# EXPLORATION OF INTELLIGENT TECHNOLOGIES FOR SMART EXPRESSWAY ELECTROMECHANICAL SYSTEMS

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**Abstract:** *With the rapid development of intelligent transportation systems, smart expressways demand higher reliability, integration, and intelligence of electromechanical (EM) systems. However, existing EM systems often suffer from fragmented architectures, limited data utilization, and low intelligence in operation and maintenance (O&M). To address these issues, this paper proposes a methodology-oriented framework for the intelligent upgrading of smart expressway EM systems. The framework integrates condition-based monitoring, a layered intelligent management platform, and a data-driven O&M mechanism. Multi-source operational data are utilized to enable real-time equipment monitoring, fault prediction, and predictive maintenance. A centralized data architecture and QR code‑based field operations are introduced to enhance data traceability and maintenance efficiency. The proposed approach improves system reliability, maintainability, and operational efficiency, providing a scalable solution for smart expressway EM systems*.

**Keywords**:*Smart Expressway, Electromechanical Systems, Condition-Based Monitoring, Intelligent Operation and Maintenance.*

# ISTRAŽIVANJE INTELIGENTNIH TEHNOLOGIJA ZA ELEKTROMEHANIČKE SISTEME PAMETNIH AUTOPUTEVA

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**Rezime:** *Uz brzi razvoj inteligentnih transportnih sistema, pametni autoputevi zahtevaju veću pouzdanost, integraciju i inteligentnost elektromehaničkih (EM) sistema. Međutim, postojeći EM sistemi često imaju problema sa fragmentiranim arhitekturama, ograničenim korišćenjem podataka i niskom inteligentnošću u eksploataciji i održavanju (E&O). Da bi se re šili ovi problemi, u ovom radu se predlaže metodološki orijentisan okvir za inteligentno unapređenje EM sistema pametnih autoputeva. Okvir integriše monitoring na osnovu stanja, slojevitu inteligentnu platformu za upravljanje i mehanizam eksploatacije i održavanja vođen podacima. Koriste se višezvorni podaci o radu kako bi se omogućilo prać enje opreme u realnom vremenu, predviđanje kvarova i prediktivno održavanje. Uvedena je centralizovana arhitektura podataka i terenska radnja na osnovu QR kodova kako bi se poboljšala praćenost podataka i efikasnost održavanja. Predloženi pristup poboljšava pouzdanost sistema, održivost i efikasnost rada, nudeći skalabilno rešenje za EM sisteme pametnih autoputeva.*

**Ključne reči**: *Pametni autoput, elektromehanički sistemi, praćenje stanja, inteligentno upravljanje i održavanje.*

## 1. INTRODUCTION

With the rapid advancement of intelligent transportation systems (ITS), smart expressways have become a key strategy for enhancing the safety, efficiency, and sustainability of highway infrastructure. By integrating emerging technologies such as the Internet of Things (IoT), big data analytics, cloud computing, artificial intelligence (AI), and satellite navigation, smart expressways aim to achieve comprehensive perception, real-time analysis, and intelligent decision-making across transportation networks.

As the physical and technical backbone of expressway operations, electromechanical (EM) systems – including traffic monitoring, toll collection, communication, power supply and distribution, and control subsystems – play a decisive role in smart expressway performance. However, despite continuous technological upgrades, existing EM systems in many expressway networks still suffer from fragmented architectures, insufficient data utilization, and limited intelligence in operation and maintenance (O&M). These limitations restrict the full realization of smart expressway functions.

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Recent studies have explored intelligent monitoring, platform integration, and digital management of expressway EM systems; however, Nevertheless, most existing research focuses on individual technologies or isolated subsystems, lacking a systematic methodology that integrates monitoring, management, and O&M from a lifecycle perspective. In addition, the engineering applicability and scalability of proposed solutions are often insufficiently discussed.

