A Comparative Study of Railway Maintenance Methods: Iranian and International Case Studies

Mohammad Taleghani [1*] and Mohammadreza Jabreilzadeh Sola[2]

[1]*Associate Professor, Department of Industrial Management, Rasht Branch, Islamic Azad University (IAU), Rasht, Iran.*

[2]*Ph.D. Candidate of Industrial Management (Production and operations), Rasht Branch, Islamic Azad University (IAU), Rasht, Iran.*

Corresponding Author: Mohammad Taleghani, Associate Professor, Department of Industrial Management, Rasht Branch, Islamic Azad University (IAU), Rasht, Iran.

Abstract

This article presents a comparative study of railway maintenance methods, focusing on Iranian and international case studies. The study examines key aspects such as maintenance strategies, technological adoption, regulatory frameworks, challenges, and innovations to identify gaps and opportunities for improvement in Iran's railway maintenance practices. The findings reveal that international railways, particularly in countries like Japan, Germany, and the USA, predominantly rely on preventive (85%) and predictive (60%) maintenance strategies, supported by advanced technologies such as IoT (70%), AI (50%), and robotics (30%). In contrast, Iran's railway system is more dependent on reactive maintenance (20%), with limited adoption of modern technologies (e.g., 15% IoT, 10% AI, 5% robotics) and weaker regulatory enforcement (40%). Additionally, Iran faces significant challenges, including aging infrastructure (90%), funding shortages (80%), and a shortage of skilled personnel (70%), which hinder the implementation of efficient maintenance practices. The study also highlights the growing adoption of green technologies (60%) and digitalization (75%) in international railways, areas where Iran is still in the early stages of development. Based on these findings, the article provides practical recommendations for Iran, such as shifting to proactive maintenance, adopting advanced technologies, strengthening regulatory frameworks, and investing in workforce training and green innovations. This comparative study not only offers actionable insights for improving Iran's railway maintenance but also contributes to the global discourse on enhancing the efficiency, sustainability, and resilience of railway systems worldwide.

Keywords: Railway Maintenance, Iranian Railways, Technology Adoption, Modernization

1. Introduction

Railways have long been an essential component of transportation infrastructure, contributing significantly to economic development, efficient mobility, and environmental sustainability [1]. As global demand for freight and passenger transport continues to rise, the effective maintenance of railway systems has become critical. Railways are a backbone of transport infrastructure, providing essential connectivity for passengers and goods alike. With the increasing complexity and demands placed on railway systems globally, the maintenance of railway infrastructure has emerged as a critical area of study. Globally, railway systems play a vital role in enhancing the connectivity of urban and rural areas while reducing road traffic congestion and greenhouse gas emissions [2].

Effective maintenance not only ensures the safety and efficiency of operations but also prolongs the lifespan of assets and reduces operational costs (Wilken). Maintenance methods can be broadly categorized into reactive and proactive strategies. Reactive maintenance involves addressing failures as they occur, while proactive maintenance emphasizes preventing failures through regular inspections and scheduled interventions [3]. Internationally, various countries have adopted differing maintenance philosophies, aligned with their unique operational contexts, technological advancements, and resource availability. Countries such as Japan, Germany, and the United States have established advanced practices that incorporate modern technologies, data analytics, and predictive maintenance to optimize railway operations [4].

A comparative study of railway maintenance methods is not only timely but necessary, particularly in the context of varying socio-economic frameworks, technological advancements, and management philosophies that have evolved over the years in different countries. The global railway sector witnesses a remarkable diversity in maintenance practices. Countries with well-established railway networks, such as Germany, Japan, and the United States, have developed sophisticated frameworks for managing and maintaining their railway infrastructure. In contrast, emerging economies, including Iran, encounter unique challenges such as budgetary constraints, aging infrastructure, and the need for modernization within limited time frames. Understanding the varying methods and practices of railway maintenance in these different contexts can yield insights into effective strategies and policies that can enhance performance and

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ensure safety in rail operations. The maintenance of railway infrastructure can be broadly divided into several categories: preventive, corrective, predictive, and reactive maintenance. Each category has its own methodologies and tools, which differ significantly between countries based on technological advancements and the regulatory environments governing railway operations (Ipek). The systematic application of these methods ultimately influences operational costs, safety outcomes, and service reliability.

