Probabilistic Modeling of Long-Term Performance and Service Life of Pavements and Road Infrastructures

M. Hoffmann & R. Blab
Chair of Road and Airfield Engineering, Vienna University of Technology, Vienna, Austria

ABSTRACT: The long-term pavement performance of flexible pavements depends on a variety of generally known factors such as mix design, layer thickness and loading parameters. Based on repeated pavement condition surveys it is possible to derive long-term pavement performance functions for different distress types. Due to the stochastic nature of loading conditions and pavement performance on road networks, a deterministic approach towards the modeling of the pavement performance is only a rough approximation. Therefore commonly used methods of pavement performance models with weighted deterministic distress propagation functions have some weaknesses with considerable influence. One main weakness consists in the overestimation of the service life due to the weighting process of different distress types and failure criteria. Another weakness of the conventional approach lies in the loss of information and the weighting itself. In addition, the selection of adequate treatment options becomes more difficult and the optimal timing of measures is biased. In this paper, a methodical framework for probabilistic modeling of distress types based on individual distress propagation, remaining service life and failure distribution is presented. Furthermore, it is possible to determine the occurrence probability of exclusion criteria for any given measure and time due to certain other distress types. Based on the model results considerable improvements and savings can be achieved due to improved design criteria and rehabilitation strategies.

KEY WORDS: Performance, stochastic, modeling, service, life

1 INTRODUCTION

Pavement management systems (PMS) are complex systems that provide an optimal strategy for maintenance and rehabilitation of roads. To achieve this goal a database as well as the existing boundary conditions (e.g. budget, failure criteria, availability etc.) must be known. Furthermore, the road data and pavement conditions have to be linked together based on comprehensive models in order to determine the required budget, optimal maintenance, and rehabilitation measures following an analytical process.

Commercial pavement management systems (e.g. HDM-4, VIAPMS, STREETSAVER, MICROPAVER etc.) try to integrate this structure into their program architecture. Like many areas of technology, such systems are subject to strong changes or upgrading due to new scientific knowledge, information sources and calculation methods over time. For this reason in most cases modular program architectures are chosen (Figure 1).

- DATABASE: The database is the central module, where all the necessary information on the road inventory (road sections, width and length), pavement conditions and strain data (traffic, weather, temperature) are stored and maintained
- BOUNDARIES: This module is one of the main user interfaces because here the boundary conditions for the optimization are set. These conditions consist of budget restrictions, statutory provision, pavement condition targets and typical measures
- PMS - MODELS: The models are formulas that describe the connection between input data and calculated results. The scope of the models has to be adapted according to the available data and results of the analysis. Usually, models for road condition assessment and forecasting, traffic and costs are implemented
- PMS - ANALYSIS: In the analysis system an optimized PMS – Strategy on road section and network level is calculated under the given boundary conditions (Knapsack – problem)
- PMS – RESULTS: The main results of a PMS – analysis are the required budget for each maintenance and rehabilitation strategy and the resulting pavement condition due to the implementation of this strategy.

