3.70$$

$$dSNPK = K_{snpk}\, a_0\, \{MIN(a_1, ACX_a)\, HSNEW + MAX\,[MIN\,(ACX_a - PACX,\, a_2),\, 0]\, HSOLD\} \quad 3.71$$

Where:

| | |
|---|---|
| $\Delta RI_s$ (IRI m/km) | Roughness Incremental Change (due to structural deterioration) |
| dSNPK | Reduction of SNP ( due to cracking) |
| $SNPK_b$ | SNP due to cracking (end of analysis year) |
| $SNP_a$ | SNP (start of the analysis year) |
| $ACX_a$ (%) | Index Cracking Area (start of the analysis year) |
| PACX (%) | Index Cracking area in old surface |
| m | Coefficient of environment (See Table Below) |
| $K_{gs}$ | Calibration factor (structural) |
| $K_{gm}$ | Calibration factor (Environment) |
| $K_{snpk}$ | Calibration factor *(SNPK)* |

The default values of Environment coefficients (m) are given in the following table

**Table 38: Environment Coefficient (m) for Roughness Models (HDM-4 V4)**
**Preglednica 38: Okoljski koeficienti modela neravnosti**

| Moisture classification | Temperature classification | | | | |
|---|---|---|---|---|---|
| | **Tropical** | **Sub-tropical hot** | **Sub-tropical cool** | **Temperature cool** | **Temperature freeze** |
| Arid | 0.005 | 0.010 | 0.015 | 0.020 | 0.030 |
| Semi-arid | 0.10 | 0.015 | 0.020 | 0.030 | 0.040 |
| Sub-humid | 0.020 | 0.025 | 0.030 | 0.040 | 0.050 |
| Humid | 0.025 | 0.030 | 0.040 | 0.050 | 0.060 |
| Per-humid | 0.030 | 0.040 | 0.050 | | |

**b. Cracking**

The following formula is used to find the roughness incremental change which is caused by cracking (HDM-4 V4):

$$\Delta RI_c = K_{gc}\, a_0\, \Delta ACRA \tag{3.72}$$

Where:

| | |
|---|---|
| $\Delta RI_c$ (IRI m/km) | Roughness incremental change (caused by cracking) |
| $\Delta ACRA$ (%) | Incremental change to the area of total cracking |
| $K_{gc}$ | Calibration Factor |

### c. Rutting

The following formula is used to find the roughness incremental change which caused by rutting deterioration (HDM-4 V4):

$$\Delta RI_r = K_{gr}\, a_0\, \Delta RDS \qquad 3.73$$

Where:

| | |
|---|---|
| $\Delta RI_r$ (IRI m/km) | Roughness incremental change (caused by rutting) |
| $\Delta RDS$ (mm) | incremental change to the rutting Standard Deviation |
| $K_{gr}$ | Calibration Factor |

### d. Potholing

Effect of potholing on roughness depends on traffic volumes and freedom of vehicle to manure. The vehicle freedom to manure is expressed by $FM$, which ranges from 0 to 1. The parameters and their relations in which are included in roughhouses model are as follows (HDM-4 V4):

- FM — Freedom to manure
- $NPT_a$ (No/km) — No of potholes at the start of analysis year
- $NPT_{bu}$ (No/km) — No of unpatched potholes at the end of the analysis year

Change in roughness due to potholing is calculated by the following equations which includes the above mentioned parameters:

$$\Delta RI_p = K_{gp} a_0 (a_1 FM)\left[NPT_{bu}{}^{a2} - NPT_a{}^{a2}\right] \qquad 3.74$$

All these parameters are expressed by the following relations:

$$FM = (MAX\{MIN[0.25(CW-3),1],0\})\left\{MAX\left[\left(1-\frac{AADT}{5000}\right),0\right]\right\} \qquad 3.75$$

$$NPT_{bu} = NPT_{ayn+1} PATQ \qquad 3.76$$

$$PATQ = NPT_b * \frac{Ppt}{100} * \frac{Fpat}{365} \qquad 3.77$$

$$NPT_{ayn+1} = NPT_b * \left(1-\frac{Ppt}{100}\right) \qquad 3.78$$

So

$$NPT_{bu} = NPT_b * \left[1-\frac{Ppt}{100}\left(1-\frac{Fpat}{365}\right)\right] \qquad 3.79$$

Where:

| | |
|---|---|
| $\Delta RI_p$ | Roughness incremental change (caused by potholing) |
| $K_{gp}$ | Calibration Factor |
| CW (m) | Width of Carriageway |
| PATQ | Quantity of Patching |
| $NPT_b$ | No of unpatched and patched potholes at the end of the analysis year |
| Ppt (%) | Potholes percentages need to be patched |
| Fpat | No of day between tow patching |

### e. Environment

Parameters of environment which has effect of roughness can be calculated by the following equation, this component of roughness is included the factors such as Temperature and moisture (HDM-4 V4):

$$\Delta RI_e = m * K_{gm} RI_a \qquad 3.80$$

Where:

| | |
|---|---|
| $\Delta RI_e$ | Roughness incremental change (caused by environment) |
| $R_a$ (IRI m/km) | Roughness at the beginning of the year |
| m | Environment coefficient |
| $K_{gm}$ | Calibration factor |

### f. Roughness Total Change

According to all parameters which affect the roughness in which mentioned and introduced in above sections the following equation is used to calculate *Total Roughness Incremental Change* (HDM-4 V4):

$$\Delta RI = [\Delta RI_s + \Delta RI_c + \Delta RI_r + \Delta RI_t] + \Delta RI_e \qquad 3.81$$

And the roughness at the end of the analysis year could be calculated by (HDM-4 V4):

$$RI_b MIN[(RI_a + \Delta RI), a0] \qquad 3.82$$

And

$$RI_{av} = \frac{RZI_a + RI_b}{2} \qquad 3.83$$

Where:

| | |
|---|---|
| $RI_b$ (IRI m/km) | Roughness at the end of the year |
| $RI_a$ (IRI m/km) | Roughness at the beginning of the year |
| $RI_{av}$ | Average Roughens (the one which is used by RUE model) |
| $a_0$ | Roughness upper limit ( Default value 16 IRI m/km) assign by user |

The following table shows the roughness parameters coefficient *($a_0$, $a_1$ and $a_2$)* default values.

**Table 39: Roughness default coefficient values (HDM-4 V4)**
**Preglednica 39: Predpostavljene vrednosti koeficientov neravnosti**

| Pavement type | Roughness component | Equation | $a_0$ | $a_1$ | $a_2$ |
|---|---|---|---|---|---|
| All pavement types | Structural | 3.69 | 134 | 100 | 2 |
| | dSNPK | 3.71 | 0.0000758 | 63.0 | 40.0 |
| | Cracking | 3.72 | 0.0066 | | |
| | Rutting | 3.73 | 0.088 | | |
| | Potholing | 3.74 | 0.00019 | | |

### 3.4.9 Surface Texture of the Pavement

The last deterioration model which is included in *HDM-4* is the pavement surface texture; this parameter can be the most important variable which has a high impact on the vehicle tire. The longitudinal and lateral forces that the tire interface is affected calculated and determined by the texture of the pavement. Actually there are two kind of pavement texture (HDM-4 V4);

- Micro texture; (determines maximum skid resistance, could be afforded by dry pavement)
- Macro texture; (determine the pavement drainage ability)

As the most accidents occurred while the pavement is wet, so changes in macro texture is so important for traffic safety. (HDM-4 V4)

#### 3.4.9.1 Texture Depth

The following model, which is used to calculate the incremental change of the macro texture, is introduced by Cenek and Griffith-Jones (1997). (HDM-4 V4)

$$\Delta TD = K_{td}\left\{ITD - TD_a - a_0 ITD \log_{10}\left(10^{\left[{ITD-TD_a}/{(a_0 ITD)}\right]} + \Delta NELV\right)\right\} \quad 3.84$$

Where:

| | |
|---|---|
| ΔTD (mm) | Texture Depth Incremental Change |
| ITD (mm) | Initial texture Depth |
| $TD_a$ (mm) | Depth of Texture at the start of the year |
| ΔNELV | No of light vehicle (1 heavy vehicle = 10 NELV) |
| $K_{td}$ | Calibration factor for texture depth |

The following table 40 includes the default values for coefficient $a_0$ and *ITD.*

To find the depth of the texture at the end of an analysis year and the average texture depth the following equations can be used (HDM-4 V4):

$$TD_b = MAX\ [(TD_a + \Delta TD),\ 0.1] \quad 3.85$$

$$TD_{av} = (TD_a + TD_b)/2 \quad 3.85$$

Where

$TD_b$ (mm) Depth of the Texture (End of the Year)
$TD_a$ (mm) Depth of the Texture (beginning of the year)
$\Delta TD$ (mm) Depth of the Texture (during the year)
$TD_{av}$ (mm) Average Texture Depth (Used in RUE Model)

**Table 40: Deafault Values for Texture depth coeffiecient and ITB Values (HDM-4 V4)**
**Preglednica 40: Predpostavljene vrednosti koeficientov globine teksture**

| Surface type | Surface material | Parameter | |
|---|---|---|---|
| | | ITD | $a_0$ |
| AM | AC | 0.7 | 0.5 |
| | HRA | 0.7 | 0.5 |
| | PMA | 0.7 | 0.5 |
| | RAC | 0.7 | 0.5 |
| | CM | 0.7 | 0.5 |
| | SMA | 0.7 | 0.5 |
| | PA | 1.5 | 0.08 |
| ST | SBSD | 2.5 | 1.20 |
| | DBSD | 2.5 | 1.20 |
| | CAPE | 0.7 | 0.006 |
| | SL | 0.7 | 0.006 |
| | PM | 1.5 | 0.008 |

### 3.4.9.2 Skid Resistance

Skid Resistance is modeled by the following relations. Micro texture is the parameter which has the highest effect on Skidding and the polishing degree of the surface material of the pavement (HDM-4 V4):

$$\Delta SFC_{50} = K_{sfc} a_0 MAX[0, \Delta QCV] \qquad 3.86$$

While the skid resistance in which calculated at 50Km/h at the end of the desired analysis year, is calculated by equations 3.87, by having this parameter the average Skid Resistance can be calculated by equation 3.88, which can be used to find the annual skid resistance values for a desired year in Equation 3.89 (HDM4 V4):

$$SFC_{50b} = MAX[(SFC_{50a} + \Delta SFC_{50}), 0.35] \qquad 3.87$$

$$SFC_{50av} = (SFC_{50a} + SFC_{50b})/2 \qquad 3.88$$

$$SFCs = K_{sfcs}\left[\frac{SFC_{50av}\{400 - [2 - MIN(TD_{av}, 2)][MAX(50, S) - 50]\}}{400}\right] \qquad 3.89$$

Where:

| | |
|---|---|
| $\Delta SFC_{50}$ | Incremental Change of the coefficient of side force (during the year) |
| $\Delta QCV$ *(veh/lane/day)* | Incremental Increase in a year to the commercial vehicle flow |
| $K_{sfc}$ | Calibration Factor |
| $SFC_{50b}$ | Coefficient of side force (End of the year) |
| $SFC_{50a}$ | Coefficient of side force (beginning of the year) |
| $SFC_{50av}$ | Average of the coefficient of side force in year |
| SFCs | Coefficient of the Sideway Force (in average Speed of Traffic) |
| $K_{sfcs}$ | Calibration Factor (with sped effect) |

Note: all denoted 50 which are mentioned in the above parameters are referenced to 50 Km/h of the vehicle Traffic Speed.

Default values of coefficient $a_0$ of Skid Resistance models relations are in traduced in table 41.

**Table 41: Default Value of Coefficient $a_0$ for the relations of Skid Resistance model (HDM-4 V4)**
**Preglednica 41: Predpostavljene vrednosti koeficientov torne sposobnosti**

| Surface type | Surface material | Coefficient $a_0$ |
|---|---|---|
| AM | AC | $-0.663x10^4$ |
| | HRA | $-0.663x10^4$ |
| | PMA | $-0.663x10^4$ |
| | RAC | $-0.663x10^4$ |
| | CM | $-0.663x10^4$ |
| | SMA | $-0.663x10^4$ |
| | PA | $-0.663x10^4$ |
| ST | SBSD | $-0.663x10^4$ |
| | DBSD | $-0.663x10^4$ |
| | CAPE | $-0.663x10^4$ |
| | SL | $-0.663x10^4$ |
| | PM | $-0.663x10^4$ |

# 4 Data

## 4.1 Introduction

This chapter will going through two parts;

- *HDM* Model Data Requirement;
- Input Data;

The first one will discuss about the data which are needed to run a model by *HDM* application according to the project purpose and also in this part classification of Information Quality Level *(IQL),* characteristics of Traffic, Pavement Structure and Environment Data will be discussed.

The second part will describe the sections which are used as case study for this research and the related data which are collected or assumed to run the model in *HDM-4*.

## 4.2 HDM Model Data Requirement

To run a *HDM* model the basic items are input data that consist of the parameters which describe the pavement and network physical characteristics, Traffic data, road user data, unit cost and economic data. The needed accuracy of data depends on the objective of the analysis. It means that if one is going to do a very approximate analysis, there is no need to have very high degree of accuracy, in other hand if one is going to do a detail analysis, it is essential to use data with high level of Information quality (HDM-4 V5).

This accuracy of data have a fundamental impact on the future intervention timing, in some cases it is more important than the rate of deterioration. This comes from the incremental models which are used in *HDM* and the start point of the modeling which is the original condition. This impact is can be clearly seen in the following figure (HDM-4 V5).

*HDM* model has the ability to work with very simple or very detailed information; this is upon the purpose and the objective of the analysis. *HDM* defines an Information Quality Levels (*IQL*) in which all input data could be classified.

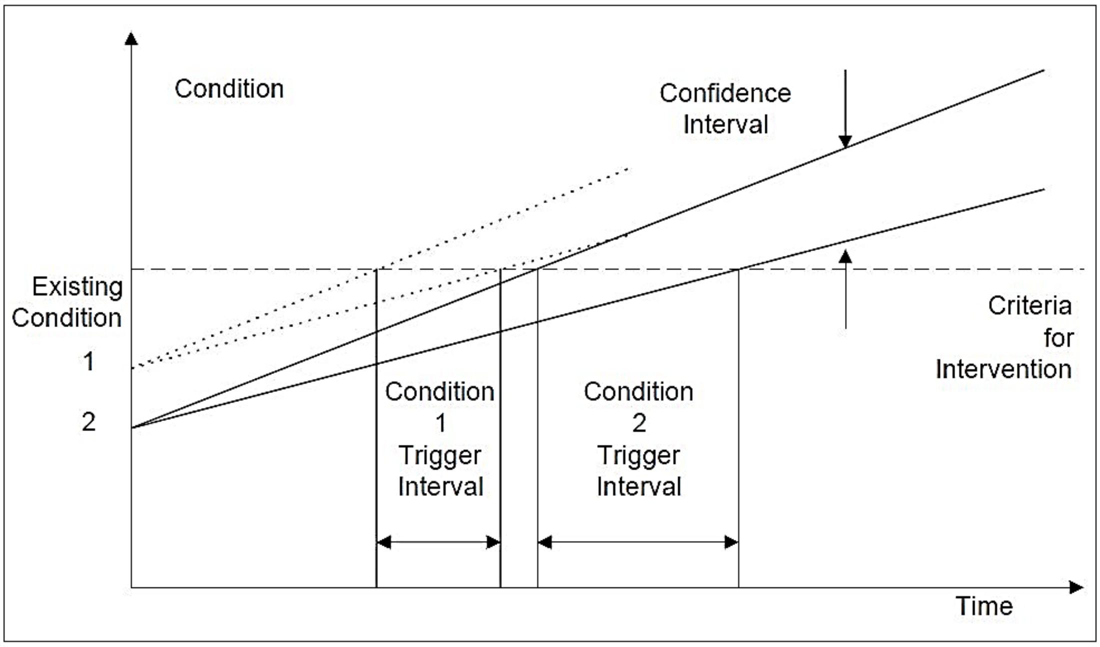


**Figure 10: Effect of existing condition on triggering maintenance (HDM-4 V5)**
**Slika 10: Učinek sedanjega stanja na začetek vzdrževanja**

