Digital Twins for Smart Pavement Management in Highway Infrastructure in India

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Abstract

India's highway sector is experiencing a significant digital transformation driven by rapid infrastructure expansion, increasing freight movement and the need for sustainable asset management.[1] Traditional pavement management practices, based on periodic inspections and fragmented engineering records, are no longer adequate for managing complex highway networks efficiently.[2] The integration of Digital Twins with Building Information Modelling (BIM), intelligent design platforms, advanced pavement evaluation technologies and asset management systems offers a comprehensive framework for data-driven lifecycle management.[3–5]

This article examines the evolution of Digital Twin technology for smart pavement management in India. It discusses the integration of BIM, Bentley OpenRoads Designer, Geographic Information Systems (GIS), Falling Weight Deflectometer (FWD), Ground Penetrating Radar (GPR), LiDAR, Unmanned Aerial Vehicles (UAVs), Internet of Things (IoT) sensors and Artificial Intelligence (AI) to support predictive maintenance and optimise lifecycle performance.[4–9] The paper also reviews implementation challenges, institutional collaboration, international best practices and future opportunities for adopting Digital Twin technology within Indian highway infrastructure. The proposed framework demonstrates how digital engineering can improve pavement performance, reduce lifecycle costs and contribute to resilient and sustainable transportation networks[10].

Keywords: Digital Twin, Pavement Asset Management, BIM, OpenRoads Designer, Digital Engineering, FWD, GIS, Artificial Intelligence, Sustainable Highways.

1. Introduction

India has developed one of the world's largest road transportation networks, serving as the backbone of national economic growth and regional connectivity. Continuous investment by the Ministry of Road Transport and Highways (MoRTH) and the National Highways Authority of India (NHAI), through programmes such as Bharatmala Pariyojana, has substantially increased the length and complexity of the national highway system.[1,2] While infrastructure expansion remains a national priority, equal emphasis is now being placed on efficient operation, maintenance, and lifecycle asset management.

Historically, pavement management relied on periodic inspections, engineering judgement, and independent documentation prepared during planning, design, construction, and maintenance. Although these methods supported highway development for many decades, they provide limited capability for integrating multidisciplinary information or predicting future pavement performance.[3] Increasing traffic volumes, higher axle loads, changing climatic conditions, and constrained maintenance budgets have highlighted the need for more intelligent and proactive infrastructure management approaches.[6]

The adoption of digital engineering has transformed the way highway assets are planned, designed, and managed. Building Information Modelling (BIM), cloud-based collaboration environments, and intelligent transportation design platforms enable engineering information to remain connected throughout the asset lifecycle.[4,5] Digital Twins extend this capability by creating continuously updated digital representations of physical infrastructure through the integration of engineering models, structural evaluation data, operational monitoring, and maintenance records.[7]

For pavement engineering, Digital Twins support continuous condition assessment, deterioration prediction, and evidence-based maintenance planning. Rather than responding only after visible distress develops, highway agencies can identify emerging defects at an early stage and implement timely interventions that optimise asset performance and reduce lifecycle expenditure.[8,9] Consequently, Digital Twin technology is emerging as a key enabler of sustainable highway asset management in India.

2. Limitations of Conventional Pavement Management Practices

Despite significant advances in highway construction technologies, pavement management practices often remain dependent on fragmented engineering workflows. Survey data, design drawings, construction records, quality control documents, traffic information, and maintenance histories are frequently maintained as separate datasets, limiting effective coordination between project stakeholders.[3]

Traditional maintenance strategies also rely heavily on scheduled inspections and manual condition assessments. Structural deterioration may therefore remain undetected until visible surface defects appear, resulting in delayed interventions and increased rehabilitation costs.[6] Such reactive maintenance practices reduce pavement service life, increase traffic disruption, and require greater investment during rehabilitation.

Another important limitation is the absence of integrated digital information throughout the project lifecycle. Design modifications introduced during construction are not always reflected in operational asset records, while maintenance activities are often documented independently of the original engineering model. Consequently, valuable engineering information becomes difficult to retrieve during future rehabilitation projects.[11]

Modern highway infrastructure demands a collaborative information environment capable of integrating planning, design, construction, operation, and maintenance within a single digital platform. Digital engineering provides this capability by establishing consistent information management practices and improving collaboration among engineers, contractors, and asset managers throughout the infrastructure lifecycle.

