InteMat4PMS

Integration of material-science based performance models into life-cycle-analysis processed in the frame of pavement management systems

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Deliverable D4: Comparative calculations and benefit analysis report

May 2013

This joint research programme was initiated by **ERA-NET ROAD**.

Deliverable 4: Comparative calculations and benefit analysis report

Project N°:	832708	
Acronym:	**InteMat4PMS**	
Title:	**Inte**gration of **mat**erial-science based performance models into life-cycle-analysis processed in the frame of **p**avement **m**anagement **s**ystems	
Project Coordinator:	Technische Universität Braunschweig Institut für Straßenwesen (ISBS)	Germany
Other Partners:		
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University of Belgrade, Faculty of Civil Engineering		Serbia
ViaTec AG		Switzerland

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Date of issue of this report:	**May 2013**

Project funded by the

“ERA-NET ROAD II” (ENR2) Programme

Contents

1 Introduction

Based on the definition and procedures described in the previous ***InteMat4PMS*** Deliverables the pre-selected empirical performance functions (EPF) are calibrated by using results from laboratory asphalt fatigue testing. This is now practically demonstrated for the selected test sites in this Deliverable D4.

In principle the developed procedure enables to assess different types of performance prediction models with regard to their applicability and their possibilities to be calibrated with results from laboratory testing. The ***InteMat4PMS*** is focusing on fatigue. Beside fatigue, performance model for resistance to permanent deformation may be used and calibrated to better predict point in time when rutting would be above the accepted level. Taking into account multiple calibrated models, the most appropriate type and timing for treatment application may be selected.

The process of calibration is shown for three different, but common performance models considering fatigue in the context of life-cycle-assessment. Hence, the workability of the developed approach of calibration is validated. For this purpose, the dTIMS analytical asset management decision support tool is used. However, any other similar asset management tool is appropriate.
Based on the tasks to be carried out within work-package 5, the structure of Deliverable 4 is subdivided into 3 main chapters:

- Chapter 2 briefly describes the test-sites, which were selected to apply the procedures in practice. In addition, a description of the laboratory tests and results is given, which provide the necessary information to calibrate the pre-selected EPF.
- Chapter 3 represents a comprehensive description of the calibration procedure and the results of the analysis. It includes the results of the comparative calculations of 3 different performance prediction models using standard calibration and laboratory calibrated prediction models
- Chapter 4 displays the benefit that results from using material-science based performance models in the life-cycle-analysis. It can be shown that the inclusion of material characteristics from laboratory tests can improve the accuracy of the prognosis to a big extent

A list of terms to be used within this Deliverable 4 can be taken from Deliverable D3.

2 Calibration input data from pavement materials

2.1 Test sections

An objective ***InteMat4PMS*** is the practical application of the procedures on test sections in Germany and Switzerland. Thus, two test sections were pre-selected and assessed according to the availability of data and materials, which could be used for fatigue testing in the laboratory. The assessment showed that the test section on the Swiss national road network does not fulfill these minimum requirements for data and material testing in comparison to the German test section. Thus this section had to be excluded from the detailed investigation. On the other hand, because of the given situation and the high number of available information the test site in Germany could be extended to two different sections, which will be described in detail as follows.

The German test site (2 test sections) is located on the main road B 35 near Stuttgart (see Figure 1), having a total length of approximately 800 meters, where each of the single test sections has a length of approximately 400 meters. The construction of the test site took place in 2007.As already mentioned, the test site is separated in two sections, which differ in the combination of the different layers (see below).

Figure 1. Location of test site on main road B 35 near Stuttgart/Germany (googlemaps); view of test site (right).

Traffic is the same for both sections. Traffic data, as available from automatic counting station of Vaihingen (Enz), B10, No. 8676, are represented in the following Table 1. A reduction of the traffic of heavy vehicles during the last years can be seen.

Table 1: Average heavy vehicles per day [HV/24h] for different years of observation.

year	HV per 24 hours	N [years]	B acc. to RStO 01 [-]	B acc. to RStO 12 [-]
2007	1 483	30	8 453 188	11 423 227
2008	1 389	29	7 570 804	10 230 816
2009	1 189	28	7 231 020	9 771 649
2010	1 070	27	6 897 899	9 321 486
2011	1 107	26	6 571 899	8 880 149

The total number of load repetitions B, which is considered in pavement design according to German Standards (RStO 01 at the time of construction, now RStO 12), is calculated from:

$$B = N \cdot DTV^{SV} \cdot q_{Bm} \cdot f_A \cdot f_1 \cdot f_2 \cdot f_3 \cdot \frac{(1+p)^N - 1}{p \cdot N} \cdot (1+p) \cdot 365 \qquad \text{Equation (1)}$$

B = weighted number of equivalent 10-t axle load repetitions in the design period,
N = design period in years,
DTV^{SV} = average number of heavy load vehicles per day [HV/24h],
q_{Bm} = load configuration factor (assumed as 0.2 acc. to RStO 01; 0.25 acc. to RStO 12)
f_A = average number of axles per heavy vehicle (assumed as f_A = 3.7 acc. to RStO 01, 4.0 acc. to RStO 12)
f_1 = lane factor (assumed as f_1 =0.5)
f_2 = lane width factor (assumed as f_2 =1.0)
f_3 = slope factor (assumed as f_3 =1.02)
p = average annual increase of heavy traffic (assumed as p = 0.0 according to the given traffic situation).

The pavement design is different for the two test sections and can be seen in the following Figure 2.

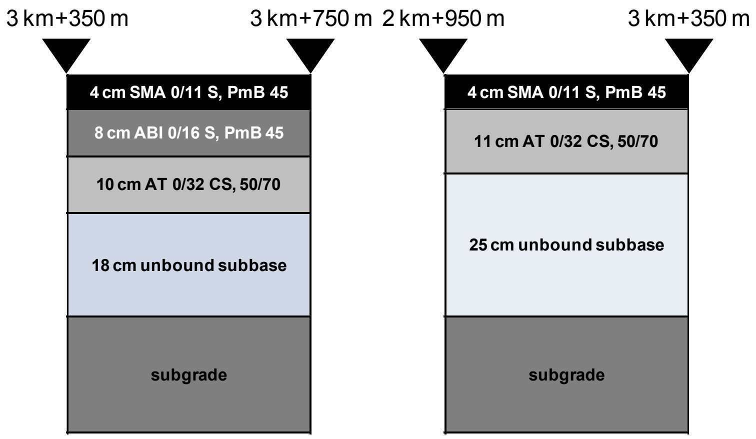


Figure 2. Pavement structure of the German test site (section 1: left and section 2: right).

Information on asphalt mix types is provided in Table 2. Abbreviations of mix types and binder types correspond to the way of use at the time of construction (2007), as well as today according to European Standards (2012).

Table 2: Asphalt mix types used for the German test section

	base course	binder course	wearing course
asphalt mix type (2007)	AT 0/32 CS	ABi 0/16 S	SMA 0/11 S
asphalt mix type (2012)	AC T 32 S	AC B 16 S	SMA 11
binder type (2007)	50/70	PmB 45 A	PmB 45 A
binder type (2012)	50/70	25/55-55 A	25/55-55 A
binder content [m-%]	3.9	4.7	6.2
softening point [°C]	56.4	64.4	67.0
void content [vol-%]	5.0	3.9	2.8
type of aggregate	gabbro	moraine	limestone

In section 1, the pavement is designed for a period of 30 years (approx. 11 Mio. ESALs) according to the German empirical pavement design catalogue (RStO 12, construction class II). As shown in Figure 2, the pavement consists of 18 cm unbound subbase (0/45 mm), 10 cm of base course (AC T 32 S, 50/70), 8 cm of binder course (AC B 16 S, PmB 45) and a wearing course of 4 cm in thickness (SMA 11 S, PmB 45).

The second section is (under)designed for a period of 8 years only (approx. 3 Mio. ESALs, according to German pavement design catalogue RStO 12). The pavement is composed of 25 cm unbound subbase (0/45 mm), 11 cm of base course (AC T 32 S, 50/70), and a wearing course of 4 cm in thickness (SMA 11 S, PmB 45).

2.2 Laboratory testing

For the purpose of characterizing the material performance and for deriving the necessary input parameters in the mechanistic design procedure, Cyclic Indirect Tensile Stress Tests (IDT) were performed in ISBS laboratory.

During IDT, a cylindrical specimen is loaded by a sinusoidal compressive stress σ_x applied vertically to the lateral area of the specimen. This provokes a stress contribution with a horizontal tensile loading of the specimen. Approximately, the stress ratio in the centre of the specimen is $\sigma_x/\sigma_y = 1/3$. By measuring the evolution of the horizontal stress σ_y (displacement of the horizontal diameter measured via LVDT), sinusoidal strain reaction can be derived from the test.

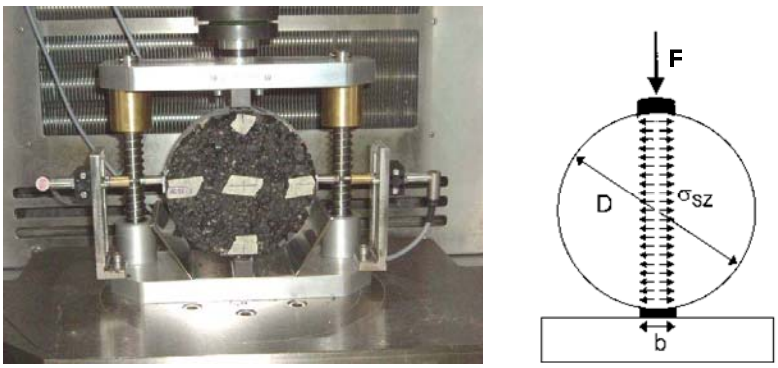


Figure 3: Layout of the Indirect Tensile Stress Test (IDT).

From IDT, stiffness characteristics and fatigue characteristics can be derived. In the fatigue test the specimen is loaded in controlled force-mode until failure. Usually, 9 single IDT are evaluated by plotting the number of load cycles until failure $N_{failure}$ versus the measured strain difference of the sinusoidal strain signal at the beginning of the test. The test results can be fitted by a power-law function, which is used as the fatigue law with the parameter a and the exponent k. For any strain value ε, the maximum allowed number of load cycles can be calculated from Equation 1. However, as distress mechanisms in pavements are far more complex that can be investigated by means of laboratory testing or modelling, any mechanistic-empirical pavement design needs to be adjusted or calibrated to the real pavement performance. For consistency, with empirical pavement design RStO an empirical shift-factor SF is introduced for IDT into the mechanistic design approach in order to adjust the output from mechanistic pavement design. The shift factor SF that is found exhibits a constant value of 1500 where the safety factor F depends on the design of the superstructure.

$$N_{f,D} = SF/F \cdot a \cdot \varepsilon^k \qquad \text{Equation (2)}$$

$N_{f,D}$ = maximum permissible number of load repetitions,
a = material parameter, determined by regression from fatigue tests,
ε = elastic strain (layered elastic theory),
k = material parameter, determined by regression from fatigue tests,
SF = shift-factor (for IDT SF = 1 500),
F = safety-factor (here F = 1.5).

Performance testing was realized, including characterization of stiffness and fatigue based on cores taken from the pavement in the years 2010 and 2012. Material originating from the year 2007 was used to produce asphalt mix specimens in the laboratory.

Results in terms of stiffness modulus in function of temperature and of fatigue behavior obtained from indirect cyclic tensile stress test are shown in Figure 4 and Table 3 respectively. Wöhler fatigue line is represented in Figure 5 for section 1. In Figure 6 and Table 4 the test results for section 2 are shown together with the Wöhler fatigue line in Figure 7.

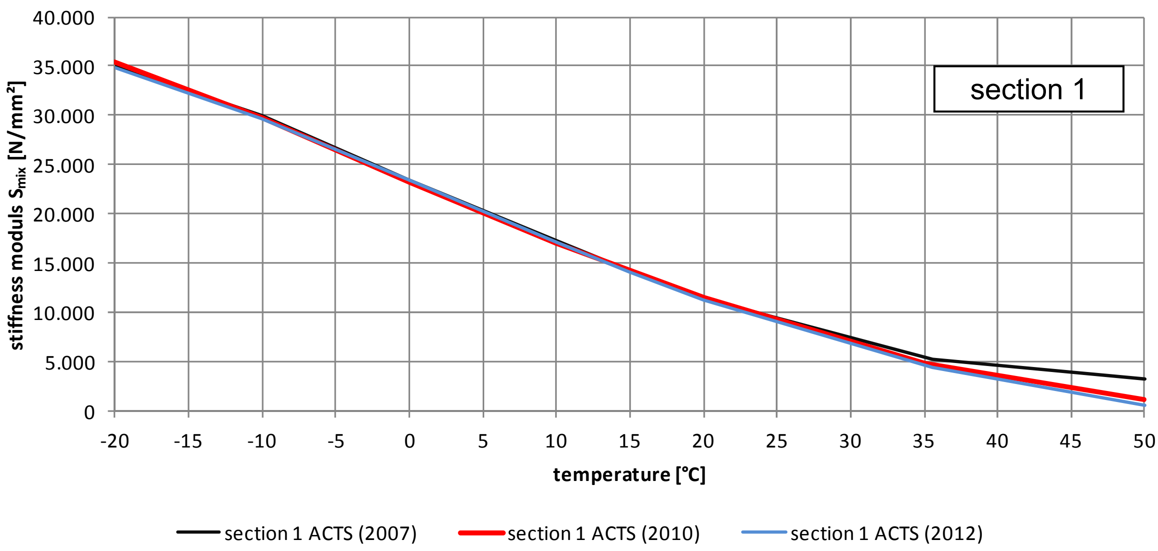


Figure 4. Section 1 Asphalt mix type AC T 32 S: stiffness modulus S_{mix} in function of temperature for the years 2007, 2010 and 2012.

Table 3: Section 1 Asphalt mix type AC T 32 S: stiffness modulus S_{mix} in function of temperature

Temperature [°C]	Stiffness moduls S_{mix} [N/mm²]		
	2007	2010	2012
-20	35000	35362	34774
-10	30058	29715	29685
0	23539	23188	23514
10	17233	17101	17102
15	14340	-	14084
20	11414	11594	11302
35	5239	4927	4522
50	3274	1159	540

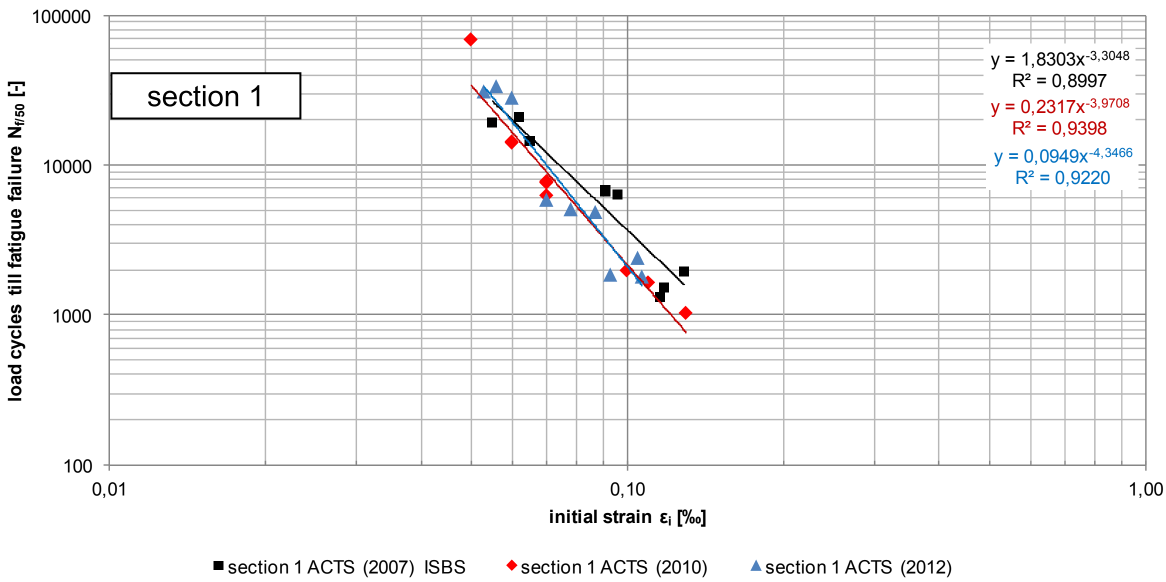


Figure 5. Section 1 Asphalt mix type AC T 32 S: fatigue behavior for the years 2007, 2010 and 2012.

Results for section 2 are shown in Figure 6, Table 4 and Figure 7.

