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PROBABILISTIC LIFE-CYCLE PERFORMANCE, DESIGN, MAINTENANCE, OPTIMIZATION, AND DECISION-MAKING IN ASPHALT PAVEMENT

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Abstract. This paper thoroughly reviews the current state of life-cycle research in asphalt pavements. It identifies the primary sources of uncertainty across the pavement life-cycle. Moreover, it emphasizes significant achievements in the research of distress and condition indicators, reliability, risk, life-cycle cost, sustainability, and resilience of asphalt pavements. Probabilistic optimization approaches that account for various pavement life-cycle phases and the latest technology trends and innovations aimed at improving the life-cycle of asphalt pavements are also discussed.

1 INTRODUCTION

Asphalt pavements, exposed to various stressors such as traffic loads and environmental conditions, can deteriorate as soon as they are in service. If not managed promptly and effectively, this deterioration can lead to significant structural integrity and safety declines, or even failure [1-4]. In such cases, implementing well-founded management strategies is essential to sustain the pavement's performance within acceptable standard limits throughout its life-cycle [5-8].

Addressing challenges in performance prediction, multi-objective optimization, and decision-making in asphalt pavement management requires handling uncertainties [9-11]. Recognizing the primary sources of uncertainty is crucial for effective pavement maintenance. Engineers typically classify uncertainty into aleatory (data-based, arising from inherent randomness) and epistemic (knowledge-based, stemming from imperfect models due to limited knowledge) [12]. Both should be considered in pavement performance analysis and assessment, as discussed in Section 2. The performance of asphalt pavement systems can be evaluated using various indicators. To quantify and characterize factors influencing pavement performance, the Long-Term Pavement Performance (LTPP) program monitors over 17 types of data related to distress, surface characteristics, and deflection [13]. In addition, advanced metrics such as reliability, risk, sustainability, and resilience are increasingly used, as discussed in Section 3. The goal of assessing asphalt pavement performance is to ensure optimal management across its life-cycle phases. The various pavement attributes can be correlated, making it essential to evaluate options using multi-objective optimization methodologies to identify the most effective life-cycle management strategies [14]. These methodologies aim to improve performance and functionality while reducing negative impacts and minimizing asphalt pavements' life-cycle costs (LCCs) [15]. Approaches to optimizing asphalt pavement life-cycle management under uncertainty are explored in Section 4.

2 UNCERTAINTY QUANTIFICATION

This section aims to identify and summarize the sources of uncertainty throughout the asphalt pavement life-cycle. Figure 1 visually categorizes these sources by parameter groups and individual parameters. It highlights uncertainties across material properties, structural characteristics, traffic, weather, climate change, construction, inspections, structural health monitoring (SHM), maintenance and rehabilitation (M&R), and prediction models. Material properties at multiple scales and climate change are integrated into life-cycle analysis, as asphalt mixtures, composed of aggregates and binder, are influenced by uncertain intrinsic attributes at molecular, micro, meso, and macro scales. Moreover, the increasing awareness of climate change, driven by extreme weather events and shifting climate patterns, underscores the need to incorporate climate change factors into pavement management adaptation strategies [16].

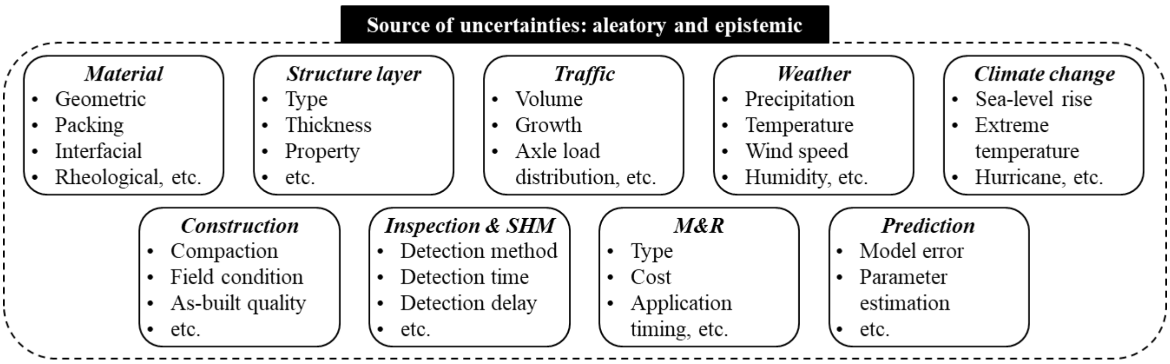

Figure 1: Types of uncertainties associated with asphalt pavement life-cycle.

3 PERFORMANCE INDICATORS

This section summarizes the performance indicators of asphalt pavement, including the 17 distress/condition indicators collected by the LTPP program [17], as shown in the lower part of Figure 2. It also covers advanced probabilistic indicators such as reliability, risk, LCC, sustainability, and resilience, depicted in the upper part of Figure 2.