Table 1: Conventional versus Digital Highway Engineering workflows

Aspect	Conventional	Digital Engineering
Engineering Data	Separate documents	Integrated digital model
Design Changes	Manual revisions	Automatic model updates
Quantities	Manual calculation	Automated extraction

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Aspect	Conventional	Digital Engineering
Cross Sections	Individual drawings	Dynamic generation
Maintenance	Reactive	Predictive
Collaboration	Fragmented	Common Data Environment
Asset Records	Independent files	Lifecycle database
Decision Making	Experience-based	Data-driven

Table 1 illustrates how digital engineering replaces fragmented documentation with integrated information management, enabling improved coordination, automated updates and informed decision-making across all project phases.

3. Digital Highway Engineering

Digital Highway Engineering represents the transition from document-based practices towards intelligent, data-driven infrastructure delivery. Instead of producing independent drawings and calculations, modern engineering platforms create coordinated digital models that integrate terrain data, alignments, pavement structures, drainage systems, utilities, road safety assets, and construction information within a Common Data Environment (CDE).[4,5]

This integrated approach improves engineering accuracy by ensuring that design modifications are automatically reflected throughout plans, profiles, cross-sections, and quantity calculations. It also enhances multidisciplinary collaboration by providing all project participants with access to a common and continuously updated information source.[12]

For pavement engineering, digital workflows support accurate corridor modelling, automated earthwork computations, material quantity estimation, and integration of pavement performance information with engineering design. The transition from conventional engineering documentation to Digital Twin-enabled asset management is illustrated in Figure 1, highlighting the progressive evolution from isolated project records towards intelligent lifecycle information management.

Figure 1: Evolution from conventional engineering documentation to intelligent Digital Twin-based highway asset management.

4. BIM in Highway Infrastructure

Building Information Modelling (BIM) has become a fundamental component of digital highway engineering by integrating physical, functional, and operational information within a coordinated digital model. Unlike traditional Computer-Aided Design (CAD), BIM enables every infrastructure element to contain engineering attributes that remain linked throughout planning, design, construction, and operation.[4, 12]

Within highway projects, BIM incorporates survey information, Digital Terrain Models (DTMs), horizontal and vertical alignments, pavement structures, drainage networks, road furniture, utilities, and asset inventories into a unified information environment. This integrated approach improves multidisciplinary coordination, minimises design conflicts, and enhances the accuracy of engineering documentation.

For pavement engineers, BIM provides an efficient platform for corridor modelling, pavement layer development, quantity estimation, and digital documentation. More importantly, it establishes the information foundation required for Digital Twin implementation by connecting engineering models with inspection records, structural evaluation results, and maintenance history. The hierarchical relationship between these information layers is presented in Figure 2.