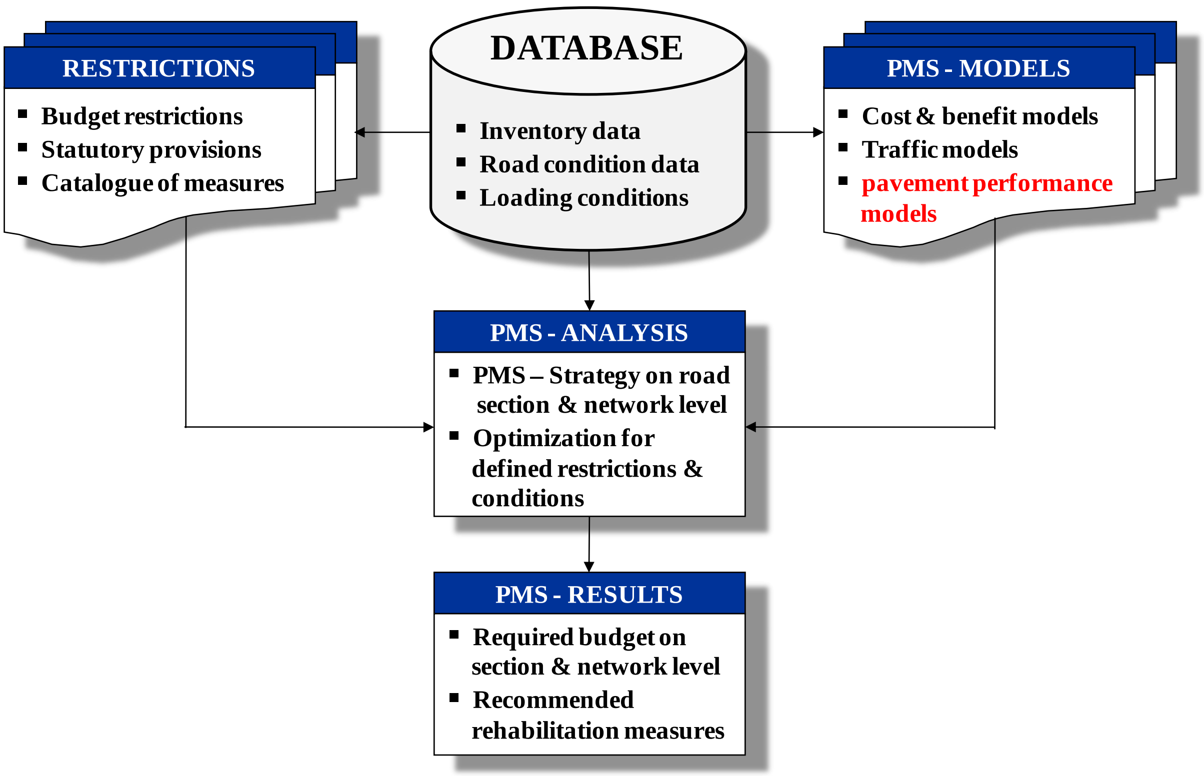

Figure 1: Overview and general structure of pavement management systems PMS (WENINGER-VYCUDIL 2003).

The pavement performance prediction and expected service life with and without treatment is one of the most important issues in any PMS, because choice and timing of measures together with the required budget are directly dependent parameters. The current paper specifically addresses the modeling methods of asphalt pavement conditions in a PMS.

2 PREDICTION OF PAVEMENT CONDITION

2.1 Main distress, failure mechanisms and propagation

The loading conditions of asphalt pavements due to traffic, weather, and temperature causes strain that appears after a certain time as a well defined distress type. According to comprehensive statistical investigations on the long-term pavement performance in Austria from MOLZER et. al. (2000) and WENINGER-VYCUDIL (2003), the failure propagation and service life for each distress type is described through deterministic functions.

Another comprehensive investigation program on the long-term pavement performance (LTPP) was started in 1987 on asphalt and Portland cement concrete pavement test sections across the U.S. and Canada. In a study on the expected service life and performance characteristics of asphalt concrete pavements, QUINTUS et. al. (2005) determined specific failure functions, average service life, failure development, and survival probability.

According to HOFFMANN (2006) the loading conditions, resulting strain, and failure types under different temperature regimes can be linked to the dominant failure types and their propagation over time (Figure 1). At high temperatures, the asphalt is heated up with rutting and shear failures as a result of stress at the pavement surface. The failure of propagation over time can be described through linear or slightly progressive regression functions (surface damages). For medium temperatures the fatigue stress with initial cracking in the wheel path from bottom to surface is dominant. The observed failure functions are steeply progressive (structural damages). At low temperatures increasing stress due to the ageing of the bitumen over time leads to progressive transverse cracking and longitudinal cracking parallel to the wheel path starting from the surface down to the bottom (structural damages).

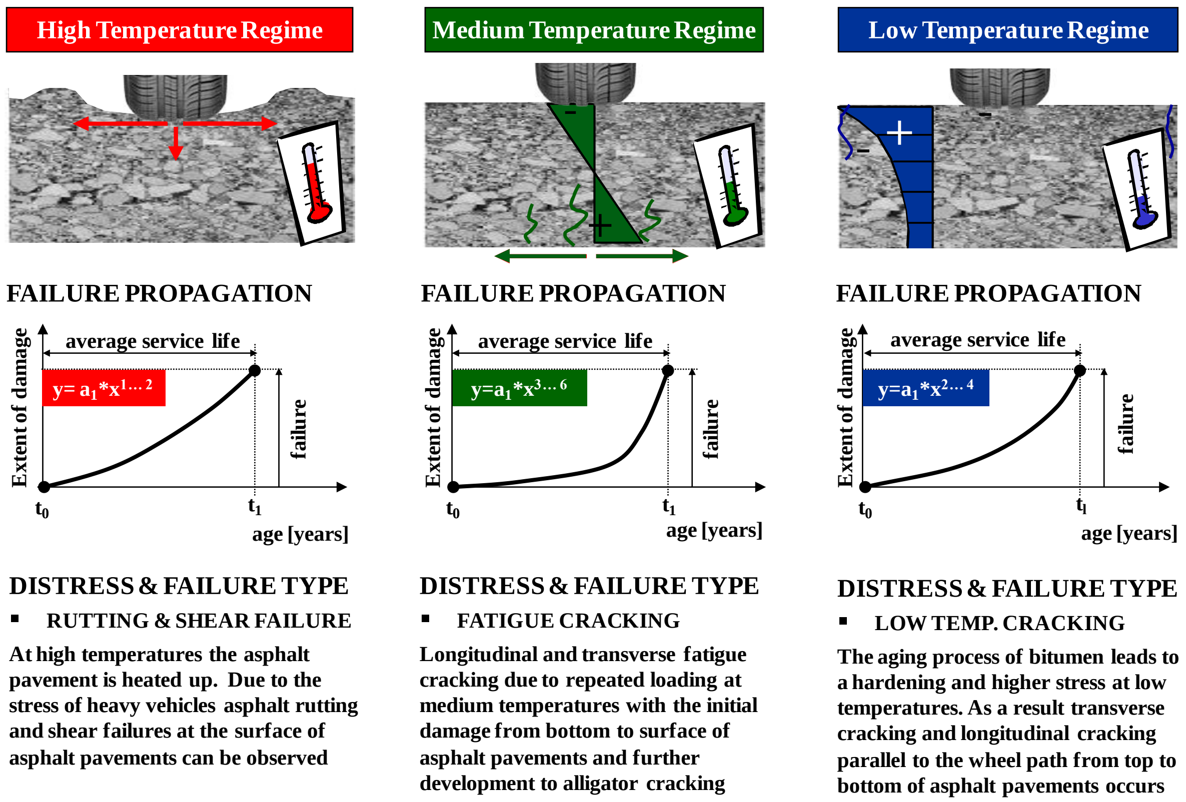

Figure 2: Temperature regimes, distress & failure types and failure propagation over time during the service life of asphalt pavements (HOFFMANN 2006).