### 4.2.1 Concept of Information Quality Level (IQL)

Paterson and scullion (1990) defined the concept of Information Quality Level (*IQL*), in which to make the structure of the road management information in a way that can be needed for different levels of making decision. This will give us the skill of collecting and processing the required data by their needs, as shown in the following figure. (HDM-4 V5)

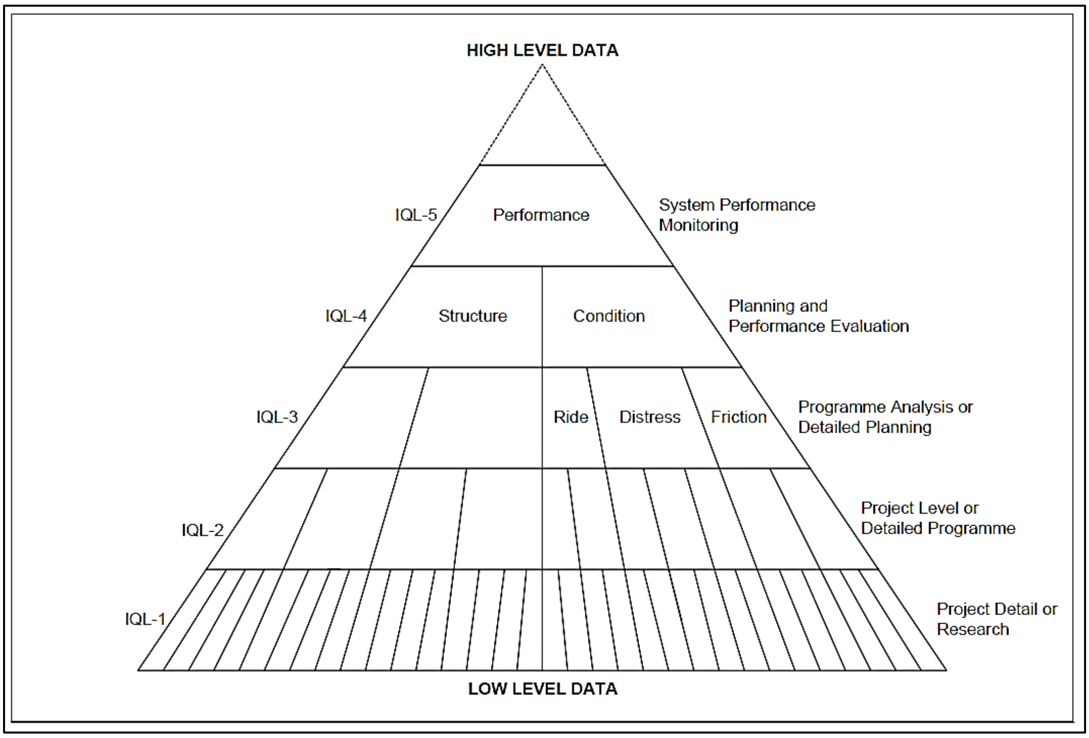


**Figure 11: Information Quality Level Concept (HDM-4 V5)**
**Slika 11: Koncept nivojev kvalitete informacij**

Five level of Information Quality which already described in fig-11 are classified in more detail in the following table.

**Table 42: Classification of Information Quality Level and Detail (HDM-4 V5, Paterson and Scullion (1990))**
**Preglednica 42: Klasifikacija na nivoje kvalitete podatkov**

| Level | Amount of Detail |
|---|---|
| I | Most comprehensive level of detail, such as would be used as a reference benchmark for other measurement methods and in fundamental research. Would also be used in detailed field investigations for an in-depth diagnosis of problems, and for high-class project design. Normally used at project-level in special cases, and unlikely to be used for network monitoring. Requires high level of staff skills and institutional resources to support and utilise collection methods. |
| II | A level of detail sufficient for comprehensive programming models and for standard design methods. For planning, would be used only on a sample coverage. Sufficient to distinguish the performance and economic returns of different technical options with practical differences in dimensions or materials. Standard acquisition methods for project-level data collection. Would usually require automated acquisition methods for network surveys and be used for network-level programming. Requires reliable institutional support and resources. |
| III | Sufficient detail for planning models and standard programming models for full network coverage. For project design, would suit elementary methods such as catalog-type with meager data needs, and low-volume road/bridge design methods. Able to be collected in network surveys by semi-automated methods or combined automated and manual methods. |
| IV | The basic summary statistics of inventory, performance and utilisation, of interest to providers and users. Suitable for the simplest planning and programming models, but for projects is suitable only for standardised designs of very low-volume roads. The simplest, most basic collection methods, either entirely manual or entirely semi-automated, provide direct but approximate measures, and suit small or resource-poor agencies. Alternatively, the statistics may be computed from more detailed data. |

In the manual of *HDM-4 volume 5* all these information quality are classified and there usage purpose are described as follows:

- IQL-1

Represent the fundamental type of data as follows:

- ❖ Research
- ❖ Laboratory
- ❖ Theoretical
- ❖ Electronic

In this case pavement condition is described by many attributes, twenty or more.

- IQL-2

This level of detail is typical in a project level decision for Engineering Analysis; here the attributes will reduce to 6-10, one or two for each distresses mode.

- IQL-3

As this level is simpler than *IQL-1* and *IQL-2,* so this is appropriate for network level survey. In this level attributes will reduced to 2-3, which are roughness, surface distress, and texture or skid resistance.

- IQL-4

This is the summery or key attribute, that is suitable to use in planning and performance evaluation, senior management reports, or alternatively with a low effort of the data collection. This one will reduce to on attribute like pavement condition, that can be calculated in values such as (good, fair, poor), or by other measurement method (i.e. 0 – 10).

- IQL-5

Represent the top level such as; system performances monitoring, that typically may combine key attributes of pavement quality with the other measurements, like structural adequacy and traffic congestion.

### 4.2.2 Relation of the local IQL to HDM model

*HDM-III* and *HDM-4* primarily use *IQL-2* for their internal operation, as this is a fairly detailed level, so it is required by the demands in which the model could be as universally as possible. This can be done only by adopting the mechanistically, fundamental and structured empirical formulation, that can operate closely to the primary principle as much as possible in practice (HDM-4 V5).

To use the local data in *HDM*, it should be adapted by transformation of data to data that can be accepted by *HDM* software, but after outputs are achieved, they can be transformed to the user desired format. The first step is the transformation of the *IQL* local data to *IQL-2* which for the software input, and the output can be transformed from *IQL-2* to the user desired form, like *IQL-3* or *IQL-4*.

### 4.2.3 Transforming Road Infrastructure Input data

The main input data to run a road infrastructure *HDM* model is classified in four groups (HDM-4 V5):

- Road Geometry;
- Pavement Condition;
- Pavement Structure;
- Environment;

These input data are described in four level of Information Quality *(IQL)* as follows:

- IQL-2; all input data in this level can directly entered into *HDM-III* and *HDM-4*
- IQL-2B; this level is special used for *HDM-4*
- IQL-3; is used for the key attributes for the each data group
- IQL-4; this is the information for a group-level

#### 4.2.3.1 Road Geometry

Four primary parameters which are requires in *HDM-4* models are (HDM-4 V5):

- Rise;
- Fall;
- Horizontal Curvature;
- Speed;

*IQL-2* would be calculated from continues measurements, but for *IQL-2B* simpler methods that are suitable to visual means are available. *IQL-3* which is a more approximation data information classify as follows:

Vertical Alignment; (Flat, Rolling, Moderate and Steep)

Horizontal Alignment; (Straight, Fairly Straight, Curvy and Winding)

At *IQL-4* these combines would be classified in to 6 to 8 combinations.

#### 4.2.3.2 Pavement Condition

All 12 inputs data for pavement conditions would be classified in three *IQL* levels as follows (HDM-4 V5):

IQl-2; for this information level, data can be classified and approximated in six indices in which can be estimated by score or classes such as: (*Roughness, Cracking, Deformation, Disintegration, Texture and Friction).*

IQL-3; this can be simplifies to three indices which all can be measured by trended observer or in case might be collected from a more detailed measurements such as : *(Riding quality class, Surface distress index and Friction class).*

IQl-4; to indicate the pavement performance, these can be combined as a rating in which can be classified in two ways; Class values such as *(Good, Fair and Poor)* or indexes such as *(Pavement Quality Index).*

#### 4.2.3.3 Pavement Structure

For these inputs several parameters are specified in *HDM-4* for example (HDM-4 V5):

IQL-2; 15 parameters for Bituminous, 3 parameters for Concrete and 14 parameters for unpaved roads

IQL-2B; 8 parameters for Bituminous, 2 parameters for Concrete and 9 for unpaved roads

IQL-3; 3 parameters such as *(Structural adequacy, Construction quality and previous intervention)* for bituminous, one parameters such as (Structural adequacy) for Concrete and 3 parameters such *as (Gravel standard, earth possibility and load rating)* for unpaved roads

IQL-4; the pavement performance indicators in this level of information can be reduced to one for bituminous and Concrete and one for unpaved roads.

#### 4.2.3.4 Environment

For the *IQL-2*, 13 input parameters for different pavement types are specified, that indicate the aspects of environment. In other hand all these parameters can be estimated approximately in *IQL-2B* and classified as follows (HDM-4 V5):

- Rainfall;
- Climate;
- Cold Climate;

While all the parameters for *IQL-3* and *IQL-4* can be reduced in one climate classification that has several classes.

Recommended classes and grouping of transforming for road infrastructure input data which related to different information levels are shown in table 60 in *Appendix A*.

### 4.2.4 Transforming of Traffic Input data

The main Traffic input data to run a road *HDM* model is classified in four groups (HDM-4 V5):

- Traffic Volume;
- Traffic Growth;
- Traffic Safety;
- Vehicle Emission;

#### 4.2.4.1 Traffic Volume

In *HDM-4 Volume 5 AADT* volumes are classified in four information quality level *IQL* as follows (HDM-4 V5):

IQL-2; In this level traffic daily volume for all vehicle classes with full information which is adopted in Classification of Fleet are included.

IQL-2B; These inputs can be approximation by applying perhaps estimation or percentage for different classes of *AADT*.

IQL-3; In this level only two parameters would be included such as *AADT* volume and the heavy vehicle percentage.

IQL-4; *AADT* Traffic Volume could be grouped by classes, in which it is preferred by factor of 3 such as *(30, 100, 300, 1000, 3000, 10000, 30000, etc.)*.

#### 4.2.4.2 Traffic Flow

In HDM-4 Manual traffic volume information quality level are classified as follows (HDM-4 V5):

IQL-2; In this level 14 to 20 calculated parameters, which is depending on fineness of the chosen flow-band.

IQL-2B; These inputs can be reduced to 7 parameters which could be estimated

IQL-3; Only two parameters are included here (Ratio of Volume Capacity and Class of Flow-type)

IQL-4; In this level measurement such as Classification of Congestion or performance indicators like delay of Vehicle-Hours per day.

#### 4.2.4.3 Traffic Safety

This information is not included in *HDM-4* Volumes yet

#### 4.2.4.4 Vehicle Emissions

This information is not included in *HDM-4* Volumes yet.

In the table 61 in *Appendix A* the above information classes for Traffic inputs are combined.

## 4.3 Input Data

In this part of the research input data which are collected to run the *HDM-4* model are described.

Because *HDM-4* predicts future road performance from current and/or historical conditions, the reliability of its results depends upon how well input data represent actual conditions and how well *HDM-4* predictions model actual behavior (Kerali, 2000a).

In this case to run a more complete and realistic model, it is decided to use 3 real sections from Kabul-Kandahar Highway which is a part of the Afghanistan Ring Road. Although to run the *HDM-4* model there also need to assume some input parameters.

### 4.3.1 Assumption

As the aim of this research is to find the most sensitive parameters of *HDM-4* pavement deterioration models, so the sensitivity of desired parameters (mentioned in section 1.2) is analyzed for two traffic loading situations; High Traffic Volume and Low Traffic Volume, which are assumed for all the sections. The following table shows these two types of the traffic volumes:

**Table 43: Low and High Traffic Volumes**
**Preglednica 43: Nizke in visoke prometne obremenitve**

| Traffic Volumes | | |
|---|---|---|
| **Name of Vehicle** | **Low Traffic** | **High Traffic** |
| 3 wheeler | 25 | 1500 |
| Bus | 50.00 | 1000.00 |
| Car | 400.00 | 6000.00 |
| Heavy Truck | 40.00 | 1000.00 |
| Jeep | 100.00 | 2000.00 |
| Light Truck | 60.00 | 1000.00 |
| M/cycle | 200.00 | 3000.00 |
| Medium Truck | 80.00 | 2000.00 |
| Minibus | 45.00 | 2000.00 |
| Tractor | 0.00 | 300.00 |
| Truck/trailer | 0.00 | 200.00 |
| **Total AADT:** | **1000** | **20000** |

### 4.3.2 Sections

Sections which are chosen as examples for this study are from **Kabul-Kandahar** Highway which is a part of the Afghanistan Ring Road. This highway was completed in 5 sections, all the required data regarding the chosen sections are collected from one of the *ADB* Consultant and Ministry of Public Work of Islamic Republic of Afghanistan as it is shown in the following tables:

**Note**: *MPW (Ministry of Public Work), ADB (Asian Development Bank)*

**Table 44: Kabul-Kandahar Sections**
**Preglednica 44: Odseki ceste Kabul-Kandahar**

| Road ID (MPW & ADB) | Road Name | Start | End | Sections | Section Length (Km) | Total Length (km) |
|---|---|---|---|---|---|---|
| RH01 | Kabul-Kandahar HW | Kabul | Kandahar | Section F | 77.17 | 425.1 |
| | | | | Section D | 90.79 | |
| | | | | Section B | 49.14 | |
| | | | | Section E | 87.08 | |
| | | | | Section C | 85.01 | |
| | | | | Kabul to Dowrany | 35.87 | |

The rehabilitation of this highway is completed between the years of 2004 to 2006 by the help of USAID with the supervision of the Ministry of Public Work of Islamic Republic of Afghanistan.

As only data for the highlighted three sections of this highway was available, so only these sections are chosen for the analysis.

