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PAVEMENT MANAGEMENT SYSTEM: CONDITION ASSESSMENT, CHALLENGES, AND FUTURE DIRECTION

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ABSTRACT. Successful pavement management plays a significant role in providing safe, long-lasting, and cost-effective road infrastructure. This study investigates the Pavement Management System (PMS) and the Pavement Maintenance Management System (PMMS) as core models to improve pavement performance and extend service life. A discussion of pavement condition assessment methodologies is presented in this paper, with emphasis on the key parameters influencing pavement performance, such as ambient conditions, traffic loading, material properties, and maintenance procedures. To enhance the pavement condition assessment process and avoid dependence on a singular approach, the study considered three significant pavement condition rating approaches: manual evaluations, relying on visual observation by qualified raters; empirical approaches, using statistical relationships based on previous experiences to predict degradation trends; and automatic systems, using sensor cars and half-automatic technologies to offer efficient, deflection-based estimates. Also considered is the convergence of different approaches with a special emphasis on nascent innovations such as artificial intelligence (AI) and real-time data capture for improved accuracy of pavement assessment and decision-making. The outcomes indicate the importance of a multi-method pavement evaluation considering cost, accuracy, and scalability. Future research should focus on improving data integration, predictive model refinement, and the use of smart infrastructure technologies to improve pavement management efficiency and sustainability.

KEYWORDS: PMS; PMMS; Condition Assessment; and Pavement distresses.

1. INTRODUCTION

Pavement management is essential to ensuring the road infrastructure's durability, safety, and performance. Road maintenance organizations are currently facing significant challenges due to the increase in traffic volumes, weather changes, and Limited budgets.

To meet these challenges, Pavement Management Systems (PMS) are widely used to conduct pavement conditions, identify maintenance types, and optimize the use of resources [1]. Pavement condition is a basic tool of PMS because it provides deterioration data that helps in maintenance prioritization.

Despite the heavy use of traditional methods such as manual inspection and empirical approaches, newer advances have included sensors, AI-based condition assessment, and automated imaging devices [2]. Despite technological developments, there are still issues with standardizing assessment methods, integrating data-driven models, and ensuring cost-effectiveness [3]. This study aims to evaluate pavement management concepts, with an emphasis on PMS, PMMS, and pavement condition assessments. It also investigates future trends in pavement inspection, including artificial intelligence (AI), sensor technologies, and predictive condition models [4].

2. PAVEMENT MANAGEMENT SYSTEM (PMS)

PMS is a collection of tools or techniques that help decision-makers identify economical strategies for offering, assessing, and preserving pavement in a usable state [5]. Also, PMS is an organized and methodical approach that performs all activities related to supplying and maintaining. pavement.

The PMS's primary purpose is to predict the condition of the pavement as well as the expenses of maintenance and rehabilitation over a particular time horizon, hence facilitating work planning and programming. A well-developed and well-implemented PMS allows for proper, consistent, and informed decisions on pavement repair, rehabilitation, or reconstruction [6].

Fig. 1 depicts PMS as a collection of components that react alternately, including programming, planning, design, building, maintenance, and rehabilitation [7]. Most PMS aims to maximize the efficacy of pavement maintenance and rehabilitation by achieving the best use of available finances [8].

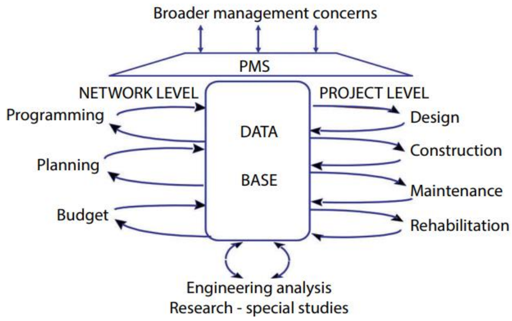

Fig. 1. Component of a Pavement Management System (PMS) [7].

3. Pavement Maintenance Management System (PMMS)

PMMS should not be mistaken for PMS. PMMS functions as a component of the PMS program, meaning they complement each other instead of replacing one another. Fig. 2 illustrates the relationship between PMMS and PMS and their overlapping concept [9].

