InteMat4PMS

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

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Final Report

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Final Report

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Contents

Executive Summary

InteMat4PMS – '**Int**egration of **Mat**erial-science based performance models into life-cycle-analysis processed in the frame of **P**avement **M**anagement **S**ystems' – is a research project under the umbrella of '*ERA-NET ROAD II – Coordination and Implementation of Road Research in Europe*' within the 7th Framework Program of the European Community.

InteMat4PMS presents an advanced analysis procedure that is able to significantly improve performance prediction modelling for asphalt road pavements. The project outcome shall lead to more appropriate selection of maintenance strategies, in both technical and economic point of view. It has potential for a better performance of asphalt pavements, for an overall improvement in pavement durability and for most cost-effective road maintenance decisions. And it may promote the choice of innovative maintenance and replacement strategies.

Performance prediction is a key element in pavement management. Most realistic prediction of pavement performance over long time periods is of vital importance for effective assessment of maintenance options and life-cycle-cost-analysis. Usually, pavement management is based on a computer-aided Pavement Management System (PMS). In PMS, performance prediction is realized by extrapolating pavement condition development into the future, based on what has been observed over the past. This is typically called empirical approach, and the so-developed mathematical performance functions are called empirical performance functions (EPF). Unfortunately, routine condition surveys on asphalt pavements are commonly confined to surface characteristics, while intrinsic material properties and structural pavement properties are left disregarded. Therefore, EPF do not depend on specific material and structural properties. This is a disadvantage for pavement managers taking maintenance decisions, as the choice of pavement materials and structures is displayed neither in the performance function nor in the constitutive economic analysis.

The key innovation of *InteMat4PMS* is the consideration of material and structural pavement properties in pavement performance prediction in the frame of PMS. General EPF can be improved by using information on material and structural pavement properties, and by following up the analysis procedure developed in *InteMat4PMS*. The needed information is obtained from material testing in the laboratory and from structural performance modelling. As a result, a new performance function is obtained, which represents the specific maintenance option for the relevant road section. This new performance function is based on the original EPF, but takes into account the material and structural pavement properties, and is therefore called 'Laboratory Calibrated Performance Function' (see Figure 1).

Within *InteMat4PMS* it is demonstrated in detail, how a suitable Laboratory Calibrated Performance Function can be derived that considers pavement failure due to bottom-up fatigue cracking. This example may assist in implementing different types of performance prediction models, as the developed procedure can be extended to other distress modes such as (top-down) thermal cracking, reflective cracking or permanent deformation (rutting), always on condition that suitable laboratory analysis is provided. Thus, *InteMat4PMS* paves the way for further improvements in pavement performance prediction.

The applicability of the new analysis procedure is also tested in *InteMat4PMS*, considering real data and focusing on fatigue failure and pavement cracking mechanisms. *InteMat4PMS* provides two demonstration case studies. Based on real data from 2 test road sections, workability of the new approach is practically demonstrated.

In order to encourage and support pavement management operators in using the project outputs, *InteMat4PMS* provides all expertise to extend conventional PMS solutions by adopting the underlying algorithms for calculating performance functions. Detailed information is provided, inter alia, as regards

- system requirements for PMS and best practice for implementation,
- adequate laboratory testing, as well as selecting and processing of material parameters,

- integrating material-science based parameters into the process of performance prediction, and employing enhanced prediction models in PMS,
- following up performance modelling, life-cycle-processing and assessing indicators of maintenance strategies, and
- practical application of advanced PMS tools for demonstration test sections.

A user-friendly manual is provided in the Final Report that may assist in practical application of the new analysis procedure and in extending any commercial PMS software solution.

Any stakeholder from road administrations, the road industry and SME (small and medium enterprise) involved in road asset management may benefit from the project outputs. Moreover, user concerns are also addressed as the project may extend pavement maintenance/rehabilitation intervals, and in consequence, reduce road closures, and increase road safety.

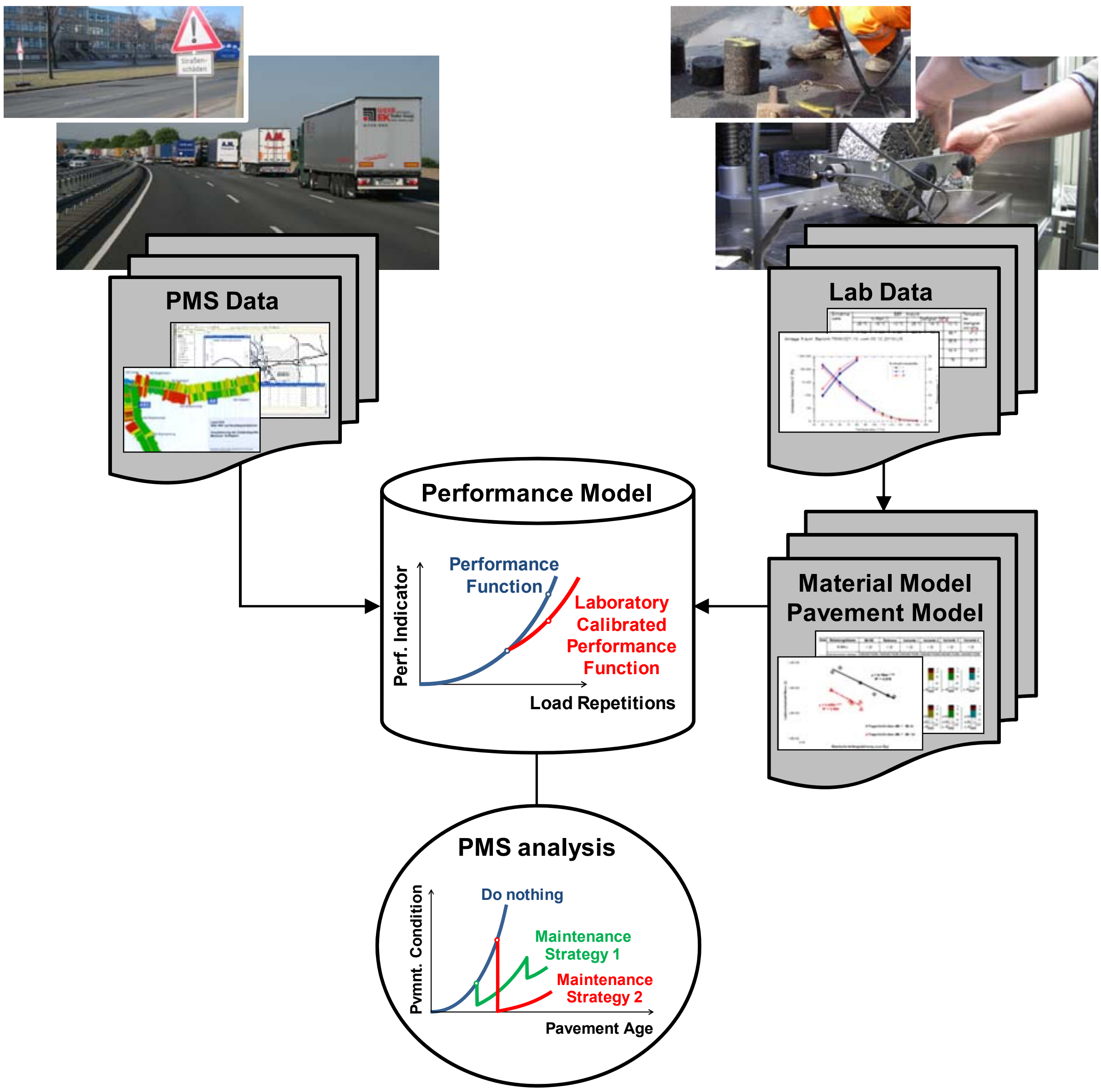


Figure 1. *InteMat4PMS* project outline.

1 Introduction

1.1 Project Framework

InteMat4PMS – '**Int**egration of **Mat**erial-science based performance models into life-cycle-analysis processed in the frame of **P**avement **M**anagement **S**ystems' – is a research project under the umbrella of a trans-national joint research program called '*ENR2011 DESIGN – Rapid and durable Maintenance Method and Techniques*' that was initiated by a coordination action in the 7th Framework Program of the European Community called '*ERA-NET ROAD II – Coordination and Implementation of Road Research in Europe*'.

A scientific and technological key element of the *InteMat4PMS* project is the merge of knowledge in the field of pavement management and of material-science. The project consortium is thus composed of partners who are working in both fields of research. Partners are affiliated to Technische Universität Braunschweig (Germany; project coordinator), PMS Consult Ltd. (Austria), University of Belgrade (Serbia), and ViaTec AG (Switzerland). In addition, a scientific quality manager is associated.

The project duration was 2 years, from September 2011 to August 2013, during which a number of 14 work meetings took place.

The project work plan was organized in 6 work packages, i. e.

Work Package 1: Project management,

Work Package 2: Specifying a holistic PMS architecture integrating material-science based pavement performance functions,

Work Package 3: Assessing physical performance functions for materials & structures,

Work Package 4: Incorporating physical performance functions into PMS,

Work Package 5: Demonstration and practical guide,

Work Package 6: Dissemination.

All project objectives, results, and work performed within *InteMat4PMS*, are documented in terms of technical Deliverables, internal reports and minutes, and 4 monitoring progress reports. All documents are available via the project website at 'www.tu-bs.de/isbs' (for password contact project coordinator). The project milestones are detailed in the following documents, i. e.

Quality Assurance Plan QAP: Summary of activities to be established for assessment of the quality of the project milestones and activities,

Deliverable D1: State of the art and holistic integrated PMS architecture,

Deliverable D2: Performance functions for road materials and pavement structures,

Deliverable D3: Manual for developing PMS based on physical performance functions,

Deliverable D4: Comparative calculations and benefit analysis report,

Deliverable D5: Final report.

1.2 Project Objectives and Limitations

The overall objective of *InteMat4PMS* is to promote most effective pavement management decisions from both a technical and an economic point of view. It has potential for a better performance of asphalt pavements, for an overall improvement in pavement durability and for most cost-effective road maintenance decisions. And it may promote the choice of innovative maintenance and replacement strategies.

InteMat4PMS presents an advanced analysis procedure that is able to significantly improve performance prediction modelling for asphalt road pavements. The project outcome shall lead to more appropriate selection of maintenance strategies.

Within the context of pavement management based on a Pavement Management System (PMS), most realistic pavement performance prediction is the primary basis for maintenance decisions and an important pre-requisite for life-cycle pavement analysis.

The key innovation of *InteMat4PMS* is an advancement of PMS operation principles. A new approach is proposed for integrating material information into life-cycle pavement analysis. Performance prediction is enhanced by taking into account data derived from the periodic assessment of pavement performance, from laboratory testing of the relevant asphalt pavement materials, and from structural pavement modelling.

In common PMS, performance prediction is realized by extrapolating pavement condition development into the future, based on what has been observed over the past. This is typically called empirical approach, and the so-developed mathematical performance functions are called empirical performance functions (EPF).

In *InteMat4PMS*, performance prediction is improved through the integration of material-science based performance models into life-cycle-assessment. The term *integrate* is used in order to point out the incorporation of new information to form enhanced performance functions, and the introduction of these physically sound performance functions into PMS which shall significantly improve the output of the PMS analysis.

Through calibration procedure developed in *InteMat4PMS*, any initial EPF can be adopted whenever laboratory data are available. As result, a new Laboratory Calibrated Performance Function is found which is directly related to the specific properties of the asphalt materials and the pavement structure used (see Figure 2).

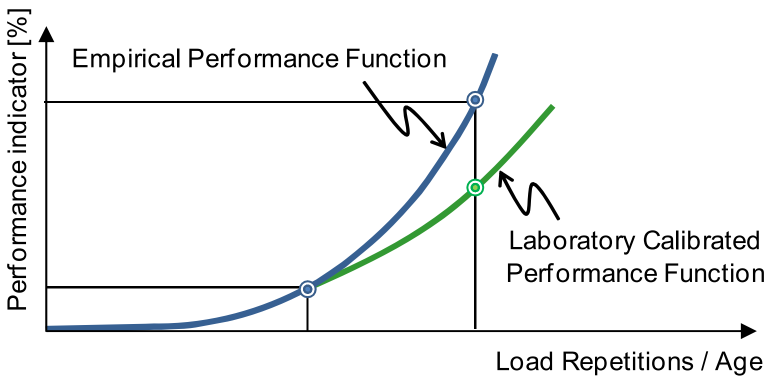


Figure 2. Using results from laboratory testing for calibration of the empirical performance function.

Research work of *InteMat4PMS* is restricted to asphalt materials. However, the principal layout of the PMS approach is designed such, that any information on other materials and layers can be integrated in the performance prediction analysis, e. g. as regards the effect of supporting (granular, cement treated, innovative, etc.) layers on pavement lifetime.

In *InteMat4PMS* no new material models or LCA/LCCA models are developed. *InteMat4PMS* focuses on project level analysis and on primary response and structural fatigue performance models. The new calibration concept focuses on pavement distress occurring over long time spans (of several decades), and is not due to a single overload event.

As regards the developed software solution for including laboratory results within the frame of the commercial PMS software '*dTIMS CT*^{TM}', full functionality is provided. But the software is not guarantee to be error free and the developer abstains from taking any responsibility what so ever. The user will use the software at own risk. It needs to be considered, that the number of available performance data is rather limited and the represented time periods of observation are short. Also the number of test runs with the newly adopted PMS-software is limited. Moreover, validation and calibration of the developed methods are omitted.

The outcome of *InteMat4PMS* can be understood as an essential step forward to develop a holistic PMS. Use of the term *holistic* emphasizes, that no new PMS modules are developed, but a whole working PMS analysis is formed by considering new inputs and by strengthening the functional relation between the input sources.

1.3 Approach

The key innovation of *InteMat4PMS* is the consideration of material and structural pavement properties in pavement performance prediction.

In most PMS, deterministic pavement performance prediction is based on periodic condition surveys and on so-derived empirical performance functions (EPF). By following up the analysis procedure developed in *InteMat4PMS*, any EPF can be improved by using information on material and structural pavement properties. The methodology of EPF calibration is described in detail in Chapter 2.3.

The information on material and structural pavement properties needed for EPF calibration is obtained from laboratory analysis. The laboratory analysis comprises both material testing and structural performance modelling. By means of mechanistic data, the initial EPF is calibrated. As a result, a new performance function is obtained, which represents the specific maintenance option for the relevant road section. As the new performance function is based on the original EPF, but takes into account the material and structural pavement properties, it is called 'Laboratory Calibrated Performance Function'. The process for identifying the Laboratory Calibrated Performance Function is explained in detail in Chapter 2.2.

In *InteMat4PMS*, the workability of the new analysis procedure is demonstrated for fatigue distress. The principal methodology of this procedure is generally applicable for any incremental distress mechanism in asphalt pavements, in which damage is accumulated in function of load repetitions. In analogy to the proposed calibration procedure for fatigue, similar calibration procedures can be developed for further distress types such as (top-down) thermal cracking, reflective cracking or permanent deformation (rutting), in subsequent research studies.

The newly developed analysis procedure can easily be adapted to any existing PMS solution. A detailed description of PMS software requirements and of system-configuration for integrating material-based performance functions into PMS is presented in Chapter 2.4. In addition, a practical implementation guide can be found in the Annex B. It assists in the practical implementation of pre-selected performance functions into PMS. It includes a comprehensive description of the different steps for the selection of models, the selection of an adequate PMS solution and finally for the incorporation of laboratory calibrated empirical performance functions into PMS. The steps described in this manual can be seen as a general framework for the implementation of any empirical or physical performance function into a computer assisted PMS. Thus, the described processes can be understood as a general approach, which is adaptable to similar projects and problems.

The new analysis procedure is exemplarily demonstrated using realistic data from test road sections. Considering different rehabilitation scenarios and boundary conditions, the advantage of using Laboratory Calibrated Performance Functions in PMS is analysed in Chapter 3.

2 Integration of material based performance functions into PMS

2.1 Background for holistic PMS development

Pavement management is the process of coordination and controlling a comprehensive set of activities in order to find most cost-effective strategies for providing, evaluating, and maintaining road pavements in serviceable condition, and to maximize the benefits for society (OECD, 1987). Pavement Management System (PMS) is called the set of tools to assist decision-makers at all levels in this process.

For practical application of pavement management processes the different components are usually implemented into software support tools (e. g. database), which enable to apply this holistic management process. PMS is then represented by an analysis framework, in which automatic data processing and data acquisition by condition assessment form a coherent system. Beside a high number of tailor-made solutions, commercial software products fulfil most of the needed requirements (e. g. 'HDM-4') and special products can be adapted to the local requirements (e. g. '*dTIMS CT*^{TM}').

Most appropriate output from PMS and most coherent data processing become possible only, if consistent functional relations exist between the individual parts of the whole system. This is perfectly realized through a holistic PMS, which is followed up in *InteMat4PMS* (Figure 3). The holistic approach calls for the extension of known PMS architectures through advanced tools, including

- methods for data collection, storage and updating,
- methods for data preparation and calculation of input values for performance prediction and modelling,
- performance based material testing in laboratory,
- most realistic performance prediction by enhanced simulation of pavement distress modes and incorporation of new modes of pavement behaviour (e. g. ageing, healing),
- techniques for calibration of existing performance prediction models using results from performance based material testing and simulated performance prediction,
- and feedback loop of LCA output for pavement management decisions.

To date, various efforts are under way to enhance performance prediction within PMS. *InteMat4PMS* focuses on adjusting empirical performance functions (EPF) through outputs from mechanistic analysis. Effective adjustment of EPF is of advantage, as by considering the mechanistic outputs important factors such as repetitive traffic loads, climate, material characteristics, layer thicknesses, and subgrade support, can be taken into account. The special importance of calibrating EPF is the economic impact, since consideration of substantial pavement loss will reduce prediction error, and hence, economic evaluation will become more accurate.

Most PMS are based on deterministic EPF displaying relationships for dimensional condition parameters. Deterministic performance prediction models describe the future condition by a functional relationship found by simple regression analysis between time variable condition parameters (technical parameter or index) and the descriptive variables (age, traffic load, number of loadings, temperature, etc.). Hence, every set of variable states is uniquely determined by parameters in the model and by sets of previous states of these variables, and therefore, deterministic models always perform the same way for a given set of initial conditions. Deterministic models are generally applied on single "homogeneous" road sections and enable an estimation of the future pavement condition and possible treatment strategies.

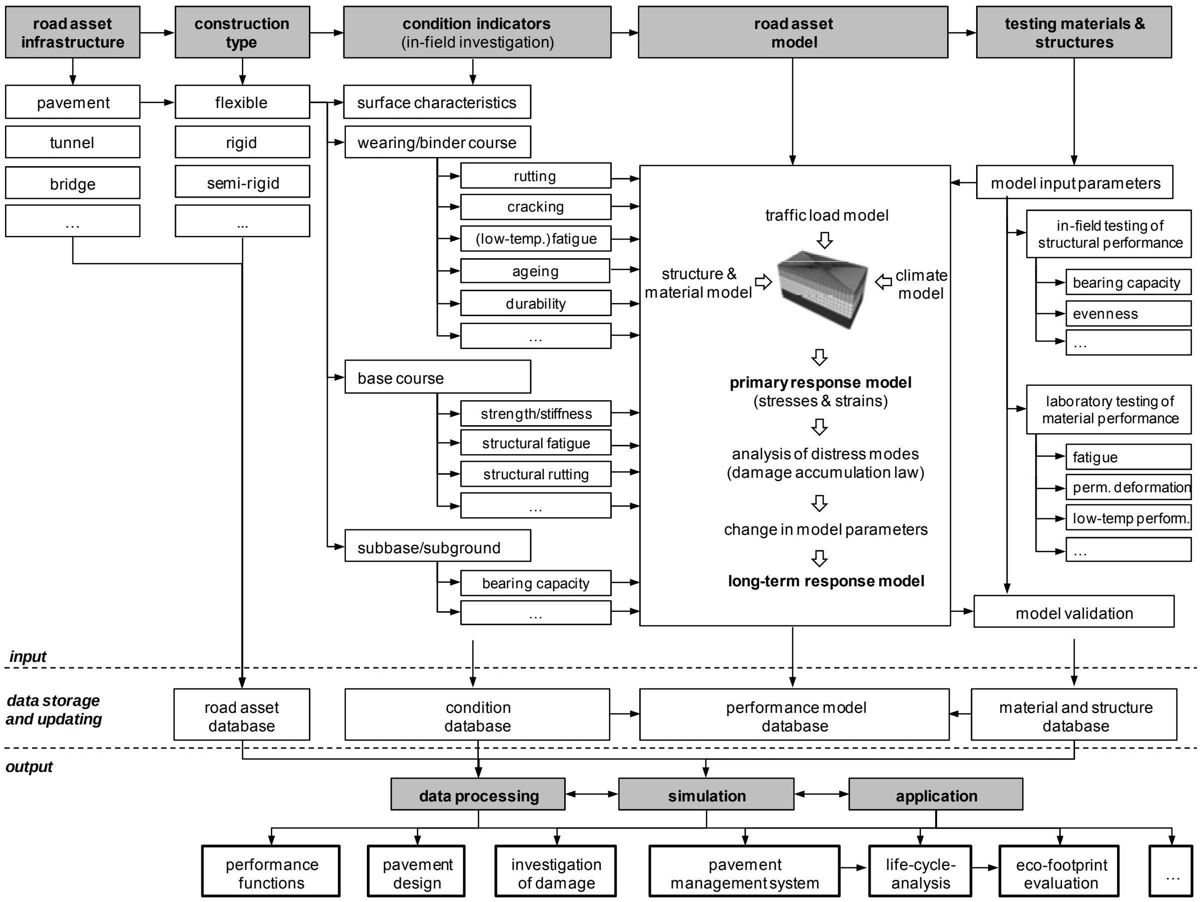


Figure 3. Integrated holistic PMS architecture.

Performance functions used in PMS to describe pavement distress on a specific road section according to representative variables (structure, traffic, geometry, climate) need to be accomplished by information from laboratory tests. In addition to laboratory testing, pavement structural analysis is needed for development of material performance laws to be used within PMS, considering the full pavement structure, and using material parameters and material performance laws as input in structural stress-strain-analysis, in damage analysis, and in pavement performance prediction.

InteMat4PMS links deterministic EPF to mechanistic analysis by means of calibration procedure. In *InteMat4PMS*, the term calibration is defined such, that parameters based on material-science are used as additional input parameters to calibrate key predictive relationships in PMS. The calibration procedure relates the results from laboratory testing of pavement samples to the empirically described condition of the specific pavement section. It does not rely on long-term pavement observation, and advantageously, it allows for theoretical performance prediction without any repetitive material testing.

In order to calibrate EPF, distress data is required that is obtained from mechanistic laboratory analysis of the relevant pavement material at any point in time. However, for perfect calibration, more than one set of laboratory data from different points in time over a long time period is of advantage.

For EPF calibration, pavement distress observation data is linked to incremental loss in material substance observed in the laboratory. Pavement distress is then correlated to the number of traffic load repetitions, and the number of load repetitions is linked with time.

However, pavement distress and distress stated in laboratory tests are not congruent. Data are not comparable a priori and thus, the results of material tests are not directly applicable to predict pavement lifetime. Using material performance laws directly within PMS is problematic. To-date, the arrogating issue of accurate modelling of pavement damage for a defined analysis interval with steady load, and of continuous accumulation of incremental damage over the total analysis period, is not satisfactorily solved for heterogeneous structures like asphalt pavements. This is primarily due to the complex visco-elasto-plastic asphalt properties and the impossibility of realistic modelling the complex distress modes observed in asphalt pavements for high numbers of load repetitions.

Therefore, the calibration procedure developed in *InteMat4PMS* focuses on fatigue-related performance initiated by diffuse micro-cracks that finally forms a macro-crack network in the whole pavement structure. It is demonstrated in detail, how a suitable Laboratory Calibrated Performance Function can be derived that considers pavement failure due to bottom-up fatigue cracking.