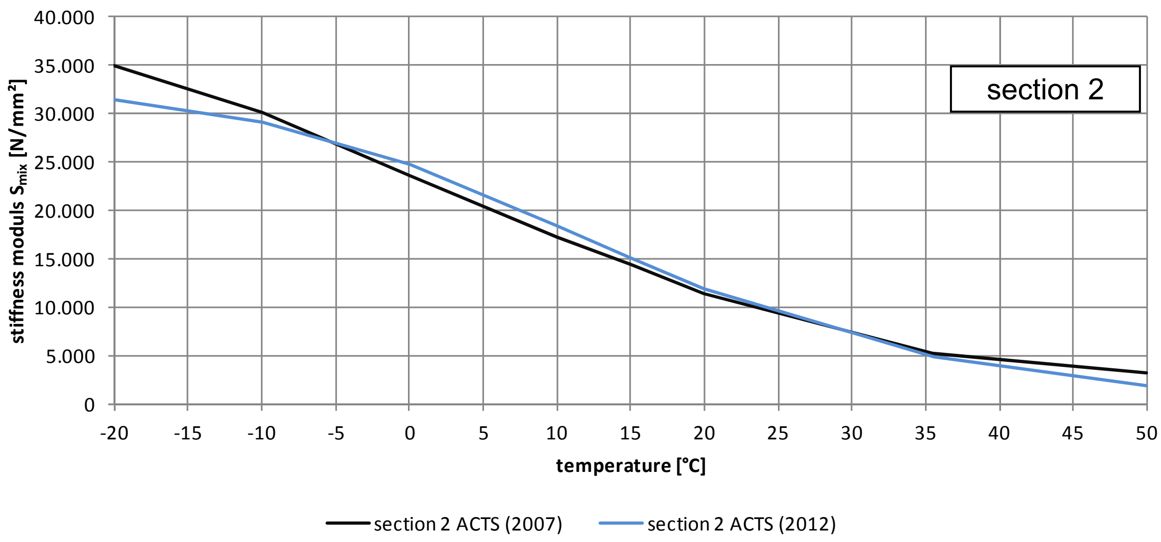


Figure 6. Section 2 Asphalt mix type AC T 32 S: stiffness modulus S_{mix} in function of temperature for the years 2007 and 2012.

Table 4: Section 2 Asphalt mix type AC T 32 S: stiffness modulus S_{mix} in function of temperature

Temperature [°C]	**Stiffness moduls S_{mix} [N/mm²]**	
	2007	**2012**
-20	35000	31469
-10	30058	29113
0	23539	24686
10	17233	18389
15	14340	15036
20	11414	11896
35	5239	4944
50	3274	1929

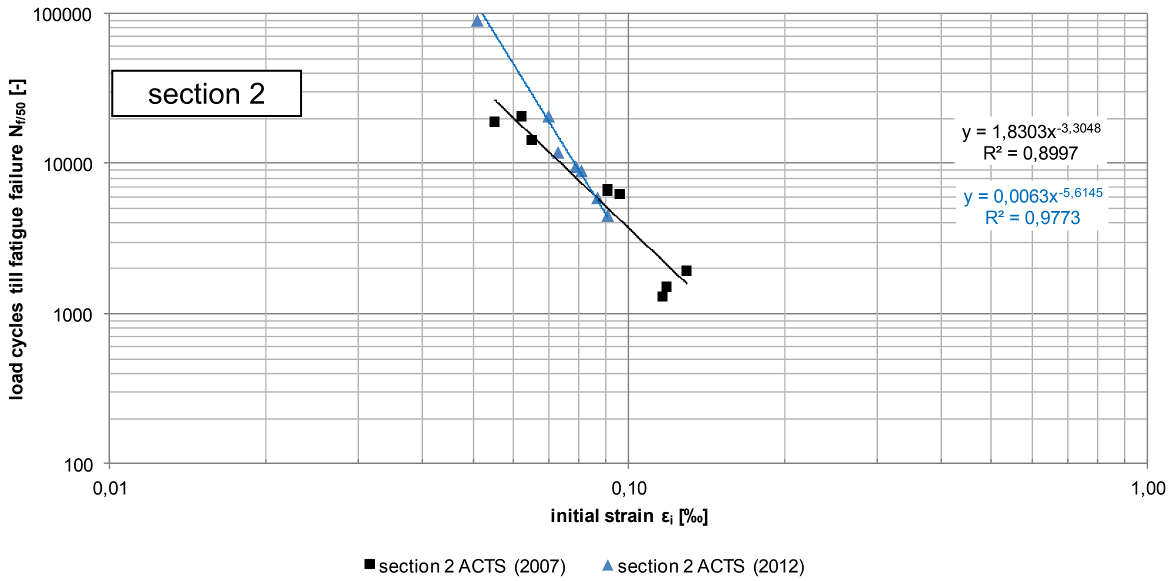


Figure 7. Section 2 Asphalt mix type AC T 32 S: fatigue behavior for the years 2007 and 2012.

Based on the laboratory data, a mechanistic pavement design model was used to estimate the remaining life of the pavement.

The number of load cycles till fatigue failure, as stated in the laboratory test, represents the fatigue life of the material for a given temperature and frequency. Fatigue life is defined as the number of cycles $N_{f/50}$ when the initial stiffness modulus S_{mix} has decreased to half of its initial value (cp. EN 12697-24). The resulting fatigue law (represented by the fatigue Wöhler line) indicates the fatigue life duration in function of the applied load amplitude.

Analysis of fatigue evolution requires a damage hypothesis. Linear damage law is assumed for constant loading conditions per analysis interval. Accumulation of damage is realized by linear summation applying Miner's law. Here the incremental damage in the analysis interval i is calculated from the number n_i of load repetitions accumulated during the interval, and the number $N_{f,i}$ of load repetitions until failure that is obtained from fatigue testing and Wöhler curve modeling. Cumulative damage D_{lab} over total analysis period is composed of individual incremental damage ratios, reading

$$D_{lab} = \sum_{i=1}^{n} \frac{n_i}{N_i} \leq 1 \qquad \text{Equation (3)}$$

where n_i is the number of actual load repetitions at strain/stress level i, and N_i is the number of allowable load repetitions to failure at strain/stress level i. This equation allows predicting fatigue life in terms of the number of theoretically allowable load repetitions (due to traffic and/or thermal load cycles). If cumulative damage value D_{lab} equals 1, the pavement fails due to material fatigue, and hence, the pavement substance value has decreased to 0 % of the initial value.

As a result the remaining life can be calculated for defined loading conditions from the ratios individually derived from the number of allowed load applications to the mean number of traffic load applications.

Load repetitions shown in Table 5 are derived from back-calculation. Here the number of load repetitions are calculated when equation 2 reaches the value 1.0. Remaining life is finally expressed by the number of load repetitions until the end of fatigue life, in terms of a

10-tons standard axle load. The analytical tool for the design analysis is described in Deliverable D1.

Table 5: Back-calculated remaining life in numbers of 10-t-axle load repetitions (ESALs) until end of fatigue life according to German RDO Asphalt 09 ("B-Zahl" for Miner Sum ≈ 1).

Year	Load repetitions (ESALs) [-]	
	Section 1	Section 2
2007	27 043 130	4 465 138
2010	19 847 422	-
2012	17 800 010	1 064 764

Based on an average value of 0.35 Mio. ESALs per year a remaining life can be estimated for the two test sections. Taking the back-calculated load repetitions of the 2007 material into account the remaining live on section 1 results to a number of more than 77 years and on section 2 to more than 12 years, which is much higher as the design period. A different result comes up, if the back-calculated load repetitions from the 2012 material will be used for this estimation. On section 1 a remaining life of 50 years and on section 2 of 3 years could be calculated for the year 2012. Taking the time difference between 2007 and 2012 into account (5 years) the service life of section 1 results in a value of 55 years and on section 2 in a value of 8 years. The value of section 2 is equal to the design period in comparison to section 1, which still shows an overdesigned situation.

A main reason of the big differences between the 2007 and 2012 material are the samples themself. The 2007 material is a retained sample and not a core of the pavement like the material from 2012. Thus, the actual compaction and other local influencing factors were not taken into consideration to the needed extend.

This example shows clearly, that more accurate results can be derived from samples taken directly from the road. Of course, during the design process the pavement is not constructed, so that these influencing factors cannot be taken into account. But it should be known, that these factors are sensitive and thus having an influence to the prognosis of future condition (see also chapter 3.3.1).

3 PMS application

3.1 Overview of approach

The procedure of integration of material-science based performance models into life-cycle-analysis in the frame of PMS, the procedure can be subdivided into the following 3 steps (see also Deliverable 3):

(1) Section based calibration of the selected EPF
(2) Analysis of laboratory fatigue testing results
(3) Integration of laboratory results into the EPF (calibration procedure)

The first step is the calculation of the actual load repetitions and the starting point of the EPF. This is usually carried out in form of section based calibration or adaptation of the EPF by using the section-specific inventory data, traffic information, the respective model-parameters and, of course, condition data from actual condition inspections or measurements. This adaptation of the EPF usually causes a change in the slope of the function and moves the curve into the measured point (= last point of condition measurement, if available). In those cases, where a new construction or a pavement without any distress (e. g. cracking) is assessed, the “general” model is taken as a section-specific performance model.

As to the next process-step, the number of load repetitions $N_{f,D}$, where the pavement construction reaches the damage D_{lab} attributed to the end of fatigue life. The number of load repetitions $N_{f,D}$ is the essential output of the coring and laboratory fatigue testing for the calibration procedure. For the testing of the samples it is important, that the coring and the last condition measurement are carried out at the same time, so that an additional damage caused by additional number of loadings is minimized. In case of using the age as the input parameter for the EPF (instead of load repetitions) the $N_{f,D}$ needs to be translated into years (or intervals).

For the integration of the results of the laboratory fatigue tests into the calibrated EPF – step 3 - , the damage D_{lab} with the corresponding load repetitions $N_{f,D}$ needs to be brought in line, on the one hand, with the section specific (calibrated) performance function and, on the other hand, with a specific damage status on the road D_{road}. Thus, it is necessary to calculate the number of load repetitions $N_{PI',D}$ where PI of the calibrated EPF reaches the damage stage D_{road}. In many cases this will be a damage stage, where the pavement shows a substantial distress and should be exhaustively maintained.

For the integration of the fatigue test results into the calibrated EPF a strain factor X_f is used, which compares the number of load repetitions from the laboratory $N_{f,D}$ and the number of load repetitions $N_{PI',D}$, where D_{lab} is in accordance with D_{road}.

In practice, the strain factor X_f stretches or shrinks the EPF along the N-axe and enables a new performance prediction of the PI for any time t+N of the analysis period in the life-cycle process.

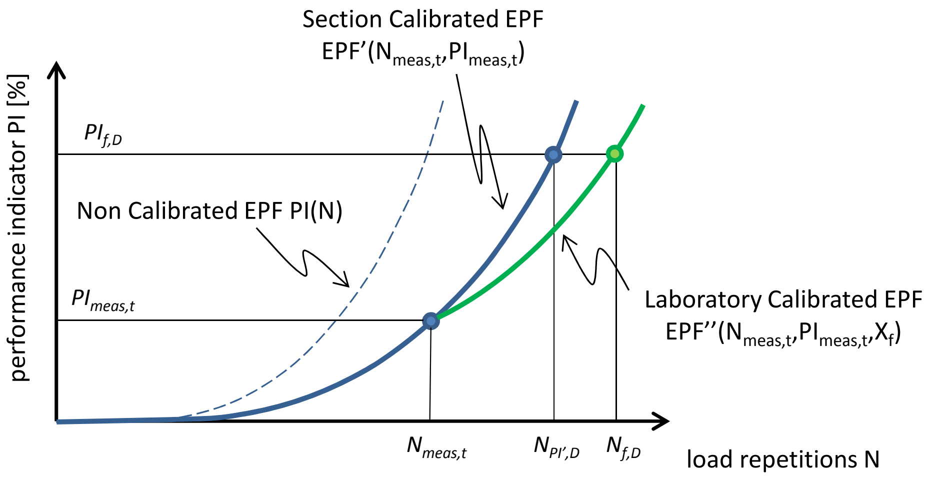


Figure 8 schematically shows the integration of the results of laboratory fatigue testing into the performance prediction model.

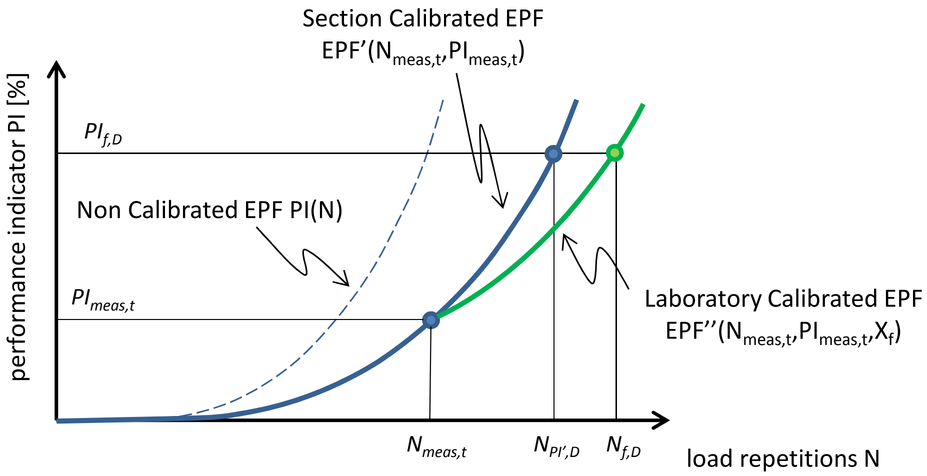


Figure 8: Overview of calibration steps (schematically)

3.2 Calibration procedure

3.2.1 Incorporation of test-site data into the general EPF

For practical application of the approach described above, three different performance prediction models were selected during the previous activities and implemented into the commercial PMS software tool dTIMS CT^{TM}. Together with the information of the test sites (see Chapter 2) all 3 models can be calibrated by using the pavement construction information, the traffic data and the condition information from the last pavement condition measurement within this first step of calibration.

The results of these activities are the section-specific calibrated EPF, which can be seen in the following Figures (section 1 in Figure 9, and section 2 in Figure 10). 2007, the year of construction, was used as the starting point for all functions.

These Figures illustrate for both test-sections, that all three calibrated EPF show a high variation of deterioration. Especially, the German model shows an increase of the cracking rate over 1% at a stage, where the Austrian model and the HDM4 model have already reached a high cracking rate.

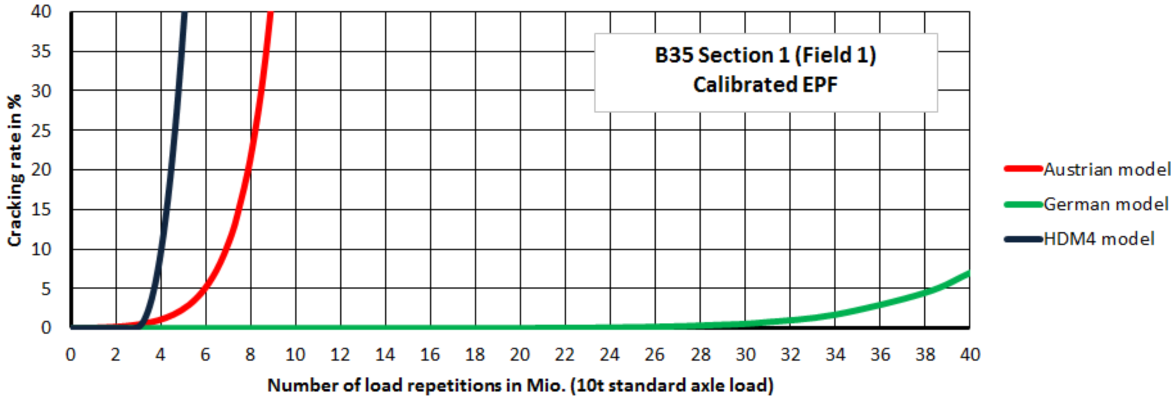


Figure 9: Calibrated EPF of test section 1, considering only the first step of calibration.

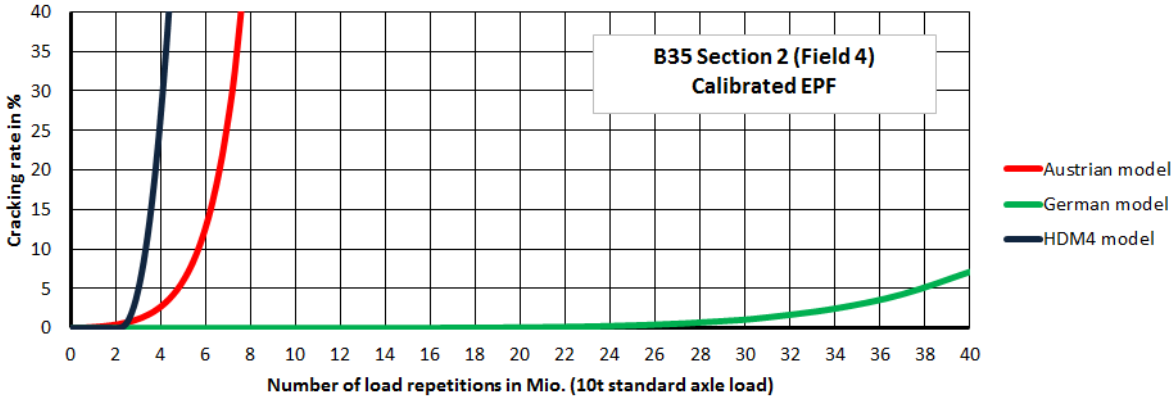


Figure 10: Calibrated EPF of test section 2, considering only the first step of calibration.