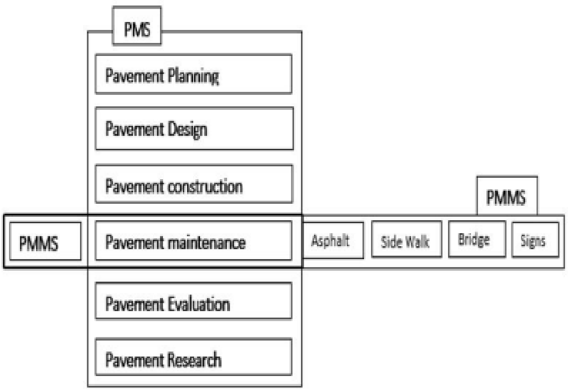

Fig. 2. Relationship between PMMS and PMS [9].

PMS offers a structured approach to making decisions regarding pavement maintenance by utilizing an objective method. There is a systematic order of steps involved in creating a pavement maintenance strategy. The PMMS follows the following process [10]: define goals, define standards, verify needs, establish resources and activities, implement, and evaluate performance. The purpose of the PMMS framework is to produce actions that use accessible resources and information while conducting analyses to improve maintenance effectiveness.

To establish an effective PMMS, it is essential to first recognize the fundamental pavement defects, which can be categorized into structural and functional distress [11], [12]

- **Structural distress** refers to the failure or deterioration of the pavement structure's components across one or more layers, leading to an inability to support the load applied to its surface.
- **Functional distress** can occur with or without structural distress. This type of distress creates discomfort for drivers while they are performing the driving task.

The pavement ability to bear the loads is associated with structural failure, while functional failure pertains to the quality of the ride and safety. As the severity of structural deterioration increases, it will ultimately lead to functional failure because of surface roughness [10].

The degree of distress in both categories vary, and the intensity of distress on any pavement is primarily determined by the observer's opinion. However, the distinction between the two sorts of failures is significant. Engineers should be able to tell the difference [11] .

4. Pavement Condition Assessment

Evaluating pavement conditions involves gathering and analyzing performance data related to the pavement, such as cracking, rutting, faulting, structural capacity, and surface characteristics, to ascertain specific or overall indices of pavement condition [13].

Evaluating the condition of pavements is an essential aspect of managing transportation infrastructure, which helps maintain the safety, effectiveness, and durability of road systems. A precise assessment of pavement conditions allows for prompt maintenance, lowers expenses, and decreases inconveniences for road users [4].

Throughout the years, different approaches have been created to evaluate pavement conditions, each possessing its advantages and drawbacks. Essentially, assessing pavement condition supplies the necessary information needed to define the present performance of the pavement, monitor its performance over time, and forecast its future conditions [8], [13].

4.1. Factors Affecting Pavement Condition Performance

Pavement performance is influenced by several interrelated factors, including traffic loading, environmental conditions, material properties, construction quality, and maintenance practices [14]. Understanding these factors is essential for designing durable pavements and implementing effective maintenance strategies. Fig. 3 shows factors affecting Pavement performance.

4.1.1. TRAFFIC LOADING

The amount and frequency of traffic loads have a substantial impact on pavement life. Heavy trucks create considerable pressure on pavement layers, leading to structural harm as time progresses [15].

Average daily traffic, annual average truck traffic, axle type, and repetition are all important factors and directly affect pavement layer capacity and strength [16]. Higher traffic volumes and higher loads cause faster wear and tear, necessitating strong pavement structures to meet such requirements.

4.1.2. ENVIRONMENTAL CONDITIONS

As stated in FHWA-HRT-16-084, variations in temperature, moisture content, and frost activity considerably influence how pavement performs [17].

Yearly variations in temperature and rainfall can lead to the expansion and contraction of pavement materials, which may cause cracking.. Moisture and yearly humidity infiltration erode the subgrade, lowering structural integrity. In colder climates, frozen-thaw cycles can induce frost-thaw weakness, jeopardizing pavement stability [16].

4.1.3. MATERIAL PROPERTIES

Materials used in pavement construction must be carefully selected and of high quality to ensure long-term performance. Pavement lifespan is strongly influenced by the mix and quality of pavement components. The parameters of asphalt mixes, aggregate type, and binder quantity all have an impact on rutting and cracking resistance [18].

