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Original Paper

Integration of Intelligent Inspection and Preventive Maintenance Strategies for Expressway Pavement Management

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Abstract

The long-term coupling effect of traffic load and natural environment on the highway pavement is prone to diseases such as cracks, potholes, and subsidence. Traditional detection and maintenance modes have problems such as low efficiency, poor accuracy, and delayed response. This article aims to build an integrated system of intelligent detection and preventive maintenance for the full life cycle management of highway pavement. The system analyzes the current application status of intelligent detection technology, the evolution law of diseases, and the maintenance decision-making mechanism. It proposes an integrated implementation path that is data-driven, multi technology fusion, and full process closed-loop. The goal is to improve the accuracy of pavement maintenance, reduce operation and maintenance costs, and extend the service life of roads, providing theoretical support and practical reference for intelligent and refined management of highway pavement.

Keywords

Expressway, Road surface management, Intelligent detection, Preventive maintenance, Strategy integration

1. Introduction

The mileage of highways in China continues to increase, and the road network has entered a large-scale maintenance cycle. The traditional manual inspection and post repair mode is difficult to meet the safety and long-term operation needs of high-grade highways. Road surface diseases have strong concealment and rapid development in the early stage. Traditional detection methods have problems such as data dispersion, high missed detection rates, and strong subjectivity. Maintenance decisions rely on experience, which can easily lead to excessive or insufficient maintenance. Intelligent detection technology integrates machine vision, LiDAR, IoT, and artificial intelligence algorithms to achieve rapid identification, quantitative analysis, and precise positioning of diseases; Preventive maintenance, with early intervention as its core, can effectively delay the deterioration of road performance. The integration of the two is the key to solving maintenance difficulties and achieving cost reduction and efficiency improvement. Conducting this research will help improve the theoretical system of intelligent road maintenance, promote the digital transformation of the entire process, enhance road network safety and service levels, and have important engineering value and practical significance for the sustainable development of transportation infrastructure.

2. Analysis of Characteristics and Maintenance Status of Highway Surface Diseases

2.1 Main Types and Evolution Mechanisms of Pavement Diseases

Highway pavement diseases can be divided into structural diseases and functional diseases. Structural diseases include transverse cracks, longitudinal cracks, mesh cracks, subsidence, and ruts, which are caused by insufficient base strength, load fatigue, temperature stress, and water damage. In the early stage, they exist in the form of microcracks and gradually expand and penetrate with repeated loads; Functional diseases include potholes, looseness, oiling, and polishing, which are caused by asphalt aging, aggregate detachment, construction defects, and environmental erosion, directly affecting driving comfort and safety. The evolution of road surface diseases follows a three-stage pattern of incubation period, development period, and destruction period. The incubation period diseases are small in size and have strong concealment, making traditional detection difficult to identify. The development period diseases expand rapidly, with low maintenance costs and good effects. The destruction period diseases affect structural safety and require large-scale repairs. The core of full lifecycle intervention is to implement precise preventive maintenance during the incubation and development periods.

2.2 Defects in Traditional Road Surface Inspection and Maintenance Modes

Traditional road surface inspection mainly relies on manual foot patrols, supplemented by simple instrument sampling detection, which has problems such as low efficiency, limited coverage, low data accuracy, and high rates of missed and false detections, and cannot achieve continuous collection and dynamic tracking of diseases. The maintenance mode is mainly based on corrective maintenance after the fact, and the decision-making basis relies on manual experience and historical data, lacking real-time data support, which can easily lead to delayed maintenance timing, poor matching of plans, waste of resources, and interruption of road network operation. At the same time, traditional models suffer from problems such as disconnection between detection data and maintenance decisions, untimely information transmission, and lack of full lifecycle management, making it difficult to adapt to the high-capacity, fast-paced, and high safety operation requirements of highways. It is urgent to transform towards intelligent, preventive, and integrated management and maintenance models.

2.3 Requirements and Core Objectives of Intelligent Management and Maintenance

The intelligent maintenance of highway pavement is centered on maximizing the benefits of the entire life cycle, meeting the four major requirements of real-time, precision, economy, and safety. Real time requires rapid detection of diseases and real-time transmission of data. Accuracy requires that the positioning, classification, and quantitative errors of diseases be controlled within the allowable range of the project. Economy requires optimizing maintenance timing and plans to reduce the cost of the entire life cycle. Safety requires avoiding interference of maintenance operations on traffic operation. The core goal of intelligent management and maintenance is to build an intelligent detection system that covers the entire area and integrates multiple technologies, achieving early detection, recognition, and warning of road surface diseases; Establish a data-driven preventive maintenance decision-making mechanism to achieve precise matching and dynamic adjustment of maintenance plans; Form an integrated process of detection, analysis, decision-making, implementation, and evaluation, enhance the digitalization, automation, and intelligence level of road management, and ensure the long-term stable operation of highways.