2.2 Derivation of pavement performance models

For the implementation in any PMS, the pavement performance model must be capable of describing both the pavement conditions at a specific time and the pavement performance over time for the road network and each road section level. Depending on the derivation of the model, mechanistic (analytical) and empirical approaches can be distinguished.

Mechanistic models are based on the theoretical determination of strains and stress under external loading and their verification in performance-based laboratory experiments (Figure 3). Empirical models are derived from observation data of the actual pavement performance and the determination of the causal relationships of pavement failure types to the main distress factors through statistical analysis (Figure 4).

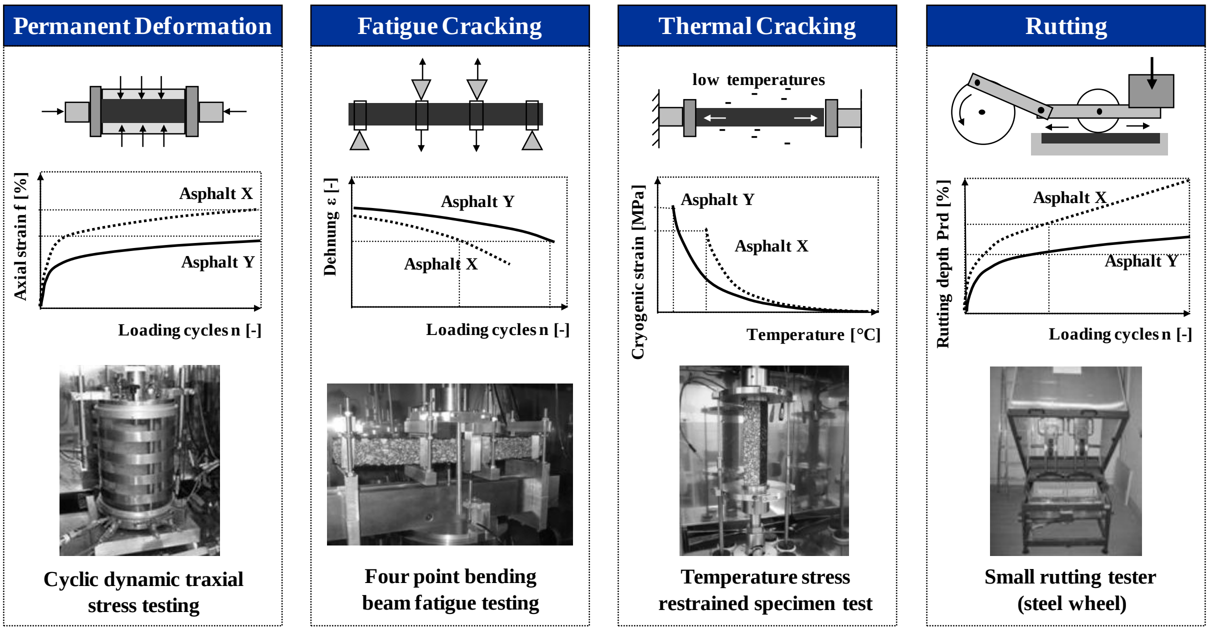

Figure 3: Verification of mechanistic pavement performance in laboratory experiments.

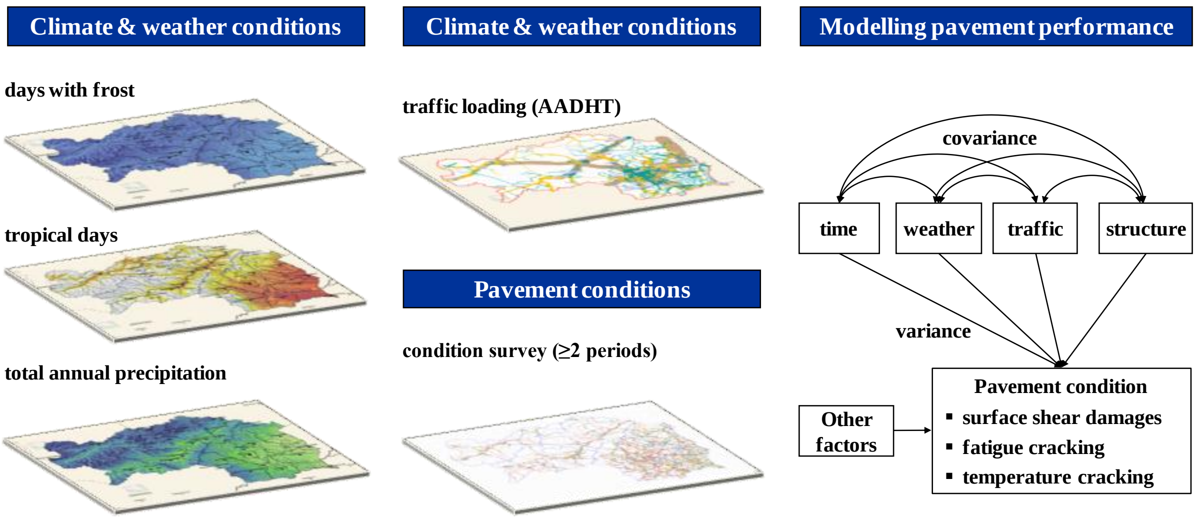

Figure 4: Empirical approach to causal relationships of distress & pavement performance.