To address these gaps, this paper proposes a methodology-oriented framework for the intelligent upgrading of smart expressway EM systems. The main contributions of this study are threefold: (1) a condition-based monitoring (CBM) methodology for continuous and proactive equipment health assessment; (2) a layered intelligent management platform architecture enabling unified data integration and coordinated operation; and (3) a data-driven intelligent O&M mechanism that bridges centralized digital management with on-site maintenance activities. These contributions aim to provide both methodological insights and practical engineering references for smart expressway development.

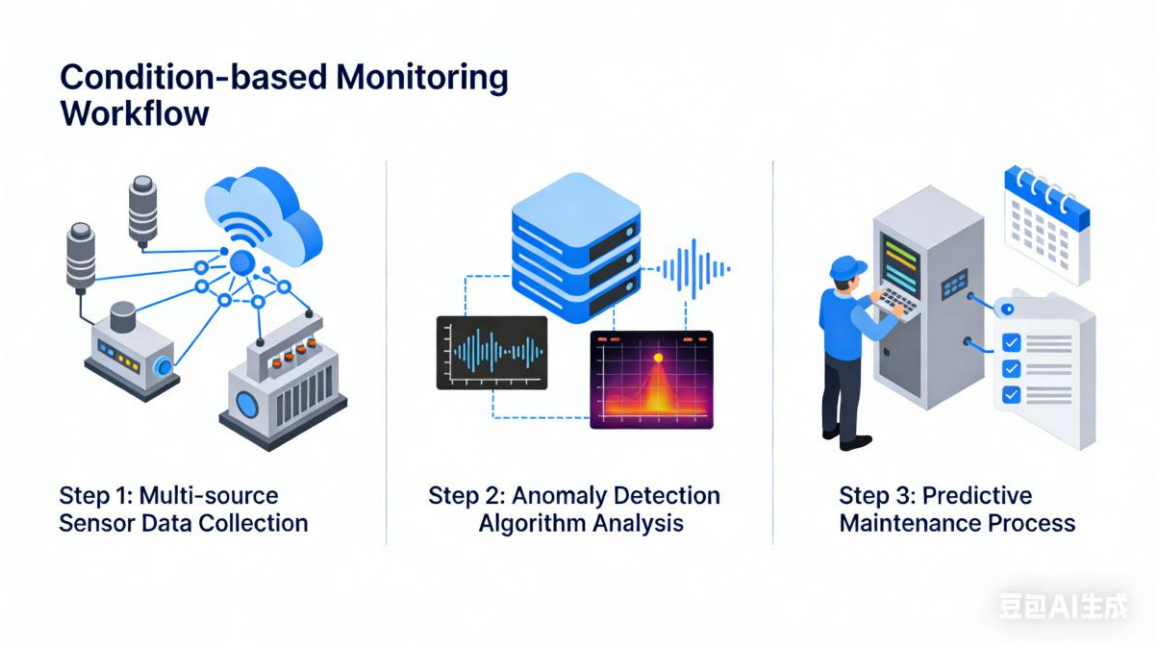


**Figure 1.** *CBM Workflow*
*Source: https://www.doubao.com*

## 2. Current Challenges in Intelligent Electromechanical Systems

### 2.1. Insufficient and Incomplete Operational Data

In smart expressway environments, intelligent EM systems rely heavily on high-quality operational data to support monitoring, diagnosis, and decision-making. However, in practice, data insufficiency and data loss remain common problems. These issues are often caused by inadequate sensor deployment, improper installation of monitoring instruments, imperfect data acquisition architectures, and unstable power or communication networks.

Insufficient data reduces the effectiveness of intelligent monitoring and increases hidden operational risks. Once a failure occurs, maintenance personnel may be unable to quickly identify fault locations or failure mechanisms, resulting in extended repair cycles and increased operation and maintenance (O&M) costs.