This example may assist in implementing different types of performance prediction models, as the developed procedure can be equally extended to other distress modes such as (top-down) thermal cracking, reflective cracking or permanent deformation (rutting), always on condition that suitable laboratory analysis is provided.

Especially, the assessment of permanent deformation (rutting) seems to be an adequate candidate for further development and fulfills most of the precondition from both, the laboratory side as well as the PMS side (Figure 4).

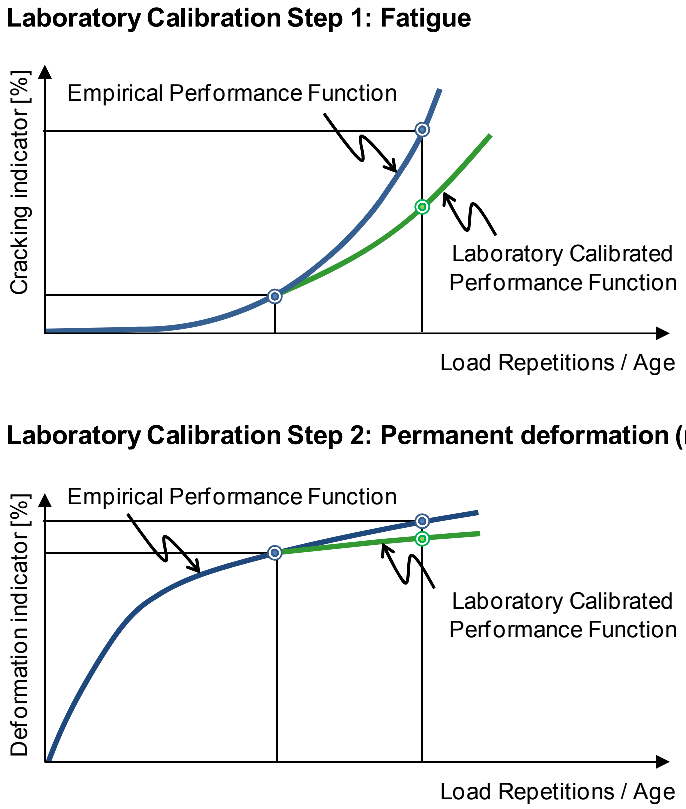


Figure 4. Two-step laboratory calibration considering fatigue cracking and permanent deformation (sketch).

2.2 Laboratory testing and structural modelling

The laboratory analysis provides all data, needed for the developed PMS algorithms to calibrate the EPF. It comprises material testing and structural pavement modelling. Material testing aims in assessing deterioration in function of load repetitions. Tests are performed on material samples taken from the relevant road section or from compacting loose asphalt mixture in the laboratory, and by performing cyclic material tests. The output from material testing is used for pavement modelling and for finding a mechanistic performance function that represents structural pavement performance in function of accumulated load repetitions.

In *InteMat4PMS*, the laboratory analysis focuses on stiffness and on fatigue-related failure mechanisms. The presented approach is of general usability and can thus be adapted to other incremental failure mechanisms as well.

2.2.1 Material testing

Various tests can be performed in laboratory to derive target mechanical properties of the compacted asphalt material. Laboratory test methods usually focus on material investigation with regard to stiffness properties, resistance to material fatigue, to low temperature cracking, and to permanent deformation. Most suitable and approved test procedures are indicated in Table 1, comprising both static and cyclic tests.

Table 1: Laboratory test procedures suitable to assess asphalt material parameters

Asphalt Course	Stiffness	Material Fatigue	Low Temperature Performance	Permanent Deformation
Surface	X	(x)	x	x
Binder	X	(x)	x	x
Base	X	x	(x)	(x)
Test Procedure	• 2-Point-Bending test with trapezoidal specimen (2PB-TR) • 2-Point-Bending test with prismatic specimen (2PB-PR) • 3-Point-Bending test (3PB) • 4-Point-Bending test (4PB) • Cyclic indirect tensile test (CIDT) • Direct tension-compression test (DCT)	• Cyclic indirect tensile test (CIDT) • 4-Point-Bending test (4PB)	• Temperature Stress Restrained Specimen Test (TSRST) • Uniaxial tension stress test (UTST) • Uniaxial Cyclic tension stress test (UCTST)	• Triaxial cyclic compression test (TCCT) • (Wheel tracking test WTT)
EN Standard	EN 12697-26	EN 12697-24	EN 12697-46	EN 12697-25 (EN 12697-22)

x…performance characteristic needed/pre-scribed, (x)…additional performance characteristic

Beside these tests various other test procedures exist which address key material properties like bitumen ageing, water sensitivity, adhesion properties, or mix compactibility. However, as regards these test procedures, no consensus on best practice has been identified in Europe so far, European harmonization is not realized, and performance functions are barely known. Therefore, they will not be considered in this research study. In *InteMat4PMS*, material testing is limited to cyclic test procedures, in which the material is subjected to oscillatory (sinusoidal) loading at varied frequencies and temperatures. A short-term non-destructive test is conducted to derive the material stiffness modulus. For determination of the deterioration mechanisms in asphalt materials the load is increased in order to damage the material.

(1) Stiffness testing

Asphalt layer stiffness is a primary material property determining structural strength of the layer. It is expressed in terms of a stiffness modulus. As asphalt is a visco-elastic material, asphalt stiffness modulus is a function of loading conditions. Within a multi-layered pavement structure, layer stiffness plays an important role in regard to the load transfer. The higher the stiffness modulus of the layer, the more stress is “absorbed” by this layer, and the smaller are the strains occurring in this layer.

Stiffness modulus is defined by a complex number described in function of load, loading time and temperature.

Various test methods can be applied for stiffness testing of asphalt materials, including both homogeneous and non-homogeneous tests. For non-homogeneous tests, the stress amplitude and the strain amplitude vary from one point of the sample to the other (Di Benedetto et al., 2001). However, determination of complex modulus by means of non-homogeneous tests becomes possible, if linear visco-elastic material behaviour can be postulated.

Asphalt mix stiffness represented by the complex stiffness modulus can be determined in a cyclic test conducted in the small strain domain. In order to guarantee linear material behaviour, stiffness tests should be performed such that testing strains are lower than 100 µS. Typically, test temperatures range from -15 °C up to +45 °C, and frequencies from 0.1 to 40 Hz. It is recommended, to test a minimum number of three specimens at about five different temperatures and five frequencies, and for further analysis, to calculate a mean value of the three specimens for every temperature and frequency concerned. Less than 100 load cycles should be applied in order to reduce thermodynamic influences on modulus measurement. Di Benedetto et al. (2001) rate the influence of heating on modulus value by some percent, due to the dissipated energy created during each cycle that heats the specimen especially at the beginning of the test and reduces the stiffness modulus (the decrease is proportional to the applied frequency and to the square of the strain amplitude).

From the force amplitude F_a and the resulting displacement amplitude u_a as well as the phase lag ϕ between the force and the deflection signal measured during the test, the complex modulus E^* (described by the real/elastic/storage modulus E_1, and the imaginary/viscous/loss modulus E_2) can be calculated.

A high consistency is observed among stiffness parameters resulting from different test procedures. Correction factors need to be considered for the respective type of stiffness test, i. e. a shape factor (γ) in function of the specimen dimensions, and a mass factor (μ) to consider the effects of inertia related to the mass of the moving specimen and the mass of the moving parts.

(2) Distress testing

Cyclic loading at high stress rates results in important degradation of the material structure. Tests are performed either in the linear domain with strain amplitudes in the order of 10^{-4} m/m (e. g. fatigue test), or in the non-linear domain when the response to the sinusoidal load is not sinusoidal (e. g. deformation test).

InteMat4PMS focuses on fatigue testing in the linear-domain. In consequence of repeated loading, strength and stiffness modulus of asphalt materials decrease progressively. This phenomenon is generally called fatigue. During laboratory fatigue testing, typically, three disparate phases appear successively. During first phase (I) initial stiffness modulus changes rapidly, then a second quasi-linear phase (II) follows, and finally, global failure is observed in the third phase (III) (see Figure 5). Fatigue is mainly attributed to phase II.

According to Di Benedetto et al. (2004), the quasi-linear fatigue degradation during the second phase results from damage that is initiated and spread in the material in the form of a diffuse micro crack network that provokes a quasi-linear change in the macroscopic rigidity. Even though the influence of fatigue on stiffness modulus change is predominant, artefact phenomena must not left disregarded for interpretation of fatigue failure. Moreover, the fatigue phenomenon may be hidden by the accumulation of irreversible strain that may occur during the test due to repeated compressive or tensile excitations. This is especially valid for stress-controlled cyclic tensile or compressive stress tests, in which, in general, specimen collapse is observed rapidly.

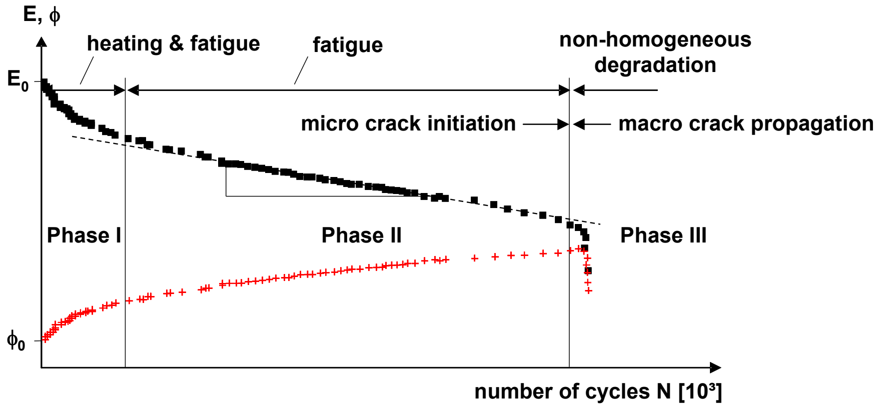


Figure 5. Typical stiffness modulus evolution curve observed in fatigue testing of asphalt mixtures (schematic).

Due to the initiation and coalescence of micro cracks during (phase I and) phase II, at a certain level of damage, macro cracking is initiated in phase III and propagates within the material and soon, global failure is observed.

An important artefact effect during cyclic testing is thermal self-heating of the specimen. Due to their viscous properties asphalt materials dissipate energy after each load cycle, which is partially converted into heat. Di Benedetto et al. (1996) measured an increase of temperature of 1.3 °C during a fatigue test and concluded that more than 30 % of the classical characterization of fatigue is due to heating. For that reason they propose to isolate the pure fatigue from the heating phenomenon by considering only phase II of the fatigue curve, which results from a controlled-strain test. Phase I and III correspond to periods, in which heating has a dominant effect, and non-homogenous large degradations occur.

The mode of loading has a crucial influence on the fatigue test result. Hence, the fatigue behaviour is very sensitive to the loading and boundary conditions applied during the test. In addition, results from different fatigue tests usually show an important scatter. For this reason, careful selection of testing conditions and interpretation of test data are needed. As concerns the mode of loading, a sinusoidal load is usually applied by maintaining either a constant stress amplitude (controlled-stress mode), or a constant strain amplitude (controlled-strain mode). For the controlled-displacement mode, the force decreases with the number of load cycles. The stiffness modulus, defined as the ratio of the stress amplitude to the strain amplitude, increases, and the energy dissipated per stress-strain cycle decreases (Van Dijk et al., 1972). The contrary relationships are valid for the controlled-force mode, but the changes occur more rapidly, as this testing procedure is comparably more severe to the material (but closer to real conditions in pavements of ≥ 10 cm thickness, cp. Monismith et al. (1965)). For both modes, the phase lag increases during testing.

Assessment of material fatigue characteristics requires knowledge of the long-term evolution of the complex modulus (E and ϕ) and the dissipated energy W_{dis}. These parameters are obtained from the measured sinusoidal forces and displacements (or directly from stresses and strains in homogeneous tests). Usually, the test results of cyclic testing on asphalt mixtures with or without rest-periods are analysed in terms of fatigue life duration and of fatigue damage characteristics in the crack initiation phase.

By fatigue life is understood the number of load applications to failure. In a macroscopic sense, failure is usually defined in terms of load carrying capacity or energy storage capacity, and is considered in empirical failure criteria, stress or strain failure criteria, energy type failure criteria, or damage failure criteria (Li, 2001). The number of load cycles N till fatigue failure represents the fatigue life of the material for a given temperature and frequency. The classical fatigue criterion is defined

- in a controlled-displacement/strain test as the number of cycles when the initial force/stress has decreased to half of its initial value,
- and in a controlled-force/stress test, when the initial displacement/strain has increased to double of its initial value, respectively (Van Dijk, 1975).

In best accordance but independently from the mode of loading (controlled-displacement/strain or controlled-force/stress), the fatigue criterion can also be defined as the number of cycles $N_{f/50}$ when the stiffness modulus S_{mix} has decreased to half of its initial value (Figure 6).

According to the European Standard for fatigue testing (EN 12697-24), this fatigue criterion shall be used, and determination of the number of load applications at failure $N_{f/50}$ shall be undertaken at not less than three levels in the chosen loading mode (such that fatigue lives are within the range 10^4 to $2 \cdot 10^6$ cycles) with a minimum of six repetitions per level, resulting in 18 single tests for a given temperature and frequency. The results are then plotted in a diagram on (natural) logarithmic scales, in which the values of $N_{f/50}$ are shown in function of initial strain amplitudes ε_i (strain amplitude at the 100th cycle). Finally, a fatigue line (called Woehler line) is drawn by making a linear regression between $N_{f/50}$ and ε_i (see Figure 6), indicating the fatigue life duration in function of the applied load amplitude. As the Woehler line can be expressed in the general form

$N = \alpha_1 \cdot \varepsilon^{-\beta}{}_1$ Equation 1

the linear regression function in the log-log-diagram reads

$\ln N_{f/50} = \alpha + \beta \cdot \ln \varepsilon_i$ Equation 2

with α and β as experimentally derived material constants (note that $\alpha = \ln \alpha_1$, and $\beta = -\beta_1$). Finally, the slope p of the fatigue line and the initial strain amplitude ε_6 corresponding with a fatigue life of 10^6 load cycles are determined, as required for CE-declaration of conformity by the European Standards (EN 13108). Based on these two characteristic material parameters, fatigue behaviour can be evaluated, as a high ε_6 value and a small slope are related to a promising fatigue resistance.

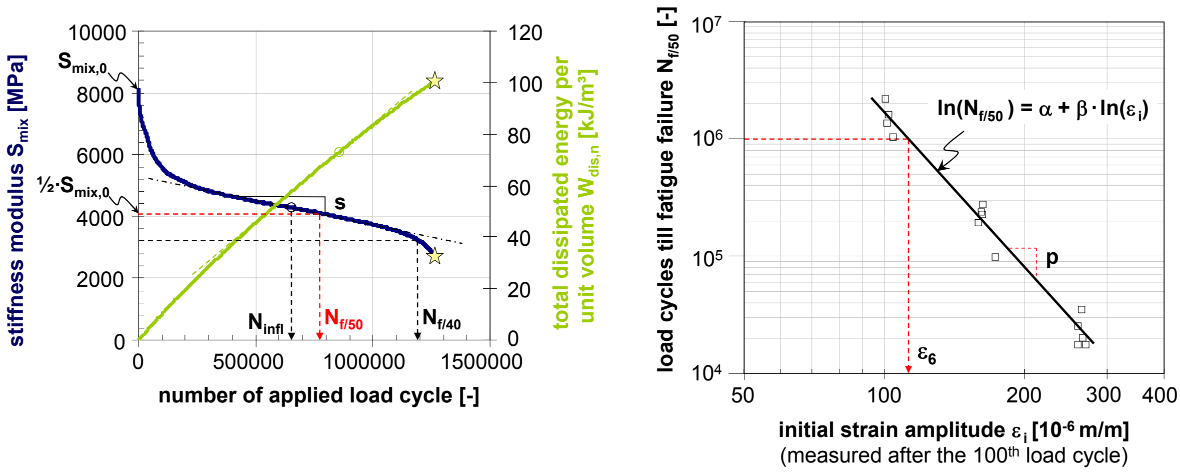


Figure 6. Fatigue life is defined as the number of cycles $N_{f/50}$ (left) when the stiffness modulus S_{mix} has decreased to half of its initial value (cp. EN 12697-24). The resulting fatigue law (represented by the fatigue Woehler line, right) indicates the fatigue life duration in function of the applied load amplitude (schematic).

2.2.2 Structural pavement modelling

For analysis of pavement distress, the entire pavement structure needs to be considered as an integrated system by taking into account the material performance properties of the individual layers. Analysis of response leads to analysis of distress. Material fatigue, permanent deformation, thermal cracking, and lack of bonding are usually regarded as the primary distress modes in asphalt pavements. These deficiencies are related to repeated heavy traffic loading and climate related factors and provoke deformation, fracture, or wear. For consideration of the different deterioration modes, distress criteria are pre-defined, assuming that the pavement fails as soon as the predicted response exceeds a limiting value. E. g., cracking starts, as soon as stress exceeds tensile strength. For description of fatigue it is assumed, that initial micro-cracking accumulates and stiffness decreases in function of time.

By means of computational technology the various distress modes are taken into account for performance modelling of materials, layers and entire pavement structures. To date, most mechanistic pavement design procedures consider the fatigue criterion only, while the distress mode of thermal cracking, and permanent deformation (rutting) are left disregarded. A comprehensive practical tool for reliable prediction of the total in-service performance of road asphalts is still missing. Research is needed for the development of enhanced prediction tools, which are capable of predicting the resistance to failure in the actual pavement environment, taking into account the complex material properties of the asphalt mixture, the complex stress conditions due to both traffic and thermal loading, the effects of aging and stripping, the effects of initial cracks, etc. *InteMat4PMS* focuses on the implementation of evolution models describing fatigue.

Analysis of fatigue evolution requires a cumulative 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 (1945). 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 Woehler curve modelling. Cumulative damage D over total analysis period is composed of individual incremental damage ratios, reading

$$D = \sum_{i=1}^{n} \frac{n_i}{N_i} \leq 1 \qquad \text{Equation 3}$$

with n_i as the number of actual traffic load applications at strain/stress level i; and N_i as the number of allowable traffic load applications 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 equals 1, the pavement fails due to material fatigue, and hence, the pavement substance value has decreased to 0 % of the initial value.

Sometimes, the theoretical residual fatigue life is expressed in the unit of years. For this purpose, the number of actual traffic load applications used for design considerations is formulated by a mean value for one design year (based on traffic counts and extrapolative estimations).

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.

For the purpose of fatigue modelling achieved in *InteMat4PMS*, the results from material stiffness and fatigue testing are turned into representative material coefficients (stiffness modulus, Poisson ratio) and into the specific material fatigue law (Woehler line). These parameters are then implemented into a multi-layered model of the pavement structure.

Based on elastic theory, the model is used to calculate primary response in terms of stresses and strains. Using an asphalt strain criteria, stress and distress are correlated according to the derived fatigue law. The calculation comes up with a damage accumulation law. From fatigue modelling, a linear damage accumulation law is obtained. Any number of load repetitions $N_{f,D}$ (-) is linked to a specific amount of damage D (%).

2.3 Calibrating performance function through laboratory data

The calibration procedure is sub-divided into the following 3 steps, i. e. (1) section based calibration of the selected EPF, (2) laboratory analysis, and (3) integrating laboratory data into EPF.

2.3.1 Section based calibration of EPF

The starting point for the calibration procedure is the EPF, which is based on condition data assessment. The number of traffic load repetitions is the key input parameter for describing the structural pavement deterioration in function of time. First, the actual load repetitions and the starting point of the EPF are calculated. This is carried out per road section using the section-specific traffic information, the respective model-parameters and condition data from actual condition inspection or measurement.

As a result from the section-based analysis, a performance indicator PI' ($N_{meas,t}$, $PI_{meas,t}$) is found, which is expressed by

- the number of load repetitions $N_{meas,t}$ (-) the pavement has already been subjected to until the time t,
- and the performance indicator $PI_{meas,t}$ that indicates the pavement condition at the time t,
- and the time t corresponds to the date of the (last) condition measurement.

To obtain the 'calibrated EPF', the initial 'non calibrated EPF' is shifted through the point ($N_{meas,t}$, $PI_{meas,t}$) by stretching or shrinking its initial shape in order to match the performance indicator PI' derived for the specific section (see Figure 7).

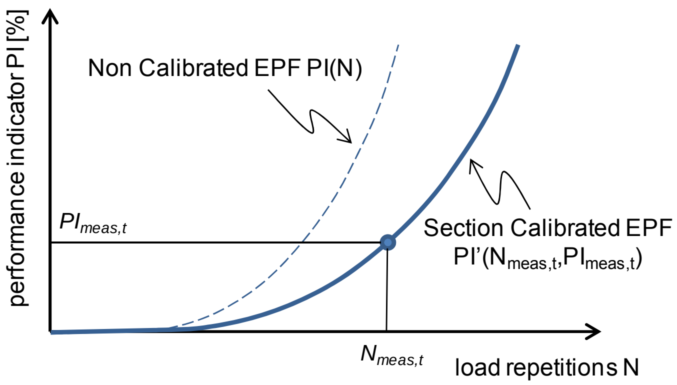


Figure 7. Calibrating the empirical performance function (EPF) by shifting the initial 'Non Calibrated EPF' to obtain a 'Section Calibrated EPF'.

2.3.2 Laboratory analysis

Pavement deterioration in function of load repetitions is assessed in the laboratory by using material samples taken from the relevant road section or from compacting loose asphalt mixture in the laboratory, and by performing cyclic material tests. Advantageously, the date of pavement sampling correlates with the date of pavement condition survey.

The output from material testing is used for pavement modelling and for finding a mechanistic performance function that represents structural pavement performance in function of accumulated load repetitions.

For the purpose of fatigue modelling achieved in *InteMat4PMS*, the results from material stiffness and fatigue testing are turned into representative material coefficients (stiffness modulus, Poisson ratio) and into the specific material fatigue law (Woehler line). These parameters are then implemented into a multi-layered model of the pavement structure. Based on elastic theory, the model is used to calculate primary response in terms of stresses and strains. Using an asphalt strain criteria, stress and distress are correlated according to the derived fatigue law. The calculation comes up with a damage accumulation law. From fatigue modelling, a linear damage accumulation law is obtained, as illustrated in Figure 8. Any number of load repetitions $N_{f,D}$ (-) is linked to a specific amount of damage D (%).

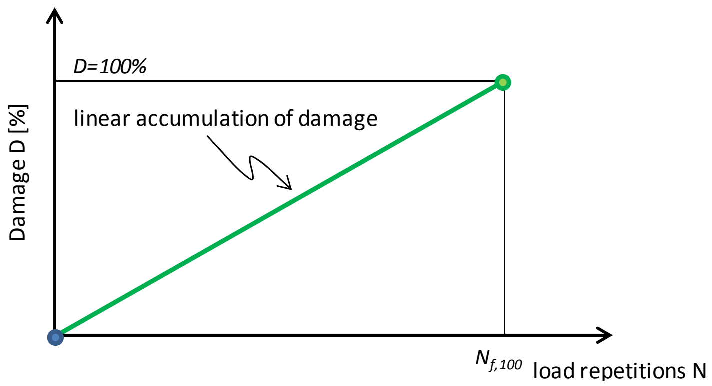


Figure 8. Linear damage accumulation law obtained from laboratory analysis of pavement fatigue.

2.3.3 Integrating laboratory data into EPF

The results from laboratory analysis – in terms of damage D (%) and corresponding number of load repetitions $N_{f,D}$ (-) – are finally used to improve the Section Calibrated EPF. Hence, the function EPF' ($N_{meas,t}$, $PI_{meas,t}$) is shifted once again in order to obtain a new function called 'Laboratory Calibrated EPF' expressed as EPF'' ($N_{meas,t}$, $PI_{meas,t}$, X_f) (see Figure 9).