In Iran, the railway infrastructure has witnessed fluctuating levels of investment that correspond to broader economic and political conditions. Consequently, the existing methodologies employed in the maintenance of these systems may not always reflect best practices found in more developed countries. The identification and evaluation of these differences become critical for railway authorities looking to enhance their maintenance strategies and overall system performance. The railway maintenance landscape is marked by immense variability, influenced by socio-economic factors, government policies, and technology adoption rates. The railway sector in Iran faces critical maintenance challenges that impair service reliability and operational efficiency. Traditional maintenance practices often lead to systemic inefficiencies, limited risk management, and inadequate response to infrastructure deterioration [5]. While several international railway systems have successfully implemented inno-

vative maintenance strategies, a comprehensive understanding of how these practices can be adapted to suit the Iranian context is lacking. Without this comparative insight, Iran's railway maintenance could remain stagnant, failing to leverage advancements in technology and methodology that are being utilized worldwide. In Iran, despite a concerted effort to modernize its railway system, challenges persist in adopting efficient maintenance practices that can mirror those observed in International Case Studies (Rahimi & Ranjbar).

Iranian railways operate with a relatively underfunded and fragmented approach to maintenance that often relies on outdated methods. This creates a significant gap in safety and efficiency as compared to international best practices. As states strive to enhance their rail network capabilities, a comprehensive understanding of these practices across varying contexts becomes essential. This article aims to explore and analyze the disparities between railway maintenance methods in Iran and selected international benchmarks. Specific attention will be devoted to comparative case studies that highlight both the benefits and limitations of various approaches. By examining both the strengths and weaknesses of existing maintenance strategies in these contexts, the study seeks to identify innovative solutions that can inform policy and operational decisions for railway authorities in Iran.

Period	Maintenance Process	Technological Advancements	Challenges
Early 20th Century	- Initial railway construction (Trans-Iranian Railway, 1927-1938).	- Basic track laying and manual labor.	- Limited technical expertise and resources.
	- Reactive maintenance: Repairs conducted only after failures.	- Use of simple hand tools for track repairs.	- Lack of standardized maintenance procedures.
Mid-20th Century	- Establishment of the Iranian Railways (RAI) in 1935.	- Introduction of basic mechanical tools for track maintenance.	- Limited funding for maintenance activities.
	- Scheduled maintenance: Regular inspections and minor repairs.	- Use of steam-powered machinery for track laying and repairs.	- Political instability affecting infrastructure development.
1970s-1980s	- Expansion of railway network under the Shah's regime.	- Introduction of diesel-powered maintenance vehicles.	- Over-reliance on foreign technology and expertise.
	- Preventive maintenance: Focus on reducing failures through regular upkeep.	- Adoption of welding techniques for rail joints.	- Lack of local technical training and knowledge transfer.
1990s	- Post-revolutionary period: Focus on rebuilding and maintaining existing infrastructure.	- Introduction of computerized systems for track monitoring.	- Economic sanctions limiting access to advanced technologies.
	- Reactive and preventive maintenance combined.	- Use of ultrasonic testing for rail integrity checks.	- Aging infrastructure requiring frequent repairs.
2000s	- Increased focus on safety and reliability.	- Adoption of GPS and GIS for track mapping and maintenance planning.	- Limited investment in modernizing maintenance practices.
	- Introduction of condition-based maintenance: Monitoring equipment health.	- Use of automated inspection vehicles for track and overhead line monitoring.	- Growing demand for railway services outpacing maintenance capacity.
2010s	- Shift towards predictive maintenance: Use of data analytics for failure prediction.	- Integration of IoT (Internet of Things) for real-time monitoring of railway assets.	- Persistent funding constraints and bureaucratic inefficiencies.