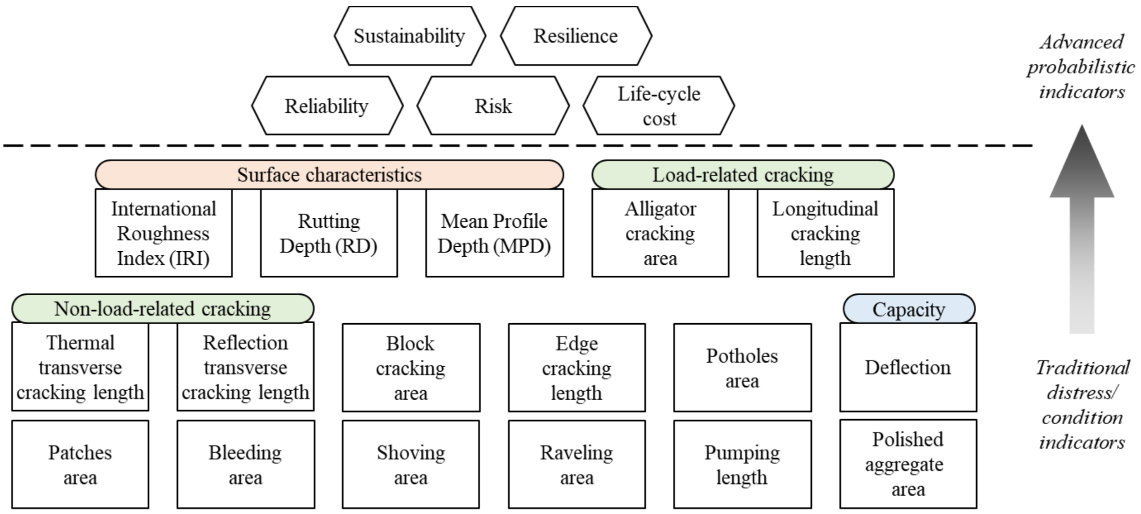

Figure 2: Life-cycle performance indicators associated with asphalt pavement.

3.1 Distress/condition indicators

The pavement performance data in the LTPP program's monitoring module are classified into three primary categories: surface characteristics, distresses, and capacity. Surface characteristics include Mean Profile Depth, International Roughness Index, and Rutting Depth. Distresses cover various forms of pavement deterioration, such as cracking (load-related and non-load-related), potholes, patches, bleeding, and more. Deflection is used to evaluate the structural capacity of the asphalt pavement [18].

3.2 Probabilistic performance indicators

Building on the above indicators, more advanced metrics such as reliability, risk, sustainability, and resilience have been widely adopted, as summarized in Table 1 [19-20].

Table 1: Comparison among probabilistic performance indicators of asphalt pavement

Indicator	Definition	Characteristic
Reliability	Probability that a pavement will perform its intended function without failure over a specified period	Accounts for the associated uncertainties
Risk	Likelihood of a pavement failure occurring, coupled with the event's consequences.	Accounts for the severity of failure impacts
LCC	Total cost of constructing, operating, and maintaining a pavement over its entire life span	Helps optimize investment decisions
Resilience	Ability of a pavement to recover quickly from disruptions	Measures the capacity for adaptation and recovery
Sustainability	Capacity of a pavement to be maintained over the long term without depleting resources, causing environmental harm, or negatively impacting future generations.	Provides a holistic view in terms of economy, environment, and society

4 PROBABILISTIC LIFE-CYCLE MANAGEMENT

The life-cycle management of asphalt pavements has evolved from single-objective optimization focused on individual phases—often based on deterministic models and empirical design methods—to multi-objective approaches that consider trade-offs among competing goals across multiple phases, including material production, design, construction, use, maintenance and rehabilitation (M&R), and end-of-life. This progression is increasingly supported by big data and machine learning, as illustrated in Figure 3 [21-23].

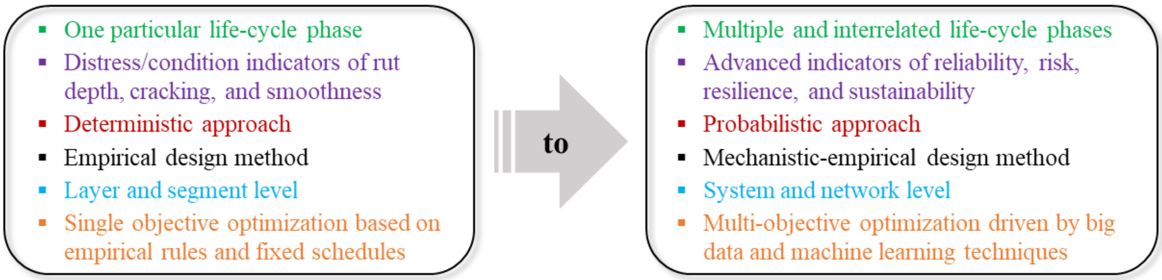

Figure 3: Development of life-cycle-based management of asphalt pavement.

Generally, the probabilistic life-cycle management optimization can be formulated as follows [24-26]:

Find:

Type (Tp_{layer}) and thickness (Tk_{layer}) of layer for design of new asphalt pavement (1)

Type ($Tp_{M\&R}$) and timing ($Tm_{M\&R}$) of M&R for existing asphalt pavement (2)

To achieve the following objectives:

Maximize performance level (e.g., reliability or resilience) (3)

Minimize expected total life-cycle cost (E_{LCC}) (4)

Subject to the constraints:

Number of M&R application ($N_{M\&R}$) (5)

Timing of M&R application ($Tm_{M\&R}$) (6)

Performance level threshold (TH_{PL}) (7)

LCC constraint (CON_{LCC}) (8)

5 CONCLUSIONS

The following conclusions are drawn:

1. Each source of uncertainty associated with asphalt pavement may involve both aleatory and epistemic uncertainties, depending on the specific context and the nature of the variable.
2. Big data-driven machine learning techniques can enhance the accuracy and efficiency

of life-cycle performance predictions, pavement design, M&R planning, and decision-making processes in asphalt pavement management [27-29].

3. Methodologies for evaluating the social impacts of asphalt pavements are still underdeveloped. When established, these methodologies should be integrated with LCC analysis and life-cycle assessment (LCA) frameworks to enable a holistic evaluation of sustainability across various dimensions.

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