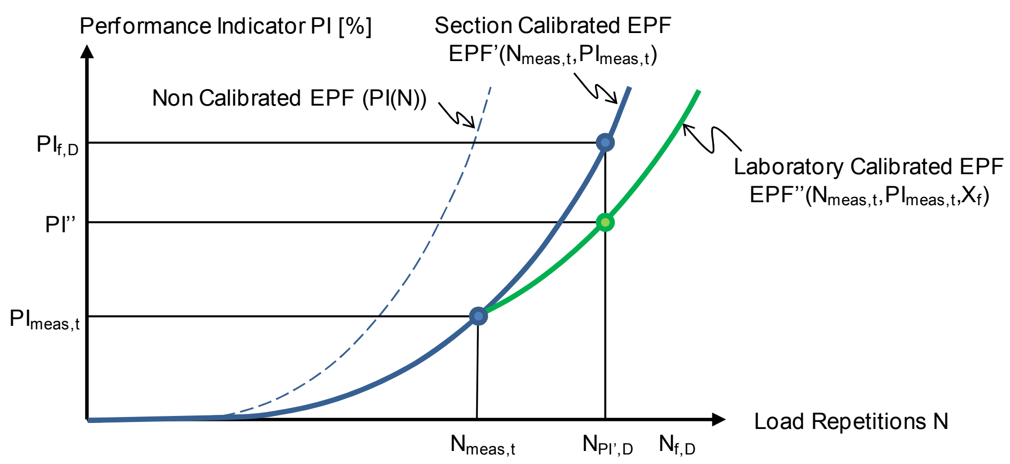


Figure 9. Calibrating the empirical performance function (EPF): The 'Section Calibrated EPF' is shifted to obtain a 'Laboratory Calibrated EPF' using a scaling factor X_f derived from material and structural laboratory analysis.

Performance analysed in laboratory is not equal to in-field pavement performance. The significant difference between laboratory and real performance depends on many factors such as the loading conditions (geometry, vehicle type, axle configuration, lateral wander), rest periods between loading phases and healing effects, environmental factors (temperature, radiation, precipitation, frost). For this purpose, pavement damage on site needs to be linked to damage observed from material and structural laboratory analysis.

As regards pavement cracking, fatigue during laboratory testing is not equal to crack rate increase in the road. Hence, the end of fatigue life is not congruent with a fully cracked pavement having a cracking rate of 100 %. Nevertheless, end of pavement life can be stated in form of distress, where cracking is one the most significant indicators. Thus, the end of fatigue life (based on laboratory testing) is usually brought in correlation with the (real) cracking on the road. For linking laboratory performance to pavement performance, a scaling factor X_f for a defined rate of damage D (%) is used (see Chapter 3.3.3).

For a defined rate of damage D the inter-relation of both numbers of load repetitions – $N_{PI',D}$ derived from pavement condition measurement, and $N_{f,D}$ derived from laboratory analysis – can be expressed through the scaling factor X_f, reading

$$X_f = \frac{N_{PI',D} - N_{meas,t}}{N_{f,D} - N_{meas,t}} \qquad \text{Equation 4}$$

with $N_{meas,t}$ as the number of load repetitions at the time t of the (last) condition measurement.

In practice, the scaling factor X_f stretches or shrinks the function EPF' ($N_{meas,t}$, $PI_{meas,t}$) along the horizontal N-axis and enables an improved performance prediction for any time t+N of the analysis period, with N as the number of load repetitions from time t until the defined rate of damage is reached. As a result of the scaling procedure, the 'Laboratory Calibrated EPF' is obtained expressed by the mathematical function EPF'' ($N_{meas,t}$, $PI_{meas,t}$, X_f) at any time t+N, reading

$$PI''_{t+N} = PI_{meas,t} + EPF''(\Delta N) = PI_{meas,t} + X_f \cdot EPF'(\Delta N) \qquad \text{Equation 5}$$

where $\Delta N = N_t - N_{meas,t}$

with $PI_{meas,t}$ as the performance indicator at the time t; EPF' as the Section Calibrated EPF; X_f as the scaling factor; N_t as the total number of load repetitions until t ($N_t > N_{meas,t}$); and $N_{meas,t}$ as the number of load repetitions at time t of condition measurement.

2.4 PMS software requirements and adaptation

2.4.1 PMS requirements

PMS is realized in terms of either a fully flexible commercial software tool or of a project specific tailor-made software solution. The new analysis procedure can be adapted to any existing PMS solution. However, the PMS solution shall advantageously meet the following general requirements.

All relevant data are stored in a data base, which is linked to the PMS analysis tool. The data base comprises inventory data covering all net specific information (road network, reference points, section lengths), pavement design data (materials, layers, construction dates), cross section data (number of lanes, widths), traffic data (AADT, $AADT_{trucks}$, traffic growth rate), pavement condition data (condition indices, date of surveys), performance models/functions (parameters, calibration factors), and other relevant information such as climate data or road network responsibilities.

Pavement performance is described in terms of suitable performance prediction model(s). Any model is composed of one or more performance functions. The prediction model is considered as appropriate, if

- it is represented through deterministic mathematically sound equation(s) of well-defined available input parameters,
- it displays the physical (long-term) pavement (material or layer) performance in function of time (or load repetitions), and
- it reflects local boundary conditions (pavement type, materials, traffic, climate) and local experience.

In many PMS, performance functions depend on analysis variables, which may change by the year of observation. Any change of the analysis variable is also stored in the data base. Especially the starting point of the performance function is well-defined if depending on specific input values (e. g. from condition survey).

The user either selects a pre-defined performance function, already available in the system, or implements a new performance function. The PMS should be open for the implementation of a new performance function, which means that also the data base should be open for all parameters of the new performance function.

The selected performance function has to be in accordance with the physical characteristics to be assessed, pavement construction type (materials, structure), any precondition (local climate), and local experience.

The PMS should be capable to execute LCA or LCCA on all road sections. It must allow that user-specific optimization procedures by using benefit/cost analysis can be realized. Furthermore it must be possible to export all results from the analysis for further data processing.

Within *InteMat4PMS*, the commercial PMS software '*dTIMS CT*™' is used to demonstrate practical application. However, any similar PMS software can be used. The choice of the PMS software tool is free, if only the above mentioned general requirements are met.

2.4.2 Adaptation of PMS

Work steps of principal importance for PMS adaptation are summarized in the following. Detailed information on the practical PMS adaptation is given in Annex B. A practical example for demonstration is given in Chapter 3.

The flow chart in Figure 10 provides an overview of the work steps for PMS adaptation. The solution is developed iteratively. Test runs are repeated until all requirements are fulfilled.

Pavement performance is described in terms of suitable performance prediction model(s), see Chapter 3.3.1.

PMS adaption is done iteratively, starting with the adjustment of the analysis variables of the initial (non-calibrated) performance model(s). It is recommended to analyze the model outcome in short time intervals (year by year), to check the input parameters and the analysis variables, and to compare the results to the outputs from known performance functions and from calculations executed separately from PMS. In case of divergence the calculation process is revised.

The data base of PMS contains a catalogue of maintenance options. All maintenance options need to be linked to EPF by means of triggers and reset values. A trigger can be defined as the threshold for the application of a specific maintenance treatment (e. g. reconstruction if cracking > 20 %). Resets define the effect of a treatment on condition, in terms of either an absolute value (e. g. no cracking after reconstruction), or a relative value (e. g. reduction of 20 % cracking after patching).

The implementation of results from laboratory analysis in combination with EPF calibration in PMS is detailed already in Chapter 2.3. Functionality and suitability of the calibration procedure needs to be checked after implementation. A comparative analysis in short time intervals is recommended for a high number of different pavement sections.

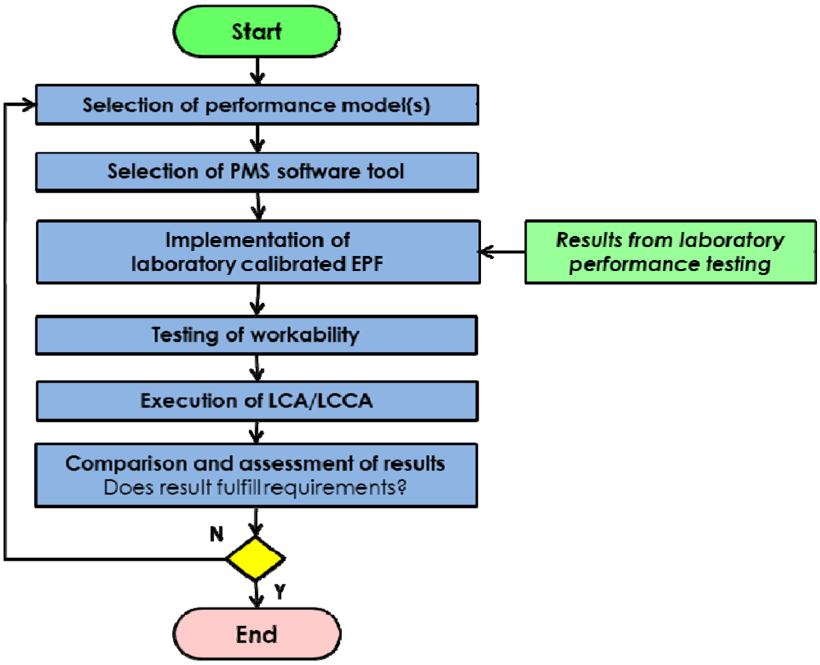


Figure 10. Work steps for adaptation of the PMS software.

LCA/LCCA is executed in two steps. In the first step, maintenance options are selected for the road sections, where the treatment catalogue of the PMS provides the necessary basis. Selected maintenance options are linked with a performance prediction model. Hence, the effects of different maintenance options can be analysed in terms of costs and benefits. Costs are either related to the road operator (construction, maintenance, operation), or to the user (vehicle operation, freight time, accidents). Benefits result from the change in the analysis variable(s) of the performance model. When determining benefits, benefit to the road user arises from improved level of service of the road (typically reduced travel time), while the ownership costs are related to the direct monetary effect to the road agency. In the second step, the best maintenance treatment strategy for each road section is found. In the framework of PMS, various measures and models are known for the objective estimation of costs and benefits, for the evaluation of maintenance treatment efficiency, and for the optimization process to find the best maintenance strategy.

Finally, the outcome of PMS adaptation is evaluated. LCA/LCCA can be used to contrast the results obtained with Laboratory Calibrated EPF and non-calibrated EPF. Distinct differences may be obtained.

However, the benefit of using Laboratory Calibrated EPF cannot be expressed in terms of costs and benefits resulting from LCA/LCCA. The benefit is that it makes PMS more effective in the long run, because performance prediction in PMS will match real pavement performance more closely.

3 Demonstration case studies

Workability of the new analysis procedure is exemplarily demonstrated based on real data from two test road sections. In the following, the test sections, the laboratory analysis of the respective asphalt materials, the choice of the initial EPF, the calibration of EPF based on the results from the laboratory analysis, and the analysis outcome are summarized.

Finally, considering different rehabilitation scenarios and boundary conditions, the effects of using Laboratory Calibrated Performance Functions in PMS are analysed.

Extended analysis details and explanations are provided in Deliverable D3 and Deliverable D4.

Within *InteMat4PMS*, it was intended to apply the developed 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. However, the assessment showed that the test section on the Swiss national road network did not fulfil the minimum requirements for data and material testing in comparison to the German test section. Thus, this section was excluded from further 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.

3.1 Test road sections

Both test road sections are located in Germany, on main road B 35 near Stuttgart, and were constructed in 2007. Pavement cross-sections are illustrated in Figure 11, Section 2 is (under)designed for a period of 8 years only. Information on asphalt mixtures is provided in Table 2. Traffic is the same for both sections and represented in Table 3.

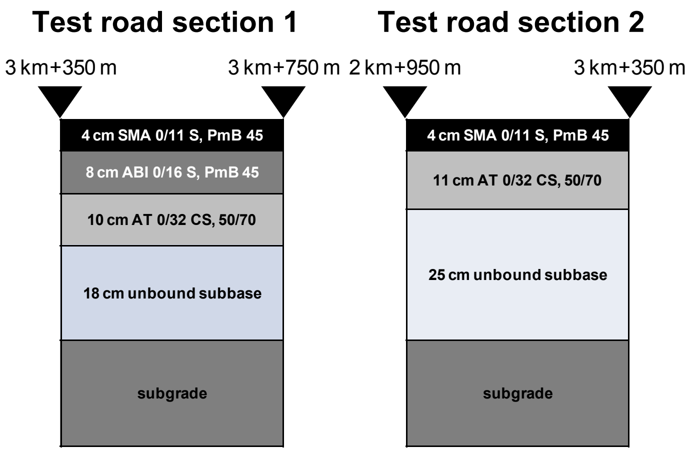


Figure 11. Pavement design of section 1 (left) and section 2 (right).

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

	base course	binder course	wearing course
asphalt mix type	AT 0/32 CS (= AC 32 T S)	ABi 0/16 S (= AC 16 B S)	SMA 0/11 S (= SMA 11)
binder type	50/70	PmB 45 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

Table 3: Average heavy vehicles per day [HV/24h] for different years of observation

Year	HV per 24 hours	N [years]	ESAL [-] *
2007	1 483	30	8 453 188
2008	1 389	29	7 570 804
2009	1 189	28	7 231 020
2010	1 070	27	6 897 899
2011	1 107	26	6 571 899

* Equivalent 10-tons Standard Axle Load according to RStO 01 (German standard)

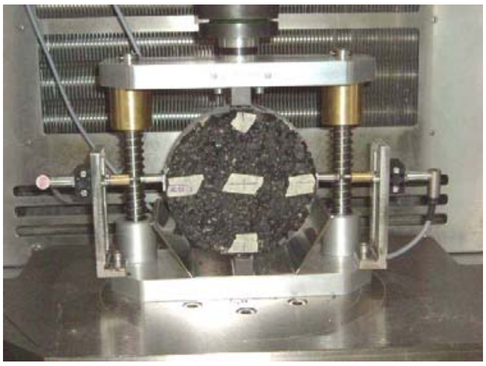
3.2 Laboratory analysis

Asphalt mix samples originating from the construction year 2007 are available from both Test Sections. During the laboratory analysis in the frame of *InteMat4PMS*, the asphalt mixture is re-heated and compacted in the laboratory to produce asphalt slabs from which cylindrical asphalt specimens are drilled.

In addition, cylindrical asphalt specimens are available from pavement coring in the years 2010 and 2012 for Test Section 1, and for the year 2012 for Test Section 2.

Testing includes characterization of stiffness and of fatigue properties of the base course layer from asphalt mix type AC 32 T S.

All specimens are investigated through Cyclic Indirect Tensile Stress Test (CIDT). During CIDT, 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 σ_x/σ_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.



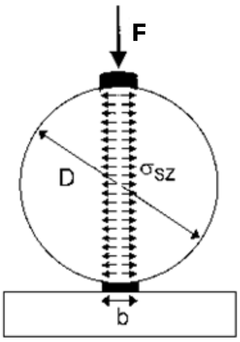


Figure 12: Layout of the Cyclic Indirect Tensile Stress Test (CIDT).

From CIDT, stiffness characteristics and fatigue characteristics are derived. In the fatigue test the specimen is loaded in controlled force-mode until failure. Nine single CIDT 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 through Equation 6. Hence, the results of CIDT are directly used to estimate the number of load cycles which can be endured without any material failure.

$$N_{perm} = SF/F \cdot a \cdot \varepsilon^k \qquad \text{Equation 6}$$

with N_{perm} as the maximum number of load repetitions, a as the material parameter, determined by regression from fatigue tests, ε as the elastic strain (layered elastic theory), k as a material parameter determined by regression from fatigue tests, SF as a shift-factor (here SF = 1 500), and F as a safety-factor (here F = 1.5).

Differences from laboratory data to real pavement performance is covered by the shift factor SF as well as a safety factor F. Correction of laboratory data through these factors is needed, as distress mechanisms in pavements are far more complex than can be investigated by means of laboratory testing or modelling. In the German Standards, an empirically derived shift-factor of SF = 1 500 is used for correcting data obtained via CIDT.

Results in terms of stiffness modulus in function of temperature and of fatigue behaviour obtained from CIDT for different years are shown for Section 1 in Figure 13 and Figure 14, for Section 2 in Figure 15 and Figure 16.

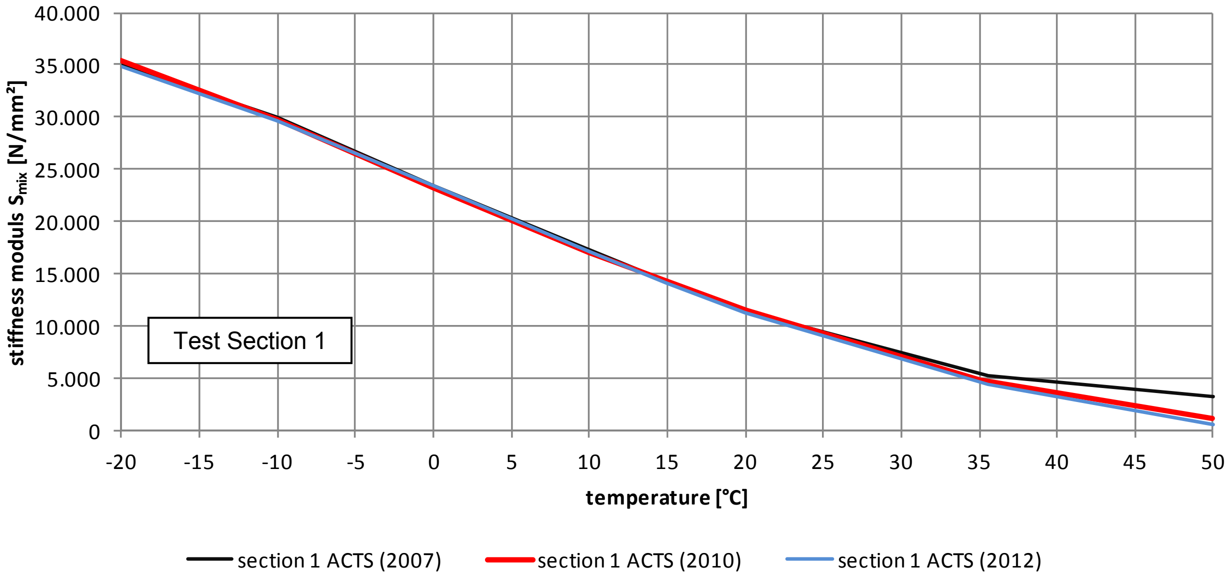


Figure 13. Section 1, asphalt mix type AC 32 T S: Stiffness modulus S_{mix} in function of temperature for the years 2007, 2010 and 2012.

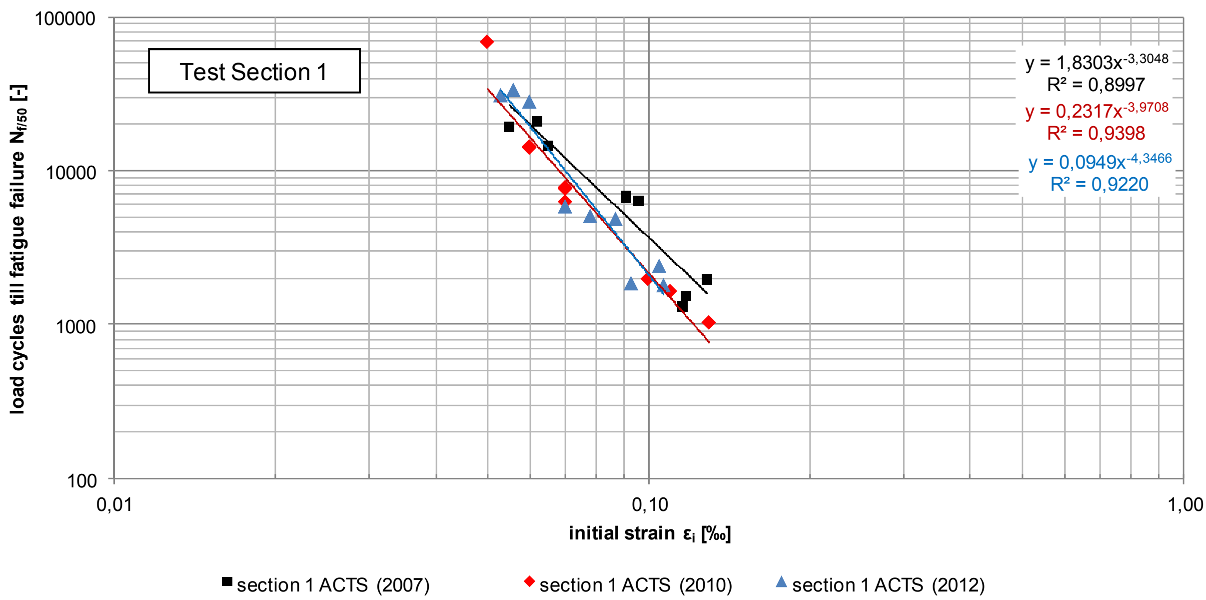


Figure 14. Section 1, asphalt mix type AC 32 T S: Fatigue behaviour for the years 2007, 2010 and 2012.

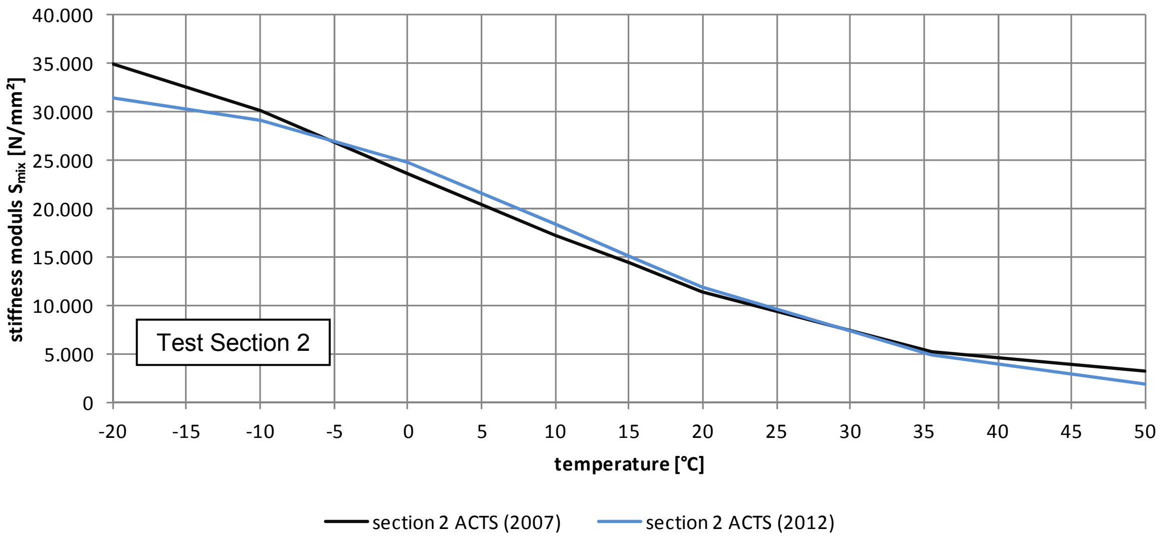


Figure 15. Section 2, asphalt mix type AC 32 T S: Stiffness modulus S_{mix} in function of temperature for the years 2007 and 2012.

