**American Journal of Advanced Technology and Engineering Solutions**
*Volume 03 Issue 03 (2023)*
*Page No:54-81*
*eISSN: 3067-0470*
**DOI: 10.63125/hftt1g82**

# ROLE OF DIGITAL TWINS AND BIM IN U.S. HIGHWAY INFRASTRUCTURE ENHANCING ECONOMIC EFFICIENCY AND SAFETY OUTCOMES THROUGH INTELLIGENT ASSET MANAGEMENT

**Mubashir Islam[1]; MKA Shahinoor Rahman Jahid[2];**

*[1]. Master of Engineering in Civil Engineering, College of Engineering, Lamar University, TX, USA; Email: muby.im454@gmail.com*

*[2]. Chief Executive Officer (CEO), GM Holdings Limited (Deshbandhu Group), Dhaka, Bangladesh; Email: mkajahid@gmail.com*

**Citation:**
Islam, M., & Jahid, M. S. R. (2023). Role of digital twins and BIM in U.S. highway infrastructure enhancing economic efficiency and safety outcomes through intelligent asset management. *American Journal of Advanced Technology and Engineering Solutions*, 3(3), 54–81. https://doi.org/10.63125/hftt1g82

**Received:**
May 18, 2023

**Revised:**
June 24, 2023

**Accepted:**
July 26, 2023

**Published:**
August 30, 2023



**ABSTRACT**
*To synthesize evidence on how Building Information Modeling (BIM) and digital twins enhance economic efficiency and safety in U.S. highway infrastructure through intelligent asset management. Guided by PRISMA 2020, searches across engineering, transportation, and standards repositories (2000–August 2023) yielded 3,146 records. After removing 1,012 duplicates, 2,134 titles/abstracts were screened; 378 full texts were assessed; 92 studies were included (empirical, mixed-methods, and rigorously reported gray literature). Data were extracted on model uses, governance, and outcomes; heterogeneity precluded meta-analysis, so a structured narrative synthesis was undertaken. Evidence clustered across four domains. (1) Economic efficiency: sixty-three studies reported fewer design clashes, reduced rework and RFIs, and more stable schedules and quantities under 3D/4D/5D coordination. (2) Predictive maintenance and lifecycle value: forty-nine studies linked digital-twin condition monitoring and deterioration forecasting to earlier, better-targeted treatments and fewer emergency interventions. (3) Safety and risk reduction: fifty-two studies associated time-aware staging, traffic management visualizations, and real-time hazard indices with lower exposure in work zones and shorter detection-to-response intervals. (4) Intelligent asset management: fifty-eight studies documented benefits when digital as-builts, IFC/COBie handovers, and sensor feeds populated governed asset registers, improving auditability and budget formulation. Cross-jurisdictional comparisons (forty-one studies) showed stronger, more consistent outcomes where open standards and owner information requirements were embedded in procurement and delivery. Across ninety-two studies, BIM provides the authoritative, object-based backbone for asset information, while digital twins synchronize that information with operational state. Under interoperable standards and clear governance, this pairing consistently supports cost control, safety performance, and reliable maintenance planning in U.S. highway programs.*

***KEYWORDS***
*BIM/Digital-Twins; Highways; Asset-Management; Safety; Efficiency.*

***American Journal of Advanced Technology and Engineering Solutions***
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*Page No:54-81*
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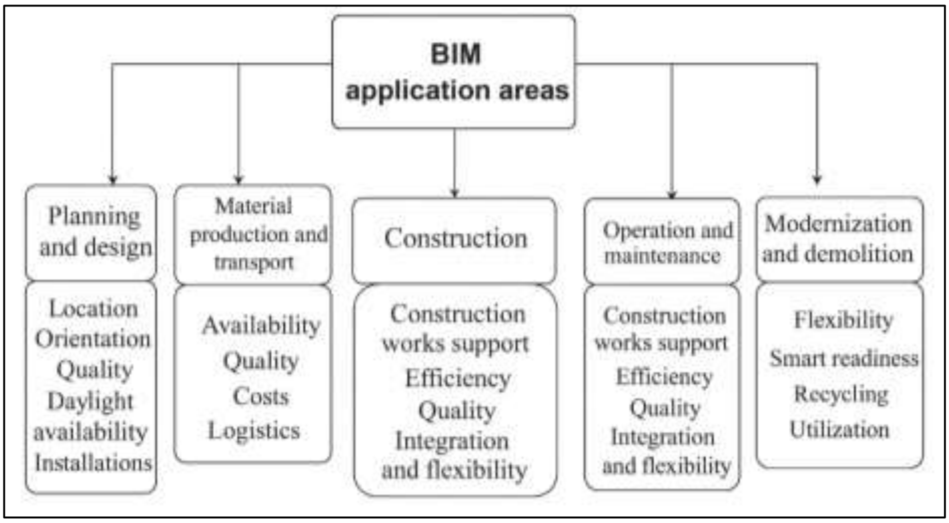
## INTRODUCTION