2.3 Failure criteria and weighted pavement condition indices

For any given failure type and pavement performance, a condition function can be derived through a regression analysis. With the definition of specific failure conditions for each condition function the average service life is also set. If the average service life and pavement performance is to be modeled in a PMS, the common deterministic approach based on weighted functional values of failure types shows a number of weaknesses (Figure 5).

Even if maxima and minima criteria are implemented, accurate results are the exception. In a probabilistic approach, system characteristics and redundancies have to be considered. For a non-redundant system (series circuit) the average service life is shorter than the shortest service life of any individual distress type. In redundant systems (parallel circuits) the average service life is longer than the longest service life of any individual distress type (Figure 6).

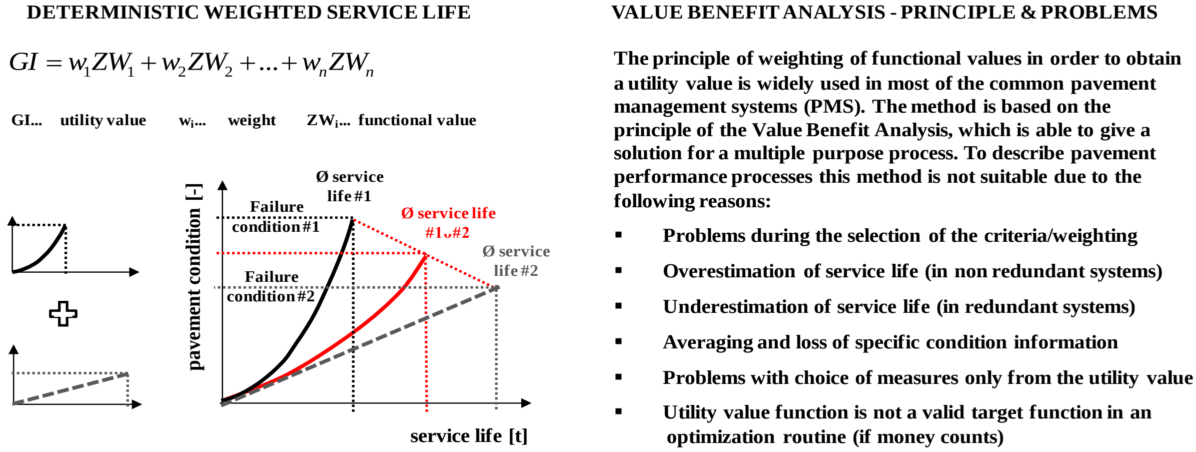

Figure 5: Methodical problems with the approach of weighted failure functions in a PMS.

