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Research and Development Trends of Expressway Maintenance Management Technology

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Abstract: Expressway safety is a crucial prerequisite for safeguarding the life and health of drivers and passengers, with maintenance management serving as its core support. To enhance the safety and sustainability of expressway maintenance management, this paper first analyzes the fundamental components, characteristics, existing problems, and corresponding countermeasures of maintenance management. Secondly, it proposes optimization measures for the safety management of expressway maintenance construction. Finally, it predicts future development trends in maintenance operations from four perspectives: management mechanisms, digital transformation, investment mechanism optimization, and full life-cycle ecologization. This study aims to provide decision-making support and technical references for expressway operating entities and maintenance personnel.

Keywords: Expressway; Maintenance Management; Construction Safety; Status Analysis

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1. Introduction

Since the opening of mainland China's first expressway (the Shanghai–Jiading Expressway) in 1988, China's expressway construction has achieved leapfrog development [1]. With socioeconomic progress, the continuous increase in the number of vehicles has directly led to a substantial rise in expressway traffic volume [2]. Under long-term load effects, pavement structures have experienced varying degrees of damage [3], while some traffic facilities are also facing aging and deterioration, making maintenance and rehabilitation work increasingly challenging. The long-standing tendency of "prioritizing construction over maintenance" has resulted in insufficient investment in maintenance infrastructure and relatively outdated management practices [4]. In actual operation, maintenance activities not only affect traffic efficiency but also cause secondary accidents due to inadequate safety protection, threatening the safety of the public and constraining the sustainable development of the expressway network.

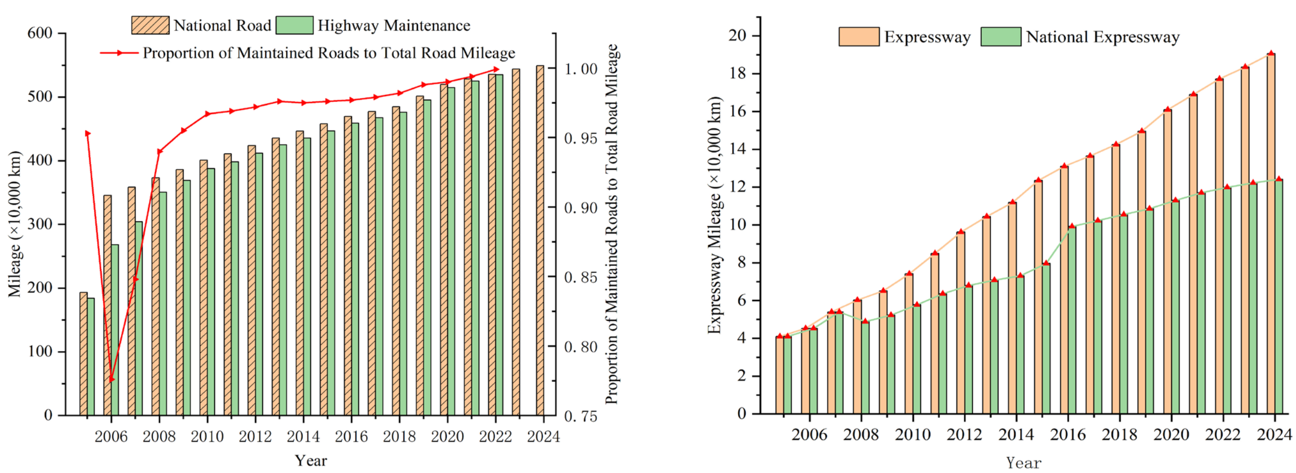
With the rapid advancement of intelligent driver assistance technologies, safety management in expressway maintenance work zones is facing new challenges. Establishing a modern maintenance construction system that is "safe, efficient, and intelligent" has become a key focus of industry development [5]. Focusing on the critical issue of safety in expressway maintenance work zones, this paper systematically reviews the current state of expressway maintenance management and construction safety, analyzes the safety hazards existing in current maintenance management, and explores future development directions, aiming to provide a reference for improving expressway maintenance management.