Digital twins and Building Information Modeling (BIM) form two foundational paradigms in the digitalization of infrastructure asset management, each offering unique but interrelated capabilities. A digital twin can be defined as a dynamic, virtual representation of a physical asset or system, continuously updated through real-time data streams to mirror performance, condition, and environment (Li et al., 2022).In transportation, this translates into synchronized virtual models of roads, bridges, tunnels, and associated subsystems equipped with sensors and monitored through connected networks. BIM, on the other hand, provides a structured, data-rich model for planning, design, construction, and lifecycle management, built around object-based representations and collaborative workflows (Hakimi et al., 2023). While BIM emphasizes parametric modeling, data coordination, and interoperability in preconstruction and construction stages, digital twins extend these functions by enabling operational visibility and predictive insights throughout the lifecycle. Standards such as ISO 19650 provide frameworks for information management in BIM-based projects, while the Gemini Principles define the purpose, trustworthiness, and function of infrastructure digital twins. Together, these systems establish a new paradigm for intelligent asset management, where the representation of physical infrastructure is continuously informed by real-world performance data and historical models, providing a foundation for efficiency, resilience, and safety in U.S. highway networks (Wang, Guo, Li, Tang, Li, et al., 2022).

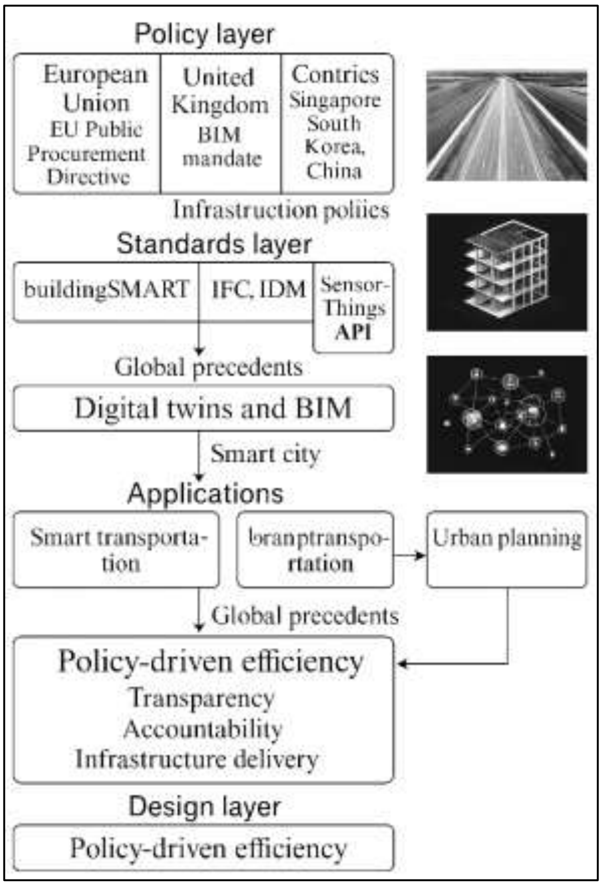
**Figure 1: BIM and Digital Twin Applications**




The significance of digital twins and BIM extends beyond national boundaries, as countries worldwide are embedding these technologies into infrastructure development strategies. The European Union has actively promoted BIM adoption through directives such as the EU Public Procurement Directive 2014/24/EU, requiring BIM in public works. Similarly, the United Kingdom's BIM mandate has set international precedents by requiring Level 2 BIM for all centrally procured projects since 2016. International bodies such as buildingSMART (Shishehgarkhaneh et al., 2022) have also facilitated interoperability through standards like Industry Foundation Classes (IFC), Information Delivery Manual (IDM), and the SensorThings API. Countries such as Singapore and South Korea have incorporated BIM into national infrastructure policies to enhance urban planning, transportation design, and project delivery. Similarly, China has led large-scale adoption of digital twin frameworks in smart city and smart transportation initiatives, integrating sensor networks and artificial intelligence into highway monitoring and traffic optimization. These global precedents highlight a transnational recognition of BIM and digital twins as not only technical tools but also as enablers of policy-driven efficiency, transparency, and accountability in infrastructure delivery. This international backdrop places U.S. highway infrastructure within a broader movement toward global digital transformation in construction and transportation sectors, demonstrating that alignment with these models is both a technological imperative and an economic necessity (Lu et al., 2022).

*eISSN: 3067-0470*
*DOI: 10.63125/hfft1g82*

**Figure 2: Global BIM and Digital Twin Roadmap**




In the United States, BIM and digital twin integration in transportation infrastructure has gained momentum through federal, state, and industry-level initiatives. The Federal Highway Administration (FHWA) has supported BIM for Infrastructure under the Every Day Counts (EDC) program to promote digital delivery and lifecycle asset management in highway projects (Olowa et al., 2022). The American Association of State Highway and Transportation Officials (AASHTO) has developed the "BIM for Bridges and Structures" roadmap to standardize information modeling across state agencies. Pilot projects in states like Utah, Texas, and Minnesota have demonstrated the benefits of BIM-based digital delivery in highway projects, including cost savings, streamlined workflows, and improved safety planning. Furthermore, emerging U.S. initiatives have extended beyond BIM to explore highway digital twins for traffic flow optimization, bridge maintenance, and pavement condition forecasting. By leveraging real-time sensor data, GIS integration, and predictive analytics, transportation agencies are embedding operational intelligence into asset management practices. Federal mandates under Infrastructure Investment and Jobs Act (Yoon, 2023) have also emphasized digital delivery methods for highway projects, aligning national investment priorities with modern digital infrastructure practices. This institutional support underscores a systematic shift in the U.S. transportation sector, situating BIM and digital twins at the center of strategies aimed at addressing aging infrastructure, cost overruns, and safety risks.