High-quality materials can improve the longevity and efficacy of preservation methods. Also, choosing the appropriate materials based on pavement conditions is crucial. Different materials may perform better under specific traffic and environmental conditions [19].

4.1.4. CONSTRUCTION QUALITY

Poor practices can lead to suboptimal performance. The contractor's skills and experience

play a critical role in the quality of the work. Inexperienced contractors may not execute the necessary procedures effectively, impacting pavement longevity [19].

Proper compaction, accurate mix proportions, and adherence to design specifications are essential to achieving the desired pavement strength and durability. Even with high-quality materials, deficiencies in workmanship can result in air voids, weak bonding, and premature distress [20].

4.1.5. MAINTENANCE AND REHABILITATION (M&R) PRACTICES

Maintenance plays a crucial role in influencing pavement conditions by either preventing deterioration or slowing down the rate at which it occurs over time. The success of maintenance efforts is frequently illustrated as an enhancement in pavement condition, which can be assessed by observing alterations in the slope of the pavement condition curve depicted in Fig. 4.

The change in the level of pavement condition before and after the implementation of maintenance strategies can indicate the effectiveness of the maintenance performed [22]. In some cases, the frequency of maintenance applied can be linked to the extension of the pavement's service life.

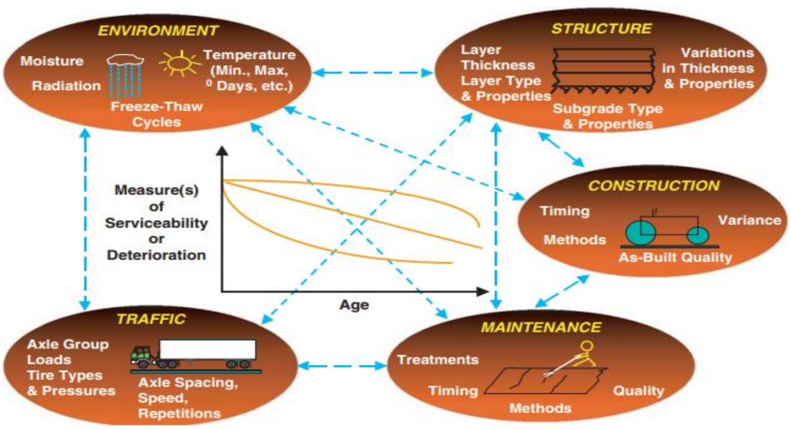

Fig. 3. Factors affecting pavement performance [14].

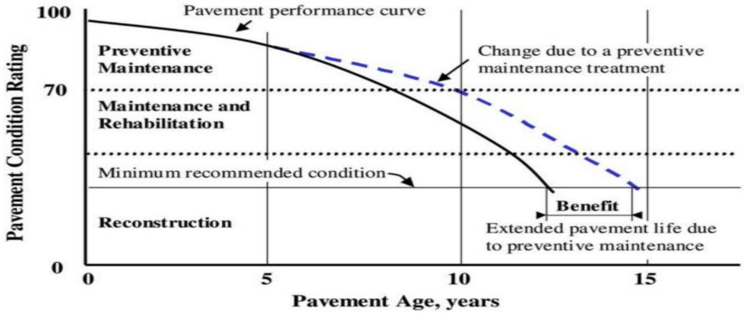

Fig. 4. Expected effects of maintenance strategies on pavement conditions [22].

4.2. TYPES OF PAVEMENT CONDITION DATA

The available data supporting pavement management decisions strongly influence its quality. The key types of pavement condition data typically collected include [10],[13]:

- Distress – Visible surface conditions observed during pavement condition surveys.
- Structural Capacity – Evaluations of how pavement responds to applied loads, subsurface conditions that may cause structural issues, and indirect assessments of strength or stiffness properties.
- Surface Characteristics – Measurements related to a pavement's smoothness (longitudinal profile), surface texture (for friction), and noise levels.

4.3. BASIC METHODS OF PAVEMENT CONDITION ASSESSMENT

Pavement condition information is generally gathered through two primary approaches: manual and automated. Furthermore, in the case of automated data collection, analysis is conducted using either fully automated or semi-automated techniques [13]. Another method for data collection is the empirical approach, which relies on the connections between pavement conditions and past data.

