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Calibration of the Crack Initiation Model in HDM 4 on the Highways and Primary Urban Streets Network in Macedonia

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Abstract

The World Bank HDM4 model has been developed on the basis of the researches carried out in Brazil and in South Africa. Those researches lead to the derivation of models regarding almost all types of damage which can occur on the roads, but in order to use them worldwide, it is necessary to adjust them to the local conditions (traffic load, climate, construction specificities, maintenance level etc.). The theme of this research is essential for the development of urban areas. This paper presents the results of the researches in view of the definition of the calibration coefficient of the crack formation model in HDM4.

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1. Introduction

The World Bank HDM4 model has been developed on the basis of the researches carried out in Brazil and in South Africa. Those researches lead to the derivation of models regarding almost all types of damage which can occur on the roads, but in order to use them worldwide, it is necessary to adjust them to the local conditions (traffic load, climate, construction specificities, maintenance level etc.) [1-12].

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This research was carried out in the period from 2010 until 2014. It is the first research concerning calibration of the coefficients, in view of coordination with the HDM models and the conditions in Macedonia. The purpose of the research is not only to provide results of the analysis of calibration and the calibration coefficient, but also to propose a strategy for the needs of calibration in the future as well as comparing the results of the measurements between cracking initiation on urban roads and highways. This paper presents the results of the calibration of the crack initiation model in HDM4.

2. Data on the cracks used for level 2 calibrations (entering data)

The data used in this research were gathered in the period of 2010-2014 (a total of five series of observations). In relation to the HDM standard it is a small number of data (at least ten years are necessary for a reliable level of calibration), but compared to the studies elaborated in many countries around the world (Australia, Argentina, Malaysia, Philippines etc.) the 4-year period can be adopted as sufficient for the establishment coefficient, with the remark that some changes may occur after the collection of a sufficient number of data referring to crack initiation. Also, the analysis uses certain data from the actual designs on rehabilitation of the pavements on the Kumanovo-Miladinovci highway.

According to the HDM instructions the data are gathered on 1 km-sections and on stretches with the representative length of 300 m. It means that on a section 1 km long only one 300m stretch can be analysed. The limitations referring to the geometric elements in a situation and in a longitudinal profile do not exist. The only limit concerns the crack initiation, that is, the fact that the selected 300m – lengths should not have cracks on them or if they do, those cracks should be small ones, so as it is still possible to establish the difference in the condition of crack appearance between two subsequent measuring. According to HDM the process of crack initiation starts when the level of cracks of the pavement attains 0.5% of the driving lane.

The regions are classified as per the quantity of precipitations and the qualities related to resistance of soil humidity. Statistically, if there are several climate zones, more than 15 sections are necessary as regarding the precipitation quantity for each climate zone, in order to obtain sufficient data for relevant results. The territory of Macedonia is not divided into regions due to the small surface of the country. This especially holds for the highway network, because generally, the regions they go through are located in the lower parts of the country with relatively uniform climate features. The average annual precipitation in Macedonia is between 460mm and 1100mm. The dominant interval of the average annual precipitations is between 600mm and 800mm. The monthly precipitations are within the limit of 30mm to 150mm. The representative value adopted is the one of 60mm. The average annual temperature is based on the seasonal records. Approximately 90% of the territory has the average annual temperature within the limits of 10 to 15⁰C, or 13⁰C on average, while on 10% of the territory (on higher altitudes) the average annual temperature is lower than 6.5⁰C. Regarding the dominant distribution of the highway network the average annual temperature is the one of 13⁰C.

The average temperature scope is the difference between the amplitudes of the maximal and minimal average annual temperatures. The minimal average annual temperature is in February and amounts 0.5⁰C, while the maximal one is in August amounting 22⁰C. On the basis of these data it is clear that the average adoptable temperature scope is the one of 22⁰C.

The number of days in the year when the temperature is beyond 32⁰C is in the interval from 35 to 73, and the adopted value is of 50 days.

The freezing index is the number of day-degrees, that is, the difference between the highest and the lowest points of the cumulative curve of degrees-days-temperature in one freezing season. It is used as measurement for combined duration and magnitude of the freezing temperature in one season. According to the data there are, in Macedonia, 30 to 150 days per year when the maximum temperature is below 0⁰C, indicating important differences between the southern and the mountainous parts of the country. The average number of days when the temperature is below 0⁰C in Skopje is 80, which is adopted as an average value on a national level.