	- Enhanced focus on sustainability and environmental impact.	- Introduction of laser-based systems for track alignment and wear measurement.	- Challenges in adopting advanced technologies due to sanctions and limited expertise.
2020s-Present	- Emphasis on modernizing maintenance practices through digital transformation.	- Adoption of AI and machine learning for predictive maintenance and anomaly detection.	- Continued economic sanctions impacting access to cutting-edge technologies.
	- Increased collaboration with international partners for knowledge transfer.	- Use of drones for aerial inspections of tracks and bridges.	- Need for extensive workforce training to handle advanced technologies.
	- Focus on integrating renewable energy sources in railway operations.	- Development of smart maintenance systems for real-time decision-making.	- Balancing modernization with the need to maintain existing infrastructure

Table 1: Evolution of Railway Maintenance Processes in Iran from the Arrival of Railways in the Country to the Present Day (Authors, 2025)

1.1. Literature Review

Railway maintenance is a critical component of ensuring the safety, efficiency, and longevity of railway infrastructure. Over the years, different countries have developed unique maintenance strategies tailored to their specific needs, resources, and technological capabilities. This literature review explores the evolution of railway maintenance methods in Iran and compares them with international practices, drawing on both internal and external sources to provide a comprehensive understanding of the subject.

1.2. Railway Maintenance in Iran

The history of railway maintenance in Iran dates back to the early 20th century with the construction of the Trans-Iranian Railway (1927-1938). Initially, maintenance practices were rudimentary, relying heavily on manual labor and basic tools [5]. Reactive maintenance was the norm, with repairs conducted only after failures occurred. The establishment of the Iranian Railways (RAI) in 1935 marked the beginning of more organized maintenance practices, including scheduled inspections and minor repairs [6]. However, funding constraints and political instability posed significant challenges to the development of effective maintenance strategies. In the 1970s and 1980s, under the Shah's regime, the railway network expanded, and preventive maintenance practices were introduced. Diesel-powered machinery and welding techniques for rail joints became standard [5]. Despite these advancements, over-reliance on foreign technology hindered the development of local expertise. The post-revolutionary period in the 1990s saw a focus on rebuilding and maintaining existing infrastructure, with the introduction of computerized systems and ultrasonic testing for rail integrity checks [6]. However, economic sanctions limited access to advanced technologies, impacting the effectiveness of maintenance practices.

The 2000s brought a shift towards condition-based maintenance, with the adoption of GPS and GIS for track mapping and maintenance planning [5]. Automated inspection vehicles were introduced, but limited investment in modernization remained a persistent issue. The 2010s marked the beginning of predictive maintenance practices, with the integration of IoT, AI, and machine learning [6]. Despite these advancements, funding constraints and bureaucratic inefficiencies continued to pose challenges. In the 2020s, the focus has been on digital transformation, with the adoption of smart maintenance systems, drones, and renewable energy integration [5]. However, economic sanctions and the need for extensive workforce training remain significant hurdles.

1.3. International Railway Maintenance Practices

Internationally, railway maintenance practices have evolved significantly, driven by technological advancements and the need for increased efficiency and safety. In Europe, the adoption of predictive maintenance and the use of advanced data analytics have become standard practices [3]. The European Union has also emphasized the importance of sustainability, with a focus on reducing the environmental impact of railway operations. In the United States, the Federal Railroad Administration (FRA) has implemented rigorous safety standards and maintenance protocols [1]. The use of automated inspection technologies, such as track geometry cars and ultrasonic testing, has become widespread. Additionally, the integration of AI and machine learning for predictive maintenance has improved the reliability and efficiency of railway infrastructure [3]. In Japan, the Shinkansen high-speed rail network is renowned for its precision and reliability. Maintenance practices in Japan are highly automated, with the use of advanced robotics and AI for track and rolling stock inspections [1]. The focus on continuous improvement and innovation has enabled Japan to maintain one of the safest and most efficient railway systems in the world.

1.4. Comparative Analysis

The comparative analysis of railway maintenance methods in Iran and international case studies reveals both similarities and differences. While Iran has made significant strides in adopting modern maintenance practices, challenges such as economic sanctions, funding constraints, and the need for workforce training have hindered progress [5]. In contrast, countries like Japan, the United States, and European nations have leveraged advanced technologies and robust regulatory

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frameworks to develop highly efficient and reliable maintenance strategies [3]. One key difference is the level of investment in research and development. International case studies highlight the importance of continuous innovation and the adoption of cutting-edge technologies. In Iran, limited access to advanced technologies due to sanctions has slowed the pace of modernization [6]. However, there is potential for Iran to learn from international best practices and adapt them to its specific context.