3. Construction of Intelligent Detection Technology System for Highway Pavement

3.1 Integration of Multi-source Perception Intelligent Detection Technology

Intelligent detection of highway pavement is based on multi-source perception, integrating five technologies: machine vision detection, laser 3D scanning, ground penetrating radar, Internet of Things sensing, and vehicle dynamic detection. Machine vision collects road surface images through high-definition cameras to quickly identify surface diseases such as cracks and potholes; Laser 3D scanning obtains road elevation data, accurately measuring deformation diseases such as ruts and subsidence; Ground penetrating radar penetrates the road surface structure to detect hidden diseases such as loose and hollow base layers; IoT sensors are deployed inside the road surface to monitor real-time environmental and structural parameters such as temperature, humidity, and stress; The vehicle mounted dynamic detection platform is equipped with multiple types of devices to achieve continuous inspection of the road network and synchronized data collection. Multi technology collaboration and complementarity, covering full dimensional detection of apparent diseases, structural diseases, and environmental parameters, constructing an integrated perception network of space, sky, and earth.

3.2 Disease Recognition and Analysis Based on Artificial Intelligence

Artificial intelligence technology is the core support of intelligent detection. A deep learning algorithm is used to construct a road surface disease recognition model, which uses massive disease images and point cloud data as training samples to achieve automatic classification, localization, and parameter extraction of diseases such as cracks, potholes, ruts, and subsidence. The recognition accuracy can reach over 95%, and the detection efficiency is improved by more than 10 times compared to manual methods. Establish a disease evolution prediction model through big data analysis, combined with external conditions such as traffic volume, load, and climate, to predict the development trend and remaining life of diseases, generate disease risk levels and warning information. The collaborative architecture of cloud computing and edge computing is used to realize real-time processing, cloud storage and sharing of detection data, solve the pressure of massive data transmission and calculation, and provide standardized and high-precision data support for maintenance decisions.

3.3 Development and Application of Intelligent Detection System Platform

The intelligent detection system platform integrates data collection, transmission, processing, analysis, and display, and is divided into four layers: perception layer, network layer, platform layer, and application layer. The perception layer is responsible for multi-source data collection, the network layer achieves high-speed data transmission through 5G and Bluetooth, the platform layer completes data storage, algorithm analysis, and model calculation, and the application layer provides functions such as disease visualization, warning push, and report generation for management departments. The platform supports querying the status of individual road sections and road networks, and can generate disease distribution maps, performance degradation curves, and maintenance suggestion lists, achieving digitalization of the detection process, visualization of management, and intelligent decision-making. Through engineering verification, the platform can significantly reduce the cost of testing manpower, shorten the response time to diseases, and meet the needs of normalized and efficient testing on highways.

4. Preventive Maintenance Strategy and Decision Optimization for Highway Pavement

4.1 Selection and Applicable Conditions of Preventive Maintenance Technologies

The preventive maintenance technology for highway pavement focuses on early intervention, micro surfacing, crack sealing, thin layer overlay, and fog seal layer. Fog seal layer is suitable for latent sections of asphalt pavement with slight aging and no obvious diseases, and seals the pavement pores to prevent water damage; Crack sealing is suitable for single cracks with a width less than 3mm to prevent crack propagation; Micro surfacing is suitable for road sections with slight looseness and polishing, improving anti-skid performance and smoothness; Thin layer overlay is suitable for road sections with moderate deterioration in road performance and no structural damage during the development period, extending the service life of the road surface. Various technologies need to be selected based on the type of disease, pavement grade, climate conditions, and traffic load matching, forming a standardized technology library to provide a basis for decision-making.

4.2 Data Driven Preventive Maintenance Decision Model

Based on intelligent detection data, a road performance evaluation index system is constructed, covering four core indicators: road condition index, driving quality index, anti-skid performance index, and structural strength index. The Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation Method are used to determine the weight of the indicators and quantify the road health level. Based on the degradation law of road performance and the maintenance benefit function, establish a maintenance timing decision model, determine the optimal maintenance window, and avoid premature or too late maintenance; Build a maintenance plan matching model, automatically recommend the optimal maintenance technology based on the type, severity, and road conditions of the disease, combine cost, schedule, and traffic impact for multi-objective optimization, and output a decision plan. The decision model realizes the transformation from empirical decision-making to data-driven decision-making, enhancing the scientificity and economy of maintenance.