As an output of the Life-Cycle-Analysis (LCA), carried out within dTIMS CT^{TM}, the year of the first major (exhaustive) maintenance treatment (related to cracking rate only) can be displayed and used as an indicator for the assessment of the three models. As trigger for the maintenance treatment a cracking threshold of 10 % cracking rate (according to German Standards) was used (see also

Table 10). In Table 6 these results are summarized for both test sections. The annual load repetitions (based on 10-tons standard axle load) can be estimated with approximately 0.35 Mio. equivalent standard axle loads (ESAL) according to the German Standard (RStO, 2012).

Table 6: Results of LCA for the calibrated EPF (1st stage of calibration)

	Model		
	Austrian	**German**	**HDM-4**
Section 1 (field 1)			
Year of 1st major treatment	20	>40	11
Type of 1st major treatment	Reinforcement	Reconstruction	Replacement wearing course and binder
Section 2 (field 4)			
Year of 1st major treatment	17	>40	9
Type of 1st major treatment	Reinforcement	Reconstruction	Replacement wearing course and binder

The curves in Figure 10 as well as the numbers in Table 6 underline the necessity of an additional calibration step including the results of laboratory asphalt testing. Without this additional step, it is difficult to find out, which of the three models offers the best approach under the given local requirements. In the following chapter this additional step is described in detail for all three models.

3.2.2 Incorporating laboratory test results into section-specific EPF

Because of the different mathematical formulation of crack deterioration in each of the three EPF, the second step of the calibration needs to be carried out in different ways. The basic idea for the incorporation of laboratory test results into the performance function is to shrink or stretch the section calibrated EPF along the loading axe (x-axe). As shown in Deliverable 2, the German model is the only function, which enables a direct calibration of load repetitions in comparison to the Austrian and the HDM4 model, which are mainly influenced by the age or the year of crack initiation. This means, that for the second level of calibration the load repetitions have to be transformed into years for the Austrian model and the HDM4 model, taking into account the estimated traffic forecast of the sections to be assessed. Because of the location of the test sites in Germany, the calculation of the traffic loading is based on the German pavement design standard RStO 12 (RStO, 2012) including the traffic data shown in Table 1.

Again, the total number of load repetitions B, which is considered in pavement design according to German Standard RStO 12 is calculated from:

$$B = N \cdot DTV^{SV} \cdot q_{Bm} \cdot f_A \cdot f_1 \cdot f_2 \cdot f_3 \cdot \frac{(1+p)^N - 1}{p \cdot N} \cdot (1+p) \cdot 365 \qquad \text{Equation (1)}$$

B = weighted number of equivalent 10-t axle load repetitions in the design period,
N = design period in years,
DTV^{SV} = average number of heavy load vehicles per day [HV/24h],
q_{Bm} = load configuration factor (assumed as 0.2 acc. to RStO 01; 0.25 acc. to RStO 12)
f_A = average number of axles per heavy vehicle (assumed as f_A = 3.7 acc. to RStO 01, 4.0 acc. to RStO 12)
f_1 = lane factor (assumed as f_1 =0.5)
f_2 = lane width factor (assumed as f_2 =1.0)
f_3 = slope factor (assumed as f_3 =1.02)
p = average annual increase of heavy traffic (assumed as p = 0.0).

The relationship between the age of the pavement and the number of load repetitions (10 tons standard axle load) are shown in the following Figure 11.

Figure 11: Load repetitions vs. age of pavement

The correlation shown in Figure 11 allows transforming the number of load repetitions into the age of the pavement and enables to calculate the strain factors X_f for both sections and for all models to be assessed within this project. By doing so, the strain factor X_f stretches or shrinks the EPF along the x-axe, which represents either the number of load repetitions or the pavement age. Because of the different characteristics of the models, the calculation of the strain factor X_f is different for each of the three functions. Table 7 gives an overview of the calculation method of the different strain factors X_f considering the three different models.

Table 7: Calculation procedure of strain factors for Austrian, German and HDM-4 model

Austrian model

Incorporation of strain factor X_f into the age-parameter:

$$TP_{cracking,labcalib} = \exp\left[-3.60517 + a \cdot X_f \cdot Age_{Surflayer} + \ln\left(X_f \cdot Age_{Surflayer} + 0{,}01\right) - 0.5 \cdot \ln\left(DI + 0.01\right)\right]$$

with $X_f = \dfrac{Age_{D(road)}}{Age_{D(lab)}}$

and:

$TP_{cracking,labcalib}$ .... technical parameter cracking laboratory calibrated
X_f .... strain factor
a .... model parameter
DI .... design index
$Age_{D(road)}$ .... age at damage D on the road (test section)
$Age_{D(lab)}$ .... age at end of fatigue life from laboratory testing

Comment: By taking the traffic model into account, the number of load repetitions can be transformed into an age-parameter.

German model

Incorporation of strain factor X_f into cumulated load repetitions:

$$z_{i,j,t,labcalib} = \alpha_{i,j,k} + \beta_{i,j,k} \cdot \left(X_f \cdot AL_{i,t}\right)^{c_{j,k}}$$

with $X_f = \dfrac{N_{D(road)}}{N_{D(lab)}}$

and:

$z_{i,j,t,labcalib}$ .... technical parameter cracking laboratory calibrated
X_f .... strain factor
$\alpha_{i,j,k}$, $\beta_{i,j,k}$, $c_{j,k}$ .... model parameter
$AL_{i,j,k}$ .... cumulative standard axle loads (load repetitions)
$N_{D(road)}$ .... number or load repetitions at damage D on the road (test section)
$N_{D(lab)}$ .... number or load repetitions at end of fatigue life from laboratory testing

HDM-4 model – option A

Incorporation of strain factor X_f into the fraction of analysis year in which cracking progression applies:

$$\delta t_{A,labcalib} = \max\{0, \min[(Age + X_f - ICA), 1]\}$$

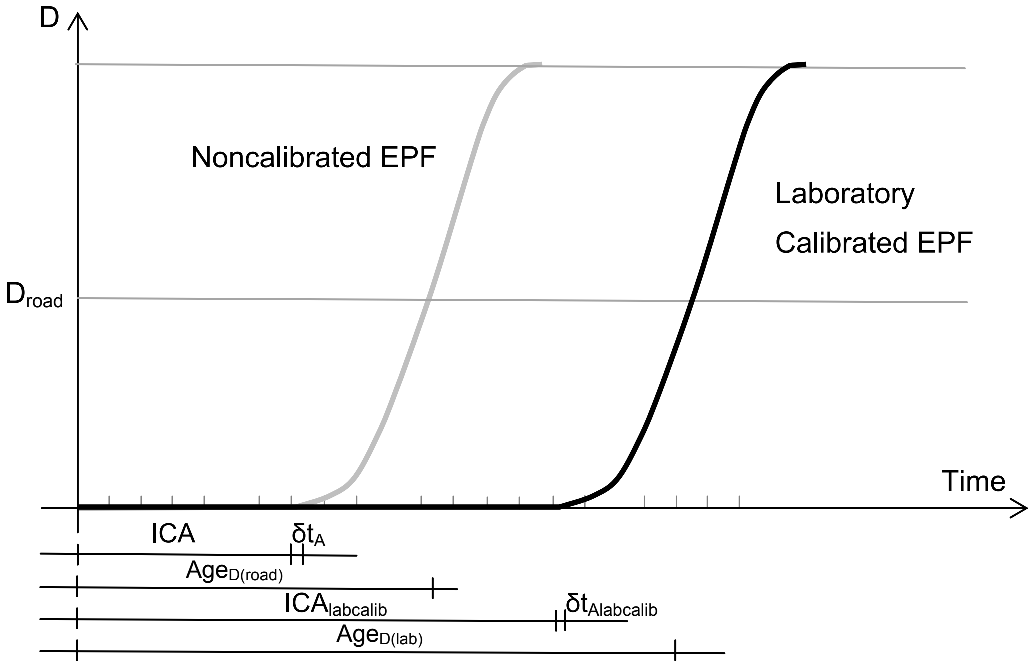
with $X_f = Age_{D(road)} - Age_{D(lab)}$

and

$\delta t_{A,labcalib}$ .... laboratory calibrated fraction of analysis year in which cracking progression applies
Age .... pavement surface age since last reseal, overlay, reconstruction, or new construction
ICA .... time to initiation of "all" structural cracking in years
$Age_{D(road)}$ .... age at damage D on the road (test section)
$Age_{D(lab)}$ .... age at end of fatigue life from laboratory testing

Comment: By taking the traffic model into account, the number of load repetitions can be transformed into an age-parameter.

The approach A assumes default length of cracking progression phase and adjust length of cracking initiation phase ICA, as presented in the following figure:



HDM-4 model – option B

Incorporation of strain factor X_f into calibration factors K_{cia} and K_{cpa} based on cumulative load repetitions or age-parameter:

with $X_f = \frac{Age_{D(road)}}{Age_{D(lab)}}$, $K_{cpa} = k \cdot X_f; K_{cia} = \frac{1}{K_{cpa}}$

and:

- Age.......................... pavement surface age since last reseal, overlay, reconstruction, or new construction
- $Age_{D(road)}$.................. age at damage D on the road (test section)
- $Age_{D(lab)}$ .... age at end of fatigue life from laboratory testing
- K_{cia}........................... calibration factor for initiation of “all” structural cracking
- K_{cpa}........................... calibration factor for progression of “all” structural cracking
- k .... scaling factor obtained from the following condition:

Comment: By taking the traffic model into account, the number of load repetitions can be transformed into an age-parameter.

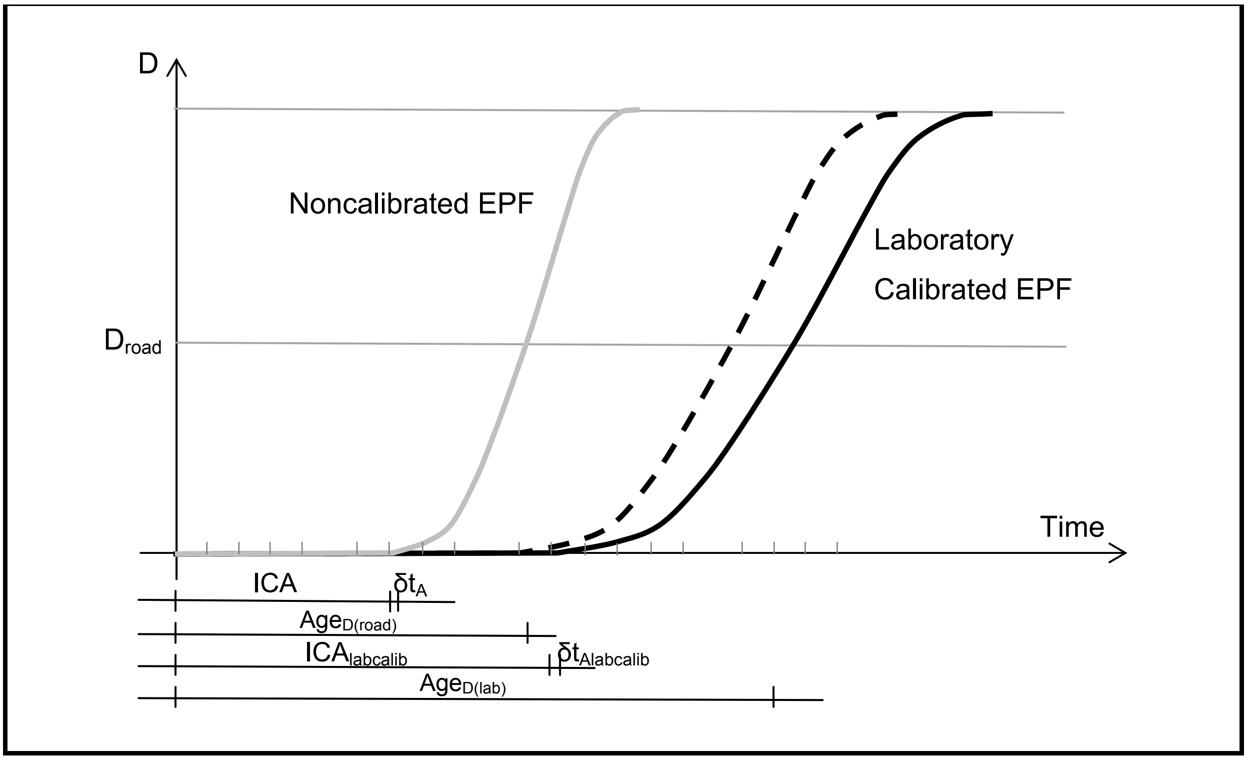
The objective of the approach B is to achieve proportional extension or shortening of both, cracking initiation and cracking progression phases. The calibration is performed in two steps.

In the first step (dashed line in the following figure) cracking progression coefficient K_{cpa} is assigned value of the strain factor Xf. In order to achieve proportional extension or shortening of cracking initiation phase, calibration factor K_{cia} has the reciprocal value of K_{cpa}. The age at which damage D is achieved with this model would not typically be equal to the age at the end of fatigue life from laboratory testing.

Therefore, in the second step, cracking progressing factor K_{cpa} is multiplied by the scaling factor k obtained from the condition:

$$AGE_{D(labcalib\ EPF)} = AGE_{D(lab)}$$

Calibration factor for cracking initiation K_{cia} has the reciprocal value of K_{cpa}.



Beside the combination of different load repetitions the damage stage from fatigue testing needs to be brought in line with damages or distresses observed on the test site. Thus, it is necessary to define a critical damage stage, which can be either a given threshold or a value, where a substantial damage stage will be reached.

3.2.3 Relationship between field and laboratory fatigue performance of asphalt mixtures

The fatigue law expressed by the cracking rate and used in the pavement management software dTIMS CT™, is based on the amount of fatigue cracking observed on the surface of road sections. The problem with prediction of fatigue cracking in the field, based on laboratory testing only, is that a significant shift factor needs to be applied to laboratory-determined fatigue relation, which depends on many factors such as:

- loading conditions including vehicle type and axle configuration, rest periods between vehicle loads, lateral wander of traffic,
- environmental effects,
- asphalt healing, and
- differences in geometry and test conditions in pavements and in laboratory tests (Molenaar, 2007).

The tolerable cracking level may vary depending on the design traffic loading, but generally ranges between 10 % and 45 % of the wheelpath area (Baburamani, 1999). Accordingly, the laboratory-field-shift-factor also varies depending on the tolerable level of cracking assigned in the design phase, and typically ranges between 10 and 20.

Based on the AASHTO Road Test data and observed cracking in the field, laboratory-field-shift-factors of 13.4 and 18.45 for 10 % and 45 % cracking (in the wheelpath areas) were obtained by Finn et al. (1986). 45 % of wheelpath cracking is considered as failure, which is equivalent to 20 % of the total pavement area. These criteria for pavement failure were later consistently applied in the design methods of Shell (1978) and of the Asphalt Institute (1982). The Asphalt Institute used a criteria of „20 % or greater fatigue cracking (based on total pavement area)".

It has to be clearly stated again, that the performance of fatigue during laboratory testing is not equal to the development of cracking (expressed by a cracking rate) on the road. Thus, the end of fatigue life does not mean a fully cracked road with a cracking rate of 100%. Nevertheless, the end of fatigue life can be seen on the road in form of distresses, where cracking is one the most significant indicators. Thus, the end of fatigue life (based on laboratory testing) has to be brought in correlation with the (real) cracking on the road. E.g. 20% of cracked area (D_{road}) on the test section is equal to D_{lab} = 1 as an output of laboratory fatigue testing. In the following up calculations the end of fatigue life (based on laboratory testing) was correlated with different cracking rates on the test sections (5, 10 and 20%) to show the sensitivity of this approach.

3.3 Results of calibration

3.3.1 Strain factors

Based on the calculation procedure for the different strain factors X_f and the described relationship between field and laboratory fatigue performance of asphalt mixtures a series of strain factors X_f for all three different performance prediction models was calculated by using data from samples and cores taken from the pavement in the year 2007 and 2012. The values of the factors and their underlying input data are shown in Table 8 and Table 9. Because of a lack of information of material taken from 2010 on section 2, the evaluation and following up assessment was carried out for the results based on data from 2007 and 2012 only.

Based on the principles described in the previous chapter, the damage status on the road D_{road} to be used for the calculation of the strain factors X_f has been varied between 5, 10 and 20% cracking rate. This enables to show the sensitivity of D_{road} within the analysis.