2. Analysis of Current Expressway Maintenance Status

By the end of 2024, the total road mileage in China reached 5,940,400 kilometers, an increase of 53,600 kilometers over the previous year. The expressway mileage stood at 190,700 kilometers, a year-on-year increase of 7,000 kilometers, of which national expressways accounted for 124,100 kilometers, an increase of 1,800 kilometers year-on-year. According to data from the Ministry of Transport (Figure 1), both total road mileage and expressway mileage in China exhibited a sustained growth trend from 2005 to 2024. Among these, the total road mileage grew most rapidly in 2006 (a year-on-year increase of 79.07%), primarily due to a statistical adjustment that included village roads in the national total road mileage for the first time. Expressway mileage reached its peak growth rate in 2016 (a year-on-year increase of 24.62%), closely related to the network densification policies during the 13th Five-Year Plan period. Although road maintenance mileage increased year by year from 2005 to 2022 (data for 2023–2024 have not yet been released), its proportion relative to total road mileage dropped sharply from 95.3% to 77.60% between 2005 and 2006. This contrast stems from a combination of statistical and policy factors: maintenance data for 2005 and earlier covered only trunk roads such as national highways, provincial highways, and county roads. However, after village roads were included in the total mileage in 2006, rural roads—constrained by issues such as funding shortages and unclear responsibility entities—maintained a consistently lower maintenance coverage rate than trunk roads, leading to a decline in the overall proportion. National expressway mileage experienced a phased decline from 2007 to 2008 (from 53,900 kilometers in 2007 to 48,900 kilometers in 2008), primarily due to the refinement of statistical classification. Data for 2007 and earlier included some provincial-level expressways. Following the implementation of the National Expressway Network Plan in 2008, a strict distinction was made between the two categories, and some routes originally classified as "national expressways" were reclassified as provincial expressways, resulting in a downward adjustment of national expressway mileage. Thereafter, with the advancement of network construction, national expressway mileage resumed its growth trend, reaching 124,100 kilometers by 2024.

Figure 1. National road and expressway mileage

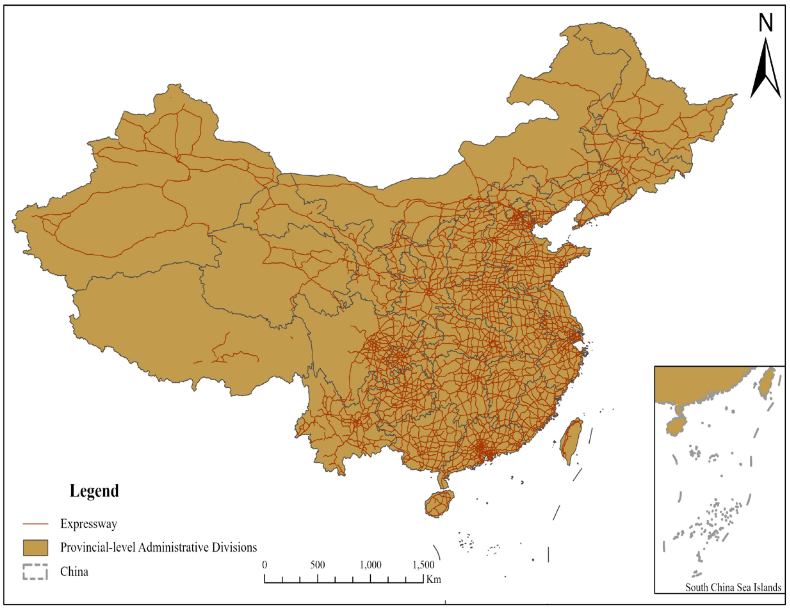
a. National Road Mileage and Maintenance Proportion *b. National Expressway Mileage*



Source: Ministry of Transport of the People's Republic of China. (https://www.mot.gov.cn/)

This study is based on 2024 expressway vector data of China from OpenStreetMap (https://openstreetmap.org) and Chinese administrative division data released by the National Catalogue of Service for Geographic Information Resources (https://www.webmap.cn/). Spatial registration and overlay analysis were conducted using the ArcGIS Pro platform. As shown in Figure 2, the spatial distribution of expressways in China exhibits significant regional imbalance: the eastern region features a dense road network with high coverage; while the western region has longer individual expressway routes (e.g., the Lianyungang–Khorgas Expressway), the number of routes and network density are considerably lower than those in the eastern region. This pattern closely aligns with China's topographic gradients and the distribution of population and economic activity [6].