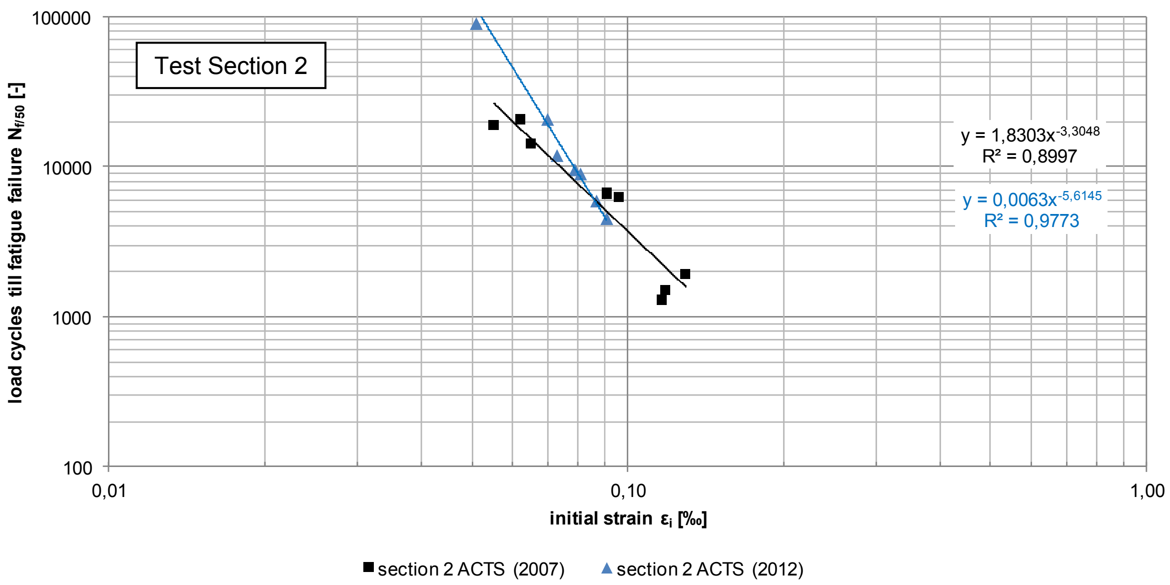


Figure 16. Section 2, asphalt mix type AC 32 T S: Fatigue behaviour for the years 2007 and 2012.

Using these laboratory data – and well-defined estimations for all analysis inputs and boundary conditions needed for pavement modelling – a mechanistic pavement design model is used to estimate the remaining life of the pavement.

Stiffness data are needed to calculate the actual stress and strain in function of the applied traffic load at given temperature. Fatigue data are needed to estimate the decrease in stiffness in function of load repetitions. 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 laws (represented through the fatigue Woehler lines shown in Figure 14 and in Figure 16) indicate the fatigue life duration in function of the applied load amplitude.

Miner's law is used to calculate for defined loading conditions the ratios individually derived from the number of allowed load applications to the mean number of traffic load applications. In Table 4 the numbers of remaining life are presented, always expressed through the number of load repetitions of an equivalent 10-tons standard axle load (ESAL).

Table 4: Calculated remaining life represented by number of load repetitions of an equivalent 10-tons standard axle load (ESAL)

Year	ESAL [-]	
	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. ESAL per year a remaining life can be estimated for the two test sections. Taking into account the back-calculated load repetitions for the material from 2007, the remaining life is 77 years for Section 1, and 12 years for Section 2. Based on the back-calculated load repetitions for the material from 2012, the remaining life is 50 years for Section 1, and 3 years for Section 2. Considering the time difference of 5 years between 2007 and 2012, the service life is 55 years for Section 1 and 8 years for Section 2. The value of Section 2 is equal to the design period in comparison to Section 1, which still shows an overdesigned situation.

The reason for the significant deviations between data from 2007 and 2012 is attributed to different types of material sampling. While for 2007, the material was recovered in the form of loose asphalt mix, pavement cores were available for 2012. Different material treatment (re-heating, compaction) influence laboratory performance data. It is concluded, that samples shall advantageously be taken directly from the road pavement.

3.3 Analysis within PMS

The inventory data of the two test road sections, road condition data, and laboratory data, are subsequently implemented in the commercial PMS software tool *dTIMS CT*^{TM}, and the effect of laboratory calibration and PMS adaptation is evaluated in terms of a Life-Cycle-Analysis (LCA).

3.3.1 Choice of the performance prediction model

For the purpose of demonstration, three different performance prediction models for asphalt pavement cracking are comparatively implemented, i. e. Austrian model, German model, and HDM-4 model. All models are detailed in Deliverable D2.

(a) Austrian model

The Austrian model (Figure 17) is derived from regression analysis of condition data and describes pavement cracking deterioration in function of the age of the surface layer, the design index DI (DI ≤ 0.5 for under-designed pavement; 0.5 < DI < 2 for properly designed pavement; DI ≥ 2 for over-designed pavement) and a material specific coefficient a.

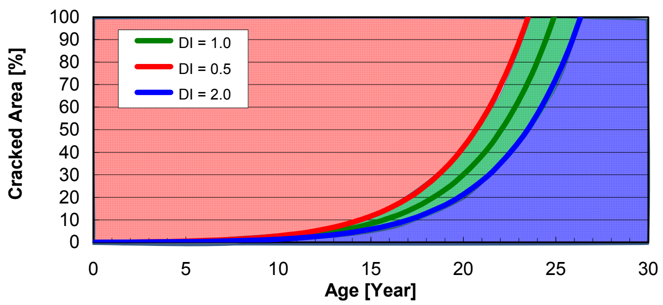


Figure 17. Examples for the Austrian cracking model for motorways and expressways (Molzer et al., 2002).

(b) German model

The German model displays alligator-cracking in function of cumulative 10-tons-ESALs (13 different pavement categories VhG are distinguished) and of the coefficients a, b and c, which are specific for the pavement type (new or already rehabilitated).

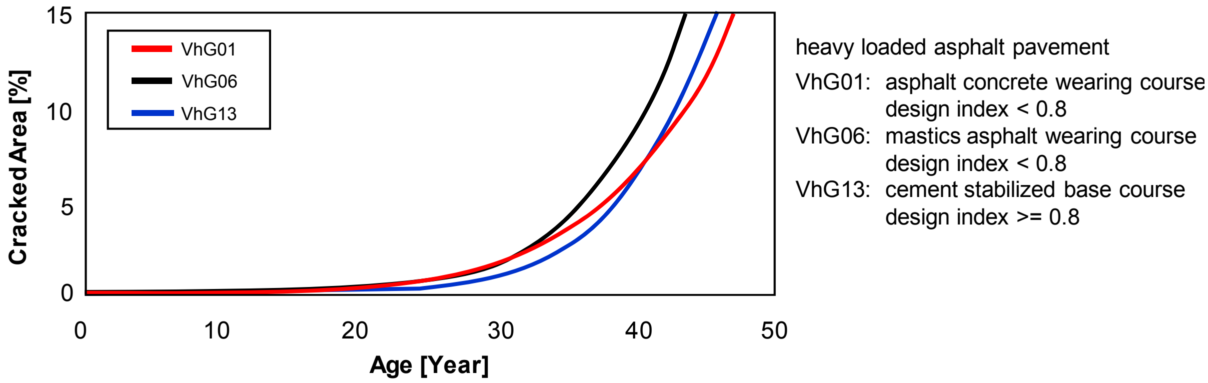


Figure 18. Examples for the German cracking model for 3 different pavement categories (acc. Hinsch et al., 2005).

(c) HDM-4 model

The HDM-4 cracking model is a complex time-based model, which distinguishes initiation and propagation phases of different types of cracks, such as structural cracks, reflective cracks, and thermal cracks (Figure 19).

Structural cracking is modelled based - inter alia - on information on pavement design (structural number, bearing capacities), layers (materials, thickness), construction defects (binder content), number of ESALs, crack retardation time due to maintenance (years), and incremental change in area of cracking during the analysis year (%).

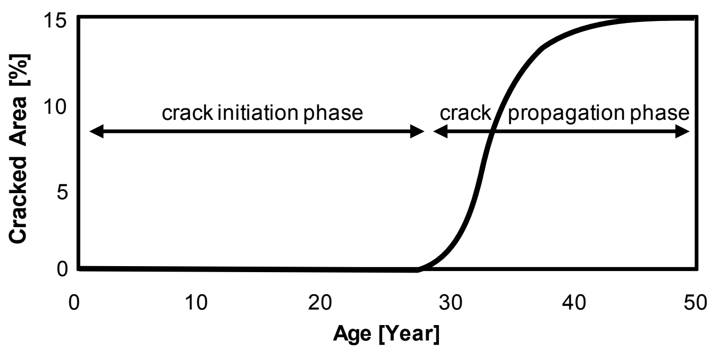


Figure 19. Example for the cracking model used in HDM-4.

3.3.2 Section Calibrated EPF

The prediction models are adapted for the two test sections. Information is considered in regard to pavement construction, and data in terms of traffic loading and of (last) pavement condition measurement. 2007, the year of construction, is used as the starting point. As a result, Section Calibrated EPF for the 3 models are obtained.

Figure 20 shows the Section Calibrated EPF regarding Section 1, and Figure 21 regarding Section 2. As can be seen, the obtained Section Calibrated EPF differ significantly: While both the Austrian model and the HDM-4 model show a distinct increase in the cracking rate at a low number of load repetitions already, cracks develop very slowly according to the German model.

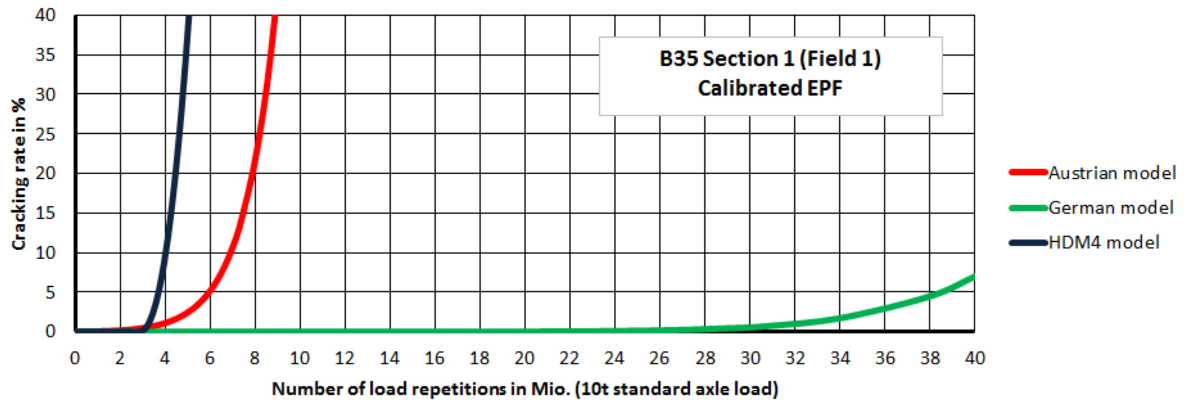


Figure 20. Test Section 1: Section Calibrated EPF, considering Austrian model, German model, and HDM-4 model.

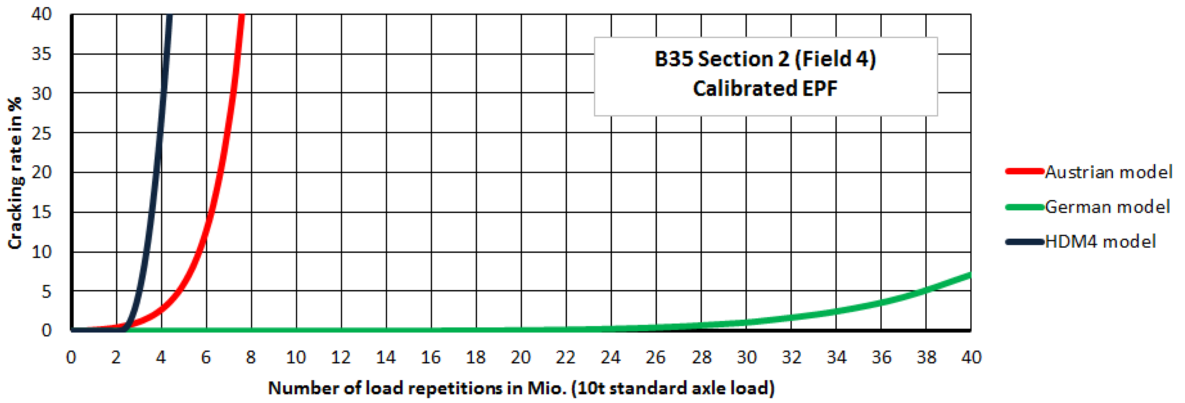


Figure 21. Test Section 2: Section Calibrated EPF, considering Austrian model, German model, and HDM-4 model.

From this comparison, showing the Section Calibrated EPF obtained from different performance models, it can already be concluded, that the choice of the performance model significantly influences the results of PMS analysis. This becomes even more obvious, if the Section Calibrated EPF are finally used for LCA.

Table 5 summarizes the analysis results for both test sections. As an output of LCA the year of the first major (exhaustive) maintenance treatment (related to cracking rate) is displayed. Through comparison of these numbers it is illustrated, how the choice of the performance model significantly influences the PMS analysis.

Table 5: Results of LCA based on Section Calibrated EPF

	Performance prediction model		
	Austrian model	**German model**	**HDM-4 model**
Test Section 1			
Year of 1st major treatment	20	>40	11
Type of 1st major treatment	Reinforcement	Reconstruction	Replacement of wearing and binder course
Test Section 2			
Year of 1st major treatment	17	>40	9
Type of 1st major treatment	Reinforcement	Reconstruction	Replacement of wearing and binder course

These results underline the need for an additional calibration step in order to improve the consistency of performance prediction. A second step of calibration is needed in order to identify the most suitable performance model under the given local requirements. This second step of calibration can be realized through the incorporation of data from laboratory asphalt testing, as shown in the following.

3.3.3 Calibration models

Second step of calibration is realized by incorporating the results from laboratory analysis. For this purpose, the scaling factor X_f is introduced which is obtained from material and structural laboratory analysis. This factor stretches or shrinks the Section Calibrated EPF along the horizontal axis to find a new Laboratory Calibrated EPF (see Chapter 2.3.3).

For identification of the shift factor, the end of fatigue life (based on laboratory analysis) is usually brought in correlation with (real) pavement cracking by using a critical level of damage. E. g. 20 % of cracked area (D_{road}) on the test section is set equal to D_{lab} = 1 as an output of laboratory fatigue testing.

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 applied i. a. in the design methods of the Asphalt Institute (1982). The Asphalt Institute used a criterion of „20 % or greater fatigue cracking (based on total pavement area)".

While for the German model a direct calibration of load repetitions is possible, the load repetitions need to be transformed into years for the Austrian model and the HDM-4 model, taking into account traffic forecasts for the specific road sections.

In this analysis, a linear relationship between the pavement age and the number of load repetitions is used (see Deliverable D2).

(a) Austrian model

The incorporation of laboratory data into the Austrian model reads

$$TP_{cracking,labcalib} = \\ = \exp\left[-3.60517+a \cdot X_f \cdot Age_{Surflayer} + \ln\left(X_f \cdot Age_{Surflayer} + 0{,}01\right) - 0.5 \cdot \ln\left(DI + 0.01\right)\right] \quad \text{Equation 7}$$

with the scaling factor

$$X_f = \frac{Age_{D(road)}}{Age_{D(lab)}} \quad \text{Equation 8}$$

and with $TP_{cracking,labcalib}$ as the laboratory calibrated technical parameter for cracking, a as a model parameter, DI as the design index (see Chapter 3.3.1), $Age_{D(road)}$ as the age at damage D on the road (test section), and $Age_{D(lab)}$ the age at the end of the fatigue life observed in laboratory testing.

(b) German model

The incorporation of laboratory data into the German model reads

$$z_{i,j,t,labcalib} = \alpha_{i,j,k} + \beta_{i,j,k} \cdot \left(X_f \cdot AL_{i,t}\right)^{c_{j,k}} \quad \text{Equation 9}$$

with the scaling factor

$$X_f = \frac{N_{D(road)}}{N_{D(lab)}} \quad \text{Equation 10}$$

and with $z_{i,j,t,labcalib}$ as the laboratory calibrated technical parameter cracking, $\alpha_{i,j,k}$, $\beta_{i,j,k}$, $c_{j,k}$ as model parameters, $AL_{i,t}$ as the cumulative ESALs, $N_{D(road)}$ as the number or load repetitions at damage D on the road (test section), and $N_{D(lab)}$ as the number or load repetitions at the end of the fatigue life observed in laboratory testing.

(c) HDM-4 model

The incorporation of laboratory data into the HDM-4 model can be realized in two different ways, i. e. option A and option B.

As to option A, a default length of crack progression phase is assumed and the length of crack initiation phase is adjusted (Figure 22):

$$\delta t_{A,labcalib} = \max\left\{0, \min\left[\left(Age + X_f - ICA\right), 1\right]\right\} \quad \text{Equation 11}$$

with the scaling factor

$$X_f = Age_{D(road)} - Age_{D(lab)} \quad \text{Equation 12}$$

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

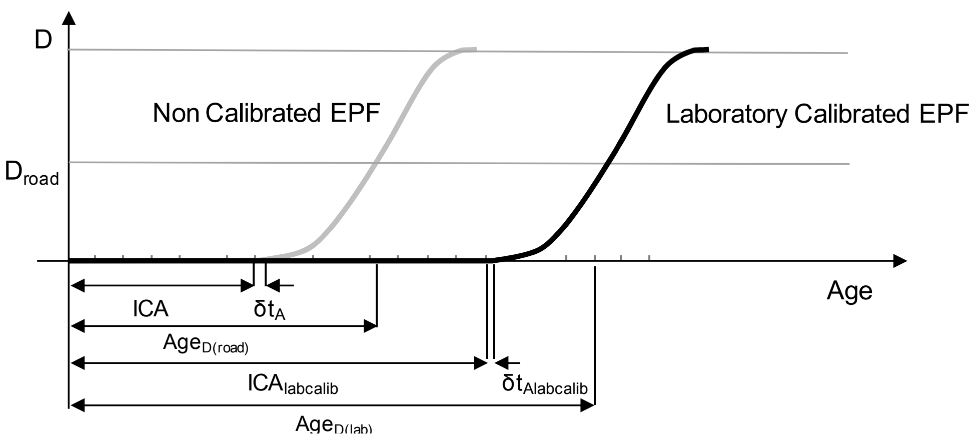


Figure 22. Incorporation of laboratory data into the HDM-4 model, option A.

As to option B, a proportional extension or shortening of both, crack initiation phase and crack progression phase is realized. The transformation of strain factor X_f into calibration factors K_{cia} and K_{cpa} based on cumulative load repetitions or age-parameter reads

$$X_f = \frac{Age_{D(road)}}{Age_{D(lab)}} \qquad \text{Equation 13}$$

and

$$K_{cpa} = k \cdot X_f \quad \text{and} \quad K_{cia} = \frac{1}{K_{cpa}} \qquad \text{Equation 14}$$

with Age as the pavement surface age since last reseal, overlay, reconstruction, or new construction, $Age_{D(road)}$ as the age at damage D on the road (test section), and $Age_{D(lab)}$ as the age at the end of the fatigue life observed in laboratory testing. K_{cpa} is the calibration factor for progression of “all” structural cracking, k is a scaling factor (see below), and K_{cia} is the calibration factor for initiation of “all” structural cracking.

The calibration is performed in two steps. First, the cracking progression coefficient K_{cpa} is the assigned value for the strain factor X_f (dashed line in Figure 23). In order to achieve proportional extension or shortening of the crack initiation phase, the calibration factor K_{cia} has the reciprocal value of K_{cpa}.

The age at which damage D is achieved is not typically equal to the age at the end of fatigue life from laboratory testing. Therefore, in the second step, the crack propagation factor K_{cpa} is multiplied by the scaling factor k obtained from the following pre-condition:

$$AGE_{D(labcalib\ EPF)} = AGE_{D(lab)} \qquad \text{Equation 15}$$

The damage stage from fatigue testing needs to be brought in line with the distress observed on the test site. Thus, it is necessary to define a critical damage stage, which can be either a given threshold value or a value, where a substantial damage stage is reached.

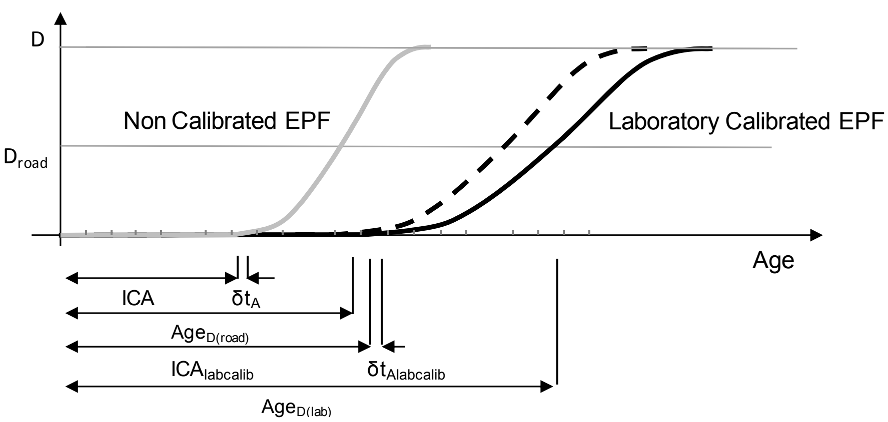


Figure 23. Incorporation of laboratory data into the HDM-4 model, option B.

3.3.4 Scaling factors and Laboratory Calibrated EPF

Based on the calculation procedure for the different scaling factors X_f and the described relationship between field and laboratory fatigue performance of asphalt mixtures the scaling factors X_f for all three performance prediction models are calculated by using data from the two Test Sections. Because of a lack of information for Section 2 from the year 2010, the evaluation is carried out based on data from the years 2007 and 2012 only.

In this study, the end of fatigue life (based on laboratory analysis) is correlated to different pavement cracking rates (the damage status D_{road} is equal to 5, 10 or 20 %), in order to show the sensitivity of this approach. The derived scaling factors and the underlying input data are presented in Table 6.

Table 6: Scaling factors for the Austrian, the German and the HDM-4 model.

	Test Section 1						**Test Section 2**					
Data basis	**2007**			**2012**			**2007**			**2012**		
D_{road} (% cracked)	**5**	**10**	**20**	**5**	**10**	**20**	**5**	**10**	**20**	**5**	**10**	**20**
Austrian model												
$Age_{D(road)}$	17	20	22	17	20	22	14	17	19	14	17	19
$Age_{D(lab)}$	77			56			13			8		
X_f	0.22	0.26	0.29	0.30	0.36	0.39	1.08	1.31	1.46	1.75	2.13	2.38
German model												
$N_{D(road)}$	38.5	42.1	45.2	38.5	42.1	45.2	38.0	42.2	46.9	38.0	42.2	46.9
$N_{D(lab)}$	27.04			19.55			4.47			2.81		
X_f	1.42	1.56	1.67	1.97	2.15	2.31	8.50	9.44	10.49	13.52	15.02	16.69
HDM-4 model, option A												
$Age_{D(road)}$	11	12	13	11	12	13	9	10	11	9	10	11
$Age_{D(lab)}$	77			56			13			8		
X_f	-66	-65	-64	-45	-44	-43	-4	-3	-2	1	2	3
HDM-4 model, option B												
$Age_{D(road)}$	10.5	11.4	12.7	10.5	11.4	12.7	8.5	9.5	10.7	8.5	9.5	10.7
$Age_{D(lab)}$	77			56			13			8		
X_f	0.136	0.148	0.164	0.188	0.205	0.227	0.670	0.743	0.842	1.063	1.178	1.336
k	0.801	0.810	0.812	0.818	0.823	0.819	0.886	0.900	0.907	0.941	0.907	1.000

Using the models presented in Chapter 3.3.3, and the scaling factors given in Table 6, the second step of calibration within the PMS analysis is realized, and the Laboratory Calibrated EPF are obtained (see Figure 24 to Figure 27).

For both Test Sections, the incorporation of laboratory analysis advantageously shows a significant reduction of the curve scatter.