Table 8: Strain factors for Austrian, German and HDM4 model – section 1

Parameter	2007 data			2012 data		
	D_{road} model			D_{road} model		
	5%	10%	20%	5%	10%	20%
Austrian model						
$Age_{D(road)}$	17	20	22	17	20	22
$Age_{D(lab)}$	77			56		
X_f	0.22	0.26	0.29	0.30	0.36	0.39
German model						
$N_{D(road)}$	38.5	42.1	45.2	38.5	42.1	45.2
$N_{D(lab)}$	27.04			19.55		
X_f	1.42	1.56	1.67	1.97	2.15	2.31
HDM4 model – option A						
$Age_{D(road)}$	11	12	13	11	12	13
$Age_{D(lab)}$	77			56		
X_f	-66	-65	-64	-45	-44	-43
HDM4 model – option B						
$Age_{D(road)}$	10.5	11.4	12.7	10.5	11.4	12.7
$Age_{D(lab)}$	77			56		
X_f	0.136	0.148	0.164	0.188	0.205	0.227
k	0.801	0.810	0.812	0.818	0.823	0.819

Table 9: Strain factors for Austrian, German and HDM4 model – section 2

Parameter	2007 data			2012 data		
	D_{road} model			D_{road} model		
	5%	10%	20%	5%	10%	20%
Austrian model						
$Age_{D(road)}$	14	17	19	14	17	19
$Age_{D(lab)}$	13			8		
X_f	1.08	1.31	1.46	1.75	2.13	2.38
German model						
$N_{D(road)}$	38.0	42.2	46.9	38.0	42.2	46.9
$N_{D(lab)}$	4.47			2.81		
X_f	8.50	9.44	10.49	13.52	15.02	16.69
HDM4 model – option A						
$Age_{D(road)}$	9	10	11	9	10	11
$Age_{D(lab)}$	13			8		
X_f	-4	-3	-2	1	2	3
HDM4 model – option B						
$Age_{D(road)}$	8.5	9.5	10.7	8.5	9.5	10.7
$Age_{D(lab)}$	13			8		
X_f	0.670	0.743	0.842	1.063	1.178	1.336
k	0.886	0.900	0.907	0.941	0.907	1.000

3.3.2 Laboratory calibrated EPF

As an output of the PMS analysis, Figure 12 to Figure 23 illustrate the laboratory calibrated EPF (second level of calibration) for all strain factors displayed in Table 8 and Table 9. The curves are calculated for damages of 5, 10 and 20 % of cracking rate on the test sites (D_{road}). On the x-axes, the numbers of load repetitions related to the 10-tons standard axle loads are always displayed.

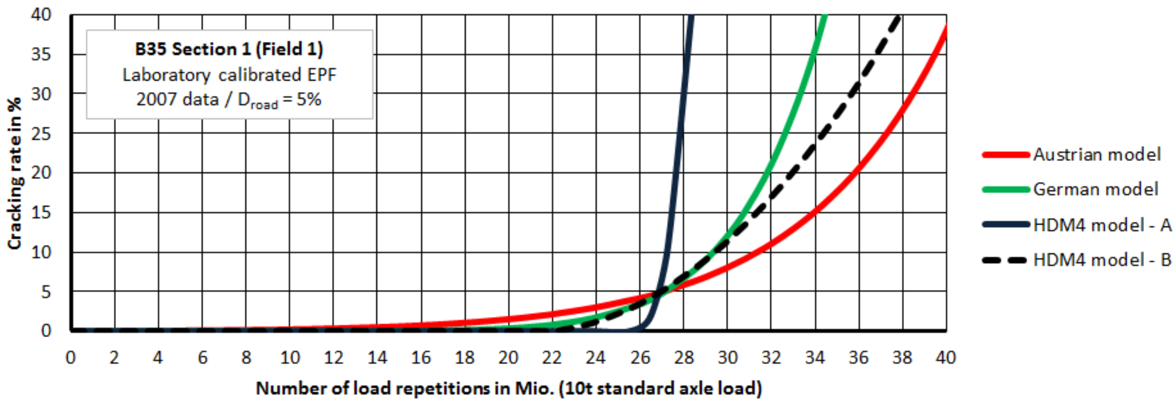


Figure 12: Laboratory calibrated EPF for section 1: 2007 data / D_{road} = 5 %.

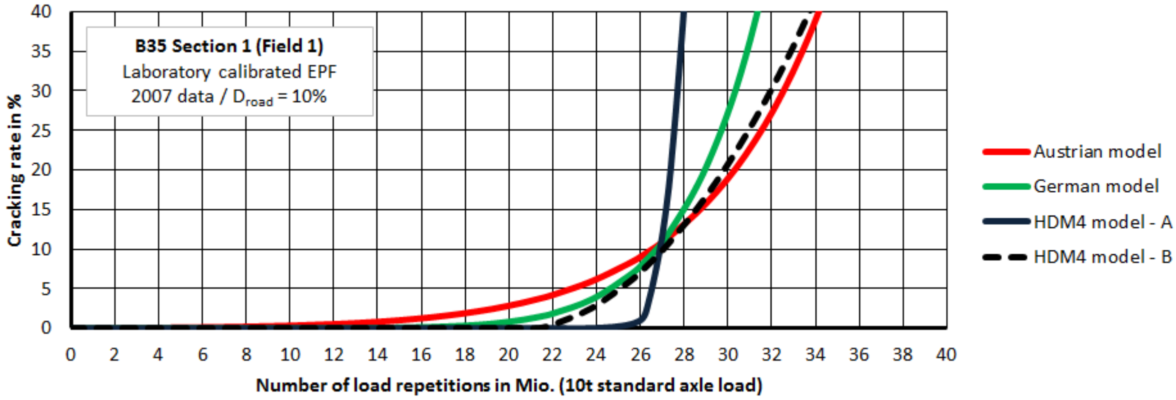


Figure 13: Laboratory calibrated EPF for section 1: 2007 data / D_{road} = 10 %.

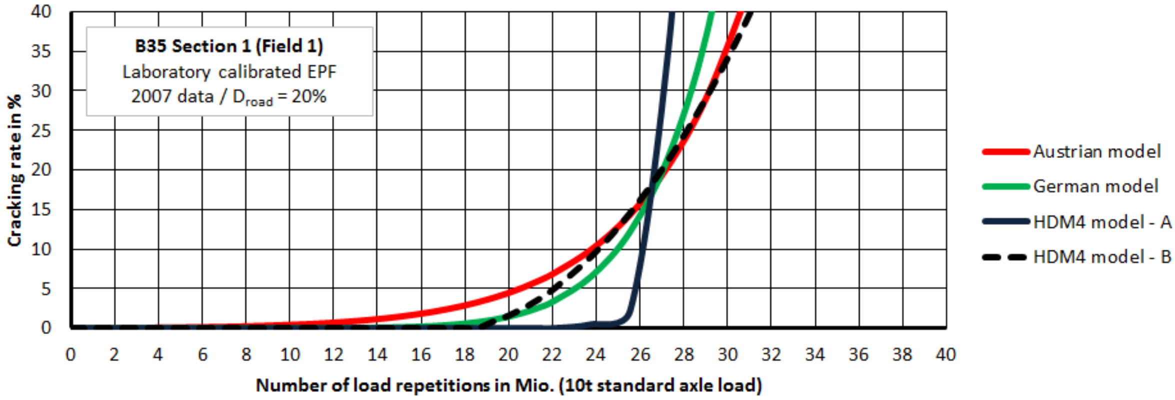


Figure 14: Laboratory calibrated EPF for section 1: 2007 data / D_{road} = 20 %.

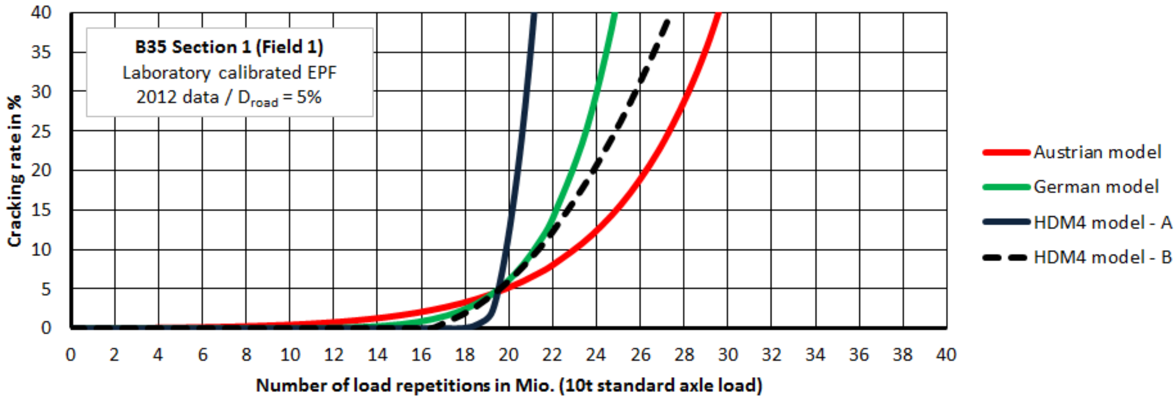


Figure 15: Laboratory calibrated EPF for section 1: 2012 data / D_{road} = 5 %.

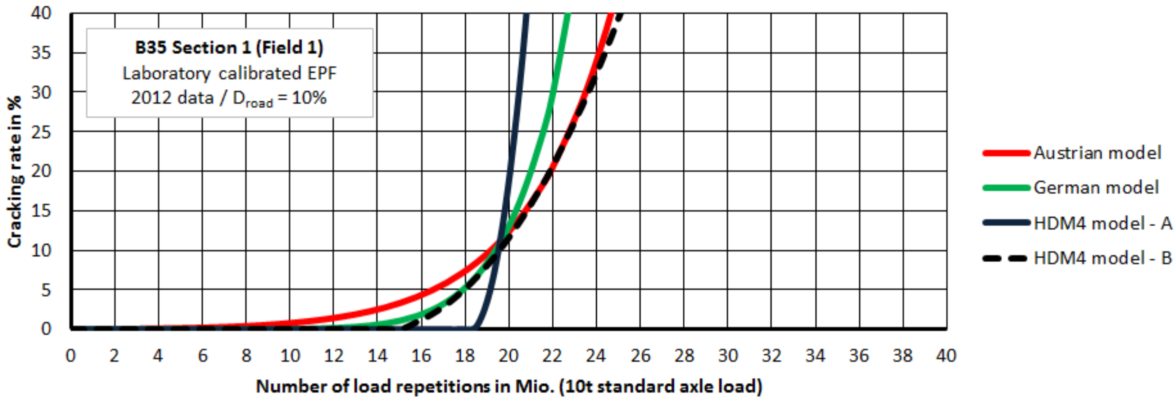


Figure 16: Laboratory calibrated EPF for section 1: 2012 data / D_{road} = 10 %.

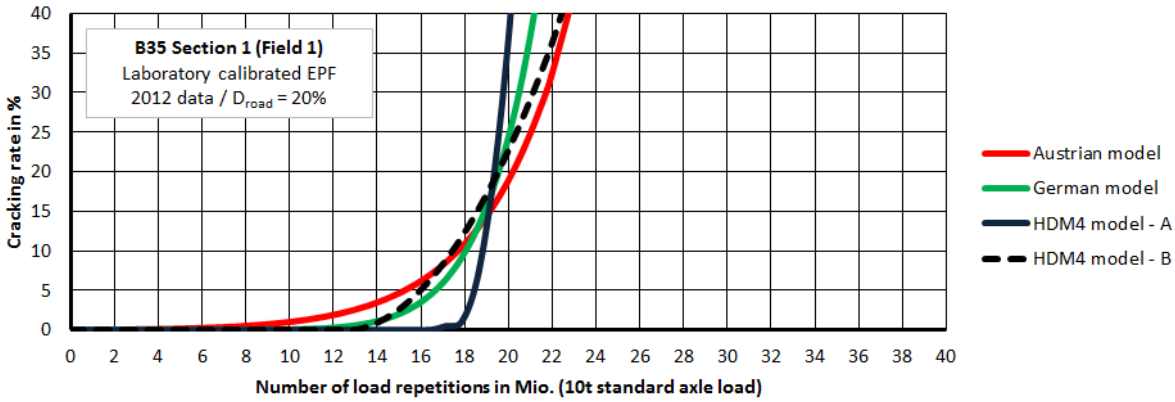


Figure 17: Laboratory calibrated EPF for section 1: 2012 data / D_{road} = 20 %.

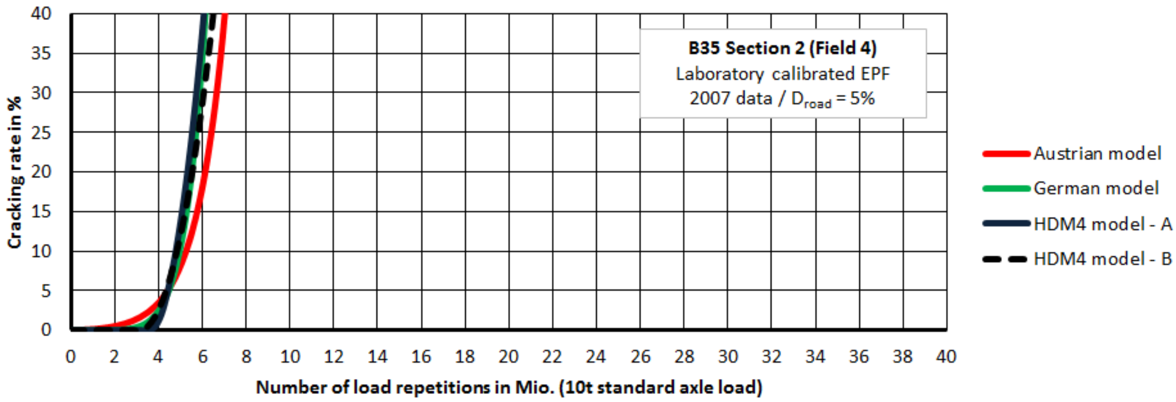


Figure 18: Laboratory calibrated EPF for section 2: 2007 data / D_{road} = 5 %.

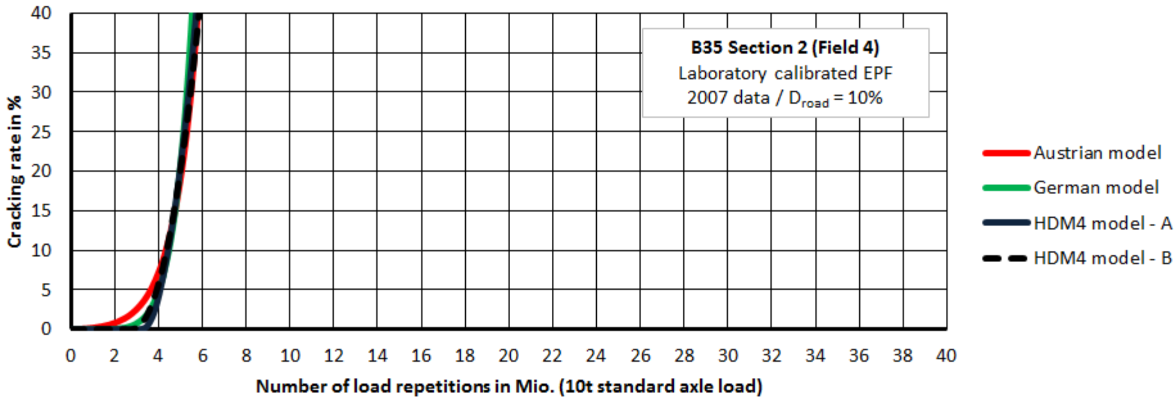


Figure 19: Laboratory calibrated EPF for section 2: 2007 data / D_{road} = 10 %.

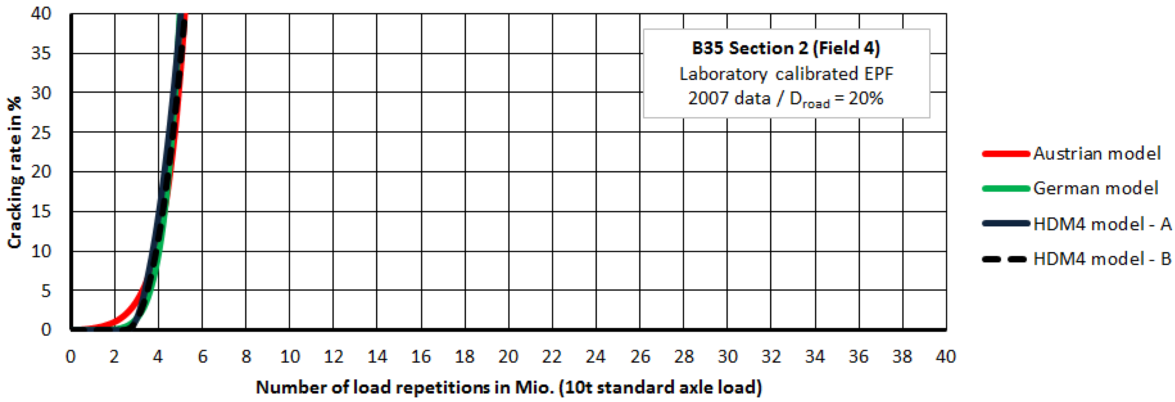


Figure 20: Laboratory calibrated EPF for section 2: 2007 data / D_{road} = 20 %.