These sections are in maintenance phase by the Asian Development Bank (ADB), and supervision of Ministry of Public Work of Islamic Republic of Afghanistan. The following information is collected from the project which is already done by the *ADB.*

#### a. Geometry

**Table 45: Road Section Geometry**
**Preglednica 45 Geometrija odsekov**

| Road Section - Geometry | | | |
|---|---|---|---|
| **Section ID** | **KKF** | **2** | **3** |
| Section Name | **Kabul-Kandahar Section F** | **Kabul-Kandahar Section C** | **Kabul-Kandahar Section B** |
| Length ( Km) | 77.7 | 85.01 | 49.14 |
| Carraigeway width (m) | 7 | 7 | 7 |
| No. of Rise & Falls ( /km) | 2 | 5 | 4 |
| Superelevation (%) | 6 | 2 | 3 |
| Rise and Falls ( m/km) | 11 | 20 | 12 |
| Horizontal curvature (° /km) | 23 | 10 | 14 |
| Altitude (m) | 1470 | 2200 | 2180 |
| Sigma adral (m/s) | 0.2 | 0.2 | 0.2 |
| Speed Limit ( Km/h) | 100 | 100 | 100 |
| Speed Enforcement Facor | 1.2 | 1.2 | 1.2 |
| Drain Type | V-Shaped soft | V-Shaped soft | V-Shaped soft |
| NMT Friction (XNMT) | 0.9 | 0.9 | 0.9 |
| Side Friction (XFRI) | 0.8 | 0.8 | 0.8 |
| MT Friction (XMT) | 1 | 1 | 1 |

### b. Road Condition

**Table 46: Road Section Condition**
**Preglednica 46 Stanje odsekov**

| Road Section - Condition | | | |
|---|---|---|---|
| **Section ID** | **KK - F** | **KK- C2** | **KK - B2** |
| Section Name | **Kabul-Kandahar Section F** | **Kabul-Kandahar Section C** | **Kabul-Kandahar Section B** |
| Condition year | 2010 | 2010 | 2010 |
| Roughness IRI (m/km) | 3.00 | 2.20 | 2.10 |
| All Structural Cracking Area (%) ACA | 10.00 | 10.00 | 5.00 |
| Wide Structural Cracking Area (%) ACW | 5.00 | 5.00 | 2.00 |
| Thermal Cracking Area (%) ACT | 2.00 | 2.00 | 2.00 |
| Ravellded Area (%) ARV | 0.00 | 0.00 | 0.00 |
| POTholes ( No./Km) NPT | 0.00 | 0.00 | 0.00 |
| Eadge Break (m./km) AEB | 0.00 | 0.00 | 0.00 |
| Rut Depth (mm) RDM | 25.00 | 0.00 | 0.00 |
| Texture Depth (mm) TD | 1.00 | 0.00 | 0.00 |
| Skid Resistance (SCRIM) SFC50 | 0.00 | 0.00 | 0.00 |
| Drainage Condition | Good | Good | Good |

### c. Section Pavement

**Table 47: Road Section Pavement**
**Preglednica 47: Vozišča konstrukcija**

| Road Section - Pavement | | | |
|---|---|---|---|
| **Section ID** | **KK - F** | **KK- C2** | **KK - B2** |
| Section Name | **Kabul-Kandahar Section F** | **Kabul-Kandahar Section C** | **Kabul-Kandahar Section B** |
| Pavement Type | AMGB | AMGB | AMGB |
| Average Structural Number SNP | 5.7 | 5.7 | 5.7 |
| Current Surface Thickness (mm) | 250 | 250 | 250 |
| Previous Surface Thickness (mm) | 0 | 0.00 | 0.00 |
| Last Construction Year | 2005 | 2005.00 | 2004.00 |
| Last Rehabilitation Year | 2005 | 2005.00 | 2004.00 |
| Last Surface Year | 2005 | 2005.00 | 2004.00 |
| Last Prevent Year | 2008 | 2008.00 | 2008.00 |
| Base Thicknesss (mm) | 100 | 100.00 | 100.00 |

### d. Temperature

Climate zone data for Afghanistan, Kabul-Kandahar Ring road are taken from the website which is mentioned bellow, as the information for the exact location of the chosen road sections are not included in the website, the chosen data may be a little bit different than the infield situation, but these data are the nearest ones.

http://www.kandahar.climatemps.com/

# 5 Sensitivity analysis of HDM Deterioration Models

## 5.1 Introduction

The purpose of sensitivity analysis is to find out the most important individual input parameters to pavement deterioration models. This will help the users to be aware of the most sensitive parameters, and then the emphasis can be put on collection of them.

Sensitivity of the individual parameters of pavement deterioration models in *HDM-4* is determined by the impact elasticity, it is in a way that when a change in an input parameter of deterioration model occur, then the impact of the change to a specific result will show the sensitivity of the input parameters to the result of the desired parameter.

Impact elasticity is the ratio of the percentage change to a specific result by the percentage change to individual input parameters of the pavement deterioration models (HDM-4 V5).

As it is mentioned in last chapter the research is focused on the sensitivity of the following input parameters to the pavement deterioration:

- Sensitivity of pavement deterioration to *SNP*
- Sensitivity of pavement deterioration to Roughness
- Sensitivity of pavement deterioration to All Structural Cracking

Pavement deterioration can be predicted by the following parameters, which in this research the sensitivity of the above mentioned individual inputs to these parameters are studied:

- Adjusted Structural Number *(SNP);*
- Pavement Roughness;
- All Structural Cracking;
- Wide Structural Cracking;
- Transvers Thermal Cracking;
- Raveled Area;
- No of Pothole;
- Edge Break;
- Mean Rut Depth;
- Rut depth Standard Deviation;
- Texture Depth;
- Skid Resistance;

## 5.2 Methodology

To find the sensitivity of parameters two methods are used in sensitivity analysis:

- Traditional Ceteris Paribus *(TCP)*

In *TCP* method by changing a single input parameter while all other parameters leave to be unchanged, the impact elasticity will be calculated. But the most visible disadvantage of the usage of this method is the interaction between parameters which won’t be included in analysis process.

- Factorial Latin Hypercube *(FLH)*

In this method all the factors which individual input parameters are involved, will be considered alongside with all out factors. In this method a large number of combinations will be needed during the analysis process.

Traditional Ceteris Paribus *(TCP)* is used in this research and the purpose is to find the sensitivity of the following parameters to the pavement deterioration:

- Sensitivity of *SNP* to pavement Deterioration;
- Sensitivity of Roughness to Pavement Deterioration;
- Sensitivity of All Structural Cracking to Pavement Deterioration;

Each one of the mentioned individual inputs is studied in a separate road section, which are introduced in table 44. These sections are assigned for each one of the input parameters as follows:

- *Kabul-Kandahar Road Section F* is assigned for *SNP* Sensitivity;
- *Kabul-Kandahar Road Section B* is assigned for All Structural Cracking Sensitivity;
- *Kabul-Kandahar Road Section C* is assigned for Roughness Sensitivity;

According to impact elasticity results of the individual input values to the deterioration parameters, the sensitivities are ranked as follows:

| | |
|---|---|
| Level 1 | Impact Elasticity greater than 0.5 |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 |
| Level 4 | Impact Elasticity less than 0.05 |

Impact elasticity is the ratio of the percentage change to a specific result by the percentage change to individual input parameters of the pavement deterioration models (HDM-4 V5).

The sensitivity of the pavement condition parameters are ranked by these levels according to their impact elasticity results.

Impact elasticity of the individual input parameters are studied in two traffic situations which are introduce in section (4.3.1 Assumption) with maintenance case and without maintenance case.

The Structural Overlay @ 4.5 IRI Maintenance which is one of the *HDM-4* Software maintenance default option, is chosen for the analysis.

Structural Overlay @ 4.5 IRI Maintenance has the following work items:

- Structural Overlay @ 4.5 IRI;
- Routine Pothole Patching;
- Routine edge;
- Heavy Patching;

But to find out the exact sensitivity of individual inputs the case with no maintenance is the research desired one, and any decision can only be taken according to those results.

## 5.3 Sensitivity to Adjusted Structural Number *(SNP)*

Sensitivities of pavement deterioration parameters to the *SNP* are determined by using the Traditional Ceteris Paribus (*TCP*), in which two input values of *SNP* are iterated and then its impact elasticity to the deterioration parameters are calculated, and then ranked as the levels mentioned in *Section 3.4*.

Sensitivity of the *SNP* to the pavement deterioration parameters are studied in two case one with no maintenance case which is the research purpose to find out the sensitivity of the parameters, and the another one is with a maintenance case in which is introduced in *section 3.4.*

Section *(F)* from table 44 the *Kabul-Kandahar* Ring road is used for this sensitivity analysis.

All the *HDM-4* application results regarding the pavement deterioration is included in *appendix A* at the end of this research job for more information.

### 5.3.1 Sensitivity to *SNP* with no maintenance case

This calculation is done in two traffic situation; one is Low volume traffic and another one is High volume traffic.

These two types of traffic volumes are chosen from table 43. The following tables 48 and 49 are the results of the impact elasticity of the Adjusted Structural Number *(SNP)* to the pavement deterioration parameters according to the results which are given by the *HDM-4* Application Software.

Sensitivity to adjusted Structural Number *(SNP)* are calculated for 10 years period, it is in a way that at the end of 5 years and the end of 10 years, the results are taken and used to calculate the impact elasticity.

Table 48 shows the impact elasticity to *SNP* in low volume traffic situation with no maintenance case, and table 49 shows the impact elasticity in high volume traffic situation with no maintenance case. As it was mentioned before, the real impact elasticity can be found in a case with no maintenance, because it is the situation in which the real life of the road pavement is determined so the exact sensitivity can be determined in this situation.

a. Low Traffic Situation

As shown in table 48 the impact elasticity values for to the *SNP* are increase as the time increase, and most impacted parameter is roughness, the values increase rather than 5 years period in 10 years.

The impact elasticity shows that the change in *SNP* is only have effect on roughness and Rut Depth of the pavement, and all other road condition parameters are with no change.

In figure 12 the total surface damage over time is shown, for low traffic situation. The bold point from the figure is the line of the total surface damage, it shows that after 5 years the surfaces is almost damaged, and the values in this period is not considerable for impact elasticity to find out the sensitive parameters to *SNP*, and it is better to consider the values before the point of surface complete damage.

**Table 48: Sensitivity to *SNP* in Low Traffic with no Maintenace Case**
**Preglednica 48: Občutljivost na strukturno število (nizek promet, brez vzdrževanja**

| Low Traffic With No Maintenance | | | | | | |
|---|---|---|---|---|---|---|
| Sensitivity to **SNP** for AFTER 5 YEARS **(Section F )** | | | | | | |
| | 1st Iteration | | 2nd Iteration | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| SNP | 5.70 | 4.21 | 3.20 | 1.76 | 43.86 | |
| Roughness | 3.00 | 3.58 | 3.00 | 3.80 | 6.15 | 0.14 |
| All Structural Cracking | 10.00 | 71.00 | 10.00 | 71.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 71.00 | 5.00 | 71.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 4.00 | 25.00 | 4.00 | 25.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 25.00 | 25.70 | 25.00 | 26.30 | 2.33 | 0.05 |
| Rut depth Standard Deviation | 1.00 | 1.10 | 1.00 | 1.30 | 18.18 | 0.41 |
| Texture Depth | 1.00 | 0.68 | 1.00 | 0.68 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.50 | 0.50 | 0.50 | 0.00 | 0.00 |
| Sensitivity to **SNP** AFTER 10 YEARS **(Section F)** | | | | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| SNP | 5.70 | 3.99 | 3.20 | 1.59 | 43.86 | |
| Roughness | 3.00 | 4.00 | 3.00 | 5.15 | 28.75 | 0.66 |
| All Structural Cracking | 10.00 | 98.00 | 10.00 | 98.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 98.00 | 5.00 | 98.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 4.00 | 0.00 | 4.00 | 0.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 25.00 | 26.40 | 25.00 | 27.70 | 4.92 | 0.11 |
| Rut depth Standard Deviation | 1.00 | 1.30 | 1.00 | 1.50 | 15.38 | 0.35 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.49 | 0.50 | 0.49 | 0.00 | 0.00 |
| | | | | | | |
| Level 1 | Impact Elasticity greater than 0.5 | | | | | |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 | | | | | |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 | | | | | |
| Level 4 | Impact Elasticity less than 0.05 | | | | | |

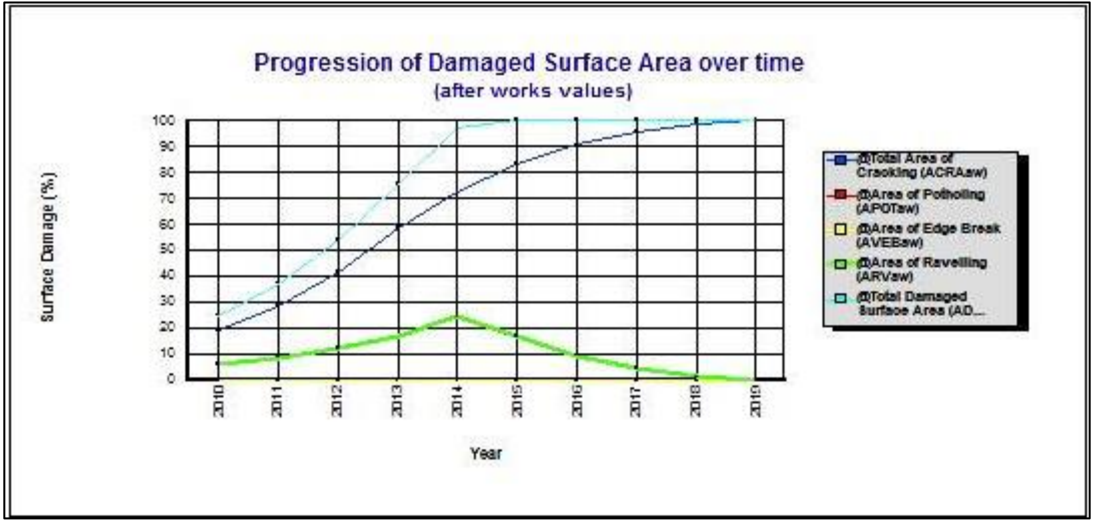


**Figure 12: Low Traffic with no Maintenace Case Surface damage over time**
**Slika 12: Spreminjanje poškodovanosti površine s časom (nizek – promet, brez vzdrževanja)**

b. High traffic Situation

Table 49 shows the sensitivity to *SNP* in high volume traffic situation as it is shown; in this situation it is in a way that the sensitivity to *SNP* is higher at the end of 10 years rather than at the end of 5 years.

The important point regarding the high traffic volume is the increase of the *SNP* values as the traffic volume increased. If make a comparison with the results from the low traffic situation, the value of the impact elasticity is higher in high traffic than in low traffic volume, but the parameters which have sensitivity to *SNP* are the same in high traffic and low traffic volume.

**Table 49: Sensitivity to SNP in High Traffic with no Maintenace Case**
**Preglednica 49: Občutljivost na strukturno število (visok promet, brez vzdrževanja)**

| High Traffic With No Maintenance | | | | | | |
|---|---|---|---|---|---|---|
| Sensitivity to **SNP** for AFTER 5 YEARS **(Section F )** | | | | | | |
| | 1st Iteration | | 2nd Iteration | | | |
| Deteriorations | **Original value** | **End Value** | **Original value** | **End Value** | **% Change** | **Impact Elastisity** |
| SNP | 5.70 | 4.21 | 3.20 | 1.76 | 43.86 | |
| Roughness | 3.00 | 3.90 | 3.00 | 9.54 | 144.62 | 3.30 |
| All Structural Cracking | 10.00 | 71.00 | 10.00 | 71.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 71.00 | 5.00 | 71.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 4.00 | 27.00 | 4.00 | 27.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 25.00 | 26.00 | 25.00 | 26.90 | 3.46 | 0.08 |
| Rut depth Standard Deviation | 1.00 | 1.20 | 1.40 | 1.40 | 16.67 | 0.38 |
| Texture Depth | 1.00 | 0.68 | 1.00 | 0.67 | 1.47 | 0.03 |
| Skid Resistance | 0.50 | 0.42 | 0.50 | 0.42 | 0.00 | 0.00 |
| Sensitivity to **SNP** AFTER 10 YEARS **(Section F)** | | | | | | |
| Deteriorations | **Original value** | **End Value** | **Original value** | **End Value** | **% Change** | **Impact Elastisity** |
| SNP | 5.70 | 3.99 | 3.20 | 1.59 | 43.86 | |
| Roughness | 3.00 | 5.29 | 3.00 | 16.00 | 202.46 | 4.62 |
| All Structural Cracking | 10.00 | 98.00 | 10.00 | 98.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 98.00 | 5.00 | 98.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 4.00 | 0.00 | 4.00 | 0.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 25.00 | 27.10 | 25.00 | 29.00 | 7.01 | 0.16 |
| Rut depth Standard Deviation | 1.00 | 1.40 | 1.00 | 1.80 | 28.57 | 0.65 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.35 | 0.50 | 0.35 | 0.00 | 0.00 |

| | |
|---|---|
| Level 1 | Impact Elasticity greater than 0.5 |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 |
| Level 4 | Impact Elasticity less than 0.05 |

Progression of damages surface area over time in high traffic volume situation is shown in figure 13, as a comparison with figure 12 regarding the low traffic volume, the damaged process is faster in high traffic situation.