Figure 2. National expressway distribution in China



With the rapid expansion of China's expressway network, the importance of maintenance management has become increasingly prominent. Compared with ordinary roads, expressways are characterized by complex road conditions, high traffic volumes, and high vehicle speeds, resulting in significantly higher rates of pavement wear and facility aging. Consequently, stricter requirements are imposed on the timeliness, technical standards, and safety of maintenance management. To systematically analyze the core challenges and practical experiences of current expressway maintenance management, this paper integrates and reviews key aspects of the maintenance management system through policy document analysis, technical specification comparison, and case studies of typical road sections [7,8].

Expressway maintenance possesses numerous characteristics. This paper provides a detailed introduction from the following aspects.

(1) Dispersion: For expressways in operation, factors such as high traffic volume, high vehicle speeds, and natural disasters result in the occurrence of pavement distress exhibiting significant randomness and spatial discreteness. This dispersion is primarily reflected in two aspects: the distribution of distress and the organization of maintenance operations. In maintenance operations, routine tasks such as median strip garbage removal, replacement of anti-glare panel reflective films, and cleaning of longitudinal drainage ditches are often not coordinated due to the dispersed timing of operations, leading to multiple lane closures. Furthermore, due to the division of professional responsibilities among different functional departments, repair work on the same road section often requires repeated lane closures as a result of uncoordinated construction schedules. This phenomenon of repeated lane closures not only leads to inefficient allocation of maintenance resources but also causes additional travel inconvenience for drivers and passengers.

(2) Service Orientation: As a leading basic industry of the national economy, expressways possess significant public welfare attributes, and their operation and management are closely related to public life. In the process of maintenance management, not only economic benefits but also social benefits must be considered. Particularly during peak traffic periods such as holidays, failure to properly coordinate the balance between maintenance operations and traffic demand may lead to severe traffic congestion and social impact. In addition, heavy rainfall during the rainy season can easily trigger slope failures and drainage ditch collapses, which not only affect the drainage function of the road but may also endanger adjacent farmland and residential facilities. Therefore, maintenance operations must strictly comply with the regulations of traffic management departments, scientifically formulate construction plans, and efficiently complete emergency repair tasks under the premise of ensuring traffic safety.

(3) High Risk: Compared with ordinary roads, expressways exhibit more complex road conditions, including not only special structures such as tunnels, river-crossing bridges, and high slopes but also higher vehicle speeds. This particularity imposes

higher requirements on maintenance operations: on the one hand, vehicles traveling through maintenance work zones constitute an uncontrollable risk source; on the other hand, various uncertain factors such as weather changes and equipment failures during construction collectively form a complex safety risk system.

(4) Complexity: The complexity of expressway maintenance management is primarily reflected in multidimensional systemic challenges. In terms of road structure, the coexistence of differentiated structures such as tunnel groups, river-crossing bridges, high slopes, and interchange hubs requires maintenance operations to simultaneously possess multidisciplinary expertise in bridge engineering, tunnel engineering, geotechnical engineering, and other fields, while different structures exhibit significant differences in maintenance cycles and technical standards. Regarding dynamic risks, the average vehicle speed of 100 km/h necessitates dynamic calculation of the buffer distance in work zones, alongside the establishment of a 15-minute rapid response mechanism for natural disasters such as heavy rainfall and landslides. Furthermore, multi-department coordination is also an important feature, requiring the integration of permit approvals from road administration departments, traffic organization from traffic police departments, and process coordination from construction units. By establishing a "multi-party coordination" joint service mechanism, traffic safety and operational efficiency in construction zones can be ensured.

Expressway maintenance work is primarily divided into two categories: "routine maintenance" and "maintenance engineering." Maintenance engineering further includes four subcategories: preventive maintenance, remedial maintenance, special maintenance, and emergency maintenance, as detailed in Table 1. Regardless of the type, maintenance is conducted to prevent and address issues related to seven key aspects: subgrade, pavement, bridges, tunnels, traffic safety facilities, electromechanical facilities, management and service facilities, as well as landscaping and environmental protection facilities.