Economic efficiency is a primary driver of BIM and digital twin integration in highway infrastructure, with implications across capital expenditures, operational costs, and lifecycle management. BIM's structured data models facilitate early detection of design conflicts, reducing rework and delays. Similarly, digital twins allow real-time monitoring and predictive maintenance, reducing unplanned downtime and extending the service life of assets. Empirical studies have shown that BIM-enabled design coordination can yield cost savings ranging from 5% to 20% in infrastructure projects. In highway contexts, digital twins allow traffic demand forecasting, pavement deterioration prediction, and construction sequencing optimization, all of which enhance cost-effectiveness. Data integration across design, construction, and operations reduces information silos, lowering lifecycle costs through improved decision-making. Additionally, infrastructure owners benefit from asset-level

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financial transparency, aligning project expenditures with long-term budgetary planning. Such efficiency outcomes are amplified when digital twins interface with Internet-of-Things devices, machine learning models, and transportation management systems, enabling state agencies to allocate resources more effectively and maximize taxpayer value (Zhou et al., 2022). Thus, economic efficiency derived from digital twins and BIM is grounded in both direct cost savings and long-term performance gains in U.S. highway infrastructure.

Safety remains a critical dimension of U.S. highway infrastructure, and BIM and digital twins provide tools to systematically improve risk identification and mitigation. BIM enables visualization of construction sequences, traffic diversions, and structural interactions, reducing worksite hazards. Digital twins extend these safety functions by integrating live data from roadway sensors, vehicular telematics, and weather monitoring systems to detect hazardous conditions in real time. Studies have demonstrated that integrating safety-in-design principles into BIM workflows reduces construction accidents and improves occupational health outcomes. In highway operations, digital twins facilitate incident management, enabling agencies to simulate accident scenarios and optimize emergency response strategies. Sensor-enabled pavement monitoring supports predictive interventions, minimizing risks of accidents due to structural failures. Furthermore, the fusion of BIM with Geographic Information Systems (GIS) provides spatial intelligence for safety-critical design elements, such as guardrails, slopes, and intersections. These applications directly contribute to reducing fatalities and injuries on U.S. highways, aligning with federal safety goals under the Vision Zero framework. The synthesis of modeling and real-time monitoring transforms highways into proactive safety systems, embedding risk prevention into asset management processes (Ara et al., 2022; J. Zhou et al., 2022).

The integration of BIM and digital twins into intelligent asset management frameworks is central to enhancing both economic and safety outcomes in U.S. highway infrastructure. Asset management traditionally relies on condition assessments, inspection reports, and historical maintenance logs. However, digital twins enrich these frameworks with real-time data streams from IoT devices, drones, and automated inspections, enabling continuous condition monitoring. BIM, meanwhile, structures asset information in a manner that facilitates decision-making across design, construction, and operations, providing a digital backbone for asset registers and facility management systems (Jahid, 2022; Nour El-Din et al., 2022). Integrated frameworks enable predictive maintenance, investment prioritization, and optimized scheduling, improving both cost control and service reliability. Highway agencies such as the Texas Department of Transportation (TxDOT) and Minnesota Department of Transportation (MnDOT) have demonstrated that BIM-based asset management improves project delivery outcomes while digital twins enhance post-construction performance monitoring (Uddin et al., 2022). Data integration across platforms requires standardized protocols and governance structures, highlighting the importance of ISO 19650 and AASHTO's implementation guides for BIM in highways. These frameworks reflect a systemic convergence of design, construction, and operations into a holistic asset management ecosystem, reinforcing the role of BIM and digital twins as enablers of intelligent infrastructure in the U.S. context (Akter & Ahad, 2022; Xu et al., 2023).

The intersection of digital twins, BIM, and intelligent asset management in U.S. highways reflects not only a domestic priority but also an alignment with global advancements in infrastructure digitalization. Countries that have embraced these frameworks demonstrate measurable gains in project efficiency, transparency, and safety performance. By adopting BIM and digital twin practices, the U.S. highway sector aligns itself with internationally recognized standards while addressing context-specific challenges such as aging infrastructure, high maintenance costs, and road safety concerns (Eneyew et al., 2022; Arifur & Noor, 2022). Academic research and industry case studies consistently highlight that integrating data-driven decision-making into infrastructure systems leads to higher resilience and optimized resource allocation. U.S. federal and state agencies' ongoing initiatives demonstrate that these technologies are no longer conceptual but are being operationalized through national investment policies, highway construction programs, and lifecycle asset management strategies (Boje et al., 2023; Rahaman, 2022). In this way, the role of BIM and digital twins in U.S. highway infrastructure stands as part of a global movement toward digital transformation in transportation, reinforcing their value as foundational instruments in building safer, more efficient, and intelligently managed national road networks (Hasan et al., 2022; Pan & Zhang, 2021).