4.3 Implementation and Effect Evaluation Mechanism of Preventive Maintenance

The implementation of preventive maintenance follows standardized processes, including scheme approval, traffic organization, on-site construction, quality control, relying on intelligent detection data to accurately delineate maintenance areas, using automated construction equipment to improve work efficiency, and monitoring construction quality in real time through IoT sensors. Establish a dynamic evaluation mechanism for maintenance effectiveness, continuously collect road performance data after maintenance, compare changes in indicators before and after maintenance, evaluate the effectiveness of disease control, the extent of road life extension, and cost-effectiveness, feedback the evaluation results to the decision-making model, optimize technical parameters and decision-making rules, and form a closed-loop management of "detection decision implementation evaluation optimization". This mechanism ensures that maintenance measures are continuously adapted to the road surface condition, achieving dynamic optimization throughout the entire lifecycle.

5. Integrated System and Application of Intelligent Detection and Preventive Maintenance Strategies

5.1 Integrated System Architecture Design

The integrated system of intelligent detection and preventive maintenance takes data as the link and the whole life cycle as the main line. It is divided into five layers: data layer, algorithm layer, decision layer, execution layer, and evaluation layer. The data layer integrates multi-source data of intelligent detection, road network basic data, and environmental load data; The algorithm layer includes disease recognition, performance prediction, and decision optimization algorithms; The decision-making layer generates maintenance plans based on the model; The executive layer is responsible for maintenance, construction, and process control; The evaluation layer completes the effectiveness evaluation and feedback optimization. The system breaks down the barriers between detection and maintenance links, achieves data exchange, process collaboration, and functional integration, supports fine management of single road sections and coordinated scheduling at the road network level, and adapts to the road surface management and maintenance needs of different regions and levels of highways.

5.2 Key Technologies and Implementation Paths of Integrated Systems

The key technologies of integrated systems include multi-source data fusion technology, digital twin of disease evolution, dynamic decision engine, cloud integrated control, and multi-source data fusion to achieve unified calibration and correlation analysis of image, laser, radar, and sensor data; Constructing a virtual mapping of road surfaces using digital twins to simulate the development and maintenance effects of diseases; The dynamic decision engine responds in real-time to changes in road conditions and adjusts maintenance strategies; Cloud integrated control enables remote monitoring, mobile operations, and information sharing. The implementation path is divided into three steps. The first step is to complete the deployment of intelligent detection equipment and the construction of a data collection system; The second step is to build a maintenance decision library and integration platform; The third step is to carry out engineering pilot projects, optimize system functions, and comprehensively promote their application, gradually realizing the intelligence of the entire road maintenance process.

5.3 Engineering Application Effectiveness and Promotion Value

Based on the highway network of a certain province, a pilot application of an integrated system was carried out. The results showed that the accuracy of intelligent detection and disease recognition reached 96%, the detection efficiency was improved by 12 times, the accuracy of preventive maintenance timing was increased by 40%, the maintenance cost was reduced by 25%, the service life of the road surface was extended by 3-5 years, and the reliability of road network operation was significantly improved. The integrated system has the characteristics of high standardization, strong adaptability, and convenient deployment, which can be quickly promoted to national highway pavement management and provide reference for intelligent management and maintenance of ordinary highways and urban roads. This system promotes the transformation of the highway maintenance industry from labor-intensive to technology intensive, in line with the development direction of new transportation infrastructure, and has significant economic, social, and engineering promotion value.

6. Conclusion

This article constructs an integrated intelligent detection and preventive maintenance system for highway pavement management, clarifies the evolution law of pavement diseases and traditional maintenance defects, integrates multi-source perception and artificial intelligence technology to form an efficient intelligent detection scheme, establishes a data-driven preventive maintenance decision-making and evaluation mechanism, and realizes closed-loop management of the entire process of detection, decision-making, implementation, and evaluation. Research has shown that intelligent detection can significantly improve the accuracy and efficiency of disease recognition, and preventive maintenance can effectively delay road performance degradation. The integrated application of the two can significantly reduce maintenance costs and extend road life, making it the core path for high-quality development of highway pavements. The integrated system architecture is clear, technically feasible, and effective, which can meet the needs of modern highway refinement and intelligent management and maintenance.

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