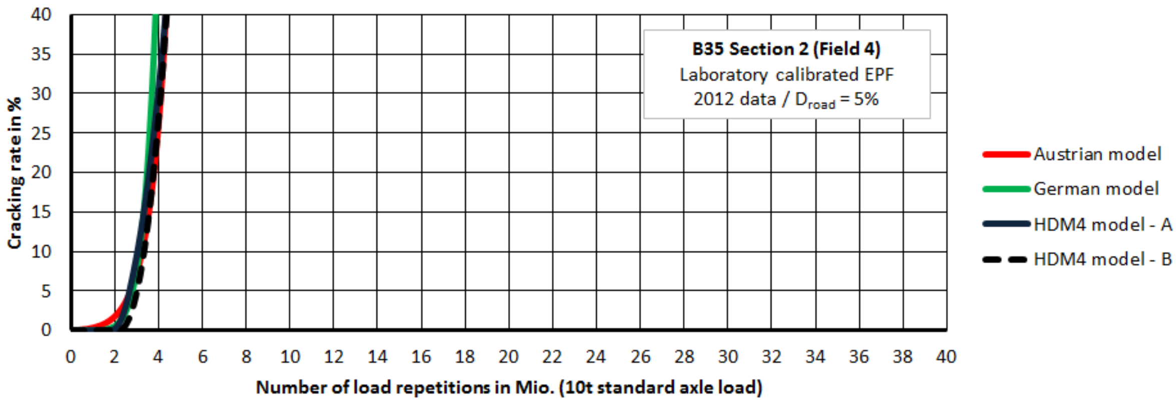


Figure 21: Laboratory calibrated EPF for section 2: 2012 data / D_{road} = 5 %.

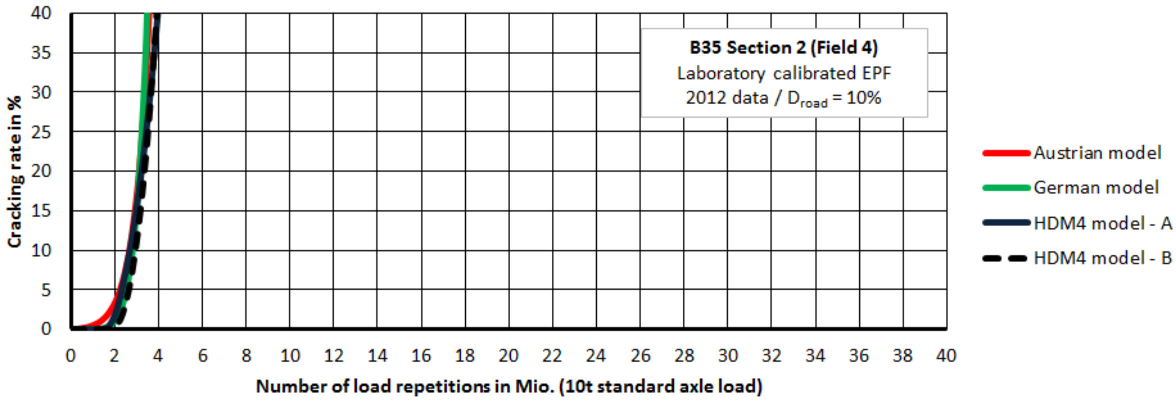


Figure 22: Laboratory calibrated EPF for section 2: 2012 data / D_{road} = 10 %.

Figure 23: Laboratory calibrated EPF for section 2: 2012 data / D_{road} = 20 %.

On both sections, the incorporation of the results from asphalt fatigue testing into the EPF shows a significant reduction of the variation of the trend. Especially on section 2 – under-designed pavement construction – the curves are almost congruent over the assessed loading period.

The curves on section 1 vary more before and after the cracking rate D_{road}, which was selected for the calculation of the strain factor X_f. This variation is strongly dependent on the model itself, and is more distinct when D_{road} is decreasing (compare section 1 with D_{road} = 5% and 20%). This means, that the selection of a calibration point after the range with the highest curvature reduces the variation of the trend.

A difference in the results can be seen by using the output of laboratory asphalt fatigue testing derived from samples, which were taken from the year 2007 (year of construction), and from cores, which were taken from the pavement of the two test sites in year 2012. However, the increase of fatigue is disproportionate to the increase of traffic loading. The annual load repetitions (based on 10-tons standard axle load) can be estimated with approximately 0.46 Mio. equivalent standard axle loads (ESAL) according to the German Standard (RStO 2012). This means, that beside the load repetitions, the aging and other influencing factors cause higher road deterioration.

3.3.3 Maintenance treatment recommendation

Beside the trend and the variation of the selected functions, the year and the type of the first major (exhaustive) maintenance treatment due to cracking is another essential indicator for the assessment of the procedure and an output of the PMS analysis based on LCA/LCCA by using dTIMS CT™.

Because of the small network analysed a threshold criteria of 10 % cracking rate was used to select adequate maintenance treatments for both test sections. In

Table 10 the triggers for the different treatments are shown.

Table 10: Triggers for major (exhaustive) maintenance treatments due to cracking used for PMS analysis

Abbrev.	Description	Trigger
REPLW	Replacement of wearing course only	Cracking rate > 10% and Age =< 10 years
REPLWB	Replacement of wearing course and binder course	Cracking rate > 10% and Age > 10 years and Age =< 15 years
REIN	Replacement of wearing course and binder course, strengthening of bituminous base course (reinforcement)	Cracking rate > 10% and Age > 15 years and Age =< 30 years
REC	Reconstruction of all bound layers	Cracking rate > 10% and Age >= 30 years

The practical application of the triggers of major (exhaustive) maintenance treatments shown in

Table 10 leads to specific maintenance recommendation for section 1 and section 2. These recommendations are listed in Table 11 and Table 12.

Table 11: Maintenance treatment recommendation for section 1

1st major treatment due to cracking	2007 data			2012 data		
	D_{road} model			D_{road} model		
	5%	10%	20%	5%	10%	20%
Austrian model						
year 1st treatment	>40	>40	>40	>40	>40	>40
type 1st treatment	-	-	-	-	-	-
German model						
year 1st treatment	>40	>40	>40	>40	>40	>40
type 1st treatment	-	-	-	-	-	-
HDM4 model A						
year 1st treatment	>40	>40	>40	>40	>40	>40
type 1st treatment	-	-	-	-	-	-
HDM4 model B						
year 1st treatment	>40	>40	>40	>40	>40	>40
type 1st treatment	-	-	-	-	-	-

REC ....Reconstruction
REIN ....Reinforcement
REPLW...........Replacement wearing course
REPLWB.........Replacement wearing course and binder course

Table 12: Maintenance treatment recommendation for section 2

1st major treatment due to cracking	2007 data			2012 data		
	D_{road} model			D_{road} model		
	5%	10%	20%	5%	10%	20%
Austrian model						
Year 1st treatment	16	13	12	10	8	7
Type 1st treatment	REIN	REPLWB	REPLWB	REPLW	REPLW	REPLW
German model						
Year 1st treatment	15	13	12	9	8	7
Type 1st treatment	REPLWB	REPLWB	REPLWB	REPLW	REPLW	REPLW
HDM4 model – option A						
Year 1st treatment	14	13	11	9	8	6
Type 1st treatment	REPLWB	REPLWB	REPLWB	REPLW	REPLW	REPLW
HDM4 model – option B						
Year 1st treatment	14	13	11	9	8	7
Type 1st treatment	REPLWB	REPLWB	REPLWB	REPLW	REPLW	REPLW

REC ....Reconstruction
REIN ....Reinforcement
REPLW...........Replacement wearing course
REPLWB.........Replacement wearing course and binder

Because of the high number of allowable load repetitions until the end of fatigue life, section 1 shows for all calculated strain factors a service life due to cracking of more or equal to 40 years without any exhaustive maintenance treatment in between. Of course, the service life of the wearing course and the binder is much shorter (because of rutting, loss of aggregate, etc.), but this is not taken into consideration within the analysis.

The analysis on section 2, which represents an under-designed pavement, provides different types of treatment recommendations beginning from year 6 (2012 data, D_{road} = 20 %) to a maximum of year 16 (2007 data, D_{road} = 5 %). The results within each data and D_{road} category (columns in Tables) illustrate a good accordance of the recommended maintenance treatments with a maximum difference of 2 years for all three EPF. In comparison to the non-laboratory calibrated results, which are shown in Table 6 (up to 29 years of difference and different treatment types), the estimation of the maintenance needs could be improved significantly. This underlines the necessity to incorporate material specific information.

On section 2, cracking is the decisive factor for maintenance activities with a high probability. As a consequence, section 2 should be investigated much more intensively (condition measurement) within the next years to provide a further basis for the short- to medium-term planning of maintenance treatments.

3.4 Results of LCCA with different EPFs

3.4.1 Objective of LCCA

One of the main objectives of using performance prediction models is the practical application of LCA/LCCA. The improvement of performance prediction causes usually an improvement of the accuracy of the results and enables a more objective decision in the context of maintenance activities.

In this chapter the effect of using laboratory calibrated EPFs will be demonstrated in form of a simplified LCCA over a time period of 35 years (maximum design period of test section 1 plus 5 years). The results are shown as a comparison between the designs, the section based calibrated EPFs and the laboratory calibrated EPFs for both test sections on the German B35 including the costs for new construction and maintenance (agency costs) as well as the estimation of time costs due to maintenance activities (user costs).

It has to be stated clearly that the cracking model (cracking rate) is the only technical parameter, which was used to select the point of time and the type of maintenance treatment. Other performance indicators, like rutting, roughness, skid resistance, etc. where not taken into consideration for this comparison and would likely change the results.

3.4.2 Basics of LCCA

Beside the agency costs (costs for new construction and costs for maintenance treatments) the effects on users due to construction activities were assessed in form of the monetary time delay. For the calculation of the time loss due to construction or maintenance activities the following model was used. It is based on the time loss Δt of each individual vehicle during the duration of disturbance D, taking into account specific time-cost-rates for two different traffic categories (passenger cars and trucks). To estimate these costs the following equations were used:

$$\Delta Cost_{\text{time}} = \sum_j \Delta t \cdot D \cdot AADT_j \cdot TCR_j \qquad \text{Equation (3)}$$

with

$$\Delta t_{\text{time}} = Length_i \cdot \left(\frac{1}{V_{constr}} - \frac{1}{V_{design}} \right) \qquad \text{Equation (4)}$$

$$D = Area_i \cdot P_m + 2 \qquad \text{Equation (5)}$$

$\Delta Cost_{time}$ = additional time costs due to disturbance
Δt = loss of time (hours) per vehicle
D = duration of disturbance (days)
$AADT_j$ = average daily traffic of vehicle category j
TCR_j = time cost ratio for vehicle category j (passenger cars = 6 €/h, trucks = 30 €/h)
$Length_i$ = length of section i
V_{constr} = speed during construction period (30 km/h)
V_{design} = design speed (100 km/h)
P_m = productivity of maintenance treatment m

Based on the treatments described in chapter 3.3.3 the treatment catalogue was extended with unit prices and the productivity P_m for the estimation of agency costs and user costs due to disturbance.

Table 13: Unit prices and productivities for major (exhaustive) maintenance treatments due to cracking used for PMS analysis

Abbrev.	Unit prices	Productivity P_m
REPLW	10 €/m^2	2500 m^2/day
REPLWB	15 €/m^2	1500 m^2/day
REIN	25 €/m^2	1000 m^2/day
REC	Section 1: 90 €/m^2 Section 2: 60 €/m^2	Section 1: 300 m^2/day Section 2: 300 m^2/day

For the calculation of the construction costs at the beginning of the analysis period (2007) a unit price of 120 €/m^2 for section 1 and of 90 €/m^2 for section 2 was included into the calculations. User costs during new construction were not taken into consideration. For the calculation of the present values of maintenance costs and user costs a discount rate of 3% was used. For the calculation of the duration of the maintenance activities 1 day for installation and 1 day for removal of the traffic diversion was taken into consideration as well. Because of the single carriageway cross section a maximum speed of 30 km/h during construction was used. The design speed for both sections is 100 km/h.

The selection of treatments is based on the triggers listed in

Table 10. An exception of these triggers was only applied in the context of LCCA of the basic design (see scenarios chapter 3.4.3).

3.4.3 LCCA-Scenarios

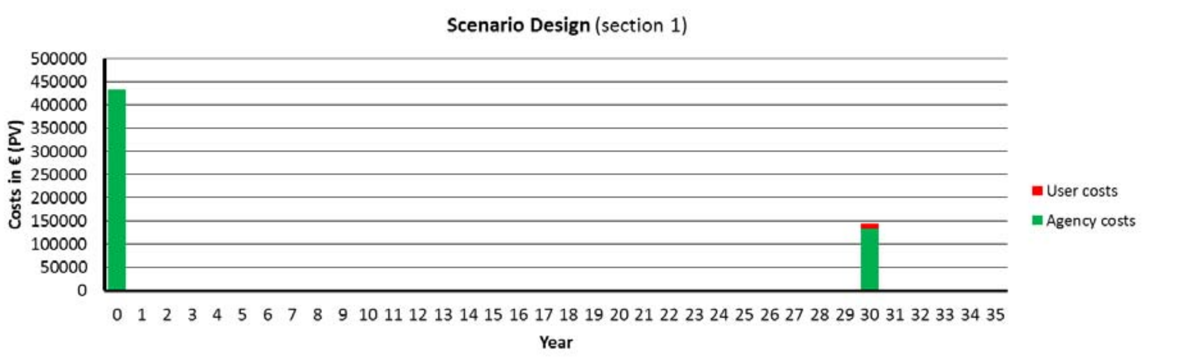
To demonstrate the effect of laboratory calibration different LCCA-scenarios were calculated. The following Table 14 gives an overview of these scenarios.

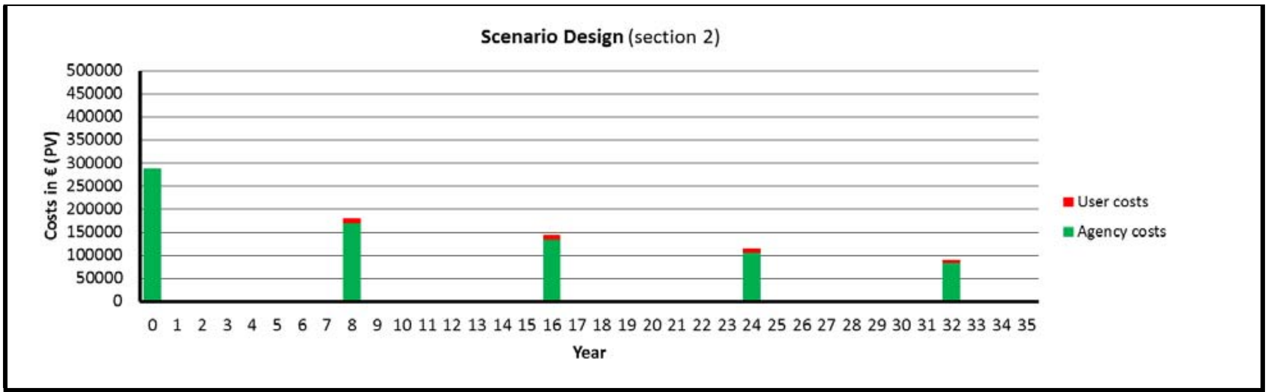
Table 14: List of LCCA-scenarios for section 1 and section 2