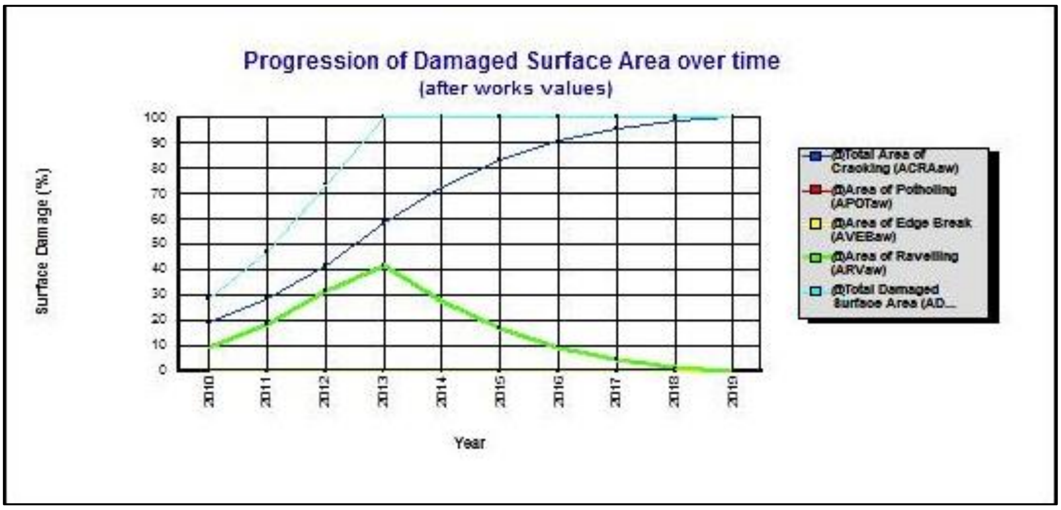


**Figure 13: High Traffic Volume with no Maintenace Case Surface damage over time**
**Slika 13 Spreminjanje poškodovanosti površine s časom (nizek – promet, brez vzdrževanja)**

From the table 48 and table 49 the Sensitivity of the pavement condition parameters to the Adjusted Structural Number *(SNP)* are observed based on the analysis with no maintenance case in low and high traffic volume situation, and they are as follows:

- Sensitivity Level one include;
  - ❖ Road Roughness,
- Sensitivity Level two include;
  - ❖ Ruth Depth Standard Deviation,
- Sensitivity Level three include;
  - ❖ Mean Ruth Depth,

### 5.3.2 Sensitivity to *SNP* with Structural Overlay @4.5 IRI

Maintenance case which is chosen is introduced in section 5.2 the methodology. This maintenance job is activated after first 5 years, as it is cleared from the result of the calculation with no maintenance; the road pavement will receive to a critical point around the year five, so this is why chosen to active the maintenance job.

Results of the maintenance road work are included in the appendix at the end of the research.

a. Low Traffic Situation

Sensitivity of the pavement condition parameters to *SNP* in low traffic with structural overlay @ 4.5 IRI maintenance as shown in table 50, It shows that there are some changes regarding the situation with no maintenance, here the sensitive level of the parameters are decreased as the road had maintenance program after the first 5 years, and there is also a little bet change to *SNP* value at the end of the 10 years period.

**Table 50: Sensitivity to *SNP* in Low Traffic wit Structural Overlay @ 4.5 IRI**
**Preglednica 35 Občutljivost na strukturno število (nizek promet, z vzdrževanjem)**

| Low Traffic With Structural Overlay @ 4.5 IRI Maintenance | | | | | | |
|---|---|---|---|---|---|---|
| Sensitivity to **SNP** for AFTER 5 YEARS **(Section F )** | | | | | | |
| | 1st Iteration | | 2nd Iteration | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| SNP | 5.70 | 4.21 | 3.20 | 1.76 | 43.86 | |
| Roughness | 3.00 | 3.58 | 3.00 | 3.80 | 6.15 | 0.14 |
| All Structural Cracking | 10.00 | 71.00 | 10.00 | 71.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 71.00 | 5.00 | 71.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 4.00 | 25.00 | 4.00 | 25.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 25.00 | 25.70 | 25.00 | 26.30 | 2.33 | 0.05 |
| Rut depth Standard Deviation | 1.00 | 1.10 | 1.00 | 1.30 | 18.18 | 0.41 |
| Texture Depth | 1.00 | 0.68 | 1.00 | 0.68 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.50 | 0.50 | 0.50 | 0.00 | 0.00 |
| Sensitivity to **SNP** AFTER 10 YEARS **(Section F)** | | | | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| SNP | 5.70 | 5.57 | 3.20 | 3.11 | 43.86 | |
| Roughness | 3.00 | 3.47 | 3.00 | 3.93 | 13.26 | 0.30 |
| All Structural Cracking | 10.00 | 10.00 | 10.00 | 10.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 4.00 | 5.00 | 4.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 4.00 | 77.00 | 4.00 | 77.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 25.00 | 26.40 | 25.00 | 27.60 | 4.55 | 0.10 |
| Rut depth Standard Deviation | 1.00 | 1.30 | 1.00 | 1.50 | 15.38 | 0.35 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.49 | 0.50 | 0.49 | 0.00 | 0.00 |
| Level 1 | Impact Elasticity greater than 0.5 | | | | | |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 | | | | | |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 | | | | | |
| Level 4 | Impact Elasticity less than 0.05 | | | | | |

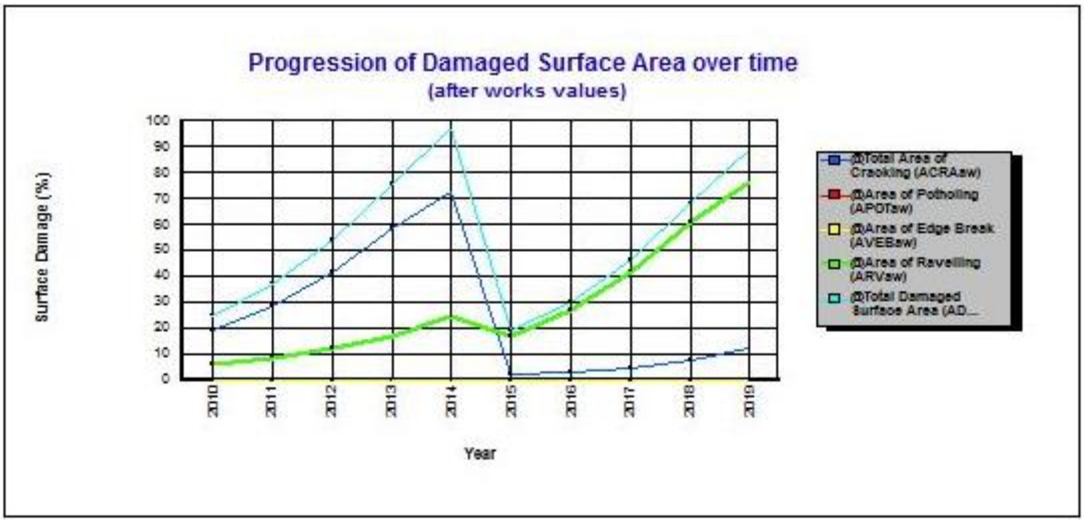


**Figure 14: Low Traffic Volume with Maintenace Case Surface damage over time**
**Slika 14: Spreminjanje poškodovanosti površine s časom (nizek – promet, z vzdrževanjem)**

In figure 14 the overall surface damaged graphs in low traffic with maintenance case is shown vs. life time of the road section.

a. High Traffic Situation

Sensitivity of the pavement condition parameters to *SNP* in High traffic volume with the maintenance is shown in table 51. In high traffic situation rather than low traffic the level of sensitivity to *SNP* is increased, it also proved the impact of Traffic volume on *SNP*.

**Table 51: Sensitivity to SNP in High Traffic wit Structural Overlay @ 4.5 IRI**
**Preglednica 51: Občutljivost na strukturno število (visok promet, z vzdrževanjem)**

| High Traffic With Structural Overlay @ 4.5 IRI Maintenance | | | | | | |
|---|---|---|---|---|---|---|
| Sensitivity to **SNP** for AFTER 5 YEARS **(Section F )** | | | | | | |
| | 1st Iteration | | 2nd Iteration | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| SNP | 5.70 | 4.21 | 3.20 | 1.76 | 43.86 | |
| Roughness | 3.00 | 3.90 | 3.00 | 9.54 | 144.62 | 3.30 |
| All Structural Cracking | 10.00 | 71.00 | 10.00 | 71.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 71.00 | 5.00 | 71.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 4.00 | 27.00 | 4.00 | 27.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 25.00 | 26.00 | 25.00 | 26.90 | 3.46 | 0.08 |
| Rut depth Standard Deviation | 1.00 | 1.20 | 1.00 | 1.40 | 16.67 | 0.38 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.42 | 0.50 | 0.42 | 0.00 | 0.00 |
| Sensitivity to **SNP** AFTER 10 YEARS **(Section F)** | | | | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| SNP | 5.70 | 5.57 | 3.20 | 3.11 | 43.86 | |
| Roughness | 3.00 | 4.17 | 3.00 | 16.00 | 283.69 | 6.47 |
| All Structural Cracking | 10.00 | 10.00 | 10.00 | 10.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 4.00 | 5.00 | 4.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 4.00 | 83.00 | 4.00 | 83.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 25.00 | 27.00 | 25.00 | 28.80 | 6.67 | 0.15 |
| Rut depth Standard Deviation | 1.00 | 1.40 | 1.00 | 1.80 | 28.57 | 0.65 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.35 | 0.50 | 0.35 | 0.00 | 0.00 |
| | | | | | | |
| Level 1 | Impact Elasticity greater than 0.5 | | | | | |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 | | | | | |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 | | | | | |
| Level 4 | Impact Elasticity less than 0.05 | | | | | |

Figure 15 show the total surface damage of the pavement in high traffic situation with the structural Overlay @4.5IRI maintenance case.

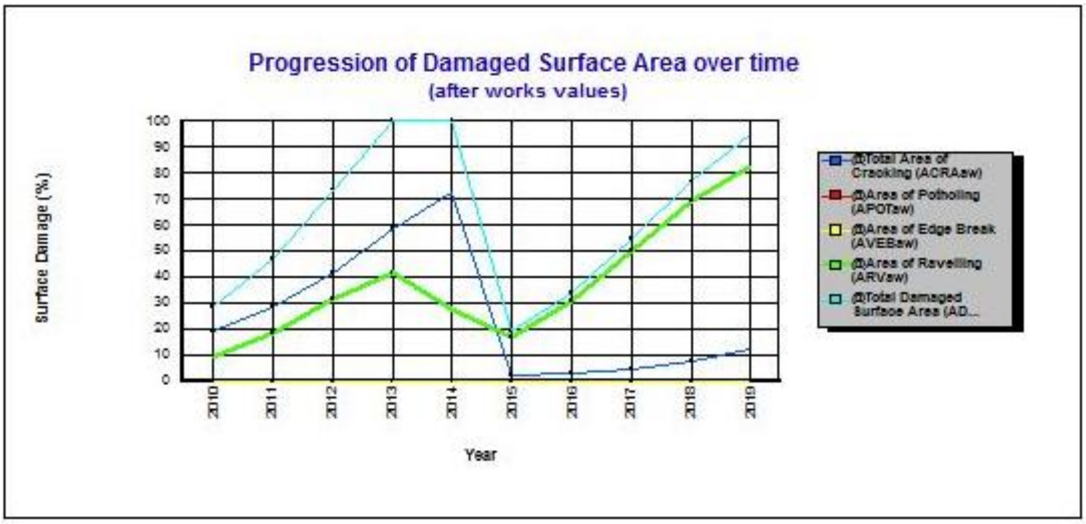


**Figure 15: High Traffic Volume with Maintenace Case Surface damage over time**
**Slika 15: Spreminjanje poškodovanosti površine s časom (visok promet, z vzdrževanjem)**

From the table 50 and table 51 the Sensitivity of the pavement condition parameters to the Adjusted Structural Number *(SNP)* which are observed based on the analysis with Structural Overlay @ 4.5IRI maintenance case in low traffic volume situation, and they are as follows:

- Sensitivity Level three include;
  - ❖ Mean Ruth Depth,
  - ❖ Road Roughness,
  - ❖ Ruth Depth Standard Deviation,

And in high traffic volume the level of the sensitivity of the parameters to *SNP* are as follows:

- Sensitivity Level one include;
  - ❖ Road Roughness,
  - ❖ Ruth Depth Standard Deviation,
- Sensitivity Level three include;
  - ❖ Mean Ruth Depth,

## 5.4 Sensitivity to Roughness

Sensitivity of the Pavement Roughness to the pavement deterioration parameters are determined by using the Traditional Ceteris Paribus *(TCP)*. In which two input values are iterated for Roughness and then their impact elasticity to the deterioration parameters are calculated. After that they are ranked as the levels mentioned in Section 5.2.

Section *(C)* from Table 44 of the *Kabul-Kandahar* Ring road is used for this Sensitivity analysis.

Here also two cases are studied, one with no maintenance, as this case will give the exact effect and impact elasticity of the individual input parameter to pavement deterioration, and another one is with a maintenance case in which is introduced in section 5.2.

All the *HDM-4* application results regarding the pavement deterioration is included in *appendix A* at the end of this research job for more information.

### 5.4.1 Sensitivity to Roughness with no maintenance case

This calculation is also done in two traffic situation; one is Low volume traffic and another one is High volume traffic.

These two types of traffic volumes are chosen from table 43. The following sections are going through sensitivity of Roughness with each traffic situations. The impact elasticity of the Roughness on deterioration parameters are calculated from the results which are given by the *HDM-4* Application Software.

a. Low Traffic Situation

Sensitivity of Roughness on pavement deterioration are calculated for 10 years period, it is in a way that at the end of first 5 years and the end of 10 years, the results are taken and used to calculate the impact elasticity.

Table 52 shows the impact elasticity of the Roughness on pavement deterioration parameters, as it is clear from the table there are no impact by the roughness to these parameters, which with any change to the roughness condition in the same traffic situation no change will happen to the results of the pavement deterioration parameters. But if the results of the roughness in low traffic compares with the results of roughness in high traffic then there will be a change in values, so it means that traffic has an impact on roughness values.

As it is described in section (3.4.8 Roughness) the following parameters has the highest impact on roughness value and the roughness model is calculated with the following parameters.

- Structural;
- Cracking;
- Rutting;
- Potholing;
- Environment;

But as it is seen by the table 52 the original condition of the roughness does not have effect on result of pavement condition, although it has an impact on fuel efficiency and user comfortable.

**Table 52: Sensitivity to Roughness in Low Traffic with no maintenance**
**Preglednica 52: Občutljivost na neravnosti (nizek promet, brez vzdrževanja)**

| Low Traffic With No Maintenance | | | | | | |
|---|---|---|---|---|---|---|
| Sensitivity to **Roughness** Section C AFTER 5 YEARS **(Section C)** | | | | | | |
| | 1st Iteration | | 2nd Iteration | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| Roughness | 2.20 | 2.71 | 4.00 | 4.60 | 81.82 | |
| SNP | 5.70 | 4.41 | 5.70 | 4.41 | 0.00 | 0.00 |
| All Structural Cracking | 7.00 | 63.00 | 7.00 | 63.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 63.00 | 5.00 | 63.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 3.00 | 21.00 | 3.00 | 21.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break Area | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 18.00 | 18.70 | 18.00 | 18.70 | 0.00 | 0.00 |
| Rut depth Standard Deviation | 1.00 | 1.10 | 1.00 | 1.10 | 0.00 | 0.00 |
| Texture Depth | 1.00 | 0.68 | 1.00 | 0.68 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.50 | 0.50 | 0.50 | 0.00 | 0.00 |
| Sensitivity to **Roughness** AFTER 10 YEARS **(Section C)** | | | | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| Roughness | 2.20 | 3.13 | 4.00 | 5.12 | 81.82 | |
| SNP | 5.70 | 3.99 | 5.70 | 3.99 | 0.00 | 0.00 |
| All Structural Cracking | 7.00 | 98.00 | 7.00 | 98.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 98.00 | 5.00 | 98.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 3.00 | 0.00 | 3.00 | 0.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break Area | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 18.00 | 19.40 | 18.00 | 19.40 | 0.00 | 0.00 |
| Rut depth Standard Deviation | 1.00 | 1.30 | 1.00 | 1.30 | 0.00 | 0.00 |
| Texture Dupth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.49 | 0.50 | 0.49 | 0.00 | 0.00 |

| | |
|---|---|
| Level 1 | Impact Elasticity greater than 0.5 |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 |
| Level 4 | Impact Elasticity less than 0.05 |

Figure 16 shows the change in roughness as vs. road life time as the pavement is going to reached to its end life the roughness will grow up and increase

.