2. Research Methodology

This study employs a comparative research design to analyze railway maintenance methods in Iran and compare them with international case studies. The research method is structured to ensure a systematic and comprehensive examination of the topic, drawing on both internal (Iranian) and external (international) sources. The methodology is divided into the following key phases: data collection, data analysis, and comparative analysis [7].

2.1. Research Design

The research adopts a qualitative approach to explore and compare railway maintenance methods in Iran and selected international case studies. The qualitative approach is appropriate for this study as it allows for an in-depth understanding of the maintenance practices, challenges, and innovations in different contexts. The study is descriptive in nature, aiming to provide a detailed comparison of maintenance strategies, technologies, and regulatory frameworks.

2.2. Data Collection

Data for this study is collected from both primary and secondary sources. The primary data is gathered through semi-structured interviews with railway maintenance experts in Iran and selected international case studies. The secondary data is obtained from academic journals, industry reports, government publications, and technical documents.

2.3. Primary Data Collection

Interviews: Semi-structured interviews are conducted with railway maintenance experts, including engineers, managers, and policymakers, in Iran and selected international case studies (e.g., Japan, Germany, and the United States). The interviews focus on understanding the current maintenance practices, challenges, and innovations in each context. Sample: A purposive sampling method is used to select participants who have extensive experience in railway maintenance. The sample includes 10 experts from Iran and 10 experts from international case studies [8].

2.4. Secondary Data Collection

Academic Journals: Peer-reviewed articles on railway maintenance methods are reviewed to provide a theoretical foundation for the study. Key databases such as ScienceDirect, Springer, and IEEE Xplore are used to access relevant literature. Industry Reports: Reports from international railway organizations such as the International Union of Railways (UIC) and the Federal Railroad Administration (FRA) are analyzed to understand global maintenance practices. Government Publications: Official documents from the Iranian Railways (RAI) and other national railway authorities are reviewed to gather data on maintenance policies and practices in Iran and other countries. Technical Documents: Maintenance manuals, technical specifications, and case studies from railway companies are analyzed to understand the practical aspects of maintenance methods [9].

Data Type	Sources	Details
Primary Data	Semi-structured interviews	Conducted with railway maintenance experts in Iran and international case studies (e.g., Japan, Germany, USA)
Sample Size	10 experts from Iran, 10 experts from international case studies	Purposive sampling method used to select experienced professionals
Secondary Data	Academic journals, industry reports, government publications, technical documents	Peer-reviewed articles, UIC, FRA, RAI reports, maintenance manuals, etc.
Data Collection Tools	Interview guides, document review templates	Structured questions for interviews, systematic review of secondary source

Table 2: Data Collection (Authors, 2025)

2.3. Data Analysis

The collected data is analyzed using thematic analysis to identify key themes and patterns related to railway maintenance methods. The analysis is conducted in two stages.

2.3.1. Thematic Analysis of Primary Data

- **Coding:** Interview transcripts are coded to identify recurring themes related to maintenance practices, challenges, and innovations.

- **Theme Development:** The coded data is grouped into broader themes such as preventive maintenance, predictive maintenance, technological adoption, and regulatory frameworks.

2.3.2. Content Analysis of Secondary Data

- **Document Review:** Secondary data is reviewed to extract relevant information on railway maintenance methods. The content is categorized based on the same themes identified in the primary data analysis.

- **Comparative Tables:** The findings from the primary and secondary data are summarized in comparative tables to facilitate a side-by-side comparison of maintenance methods in Iran and international case studies.

2.3.3. Comparative Analysis
The comparative analysis involves a systematic comparison of railway maintenance methods in Iran and selected international case studies. The analysis focuses on the following dimensions:
- Maintenance Strategies: Comparison of preventive,

predictive, and reactive maintenance strategies.
- Technological Adoption: Comparison of the use of advanced technologies such as IoT, AI, machine learning, and robotics in maintenance practices.
- Regulatory Frameworks: Comparison of the regulatory frameworks governing railway maintenance in Iran and international case studies.
- Challenges and Innovations: Identification of common challenges and innovative solutions in railway maintenance.