The following division has been suggested for the calculation of the freezing index:

- 50 days with an average temperature of -20C to 00C

- 20 days with an average temperature in the interval of -40C to -20C
- 10 days with an average temperature in the interval of -60C to -40C

The minimal value of the freezing index is obtained by the following equation:

$$50 \cdot |-1^0 C| + 20 \cdot |-3^0 C| + 10 \cdot |-5^0 C| = 160 \text{ day-degrees (C-days HDM)}$$

Table 1 gives a review of the adopted representative vehicles of the driveways in Macedonia according to the Study on the Regional Roads in Macedonia, elaborated by BCEOM in 2005.

Table 1. The vehicle fleet in Macedonia

Vehicle category	Vehicle types
Car/Taxi	Skoda Fabia 1.4, Volkswagen Golf 1.4
Van/Pickup	Volkswagen T4 2.0
2-axe truck (<3 t)	Rival 40.8X
2- axe truck (3-7t)	Fiat-Zastava Turbo Zeta 380, MAN
3- axe truck (7-10t)	Mercedes 1620
>3- axe truck	Mercedes Acros 1848 (2 axes of towing vehicle, 3 axes caravan)
Bus	Neoplan (FAP, Sanos)

Source: BCEOM 2005

Note: 3 axe trucks (2axes of towing vehicle, 3 axes caravan) were excluded for the primary urban streets network

3. Review of the format of the model of appearance in HDM4

According to HDM 4, the crack initiation model for rehabilitated pavements is given with the following equation:

$$ICA = K_{CIA} \left\{ CDS^2 \left[\text{MAX} \left(\begin{array}{l} a_0 \exp \left[a_1 \text{SNP} + a_2 \left(\frac{YE4}{\text{SNP}^2} \right) \right] \cdot \\ \text{MAX} \left(1 - \frac{\text{PCRW}}{a_2}, 0 \right) a_4 \text{HSNEW} \end{array} \right) \right] + CRT \right\} \quad (1)$$

where:

ICA - time necessary for initiation of all cracks in the construction [years]

CDS - indicator of the defects in the asphalt surface construction (CDS=0 for well-built pavements without defects; CDS=1 correctly built pavements with a few defects; CDS=2 badly built pavements with a combination of defects)

YE4 - average annual number of equivalent axes as per the standard [millions/lane]

SNP - average annual modified structure number of the pavement

HSNEW – thickness of the final layer [mm] upon rehabilitation

PCRW - surface on which cracks have appeared before the latest rehabilitation [m²]

K_{CIA} - calibration coefficient for the initiation of all structural cracks

CRT - lagging time in the formation of the crack due to maintenance [years]

a₁ - model coefficients

The model calibration corresponds the following equation:

$$K_{CI} = \frac{\text{MeanOTCI}}{\text{MeanPTCI}} \quad (2)$$

$$RMS = \sqrt{\left\{ \text{Mean} \left[\left(OTCI_j - PTCI_j \right)^2 \right]_{j=1,n} \right\}} \quad (3)$$

RMS - (Root Means Square) the error square is a function of the error that is to be minimized

OTCI - measured time until crack initiation

PTCI - predicted time for crack initiation

The research started with an estimation of the length of the pavement on which cracks had appeared, and then the length was converted in cracking percentage, according to the conversion factors documented in:

$$\text{CRACK\%} = 0.0004 \left(\text{Alligator} \cdot \frac{50}{\text{insp_length}} \right)^2 + 0.28 \cdot \text{Crack} \cdot \frac{50}{\text{insp_length}} \quad (4)$$

Where:

CRACK% - percentage of the lane surface covered with cracks

Alligator - surface in m² of the lane where alligator type cracks appeared

Crack - length of all types of cracks except those of the crocodile skin type

insp_length - length of the observed section in meters

The precision of this equation is satisfactory for a small percentage of cracks, because the crack appearance is identified on a surface where percentage of cracks exceeds 0.5%. Thus, due to the small length the precision is not so sensitive to the result. However, it is important to select the most appropriate sections on which the analysis is ranked in order to make it possible to analyse the section in the course of several years. The specific sections for analysis have been determined as in compliance with the following criteria:

- Sections where no activities have been carried out for a considerable period are included
- The sections on which the condition of the pavement is so bad that it is practically impossible to notice the differences from one to the next observation are excluded
- Each section is analysed at least during four years
- Relatively new sections and sections on which there are more than three asphalt layers are separated (some intervention has been carried out at those sections in the exploitation course but much before the observation time)
- Sections are included on which there are no cracks in the beginning of the research and sections where the percentage of crack appearance is relatively small (less than 0.5% of the driving lane).

