

Original Paper

Transition from Reactive to Proactive Maintenance: A Data-Driven Approach for Expressway Asset Management

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Received: March 26, 2026

Accepted: April 23, 2026

Online Published: May 13, 2026

doi:10.22158/asir.v10n2p8

URL: <http://dx.doi.org/10.22158/asir.v10n2p8>

Abstract

China's highways have fully entered a new stage of maintenance management. The traditional passive maintenance mode, which focuses on post repair and experience decision-making, has problems such as high cost, slow response, and rapid road condition degradation, making it difficult to meet the long-term operational needs of the road network. Promoting the transformation of highway asset management from passive maintenance to active maintenance has become an inevitable trend for the high-quality development of the industry. This article refers to the standardized academic paper architecture, systematically elaborates on the core differences between passive maintenance and active maintenance, constructs a data-driven framework with full lifecycle data as the core, multi-source perception as the support, and intelligent decision-making as the engine, studies the key implementation paths of data collection, fusion analysis, dynamic prediction, active decision-making, and closed-loop control, proposes a technology system and guarantee measures for transformation and implementation, aiming to provide theoretical and practical support for improving the quality and efficiency of highway asset management, extending facility life, and reducing full cycle costs.

Keywords

Expressway, Asset management, Passive maintenance, Proactive maintenance, Data driven, Intelligent decision-making

1. Introduction

1.1 Research Background and Significance

With China's expressway mileage ranking first in the world, the overall road network has entered a period of aging and high incidence of diseases. The traditional passive maintenance mode that relies on manual inspection, post fault maintenance, and experiential arrangements has prominent shortcomings such as

lagging disease detection, untimely disposal, unreasonable resource allocation, and high long-term investment, which seriously do not meet the goals of safe, efficient, green, and economical road network operation. Active maintenance, with early identification of diseases, life prediction, proactive intervention, and dynamic optimization as its core, can significantly improve road conditions, reduce comprehensive costs, and extend road service life. Data driven technology integrates multi-dimensional information such as road conditions, loads, environment, and historical maintenance to provide accurate basis for active maintenance, which is the core support for realizing the transformation of asset management mode. Conducting this research will help improve the theoretical system of active maintenance of highways, promote the industry's transformation from "repairing damaged roads" to "maintaining good roads", and have important engineering value and practical significance for enhancing the modernization of transportation infrastructure governance capabilities.

1.2 Review of Domestic and Foreign Research

Developed countries abroad have established highway asset management systems earlier and generally adopt data-driven and full lifecycle concepts. They have developed mature tools and standards in road performance prediction models, maintenance decision optimization, and road network level resource allocation, with high coverage of active maintenance and outstanding scientific decision-making levels. In recent years, a large amount of research has been conducted in China on intelligent detection, big data analysis, and maintenance decision models, and significant progress has been made in data collection equipment, disease recognition algorithms, and other aspects. However, there are still problems such as prominent data silos, insufficient fusion of multi-source information, limited prediction accuracy, disconnection between decision-making and implementation, and incomplete active maintenance mechanisms. Most road sections are still mainly maintained passively. Existing research often focuses on a single technology or local link, lacking a systematic data-driven framework and implementation path for the transition from passive to active. This article takes this as a starting point to construct an integrated system, filling the current research gap.

2. Current Situation and Transformation Needs of Highway Maintenance Mode

2.1 Characteristics and Practical Shortcomings of Passive Maintenance

Passive maintenance is mainly characterized by emergency response after the occurrence of diseases, periodic routine maintenance, and experience judgment. The management process presents a lag response of "failure occurrence manual inspection reporting approval organization repair", and the decision-making basis is mainly based on historical experience and simple statistics, lacking quantitative analysis of disease evolution, road condition trends, and long-term benefits. There are obvious shortcomings in this model: failure to detect diseases in a timely manner can lead to minor illnesses and major illnesses, resulting in doubled repair costs; The maintenance plan has a low degree of matching with the actual road conditions, which is prone to excessive or insufficient maintenance; Data fragmentation and lack of unified standards make it difficult to support scientific decision-making; Frequent emergency repairs

disrupt traffic operations, making it difficult to maintain stable service levels and safety in the road network. In the new situation of expanding road network scale, increasing load, and complex environment, it is difficult to continue.