Technology for obtaining pavement condition data—whether manual, semi-automated, or fully automated—is rapidly advancing in pavement management. Innovations in ultrasonic, infrared, and laser sensors, along with high-speed computing, have considerably improved transportation agencies' ability to efficiently collect huge amounts of pavement condition data.[23]. Recently, line and area scan digital video cameras have enabled fully or semi-automated crack detection. Additionally, empirical methods have been incorporated into pavement evaluation, alongside the growing use of artificial intelligence applications in assessing pavement conditions. Below is a brief overview of the main methods used for collecting pavement condition data.

4.3.1. MANUAL INSPECTIONS: VISUAL ASSESSMENTS BY CERTIFIED RATERS

Manual inspections involve visual assessments conducted by certified raters who evaluate pavement conditions based on predefined criteria. This method is one of the oldest and most widely used approaches, relying on human expertise to identify and classify distresses such as cracks, potholes, and rutting [24].

Inspectors typically use standardized rating manuals, such as the Pavement Surface Condition Rating Manual, to assess the severity and extent of distress. Pothole readings, cracking dimensions, and rut depth measurements are commonly used to increase precision. The ASTM D6433 guideline specifies the necessary techniques and calculations for conducting pavement condition index (PCI) evaluations, which are utilized throughout manual inspections [12], [25].

Manual methods are affordable and don't need any specialist equipment. They allow inspectors to detect localized defects that automated methods may overlook, such as small cracks or surface imperfections. Furthermore, this technique provides a qualitative evaluation of pavement conditions, which may aid in making decisions.

However, its widespread adoption takes time and requires tremendous effort. Visual judgments may be inconsistent because of their subjective nature. Inspectors may sense discomfort in a variety of ways. Also, manual inspections are prone to errors by humans and might be unable to detect the full extent of pavement deterioration, particularly in large-scale networks [25].

4.3.2. EMPIRICAL APPROACHES: STATISTICAL RELATIONSHIPS BASED ON HISTORICAL DATA

Empirical approaches utilize statistical relations derived from historical data to expect pavement conditions. These Approaches could be links between pavement defects, traffic volumes, environmental factors, and material characteristics [1].

Popular empirical approaches involve several pavement indicators like: Pavement Serviceability

Index (PSI), International Roughness Index (IRI), PCI, and other indexes. Other approaches, such as the mechanics-empirical Pavement Design Guide (MEPDG), predict pavement behavior using mechanical concepts and empirical data [25], [26].

One of the most important features of empirical approaches is that they are not expensive, and they provide a clear methodology for evaluating the condition of the pavement. It can also predict the condition of the pavement over the long term, which in turn helps determine maintenance priorities based on the extent of the expected deterioration. In addition, the mathematical models derived from them can be supported, and then modifications made to them to be more compatible with local conditions that lead to increasing its accuracy [26].

It should be considered that empirical approaches have limitations as they depend mainly on stored data that may be weakly related to each other, which can lead to not accurately reaching the extent of the correlation between components. It typically fails to prepare for changing conditions, such as climate change or new materials, and may not be appropriate for all pavement kinds. In addition, such models must be updated regularly, which might take time [26]. Table 1 shows the most common techniques of pavement empirical approaches.

4.3.3. AUTOMATED SYSTEMS: SENSOR-EQUIPPED VEHICLES AND SEMI-AUTOMATED METHODS

Automated pavement condition is a system that collects pavement surface condition information at highway speeds while also identifying and quantifying distresses/conditions using software and human experience [27]. It mainly depends on advanced technologies, such as digital cameras, sensors, drones, and AI algorithms, to conduct pavement conditions [26]. It can be installed on vehicles or drones, hence enabling the collection of data with minimum human intervention.

Vehicle-mounted sensors utilize technologies like ground-penetrating radar (GPR), which is an electromagnetic-based geophysical method using radar pulses to image the subsurface, as shown in Fig. 5. GPR is a non-destructive device used to collect and assess pavement conditions like determining pavement thickness and evaluating material boundaries in transportation assets [28]. The technique emits radar waves into the ground, which are reflected when encountering different materials based on their dielectric properties.