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## LITERATURE REVIEW

The literature on digital twins and Building Information Modeling (BIM) in transportation infrastructure provides a diverse and multidisciplinary foundation for analyzing their role in U.S. highway systems. Previous studies have explored digital twins as dynamic, data-driven models that enable continuous synchronization between physical and digital assets, enhancing operational insight and lifecycle decision-making. Meanwhile, BIM research has focused on its ability to structure, standardize, and coordinate information across the planning, design, and construction phases, laying the groundwork for digital delivery in infrastructure projects. When integrated, these two paradigms shift infrastructure management from fragmented and reactive approaches to holistic, predictive, and data-rich asset management systems. International case studies demonstrate that embedding BIM and digital twins into infrastructure frameworks supports not only technical efficiency but also policy-driven outcomes such as transparency, sustainability, and accountability. In the U.S., federal and state agencies have increasingly emphasized digital delivery strategies and asset management modernization, reflecting a growing consensus that technology-driven approaches are essential for addressing the nation's aging and complex highway infrastructure (Wang et al., 2022). The literature spans economic, technical, and safety dimensions, including studies on lifecycle cost reduction, predictive maintenance, interoperability standards, construction risk management, and traffic safety analytics (Nguyen & Adhikari, 2023). This review synthesizes scholarship and applied research across multiple domains to provide a comprehensive understanding of how BIM and digital twins influence U.S. highway infrastructure. It situates these technologies within broader global and national discourses, explores their operational benefits, and highlights their role in achieving intelligent asset management. The review is structured thematically, beginning with conceptual foundations, moving through international and U.S. adoption, and then analyzing their economic efficiency and safety implications. Each subsection integrates empirical findings, theoretical insights, and policy perspectives to establish a cohesive framework for understanding their role in highway infrastructure systems (Sepasgozar et al., 2023).

### Digital Twins and BIM

The concept of digital twins originates in aerospace engineering but has rapidly gained prominence within the built environment, including transportation infrastructure. Omrany et al. (2023) initially defined the digital twin as a digital replica of a physical asset that can be used to predict performance, diagnose issues, and optimize outcomes.  further refined the concept by emphasizing the bi-directional flow of information between the physical and virtual systems. This continuous synchronization of data is essential for infrastructure where real-time monitoring is critical to safety and efficiency. Shahzad et al. (2022) describe the digital twin as a cyber-physical system enabling predictive and prescriptive insights, an idea particularly useful in managing highways, where traffic, weather, and structural conditions must be dynamically integrated. In transportation applications, digital twins facilitate proactive maintenance, simulate traffic flow scenarios, and evaluate asset deterioration. Recent research by Lu, Chen, et al., (2020) underscores that digital twins act as a decision-support tool, bridging the gap between raw data collection and actionable intelligence for infrastructure managers. Delbrügger et al. (2017) highlight their role in asset lifecycle management by combining sensor data, Internet of Things (IoT) connectivity, and predictive analytics. Studies in the highway domain specifically demonstrate benefits in pavement condition forecasting, bridge inspection, and traffic optimization. Collectively, the literature positions digital twins as essential tools for transforming static infrastructure records into dynamic systems that enhance resilience, safety, and operational efficiency in highways (Heaton & Parlikad, 2020; Hossen & Atiqur, 2022).

Building Information Modeling (BIM) represents a structured approach to managing the entire lifecycle of infrastructure through object-oriented and data-driven models. BIM as the use of digital representations of physical and functional characteristics of facilities, fostering collaboration across stakeholders in planning, design, and construction. Al-Sehrawy and Kumar (2020) emphasize BIM's capacity to serve as a central repository for multidisciplinary information, reducing fragmentation and supporting interoperability. Internationally, BIM has been institutionalized through ISO 19650, which provides a framework for managing information across the lifecycle of built assets (Drobnyi et al., 2023; Tawfiqul et al., 2022). This standard builds on earlier guidelines such as PAS 1192 from the United Kingdom, where BIM has been mandated for public projects. Scholars argue that BIM