Table 1. Classification of highway maintenance engineering operations

Expressway maintenance	**Maintenance Category**	**Description**
Routine Maintenance	——	Subgrade
		Pavement
		Bridges
		Tunnels
		Traffic Safety Facilities
		Electromechanical Facilities
		Management and Service Facilities
		Landscaping and Environmental Protection Facilities
Maintenance Engineering	Preventive Maintenance	Subgrade
		Pavement
		Bridges and culverts
		Tunnels
	Remedial Maintenance	Subgrade
		Pavement
		Bridges and culverts
		Tunnels
		Traffic Safety Facilities
		Electromechanical Facilities
		Management and Service Facilities
		Landscaping and Environmental Protection Facilities
	Special Maintenance	Various Facilities
	Emergency Maintenance	Various Facilities

Despite the continuous increase in government investment and technical support for maintenance management, current expressway maintenance still faces numerous challenges. First, the identification of potential risks remains predominantly reliant on traditional manual methods, which are not only time-consuming and labor-intensive but also struggle to achieve comprehensive coverage of high-risk areas such as steep geological regions. Second, the maintenance philosophy lags behind, with a prevailing reactive approach of "addressing issues as they arise," lacking systematic and forward-looking integrated governance strategies. Third, maintenance methods urgently require upgrading. Although intelligent maintenance technologies have been piloted in some operating entities, front-line maintenance personnel still primarily rely on foot patrols, resulting in low management efficiency. Furthermore, the multi-department coordination mechanism is inadequate. Due to unclear division of management responsibilities, the same road section is often subject to duplicate inspections, leading to resource waste. Finally, maintenance resources are particularly scarce in complex sections such as mountainous areas. The maintenance of special structures like tunnels, bridges, and high slopes requires multidisciplinary expertise; however, constrained by industry compensation levels, there is a severe shortage of highly qualified maintenance personnel.

3. Analysis of Safety Management in Expressway Maintenance Construction

With the end of the traditional "prioritizing construction over maintenance" model, the highway maintenance industry is facing unprecedented development opportunities. This transformation has prompted a large number of construction enterprises to expand into the maintenance sector. However, the rapid increase in market participants has also brought issues such as lowered industry entry barriers and inconsistent implementation of construction standards. Consequently, maintenance operations are confronted with multiple safety challenges. In practice, factors such as improper placement of construction signs, insufficient safety personnel, weak safety awareness among workers, and the uncontrollable nature of high-speed passing vehicles have led to frequent safety accidents in maintenance work zones [9]. In response to the above issues, China has established clear provisions in maintenance engineering technical standards, formulating a series of detailed specifications and guidelines. However, the effectiveness of their implementation is constrained by the uneven quality of practitioners [10]. Empirical studies indicate that construction teams receiving standardized training can significantly reduce the incidence of operational accidents. Therefore, it is necessary to establish a tiered training and certification mechanism.

As a core component of the modern transportation infrastructure operation and maintenance system, expressway maintenance construction holds strategic value in two dimensions: at the physical level, it ensures the structural integrity and functional continuity of the road through systematic maintenance; at the socioeconomic level, it directly affects public travel safety and regional logistics efficiency. To maximize maintenance effectiveness, it is necessary to construct a "Quality-Efficiency-Safety" (QES) collaborative optimization model based on full life-cycle management [11]. Specifically, this system comprises two key elements: first, a scientific planning system based on pavement performance deterioration laws, integrating multi-source data-driven distress diagnosis (using dual assessment of PCI and IRI indicators), dynamic resource allocation algorithms, weather window optimization models, and tiered emergency response plans. Second, a standardized management system relies on the PDCA cycle mechanism, clarifies the responsibilities of all participants through the RACI responsibility matrix, and leverages a BIM+GIS collaborative platform to achieve real-time interaction of design parameters, construction progress, and quality inspection data [12].

Safety management in expressway maintenance construction is a systematic endeavor requiring multi-department coordination. Before commencing maintenance operations, construction units must strictly adhere to the "Three Advances" principle: submit detailed traffic organization plans to traffic police, road administration departments, and expressway operating entities 72 hours in advance for joint review; conduct comprehensive hazard inspections of the work area using technological means such as UAV aerial photography and ground-penetrating radar in advance, ensuring inspection coverage of no less than 95%; and conduct quarterly emergency drills for high-risk scenarios such as slope collapses and vehicle intrusions in advance, ensuring emergency response times are controlled within 15 minutes.