One of the most mechanized tools used in assessing pavement condition rating is Light Detection and Ranging (LiDAR), a remote sensing technology that uses laser light in distance measurement to generate detailed maps of road surface, as indicated in Fig. 6. Various types of LiDAR with equipment on mounted lasers are present, including the Terrestrial Laser Scanner (TLS) and the Mobile Laser Scanner (MLS) [29]. LiDAR measures the time taken by laser pulses to be reflected back after hitting an object, thereby enabling high-resolution 3D images to be constructed [30].

California Pavement Condition Index Viewer (CaPCIV) is a system designed to evaluate and visualize pavement conditions using image-based distress quantification. CaPCIV's main functions include (1) synchronizing and displaying all of the agency's raw data, (2) flexible yet simple image editing and profile filtering, and (3) producing distress identification and quantification reports [27]. Fig. 7 shows a screenshot of this application. CaPCIV generates distress maps manually using the operator's interactive input linked with a geospatial coordinate system.

To evaluate the structural condition of the pavement layer, a device like the Falling Weight Deflectometer (FWD) determines pavement deflection based on loading, which is indicative of structural capacity [7]. Back-calculation is commonly employed for interpreting deflection data, to establish modulus values for all layers of the pavement. The back calculation is typically performed using a computer program such as MODULUS®, developed by the Texas Transportation Institute, to calculate layer moduli and identify pavement section uniformity. Surface deflection, thicknesses of structural layers, material Poisson's ratio, and initial moduli estimates are among the most important parameters [31]. Table 2 classifies the most common devices used in the measurement of structural capacity based on deflection data [32]

Semi-automatic methods, through which data is collected and then analyzed using one of the applications of AI, such as deep learning (DL), and image processing, are being used to detect and classify cracks. YOLOv8, for instance, has been applied for extracting pavement crack data with high accuracy [33], [34]. Fig. 8 illustrates the automated pavement distress survey using image processing.

Computerized systems significantly increase data-gathering efficiency and reduce the subjectivity of hand inspections. The systems can cover wide areas in a short duration and produce quantitative information, which is required for formalized assessment. The systems are also integrated PMS to aid in decision-making based on information [36].

It should be noted that automated systems are very expensive and require a high level of expertise to handle. The presence of unusual phenomena such as shadows or complex defect patterns may lead to the inaccuracy of the extracted data. Automated systems require continuous calibration all the time to ensure accuracy, which requires human intervention to verify the conducted data and the accuracy of its interpretation [32].

Table 1. Various techniques of pavement empirical approaches

Techniques	Methodology	Advantages	Limitations
Deterministic models	Estimate a single dependent value (such as pavement quality) using one or more independent factors (such as pavement age, historical traffic volume, environment, and pavement construction parameters). The models are often created based on the findings of a statistical investigation.	Effective in straightforward scenarios; provide clear and specific outputs based on input conditions.	Lack of flexibility in accommodating variability; may not always accurately predict performance under changing conditions
Probabilistic models	forecasting a range of values for the dependent variable, such as the probability that a pavement would transition from one condition state to another.	Beneficial for understanding the pavement performance of different results under varying conditions. Also, it's useful for risk assessment and developing a range of possible outcomes.	More complex to develop; require extensive data, which may not always be available.
Bayesian models	Include objective and subjective data. Each of the model's variables is specified using a probability distribution.	Powerful in circumstances when data is scarce or growing over time. Ability to change predictions as new data becomes available; important in adaptive management scenarios.	Complexity in implementation and dependence on prior distributions, which may introduce bias if not chosen carefully
Subjective/expert models	Identical to deterministic models, with the exception that the relationships between independent and dependent variables are based on expert opinion rather than past data.	Valuable when quantitative data is scarce; leverage expert judgment for decision-making.	Subject to bias; less reproducible than other models; outcomes can vary significantly based on the subjective nature of expert input.
Artificial Intelligence (AI) models	Incorporates the use of historical performance records, as well as relevant information such as weather conditions, traffic, pavement age, construction data, and other structural features, to generate prediction models using machine learning (ML) algorithms. It uses real-time data from pavement sensors to monitor conditions and anticipate performance. Artificial Neural Networks (ANNs), Random Forest (RF), and Support Vector Machines (SVM) are widely used for analyzing and predicting pavement performance based on input parameters.	Utilizing AI in pavement management leads to more efficient design and maintenance practices, ultimately reducing costs. ML algorithms can analyze large datasets efficiently, identifying important factors affecting pavement performance.	The accuracy of predictions heavily relies on the availability and quality of historical and real-time data, resulting in its sensitivity to input variability. While ML methods can capture complex relationships in data, they may require significant computational resources and expertise to develop and maintain.