2.2 Connotation and Core Advantages of Proactive Maintenance

Active maintenance focuses on prevention, precise intervention, dynamic optimization, and optimal life cycle, emphasizing the implementation of preventive measures when diseases have not yet occurred or are in the early stages. By predicting the trend of road condition deterioration through data, the optimal maintenance timing and technical solution are scientifically determined, achieving a transformation from "passive response" to "active prediction", from "experience decision-making" to "data decision-making", and from "single point maintenance" to "road network coordination". Its core advantages are reflected in significantly reducing the frequency of major and medium repairs and the total lifecycle cost; Maintain stable road conditions and improve driving safety and comfort; Optimize the allocation of human, mechanical, and material resources to improve management efficiency; Extending the service life of road surfaces and structures and enhancing the sustainable operation capability of road networks are advanced maintenance models that meet the requirements of high-quality development.

2.3 Key Bottlenecks in the Transition from Passive to Active

The transformation of highway maintenance from passive to active faces three core bottlenecks: firstly, weak data foundation, incomplete, non-standard, and untimely traditional maintenance data collection, lack of data interoperability among multiple departments, and difficulty in forming a unified data base; Secondly, the decision-making ability is insufficient, lacking high-precision road condition prediction models and multi-objective maintenance decision-making algorithms, making it impossible to achieve active prediction and optimal solution selection; Thirdly, there is a mismatch in management mechanisms, with organizational processes, assessment systems, and personnel skills still designed around passive maintenance, making it difficult to support data-driven, dynamic closed-loop active maintenance operations. To overcome the above bottlenecks, it is necessary to take data as the main line, technology as the support, and mechanisms as the guarantee, and build a systematic data-driven methodology system.

3. Overall Architecture of Data-driven Active Maintenance System

3.1 Core Logic and Operating Mechanism Driven by Data

Data driven active maintenance takes the full life cycle data of highway facilities as the core production factor, follows the closed-loop operation logic of "data perception data governance intelligent analysis scientific decision-making precise execution effect evaluation", and establishes a standardized data platform through real-time collection of multi-dimensional data such as road conditions, traffic, environment, structure, and maintenance. It uses technologies such as artificial intelligence, big data, and digital twins to explore the evolution laws of diseases and road condition attenuation trends, output decision-making instructions such as active maintenance timing, road sections, plans, and resource allocation, guide precise implementation on site, continuously monitor maintenance effects, optimize

model parameters in reverse, and achieve continuous iteration and upgrading of maintenance management, so that decision-making shifts from experience dependence to data dependence, and from static lag to dynamic lead.

3.2 Active Maintenance Data System and Standard Specifications

The active maintenance data system covers four categories: basic data, monitoring data, business data, and external data. Basic data includes road parameters, structural parameters, and construction archives; Monitoring data includes road surface diseases, structural stress, traffic volume, temperature and humidity, settlement, etc; Business data includes historical maintenance, construction technology, costs, and assessment and evaluation; External data includes meteorological, geological, and policy standards. The construction of a data system requires unified collection frequency, format, accuracy, storage, and interface standards, establishing rules for data cleaning, verification, deduplication, and fusion, forming high-quality data assets, providing reliable support for predictive analysis and intelligent decision-making, and solving the problems of data fragmentation and unavailability.

3.3 Five Layer Integrated Overall Architecture Design

The data-driven active maintenance system adopts a five layer integrated architecture: the perception layer achieves global data collection through vehicle detection, fixed sensing, drones, manual inspections, etc; Building a data platform in the data layer to achieve multi-source data aggregation, governance, storage, and sharing; Algorithm layer integrates performance prediction, disease identification, decision optimization, and benefit evaluation models; Develop road condition monitoring, maintenance planning, resource scheduling, effectiveness evaluation, and emergency command functions for management needs at the application layer; The execution layer interfaces with on-site maintenance operations, quality control, and traffic organization to achieve decision-making implementation. The five layer architecture is vertically interconnected and horizontally coordinated, forming an integrated management system that is data-driven, proactive prediction, and closed-loop control.

4. Key Technology Methods for Data-driven Active Maintenance

4.1 Multi Source Data Fusion and High-quality Governance Technology

Multi source data fusion adopts spatiotemporal alignment, feature correlation, and heterogeneous data unified representation methods to integrate image, laser, radar, sensing, manual recording and other data into standardized information, eliminating conflicts and redundancies. Data governance includes data cleaning, outlier removal, missing value filling, data annotation and quality assessment, establishing data lineage tracking and permission management mechanisms to ensure the authenticity, accuracy, completeness, and usability of data. Through the collaboration of edge computing and cloud computing, real-time data processing and efficient storage are realized, providing high-quality data bases for subsequent analysis and decision-making.