In terms of management measures, maintenance construction management departments should focus on three key areas: first, implement differentiated control measures in accordance with the requirements of the Safety Work Rules for Highway Maintenance (JTG H30), developing customized "one-road-one-policy" plans for special sections such as long steep slopes and tunnel groups. Second, strengthen intelligent supervision by promoting the application of vehicle-mounted video surveillance systems equipped with AI recognition capabilities to monitor critical aspects such as safety equipment wearing and construction sign placement in real time. The system currently applied in Jiangsu Province has achieved a recognition accuracy of 92%. Third, enforce strict qualification management by establishing an "one-person-one-file" electronic certificate database and achieving real-time integration with the National Highway Construction Market Credit Information System, thoroughly eliminating irregular practices such as certificate leasing.

The construction of the personnel training system should focus on three priorities: implement a three-tier safety education system, requiring new employees to complete 24 hours of online theoretical training and 8 hours of VR accident simulation drills; strictly enforce the requirement of working with certificates, requiring special operation personnel to obtain the Highway Maintenance Operation Post Certificate issued by the Ministry of Transport; and adhere to case-based safety education, organizing monthly analyses of typical accident cases, such as the profound lesson from the March 29, 2025, incident in Tongling, Anhui, where a new energy vehicle collided with a concrete barrier and caught fire.

In terms of technological innovation, active promotion of mechanization and intelligent transformation should be pursued: advanced equipment such as laser obstacle removal devices should be adopted to replace manual operations, achieving operational efficiency up to six times that of traditional methods. Digital twin technology should be promoted to simulate construction traffic impacts based on BIM models and optimize traffic diversion plans. A project in Zhejiang Province achieved a 37% reduction in congestion complaints on construction sections after application. Additionally, a sound construction safety credit evaluation system should be established, implementing a blacklist system for violations to form a strong deterrent. Through these multiple measures, a comprehensive, multi-dimensional safety assurance system for maintenance construction can be established.

4. Future Development Trends of Expressway Maintenance Operations

4.1 Management Mechanism Innovation

The conceptual limitations of expressway maintenance managers are primarily reflected in the failure to carry out maintenance work from a full life-cycle perspective, resulting in a disconnect between the construction and operation phases. Operating entities typically take over maintenance only after the road opens to traffic, making it difficult for them to fully grasp the structural information of the road sections or develop customized maintenance plans (such as "one-road-one-policy"). To address management gaps, additional human and material resources are often required. Future efforts should focus on management mechanism innovation to resolve this issue, including: organizing regular management training, facilitating cross-provincial exchanges on real-time road conditions and maintenance technologies, formulating a unified national Smart Maintenance Technical Standard (clarifying specifications for UAV inspections, IoT-based detection, etc.), and developing an integrated system platform to enable full-process online management of defect reporting, task assignment, and acceptance evaluation [13].

4.2 Digital Transformation

With the rapid advancement of artificial intelligence technology, many industries have successfully leveraged AI to enhance work efficiency. However, some expressway operating entities still primarily rely on traditional manual inspection methods for maintenance operations. This approach, constrained by the professional competence of maintenance personnel, often fails to detect hidden distress such as subgrade cracks and internal structural damage. To improve maintenance effectiveness, the future should see vigorous promotion of intelligent monitoring technologies: automated identification of surface distress such as pavement cracks and subsidence through "UAV + AI image recognition"; real-time monitoring of structural conditions such as bridge stress and tunnel deformation via embedded fiber optic sensor networks; development of pavement performance deterioration prediction models based on big data analytics to scientifically determine optimal maintenance timing; and simulation-based comparison of the economic viability of different maintenance alternatives using BIM-GIS integrated platforms. The coordinated application of these intelligent methods will drive expressway maintenance from reactive repair to proactive prevention, significantly enhancing maintenance efficiency while ensuring traffic safety [14].