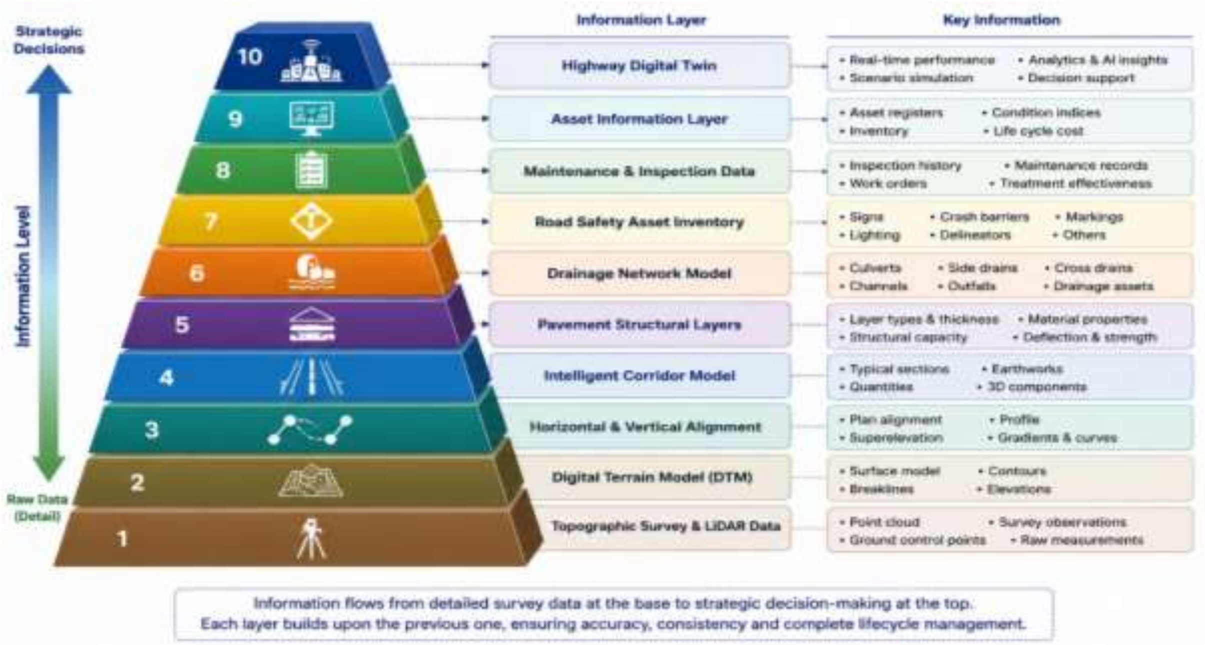

Figure 2: Hierarchical information structure supporting BIM-enabled highway lifecycle management.

5. OpenRoads Designer Platform

Bentley OpenRoads Designer (ORD) is a comprehensive BIM-based highway engineering platform that integrates survey data, terrain models, alignments, corridors, drainage systems, and pavement structures within a unified digital environment.[5] Unlike conventional CAD applications, ORD establishes dynamic relationships among engineering components, ensuring that modifications made to one element are automatically reflected throughout the project model.

The platform supports the complete highway design process, from preliminary alignment optimisation to detailed corridor modelling and construction documentation. Intelligent templates enable engineers to generate pavement layers, embankments, cuttings, drainage systems, and ancillary road assets while maintaining consistency with applicable design standards. The software also facilitates automated quantity estimation, cross-section generation, and clash detection, thereby improving engineering efficiency and reducing design rework.[5,12]

Another significant advantage is interoperability. OpenRoads Designer exchanges information with GIS platforms, survey databases, Common Data Environments (CDEs), and asset management systems, enabling digital continuity from planning through operation. This capability provides the digital foundation required for implementing Digital Twins within highway infrastructure projects.

Table 2: Benefits of OpenRoads Designer for Highway Projects

Function	Engineering Benefit
Terrain Modelling	Accurate representation of existing ground conditions
Corridor Modelling	Intelligent road model generation
Template Management	Standardised pavement structures
Superelevation Design	Automated calculations compliant with IRC standards
Quantity Estimation	Faster and more accurate reporting
Drawing Production	Automatically updated plans, profiles, and cross-sections
BIM Integration	Improved multidisciplinary coordination
Data Exchange	Compatibility with GIS and Digital Twins

As summarised in Table 2, the platform enhances engineering productivity through intelligent modelling, automated documentation and improved multidisciplinary coordination.

6. Comparative Workflow Analysis

Conventional highway engineering workflows rely on independent drawings, manual calculations, and disconnected spreadsheets, making project updates time-consuming and susceptible to inconsistencies. Any modification in alignment or pavement geometry generally requires multiple revisions across plans, profiles, cross-sections, and quantity calculations, increasing both engineering effort and the potential for errors.

BIM-enabled workflows fundamentally improve this process by maintaining all engineering information within a coordinated digital model. Design revisions automatically propagate throughout associated project deliverables, ensuring consistency between drawings, quantities, and construction documentation. Automated clash detection further minimises conflicts between pavement, drainage, utilities, and road safety elements before construction begins.[4,5]

Digital information exchange also strengthens collaboration among designers, contractors, independent engineers, and asset managers by providing access to a common and continuously updated information source. Consequently, engineering decisions become more transparent, traceable, and efficient throughout the project lifecycle.