4.2 Road Condition Performance Prediction and Early Warning Model for Diseases

Road condition performance prediction is based on long-term monitoring data, and a hybrid prediction

model based on machine learning and mathematical statistics is constructed. By integrating factors such as traffic load, climate environment, service life, and historical maintenance, the model accurately predicts the trend of changes in road condition index, driving quality index, structural strength index, and other indicators, and predicts the road condition level in the next 1-5 years. Early warning of diseases focuses on hidden early diseases such as micro cracks, slight looseness, and voids. Through methods such as abnormal feature recognition, trend comparison, and threshold warning, warnings are issued before the disease expands, and key maintenance sections are identified to provide precise targets for active intervention.

4.3 Active Maintenance Decision Optimization and Dynamic Configuration Method

Proactive maintenance decision-making aims to minimize the cost of the entire lifecycle, improve road conditions, and minimize traffic impact. A maintenance timing decision, scheme selection, and resource allocation optimization model is established to automatically match preventive maintenance techniques such as fog sealing layer, micro surface area, crack sealing, and thin layer covering based on disease type, severity, road section level, and climate conditions. The optimal maintenance time and scope of operation are determined. By dynamically scheduling personnel, equipment, and materials based on the maintenance needs of the road network, a refined maintenance plan and construction organization scheme are generated to achieve the transformation from "passive dispatching" to "active scheduling" and improve the overall efficiency of maintenance.

5. Transformation Implementation Path and Guarantee Measures

5.1 Implement the Transformation Path in Stages

The implementation of transformation is divided into three stages: the first stage is the infrastructure construction period, which completes the deployment of data collection equipment, the formulation of data standards, and the construction of data middleware, achieving data collection, accessibility, and usability; The second stage is the capability enhancement period, during which predictive models and decision-making systems will be launched, pilot road sections will be actively maintained, and the effectiveness of data-driven processes will be verified; The third stage is the comprehensive promotion period, which aims to improve the system functions and management mechanisms, comprehensively promote active maintenance within the road network, and achieve the overall transformation of asset management mode. Staged promotion can reduce risks, achieve quick results, and ensure smooth implementation of transformation.

5.2 Technical Equipment and Platform Construction Support

Technical equipment support focuses on automated and intelligent detection equipment, promoting vehicle mounted rapid detection, unmanned aerial vehicle inspection, and IoT sensing monitoring to improve data collection efficiency and accuracy. The platform construction guarantee focuses on the development of an integrated active maintenance management platform, integrating monitoring, analysis, decision-making, execution, and evaluation functions, achieving collaboration between PC and mobile

terminals, supporting road network visualization, automatic report generation, and real-time warning push. Strengthen system integration and interface standardization, break down departmental barriers, and achieve comprehensive integration of data and business.

5.3 Management Mechanism and Talent Team Guarantee

The management mechanism needs to establish a maintenance management system, assessment indicators, and standardized processes that match proactive maintenance. The road condition maintenance rate, timely maintenance rate, cost-effectiveness, and proportion of preventive maintenance should be included in the assessment to guide the shift of management focus towards proactive prevention. The talent team is guaranteed through professional training, technology introduction, and school enterprise cooperation to cultivate composite talents with maintenance business, data technology, and management capabilities, enhance frontline personnel's data application and intelligent system operation skills, and provide continuous human resources support for transformation.

6. Conclusion

This article systematically studies the data-driven approach of highway asset management from passive maintenance to active maintenance, clarifies the shortcomings of passive maintenance and the advantages of active maintenance, proposes the core logic and five layer integrated architecture of data-driven transformation, and forms a complete system of multi-source data governance, performance prediction and early warning, active decision optimization, phased implementation, and dual guarantee of technology and management. Research has shown that data-driven approaches are a key support for transforming maintenance models, effectively enhancing disease identification and warning capabilities, optimizing maintenance decisions, reducing lifecycle costs, and stabilizing road network service levels. The constructed system architecture is scientific, technically feasible, and has a clear path, which can directly guide engineering practice.

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