The distribution of data on cracks on the Skopje-Tetovo, Kumanovo-Tabanovce and the North Skopje Roundabout is given on Figures 1, 2 and 3.

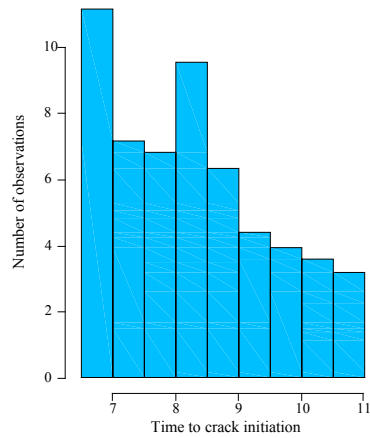
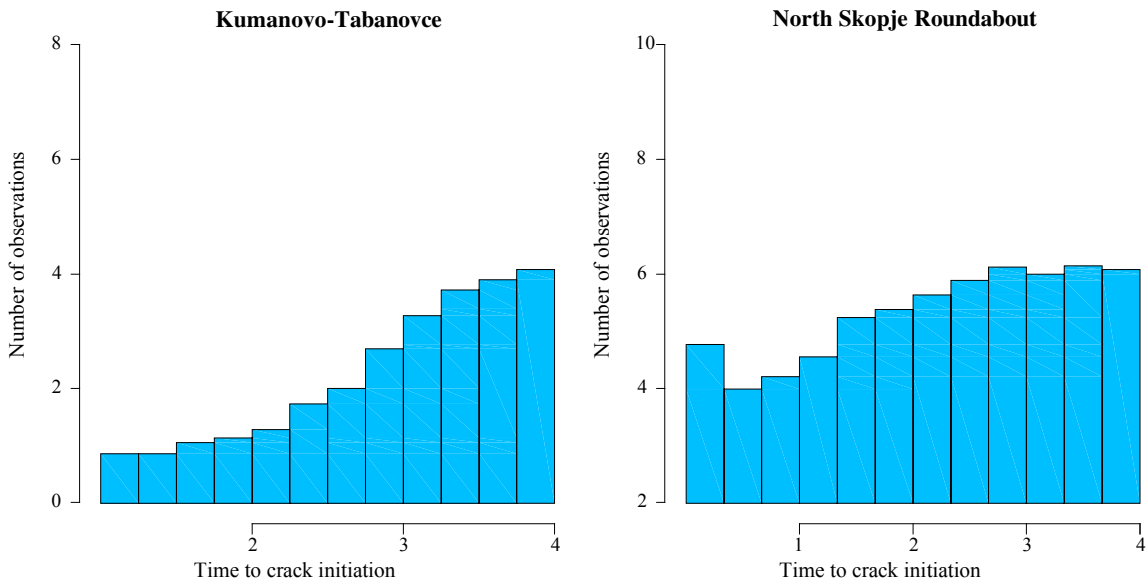


Fig. 1. Distribution of the formation of cracks on the Skopje-Tetovo highway



Source: own research

Fig. 2. Distribution of the formation of cracks on the Kumanovo-Tabanovce highway and the North Skopje roundabout

The sections on which crack initiation was analysed are chosen so that the period of exploitation is relatively short (about 12 years on the Skopje-Tetovo section, about five years on the sections of the North Skopje Roundabout (urban highway) and three years at the section of Kumanovo-Tabanovce). Also field measurements of some main streets in Skopje were included in order to compare the actual field measurements of state highways and urban streets. In the beginning of the research no existing cracks were found on the majority of these sections, which means that there were cracks on some of the sections but in percentage lower than 0.5%. It should be concluded that the pictures refer only to the appearance of the cracks, but not to their scope. In conditions of similar climate characteristics the main reasons for the initiation of the cracking process are the traffic load, the construction quality and the maintenance level.