For Test Section 1, the difference in performance prediction is more distinct for any number of load repetitions unequal to the one, which was selected for the calculation of the scaling factor X_f. This variation is strongly dependent on the model itself, and is bigger for smaller D_{road}-values (cp. D_{road} = 5 % to 20 %). Thus, the selection of a specific calibration point in line with a high damage status D_{road} is of advantage.

A difference in the results is stated between data from the years 2007 (year of construction), and 2012. However, the increase of fatigue damage is disproportionate to the increase of traffic loading. Hence, aging and other influencing factors distinctively affect real pavement performance.

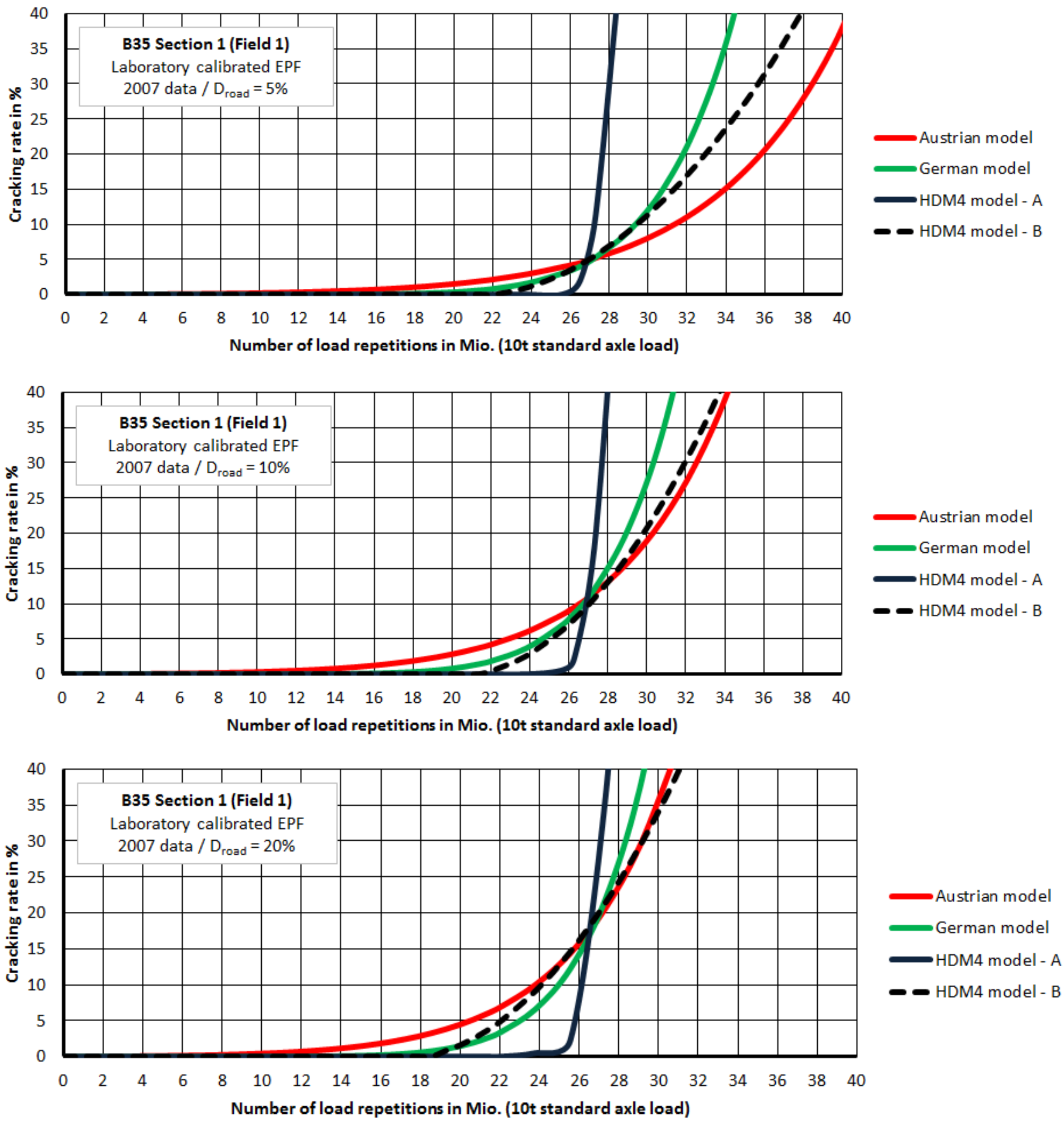


Figure 24. Laboratory Calibrated EPF for Test Section 1: 2007 data / D_{road} = 5 %, 10 % and 20 %.

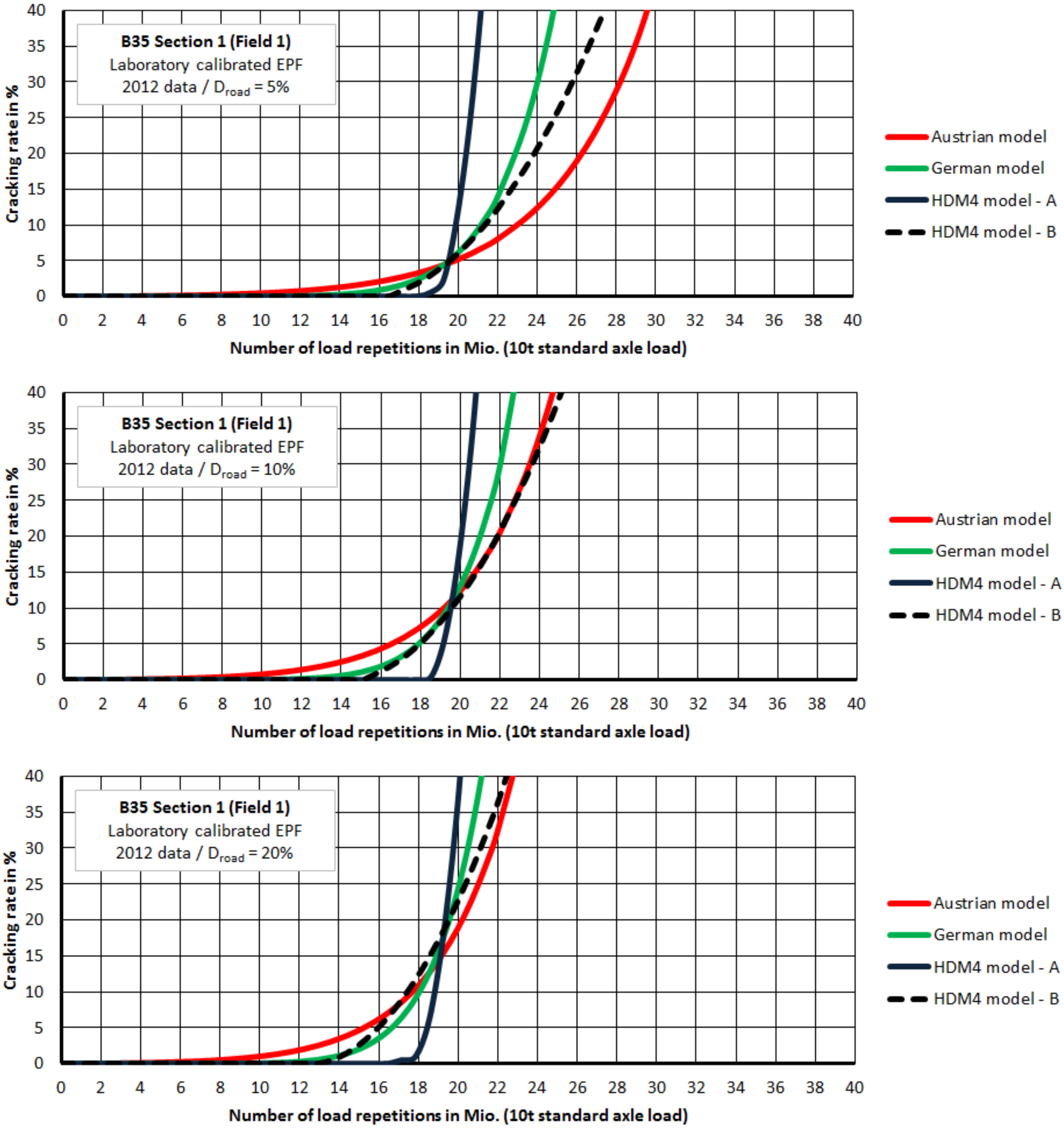


Figure 25. Laboratory Calibrated EPF for Test Section 1: 2012 data / D_{road} = 5 %, 10 % and 20 %.

For Test Section 2, the differences in performance prediction are less distinct for the different models (Figure 26 and Figure 27).

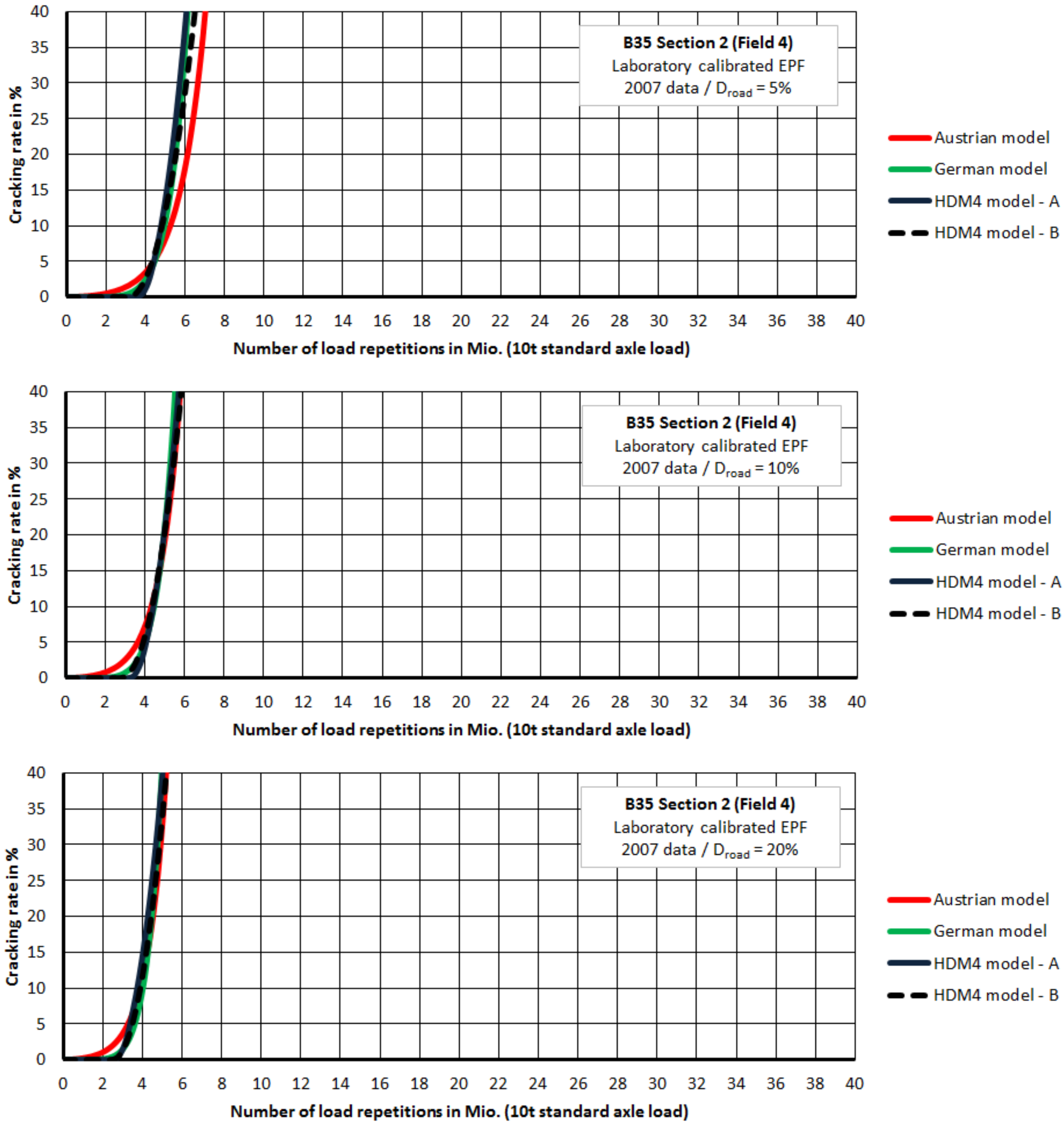


Figure 26. Laboratory Calibrated EPF for Test Section 2: 2007 data / D_{road} = 5 %, 10 % and 20 %.

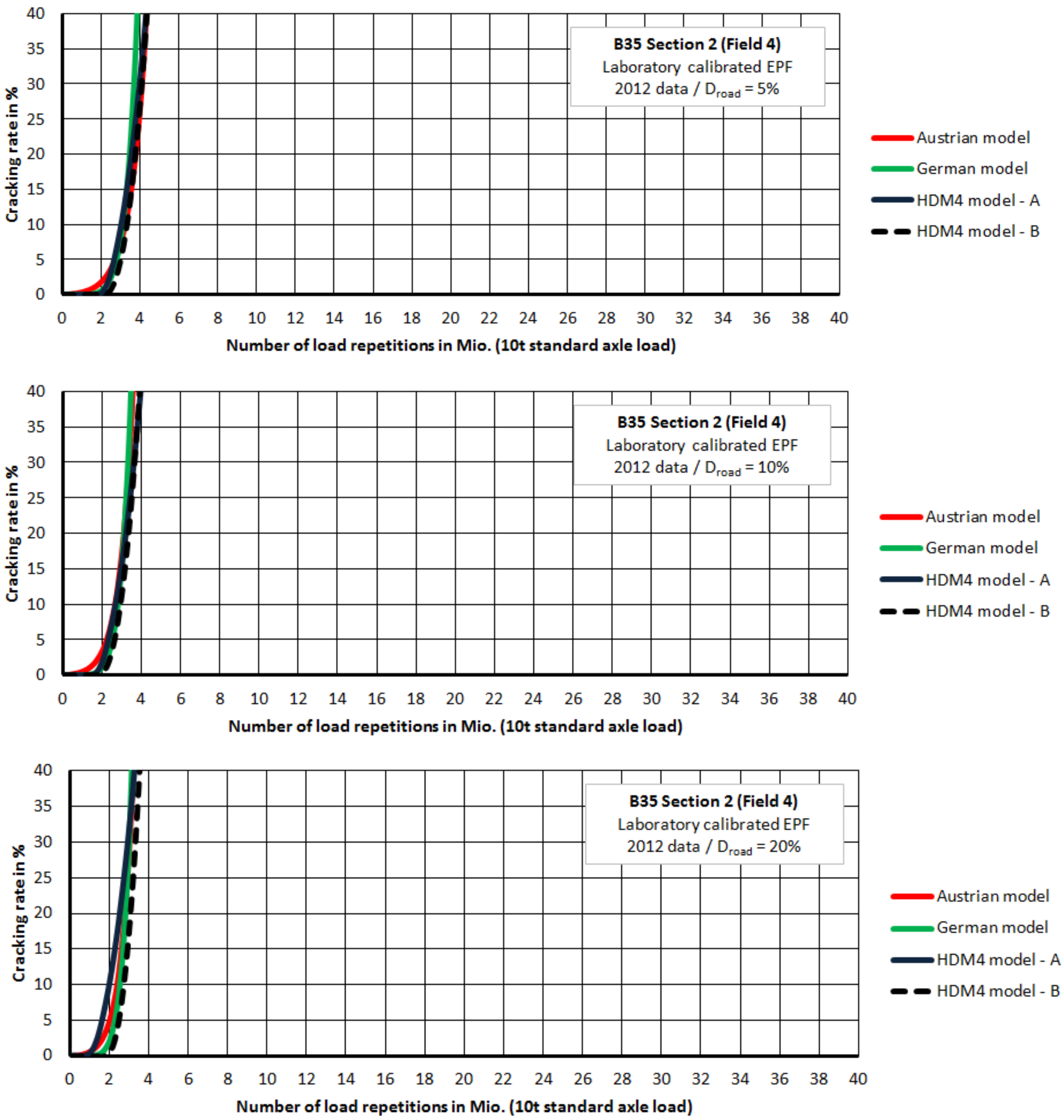


Figure 27. Laboratory Calibrated EPF for Test Section 2: 2012 data / D_{road} = 5 %, 10 % and 20 %.

3.4 Results

One of the main objectives of using sophisticated performance prediction models is the realistic application of Life-Cycle-Analysis (LCA) and Life-Cycle-Cost-Analysis (LCCA). The improvement of performance prediction shall lead to far more accurate results of the PMS analysis and to most effective maintenance decisions.

3.4.1 Life-Cycle-Analysis and maintenance treatment recommendation

Life-Cycle-Analysis (LCA) is performed to evaluate the outcome of PMS adaptation based on Laboratory Calibrated EPF. The year and the type of the first major (exhaustive) maintenance treatment due to cracking are most essential outputs of the PMS analysis and important indicators for evaluation.

Because of the comparatively small road network analysed, a threshold criteria (trigger) of 10 % cracking rate for applying the first time a maintenance treatment is used to select adequate maintenance treatments. In principle, the choice of the trigger values is free, as they are independent from D_{road}. A trigger value equal to D_{road} is usually most useful. The trigger values for the different treatments selected in this study are shown in Table 7. The resulting maintenance recommendations are listed for different D_{road}-models (5, 10 and 20 %) in Table 8.

For Test Section 1 high numbers of allowable load repetitions until the end of fatigue life are calculated. Service life (due to structural cracking) always exceeds 40 years without any exhaustive maintenance treatment. It needs to be mentioned, that neither the service life of the wearing course nor the one of the binder course are taken into consideration within the analysis.

For Test Section 2, cracking is the decisive factor for maintenance activities with a high significance. Pavement condition needs to be investigated more frequently to provide a proper basis for the short- to medium-term planning of maintenance treatments.

The analysis for Test Section 2, which represents an under-designed pavement, provides different types of treatment recommendations, starting from year 6 (2012 data, D_{road} = 20 %) to a maximum of year 16 (2007 data, D_{road} = 5 %). The results within each data group for a specific D_{road} category (Table columns) illustrate a good accordance of the recommended maintenance treatments with a maximum difference of 2 years for all models. In comparison to the non-laboratory calibrated results, which are shown in Table 5 (up to 29 years of difference and different treatment types), the estimation of the maintenance needs is improved significantly by using the laboratory calibrated models.

Table 7: Maintenance treatments and triggers considered for LCA

Abbrev.	Description	Trigger
REPLW	**Repl**acement of **w**earing course only	Cracking rate > 10 % and Age =< 10 years
REPLWB	**Repl**acement of **w**earing course and **b**inder 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 (**Rein**forcement)	Cracking rate > 10 % and Age > 15 years and Age =< 30 years
REC	**Rec**onstruction of all bound layers	Cracking rate > 10 % and Age >= 30 years

Table 8: Recommended maintenance treatments

	Test Section 1						Test Section 2					
	2007 data			2012 data			2007 data			2012 data		
D_{road}-model	5	10	20	5	10	20	5	10	20	5	10	20
Austrian model												
year 1st treatment	>40	>40	>40	>40	>40	>40	16	13	12	10	8	7
type 1st treatment	-	-	-	-	-	-	REIN	REPLWB	REPLWB	REPLW	REPLW	REPLW
German model												
year 1st treatment	>40	>40	>40	>40	>40	>40	15	13	12	9	8	7
type 1st treatment	-	-	-	-	-	-	REPLWB	REPLWB	REPLWB	REPLW	REPLW	REPLW
HDM-4 model, option A												
year 1st treatment	>40	>40	>40	>40	>40	>40	14	13	11	9	8	6
type 1st treatment	-	-	-	-	-	-	REPLWB	REPLWB	REPLWB	REPLW	REPLW	REPLW
HDM-4 model, option B												
year 1st treatment	>40	>40	>40	>40	>40	>40	14	13	11	9	8	7
type 1st treatment	-	-	-	-	-	-	REPLWB	REPLWB	REPLWB	REPLW	REPLW	REPLW

3.4.2 Life-Cycle-Cost-Analysis

A simplified Life-Cycle-Cost-Analysis (LCCA) over a time period of 35 years (maximum design period of Test Section 1 plus 5 years) is performed to evaluate the budgetary effects of PMS adaptation based on Laboratory Calibrated EPF.

The following items are considered for both Test Sections: pavement design, Section Calibrated EPF versus Laboratory Calibrated EPF, pavement construction costs, maintenance costs (agency costs), and time costs due to maintenance activities (user costs). This LCCA is limited to crack modelling. Type and time of maintenance treatment depend on cracking rate only, while other performance indicators are not taken into consideration.

Construction costs are referred to the start of the analysis period (year 2007), and unit costs of 120 €/m^2 for Test Section 1, and of 90 €/m^2 for Test Section 2 are determined.

User costs during pavement construction are not taken into account. For the estimation of agency costs and user costs (time costs) during the maintenance activities the catalogue of treatments given in Table 8 is extended by unit cost and productivity values (Table 9).

A discount rate of 3 % is considered. The duration of maintenance activities is estimated by 1 additional day for installation and 1 day for removal of the traffic diversion. Because of the single carriageway cross section a maximum speed of 30 km/h during construction is defined. The design speed for both sections is 100 km/h.

To demonstrate the effect of PMS adaptation 10 different LCCA-scenarios for each Test Section are comparatively analysed, resulting in a total number of 20 scenarios (Table 10).

Table 9: Unit costs and productivities of maintenance treatments considered for LCCA

Abbrev.	Unit cost	Productivity P_m
REPLW	10 €/m^2	2 500 m^2/day
REPLWB	15 €/m^2	1 500 m^2/day
REIN	25 €/m^2	1 000 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

Table 10: LCCA-scenarios for Test Section 1 and Test Section 2

Scenario	Description
Design	30 years design period of Test Section 1; 8 years design period of Test Section 2; reconstruction based on basic design period only
Austrian model - section based calibration	Austrian standard model with section based calibration
German model - section based calibration	German cracking model with section based calibration
HDM-4 model - section based calibration	HDM-4 cracking model with section based calibration
Austrian model - laboratory calibration (2007 data)	Austrian laboratory calibrated model based on 2007 data and on a crack rate of D_{road} = 10%
German model - laboratory calibration (2007 data)	German laboratory calibrated model based on 2007 data and on a crack rate of D_{road} = 10%
HDM-4 model - laboratory calibration (2007 data)	HDM-4 laboratory calibrated model based on 2007 data and on a crack rate of D_{road} = 10%
Austrian model - laboratory calibration (2012 data)	Austrian laboratory calibrated model based on 2012 data and on a crack rate of D_{road} = 10%
German model - laboratory calibration (2012 data)	German laboratory calibrated model based on 2012 data and on a crack rate of D_{road} = 10%
HDM-4 model - laboratory calibration (2012 data)	HDM-4 laboratory calibrated model based on 2012 data and on a crack rate of D_{road} = 10%

The results of LCCA are represented in Figure 28 to Figure 37, considering a discount rate of 3 % and present value (PV) costs. These figures clearly indicate that generally more maintenance activities are needed on Test Section 2 than on Test Section 1. The time interval of maintenance activities strongly depends on the data used for model calibration. For 2007 data (based on retained samples from the construction phase) the maintenance interval is 12 to 13 years, in order to keep the crack rate below 10 % over the whole assessment period. For 2012 data (based on core samples), the maintenance interval is reduced to 8 years.