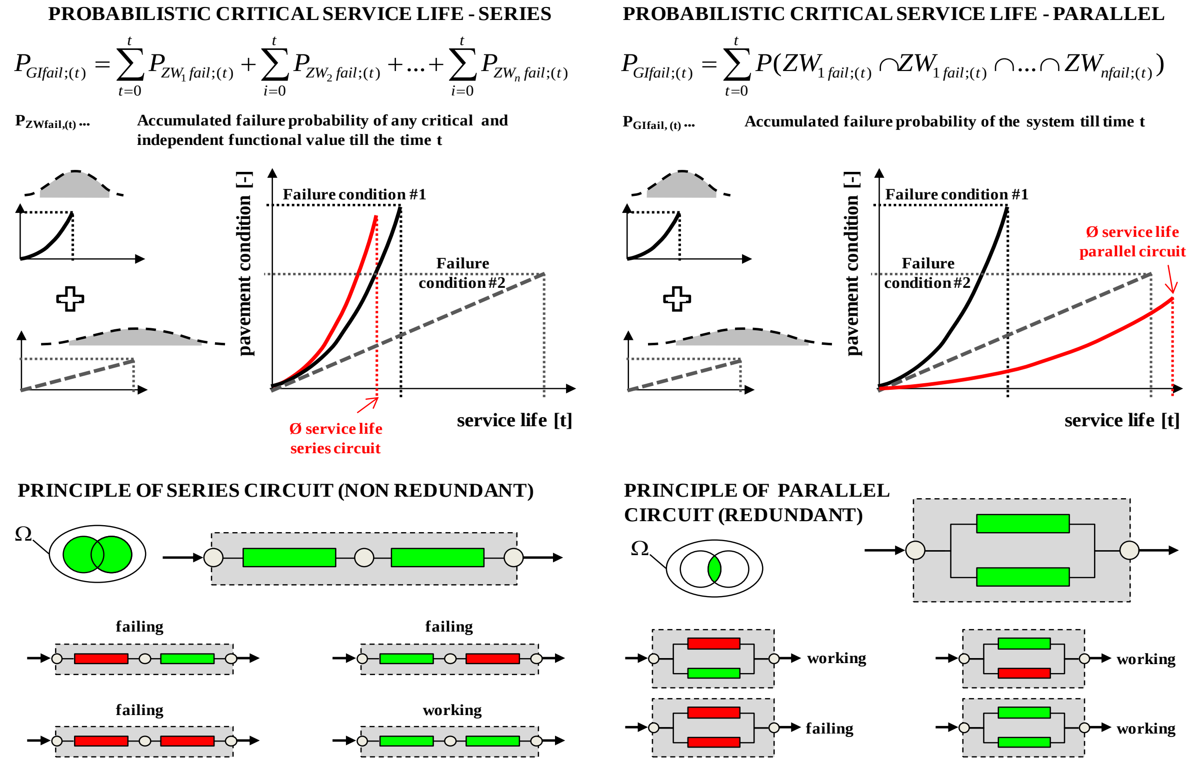

Figure 6: Probabilistic service life of a system based on independent failure functions.

2.4 Modeling of pavement performance on project and network level

Pavement performance models that are based on any fitted function and a deterministic approach predicts one particular condition for one service lifetime (Figure 7, top). This might be reasonable, if the function is fitted for each road section but is certainly not the case on road network level. On road network level probabilistic models show a certain distribution of road conditions over time. This distribution can be interpreted as probability of occurrence of a specific condition at any road section over time or the absolute shares of specific conditions at any time for the entire road network.

According to WENINGER-VYCUDIL et. al. (2009) and others the usual probabilistic approaches like Markov – Chains are very rarely used in any PMS. Their shortcoming lies in their constant transition rate over time, which results in inaccuracies, if the road network is either very young or very old (Figure 7, center). This problem can be solved according to HOFFMANN (2006) by introducing a combination of normalized pavement performance functions and failure distributions (Figure 7, bottom). With this approach the performance of all road sections from each year of construction can be accurately modeled. By adding up the predicted distributions for all sections and years of construction the total performance of the road network can be predicted. The same approach applies for rehabilitation measures.