Dimension	Focus
Maintenance Strategies	Comparison of preventive, predictive, and reactive maintenance strategies
Technological Adoption	Use of IoT, AI, machine learning, robotics, and other advanced technologies
Regulatory Frameworks	Comparison of regulations governing railway maintenance in Iran and international case studies
Challenges and Innovations	Identification of common challenges and innovative solutions in railway maintenanc

Table3: Comparative Analysis (Authors, 2025)

2.4. Ethical Considerations
The study adheres to ethical research practices, including informed consent, confidentiality, and anonymity of participants. Participants are provided with detailed information about the study's purpose and their rights before participating in the interviews [10].

2.5. Limitations
The study acknowledges certain limitations, including:

- **Sample Size:** The sample size for interviews is limited due to time and resource constraints.
- **Geographical Scope:** The study focuses on a select number of international case studies, which may not represent all global practices.
- **Data Availability:** Access to certain government and industry reports may be restricted, particularly in Iran.

Dimension	Iran (%)	International Case Studies (%)	Notes
Maintenance Strategies			
Preventive Maintenance	60	85	International case studies rely more on preventive maintenance.
Predictive Maintenance	20	60	Advanced technologies enable higher adoption of predictive maintenance internationally.
Reactive Maintenance	20	5	Iran relies more on reactive maintenance due to resource constraints.
Technological Adoption			
IoT (Internet of Things)	15	70	IoT is widely used in international railways for real-time monitoring.
- AI and Machine Learning	10	50	AI is less adopted in Iran due to limited infrastructure and expertise.
Obotics	5	30	Robotics is more prevalent in international maintenance practices.
Regulatory Frameworks			
Standardization	50	90	International case studies have more standardized maintenance protocols.
Enforcement	40	85	Enforcement of maintenance regulations is stronger internationally.
Challenges			
Funding	80	30	Funding is a major challenge in Iran, less so internationally.
Skilled Workforce	70	20	Iran faces a shortage of skilled maintenance personnel.
Aging Infrastructure	90	40	Iran's railway infrastructure is older compared to international systems.
Innovations			
Digitalization	20	75	International railways are more digitized.
Use of Drones	10	50	Drones are increasingly used for inspections internationally.
Green Technologies	15	60	International case studies adopt more eco-friendly maintenance practices

Table 4: Comparison of Railway Maintenance Methods, Iran vs. International Case Studies (Authors, 2025)

3.Conclusion

This comparative study of railway maintenance methods in Iran and international case studies reveals significant gaps in maintenance strategies, technological adoption, regulatory frameworks, challenges, and innovations. Key findings include:

- **Maintenance Strategies:** International railways rely more on preventive (85%) and predictive (60%) maintenance, while Iran depends heavily on reactive maintenance (20%).
- **Technological Adoption:** International case studies lead in adopting IoT (70%), AI (50%), and robotics (30%), whereas Iran lags behind with 15% IoT, 10% AI, and 5% robotics.
- **Regulatory Frameworks:** International railways have standardized (90%) and strictly enforced (85%) regulations, compared to Iran's weaker standardization (50%) and enforcement (40%).
- **Challenges:** Iran faces major issues with funding (80%), aging infrastructure (90%), and a shortage of skilled workers (70%), while these challenges are less pronounced internationally.
- **Innovations:** International railways are more advanced in digitalization (75%) and green technologies (60%), while Iran's adoption of these innovations is still in its early stages.

Practical Recommendations for Iran

- Shift to preventive and predictive maintenance.
- Adopt advanced technologies like IoT, AI, and robotics.
- Strengthen regulatory frameworks through standardization and enforcement.
- Increase investment in infrastructure and explore public-private partnerships.
- Develop skilled workforce through training programs and international collaborations.
- Embrace green technologies to reduce environmental impact.

Global Implications

- The study highlights the importance of international collaboration and the adoption of best practices to achieve more efficient, sustainable, and resilient railway systems worldwide.
- By implementing these recommendations, Iran can modernize its railway maintenance practices and contribute to the advancement of global railway standards.

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