4.3 Investment Mechanism Optimization

Although the state has continuously increased its emphasis on highway maintenance, the compensation for maintenance personnel remains relatively low, resulting in a sustained loss of multidisciplinary talent. To improve this situation, the following measures are recommended: first, reasonably increase the income levels of maintenance management personnel to attract professionals with expertise in bridges, tunnels, and pavement, thereby alleviating the current shortage of specialized talent [15]; second, organize regular professional skills training to continuously enhance the competence of the maintenance workforce; at the same time, establish a special fund for geological disaster prevention and control on mountainous expressways to ensure dedicated use of funds—a particularly necessary measure given the complex road conditions in mountainous areas. Additionally, special incentives should be provided to individuals who achieve results in maintenance process innovation and key technical research. Finally, based on the maintenance needs of specific road sections, the application of new materials, new processes, and new technologies should be actively promoted to reduce safety risks in maintenance operations.

4.4 Full Life-Cycle Ecologization

Based on the current state of expressway development in China, the concept of full life-cycle ecologization should be comprehensively promoted. Specific measures include: first, promoting 100% recycling technology for asphalt pavement (for example, Shandong Province has achieved a recycling rate of 92% for old pavement materials), thereby improving the level of resource circular utilization; second, constructing integrated “photovoltaic-storage-charging” energy stations in service areas and tunnels to supply power for facilities and reduce electricity waste; third, applying bioengineering techniques for slope stabilization to prevent water-induced slope damage (such as the demonstration technology of vine plant slope stabilization applied in Yunnan Province); at the same time, planting vegetation with dust absorption and noise reduction functions in the central median to further enhance ecological benefits. Through multi-dimensional optimization, coordinated development of expressway maintenance and ecological environment protection can be achieved [16].

5. Conclusion

This paper elaborates on the current basic content of maintenance management from three aspects: the current status of expressway maintenance, safety management in maintenance construction, and future development trends of maintenance operations, providing reference suggestions for maintenance personnel to systematically understand the fundamental aspects of maintenance work. Expressway construction and maintenance are important links in ensuring the normal use of expressways. Preliminary construction encompasses the entire process from planning to opening, while subsequent maintenance provides sustainability assurance. The two complement each other; through construction-maintenance synergy, the level of expressway safety protection can be jointly enhanced, ensuring efficient travel for drivers and passengers. Expressway maintenance management must adhere to the concept of sustainable development, taking a holistic approach by fully considering the needs of later maintenance during the initial construction phase, and integrating preventive maintenance concepts into design, construction, and other stages.

To comprehensively improve maintenance levels, it is recommended to establish a modern, intelligent integrated expressway maintenance system: reasonably increase maintenance investment, establish dynamic adjustment mechanisms, introduce multidisciplinary talent, implement differentiated resource allocation, and improve the efficiency of fund utilization; leverage the coordination advantages of provincial operation platforms to establish cross-regional collaboration mechanisms through resource integration and unified management, achieving complementary experience and advantages; in terms of technological innovation, actively promote digital transformation, deeply apply cutting-edge technologies such as big data analytics, artificial intelligence decision-making, and smart highway systems, transforming the expressway into an integrated “management-maintenance-construction” comprehensive display system. This will not only effectively extend the service life of expressways but also promote the high-quality, sustainable development of the maintenance industry, providing solid support for the construction of a leading transportation nation.

Conclusion

In summary, LeBron James has demonstrated his unique value as an all-around basketball player through his outstanding performance in scoring, organization, defense and leadership. By comparing multiple key data of his career, including scoring efficiency, assists, defensive comprehensiveness and career durability, LeBron shows that he is not only a scoring machine, but also a core player who can lead the overall situation and drive the team. In particular, throughout his career, LeBron has been able to maintain a high level of performance and adapt to the needs of different teams by adjusting his role, which further proves his outstanding ability and flexibility in multiple positions. These traits have gradually established LeBron as a more complete basketball player in terms of data dimensions and overall comprehensiveness.

Although Michael Jordan is undoubtedly one of the most influential players in basketball history, his six championships and unparalleled competitive spirit have established his position as a basketball "myth". LeBron has surpassed the traditional shooting guard role through his comprehensiveness and career continuity and has become an all-around symbol of contemporary basketball. Whether it is scoring, assists, or defense, LeBron has demonstrated top-notch abilities in all aspects, combined with his leadership performance, forming a unique basketball style. Readers can further think about who is the greatest player in basketball history and form their own opinions based on the data and analysis provided in this article.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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