4. Refining of the existing HDM model format

The following two methods of improvement of the crack formation method were presented in 2004 Transit study:

- Acceptance of the HDM model format, but by modifying all coefficients of the model based on the local data,
- Acceptance of the HDM model, but by change of the model coefficients.

The model coefficients, a_0 to a_4 , are modified by minimizing of the error between the predicted and measured time to crack initiation. Sections with and without cracks have thereby been taken into consideration.

Table 2 gives the values of the coefficients of the default (non-calibrated) model of crack formation, and Table 3 gives the values of the coefficients of the calibrated model.

Table 2. Coefficients of the existing model of crack appearance in HDM

a_0	a_1	a_2	a_3	a_4
4.21	0.14	17.1	30	0.25

Table 3. Modified coefficients of the model of crack appearance in HDM

a_0	a_1	a_2	a_3	a_4
8.3	0	16.2	0.01	0.34

Source: Own research

The changes in the model coefficients suggest that the crack formation caused by the relation traffic load/structural number of $YE4/SNP^2$ is reduced (both a_0 and a_2 are reduced). This means that the traffic load expressed through the number of equivalent axes does not have any considerable influence on the crack initiation. The influence of the thickness of the newly built pavement surface (Skopje-Tetovo, Kumanovo-Tabanovce, urban streets) on the crack initiation is increased (a_4 increased). The influence on the percentage of the cracks before the rehabilitation is entirely changed. The a_3 coefficient is changed from the value of 30 to a considerably lower number (0.01). This suggests that the crack initiation on rehabilitated pavements is a function of whether there was any appearance of cracks on the previous pavement surface or not, that is, considering that there were cracks before the rehabilitation this means that the cracks are bound to appear sooner on rehabilitated than on new pavements. The calibration coefficient for the conditions in Macedonia are given on Tab. 4.

Table 4. Summary of the calibration result

Coefficient	Obtained values
K_{ci}	0.59
Error	17597.7
Error-calibrated	6697.9

Source: own research

The Table shows a lower crack formation factor (K_{cia}) compared to the basic value in HDM ($K_{cia}=1$), due to local conditions (climatic features, traffic load, maintenance level, construction specificities), and to the fact that on some test sections on the beginning of the research there is already a very small percentage of already formed cracks. The results (the value of K_{cia} is approximately 0,6) are compared to the other results of the calibration on international level.

Figure 3 gives a graphic presentation of the results of the non-calibrated model ($K_{cia}=1$).

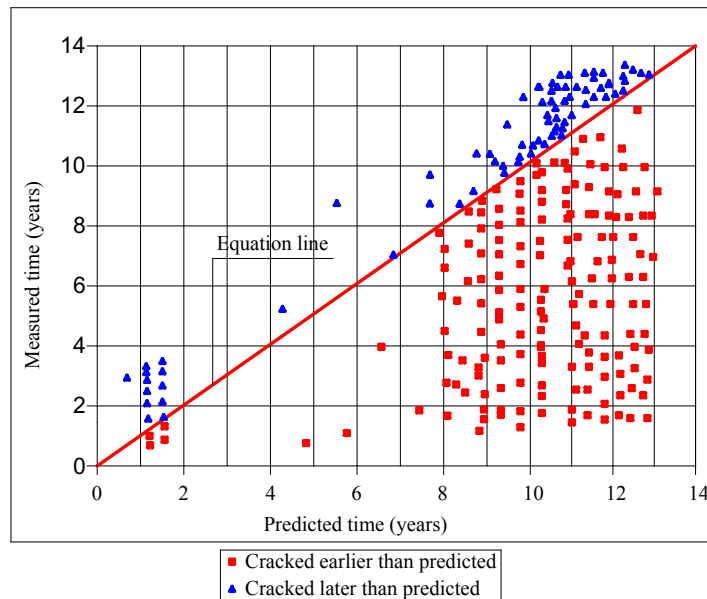


Fig. 3. Non-calibrated model of crack initiation (Default model)

In the default model the predicted time to crack initiation is 1 to 13 years. Thereby, most of the predicted periods of crack initiation in this model are in the interval of 10 to 13 years after the construction. But, pursuant to the field prospects, cracks on most researched sections appear much earlier. This means that the existing HDM model, with the calibration coefficient of $K_{cia}=1$ (default model) and with the existing coefficients a_i of the model (table 2), does not give satisfactory results in planning.