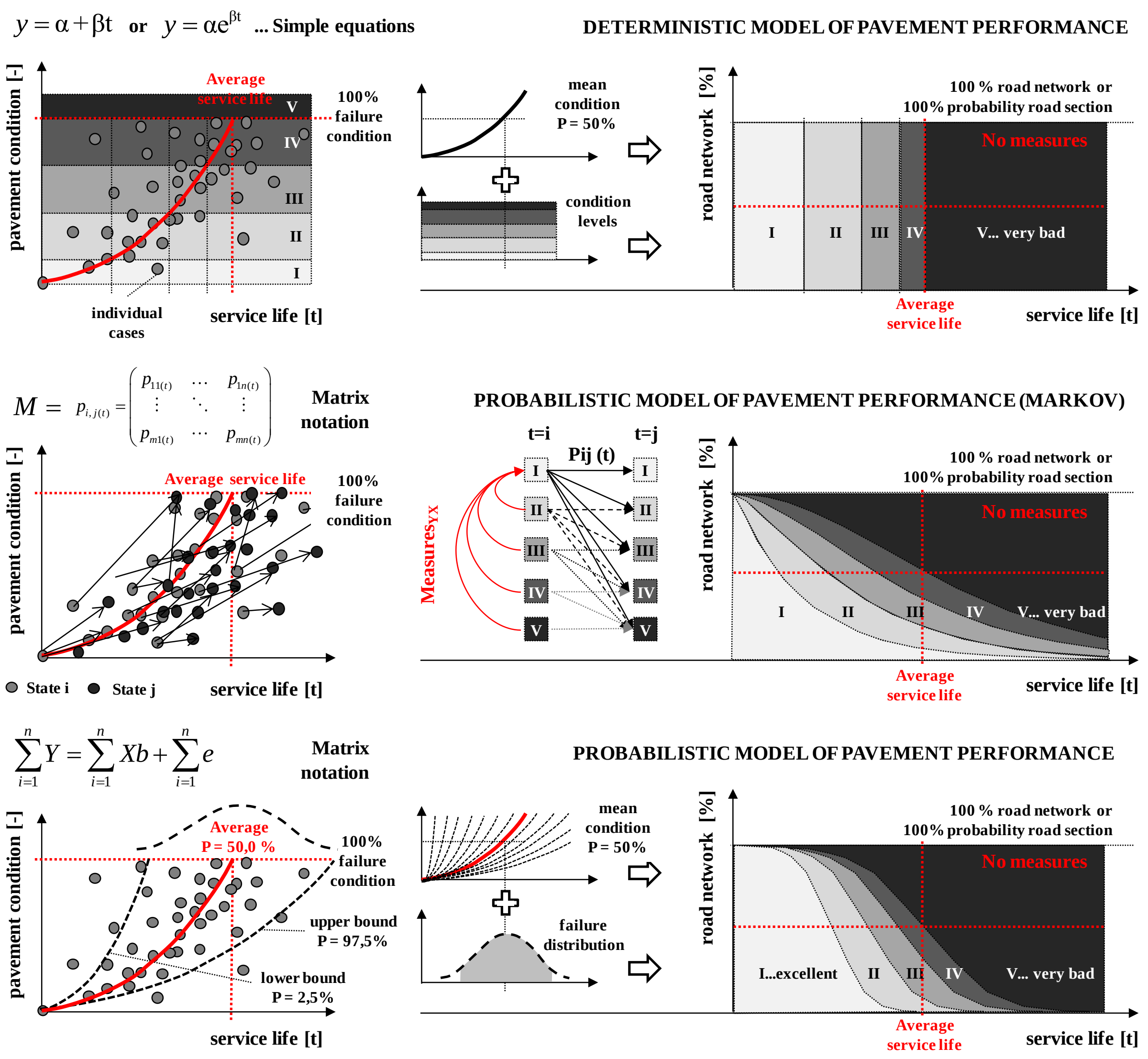

Figure 7: Deterministic and probabilistic models of pavement performance.

2.5 Pavement performance comparison for dominant failure types

Based on the presented probabilistic approach the pavement performance for the dominant distress and failure types under different temperature regimes can be modeled. With a simple bivariate fitted regression function, a standard deviation of 30% of the average service life, and ten equally distributed condition levels the probabilistic pavement performance is presented in Figure 8. For rutting and shear failures with a linear failure propagation there are no sections in good or very good condition (less than 20% damage) after a service time of one half of the average service life compared to over 65% for low temperature cracking or more than 85% for fatigue cracking under the assumption of the same average service life.

Furthermore it is possible with this approach to estimate the amount of road sections with specific combined conditions. If for instance a surface treatment should be applied for failed sections with surface damages but less than 20% of fatigue cracking, the treatment can be applied to a percentage of failed sections for rutting (>100% damage) multiplied with the amount of sections with less than 20% fatigue cracking at the same time. For the example this amount can be estimated with 4% after one halve of the average service life has passed.

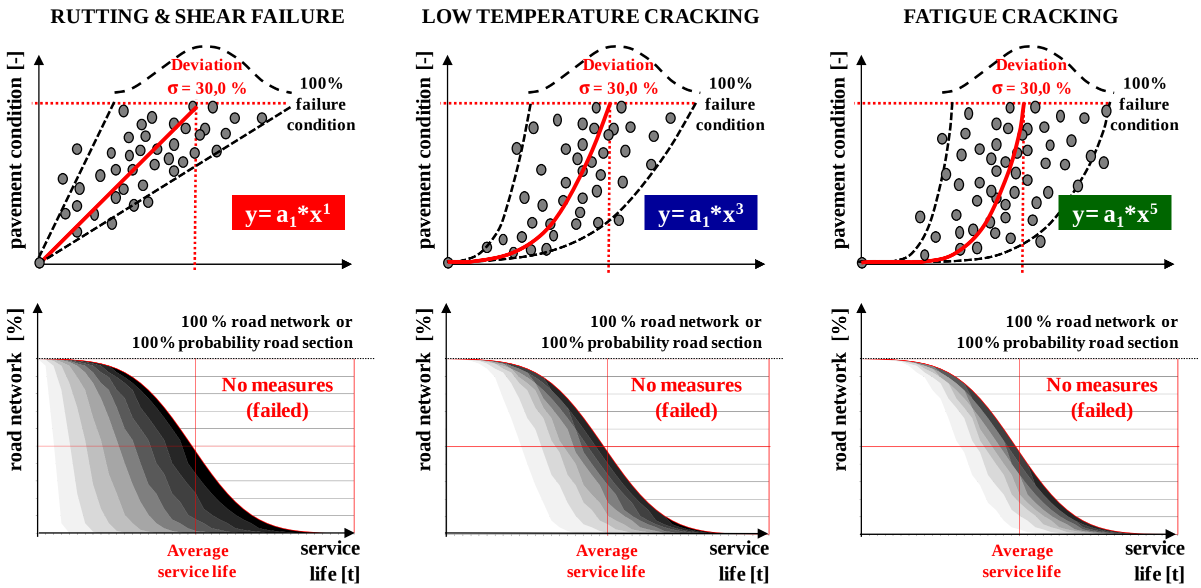

Figure 8: Probabilistic pavement performance for the dominant failure types of asphalt concrete pavements with ten equally distributed condition levels.

3 DETERMINATION OF SERVICE LIFE

3.1 Calculation of remaining service life

The expected service life with/without treatment and the remaining service life are key parameters in any PMS or allocation of infrastructure costs. The remaining service life of each road section is calculated as the difference between the expected/fitted service life and the service time since the construction/rehabilitation of the road section. As long as both failed and surviving sections are considered at the same time the average remaining service life is always the difference between expected average service life and service time (Figure 9, top). However; in most cases this approach is not applicable because the percentage of already failed sections is not known.

By means of a probabilistic approach based on normalized pavement performance functions and its failure distribution, already failed sections can be accounted for. The average remaining service life of the surviving road sections at any given service time can be calculated through the weighted normalized failure functions of the surviving road sections. Therefore, the life expectancy of prior unfailed sections is in general higher than the average service life of all sections (Figure 9, center).