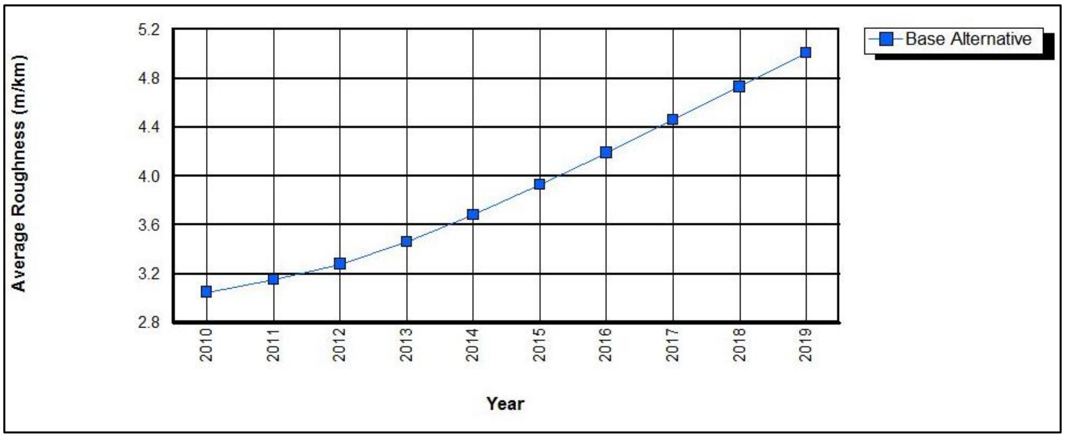


**Figure 16: Average Roughness vs. section life time**
**Slika 16: Spreminjanje neravnosti s časom (nizek promet)**

a. Hih Traffic Situation

As it is shown in table 53, the same as the low traffic with no maintenance case, roughness does not have impact on the results of the pavement conditions parameters, although it will affected by the factors which was mentioned in last section. But then the after roughness values changed it will effect on the vehicle emission usage, and the comfortable of ride.

The only thing is the change of the roughness values in low and high traffic volume, that the roughness result values are greater in high traffic volume than in low traffic.

**Table 53: Sensitivity to Roughness in High Traffic with no maintenance**
**Preglednica 53: Občutljivost na neravnost (visok promet, brez vzdrževanja)**

| High Traffic With No Maintenance | | | | | | |
|---|---|---|---|---|---|---|
| Sensitivity to **Roughness** Section C AFTER 5 YEARS **(Section C)** | | | | | | |
| | 1st Iteration | | 2nd Iteration | | | |
| Deteriorations | **Original value** | **End Value** | **Original value** | **End Value** | **% Change** | **Impact Elastisity** |
| Roughness | 2.20 | 2.98 | 4.00 | 4.88 | 81.82 | |
| SNP | 5.70 | 4.41 | 5.70 | 4.41 | 0.00 | 0.00 |
| All Structural Cracking | 7.00 | 63.00 | 7.00 | 63.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 63.00 | 5.00 | 63.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 3.00 | 35.00 | 3.00 | 35.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break Area | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 18.00 | 19.00 | 18.00 | 19.00 | 0.00 | 0.00 |
| Rut depth Standard Deviation | 1.00 | 1.20 | 1.00 | 1.20 | 0.00 | 0.00 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.42 | 0.50 | 0.42 | 0.00 | 0.00 |
| Sensitivity to **Roughness** AFTER 10 YEARS **(Section C)** | | | | | | |
| Deteriorations | **Original value** | **End Value** | **Original value** | **End Value** | **% Change** | **Impact Elastisity** |
| Roughness | 2.20 | 4.37 | 4.00 | 6.36 | 81.82 | |
| SNP | 5.70 | 3.99 | 5.70 | 3.99 | 0.00 | 0.00 |
| All Structural Cracking | 7.00 | 98.00 | 7.00 | 98.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 98.00 | 5.00 | 98.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 3.00 | 0.00 | 3.00 | 0.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break Area | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 18.00 | 20.10 | 18.00 | 20.10 | 0.00 | 0.00 |
| Rut depth Standard Deviation | 1.00 | 1.40 | 1.00 | 1.40 | 0.00 | 0.00 |
| Texture Dupth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.35 | 0.50 | 0.35 | 0.00 | 0.00 |

| | |
|---|---|
| Level 1 | Impact Elasticity greater than 0.5 |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 |
| Level 4 | Impact Elasticity less than 0.05 |

Figure 17 shows the average roughness vs. road section life time, if these values compare with the values of the figure 16, it can be seen that in high traffic volume, the roughness end values are greater.

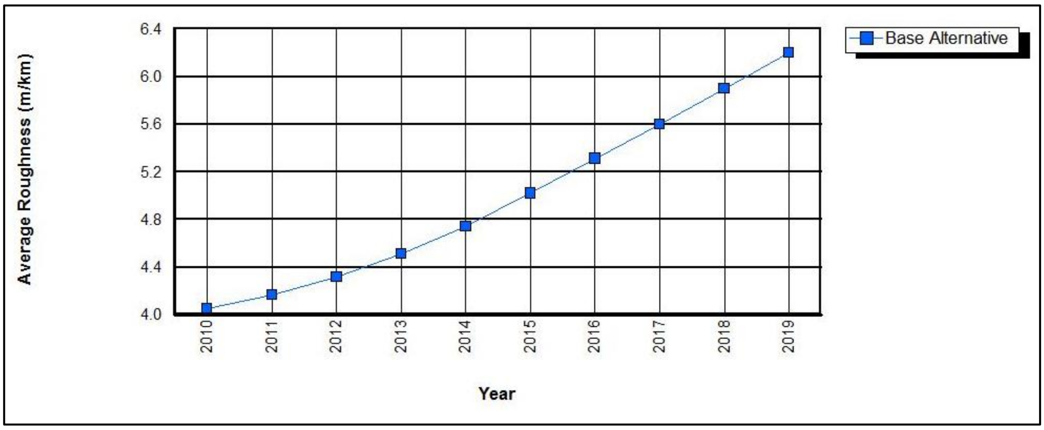


**Figure 17: Average Roughness vs. section life time with high traffic volume**
**Slika 17: Spreminjanje neravnosti s časom (visok promet)**

From the table 52 and table 53the Sensitivity of the pavement condition parameters to the Roughness are zero, it means that by any change to the roughness condition there will be no change in pavement deterioration parameters. The only change that is clear in those tables is the change in end values of roughens in two traffic values.

### 5.4.2 Sensitivity to Roughness with Structural Overlay @4.5 IRI

This maintenance case is activated after 5 years. The first 5 years has no impact elasticity in both high and low traffic volumes, but at the end of the 10 years, then it can be seen some of the pavement condition parameters are changed and there can be the impact of the roughness with maintenance on pavement condition parameters.
Results of the maintenance road work are included in the *appendixes A* at the end of the research.

a. Low Traffic Situation

Table 54 shows the impact elasticity of roughness on the pavement condition parameters with chosen maintenance case and it show that after the maintenance job is done, cracking, rutting and texture depth has the highest effected by roughness input values.

Figure 18 show the effect of the maintenance case on the roughness results vs. road life time.

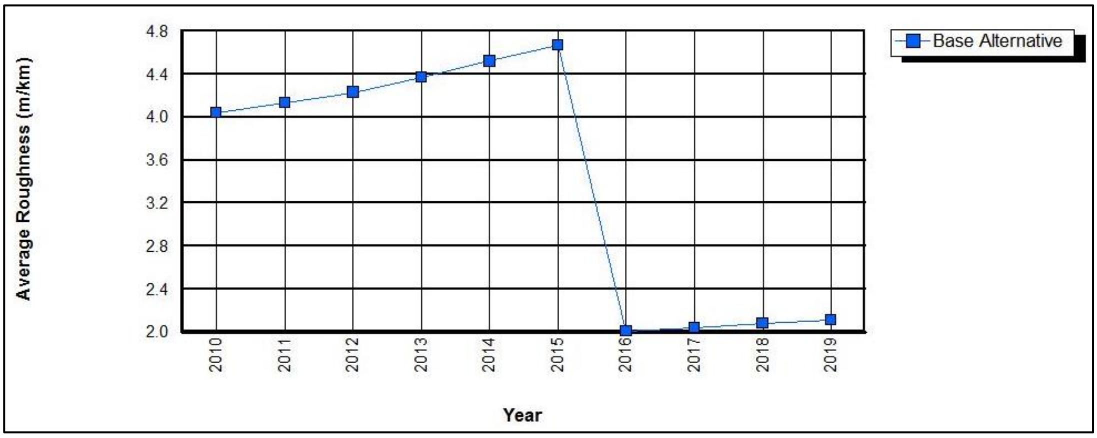


**Figure 18: Average Roughness vs. section life time with maintenance case in low traffic**
**Slika 18: Spreminjanje neravnosti s časom (nizek promet, z vzdrževanjem)**

**Table 54: Sensitivity to Roughness in Low Traffic with structural overlay @ 4.5 IRI**
**Preglednica 54: Občutljivost na neravnost (nizek promet, vzdrževanje)**

| Low Traffic With Structural Overlay @ 4.5 IRI Maintenance | | | | | | |
|---|---|---|---|---|---|---|
| Sensitivity to **Roughness** Section C AFTER 5 YEARS **(Section C)** | | | | | | |
| | 1st Iteration | | 2nd Iteration | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| Roughness | 2.20 | 2.71 | 4.00 | 4.60 | 81.82 | |
| SNP | 5.70 | 4.41 | 5.70 | 4.41 | 0.00 | 0.00 |
| All Structural Cracking | 7.00 | 63.00 | 7.00 | 63.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 63.00 | 5.00 | 63.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 3.00 | 21.00 | 3.00 | 21.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break Area | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 18.00 | 18.70 | 18.00 | 18.70 | 0.00 | 0.00 |
| Rut depth Standard Deviation | 1.00 | 1.10 | 1.00 | 1.10 | 0.00 | 0.00 |
| Texture Depth | 1.00 | 0.68 | 1.00 | 0.68 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.50 | 0.50 | 0.50 | 0.00 | 0.00 |
| Sensitivity to **Roughness** AFTER 10 YEARS **(Section C)** | | | | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| Roughness | 2.20 | 2.67 | 4.00 | 2.14 | 81.82 | |
| SNP | 5.70 | 5.57 | 5.70 | 5.41 | 2.87 | 0.04 |
| All Structural Cracking | 7.00 | 6.00 | 7.00 | 3.00 | 50.00 | 0.61 |
| Wide Structural Cracking | 5.00 | 0.00 | 5.00 | 0.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 0.00 | 100.00 | 1.22 |
| Raveled Area | 3.00 | 81.00 | 3.00 | 0.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break Area | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 18.00 | 19.40 | 18.00 | 3.10 | 84.02 | 1.03 |
| Rut depth Standard Deviation | 1.00 | 1.30 | 1.00 | 1.50 | 15.38 | 0.19 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.68 | 1.49 | 0.02 |
| Skid Resistance | 0.50 | 0.49 | 0.50 | 0.55 | 12.24 | 0.15 |

| | |
|---|---|
| Level 1 | Impact Elasticity greater than 0.5 |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 |
| Level 4 | Impact Elasticity less than 0.05 |

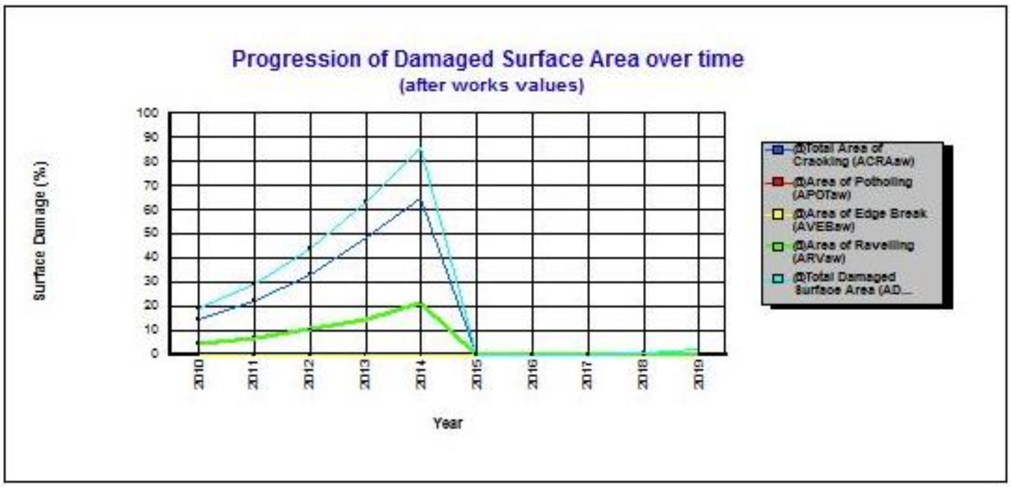


**Figure 19: Progression of Surface Damage vs. section life with maintenance case in low traffic**
**Slika 19: Spreminjanje poškodovanosti s časom (nizek promet, z vzdrževanjem)**

Figure 19 shows the progression of the surface damage during the road section life time, and the effect of the structural overlay maintenance toe pavement life.

b. High Traffic Situation

Table 55 shows the results of the impact elasticity of the roughness with maintenance case to the pavement condition parameters in high traffic volume situation.

**Table 55: Sensitivity to Roughness in High Traffic with structual overlay @ 4.5 IRI maintenance**
**Preglednica 55: Občutljivost na neravnost (visok promet, z vzdrževanjem)**

| High Traffic With Structural Overlay @ 4.5 IRI Maintenance | | | | | | |
|---|---|---|---|---|---|---|
| Sensitivity to **Roughness** Section C AFTER 5 YEARS **(Section C)** | | | | | | |
| | 1st Iteration | | 2nd Iteration | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| Roughness | 2.20 | 2.98 | 4.00 | 4.88 | 81.82 | |
| SNP | 5.70 | 4.41 | 5.70 | 4.41 | 0.00 | 0.00 |
| All Structural Cracking | 7.00 | 63.00 | 7.00 | 63.00 | 0.00 | 0.00 |
| Wide Structural Cracking | 5.00 | 63.00 | 5.00 | 63.00 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 3.00 | 35.00 | 3.00 | 35.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break Area | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 18.00 | 19.00 | 18.00 | 19.00 | 0.00 | 0.00 |
| Rut depth Standard Deviation | 1.00 | 1.20 | 1.00 | 1.20 | 0.00 | 0.00 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.42 | 0.50 | 0.42 | 0.00 | 0.00 |
| Sensitivity to **Roughness** AFTER 10 YEARS **(Section C)** | | | | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| Roughness | 2.20 | 3.25 | 4.00 | 2.36 | 81.82 | |
| SNP | 5.70 | 5.57 | 5.70 | 5.41 | 2.87 | 0.04 |
| All Structural Cracking | 7.00 | 10.00 | 7.00 | 3.00 | 70.00 | 0.86 |
| Wide Structural Cracking | 5.00 | 4.00 | 5.00 | 0.00 | 100.00 | 1.22 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 0.00 | 100.00 | 1.22 |
| Raveled Area | 3.00 | 87.00 | 3.00 | 0.00 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Edge Break Area | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mean Rut Depth | 18.00 | 20.00 | 18.00 | 3.30 | 83.50 | 1.02 |
| Rut depth Standard Deviation | 1.00 | 1.40 | 1.00 | 1.70 | 21.43 | 0.26 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.35 | 0.50 | 0.45 | 28.57 | 0.35 |

| | |
|---|---|
| Level 1 | Impact Elasticity greater than 0.5 |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 |
| Level 4 | Impact Elasticity less than 0.05 |

Figure 20 shows the average roughness during road life time with maintenance case in high traffic volume.