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Table 3: Conventional versus BIM-enabled Highway Workflow

Aspect	Conventional Workflow	BIM-enabled Workflow
Engineering Data	Separate documents	Integrated digital model
Design Revision	Manual	Automatically updated across all deliverables
Quantity Estimation	Separate calculations	Derived directly from the digital model
Cross Sections	Independently drafted	Automatically generated
Clash Detection	During construction	During design
Data Sharing	Unlinked standalone files	Common Data Environment
Asset Records	Separate databases	Integrated digital model
Lifecycle Management	Limited	Continuous information management

The progression from traditional engineering practices to intelligent lifecycle asset management is illustrated in Figure 3, demonstrating how integrated digital workflows support improved project delivery and long-term infrastructure performance

Figure 3: Transformation from conventional highway engineering workflows to integrated Digital Twin-based asset management

7. Evolution of Pavement Asset Management

Pavement Asset Management has evolved considerably from routine visual inspections towards comprehensive performance-based management supported by advanced investigation technologies and digital information systems. Modern practice combines structural evaluation, functional assessment, traffic loading, and environmental data to provide a holistic understanding of pavement condition and future performance.[6,8]

In India, the Falling Weight Deflectometer (FWD) remains one of the most reliable techniques for evaluating pavement structural capacity in accordance with IRC recommendations.[3] Complementary technologies such as Ground Penetrating Radar (GPR), laser profilers, LiDAR, UAV surveys, Weigh-in-Motion (WIM) systems, and automated distress detection improve the accuracy and efficiency of pavement condition assessment.[7,8]

The integration of these technologies enables highway agencies to collect high-quality engineering data for condition evaluation, deterioration modelling, and maintenance planning. Rather than relying solely on periodic inspections, asset managers can use continuously updated information to identify deterioration trends, prioritise interventions, and optimise maintenance investment throughout the pavement lifecycle.[9,13]

The principal technologies supporting smart pavement management are summarised in Table 4.

Table 4: Technologies Supporting Smart Pavement Management

Aspect	Conventional Workflow	BIM-enabled Workflow
Falling Weight Deflectometer	Structural evaluation	Deflection basin and layer modulus
Ground Penetrating Radar	Layer thickness assessment	Detailed pavement layer profile
Laser Profiler	Ride quality evaluation	International Roughness Index (IRI)
LiDAR Survey	Surface geometry	High-resolution point cloud
UAV Photogrammetry	Visual inspection	Orthophotos and Digital Surface Model
Weigh-in-Motion (WIM)	Traffic loading	Axle load spectrum
IoT Sensors	Environmental monitoring	Temperature and moisture data
AI Vision Systems	Automated distress mapping	Automated crack and rut detection

The combination of structural evaluation, digital surveys and intelligent monitoring establishes the information base required for implementing Digital Twin technology, which is discussed in the following section.

8. Digital Twin Concept for Smart Pavement Management

A Digital Twin is a dynamic digital representation of a physical highway asset that continuously integrates engineering information with operational and maintenance data throughout its lifecycle.[14] Unlike static three-dimensional models, a Digital Twin is continuously updated using information from design, construction, structural evaluation, traffic monitoring, and environmental observations, enabling highway agencies to monitor asset performance in near real time.[15]

Within pavement engineering, the Digital Twin integrates BIM models developed in OpenRoads Designer with Geographic Information Systems (GIS), Pavement Management Systems (PMS), Falling Weight

Deflectometer (FWD) surveys, Ground Penetrating Radar (GPR), laser profiler data, LiDAR surveys, UAV imagery, and IoT-based monitoring systems.[3,5,7] The resulting digital environment provides a comprehensive engineering database that supports structural evaluation, deterioration modelling, and maintenance planning.

The architecture of an integrated Digital Twin is presented in Figure 4, illustrating the interaction between engineering data sources, BIM models, cloud-based information management and decision-support systems.