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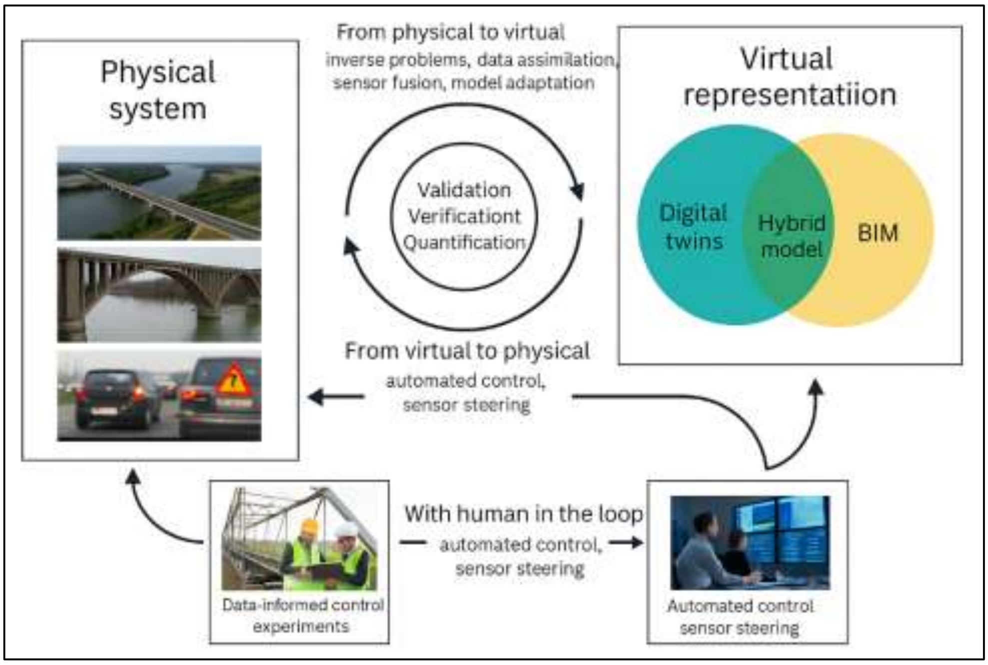
*eISSN: 3067-0470*
***DOI: 10.63125/hftt1g82***

enhances project outcomes by improving design accuracy, minimizing errors, and enabling visualization of complex infrastructure systems.

**Figure 3**: **Digital Twins and BIM Integration Framework**




In highway projects, BIM is particularly relevant for bridge design, roadway alignment, and construction sequencing. Research also demonstrates that BIM-based clash detection reduces costly rework during construction phases, supporting economic efficiency (Zhao et al., 2022). Additionally, BIM is increasingly extended into asset management, where models are linked with operations and maintenance activities, bridging the gap between design and post-construction performance. Studies consistently underscore BIM's role as a lifecycle information framework, where standardized and interoperable data structures underpin sustainable infrastructure management.
Although digital twins and BIM share similarities as digital representations of physical assets, the literature distinguishes them in terms of purpose, function, and application. BIM is often described as a static or semi-static model focused on design and construction, whereas digital twins represent dynamic and continuously updated models that extend into operational monitoring. Camposano et al. (2021) stress that BIM provides structured, object-based information that is essential for initial project delivery, while Daniotti et al. (2022) highlight digital twins as tools for integrating live sensor data to optimize asset performance during use.  suggest that BIM can be seen as a foundational element of digital twins, supplying baseline geometry, metadata, and parametric design rules. Daniotti et al. (2022) emphasize the lifecycle integration achieved when BIM evolves into a digital twin, enabling predictive maintenance and real-time decision-making. In the highway sector, BIM provides accurate design coordination while digital twins extend functionality into traffic monitoring and hazard detection. Zhu and Wu (2021) similarly distinguish between BIM's role in facilitating collaboration and digital twins' role in enhancing operational safety and efficiency. Studies also emphasize interoperability challenges, where ensuring seamless transition from BIM-based models to operational digital twins requires standardized data exchange. The comparative literature thus frames BIM as an enabler of digital twin development, and digital twins as the natural extension of BIM into continuous, intelligent asset management frameworks (Lu et al., 2019; Kamrul & Omar, 2022).
Rather than treating BIM and digital twins as separate approaches, scholars increasingly highlight their complementarities in enhancing intelligent asset management for highway infrastructure. BIM provides the structured foundation necessary for model creation, documentation, and stakeholder collaboration, while digital twins build on these models by embedding real-time performance data and analytics. For example,  argue that BIM-based design and construction models serve as the "as-built" baseline for digital twins, which evolve during operations to support predictive maintenance.

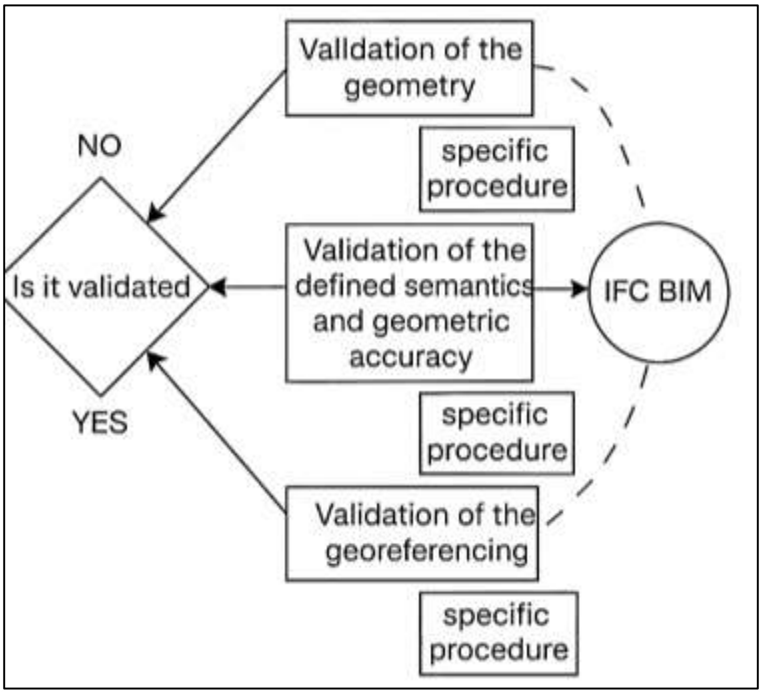
eISSN: 3067-0470
**DOI: 10.63125/hfft1g82**