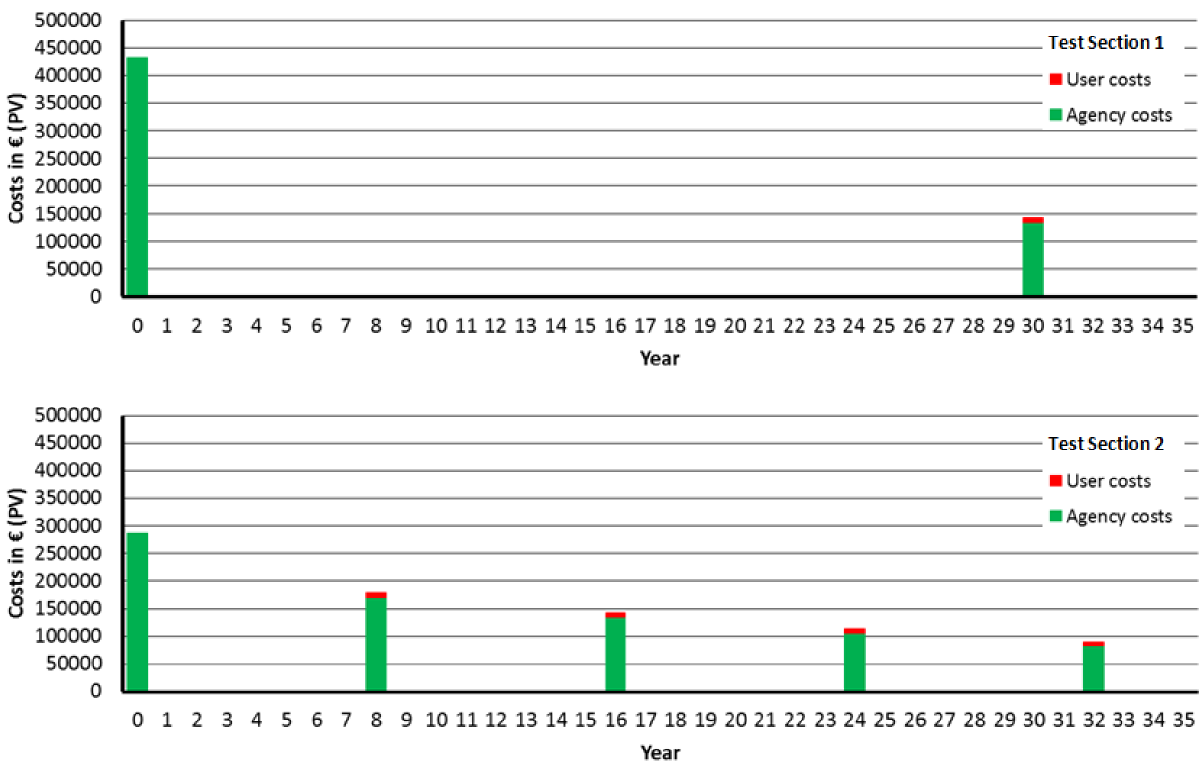


Figure 28. LCCA for Scenario *Design*: 30 years design period of Test Section 1; 8 years design period of Test Section 2.

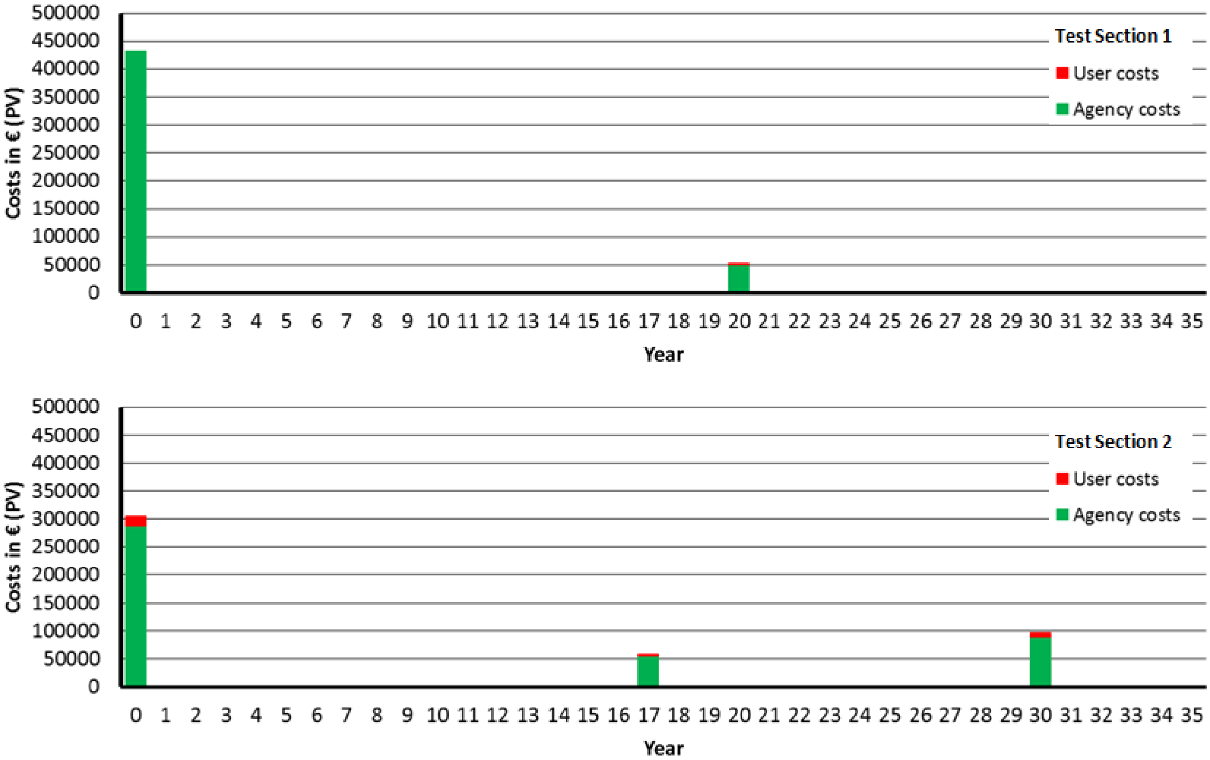


Figure 29. LCCA for Scenario *Austrian model - section based calibration*.

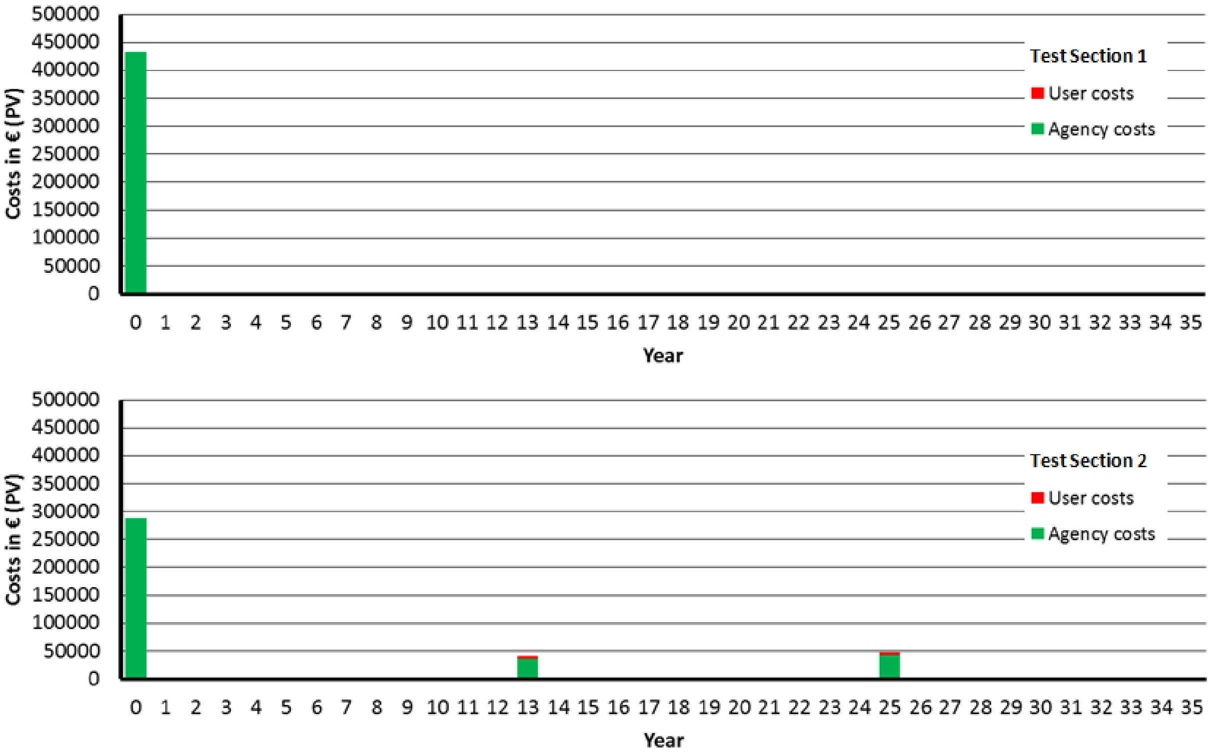


Figure 30. LCCA for Scenario *Austrian model - laboratory calibration (2007 data)*.

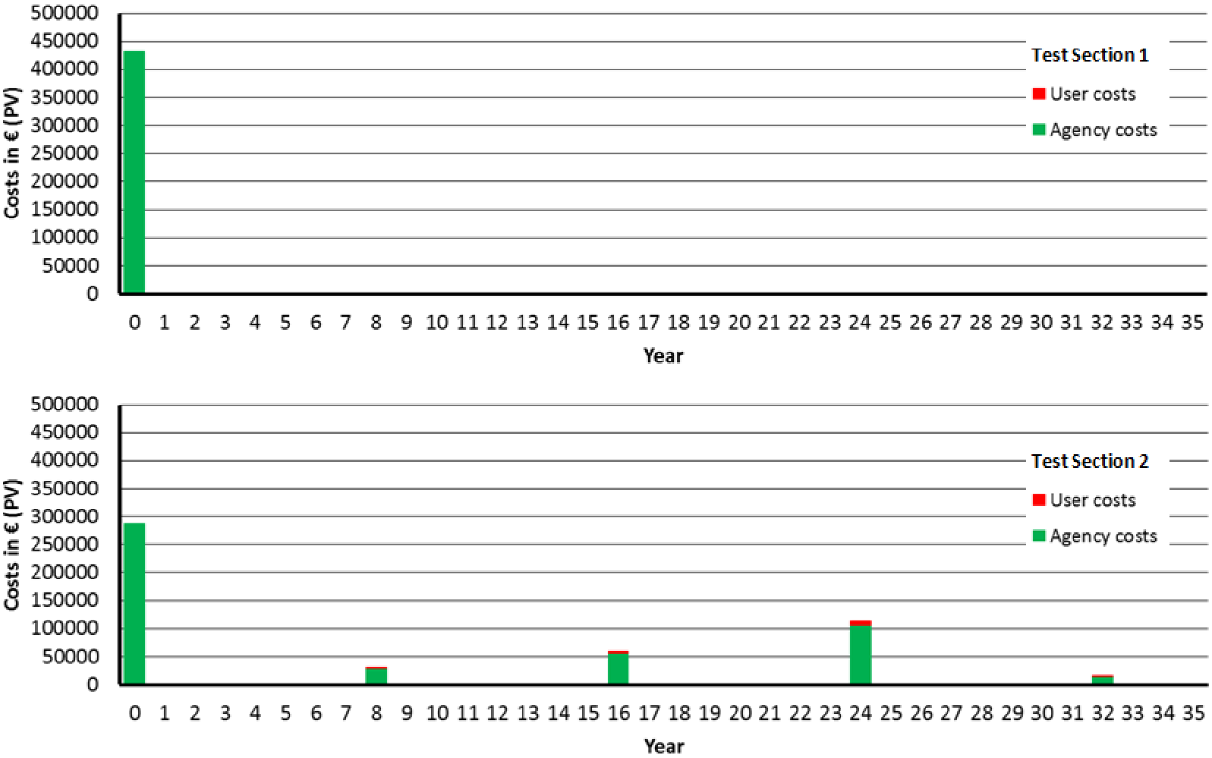


Figure 31. LCCA for Scenario *Austrian model - laboratory calibration (2012 data)*.

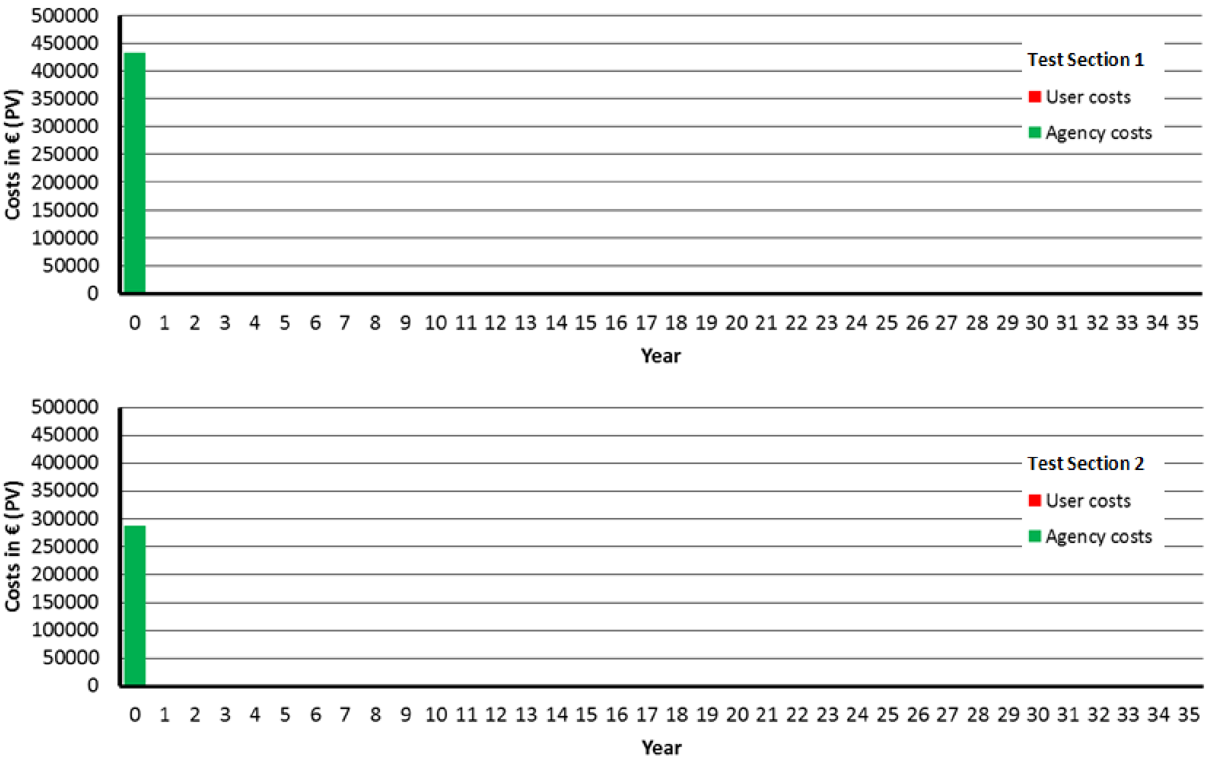


Figure 32. LCCA for Scenario *German model - section based calibration*.

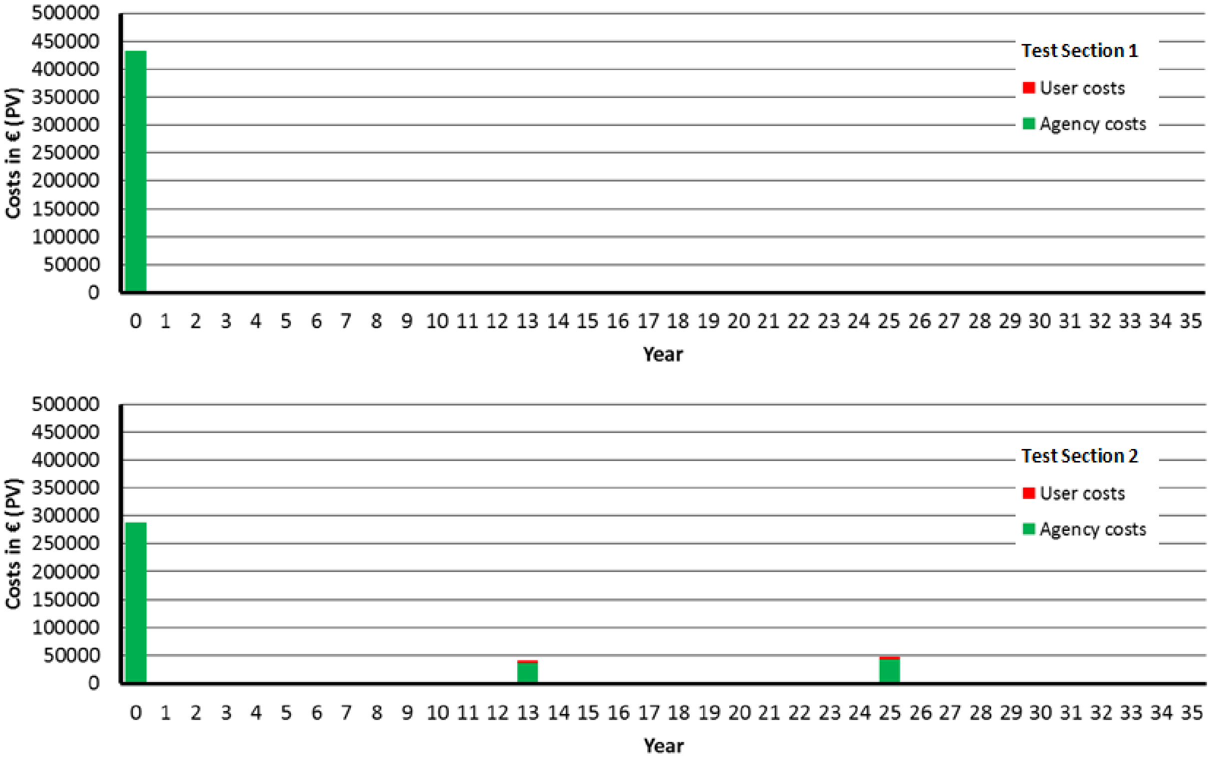


Figure 33. LCCA for Scenario *German model - laboratory calibration (2007 data)*.

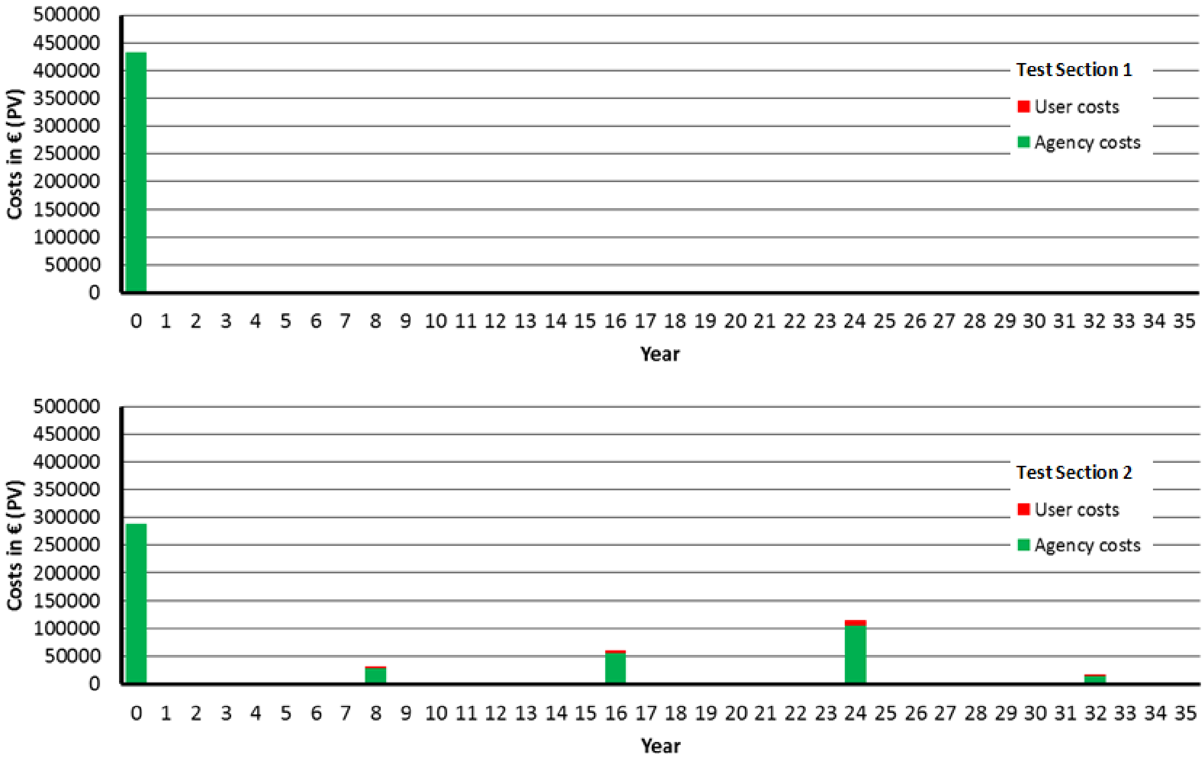


Figure 34. LCCA for Scenario *German model - laboratory calibration (2012 data)*.

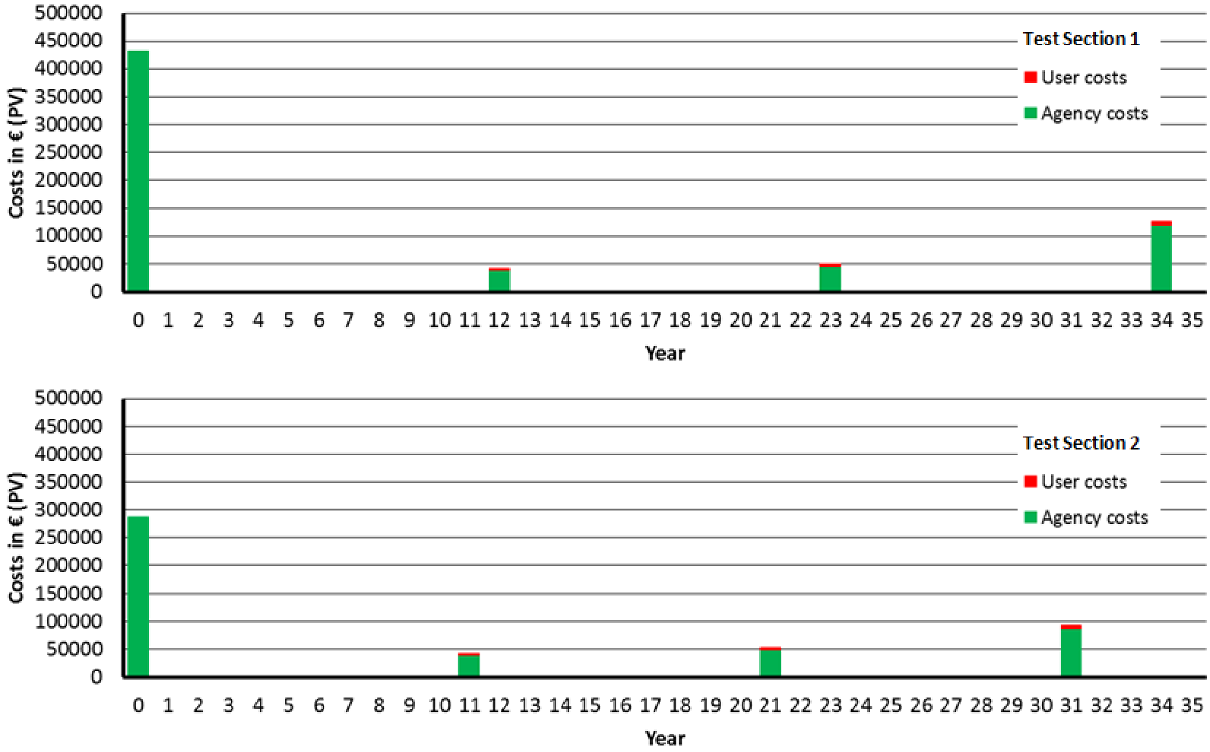


Figure 35. LCCA for Scenario *HDM-4 model - section based calibration*.