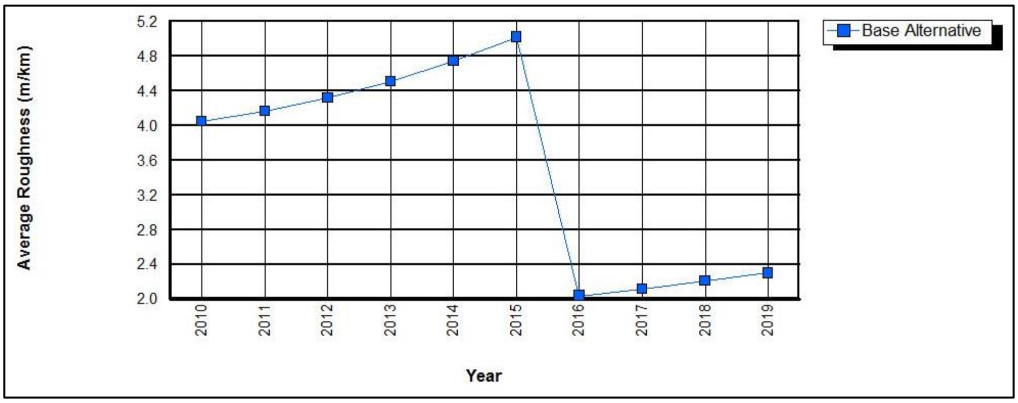


**Figure 20: Average Roughness vs. section life time with maintenance case in High traffic**
**Slika 20: Spreminjanje neravnosti s časom (visok promet, z vzdrževanjem)**

Figure 21 shows the pavement surface damage progression over time with the structural overlay maintenance case in high traffic volume. The results of the maintenance job can be seen in the figure 21, which shows how it gives a new life time to the pavement.

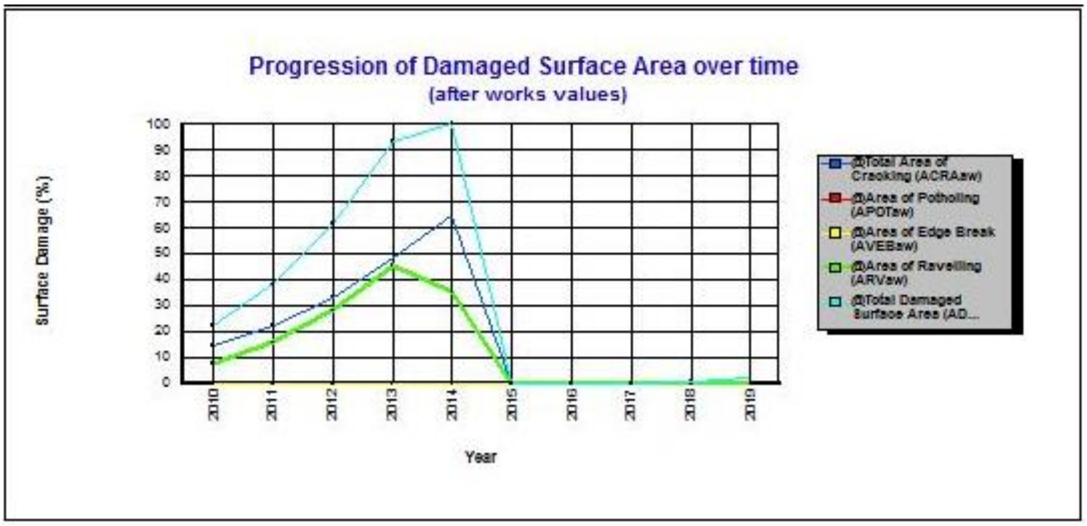


**Figure 21: Progression of Surface Damage vs. section life time with maintenance case in high traffic**
**Slika 21: Spreminjanje poškodovanosti s časom (visok promet, z vzdrževanjem)**

From the table 54 and table 55 the Sensitivity of the pavement condition parameters to the Roughness are observed based on the analysis with Structural Overlay @ 4.5IRI maintenance case in low and High traffic volume situation, which are shown respectively as follows:

Levels of the sensitivity with low traffic:

- Sensitivity Level One include;
  - ❖ All Structural Cracking,
  - ❖ Transvers Thermal Cracking,
  - ❖ Mean Ruth Depth,

- Sensitivity Level Three include;
  - ❖ Ruth Depth Standard Deviation,
  - ❖ Skid resistance,

Levels of the sensitivity with high traffic:

- Sensitivity Level one include;
  - ❖ All Structural Cracking,
  - ❖ Wide Structural Cracking,
  - ❖ Transvers Thermal Cracking,
  - ❖ Mean Ruth Depth,

- Sensitivity Level Two include;
  - ❖ Ruth Depth Standard Deviation,
  - ❖ Skid resistance,

## 5.5 Sensitivity to All Structural Cracking

Sensitivity of the pavement deterioration parameters to All Structural Cracking are studied also in two ways with and without maintenance cases in high and low traffic volumes for a 10 years period.
Section *(B)* from Table 44 of the Kabul Kandahar Ring road is used as a case study.

Sensitivity of the All Structural Cracking to the pavement deterioration parameters is also determined by using the Traditional Ceteris Paribus *(TCP)*, in which two input values are iterated for All Structural Cracking and then its impact elasticity to the deterioration parameters are calculated, then ranked as the levels mentioned in Section 5.2.

All the *HDM-4* application results regarding the pavement deterioration is included in *appendix A* at the end of this research job for more information.

### 5.5.1 Sensitivity to All Structural Cracking with no maintenance

Impact elasticity of the pavement deterioration parameters on All Structural Cracking is calculated in both low and high traffic volumes, by the result which are given by *HDM-4* Application pavement condition at the end of the analyze period.

a. Low Traffic Situation

Table 56 shows the impact elasticity of the road condition parameters after 5 and 10 years period. As it is clear from the table, the impact elasticity is greater in 1st 5 years and as it goes farther it decrease, so at the end of the analysis period the level of sensitivity is decreased, except the level of the raveled area is increased.

Figure 22 shows the progression of the damaged area from the pavement surface

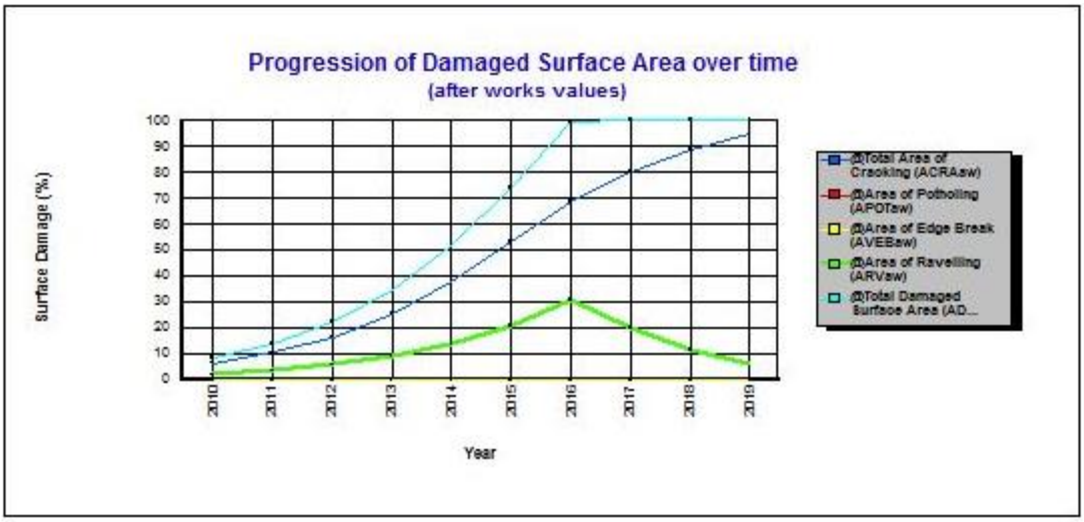


**Figure 22: Progression of Surface Damage vs. section life time in low traffic**
**Slika 22: Spreminjanje poškodovanosti s časom (nizek promet, brez vzdrževanja)**

**Table 56: Sensitivity to All Structural cracking in low Traffic with no maintenance**
**Preglednica 56: Občutljivost na vse strukturne razpoke (nizek promet, brez vzdrževanja)**

| Low Traffic With No Maintenance | | | | | | |
|---|---|---|---|---|---|---|
| Sensitivity to All Structural Cracking AFTER 5 years (Section B) | | | | | | |
| | 1st Iteration | | 2nd Iteration | | | |
| Deteriorations | Original value | End Value | Original value | End Value | % Change | Impact Elastisity |
| All Structural Cracking | 5 | 54 | 2 | 35 | 60.00 | |
| SNP | 5.7 | 4.62 | 5.7 | 5.03 | 8.87 | 0.15 |
| Roughness | 2.10 | 2.58 | 2.10 | 2.45 | 5.04 | 0.08 |
| Wide Structural Cracking | 2.00 | 54.00 | 2.00 | 35.00 | 35.19 | 0.59 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 1.00 | 11.00 | 1.00 | 14.00 | 27.27 | 0.45 |
| No of Pothole | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Mean Rut Depth | 15.00 | 15.7 | 15.00 | 15.7 | 0.00 | 0.00 |
| Rut depth Standard Deviation | 1.00 | 1.1 | 1.00 | 1.1 | 0.00 | 0.00 |
| Texture Depth | 1.00 | 0.68 | 1.00 | 0.68 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.5 | 0.50 | 0.5 | 0.00 | 0.00 |
| Sensitivity to All Structural Cracking AFTER 10 years (Section B) | | | | | | |
| Deteriorations | Original value | 2nd Value | Original value | End Value | % Change | Impact Elastisity |
| All Structural Cracking | 5 | 97 | 2 | 92 | 60.00 | |
| SNP | 5.7 | 3.99 | 5.7 | 4 | 0.25 | 0.00 |
| Roughness | 2.10 | 3.02 | 2.10 | 3 | 0.66 | 0.01 |
| Wide Structural Cracking | 2.00 | 97 | 2.00 | 92 | 5.15 | 0.09 |
| Transvers Thermal Cracking | 2.00 | 2 | 2.00 | 2 | 0.00 | 0.00 |
| Raveled Area | 1.00 | 1 | 1.00 | 6 | 500.00 | 8.33 |
| No of Pothole | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Mean Rut Depth | 15.00 | 16.4 | 15.00 | 16.4 | 0.00 | 0.00 |
| Rut depth Standard Deviation | 1.00 | 1.3 | 1.00 | 1.3 | 0.00 | 0.00 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.49 | 0.50 | 0.49 | 0.00 | 0.00 |

| | |
|---|---|
| Level 1 | Impact Elasticity greater than 0.5 |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 |
| Level 4 | Impact Elasticity less than 0.05 |

b. High traffic Situation

Sensitivity of the pavement condition parameters to the All Structural Cracking according to their impact elasticity value is shown is table 57 for high traffic volume, and in most parts it look like the same as low traffic situation. It means that a Traffic volume does not have much more effect on pavement deterioration due to All Structural Cracking.

The only change that seems from the figure 23 regarding the pavement damage situation is the pavement life, which is decreased by one year than the same situation in low traffic volume.

**Table 57: Sensitivity to All Structural cracking in high Traffic with no maintenance**
**Preglednica 57: Občutljivost na vse strukturne razpoke (visok promet, brez vzdrževanja)**

| High Traffic With No Maintenance | | | | | | |
|---|---|---|---|---|---|---|
| Sensitivity to All Structural Cracking AFTER 5 years (Section B) | | | | | | |
| | 1st Iteration | | 2nd Iteration | | | |
| Deteriorations | Original value | End Value | Original value | End Value | % Change | Impact Elastisity |
| All Structural Cracking | 5 | 54 | 2 | 35 | 60.00 | |
| SNP | 5.7 | 4.62 | 5.7 | 5.03 | 8.87 | 0.15 |
| Roughness | 2.10 | 2.81 | 2.10 | 2.65 | 5.69 | 0.09 |
| Wide Structural Cracking | 2.00 | 54.00 | 2.00 | 35.00 | 35.19 | 0.59 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 1.00 | 44.00 | 1.00 | 51.00 | 15.91 | 0.27 |
| No of Pothole | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Mean Rut Depth | 15.00 | 16 | 15.00 | 15.9 | 0.62 | 0.01 |
| Rut depth Standard Deviation | 1.00 | 1.2 | 1.00 | 1.2 | 0.00 | 0.00 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.42 | 0.50 | 0.42 | 0.00 | 0.00 |
| Sensitivity to All Structural Cracking AFTER 10 years (Section B) | | | | | | |
| Deteriorations | Original value | 2nd Value | Original value | End Value | % Change | Impact Elastisity |
| All Structural Cracking | 5 | 97 | 2 | 92 | 60.00 | |
| SNP | 5.7 | 3.99 | 5.7 | 4 | 0.25 | 0.00 |
| Roughness | 2.10 | 4.22 | 2.10 | 4.06 | 3.79 | 0.06 |
| Wide Structural Cracking | 2.00 | 97 | 2.00 | 92 | 5.15 | 0.09 |
| Transvers Thermal Cracking | 2.00 | 2 | 2.00 | 2 | 0.00 | 0.00 |
| Raveled Area | 1.00 | 1 | 1.00 | 6 | 500.00 | 8.33 |
| No of Pothole | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Mean Rut Depth | 15.00 | 17 | 15.00 | 17 | 0.00 | 0.00 |
| Rut depth Standard Deviation | 1.00 | 1.4 | 1.00 | 1.4 | 0.00 | 0.00 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.35 | 0.50 | 0.35 | 0.00 | 0.00 |

| | |
|---|---|
| Level 1 | Impact Elasticity greater than 0.5 |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 |
| Level 4 | Impact Elasticity less than 0.05 |

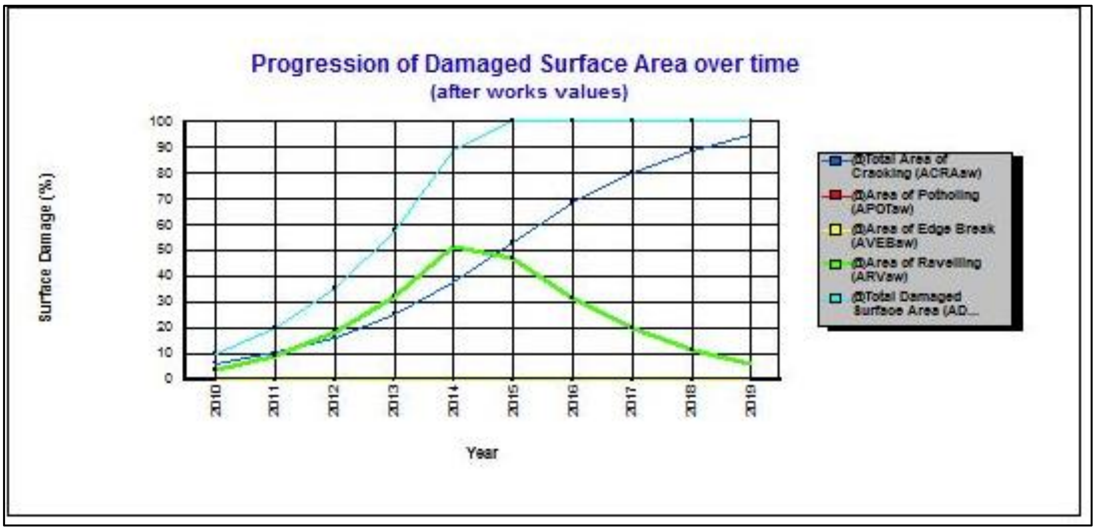


**Figure 23: Progression of Surface Damage vs. section life time with high traffic**
**Slika 23 Spreminjanje poškodovanosti s časom (visok promet, brez vzdrževanja)**

From the table 56 and table 57 the Sensitivity of the pavement condition parameters to the all Structural Cracking are observed based on the analysis with no maintenance case in low and high traffic volume situation, they are as follows:

- Sensitivity Level One include;
  - ❖ Wide Cracking,
  - ❖ Raveled Area,

- Sensitivity Level Three include;
  - ❖ Adjusted Structural number *(SNP),*
  - ❖ Roughness,

### 5.5.2 Sensitivity to All Structural Cracking with Structural Overlay @ 4.5 IRI

After the maintenance activated after the 1st 5 years there will be some changes in the level of the sensitivity and the parameters in which they are affected by the change in the original value of the All Structural Cracking. The two traffic cases for this purpose are provided in sections bellow.

Results of the maintenance road work are included in the *appendix A* at the end of the research.

a. Low Traffic

As this maintenance case is activated after the 1st 5 years, so the up to this point of the life there is no change, and is the same as the case with no maintenance. But after that there are some change in the parameters which are affected by the all structural cracking, their impact elasticity is prove for that.

Figure 24 shows the surface damaged progression with this maintenance case in low traffic situation.