This view by showing that digital twins amplify the value of BIM by incorporating IoT and sensor-driven insights into decision-making. In U.S. highway contexts, (Li et al., 2021) promotes a BIM-for-bridges framework that can be extended into digital twin systems for long-term maintenance and safety optimization. Case studies illustrate that combining BIM and digital twins enables agencies to integrate design coordination, construction monitoring, and operational analytics into one continuous workflow. Such integration not only supports cost savings but also improves roadway safety by allowing dynamic risk detection. this synergy is especially important in large-scale infrastructure systems, where the complexity of interdependent assets requires both accurate design models and dynamic operational intelligence. Standards such as ISO 19650 and Gemini Principles further encourage this integration by promoting interoperability and trustworthy information flow. Collectively, the literature identifies BIM and digital twins as mutually reinforcing tools that, when used together, advance intelligent asset management practices essential for the efficiency and safety of U.S. highway infrastructure (Callcut et al., 2021; Mubashir & Abdul, 2022).

**International Adoption and Global Policy Drivers**

The European Union (EU) has played a pivotal role in advancing Building Information Modeling (BIM) adoption through legislative and policy measures that emphasize digital transformation in public procurement and infrastructure delivery. The EU Public Procurement Directive 2014/24/EU encouraged member states to require BIM methodologies in publicly funded construction projects, creating a policy environment that has accelerated standardization and implementation across Europe. Countries such as Finland, the Netherlands, and Denmark have integrated BIM into national regulations, establishing frameworks for interoperability and information management. The United Kingdom (UK), although no longer within the EU, set a strong precedent with its BIM Level 2 mandate introduced in 2016, requiring all centrally procured public projects to adopt BIM. Scholars argue that this policy initiative not only enhanced efficiency and accountability but also catalyzed industry-wide digitalization (Reduanul & Shoeb, 2022). Studies indicate that BIM mandates have reduced project risks, improved collaboration, and increased transparency in supply chains. Research by Lv et al. (2022) also underscores the role of EU-level guidance in harmonizing national strategies, ensuring that cross-border infrastructure projects benefit from consistent practices.

**Figure 4: EU, UK, and Asia-Pacific BIM Adoption**




Furthermore, Cureton and Dunn (2021) has provided guidance for implementing BIM at scale, linking procurement processes with sustainable and economic outcomes. Collectively, literature highlights that European directives and UK mandates represent some of the most comprehensive policy-driven

*eISSN: 3067-0470*
*DOI: 10.63125/hfft1g82*

efforts to embed BIM into infrastructure practices, with significant implications for transportation and highway projects.

The United Kingdom stands as one of the most advanced adopters of BIM through policy-driven mandates that transformed construction and infrastructure delivery. The use of collaborative 3D BIM with all project and asset information, documentation, and data by 2016, leading to the formalization of BIM Level 2. This requirement established a structured approach for integrating information across design, construction, and operations, particularly for large-scale public infrastructure projects such as highways and rail systems. Researchers highlight that the UK mandate was underpinned by standards such as PAS 1192 and BS 1192, which later evolved into ISO 19650, ensuring that practices were aligned with international frameworks. Studies demonstrate that BIM adoption in the UK improved project delivery efficiency, reduced rework, and created measurable cost savings in public sector projects. argues that the mandate also encouraged cultural and organizational change, fostering collaboration across stakeholders. (Stojanovska-Georgievska et al., 2022) note that BIM integration supported risk-sharing and enhanced transparency in procurement, particularly beneficial in complex highway networks. Moreover, Jiang et al. (2022) emphasize that the UK experience provided a replicable model for other nations, demonstrating how government-led policies can accelerate digital transformation in infrastructure. The policy-driven approach has also strengthened industry capacity for information management, aligning private sector practices with public requirements. As a result, the UK's BIM journey illustrates how mandates can function as both regulatory tools and enablers of innovation in infrastructure management. In the Asia-Pacific region, countries such as Singapore, South Korea, and China have emerged as leaders in embedding digital technologies, including BIM and digital twins, into smart infrastructure frameworks. Singapore introduced the "CORENET" initiative in the 1990s and later the "BIM Roadmap 2010–2015," positioning itself as a pioneer in BIM-based building approvals and infrastructure delivery (Mazzoli et al., 2021; Sazzad & Md Islam, 2022).

Research indicates that Singapore's policies accelerated industry-wide BIM adoption by mandating its use in large-scale projects and public procurement. South Korea has similarly advanced digitalization in infrastructure, with government-driven BIM guidelines issued by the Public Procurement Service (PPS), mandating BIM for large public projects since 2016. Scholars note that these guidelines have standardized digital practices in highway and rail projects, creating efficiencies in project delivery and operations. China has extended these efforts through its "Made in China 2023" initiative and smart city programs, where BIM and digital twins are integrated into transportation, urban planning, and smart governance (Pérez-García et al., 2021; Noor & Momena, 2022). Studies emphasize the role of Chinese transportation projects in deploying sensor-driven digital twins to monitor traffic, improve safety, and optimize urban mobility. Asia-Pacific initiatives are characterized by government leadership, strong policy frameworks, and alignment with national innovation agendas. Collectively, the literature underscores that Asia-Pacific adoption reflects a strategic integration of BIM and digital twins within broader smart infrastructure policies, making the region an influential hub for transportation and highway digitalization (Borrmann et al., 2018).