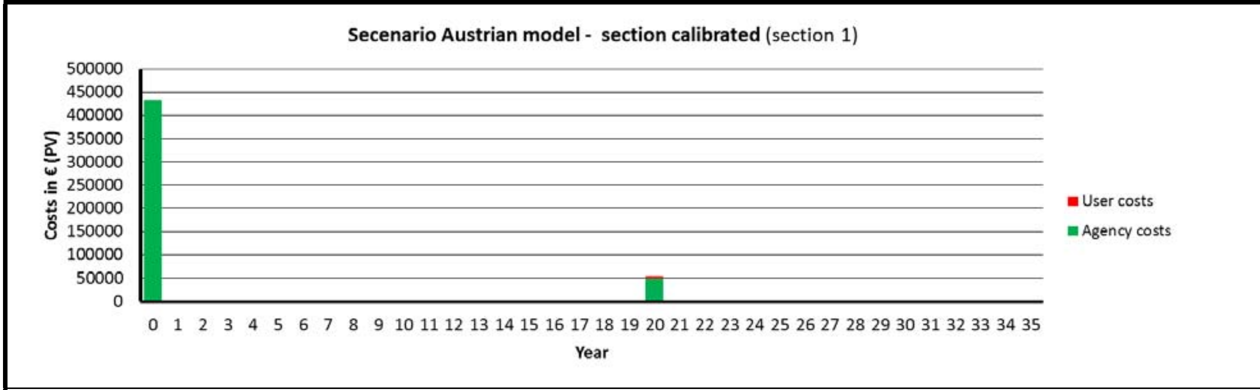
Scenario	Description
Design scenario	30 years design period of section 1 and 8 years design period of section 2; reconstruction of pavement based on basic design period only
Austrian model - section based calibration	Austrian standard cracking model with section based calibration
German model - section based calibration	German cracking model with section based calibration
HDM4 model (A & B) - section based calibration	HDM4 cracking model with section based calibration
Austrian model - laboratory calibration (2007 data)	Austrian laboratory calibrated cracking model based on 2007 data with D_{road} = 10%
German model - laboratory calibration (2007 data)	German laboratory calibrated cracking model based on 2007 data with D_{road} = 10%
HDM4 model (A & B) - laboratory calibration (2007 data)	HDM4 laboratory calibrated cracking model based on 2007 data with D_{road} = 10%
Austrian model - laboratory calibration (2012 data)	Austrian laboratory calibrated cracking model based on 2012 data with D_{road} = 10%
German model - laboratory calibration (2012 data)	German laboratory calibrated cracking model based on 2012 data with D_{road} = 10%
HDM4 model (A & B)- laboratory calibration (2012 data)	HDM4 laboratory calibrated cracking model based on 2012 data with D_{road} = 10%

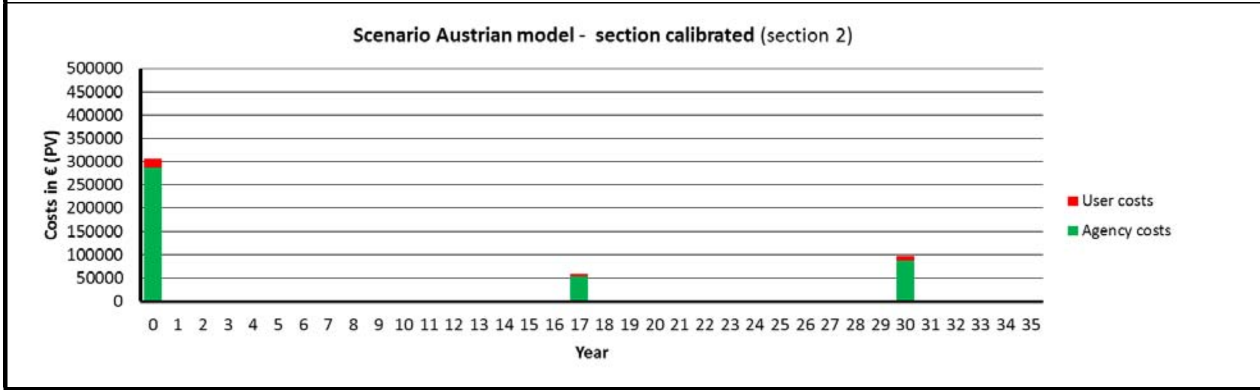
In the following Table 15 the results of the different LCCA-scenarios are shown in detail in form of agency costs and user costs over the whole assessment period of 35 years. The costs are displayed as present values using a discount rate of 3%.
The main objective of the analysis is not a comparative assessment of the two pavements applied on test section 1 and 2, but to show the consequences and effects of using laboratory calibrated EPFs within LCCA. Of course, the values itself are strongly dependent on the input parameters of LCCA, especially on the unit prices and the time cost ratios.

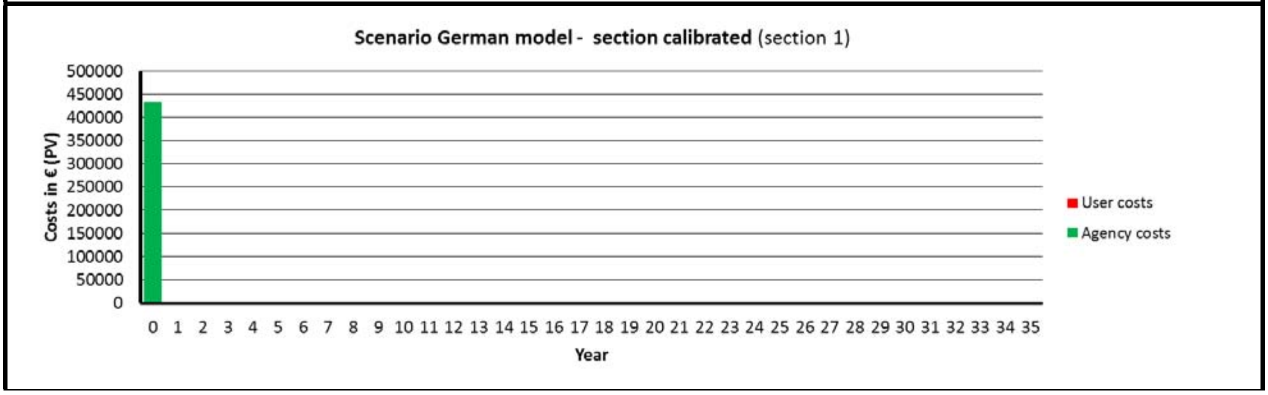
Table 15: Results LCCA-scenarios for section 1 and section 2

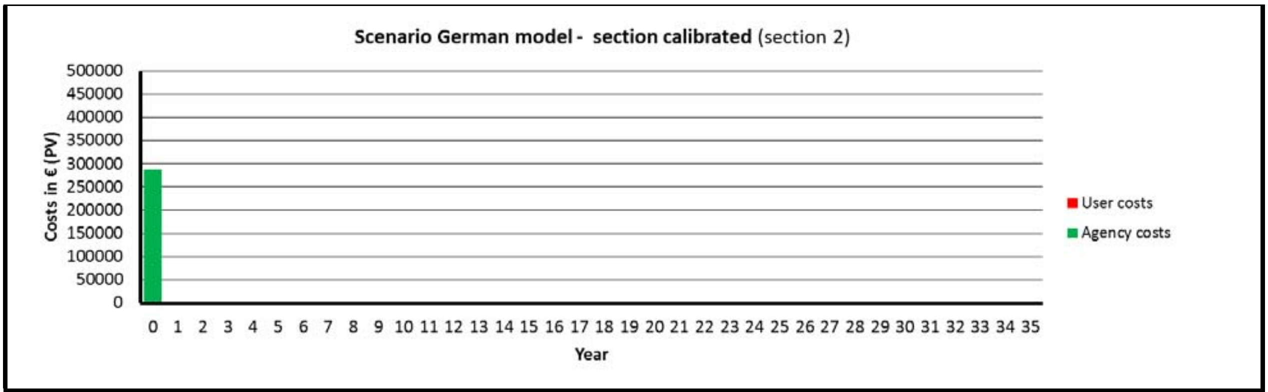



Scenario Design (section 2)
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs

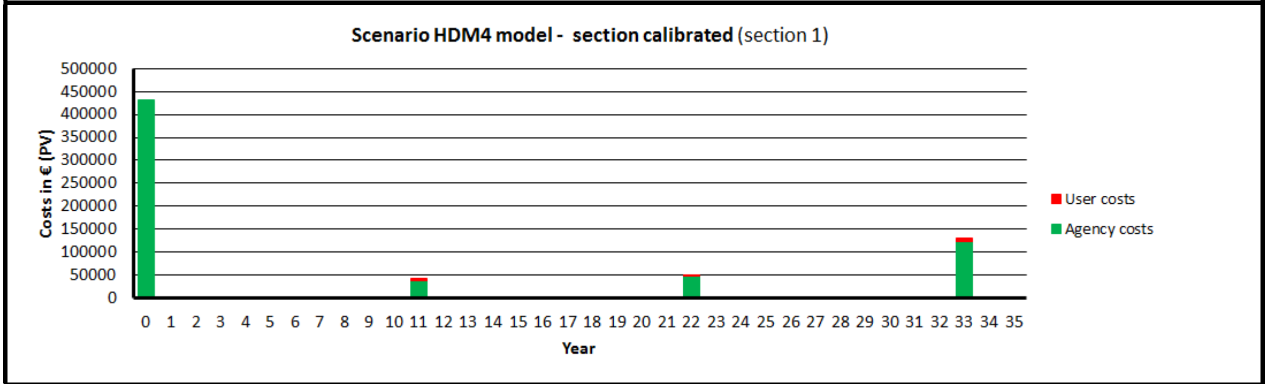

Secenario Austrian model - section calibrated (section 1)
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs


Scenario Austrian model - section calibrated (section 2)
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs

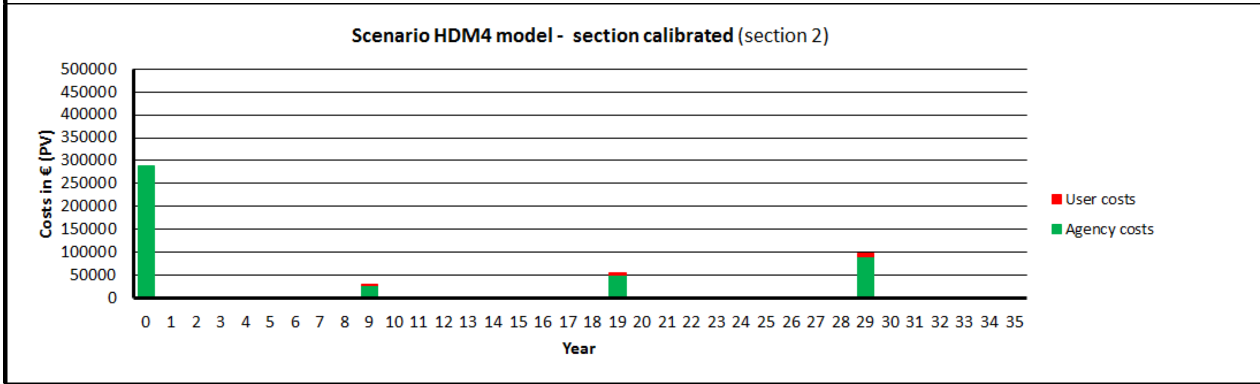

Scenario German model - section calibrated (section 1)
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs



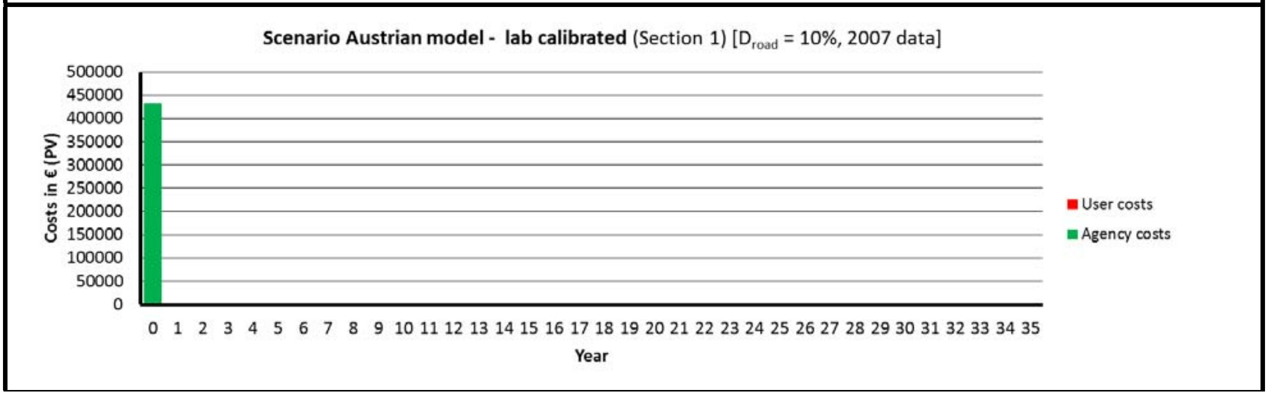
Scenario German model - section calibrated (section 2)
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs



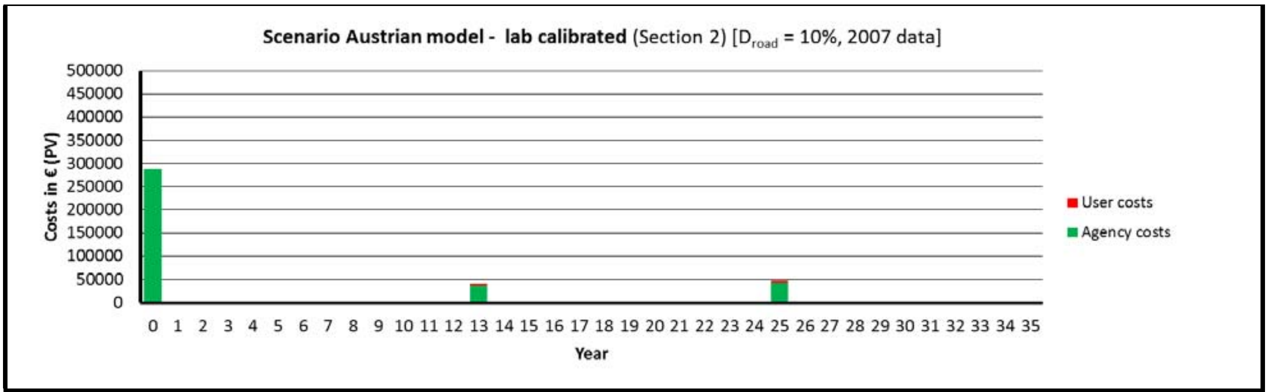
Scenario HDM4 model - section calibrated (section 1)
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs

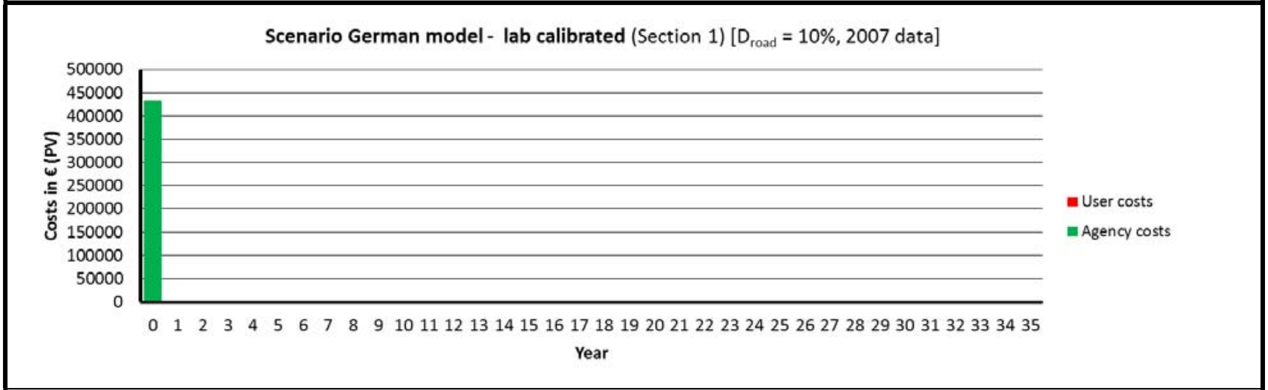


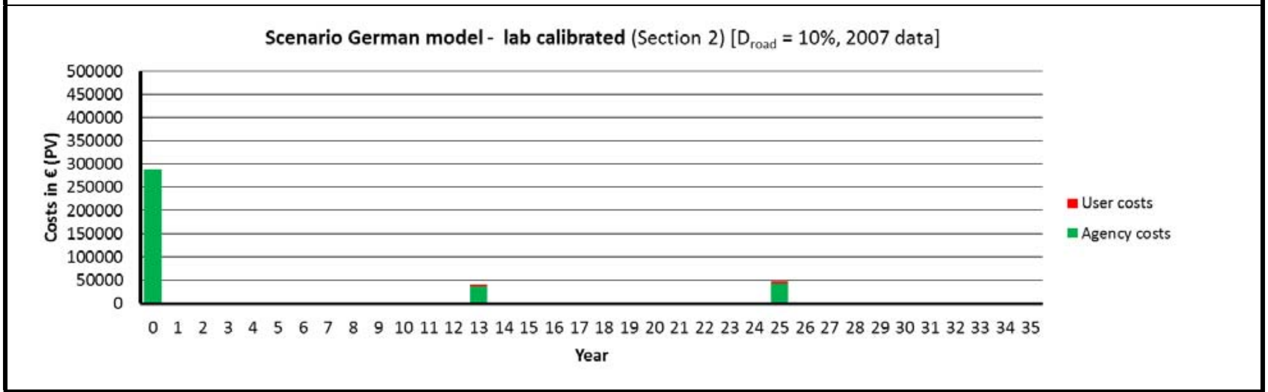
Scenario HDM4 model - section calibrated (section 2)
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs

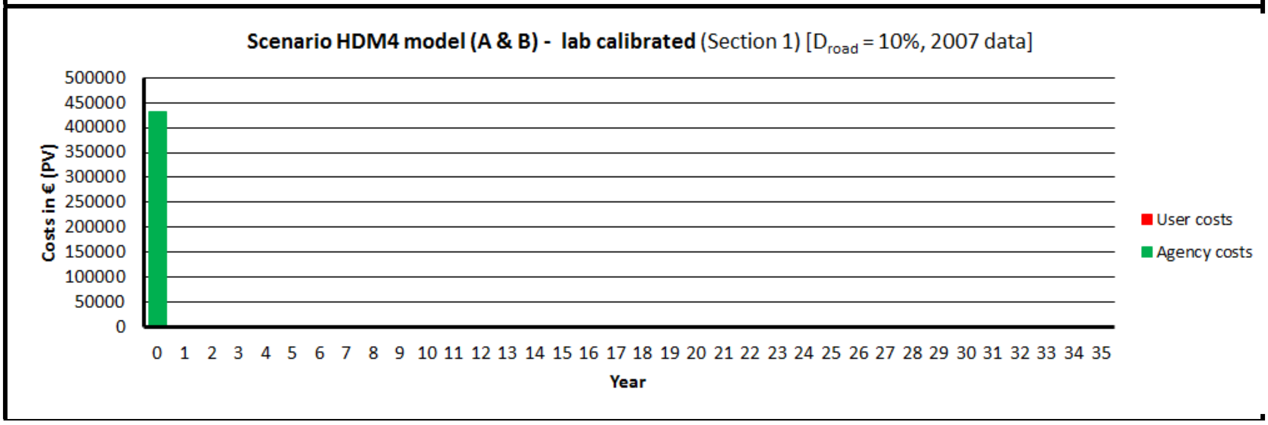


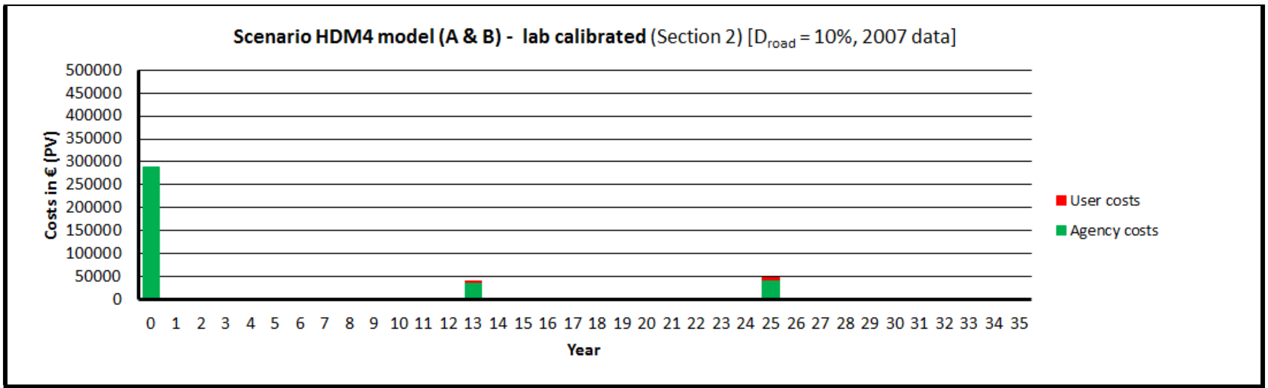
Scenario Austrian model - lab calibrated (Section 1) [D_{road} = 10%, 2007 data]
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs

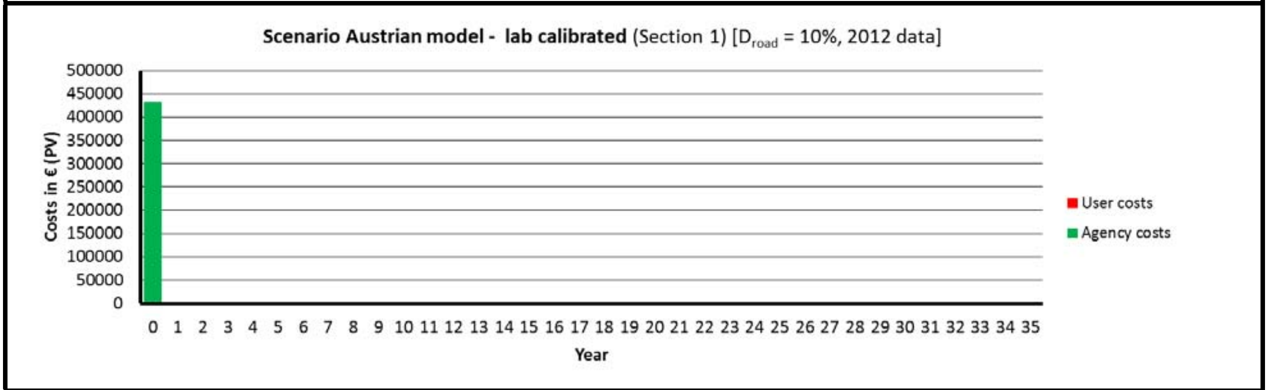

Scenario Austrian model - lab calibrated (Section 2) [D_{road} = 10%, 2007 data]
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs

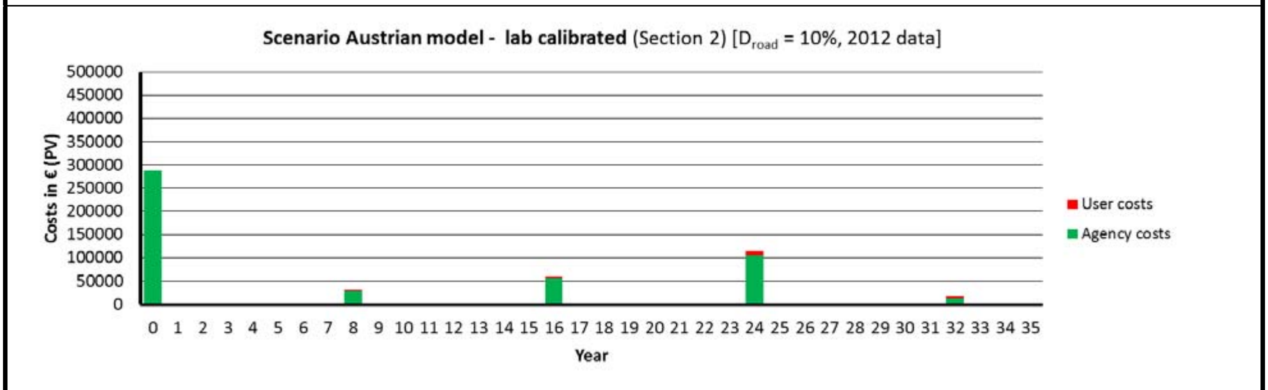

Scenario German model - lab calibrated (Section 1) [D_{road} = 10%, 2007 data]
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs

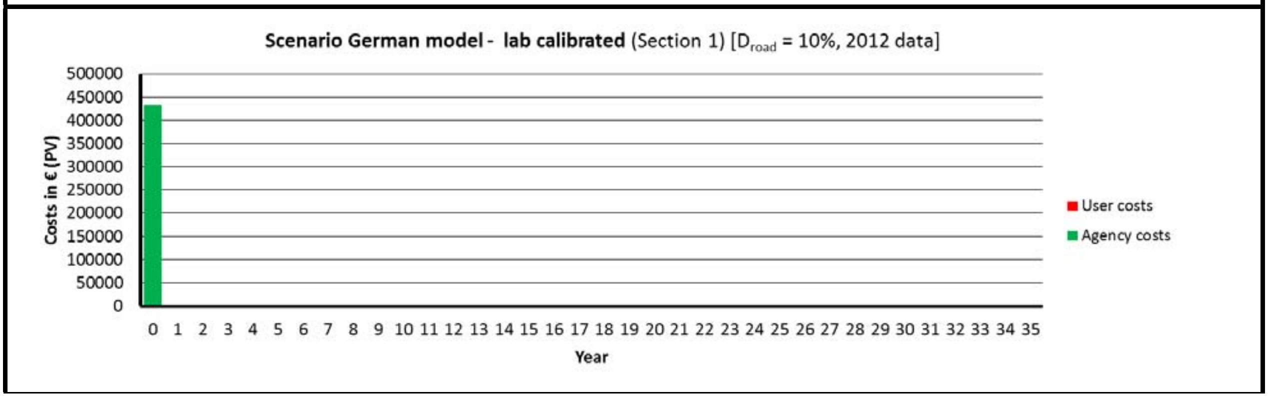

Scenario German model - lab calibrated (Section 2) [D_{road} = 10%, 2007 data]
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs

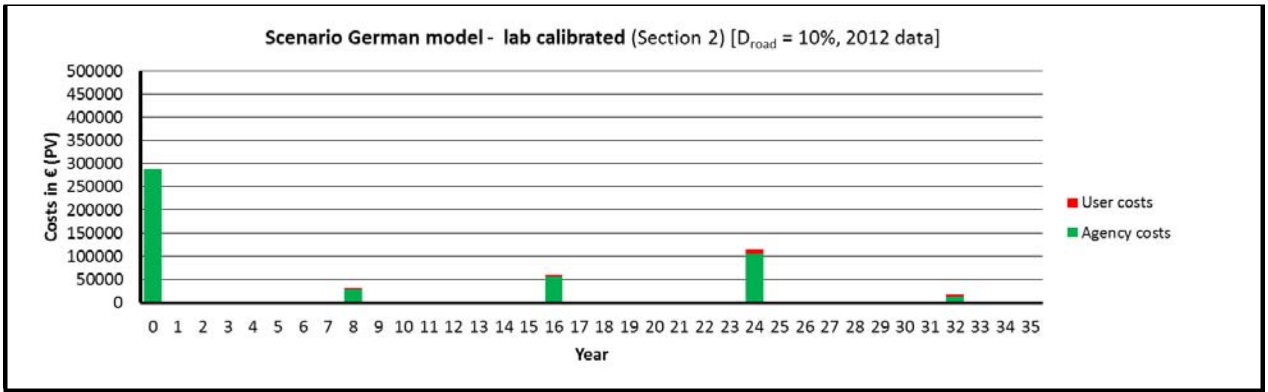

Scenario HDM4 model (A & B) - lab calibrated (Section 1) [D_{road} = 10%, 2007 data]
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs

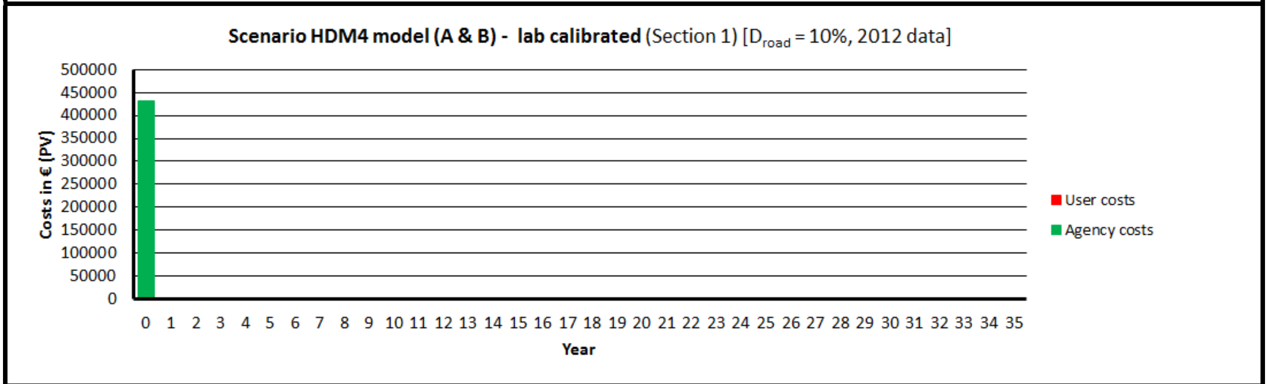

Scenario HDM4 model (A & B) - lab calibrated (Section 2) [D_{road} = 10%, 2007 data]
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs

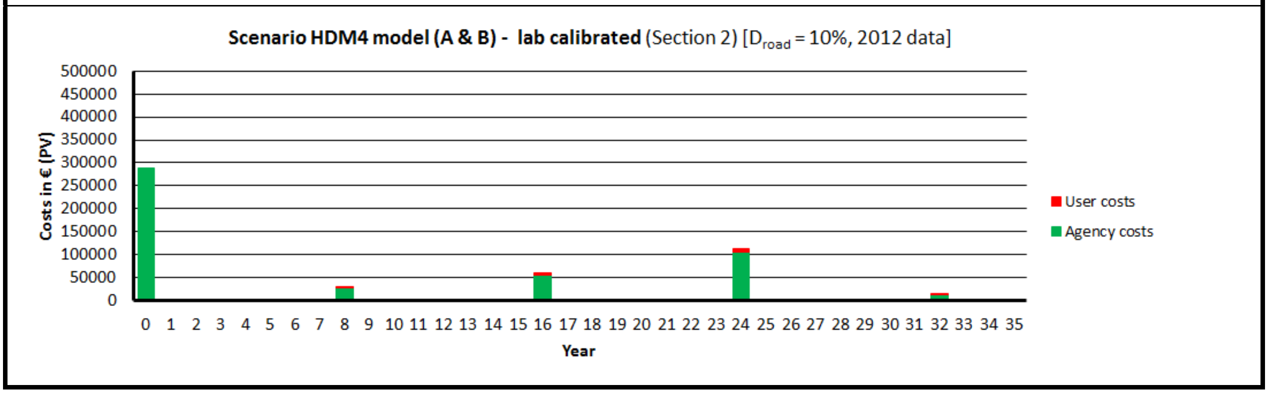

Scenario Austrian model - lab calibrated (Section 1) [D_{road} = 10%, 2012 data]
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs


Scenario Austrian model - lab calibrated (Section 2) [D_{road} = 10%, 2012 data]
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs


Scenario German model - lab calibrated (Section 1) [D_{road} = 10%, 2012 data]
Costs in € (PV)
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
User costs
Agency costs







The figures in Table 15 clearly show for the laboratory calibrated EPFs that on section 2 more maintenance activities are predicted in comparison to section 1, where no treatment (caused by cracking) appears within the assessment period of 35 years. The interval of these activities is strongly dependent on the data to be used for the calibration of the model. The 2007 data (based on retained samples from the construction phase) predict a maintenance interval of 12 to 13 years, so that a two-maintenance treatment strategy will hold the cracking rate below 10% over the whole assessment period. By comparison with the results based on core samples from the year 2012, the maintenance interval on section 2 will be reduced to 8 years, which causes a four-maintenance treatment strategy and which is similar to the design interval. Of course, not every 8 years the pavement construction has to be fully reconstructed. On section 1 no change of results could be shown by using 2012 data.

3.4.4 Comparison of results

The cumulative total costs (sum of agency costs and user costs) over 35 years of assessment period enable an easy comparison of the different LCCA-scenarios. As already mentioned, the main objective of the analysis is not a comparative assessment of the two different pavement constructions, which were applied on test section 1 and 2. The focus is to show the consequences and effects of using laboratory calibrated EPFs within LCCA and how results from the design process can be verified by incorporating results from laboratory tests.

In the following Figure 24 the total costs are shown for both sections for the design scenarios and for all scenarios with section based calibration only. It can be seen that the variation of the total costs at the end of the assessment period of 35 years is quite big, which underlines the necessity for an extended (improved) calibration of the models to be used in this LCCA.

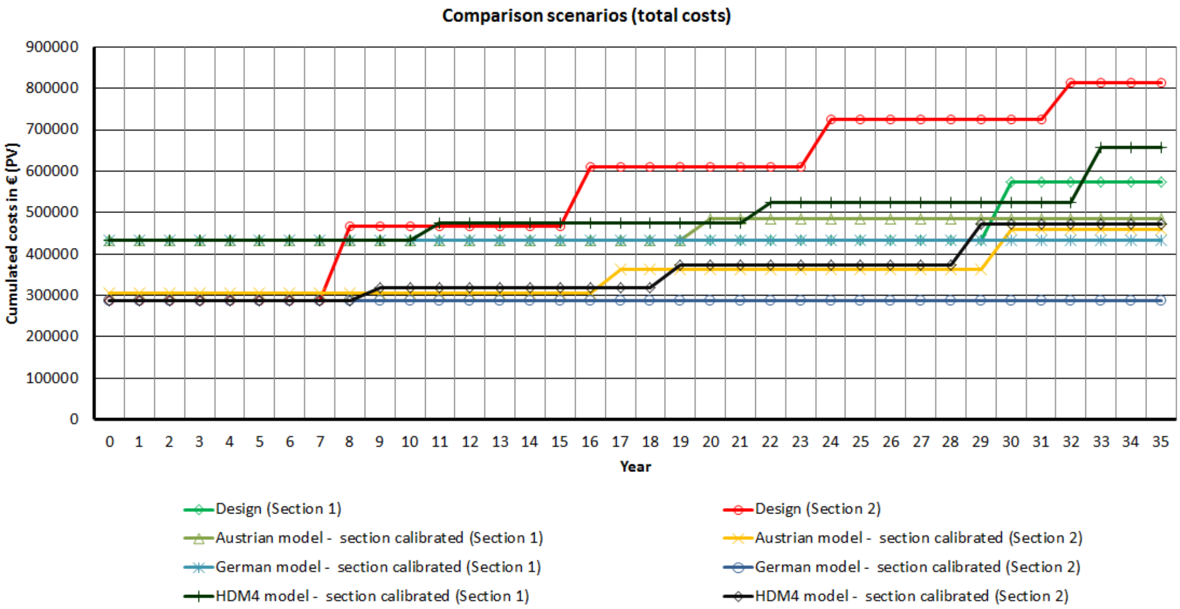


Figure 24: Comparison of LCCA-scenarios.