Fig. 4 gives the results of the predicted cracks on the calibrated model with the calibration coefficient of K_{cia} .

The scope of the predicted crack initiation on the calibrated model with the calibration coefficient of $K_{cia}=0.59$ is from 2 to 8 years, while most of the predicted periods of crack initiation are in the interval of 6 to 8 years after the construction, and 4-6 years after the rehabilitation on the rehabilitated pavements. The field prospects demonstrate relatively good coincidence with the calibrated model (7 to 8 years after the construction of new, that is 5 years after the rehabilitation of the existing pavements). Thus, it can be concluded that the calibrated model gives more realistic previews as related to the basic HDM model.

However, there is some dissipation of the data of the envisaged and actual appearance of cracks due to limitations that cannot be included into the model.

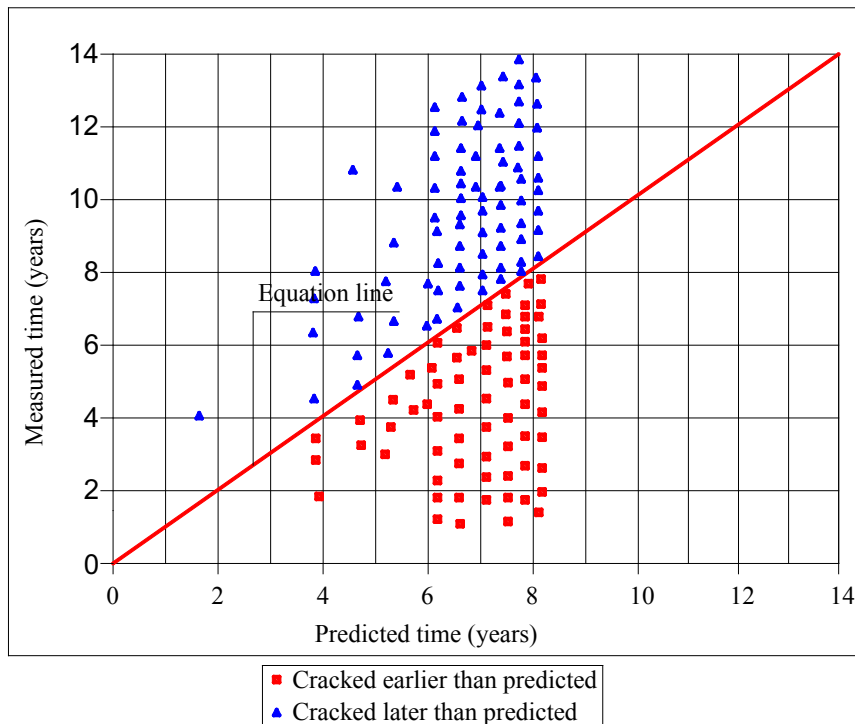


Fig. 4. Calibrated model of crack initiation, Source: own research

Although the calibrated model is considerably better in predicting the crack initiation in comparison with the real time of their appearance, it can be noticed that the deviation between the predicted and the real time of crack initiation is still important. Therefore, it can be supposed that maybe the dependence is of some other mathematic relation type or that many other factors influence the results of the model which are not included in the HDM model, and in many cases, are not covered or are impossible to be covered by data. Some of these variables that influence the model and cannot be included therein are the following:

- The quality of the bitumen,
- Construction practices,
- Oxidation properties of bitumen,
- Specific rainfalls and snowfalls in a certain period and/or other climatic influences.
- Maintenance degree

5. Conclusions

The obtained calibration coefficient yields satisfactory results in comparison with the non-calibrated model, with certain reserve regarding the scope of dissipation of the data on the predicted and measured time of crack initiation.

Field measurements showed that there was no difference in crack initiation between the state highways and selected major urban streets. Thus, the obtained calibration coefficient K_{cia} can be used for the primary city network of Skopje as well as for the state highways.

Nevertheless, more comprehensive analyses are necessary, within the period of at least 10 years as well as possible development of another model, which in fact is calibration of level 3 according to HDM.

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