If a more accurate estimation of the expected service life of surviving road sections is needed, the actual condition at the time of prediction has to be taken into account. With the presented approach the remaining service life for ten equally distributed condition levels can be modeled for any given service time (Figure 9, bottom). Furthermore a threshold to the remaining service lives is introduced to cut off unlikely behavior of individual sections (1% for this example). With the standardized charts a straightforward estimation without further calculation is also possible if the normalized values are multiplied with the actual service life in years and/or condition. For the given example the average remaining service life of sections with a service time equally to the average service life and a condition with around 60% of the failure condition have a slightly above average remaining service life compared to all surviving sections at this time.

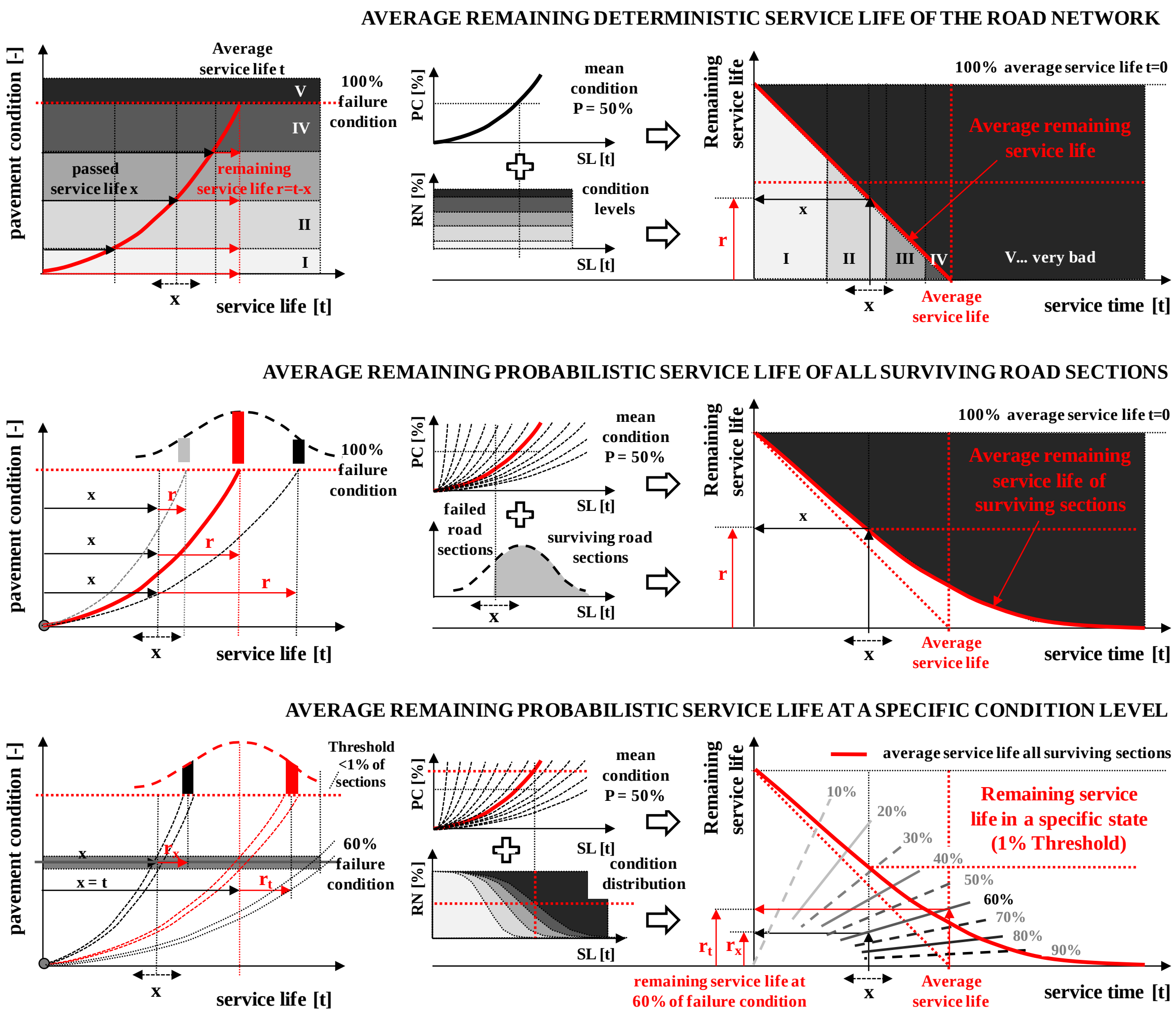

Figure 9: Deterministic and probabilistic average remaining service life.

3.2 Remaining service life for dominant failure types

With a probabilistic model for the remaining service life of surviving road sections the influence of the dominant failure types can be accounted for. While the average remaining service life for all surviving road sections and dominant failure types stays the same the remaining service life at a specific condition level is heavily influenced by the failure type/function.

For rutting and shear failures with 60% damage and the assumption of a linear failure propagation the remaining service life after a service time of 50% can be estimated with 33% of the average service life of all sections (Figure 10, left). The remaining service life for low temperature failures based on the same assumptions except a nonlinear progressive failure mechanism can be estimated with 9% of the average service life and is therefore considerably lower (Figure 10, center). For fatigue cracking the estimated remaining service life for this example is 5% (Figure 10, right).