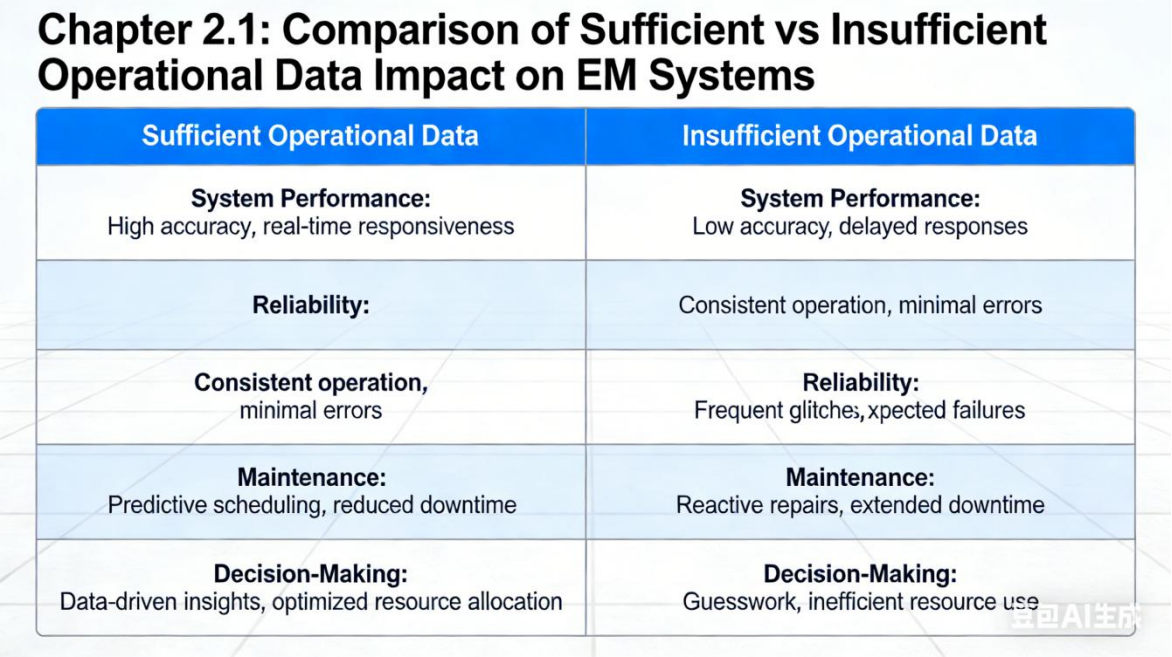


**Figure 2.** *Comparison of Sufficient vs Insufficient Operational Data Impact on EM Systems*
*Source: https://www.doubao.com*

### 2.2. Limited Automatic Monitoring and Early Warning Capability

Automatic monitoring and early warning functions are core requirements for intelligent EM systems in smart expressways. If monitoring systems lack functional completeness or real-time responsiveness, latent equipment defects cannot be identified at an early stage. This significantly undermines system reliability and increases the probability of cascading failures.
In high-traffic expressway scenarios, delayed fault detection may lead to congestion, service interruption, or even traffic accidents, posing serious threats to operational safety.


**Figure 3.** *Current Challenges of EM Systems*
*Source: https://www.doubao.com*

### 3. Methodology and Intelligent Functional Design for Smart Expressway EM Systems

To meet the requirements of SCI Q2 transportation engineering journals, this study adopts a methodology-oriented research framework that integrates system analysis, engineering practice, and intelligent technology

application. The proposed methodology focuses on enhancing system-level intelligence through data-driven monitoring, integrated management platforms, and intelligent operation and maintenance mechanisms.

### 3.1 Intelligent Automatic Detection and Condition Monitoring Methodology

This study proposes a condition-based monitoring (CBM) methodology for smart expressway electromechanical systems, By deploying multi-source sensors across key EM subsystems, real-time operational parameters – including electrical load, communication latency, equipment temperature, and functional status–can be continuously collected.
A 24/7 online monitoring mechanism is established to enable early detection of abnormal operating trends. Combined with intelligent data filtering and anomaly recognition algorithms, potential failures can be identified at an early stage, providing technical support for predictive maintenance strategies.
Methodological Contribution: Compared with traditional periodic inspection approaches, the proposed CBM-based methodology enhances monitoring continuity and fault sensitivity, effectively reducing unexpected equipment downtime.