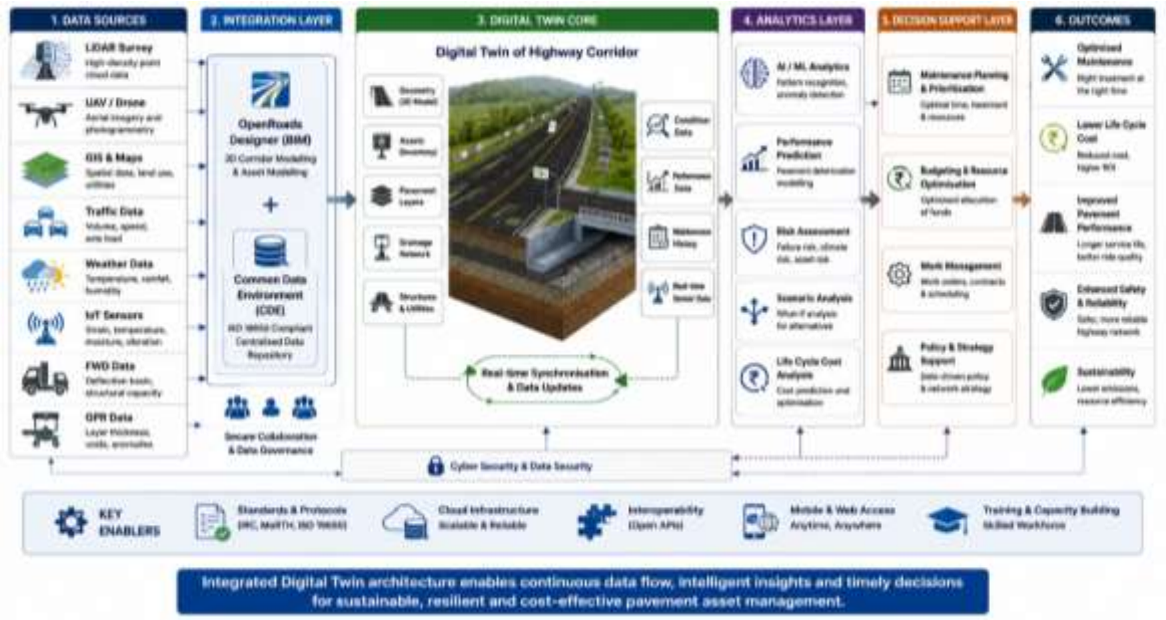

Figure 4: Integrated Digital Twin architecture supporting intelligent pavement management.

The effectiveness of a Digital Twin depends on seamless information exchange between engineering disciplines. Survey data, GIS layers, IoT sensors and pavement performance databases must operate within a coordinated digital ecosystem rather than as isolated information repositories. This relationship is illustrated in Figure 5, which demonstrates the integration of BIM, GIS and IoT technologies for intelligent pavement management.

Figure 5: Integration of BIM, GIS and IoT for smart pavement asset management.

By integrating these digital technologies, highway agencies can shift from reactive maintenance towards predictive asset management, improving pavement performance while reducing lifecycle costs and service interruptions.[14,16]

9. Illustrative Application on an Indian Highway Corridor

The practical implementation of a Digital Twin may be illustrated through a typical National Highway improvement project. The process begins with high-resolution topographic surveys using LiDAR, UAV photogrammetry, and conventional engineering surveys to establish an accurate Digital Terrain Model (DTM). Survey outputs are subsequently incorporated into BIM-based highway models developed using OpenRoads Designer, where alignments, pavement structures, drainage systems, and safety features are designed within an integrated digital environment.[5]

During construction, quality assurance records, material test results, and as-built information are linked with the engineering model to establish an initial digital asset database. After project completion, periodic structural evaluations using FWD, functional assessments using laser profilers, GPR investigations, and traffic loading information are incorporated into the Digital Twin to support continuous pavement monitoring.[3,6]

Figure 6 illustrates the flow of engineering information throughout the highway asset lifecycle, demonstrating how successive project phases contribute to a continuously updated Digital Twin.

Figure 6: Digital Twin data flow throughout the highway asset lifecycle.

Such an integrated workflow enables asset managers to identify deterioration trends, prioritise maintenance activities and evaluate alternative rehabilitation strategies based on engineering evidence rather than periodic inspections alone.

10. Sustainability Benefits of Digital Twins

Digital engineering contributes significantly to sustainable highway infrastructure by improving design efficiency, reducing construction waste, and extending pavement service life. Intelligent modelling enables optimisation of earthworks, material quantities, and drainage systems before construction commences, thereby minimising unnecessary resource consumption.[4,12]

The integration of Digital Twins with pavement asset management further enhances sustainability by supporting predictive maintenance strategies. Early identification of structural deterioration allows maintenance interventions to be undertaken before significant pavement failures occur, reducing rehabilitation requirements, lowering greenhouse gas emissions associated with reconstruction, and improving long-term infrastructure resilience.[16]

Additional benefits include enhanced road user safety, reduced traffic disruption during maintenance, and more efficient utilisation of public investment. Figure 7 summarises the smart pavement asset management decision-support framework, linking condition assessment, performance analysis, and maintenance prioritisation within a Digital Twin environment.