Based on the results of the model it can be shown that road sections with structural damages and progressive failure propagation (low temperature & fatigue cracking) might appear in a good condition while their remaining service life is already considerably reduced. Surface damages (rutting, shear failures) with linear or slightly progressive failure propagation on the other hand show a less critical (e.g. rehabilitation, budgeting etc.) and a longer remaining service life at any specific condition.

For an estimation of the remaining service life of sections with surface damages based on passed service time and condition the accuracy of the condition assessment is of high importance for a reliable prognosis. If the remaining service life for sections with structural damages is to be estimated more accurate values of the service time, traffic data, pavement structure etc. are needed.

As a result periodic condition assessments every 3 – 7 years might show a majority of road sections with very few structural damages in the first assessment and a high amount in the follow up assessment. Therefore especially fatigue cracking on road sections or more general progressive failures in constructions should largely be avoided, because they are critical for rehabilitation and budgeting needs in any PMS. Thus robust constructions and sufficient pavement design are keys to a successful pavement management and low life cycle costs.

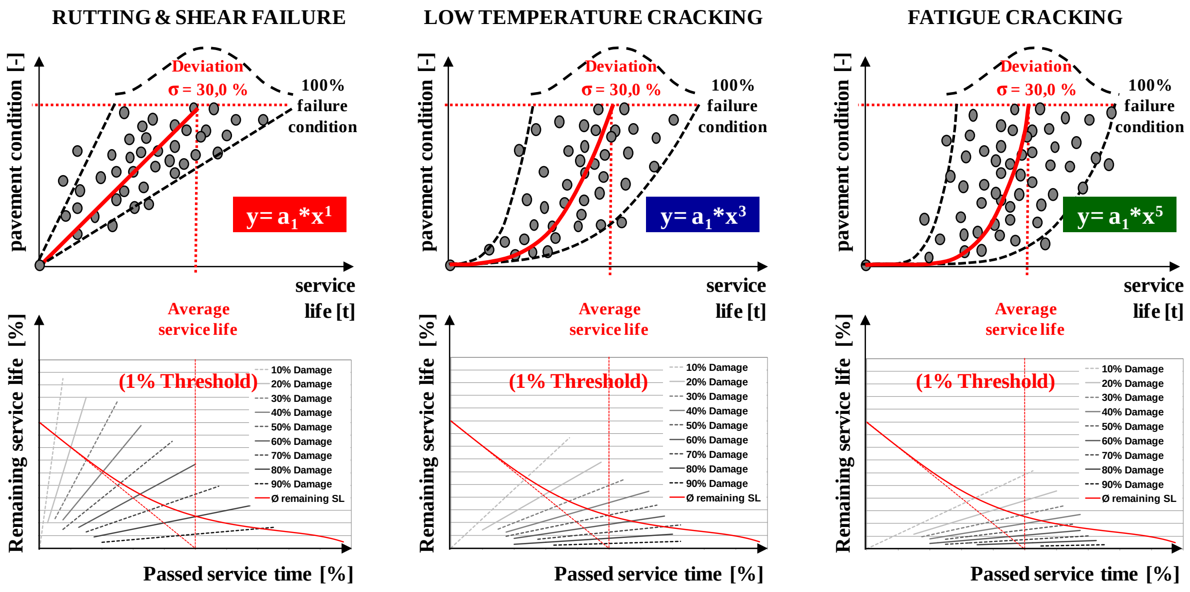

Figure 10: Probabilistic models of remaining service life for the dominant failure types of asphalt concrete pavements with ten equally distributed condition levels

4 CONCLUSIONS AND OUTLOOK

Loading conditions, resulting distress, and failure types can be linked through causal relationship based on empirical data or performance-based testing in the laboratory. The typical distress and failure types as well as failure propagation during the service life of asphalt pavements, however, show huge deviations over time. The commonly used deterministic approaches in a PMS based on weighted functional values of failure types are a standard in most programs, but show a number of weaknesses with considerable drawbacks.

With the presented methodological framework and probabilistic prognosis of pavement performance, these weaknesses can largely be avoided. Furthermore, it is possible to determine both the optimal timing of maintenance and rehabilitation if costs and impact of the measures are included in the model. Additional advantages are the possibility to calculate the probability of the occurrence of specific conditions for the implementation of any given measure and the life cycle costs of different treatment options or strategies.

Moreover, the presented methodological framework and probabilistic prognosis can be applied to any system with specific failure propagation and distribution as well as the possibility for different rehabilitation measures or strategies. Currently the presented model is implemented in a new Asset Management Software Tool for road infrastructures, which is developed by the authors at the Technical University in Vienna.

Even though the methodological framework and the probabilistic prognosis tool have shown promising and robust results, there are still many questions to be answered. One main topic for future research will be the derivation of improved pavement condition functions and improved correlations to the main distress and failure types and their interaction at different road network levels. Another important topic is the deduction of robust scaling factors for the conversion of mechanistic performance-based laboratory results into probabilistic expected service life as well as a verification of the used failure distributions.

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