By taking the laboratory test results from 2007 and 2012 data into account, the following cumulated costs can be displayed in Figure 25 and Figure 26. Of course, there is still a difference between sections 1 and 2 (yet smaller than before), but the laboratory based calibration leads to identical total costs for all 3 models (Austrian, German and HDM4) at the end of the assessment period.

The unit prices for the maintenance treatments as well as for the new construction have a significant influence to the results. Nevertheless, the integration of laboratory test results into the prognosis of pavement condition and finally into the whole LCCA process enables a technical objective conclusion about different pavement design concepts. By verifying the unit prices it is possible to find out how big the difference of the construction costs between pavement design alternatives should be, so that at the end of the design phase the total costs are approximately the same.

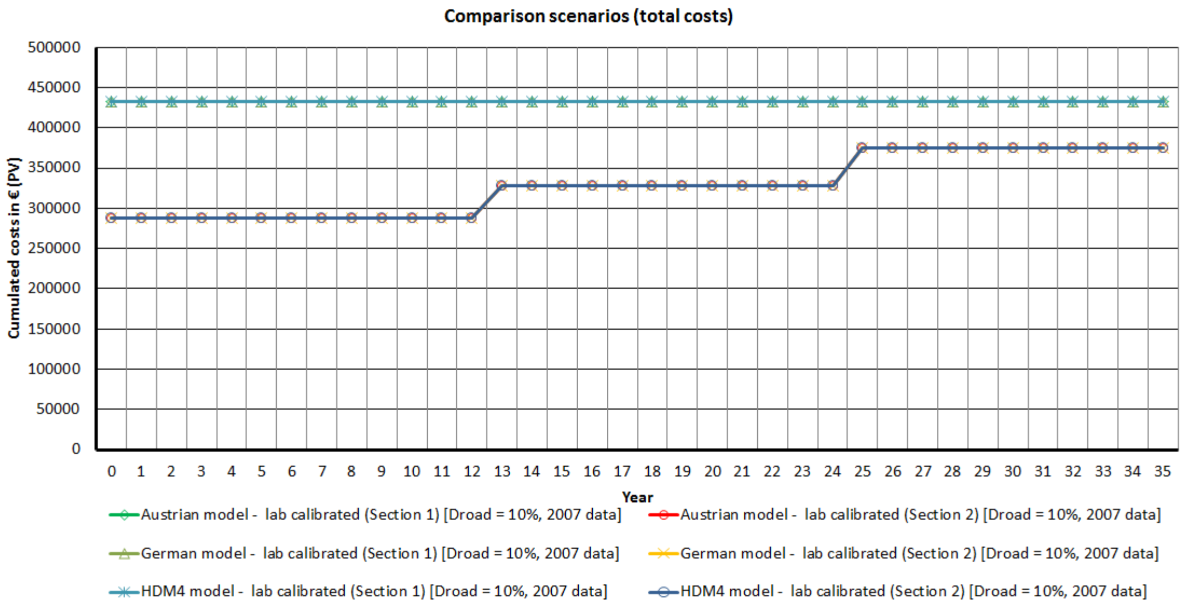


Figure 25: Comparison of total costs using laboratory calibrated EPFs (2007 data)

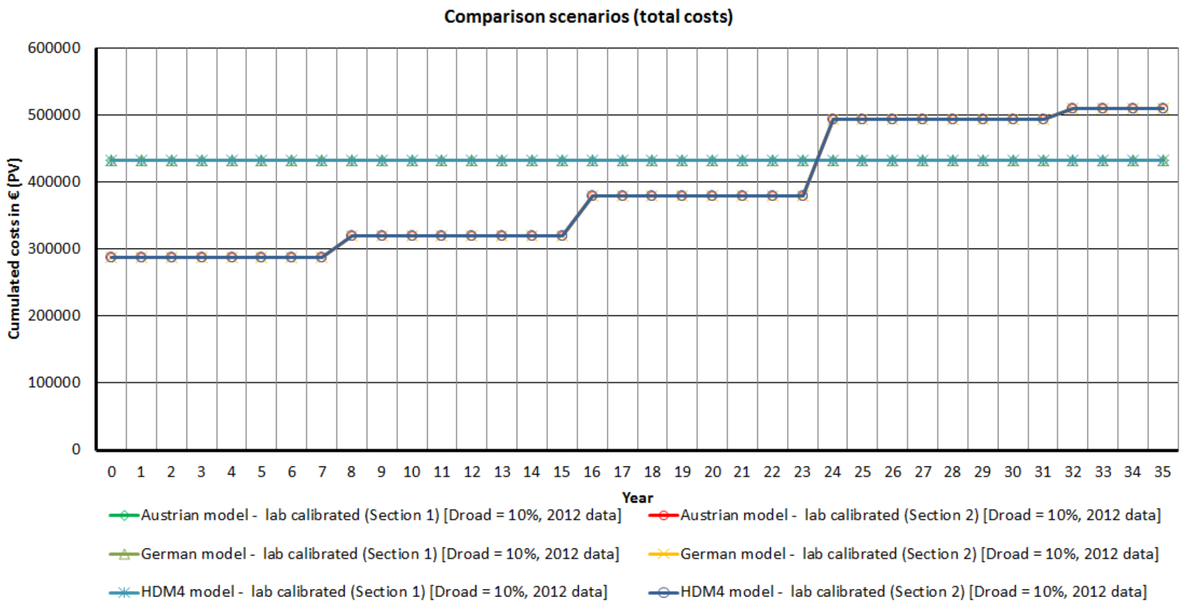


Figure 26: Comparison of total costs using laboratory calibrated EPFs (2012 data)

4 Benefit of using material-science based performance models

The prediction of future condition for the assessment of maintenance treatments is an essential part of any PMS using LCA or LCCA in the decision process. A decisive factor is the exactness of the prediction, which is strongly related to the applicability of the prediction model and the underlying information or input data. On project (object) level the degree of accuracy for the prediction is much higher in comparison to a general prediction over the whole network. Especially on road sections, which consist of a new pavement (new construction or reconstruction) or which do not show any distress, the prediction is mainly depending on the model characteristics and on the input parameters. In contrast, for sections, where distress already appeared, calibration can be carried out more easily taking into account the extent and the severity of the distress detected.

The practical application of PMS shows, that most of the performance prediction models offer a general nature. This is of advantage, as they can be applied on a high percentage of the network and for different types of pavements. However, it is always a disadvantage, when being too general for an accurate prediction on project (object) level on sections, where a distress related calibration is not possible (at the moment) and where detailed material information needs to be incorporated. The consequence of this inaccuracy is a high variation in the prediction of future maintenance needs. Analysis output usually does not show a high significance of short- to medium-term maintenance needs (new or reconstructed or free of defects).

In this study, the results of the practical application of three different EPF on a German test site with two different test sections demonstrate this problem. All three models (German, Austrian, HDM4) seem to be applicable on the test site in principle, but show a very high variance in the results, in the first run.

The first level calibration, which takes the local information of the pavement and the traffic load into account, leads to non-satisfying results. This underlines the necessity to integrate additional information from laboratory tests. The example shows, that the laboratory based calibration improves all models and reduces the variation of the results distinctively. In addition, performance prediction needs to be validated through regular pavement condition inspection. Again, this leads to increase in calibration quality and in prediction quality.

Based on the results of the practical application of the procedure, the benefit of the integration of material-science based performance models into the life-cycle-analysis of a PMS can be summarized as follows:

- A significant improvement of the performance prediction is reached if the results of laboratory tests are incorporated into the modelling process. Especially on those sections, which are newly built or reconstructed or where no distress / defects is stated at the moment. The laboratory calibration enables to improve the degree of prediction accuracy for future maintenance needs (type of maintenance treatment, year of maintenance treatment) in the LCA or LCCA. Thus, an improved planning of monetary preconditions can take place and the probability of unexpected issues will be reduced significantly.
- The improvement of PMS applications on object (project) level by using material specific input parameters enables to extend the field of PMS applications.
- Different performance prediction models can be brought together and compared in practice for specific test sites. The practical application of the German, Austrian and HDM4 model, as demonstrated in this study, shows practicability in principle,

although the general models show a high variation before laboratory based calibration.

In addition, the procedure enables to assess different types of performance prediction models with regard to their applicability and their possibilities to be calibrated with results from laboratory testing. Beside fatigue, performance model for resistance to permanent deformation may be used and calibrated to better predict point in time when rutting would be above the accepted level. Taking into account multiple calibrated models, the most appropriate type and timing for treatment application may be selected. The Figure 27 illustrates the proposed approach with using EPFs for fatigue and permanent deformation.

The incorporation of results from laboratory testing enables a better understanding of physical deterioration on road sections and enables better prediction of the future condition. Furthermore, this underlines the necessity to extend asphalt laboratory testing in the context of LCA / LCCA.

- ***InteMat4PMS*** offers a practically applicable solution for the integration of laboratory asphalt fatigue testing results into the PMS process. In a similar way other pavement characteristics can be incorporated. Especially, the assessment of deformation (rutting) seems to be an adequate candidate for further development and fulfils most of the precondition from both, the laboratory side as well as the PMS side.

  Table 16 and Table 17 provide the summary of the example of two test sections in Germany presented throughout this report to illustrate potential benefits of the proposed approach. (for labdata from 2012).

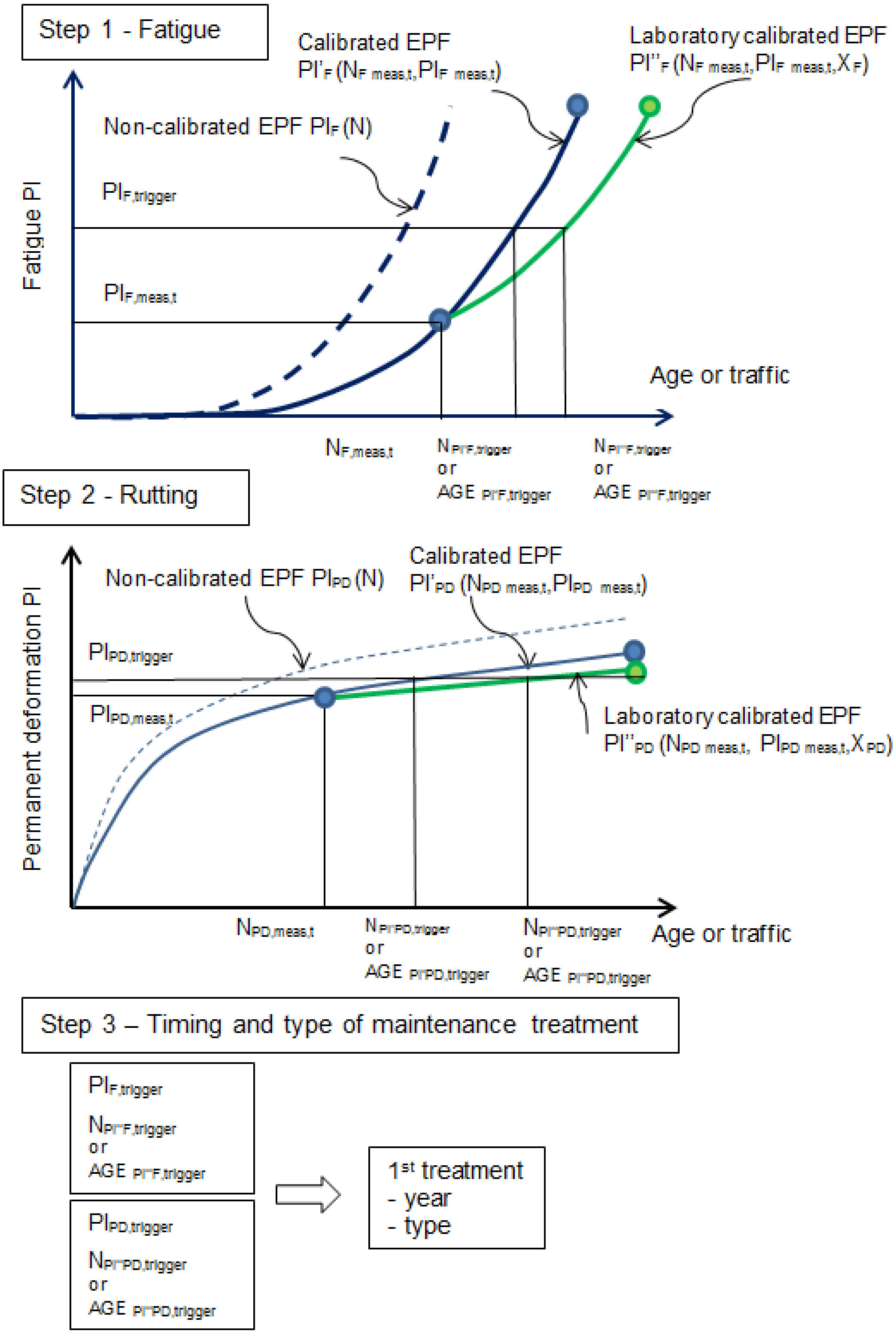


Figure 27. The proposed approach with using EPFs for fatigue and permanent deformation (option 1).

Table 16: Summary of the results for test section 1

Calibration stage	Trigger level (% cracking area)	1st major treatment	Model		
			Austrian	German	HDM-4
Section 1 (field 1)					
Calibrated EPF (1st stage of calibration)		**Year**	17	>40	12
		Type	REPLWB	REC	REPLWB
Laboratory calibrated EPF (2nd stage of calibration)	**5**	**Year**	>40	>40	>40
		Type	-	-	-
	10	**Year**	>40	>40	>40
		Type	-	-	-
	20	**Year**	39	40	>40
		Type	REC	REC	-

Table 17: Summary of the results for testing section 2

Calibration stage	Trigger level (% cracking area)	1st major treatment	Model		
			Austrian	German	HDM-4
Section 2 (field 4)					
Calibrated EPF (1st stage of calibration)		**Year**	16	>40	11
		Type	REPLWB	REC	REPLWB
Laboratory calibrated EPF (2nd stage of calibration)	**5**	**Year**	9	8	8
		Type	REPLW	REPLW	REPLW
	10	**Year**	7	8	7
		Type	REPLW	REPLW	REPLW
	20	**Year**	6	7	6
		Type	REPLW	REPLW	REPLW

REC ....Reconstruction
REIN ....Reinforcement (strengthening bit. base course)
REPLW ....Replacement wearing course
REPLWB.........Replacement wearing course and binder course

The proposed timing and type of maintenance treatments for two sections that have substantially different pavement structures and lives using only calibrated performance functions would be almost identical for each of the models, but the timing and type of treatment would depend on the EPF used.

Further calibration of models based on laboratory testing clearly showed the different structural capacity and life of these two sections resulting in different timing and type of treatments, but also showed that there are almost no differences among proposed treatments resulting from the models used.

In order to reach the highest possible benefit of this approach a certain number of requirements have to be fulfilled. In the following, these preconditions are summarized, as an output of the experiences made within ***InteMat4PMS***:

- The models to be calibrated have to be applicable to local requirements with regard to the availability of the needed input information.
- The PMS should be able to incorporate the results of laboratory testing in an additional calibration level, which means that the system has to offer a certain flexibility to change or adapt the models with new factors.
- For laboratory tests the material to be tested should be available with the needed quality and quantity.
- For the sites to be assessed the following information have to be available at least:
    - pavement construction information (type of material, thickness of layers, year of placement, information about the bearing capacity on the subgrade and on the subbase),
    - traffic data including $AADT_{cv}$ and information about the traffic forecast,
    - and actual condition data related to the characteristics to be assessed within the process.
- A transformation or integration of the results from laboratory testing into the performance prediction model is possible and the laboratory tests describe the correct characteristics to be predicted within the model.
- A relationship between the theoretical deterioration in the laboratory and the deterioration on site can be formulated. Within the given example the end of fatigue life has to be in accordance with given thresholds or limits of cracking.

Hints to other types of deterioration – rutting – could perhaps be added here taking the texts and figures from above.

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