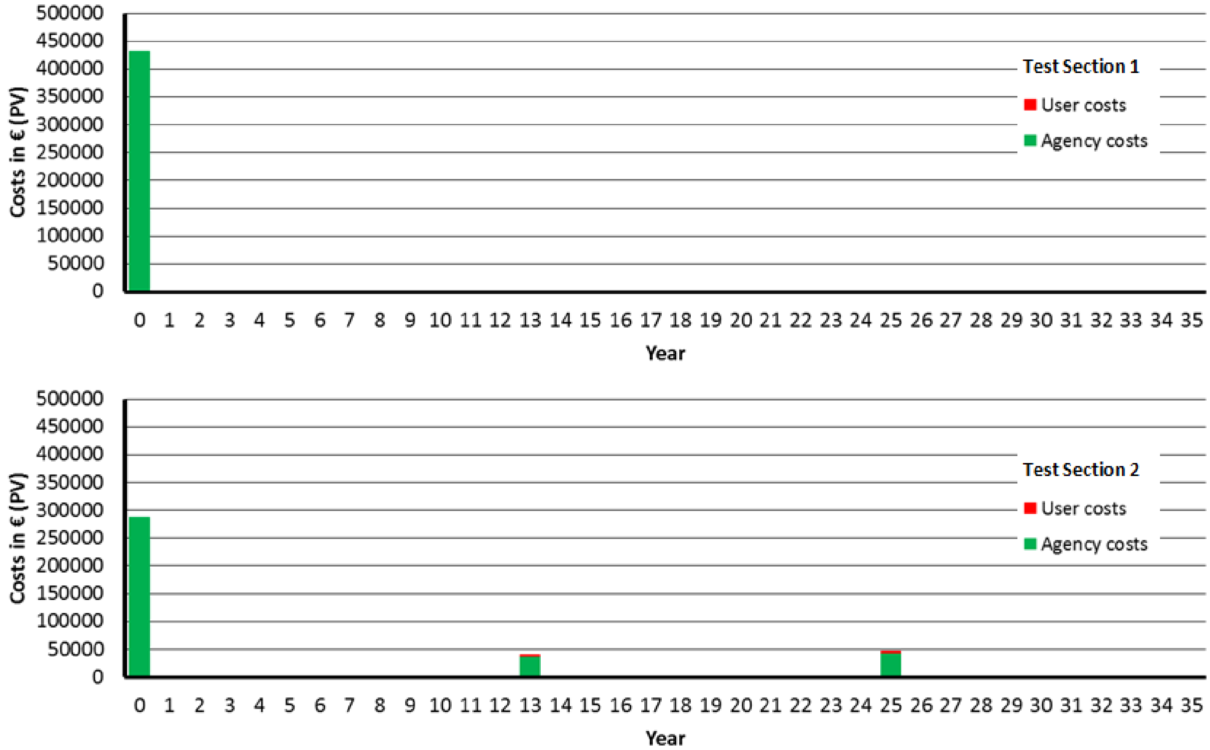


Figure 36. LCCA for Scenario *HDM-4 model (options A and B) - laboratory calibration (2007 data)*.

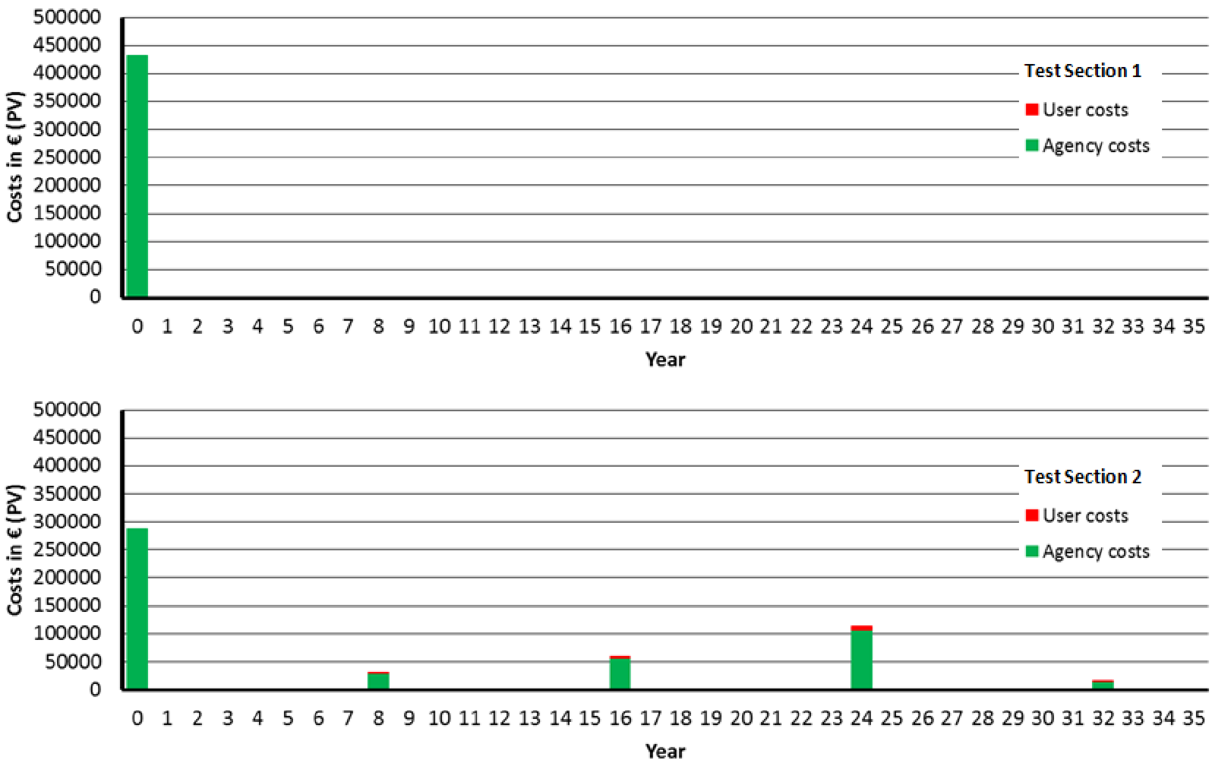


Figure 37. LCCA for Scenario *HDM-4 model (options A and B) - laboratory calibration (2012 data)*.

3.4.3 Discussion of results

From the output of LCA and LCCA the effects of using Laboratory Calibrated EPF within PMS analysis can be evaluated qualitatively. The objective of the analysis within *InteMat4PMS* is not the comparative assessment of two different pavement constructions applied for Test Section 1 and Test Section 2. However, the focus is to evaluate the consequences of the new approach, how results from the design process within PMS can be verified by incorporating results from laboratory analysis.

Through LCA it is shown, that the consideration of laboratory calibration within PMS significantly influences the assessment of maintenance needs. Advantageously, maintenance strategies are expected to become far more realistic.

By means of LCCA, the cumulative total costs (agency costs and user costs) over the assessment period enable the comparison of different maintenance scenarios. The unit prices assumed for construction and maintenance treatments significantly influence the results of LCCA. However, the integration of laboratory analysis into performance prediction and finally into the whole LCCA enables objective evaluation of different design concepts and maintenance strategies.

In Figure 38, the total costs for both Test Sections and all performance models are compared for the Scenario Design and for all Scenarios with section based calibration. It can be seen that the scatter of the total costs at the end of the assessment period (35 years) is distinct, which underlines the need for an improved model calibration.

By taking 2007 data and 2012 data from laboratory analysis into account, cumulated costs change significantly, as shown in Figure 39 for 2007 data and in Figure 40 for 2012 data. Of course, there is still a difference between Test Section 1 and 2 (yet smaller than before), but the laboratory based calibration leads to identical total costs for all 3 applied models (Austrian, German and HDM-4) at the end of the assessment period. Hence, by using the new approach the PMS analysis results become much less sensitive to the general performance model applied, which is an important advantage.

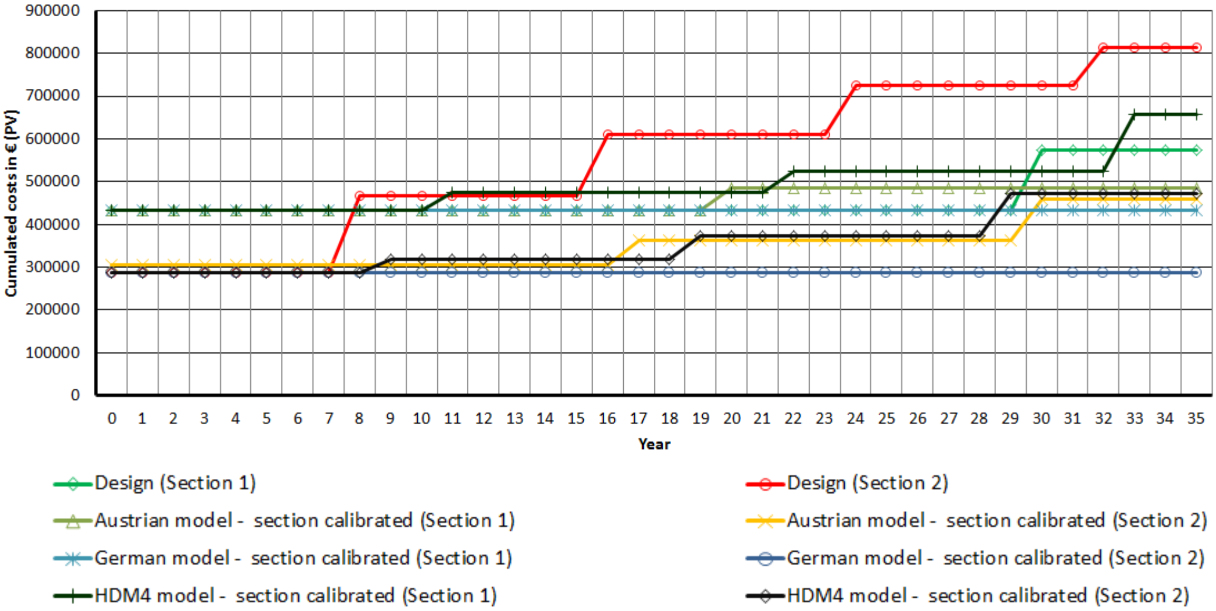


Figure 38. Cumulated costs obtained for different maintenance scenarios using Section Calibrated EPF.

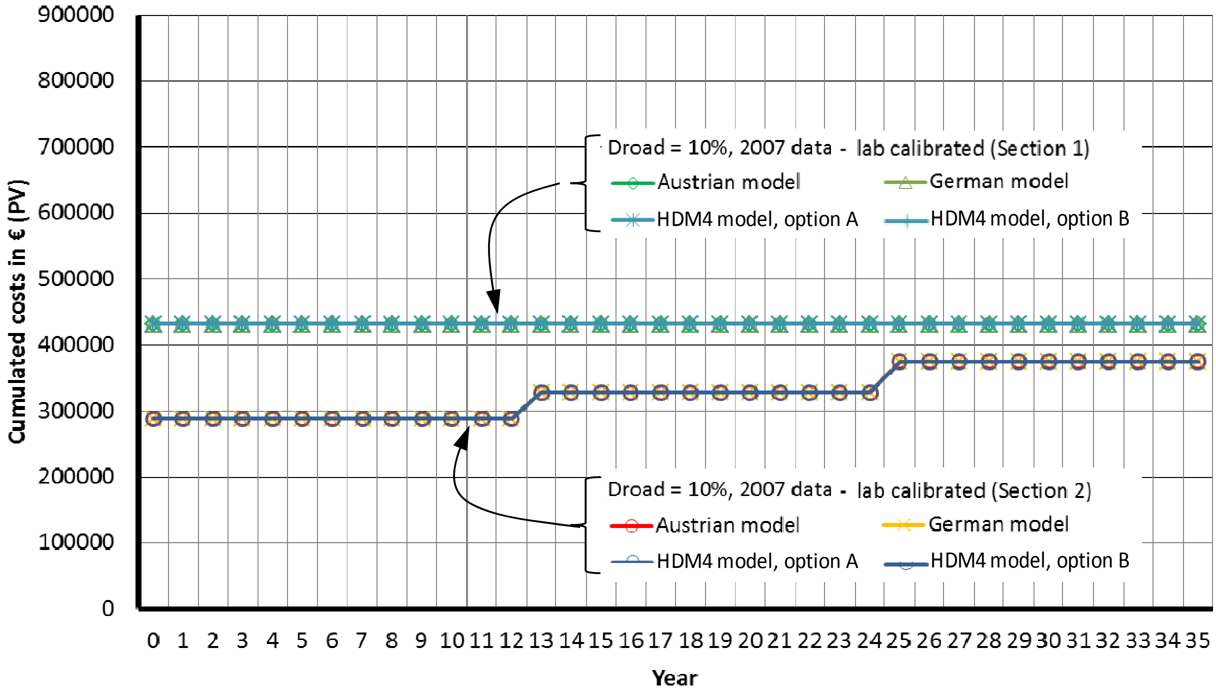


Figure 39. Cumulated costs obtained for different maintenance scenarios using Laboratory Calibrated EPF (2007 data).

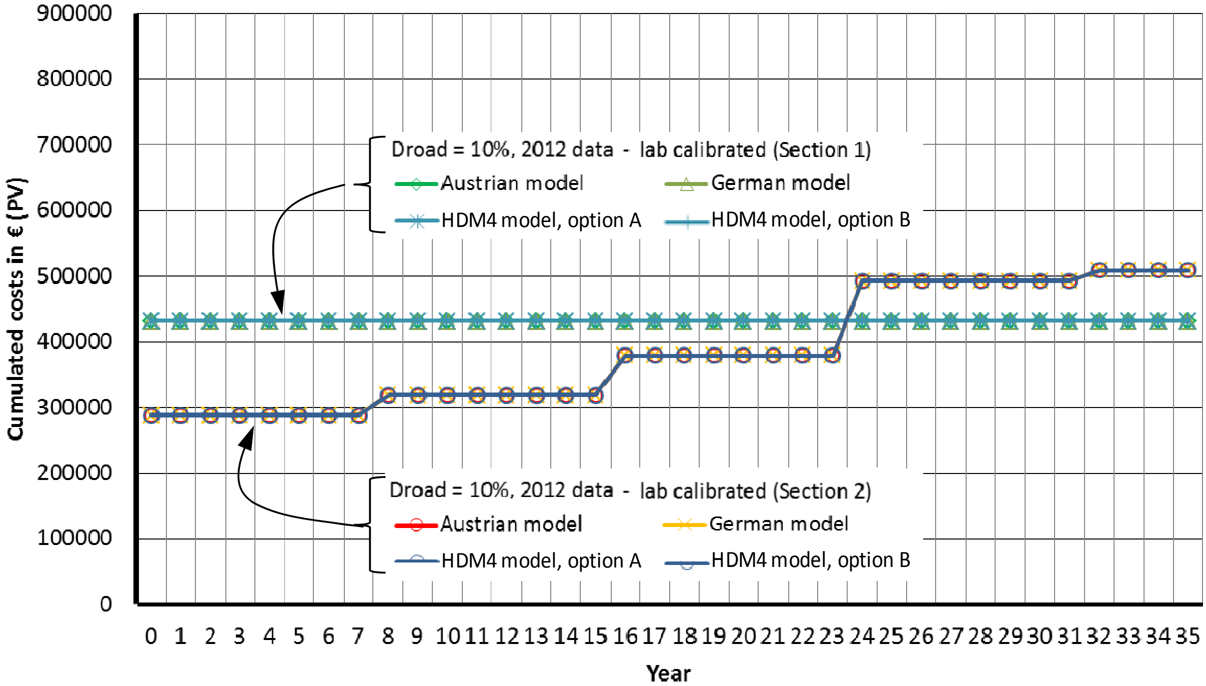


Figure 40. Cumulated costs obtained for different maintenance scenarios using Laboratory Calibrated EPF (2012 data).

Table 11 provides a summary of the analysis example of the two Test Sections (for 2012 data) in order to illustrate potential benefits of the new approach for PMS adaptation. The proposed timing and type of maintenance treatments for the two Test Sections, that have substantially different pavement structures and design lives, significantly depend on the mode of calibration of the performance models. If only section specific calibration is realized, different recommendations are obtained from the models. Contrary, independently from the used model almost identical recommendations for type and timing of maintenance treatment are obtained, if the models are further calibrated based on data from laboratory analysis.

Table 11: Summary of results from PMS analysis (basis 2012 data)

Calibration stage	**Trigger level (% cracked)**	**1st major treatment**	**Austrian model**	**German model**	**HDM-4 model**
Test Section 1					
Section Calibrated EPF (1st calibration level)		**Year**	17	>40	12
		Type	REPLWB	REC	REPLWB
Laboratory calibrated EPF (2nd calibration level)	**5**	**Year**	>40	>40	>40
		Type	-	-	-
	10	**Year**	>40	>40	>40
		Type	-	-	-
	20	**Year**	39	40	>40
		Type	REC	REC	-
Test Section 2					
Section Calibrated EPF (1st calibration level)		**Year**	16	>40	11
		Type	REPLWB	REC	REPLWB
Laboratory calibrated EPF (2nd calibration level)	**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

4 Conclusions

Performance prediction is a key element in pavement management. Most realistic prediction of pavement performance over long time periods is of vital importance for effective assessment of maintenance options. Usually, life-cycle-cost-analysis in the frame of pavement management is based on a computer-aided Pavement Management System (PMS). A decisive factor of a PMS is the accuracy of performance prediction. Prediction quality - and therefore the efficiency of the whole PMS - strongly depends on the prediction model of pavement performance and the underlying input data. Most realistic performance modelling is especially needed for decision processes at project (object) level, at which the degree of accuracy needs to be much higher in comparison to more general consideration at network level.

The primary result of *InteMat4PMS* is the demonstration that material and structural pavement properties can advantageously be taken into account in performance prediction modelling in the frame of PMS. Data from laboratory analysis are used to improve the model assumptions. In principal, the presented approach is applicable for any incremental distress mechanism. However, *InteMat4PMS* is a demonstration project that focuses on the specific distress mechanism of fatigue, starting at the bottom of the supporting asphalt layer.

By following up the analysis procedure developed in *InteMat4PMS*, any Empirical Performance Function (EPF) for fatigue performance can be improved by using information on material and structural pavement properties. The needed information is obtained from material testing in the laboratory and from structural performance modelling. As a result, a new performance function is obtained. This new performance function is based on the original EPF, but takes into account the material and structural pavement properties, and is therefore called ‘Laboratory Calibrated EPF’.

The applicability of the new analysis procedure based on Laboratory Calibrated EPF is also tested in *InteMat4PMS* in terms of a case study. Considering real data of two Test Sections and focusing on fatigue failure and pavement cracking mechanisms, the workability of the new approach is practically demonstrated.

In the case study, three different performance prediction models with different initial EPF that are documented in the German PMS, in the Austrian PMS, and in HDM-4 are practically implemented in the commercial PMS software tool *dTIMS CT*^{TM}. The new approach enables to compare the effects of these models on the analysis result.

The practical application of advanced 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 and where detailed material information is not available. 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).

The results obtained for the three different performance models clearly indicate this problem. All three models (German, Austrian, HDM-4) seem to be applicable on the test site in principle, but show a very high variance in the results if only section based calibration is performed. Hence, the section specific 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 need to integrate an additional calibration.

While all three models lead to unsatisfying results in the first run, interrelation to real pavement performance is significantly improved if in addition Laboratory Calibrated EPF are taken into account. The demonstration example in *InteMat4PMS* clearly shows, that a laboratory based calibration improves all models and reduces the variation of the results significantly.

Based on the results of the practical application of an advanced PMS, the benefit of the integration of material-science based performance models into the LCA and LCCA can be summarized as follows:

- Performance prediction modelling in the framework of PMS becomes more accurate, if model input parameters are taken into account that are related to material and structural pavement characteristics. In the two case studies performed within *InteMat4PMS*, a significant improvement of performance prediction at project level is achieved when the results of laboratory tests are incorporated into the PMS analysis process.
- This is effectually demonstrated in *InteMat4PMS* for one specific distress mechanism, which is fatigue distress starting at the bottom of the supporting asphalt layer. In analogy to the presented calibration procedure for fatigue distress, similar calibration procedures can be developed for further distress types in subsequent research studies which will further complete the holistic PMS approach. Especially the assessment of permanent deformation (rutting) seems to be an adequate candidate for further development and fulfils most of the precondition from both the laboratory point of view as well as the PMS point of view.
- The new procedure enables the assessment of different types of performance prediction models with regard to their applicability and their possibilities to be calibrated with results from laboratory testing.
- The improvement of PMS on object (project) level by using material specific input parameters will extend the field of PMS application. For LCA or LCCA, laboratory calibration of EPF improves prediction accuracy for future maintenance strategies (type of maintenance treatment, year of maintenance treatment). This will consequently help road managers to realize budgetary planning more effectively.
- The incorporation of results from laboratory analysis in PMS will lead to a better understanding of physical deterioration in road pavements. Contrary, results from asphalt laboratory testing will be demanded in the context of LCA and LCCA. This may bring together more closely engineers from both fields of pavement engineering, asphalt technology and pavement management.

A user-friendly manual is provided in the Annex B that may assist in practical application of the new analysis procedure and in extending any commercial PMS software solution.

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InteMat4PMS

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

Technische Universität Braunschweig
PMS-Consult Vienna
University of Belgrade
ViaTec AG Winterthur

Final Report

Annex A: Definition of terms

September 2013

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

Annex A: Definition of terms

Asset management: a comprehensive and structured approach to the whole of life management of assets (such as roads, bridges, tunnels, buildings, plant and equipment, and human resources) as tools for the efficient and effective delivery of services (PIARC, 2011).

Benefit/cost-analysis: used to compare the (ownership) costs with the benefit of a maintenance treatment over a certain time period. The benefit can be defined as the positive effects of a maintenance treatment on the condition and/or the different stakeholders (users, neighbors, environment, etc.). The benefit can be expressed either by a monetary value or as a technical function (e. g. “Area Under the Curve”).

Complex Modulus: a modulus characterizing the recoverable deformation behaviour of linear viscoelastic materials under harmonic stress. It is a complex number which is the ratio of complex stress to complex strain. This quantity is used to characterize the recoverable deformation behaviour of bituminous mixtures at low stress amplitude (PIARC, 2011).

Condition indicator: a parameter used to quantify an attribute of pavement condition (e. g. evenness, bearing capacity) (PIARC, 2011).

Deterioration model: a mathematical description that can be used to predict future pavement deterioration based on present pavement condition, deterioration factors (traffic, climate, and environment) and the effect of maintenance (PIARC, 2011).

Dynamic modulus (E*): the relationship between stress and strain under continuous sinusoidal loading used to evaluate the elastic/visco-elastic response parameters of a material The dynamic modulus of a material is typically defined as the absolute value of the complex modulus E* (NCHRP, 2004).

Empirical performance function (EPF): a performance function based on empirical information, which is e.g. obtained from condition measurements.

Fatigue cracking: cracking of the pavement surface as a result of repetitive loading; may be manifested as longitudinal or alligator cracking in the wheel paths for flexible pavement and transverse cracking (and sometimes longitudinal cracking) for jointed concrete pavement (NCHRP, 2004).

Fundamental characteristic: an essential property of a binder-aggregate mixture expressed in terms of performance (PIARC, 2011).

Life cycle cost (whole life cost): the total costs for acquiring, operating, maintaining and disposing of an asset, reduced to a common base called the "net present cost" (PIARC, 2011).

Life-cycle-assessment (LCA), Life-cycle-cost-analysis (LCCA): In general, LCA/LCCA is a method to assess the behaviour of a road pavement or pavement material over a certain time period including the loadings and the effects of maintenance treatments. If costs are considered, LCA leads to LCCA.

Mechanistic-empirical: a design philosophy or approach wherein classical mechanics of solids is used in conjunction with empirically derived relationships to accomplish the design objectives (NCHRP, 2004).