Figure 7: Smart pavement asset management decision-support framework.

11. Implementation Challenges and Mitigation

Despite its considerable potential, the implementation of Digital Twin technology within Indian highway projects continues to face several technical and institutional challenges. The principal constraints include limited availability of skilled BIM professionals, inconsistent data standards, fragmented information systems, contractual limitations, and resistance to organisational change.[4,17]

Successful implementation also depends upon standardised information management procedures, effective interoperability between software platforms, and long-term investment in digital infrastructure. Capacity building through professional training, academic collaboration, and national digital engineering guidelines will therefore be essential for widespread adoption.

Table 5 presents the key implementation challenges along with recommended mitigation measures, highlighting the importance of professional training, interoperability standards, phased deployment, and organisational change management.

Table 5: Key Implementation Challenges and Mitigation Measures

Challenge	Recommended Mitigation
Limited digital skills	Professional training and certification
Fragmented project data	Common Data Environment (CDE)
Software interoperability	Adoption of IFC, LandXML and ISO 19650
High implementation cost	Phased deployment on pilot projects
Cybersecurity risks	Secure cloud infrastructure and governance
Organisational resistance	Change management and leadership support

12. Institutional Collaboration Framework

The successful adoption of Digital Twin technology in highway infrastructure requires coordinated institutional collaboration among government agencies, industry stakeholders, academic institutions, and technology providers. National-level organisations such as the Ministry of Road Transport and Highways (MoRTH), the National Highways Authority of India (NHAI), and the Indian Roads Congress (IRC) must establish consistent digital engineering standards, compliance frameworks, and training programmes to ensure uniform implementation across projects.[17]

Industry participation is equally important, with consultants, contractors, and technology vendors contributing to the development of interoperable platforms, standardised data formats, and secure cloud-based information environments. Academic institutions can support capacity building by integrating BIM and Digital Twin concepts into civil engineering curricula, while research organisations may contribute to the development of advanced pavement evaluation technologies and predictive deterioration models.

Figure 8 illustrates the institutional collaboration framework required for Digital Twin adoption, highlighting the interaction between government agencies, industry stakeholders, academic institutions, and technology providers.

Figure 8: Institutional collaboration framework for Digital Twin implementation in Indian highway infrastructure.

Such collaboration will enable the creation of a national digital ecosystem for highway asset management, ensuring that engineering information remains consistent, accessible, and reliable throughout the infrastructure lifecycle.

13. International Best Practices in Digital Twin Adoption

Several countries have successfully integrated Digital Twins and BIM into transportation infrastructure management through national standards and asset management frameworks. The ISO 19650 series provides internationally recognised principles for BIM-based information management across the asset lifecycle. Similarly, ISO 55000, the *PIARC Road Asset Management Manual*, the *Austroads Guide to Pavement Technology*, and the *AASHTO Pavement Management Guide* support data-driven decision-making for sustainable infrastructure management.[7–9]

International experience demonstrates that open information standards, interoperable digital platforms, and structured asset databases significantly improve maintenance planning, engineering coordination, and long-term infrastructure performance.

Figure 9 illustrates international best practices in Digital Twin adoption, highlighting the role of ISO standards, global asset management frameworks, and interoperable digital platforms in achieving sustainable highway infrastructure.