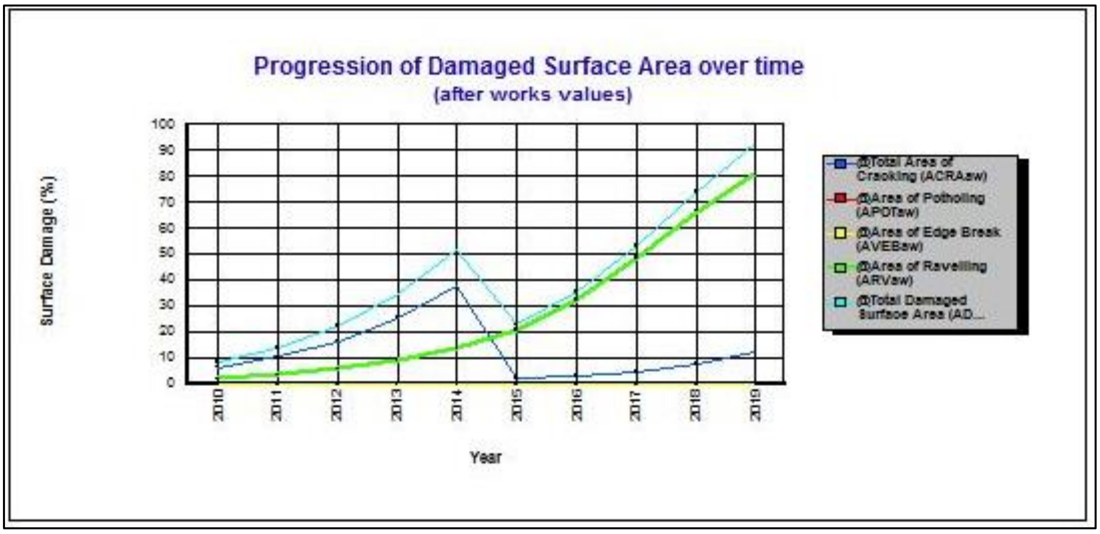


Figure 24: Progression of Surface Damage vs. section life time with low traffic
Slika 24: Spreminjanje poškodovanosti s časom (nizek promet, z vzdrževanjem)

Table 58: Sensitivity to All Structural cracking in low Traffic with Structural overlay @4.5IRI
Preglednica 58: Občutljivost na vse strukturne razpoke (nizek promet, z vzdrževanjem)

| Low Traffic With Structural Overlay @ 4.5 IRI Maintenance | | | | | | |
|---|---|---|---|---|---|---|
| Sensitivity to **All Structural Cracking** AFTER 5 years **(Section B)** | | | | | | |
| | 1st Iteration | | 2nd Iteration | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| All Structural Cracking | 5 | 54 | 2 | 35 | 60.00 | |
| SNP | 5.7 | 4.62 | 5.7 | 5.03 | 8.87 | 0.15 |
| Roughness | 2.10 | 2.56 | 2.10 | 2.45 | 4.30 | 0.07 |
| Wide Structural Cracking | 2.00 | 54 | 2.00 | 35.00 | 35.19 | 0.59 |
| Transvers Thermal Cracking | 2.00 | 2 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 1.00 | 11 | 1.00 | 14.00 | 27.27 | 0.45 |
| No of Pothole | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Mean Rut Depth | 15.00 | 15.7 | 15.00 | 15.7 | 0.00 | 0.00 |
| Rut depth Standard Deviation | 1.00 | 1.1 | 1.00 | 1.1 | 0.00 | 0.00 |
| Texture Depth | 1.00 | 0.68 | 1.00 | 0.68 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.5 | 0.50 | 0.5 | 0.00 | 0.00 |
| Sensitivity to **All Structural Cracking** AFTER 10 years **(Section B)** | | | | | | |
| Deteriorations | **Original value** | **2nd Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| All Structural Cracking | 5 | 10 | 2 | 10 | 60.00 | |
| SNP | 5.7 | 5.57 | 5.7 | 5.56 | 0.18 | 0.00 |
| Roughness | 2.10 | 5.51 | 2.10 | 2.52 | 54.26 | 0.90 |
| Wide Structural Cracking | 2.00 | 4 | 2.00 | 4 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2 | 2.00 | 2 | 0.00 | 0.00 |
| Raveled Area | 1.00 | 76 | 1.00 | 81 | 6.58 | 0.11 |
| No of Pothole | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Mean Rut Depth | 15.00 | 16.4 | 15.00 | 16.4 | 0.00 | 0.00 |
| Rut depth Standard Deviation | 1.00 | 1.3 | 1.00 | 1.3 | 0.00 | 0.00 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.49 | 0.50 | 0.49 | 0.00 | 0.00 |
| | | | | | | |
| Level 1 | Impact Elasticity greater than 0.5 | | | | | |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 | | | | | |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 | | | | | |
| Level 4 | Impact Elasticity less than 0.05 | | | | | |

b. High trafic Situation

With high traffic situation the first 5 years is the same as with low traffic volume, but the difference is when the maintenance is activated. The results at the end of the 10 years show that the sensitivity to the All Structural Cracking is decreased and reached to zero in most cases by activation of the maintenance job.

Figure 25 shows the pavement surface damage progression vs. road section life time.

**Table 59: Sensitivity to All Structural cracking in highTraffic with maintenance**
**Preglednica 59: Občutljivost na vse strukturne razpoke (visok promet, z vzdrževanjem)**

| High Traffic With Structural Overlay @ 4.5 IRI Maintenance | | | | | | |
|---|---|---|---|---|---|---|
| Sensitivity to **All Structural Cracking** AFTER 5 years **(Section B)** | | | | | | |
| | 1st Iteration | | 2nd Iteration | | | |
| Deteriorations | **Original value** | **End Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| All Structural Cracking | 5 | 54 | 2 | 35 | 60.00 | |
| SNP | 5.7 | 4.62 | 5.7 | 5.03 | 8.87 | 0.15 |
| Roughness | 3.00 | 2.81 | 3.00 | 2.65 | 5.69 | 0.09 |
| Wide Structural Cracking | 2.00 | 54.00 | 2.00 | 35.00 | 35.19 | 0.59 |
| Transvers Thermal Cracking | 2.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 |
| Raveled Area | 1.00 | 44.00 | 1.00 | 51.00 | 15.91 | 0.27 |
| No of Pothole | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Mean Rut Depth | 15.00 | 16 | 15.00 | 15.9 | 0.62 | 0.01 |
| Rut depth Standard Deviation | 1.00 | 1.2 | 1.00 | 1.2 | 0.00 | 0.00 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.42 | 0.50 | 0.42 | 0.00 | 0.00 |
| Sensitivity to **All Structural Cracking** AFTER 10 years **(Section B)** | | | | | | |
| Deteriorations | **Original value** | **2nd Value** | **Original valu** | **End Value** | **% Change** | **Impact Elastisity** |
| All Structural Cracking | 5 | 10 | 2 | 10 | 60.00 | |
| SNP | 5.7 | 5.57 | 5.7 | 5.56 | 0.18 | 0.00 |
| Roughness | 3.00 | 3.11 | 3.00 | 3.03 | 2.57 | 0.04 |
| Wide Structural Cracking | 2.00 | 4 | 2.00 | 4 | 0.00 | 0.00 |
| Transvers Thermal Cracking | 2.00 | 2 | 2.00 | 2 | 0.00 | 0.00 |
| Raveled Area | 1.00 | 88 | 1.00 | 88 | 0.00 | 0.00 |
| No of Pothole | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Edge Break | 0.00 | 0 | 0.00 | 0 | 0.00 | 0.00 |
| Mean Rut Depth | 15.00 | 17 | 15.00 | 16.9 | 0.59 | 0.01 |
| Rut depth Standard Deviation | 1.00 | 1.4 | 1.00 | 1.4 | 0.00 | 0.00 |
| Texture Depth | 1.00 | 0.67 | 1.00 | 0.67 | 0.00 | 0.00 |
| Skid Resistance | 0.50 | 0.35 | 0.50 | 0.35 | 0.00 | 0.00 |

| | |
|---|---|
| Level 1 | Impact Elasticity greater than 0.5 |
| Level 2 | Impact Elasticity greater than 0.2 and less than 0.5 |
| Level 3 | Impact Elasticity greater than 0.05 and less than 0.2 |
| Level 4 | Impact Elasticity less than 0.05 |

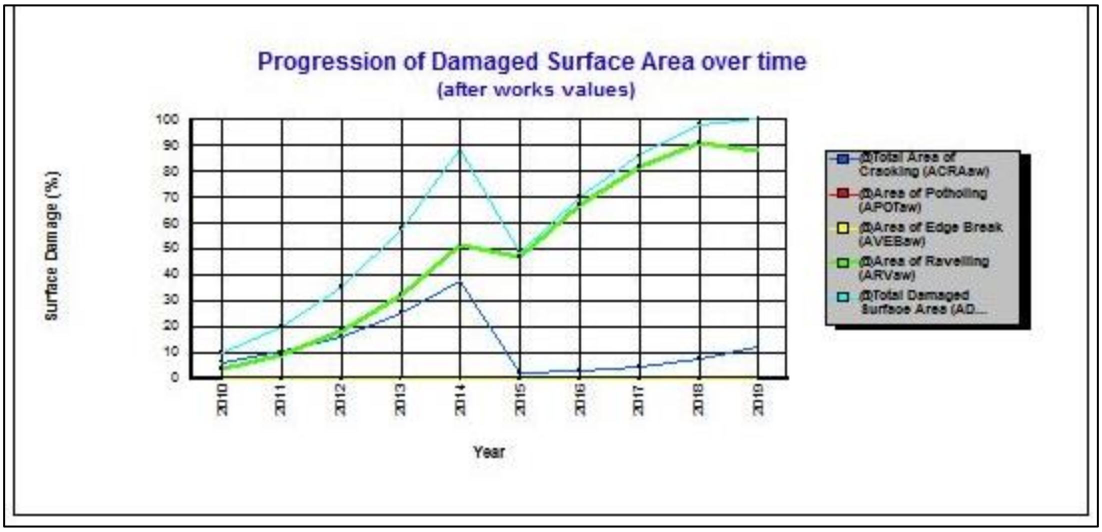


**Figure 25: Progression of Surface Damage vs. section life time with High traffic**
**Slika 25: Spreminjanje poškodovanosti s časom (visok promet, z vzdrževanjem)**

From the table 58 and table 59 the Sensitivity of the pavement condition parameters to the all Structural Cracking are observed based on the analysis with the structural overlay @ 4.5IRI maintenance case in low traffic volume situation, and they are as follows:

- Sensitivity Level One include;
  - ❖ Roughness,

- Sensitivity Level Three include;
  - ❖ Raveled Area,

But in High traffic volume there is no impact elasticity after the maintenance job is done.

# 6 Conclusion

Pavement deterioration models which are selected here to find their sensitivity are chosen because they are introduced as the highest level of the sensitivity by the *HDM-4 Manual Volume 5*.

Here only their impact elasticity on the remaining parameters of the pavement deterioration is studied, as mentioned in section 1.2.

By the analyze of desired sections to get the sensitivity of the chosen deterioration models, it is found out that only limited numbers of the pavement deterioration parameters are sensitive to any change which is occurred to the chosen individual input parameter.

The impact elasticity of these pavement condition parameters are varying a lot, depending upon some other situations and inputs values, such as; *traffic volumes* and *loading, climate zones* in which the section is located, *analysis period* which is considered, and the *existing condition* of the network.

It is found that the *Traditional Ceteris Paribus (TCP)* method is useful. It is easy to use because only one parameter needs to be changed and varied to find its sensitivity by impact elasticity.

Because of the limited usage of the *HDM-4* Application which was accessible in this study, only the sensitivity to deterioration models are studied (only limited numbers with no economic analysis), but it not enough, it needs to include the sensitivity to *strategy generation*, and sensitivity to *economic optimization* to the project analysis and prediction model to get the best of a road project.

The results of the impact elasticity of deterioration model shows that the original condition of *Roughens* has no direct effect on the other road condition parameters, but it has direct effect on the Road User Cost and other economic and accident analysis, but as described in Section 3.4.8 Roughness has affected directly by:

- Structural;
- Cracking;
- Rutting;
- Potholing;
- Environment;

Which are all these parameters are included in Roughness prediction models.

For the Adjusted Structural number *(SNP)* in which was used in this study as the representative of the Pavement strength among (Structural Number *(SN*), Deflection and Adjusted Structural Number *(SNP)*, the results of the pavement condition from *HDM-4* software was used to find the impact elasticity, it seems that the sensitive parameters of pavement condition in low and high traffic volume are *pavement Roughens, Meant Ruth Depth* and *Rut depth Standard Deviation*. They were ranked as sensitivity levels as introduced in section 5.2 methodology. Their impact elasticity shows that, sensitivity in low traffic is much lower than the sensitivity in high traffic volumes in which have greater impact elasticity.

The results of the impact elasticity of the *All Structural Cracking* on the other pavement condition parameters show that in the 1$^{st}$ 5years the following parameters have sensitivity to that:

- SNP;
- Roughness;
- Wide Structural Cracking;
- Raveled Area;

But after the 10 years the level of sensitivity of these parameters are decreased, so it means that in low Cracking the sensitivity of the mentioned parameters are higher, as the cracking area is increased this sensitivity is decreased and reach to lower level, as was shown in table 56.

It is in a case that the change in traffic situation does not have effect on the sensitivity of this parameter.

All these calculation and analysis were done in the two traffic situations, and the results show that traffic volumes have the highest effect on the sensitivity of the *Adjusted Structural Number (SNP)* while there is not a great effect on *All Structural Cracking* and Roughness.

# 7 Povzetek

## Uvod

Kvalitetno in racionalno vzdrževanje cest je možno zgolj s podporo sodobnih sistemov za gospodarjenje z vozišči. Namen razvoja sistemov za gospodarjenje z vozišči je zagotoviti objektivne informacije in koristne podatke, da lahko upravljavci cestnega omrežja bolj dosledno, stroškovno učinkovito in argumentirano sprejemajo odločitve pri vzdrževanju omrežja. S sistemom za gospodarjenje z vozišči lahko ugotavljamo, kakšne bi bile posledice različnih politik vzdrževanja vozišč.

Eden od takih sistemov je programski paket *HDM-4*. Ključna sestavina teh sistemov so kalibrirani in validirani modeli za napoved propadanja vozišč, ki pa zahtevajo vrsto vhodnih podatkov.

Občutljivost *HDM-4* modelov propadanja vozišč na točnost vhodnih podatkov je sicer že prikazana v dokumentaciji *HDM-4* paketa, a zgolj na kvalitativnem nivoju. Namen te naloge pa je, da kvantitativno ocenimo elastičnost modelov na spremembe nekaterih vhodnih podatkov, katerih natančno zbiranje zahteva obsežne terenske raziskave. V primeru, da za katerega od teh podatkov ugotovimo, da ne vpliva bistveno na rezultate modela, se lahko točnemu zbiranju izognemo ter jih zgolj ocenimo, s čimer lahko dosežemo velike prihranke.

V tej nalogi smo analizirali občutljivost vhodnih podatkov, ki so bili v dokumentaciji *HDM-4* modela razvrščeni v I. razred, to so modificirano strukturno število, začetna neravnost *(IRI)* in začetni obseg strukturnih razpok.

**Sistem za gospodarjenje z vozišči *HDM-4***

Eden od najbolj razširjenih sistemov za gospodarjenje z vozišči je Highway Development and Management *(HDM-4)*, ki je bil razvit pod okriljem World Bank.

*HDM-4* se lahko uporablja za projektne, programske in strateške analize.

S projektnimi analizami lahko ocenimo učinkovitost investicijskega vzdrževanja na posameznem cestnem odseku, s programskimi in strateškimi analizami pa na celotnem omrežju.

V paketu *HDM-4* so vgrajeni naslednji modeli:

- Model za izračun propadanja vozišč;
- Model za izračun učinkov in stroškov ukrepov;
- Model za izračun stroškov uporabnikov (stroški uporabe vozil, nezgod in porabečasa);
- Model za izračun socialnih in okoljskih vplivov (emisije plinov, hrupa in poraba energije);

V nalogi smo se omejili zgolj na analizo vpliva točnosti vhodnih podatkov za model propadanja vozišč.