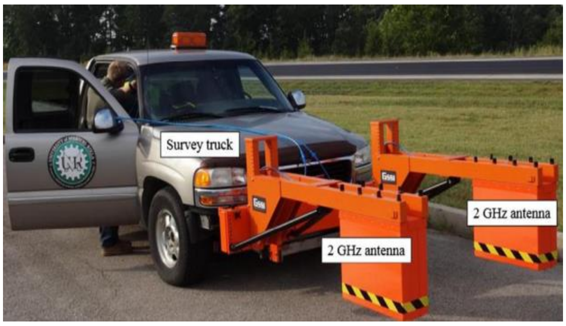

Fig. 5. GPR Mounted on a Survey Vehicle [28].

Fig. 6. LiDAR System on Moved Vehicle [30].

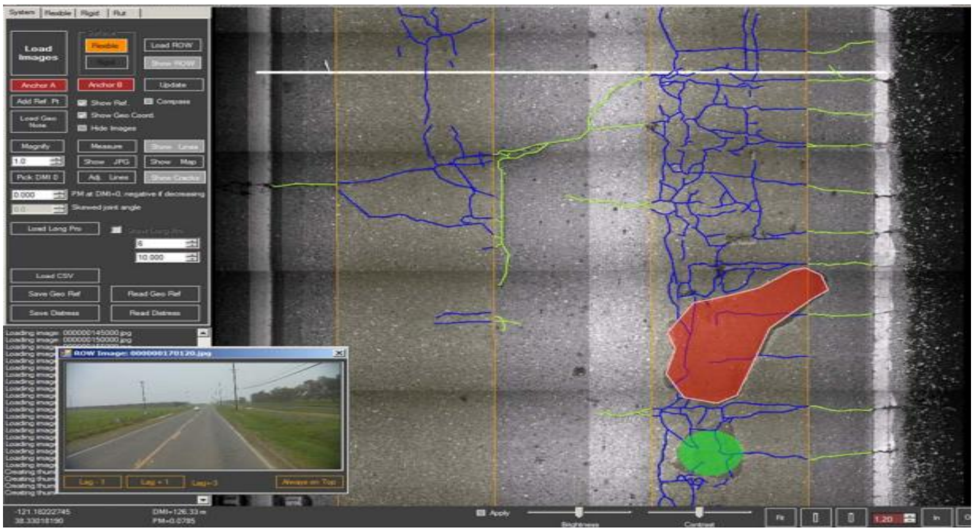

Fig. 7. Screenshot of CaPCIV system [27].

Table 2. Moving pavement deflection devices for measuring structural capacity [32].

Device	Operational Speed	Distance between Readings	Applied Load	Deflection Sensor Accuracy
Texas Rolling Dynamic Deflectometer (RDD)	1 mph	2 to 3 f	10 kips static + 5 kips dynamic	0.05 miles
Highway Rolling Weight Deflectometer (HRWD)	20 mph	9 f	9 kips	N/A
Rolling Wheel Deflectometer (RWD)	45 to 65 mph	0.5 in	18 kips	±2.75 miles
Rolling Deflection Tester (RDT)	60 mph	0.001 s	8 to 14 kips	±10 miles
Travel Speed Deflectograph (TSD)	50 mph	0.80 in.	11 kips	±4 miles

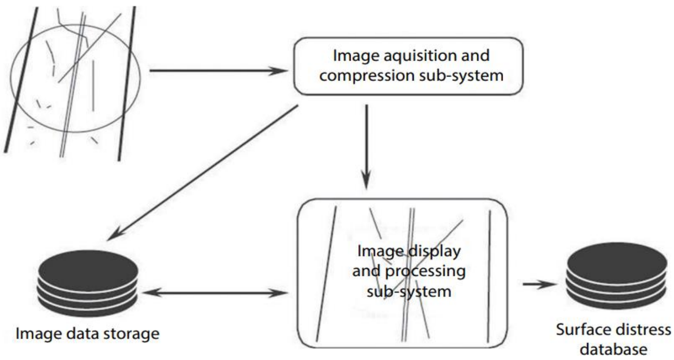

Fig. 8. Automated pavement distress survey using image processing [35].