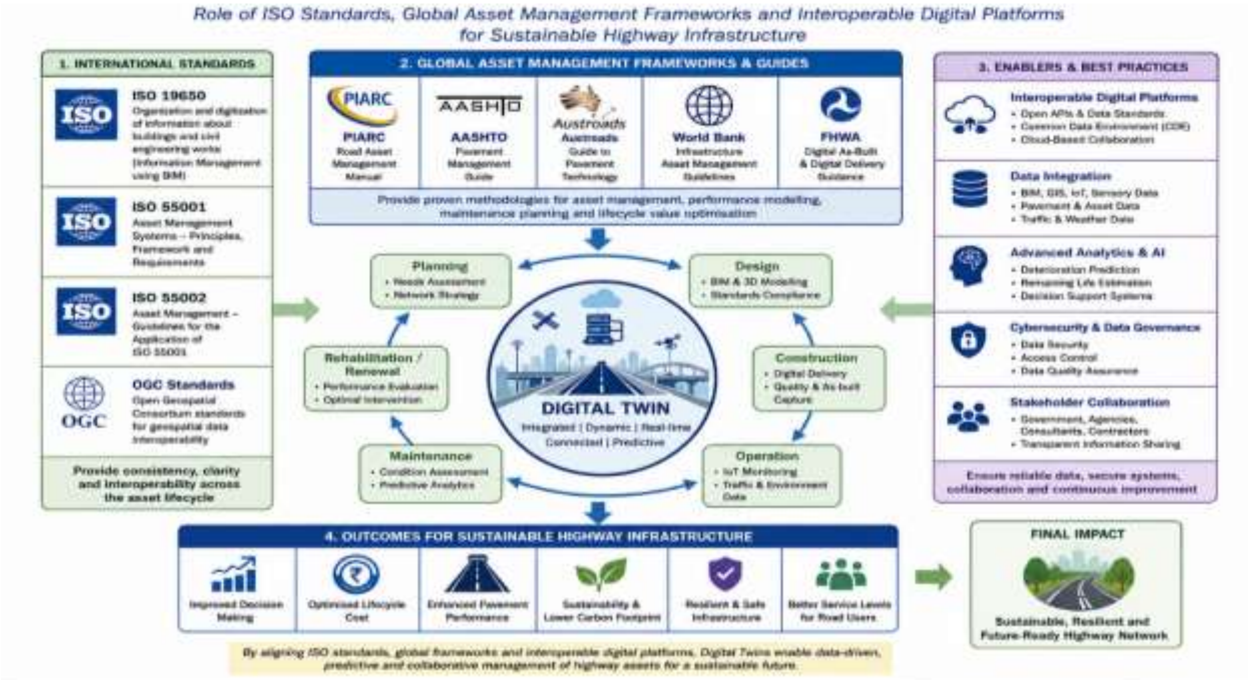

Figure 9: International best practices in Digital Twin adoption

These lessons provide valuable guidance for developing national Digital Highway standards suitable for Indian conditions.

14. Lifecycle Cost Optimisation Strategies

Lifecycle cost optimisation represents one of the most significant benefits of Digital Twin implementation. By integrating structural condition, traffic loading, environmental influences, and historical maintenance records, Digital Twins enable highway agencies to predict deterioration and identify the most cost-effective intervention strategies.[16]

Rather than adopting fixed maintenance intervals, predictive analysis enables interventions to be schedu-

led according to actual pavement performance. This approach extends service life, reduces emergency repairs, improves budget allocation, and enhances the overall return on public investment.
Figure 10 illustrates the lifecycle optimisation process enabled by Digital Twin technology, demonstrating how continuous monitoring supports informed maintenance and rehabilitation planning.

Figure 10: Lifecycle cost optimisation process using Digital Twin technology.

15. Evolving Role of Pavement Engineers

The transition towards Digital Twin-enabled highway infrastructure has significantly expanded the role of pavement engineers from conventional design and quality control to integrated asset lifecycle management. Modern pavement engineers are expected to combine expertise in pavement materials, structural evaluation, BIM, digital engineering, and asset management to support evidence-based decision-making.[3,5,6]
In addition to conventional engineering responsibilities, professionals must interpret information obtained from FWD testing, GPR investigations, LiDAR surveys, laser profiling, UAV inspections, and IoT monitoring systems. The integration of these datasets within BIM and Digital Twin platforms enables engineers to evaluate pavement performance more accurately and recommend timely maintenance interventions.[14,16]
Continuous professional development, interdisciplinary collaboration, and familiarity with international digital engineering standards will therefore become essential competencies for future pavement engineers. Academic institutions, professional organisations, and industry stakeholders should work together to strengthen capacity building in Digital Highway Engineering and Smart Pavement Management.[7,17]

16. Future Directions for Digital Highways

Digital transformation within highway infrastructure is expected to accelerate with the convergence of Artificial Intelligence (AI), Internet of Things (IoT), cloud computing, connected vehicles, and Digital Twin technology. Future highway networks will increasingly rely on continuous monitoring, predictive analytics, and automated decision-support systems to improve operational efficiency and infrastructure resilience.[14,18]

Emerging technologies will enable Digital Twins to incorporate real-time traffic information, environmental conditions, pavement structural responses, and maintenance records within a unified engineering platform. Artificial Intelligence will further enhance deterioration prediction, maintenance prioritisation, and lifecycle investment planning through advanced machine learning algorithms.[18,19]

For India, progressive implementation of Digital Twin technology should be supported through national BIM standards, Common Data Environments, open information exchange protocols, and structured asset databases. Collaboration between MoRTH, NHAI, State Highway Authorities, consultants, concessionaires, academia, and technology providers will be essential for achieving nationwide digital transformation.