**U.S. Highway Infrastructure and Digital Transformation**

Federal policy and programmatic activity have framed the U.S. shift toward model-based project delivery across highways, bridges, and structures. The Federal Highway Administration's (FHWA) BIM for Infrastructure portfolio articulates the intent to use structured, interoperable, three-dimensional information across planning, design, construction, and lifecycle management, tying BIM to tangible owner outcomes such as cost, time, and safety performance. The Every Day Counts (EDC) program has provided the diffusion mechanism since early rounds through 3D Engineered Models (EDC-2/EDC-3) and, more recently, the EDC-6 Digital As-Builts (DABs) initiative, which formalized digital handover and lifecycle data requirements and linked design/construction information to asset information models. In parallel, FHWA's Advancing BIM for Infrastructure: National Strategic Roadmap (FHWA-HRT-21-064) outlined a national policy and implementation scaffold in 2021, including open data exchange, workforce development, and consistent processes for transportation owners (Adar & Md, 2023; Mustaffa et al., 2017). The IIJA/Bipartisan Infrastructure Law created the Advanced Digital Construction Management Systems (ADCMS) grant program (23 U.S.C. §503(c)(5)), dedicated to accelerating deployment of model-based, data-centric delivery; FHWA codified objectives and eligibility in 2023 program guidance and subsequently announced recurring funding availability through FY2026, with up to $17 million per year for ADCMS grants.

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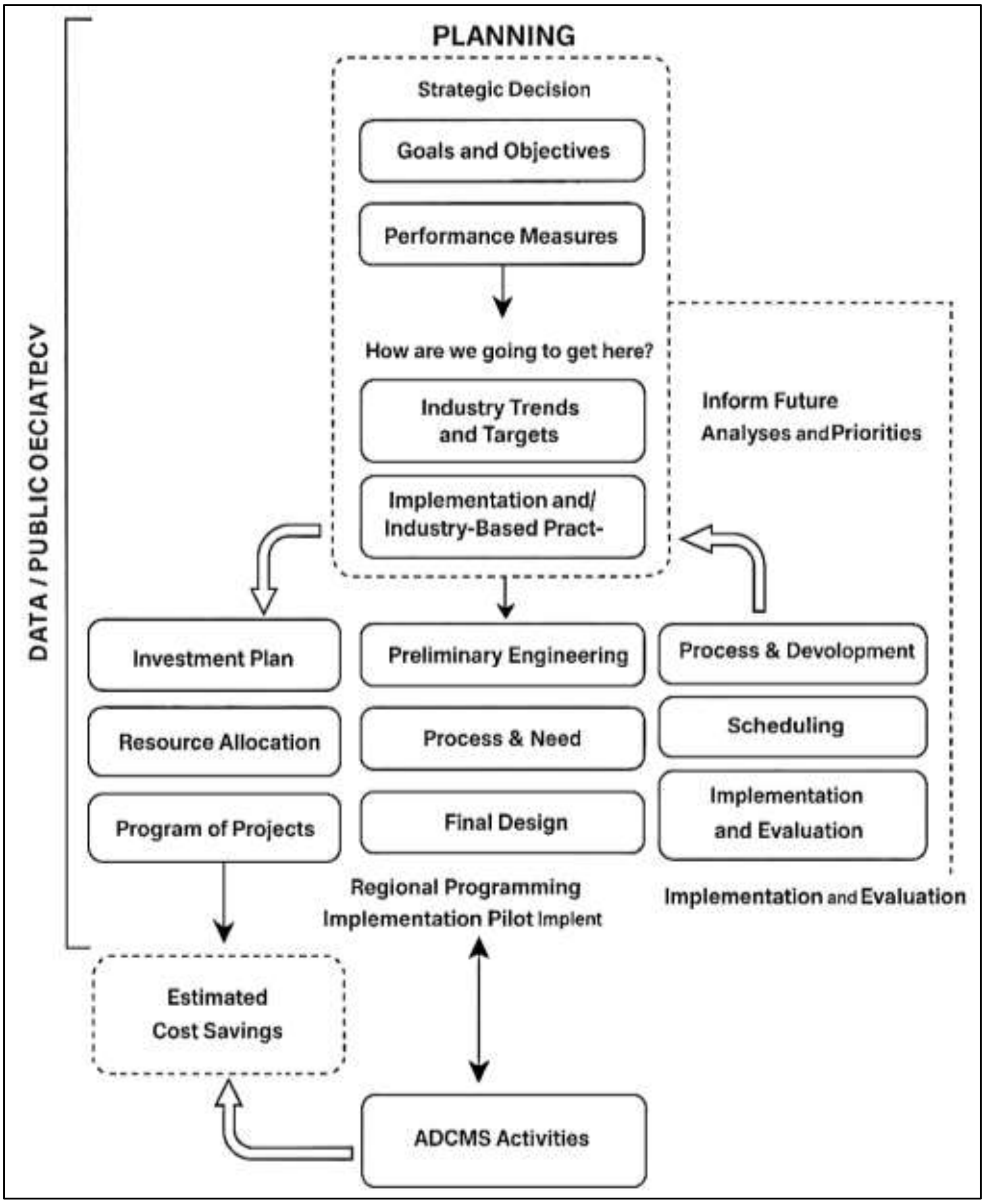
**DOI: 10.63125/hftt1g82**