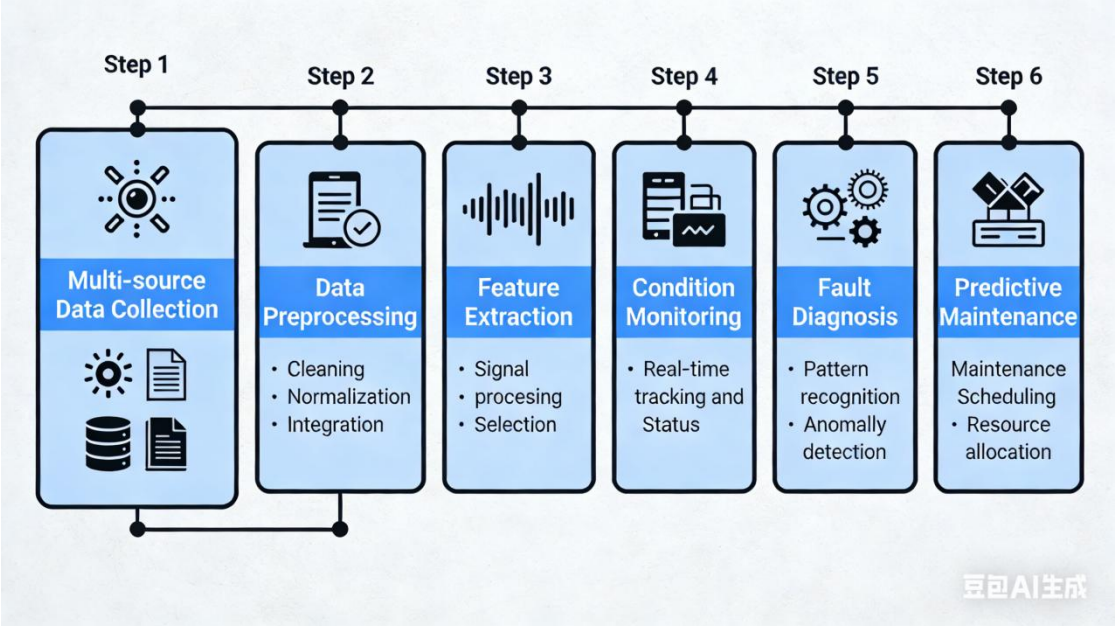


**Figure 4.** *CBM methodology*
*Source: https://www.doubao.com*

### 3.2 Integrated Intelligent Management Platform Architecture

An integrated intelligent management platform architecture is designed to address the fragmentation of traditional EM management systems. The platform adopts a layered architecture consisting of a perception layer, transmission layer, data layer, and application layer, enabling unified data integration and system-level coordination.
Through cloud-based control centers and big data analytics, the platform supports real-time visualization of equipment status, traffic conditions, and incident information. This architecture enables rapid cross-departmental coordination and improves emergency response efficiency under high-traffic conditions.
Methodological Contribution: The proposed architecture provides a scalable and extensible framework for smart expressway EM system integration, supporting future upgrades such as AI-based decision support and digital twin applications.

### 3.3 Data-Driven Intelligent O&M Mechanism Based on Databases and QR Codes

This study further proposes a data-driven intelligent operation and maintenance (O&M) mechanism. Centralized databases are constructed to store long-term historical data generated by EM systems, supporting lifecycle analysis and performance evaluation.
QR code-based equipment identification is integrated into the O&M workflow, enabling maintenance personnel to rapidly access equipment configuration, fault history, and maintenance records via mobile terminals. This mechanism significantly improves maintenance efficiency and data traceability.

Methodological Contribution: By coupling centralized databases with QR code-based field operations, the proposed O&M mechanism bridges the gap between digital management platforms and on-site maintenance activities.