**Modeli za napovedovanje propadanja vozišč v *HDM-4***

V *HDM-4* so vključeni modeli za napovedovanje naslednjih vrst poškodb vozišč:

Poškodbe površine

- Razpoke;
- Luščenje;
- Udarne jame;
- Lom robov;

Deformacije

- Kolesnice;
- Neravnost;

Zmanjševanje drsnega trenja

- Zmanjševanje globine teksture;
- Glajenje;

Glavne vhodne podatke modelov lahko razdelimo v naslednje skupine:

- Značilnosti voziščne konstrukcije (nosilnost, debeline in material slojev, kvaliteta izdelave in nosilnost temeljnih tal);
- Stanje voziščne konstrukcije (razpoke, luščenje,…);
- Zgodovina vzdrževanja;
- Geometrija ceste (širina vozišča, bankin, vzdolžni nagib) in vreme (padavine, temperature,…);
- Promet;

Celotno logiko modeliranja propadanja lahko povzamemo v naslednjih korakih:

- Inicializacija vhodnih podatkov in stanja na začetku vsakega leta;
- Izračun parametrov nosilnosti konstrukcije;
- Izračun sprememb poškodb površine v naslednjem vrstnem redu:
    - ❖ Razpoke,
    - ❖ Luščenje,
    - ❖ Udarne jame,
    - ❖ Lom robov,

- Izračun poškodb površine na koncu leta in povprečno v letu;
- Izračun deformacij;
- Izračun drsnosti;
- Zapis rezultatov za uporabo v naslednjem letu in v modelih za izračun stroškov uporabnikov, učinkov ukrepov, ekoloških vplivov in za izdelavo poročil;

**Analiza občutljivosti**

Za analizo občutljivosti rezultatov modelov smo uporabili metodo Traditional Ceteris Paribus *(TCP).*

Pri tej metodi izračunamo elastičnost izhodnih rezultatov s spreminjanjem enega vhodnega podatka, medtem ko ostale pustimo nespremenjene. Zaradi takega pristopa je ta metoda dokaj enostavna in hitra, ima pa to pomanjkljivost, da ne upošteva interakcije med vhodnimi podatki.

V nalogi smo analizirali občutljivost naslednjih izhodnih rezultatov modelov:

- Modificirano strukturno število;
- Neavnost;
- Obseg strukturnih razpok;
- Obseg širokih strukturnih razpok;
- Obseg prečnih kriogenih razpok;
- Obseg luščenja;
- Število udarnih jam;
- Obseg lomov robov;
- Povprečna globina kolesnic;
- Standardna deviacija globine kolesnic;
- Globina teksture;
- Drsno trenje;

pri čemer smo spreminjali začetno

- Modificirano strukturno število;
- Neravnost;
- Obseg strukturnih razpok;

Elastičnost izračunamo kot razmerje med odstotkom spremembe izhodnih rezultatov in odstotkom spremembe vhodnih podatkov.

**Vhodni podatki**

Občutljivost modelov smo analizirali na treh realnih cestnih odsekih ceste v Kandaharju v Afganistanu. Ker nismo imeli na voljo vseh podatkov, ki so potrebni za modeliranje s programom *HDM-4*, smo morali manjkajoče podatke oceniti.

Vse analize smo izdelali za dva razreda prometnih obremenitev:

- Nizek promet 1,000 *PLDP;*
- Visok promet 20,000 *PLDP;*

Analizirali smo občutljivost izhodnih rezultatov po 5 in 10 letnem obdobju, poleg tega pa smo analizirali tudi vplive različnih scenarijev vzdrževanja na rezultate modelov propadanja vozišč.

**Rezultati**

**Občutljivost rezultatov na spremembe modificiranega strukturnega števila *(SNP)***

Rezultati analize so prikazani v preglednicah 48 in 49. Ugotovili smo, da sprememba *SNP* vpliva samo na neravnost in globino kolesnic in nima nobenega vpliva na ostale rezultate modelov. Poleg tega smo ugotovili, da je občutljivost večja z daljšanjem obdobja analize in pri večjih prometnih obremenitvah. Rezultati analize v primeru interventnega vzdrževanja (preplastitev pri 4.5 IRI) so prikazani v preglednicah 50 in 51. Iz preglednic je razvidno, da se občutljivost rezultatov v primeru interventnega vzdrževanja zmanjša.

**Občutljivost rezultatov na spremembe začetne neravnosti**

Rezultati analize so prikazani v preglednicah 52 in 53. Presenetljivo je, da sprememba začetne neravnosti nima nobenega vpliva na ostale rezultate modelov. Rezultati analize v primeru interventnega vzdrževanja (preplastitev pri 4.5 IRI) so prikazani v preglednicah 54 in 55. Iz preglednic je razvidno, da se v primeru interventnega vzdrževanja pokaže velika elastičnost izračunanih strukturnih razpok, kriogenih razpok in globine kolesnic, v primeru visokih prometnih obremenitev pa tudi širokih razpok.

**Občutljivost rezultatov na spremembe začetnega obsega strukturnih razpok**

Rezultati analize so prikazani v preglednicah 56 in 57. Sprememba začetnega obsega strukturnih razpok močno vpliva na izračunan obseg širokih razpok in srednje na obseg luščene površine. V desetletnem obdobju modeliranja pa je elastičnost velika pri obsegu luščene površine, medtem ko se pri širokih razpokah bistveno zmanjša. Na prvi pogled je to presenetljivo, a ta pojav lahko razložimo s tem, da se vpliv začetnega stanja z daljšanjem obdobja napovedi zmanjša.

Rezultati analize v primeru interventnega vzdrževanja (preplastitev pri 4.5 IRI) so prikazani v preglednicah 58 in 59.

Iz preglednic je razvidno, da se občutljivost rezultatov v primeru interventnega vzdrževanja zmanjša.

**Zaključek**

V nalogi smo analizirali občutljivost modelov za napovedovanje propadanja vozišč, ki so vgrajeni v programski paket *HDM-4*. Osredotočili smo se na elastičnost rezultatov na spremembe modificiranega strukturnega števila, začetne neravnosti in začetnega obsega strukturnih razpok. Analizo elastičnosti smo izdelali z uporabo metode »ceteris paribus« na treh konkretnih odsekih cest v Afganistanu. Ugotovili smo, da se rezultati analize večinoma ujemajo s pričakovanji, da točnost vhodnih podatkov o strukturnem številu in začetnem obsegu razpok močno vpliva na rezultate modelov propadanja vozišč in je zato potrebno zbiranju teh podatkov posvetiti največjo pozornost.

Presenetilo nas je, da napake pri oceni začetne ravnosti ne vplivajo na rezultate napovedi propadanja vozišč, kar pa je potrebno podrobneje preveriti.

Žal smo imeli na voljo zgolj demo verzijo programskega paketa, zato nismo mogli oceniti, kakšen bi bil vpliv na stroške vzdrževanja in stroške uporabnikov, kar pa ostaja izziv za nadaljnje delo.

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# 9 Appendix

## Appendix A

**Table 60: Information Quality Level Examples for Road Data (HDM-4 Volume 5)**
**Preglednica 60: Primeri informacije stopnjo kakovosti cestnega podatkov**

| | Information Quality Level | | | |
|---|---|---|---|---|
| | IQL-2 | IQL-2B | IQL-3 | IQL-4 |
| Road geometry | Rise and fall (m/km) | Average absolute gradient (%) | Gradient class (4 classes) | Geometry class (6-8 classes) |
| | Number of rises and falls (no./km) | No. of gradient changes (no./km) | | |
| | Average horizontal curvature (deg/km) | No. of curves by speed class (class-freq/km) | Curvature class (4 classes) | |
| | Super-elevation | | | |
| | Speed limit (km/h) | Desired speed (km/h) | Speed environment (6 classes) | n/a |
| | Speed limit enforcement factor | | | |
| | Roadside friction (factor) | Speed reduction factors | | |
| | Non-motorised transport speed reduction (factor) | | | |
| | Motorised transport speed reduction (factor) | | | |
| Pavement condition | Lane roughness (m/km IRI) | Roughness (6 ranges) | Ride quality (class) | Pavement condition (class) |
| | All cracks area (% area) | Cracking (score, or Universal Cracking Index, UCI) | Surface Distress Index (SDI) | |
| | Wide cracks area (% area) | | | |
| | Transverse thermal cracks (no./km) | | | |
| | Ravelled area (% area) | Disintegration (score) | | |
| | Potholes number (units/lane-km) | | | |
| | Edge-break area (m2/km) | | | |
| | Patched area (% area) | | | |
| | Rut depth mean (mm) | Deformation (score) | | |
| | Rut depth standard deviation (mm) | | | |
| | Macro-texture depth (mm) | Surface texture (class) | Surface friction (class) | |
| | Skid resistance (SF50) | Friction (class) | | |
| Pavement structure | Pavement type (class) | | Pavement type (class) | Pavement class (class) |

*... Continued*

<table>
<tr><th rowspan="2"></th><th colspan="4">Information Quality Level</th></tr>
<tr><th>IQL-2</th><th>IQL-2B</th><th>IQL-3</th><th>IQL-4</th></tr>
<tr><td rowspan="15">Bituminous</td><td>Pavement Structural Number (adjusted SNP)</td><td rowspan="2">Deflection (mm BB)</td><td rowspan="5">Pavement structural adequacy (index)</td><td rowspan="18">Remaining service life (yrs)</td></tr>
<tr><td>Deflection (mm BB)</td></tr>
<tr><td>Thickness of surfacing (mm)</td><td>Surface thickness (class)</td></tr>
<tr><td>Thickness of base (mm)</td><td>Pavement depth (class)</td></tr>
<tr><td>Shoulder effect (factor)</td><td>Shoulder type</td></tr>
<tr><td>Construction defects surfacing (index)</td><td rowspan="3">Construction quality (index)</td><td rowspan="5">Construction quality (class)</td></tr>
<tr><td>Construction defects base (index)</td></tr>
<tr><td>Relative compaction (%)</td></tr>
<tr><td>Drainage (index)</td><td rowspan="2">Pavement environment (index)</td></tr>
<tr><td>Pavement environment (index)</td></tr>
<tr><td>Pavement age (yr)</td><td rowspan="2">Surfacing age (range)</td><td rowspan="5">Previous intervention (class)</td></tr>
<tr><td>Surfacing age (yr)</td></tr>
<tr><td>Previous all cracking area (%)</td><td rowspan="3">Previous condition (class)</td></tr>
<tr><td>Previous wide cracking area (%)</td></tr>
<tr><td>Previous thermal cracking (number)</td></tr>
<tr><td rowspan="3">Concrete</td><td>Thickness of slab (mm)</td><td>Slab thickness (class)</td><td rowspan="3">Pavement Structural Adequacy (index)</td></tr>
<tr><td>Modulus of rupture (MPa)</td><td rowspan="2">Material strength (class)</td></tr>
<tr><td>Reinforcing steel (%)</td></tr>
</table>

*... Continued*

| | Information Quality Level | | | |
|---|---|---|---|---|
| | IQL-2 | IQL-2B | IQL-3 | IQL-4 |
| Unpaved | *Surfacing Material:* | | Gravel standard (class) | Durability standard (class) |
| | Material Type | Material Type (class) | | |
| | Max. Particle Size (mm) | Material Size (class) | | |
| | Material passing 2.0 mm (%) | Material Gradation (class) | | |
| | Material passing 0.425 mm (%) | | | |
| | Material passing 0.075 mm (%) | | | |
| | Plasticity Index | Plasticity (class) | | |
| | *Subgrade Material:* | | Earth passability (class) | |
| | Material Type | Material Type (class) | | |
| | Max. Particle Size (mm) | Material Size (class) | | |
| | Material passing 2.0 mm (%) | Gradation (class) | | |
| | Material passing 0.425 mm (%) | | | |
| | Material passing 0.075 mm (%) | | | |
| | Plasticity Index | Plasticity (class) | | |
| | *Structure:* | | Load rating (class) | |
| | Gravel depth (mm) | Surface depth (class) | | |
| | Cross-section (class) | | | |
| Environment | Rainfall monthly mean (mm) | Rainfall class | Climate classification (class) | Climate classification (class) |
| | Dry season duration (fraction) | | | |
| | Moisture classification (class) | Climate (class) | | |
| | Temperature classification (class) | | | |
| | Temperature mean annual (deg C) | Cold climate classification (class) | | |
| | Temperature range (deg C) | | | |
| | Time above freezing (days) | | | |
| | Freezing Index (degC-days) | | | |
| | De-icing salt use (class) | | | |
| | Studded tire use (%) | | | |
| | Snow-driving time (%) | | | |
| | Wet-road driving time (%) | | | |
| | Air density (kg/m2) | | | |

**Table 61: IQL Examples for Traffic Volume (HDM-4 Volume 5)**
**Preglednica 61: RKI Primeri prometa zvezek**

| | Information Quality Level | | | |
|---|---|---|---|---|
| | IQL-2 | IQL-2B | IQL-3 | IQL-4 |
| Traffic volume | | Volume (AADT veh/day) | Volume (AADT veh/day) | Traffic class (class) |
| | Volume – veh. class 1 (veh/day) | Percent veh. class 1 | | |
| | Volume – veh. class *n* (veh/day) | Percent veh. class *n* | | |
| | Volume – veh. class 5 (veh/day) | Percent veh. class 5 | Heavy traffic (% AADT) | |
| | Volume – veh. class *n* (veh/day) | Percent veh. class *n* | | |
| | Volume growth (%/yr) – class 1 | Volume growth (%/yr.) (all classes) | Volume growth (% AADT/yr) | |
| | Volume growth (%/yr) – class *n* | | | |
| Traffic flow | Ultimate capacity (pcse/la/h) | Ultimate capacity (class) | Volume-capacity ratio | Congestion class (class) |
| | Free-flow capacity (%) | Free-flow capacity (class) | | |
| | Nominal capacity (fraction) | Nominal capacity (class) | | |
| | Jam speed at capacity (km/h) | Jam speed at capacity (class) | | |
| | Acceleration noise max. (m/s$^2$) | Acceleration noise max. (class) | | |
| | Flow-frequency periods (no.) | Flow type (3 classes) | Flow type (3 classes) | |
| | Duration of F-F period 1 (h) | | | |
| | Duration of F-F period *n* (h) | | | |
| | Percent AADT in F-F period 1 | | | |
| | Percent AADT in F-F period *n* | | | |
| | Intersection type (class) | Intersection type (class) | | |
| Safety | *To be completed* | | | |
| Emissions | *To be completed* | | | |

**Table 62: Sensitivty Classes of RDWE (HDM-4 V5)**
**Preglednica 62: Občutljivost Razredi CPDU**

| Sensitivity class | Impact elasticity | Parameter | Outcomes most impacted | | |
|---|---|---|---|---|---|
| | | | Pavement performance | Resurfacing and surface distress | Economic return on maintenance |
| S-I | > 0.50 | Structural number [1/] | ▪ | ▪ | ▪ |
| | | Modified structural number[1/] | ▪ | ▪ | ▪ |
| | | Traffic volume | | | ▪ |
| | | Deflection[3/] | ▪ | ▪ | ▪ |
| | | Roughness | ▪ | | ▪ |
| S-II | 0.20-0.50 | Annual loading | ▪ | ▪ | ▪ |
| | | Age | | ▪ | ▪ |
| | | All cracking area | | ▪ | ▪ |
| | | Wide cracking area | | ▪ | ▪ |
| | | Roughness-environment factor | ▪ | | ▪ |
| | | Cracking initiation factor | ▪ | ▪ | ▪ |
| | | Cracking progression factor | | ▪ | |
| S-III | 0.05-0.20 | Subgrade CBR (with SN) | ▪ | | |
| | | Surface thickness (with SN) | | ▪ | ▪ |
| | | Heavy axles volume | | ▪ | ▪ |
| | | Potholing area | ▪ | ▪ | |
| | | Rut depth mean | ▪ | | |
| | | Rut depth standard deviation | ▪ | | |
| | | Rut depth progression factor | ▪ | | |
| | | Roughness general factor | ▪ | | ▪ |
| S-IV | < 0.05 | Deflection (with SNC) | | ▪ | |
| | | Subgrade compaction | ▪ | | ▪ |
| | | Rainfall (with Kge) | ▪ | | |
| | | Ravelling area | | ▪ | |
| | | Ravelling factor | | ▪ | |