Modulus of elasticity (E): the ratio of stress to strain in the elastic portion of a stress strain curve (NCHRP, 2004).

Network level: the level of administrative decisions that affect the entire highway network (PIARC, 2011).

Nonlinear material: a pavement material having properties such that the relationship between stress and strain in nonlinear (NCHRP, 2004).

Pavement Management System: a set of tools that can assist decision-makers in finding cost-effective strategies for providing, evaluating, and maintaining pavements in a serviceable condition.

Pavement Management: a process of coordination and controlling a comprehensive set of activities in order to maintain pavements, so as to make the best possible use of resources available, i.e. maximize the benefits for society.

Pavement performance: measure of accumulated service provided by a pavement (i. e., the adequacy with which it fulfils its purpose). Often referred to the record of pavement condition or serviceability over time or with accumulated traffic (NCHRP, 2004).

Performance Index (PI): an assessed Technical Parameter of the road pavement, dimensionless number or letter on a scale that evaluates the Technical Parameter involved (e. g. rutting index, skid resistance index, etc.) on a 0 to 5 scale, 0 being a very good condition and 5 a very poor one (Litzka et al., 2008).

Performance Indicator: a superior term of a technical road pavement characteristic (distress), that indicates the condition of it (e. g. transverse evenness, skid resistance, etc). It can be expressed in the form of a Technical Parameter (dimensional) and/or in the form of an Index (dimensionless) (Litzka et al., 2008).

Performance period: the period of time that an initially constructed or rehabilitated pavement structure will last (perform) before reaching its terminal condition when rehabilitation is performed. This is also referred to as the **design period** (NCHRP, 2004).

Physical performance function: a (mathematical) model for the description of the stress / time-dependent behaviour of physical properties of road pavements or pavement materials.

Project level: the level of technical management decisions for specific projects or road segments (PIARC, 2011).

Reliability: the probability that a given pavement design will last for the anticipated design life (NCHRP, 2004).

Resilient modulus: a modulus characterizing the recoverable deformation behaviour of unbound granular materials. In a repetitive loading triaxial test under constant lateral stress, it is the secant modulus at unloading calculated as the ratio of the stress deviator to the axial recoverable strain (PIARC, 2011).

Road Infrastructure / road asset: all constructions (pavements, bridges, drainage structures…) and equipments (safety barriers, signs, lights…), including the land reservation which composed the facilities devoted to road transport (Lepert et al., 2011).

Technical Parameter: a physical characteristic of the road pavement condition, derived from various measurements, or collected by other forms of investigation (e. g. rut depth, friction value, etc.) (Litzka et al., 2008).

Transfer function: a mathematical function used to transform a technical parameter into a dimensionless performance index (Litzka et al., 2008).

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Annex B: Practical Guide

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Contents

1 Introduction

The “Manual for developing PMS based on physical performance functions” is a basis for the practical implementation of pre-selected performance functions into a Pavement Management System (PMS). It includes a comprehensive description of the different steps for the selection of models, the selection of an adequate PMS solution and finally the process for the incorporation of laboratory calibrated empirical performance functions into the PMS.

These steps described in the theoretical and in the practical part can be seen as a general framework for the implementation of any EPF into a computer assisted PMS. Thus, the described processes should be understood as a general approach, which is adaptable to similar projects and problems.

2 General framework for PMS development

The approach for PMS development is based on single steps, which can be categorized on the one hand into a selection process and on the other hand into the implementation of EPFs including the calibration procedures for the incorporation of laboratory testing results into a holistic solution. The following framework gives an overview of these steps. In the following chapters a detailed description of sub-processes and the requirements for the selections is given.

Figure 1 shows the general framework for the PMS development using physical performance functions.

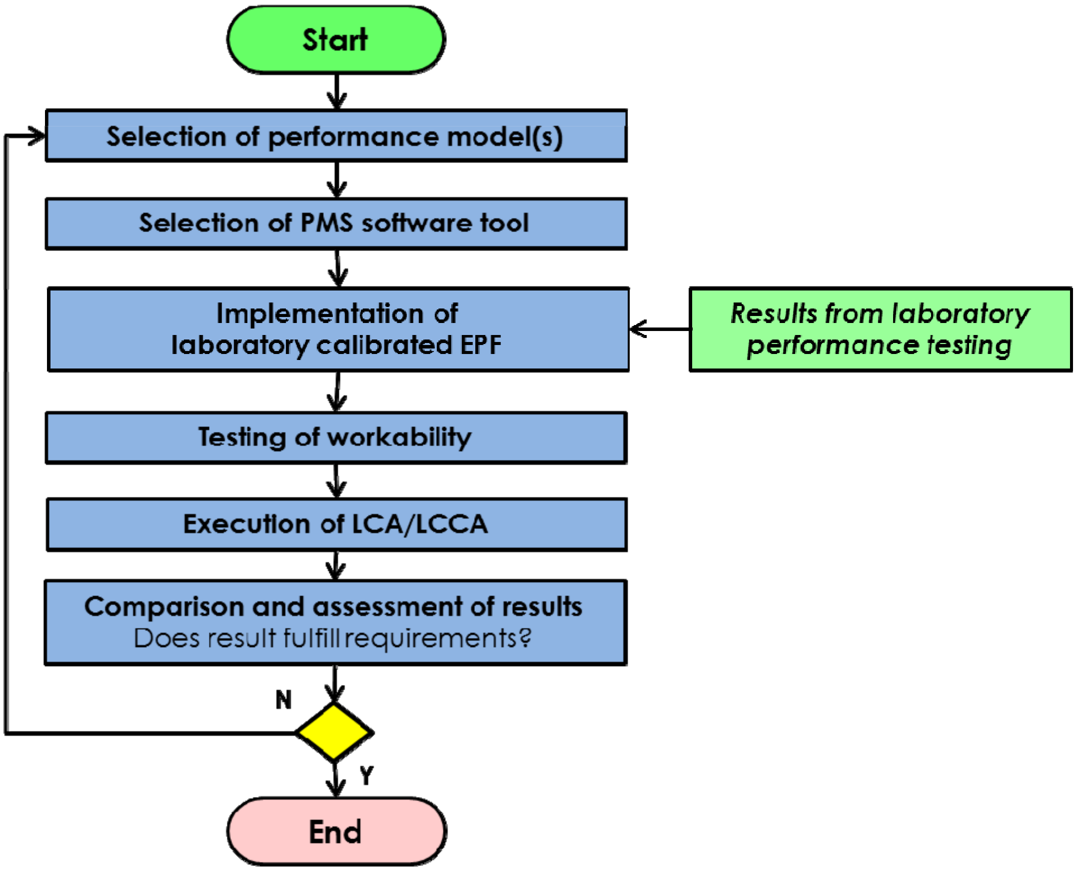

Figure 1: General framework for the PMS development

3 Developing PMS based on physical performance functions

3.1 Selection of models

Independent from the type of deterioration and the properties to be assessed, the models have to fulfill different requirements before the implementation process can be started. The following list is a general overview of these requirements, which can be used in the first selection process:

- The local data and information can be used as input parameter for the selected model
- The model fulfills the local requirements.
- The model represents the technical status of the art and is in coincidence with the experiences of the local engineers
- The model describes the physical properties to be assessed sufficiently.
- The model can be linked to specific laboratory tests and uses a similar loading assumption (e.g. load cycles)
- The model can be described by mathematical (deterministic or probabilistic) functions.

3.2 Selection of PMS software tool

The improvement of the efficiency of a pavement management system (PMS) is one of the main objectives for a modern and future oriented road administration. It is essential, that the decision makers on the different levels of the processes will be supported by effective tools, which are adapted to the different management functions and processes.

To implement physical performance functions into a PMS and to execute the related tasks, it is necessary, to find either a fully flexible commercial software tool or to program a project specific, tailor-made software solution. The following requirements can be used for the selection and the decision respectively:

- The system should be able to store all model specific data and information of the road sections.
- The system should be able to define a model specific data base structure.
- The system should be able to integrate the mathematical procedures and to prepare the data for the analysis
- The system should be able to implement the pre-selected performance prediction models and functions
- The system should be able to implement a mathematical procedure for the calibration of pre-selected performance prediction models and functions.
- The system should be able to define and execute LCA or LCCA on all test-sections.
- The system should be able to define user-specific optimization procedures by using benefit/cost analysis.
- The system should be able to export all results from the analysis.

3.3 Implementation of laboratory calibrated EPF

3.3.1 Overview of approach

The implementation of a LCA/LCCA application should be based on several steps, which enable a repeatable and adjustable processing under the given requirements. Within ***InteMat4PMS*** the different, pre-selected empirical performance functions (EPF) have to be incorporated into a fully working LCA/LCCA approach. This approach has to be used to compare and finally to assess different maintenance treatment strategies by using these EPFs. Based on the experiences of the project team and the given requirements and the objectives of the project, the following process (see Figure 2) was developed and used within ***InteMat4PMS*** for the implementation of the EPF and the calibration procedure.

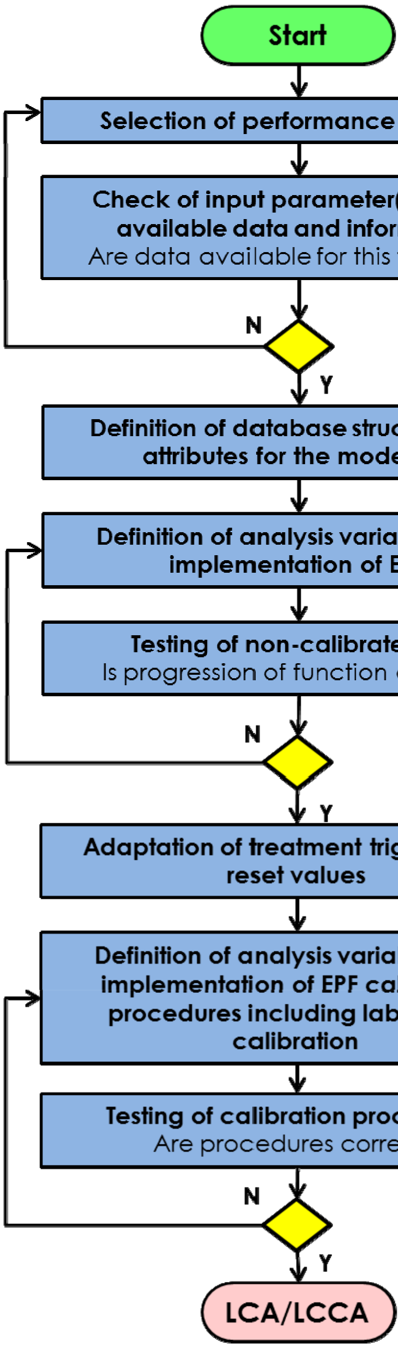

Figure 2: Outline for the implementation procedure

In the following chapters a comprehensive description of the implementation steps is given. As already stated, these steps have to be seen as a general framework for the implementation of any EPF into a computer assisted PMS including a calibration procedure for the incorporation of laboratory testing results. Furthermore, this approach can be adapted and extended to other performance indicators as well as to other economic assessment methods (e.g. asset value development, minimize cost optimization, etc.).

3.3.2 Steps of decision process

(a) Selection of performance function

The first step is the selection of the performance function, which describes mathematically the behavior of the pavement material or layer over time (or load repetitions). A performance prediction model uses one or more functions with different input parameters for different pavements and materials. This means, that the selection of an adequate function has to be in coincidence at least with:

- The pavement construction (type of layers, sequence of layers)
- Pavement material
- Physical characteristic to be described or assessed
- Climatic situation and other local preconditions

(b) Check of input parameter(s) versus available data and information

After the selection process the input parameters of the functions has to be faced with the available data and information. Only those functions, where data are available can be used. In case of lacking a new function has to be selected or the function has to be simplified.

(c) Definition of database structure and attributes for the modeling

The database is responsible for the storage of all relevant information and has to be designed in coincidence with the data, models and parameters. The data can be categorized into the following groups:

- Net specific information (road, referencing points or sections, length, etc.)
- Pavement construction information (type of layers, thicknesses, construction year, etc.)
- Cross section information (number of lanes, widths, etc.)
- Traffic information ($AADT_{total}$, $AADT_{trucks}$, growing rates, etc.)
- Pavement condition information (condition attributes, year of measurement, etc.)
- EPF information (model parameters, calibration factors, etc.)
- Other relevant information (climate information, responsibilities, etc.)

(d) Definition of analysis variables and implementation of EPF

In many modern PMS the performance functions will be defined in form of so called analysis variables. These variables enable to calculate the yearly values of the functions and to store these results in a database. Because of different types of functions and other time-dependent parameters, these variables have to be defined in coincidence with the parameter to be calculated. Thus, the requirements for such variables can be defined as follows:

- Definition of analysis variable type in coincidence with the function to be calculated
- Storage of calculation results into a database
- Definition of dependencies between different analysis variables (e.g. definition of traffic forecast within a variable and use of this variable within an EPF)
- Definition of starting point of curve based on input values (e.g. from condition measurements)

To have a high flexibility in using user-specific performance functions and to integrate specific calibration functions the PMS should enable to use flexible analysis variables as well. Thus, it is necessary to define the necessary extent of PMS-flexibilty as a selection criteria for the system.

(e) Testing of non-calibrated EPF

After the implementation of the non-calibrated functions (in form of analysis variables) the calculation process has to be controlled. It is recommended, to compare the yearly values of the input parameters as well as the values of the non-calibrated EPF with test calculations executed out of the PMS. In case of divergency the calculation process has to be revised until accordance. Furthermore, it is recommended to compare the performance functions with the results of existing applications using the pre-selected (but non-calibrated) functions.

(f) Adaptation of treatment triggers and reset values

The treatment catalogue of the PMS has to be harmonized with the new function. Thus, it will be necessary to adapt or implement the following elements in the PMS:

- Adaptation of triggers:
  For modeling the maintenance treatment strategies the triggers of the maintenance treatments has to be adapted to the new EPF. A trigger can be defined as the threshold for the application of a certain maintenance treatment (e.g. Reconstruction if cracking > 20%)
- Resets:
  The resets define the effect of a treatment on the EPF. The reset can be an absolute value (e.g. no cracking after reconstruction) or a relative one (reduction of 20% cracking after patching)

(g) Definition of analysis variables and implementation of EPF calibration procedures including laboratory calibration

As shown in Figure 2 the implementation of an adequate calibration procedure is an essential part for the integration of EPF and laboratory testing results into a PMS. In general, the approach consists of 2 main steps, which are based on the calibration procedures described in detail in Deliverable 2. The two steps are as follows:

1. Section based calibration of the EPF:
   The first step includes the calculation of the actual load repetitions and the starting point of the EPF. This will be carried out usually in form of section based calibration (or adaptation) of the EPF by using the section-specific traffic information, the respective model-parameters and condition data from actual condition inspections or measurements before LCA/LCCA will be carried out. Thus, the input data for LCA/LCCA has to be prepared and the calibration has to be executed
2. Integration of laboratory results into the EPF:
   To integrate the results of the laboratory fatigue testing and analysis into the calibrated EPF the damage D with the corresponding load repetitions $N_{f,D}$ and the

scaling factor X_f must be included into the LCA/LCCA process as well. This will be carried out by using on the one hand attributes, which are representing the damage and the number of number of load repetitions and on the other hand in form of an analysis variable, which represents the necessary scaling factor.

(h) Testing of calibration procedures

After the implementation of the calibration procedures the calculation process has to be controlled as well. It is recommended, to compare the yearly values of the calibrated EPF with test calculations executed out of the PMS. In case of divergency the calculation process has to be revised until accordance.

3.4 Testing of workability

The testing of the workability of the EPF calculation as well as of the calibration procedures is a main issue for the quality control of such an implementation. It is recommended to use a testing system or process, which enables to control and recalculate the yearly values of the input parameters as well as the values of the calibrated and non-calibrated EPF on a high number of different sections and to carry out the LCA/LCCA over the whole network to be tested.

3.5 Execution of LCA/LCCA

3.5.1 Understanding of LCA/LCCA and benefit/cost-analysis

Within a modern PMS a pavement related LCA/LCCA predicts the future condition of a road section and enables to compare different maintenance treatment strategies by their effects (benefits). The selection of an adequate maintenance solution (treatment) is usually related to technical and strategic requirements, where a target function has to be optimized. The main approach is either minimize cost analysis or maximizing the monetary or non-monetary benefit of all treatments over the whole network (all sections) under different (technical) constraints. Thus, performance prediction and optimization has to be seen as inseparably component of any modern PMS using LCA/LCCA.

Predicting the future condition of the infrastructure would be of little interest unless one was able in some way to influence how this condition changes with time. This is done by maintenance treatments which, in computing terms, is some action which (a) has a cost while (b) provides a benefit. The latter is defined in the way the treatment modifies one or more analysis variables. The combination of performance prediction and maintenance treatments enables to assess the different recommended solutions in form of benefit/cost analysis.

There are two different types of monetary effects, which can be linked to a maintenance treatment. The first type is the ownership costs, which are costs to initially construct, to improve, to maintain and to operate the respective asset. The second group of effects is related to the users or other affected groups (stakeholders). There are the vehicle operation costs, the freight time, the accidents etc. When determining benefits, it becomes a difference between the two sets of effects (see Deighton, 2012). The benefit to the road users usually arises from improved level of service of the road (typically reduced travel time), while the ownership costs describes the direct monetary effect to the agency. In the benefit/cost analysis the two effects needs be compared on an objective level.

While ownership costs are normally expressed in monetary terms, benefits are expressed in more abstract terms. Because of this, often an agency will assume a certain level of condition or service. It then becomes an analysis of the best and cheapest way to maintain that level (Deighton, 2012).

One measure of the benefit of a strategy is the “Area Under the Curve” (technical approach). This benefit is calculated by summing the present value of the difference between the condition index resulting from the strategy and the condition index for the do-nothing strategy for each year in the analysis period. The condition index most agencies use for calculating the area under the curve is some form of composite index which gives an overall indication of the element’s condition (Deighton, 2012).

A second measure of the benefit is the sum of external costs during the whole life-cycle process, where the effects of the pavement condition as well as the effect caused by a maintenance treatment will be expressed by monetary values (macro-economic approach). The effects can be evaluated by different indicators. The most common are time costs, accident costs, vehicle operating costs (VOC) but also environmental costs like CO_2 equivalents or costs caused by noise. The benefit can be defined in the same way like the technical approach in form of a comparison between a maintenance treatment strategy and a do-nothing strategy. The following Figure 3 shows the different definitions of benefit.

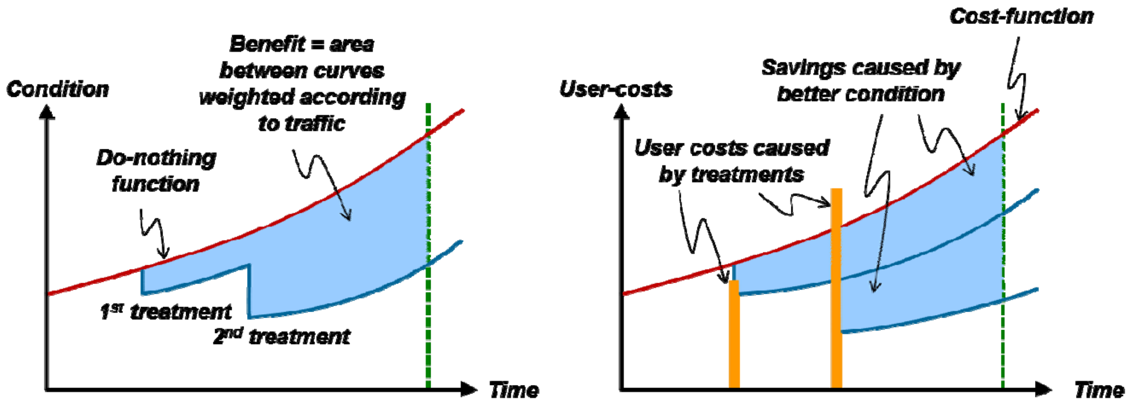

Figure 3: Definition of non-monetary and monetary benefit (Brozek, et.al. 2012)

Based on the calculation of the ownership costs and the benefit a comparison between both indicators is possible and enables a selection of adequate solutions under given requirements. The following Figure 4 shows the efficiency graph for the selection of adequate treatment strategies in the optimization process. All maintenance treatment strategies (points in the graph) which show a low benefit/cost ratio (BC) or incremental benefit/cost ratio (IBC) have to be excluded from the optimization (e.g. S_4 or S_5). The target for the optimization is to find the best solution of the efficiency frontier under given requirements (S_1, S_2 or S_3).

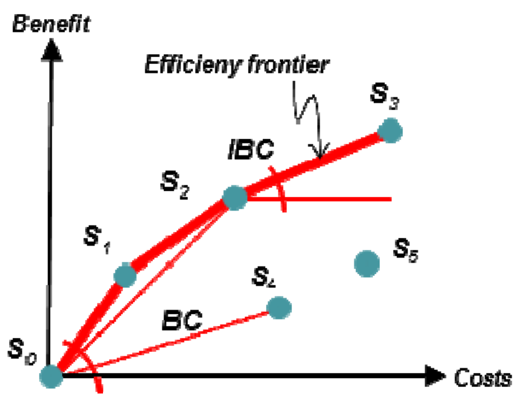

Figure 4: Benefit/Cost analysis – efficiency graph (according to Deighton, 2009)

An analysis scenario defines the second stage of the LCA/LCCA. Optimization normally requires two information, a target function and a resource constraint. Thus, the key components are as follows:

- Type of optimization to be used.
- Parameters to be maximized or minimized in the optimization
- Constraints

3.5.2 Requirements for the execution of LCA/LCCA

The execution of a LCA/LCCA takes place in two stages. In the first stage, maintenance treatment strategies are generated for each section, where the treatment catalogue of the PMS (including treatment triggers, resets, cost calculation procedures, etc.) provides the necessary basis. The second stage is to select the best maintenance treatment strategy for each element, the process called optimization. Thus, the principal requirements that need to be fulfilled for the practical execution of LCA/LCCA are as follows:

- Integration of laboratory calibrated EPFs into the PMS
- Provision of a treatment catalogue with treatment costs, triggers and reset values
- Implementation of a calculation procedure for modeling the costs and the benefit of a treatment strategy into the PMS
- Implementation of a calculation procedure for modeling cost/benefit analysis
- Setting of time frames for analysis (treatment application period, analysis period, etc.)
- Setting of economic factors (discount rate, etc.)
- Formulation of optimization problem in form of target function and restrictions (scenarios)
- Other settings

3.6 Comparison and assessment of results

The output of LCA/LCCA is on the one hand strongly dependent on the quality and quantity of available information and data and on the other hand on the quality of the EPF and the calibration procedures.

The comparison of calibrated with non-calibrated EPF can be based on the results of LCA/LCCA and should enable to assess the improvement of the integration of laboratory testing results into the PMS process on project level. The following list gives an overview of the results, which can be derived from the analysis, and their use in the following up assessment process:

- Comparison of progression (yearly values) of calibrated and non-calibrated EPF (same model)
- Comparison of progression of different calibrated or non-calibrated EPF models (e.g. HDM-4 with German model)
- Comparison of maintenance treatment strategies (type, year) by using calibrated and non-calibrated EPF (same model) or by using different calibrated or non-calibrated EPF models under given monetary of conditional requirements
- Comparison of cost, benefit and other economic indicators by using calibrated and non-calibrated EPF (same model) or by using different calibrated or non-calibrated EPF models

- Assessment of effects of different maintenance treatment strategies on the calibrated and non-calibrated EPFs
- Assessment of monetary or non-monetary savings or losses by using calibrated and non-calibrated EPFs

The assessment of the results should enable to make a clear and repeatable decision about the use of laboratory testing results within a PMS. Of course, a net-wide approach will be too cost-intensive and time-consuming. Nevertheless, the experiences derived from such projects can improve existing EPFs and thus improve the results and the accuracy of the prediction finally.

4 References

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