Table 6: Digital Twin Maturity Levels for Highway Agencies

Maturity Level	Digital Capability	Key Technologies	Characteristics	Typical Indian Status
Level 0 – Conventional Practice	Paper-based documentation and standalone CAD drawings	2D CAD, spreadsheets, printed reports	Fragmented information, manual calculations, reactive maintenance	Still used on many legacy highway projects
Level 1 – Digital Design	Basic digital engineering with limited collaboration	CAD, Total Station, Digital Survey, DTM	Electronic drawings, improved accuracy, limited data sharing	Common in DPR and detailed design projects
Level 2 – BIM-enabled Highway Engineering	Collaborative 3D information modelling	BIM, OpenRoads Designer, Civil 3D, CDE, GIS	Intelligent corridor modelling, automated quantities, coordinated multidisciplinary design	Increasing adoption in major NHAI, Expressway, and Metro projects
Level 3 – Digital Asset Management	Integration of design, construction, and operation data	BIM, GIS, FWD, GPR, LiDAR, UAV, PMS	Centralised asset database, performance monitoring, lifecycle information management	Emerging in selected highway concession and O&M projects
Level 4 – Intelligent Digital Twin	Real-time monitoring and predictive asset management	IoT Sensors, AI, Machine Learning, Cloud Computing, Digital Twins	Continuous monitoring, predictive maintenance, risk-based decision support, lifecycle optimisation	Pilot stage in India; adopted internationally for smart infrastructure

Maturity Level	Digital Capability	Key Technologies	Characteristics	Typical Indian Status
Level 5 – Autonomous Smart Highway Ecosystem	Self-learning and autonomous infrastructure management	Digital Twins, AI, Digital Twin Analytics, Connected Vehicles, V2X Communication, 5G, Edge Computing	Autonomous inspection, self-updating asset models, predictive maintenance, network-wide optimisation, carbon-aware infrastructure management	Future vision for India's Digital Highway Mission

Table 6 presents a progressive maturity model illustrating how highway agencies can evolve from conventional engineering practices towards intelligent Digital Twin-enabled asset management.

Figure 11: Future smart highway ecosystem integrating digital technologies.

Figure 11 illustrates the future smart highway ecosystem integrating Artificial Intelligence, IoT, BIM, and predictive analytics.

Figure 12 presents a phased implementation roadmap for Indian highway projects, highlighting the transition from digital surveys and BIM adoption to fully integrated Digital Twin platforms supporting predictive asset management.

Figure 12: Proposed roadmap for implementing Digital Twin technology in Indian highway projects.

17. Conclusions

Digital Twins represent the next stage in the evolution of highway infrastructure management by integrating engineering design, construction information, structural evaluation, and operational data within a continuously updated digital environment. Unlike conventional pavement management systems, Digital Twins enable highway agencies to monitor infrastructure performance proactively, predict deterioration, and optimise maintenance interventions using reliable engineering evidence.[14]

The integration of BIM, OpenRoads Designer, GIS, Pavement Management Systems, FWD, GPR, LiDAR, UAV surveys, and IoT technologies establishes a comprehensive information ecosystem capable of supporting intelligent asset management throughout the highway lifecycle. Such integration improves engineering coordination, enhances pavement performance, reduces lifecycle costs, and contributes to sustainable infrastructure development.[4,5,7]

For India, successful implementation will depend upon institutional collaboration, adoption of international digital engineering standards, development of skilled professionals, and establishment of interoperable information management frameworks. With continued investment in digital infrastructure and capacity building, Digital Twin technology has the potential to transform pavement management from reactive maintenance towards predictive, performance-based asset stewardship, supporting safer, more resilient, and sustainable highway networks.[18,20]

Figure 13 illustrates the integrated vision of Digital Twin-enabled highway infrastructure, showing how design, construction, evaluation, and operations converge into a unified digital ecosystem that supports sustainability, lifecycle optimisation, and resilience.

Figure 13: Integrated Digital Twin Highway Vision

18. Acknowledgement

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