**Figure 5.** *QR Code-based O&M Mechanism*
*Source: https://www.doubao.com*

**4.Enhanced Contributions and Engineering Implications**

The primary contributions of this study can be summarized as follows:
(1) A CBM-based intelligent monitoring methodology tailored to smart expressway EM systems is proposed, enhancing early fault detection and predictive maintenance capability.
(2) An integrated intelligent management platform architecture is designed to overcome system fragmentation and improve coordinated operation across EM subsystems.
(3) A data-driven intelligent O&M mechanism combining centralized databases and QR code identification is established, improving maintenance efficiency and lifecycle management.
These contributions provide practical engineering solutions for the intelligent upgrading of expressway EM systems and offer methodological references for future research in smart transportation infrastructure.

**5. Conclusion**

This study addresses key challenges in the intelligent upgrading of smart expressway electromechanical systems, including fragmented system architectures, limited data utilization, and insufficient intelligence in operation and maintenance. A methodology-oriented framework integrating condition-based monitoring, an intelligent management platform, and data-driven O&M mechanisms is proposed.
From an engineering perspective, the proposed CBM methodology enhances continuous equipment health assessment and enables early fault detection, while the layered management platform improves system integration and coordinated operation across EM subsystems. The data-driven O&M mechanism further strengthens maintenance efficiency and lifecycle management by connecting digital platforms with on-site operations.
The findings of this study indicate that intelligent upgrading of EM systems is a fundamental prerequisite for the realization of smart expressways. The proposed framework provides a scalable and extensible solution that can support future integration with advanced technologies such as AI-based decision support and digital twin systems.

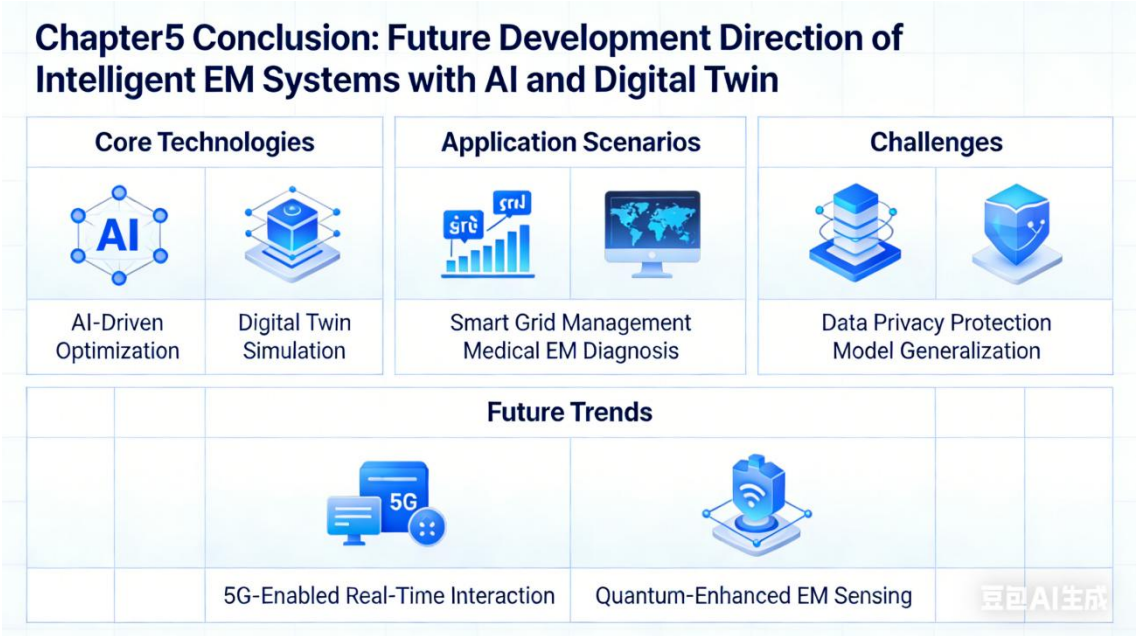


**Figure 6.** *Future Development Direction of Intelligent EM Systems with AI and Digital Twin*
*Source: https://www.doubao.com*

Future work will focus on quantitative performance evaluation, field validation, and the integration of advanced analytics to further enhance the scientific rigor and practical applicability of intelligent expressway EM systems.

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