4.3.4. INTEGRATION OF METHODS AND FUTURE DIRECTIONS IN PAVEMENT CONDITION ASSESSMENT

To avoid deficiencies of traditional methods, hybrid techniques combine manual, empirical, and automated systems [13]. Manual inspections may be used to verify data obtained by automated systems, whereas empirical approaches are used to illustrate the accuracy of measurement results. The hybrid techniques provide a comprehensive view of pavement conditions and enable making the right decision [7], [25].

Remote sensing tools, such as drones, provide new directions for collecting vast amounts of data. Moreover, standard dataset development and hybrid models will improve the credibility and usability of pavement evaluation methods [4], [26]. The pavement assessment process is in constant development and requires a combination of manual, empirical, and automated ones. Each has its limitations as well as advantages, and their combination can optimize the overall performance of PMS. As technology continues to improve, the use of advanced equipment and techniques will be the secret to ensuring safety, longevity, and efficiency in transportation infrastructure [37]. Through use of the relative strengths of each process and avoidance of each process's weaknesses, stakeholders are able to make wise decisions that promote resource optimization and pavement network life extension. Table 3 shows the aspects of the basic methods of pavement condition assessment: Manual Inspections, Empirical Approaches, and Automated Systems. This table highlights their processes, Technologies, advantages, limitations, and Accuracy for easy comparison.

Table 3. Key aspects of pavement condition assessment: Manual Inspections, Empirical Approaches, and Automated Systems.

Aspect	Manual Inspections	Empirical Approaches	Automated Systems
Process	Inspectors visually identify and classify distresses (e.g., cracks, potholes).	Analyze relationships between distress, traffic, environment, and material properties.	Sensors (e.g., lasers, cameras) collect data; AI algorithms process and analyze it.
Tools/Technologies	Crack gauges, rut depth meters, digital cameras, ASTM D6433 standards	Pavement Serviceability-Performance Concept, IRI, MEPDG.	Laser scanners, GPR, FWD, YOLOv8, drones, and AI technologies.
Advantages	Cost-effective, qualitative insights, localized issue detection.	Systematic, cost-effective, long-term performance prediction.	High efficiency, quantitative data, large-scale coverage, reduced subjectivity.
Limitations	Requires significant manual effort, is subjective, susceptible to mistakes made by humans, and takes a considerable amount of time.	Constrained by historical information, it may fail to encompass intricate interactions and necessitates regular updates.	High initial cost, technical expertise needed, struggles with complex conditions.
Cost	Low initial cost but high labor costs over time.	Low to moderate cost for development and maintenance.	High initial investment but lower operational costs in the long term.
Accuracy	Subjective and variable depending on inspector expertise.	Limited by data quality and model assumptions.	High accuracy but may struggle with complex or environmental challenges.

5. CONCLUSION

Efficient pavement management is essential for sustaining road networks amid rising traffic and climate challenges. This study explores assessment methods, highlighting the need for standardized data collection and advanced technologies. Integrating predictive modeling can enhance cost-effective and sustainable maintenance strategies. The following points summarize the key findings of the study:

- Pavement Management Systems (PMS) plays a crucial role in enhancing road network performance by assessing pavement conditions and planning effective maintenance strategies.

- With increasing traffic loads and climate variability, maintaining road infrastructure has become more challenging, necessitating the adoption of advanced assessment techniques.
- This study focuses on pavement management systems, emphasizing different pavement condition assessment methods, including manual inspections, empirical approaches, and automated systems.
- Despite advancements in pavement evaluation technologies, several challenges persist, including inconsistencies in assessment methodologies, lack of integration with modern technologies, budget constraints, and the absence of predictive maintenance strategies.
- Further studies are required for the development and implementation of standardized methods for data collection and interpretation at the network level.
- This study is expected to improve pavement management and maintenance by integrating advanced assessment technologies, predictive modeling, and data-driven decision-making strategies.
- Transportation agencies, engineers, and policymakers should implement more efficient, cost-effective, and sustainable pavement maintenance practices using the integration between pavement condition assessment methods.

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