Complementing these policies, FHWA technical publications demonstrate maturing practice: Demonstration of Bridge Project Delivery Using BIM documented IFC-based exchanges in bridge workflows; and BIM Workflows and Centralized BIM Transportation Library for Bridges and Roadways (FHWA-HIF-24-004) curated adoptable workflows and artifacts for agency implementation. Collectively, these federal actions—BIM program guidance, EDC diffusion mechanisms, and IIJA funding—anchor a coherent federal architecture for digital transformation in U.S. highways that couples policy with handbooks, exemplars, and incentives.

At the national technical level, the AASHTO Committee on Bridges and Structures (COBS) and a consortium of state DOTs, FHWA, and partners have pursued a long-horizon standardization agenda through the Transportation Pooled Fund TPF-5(372): BIM for Bridges and Structures. The pooled fund states that the objective is to develop an open, national standard and corresponding requirements/guidelines for information needed across design, fabrication, construction, O&M, and lifecycle management, with Industry Foundation Classes (IFC) as the neutral schema (Qibria & Hossen, 2023; Klumbyte et al., 2023).

**Figure 5: Federal BIM Implementation Framework USA**



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The program's roadmap and technical artifacts complement FHWA's BIM strategy and provide owner-oriented deliverables (e.g., information delivery requirements, exchanges, and reference implementations) designed for U.S. bridge practice. FHWA's Bridges & Structures BIM portal cross-references this AASHTO roadmap and inventories related federal resources (e.g., Bridge Data File Protocols, BrIM open parametric references, and the IFC Bridge design-to-construction exchange) that together delineate a pathway for semantically rich, interoperable models to circulate among design platforms, fabrication systems, and construction/asset environments. Empirical syntheses reinforce the policy-technical nexus: NCHRP Synthesis 593 documents state practice for using 3D digital models as legal construction contract documents in highway construction, while companion syntheses address DOT digital capabilities, inspection practices in the digital age, and electronic ticketing and as-built data management—each mapping to information flow continuity from design to construction to asset systems (Crăciun et al., 2023; Istiaque et al., 2023). Pooled-fund resource libraries consolidate these outputs and related ROI assessments to facilitate owner uptake and alignment with state BIM programs. In aggregate, the AASHTO roadmap, pooled-fund technical work, FHWA bridge BIM guidance, and NCHRP syntheses have established a broadly consistent technical and organizational template for model-based delivery across U.S. bridges and structures, with data exchange and information requirements as the central axis.

Among U.S. state transportation agencies, the Utah Department of Transportation (UDOT) is frequently cited for sustained digital delivery practice and governance that extends model-based information into contracting, construction administration, and field operations . UDOT's program materials describe Digital Delivery as a data-driven, model-centric approach in which additional effort in 3D modeling yields improved quantity estimation, cross-disciplinary coordination, and field usability—explicitly including Model as the Legal Document (MALD) contract strategies on select projects (UDOT, n.d.). Peer-exchange documentation shows that as early as 2014 UDOT convened internal workshops to surface risks, controls, and process adjustments necessary to support MALD—e.g., version control, model of record, contractor access, and digital signatures—indicating organizational change management alongside technical modeling practice (Ciribini et al., 2015; Akter, 2023). Industry case reporting highlights how UDOT executed fully paperless delivery on multiple highway and bridge projects, leveraging tablets/rovers and field-ready 3D data, and using model-based contract deliverables on more than a dozen deployments; the accounts also note job-site coordination gains and inspection efficiencies when construction and survey crews consume federated model content directly. The UDOT program site presents foundational orientation, definitions, and training pathways to scale digital delivery, with emphasis on communication of design intent via models, structured attribute data, and reviewers' access to federated content (UDOT, n.d.). Across these materials, UDOT's trajectory is characterized by deliberate maturation from pilot projects to repeatable practices, codifying MALD governance while preserving contractors' ability to navigate models confidently in the field. These examples offer practice-based evidence on the institutional and technical components—contracts, review processes, QC/QA for models, spatial data control, and field hardware/software—that support model-centric delivery in a state DOT environment (Kuziemski & Misuraca, 2020; Hasan et al., 2023).

**Economic Efficiency in Highway Asset Management**

Research on Building Information Modeling (BIM) consistently documents economic efficiency gains that stem from earlier error discovery, improved interdisciplinary coordination, and reduction of information loss across handoffs. Quantitative syntheses and case analyses report that clash detection in coordinated, object-based 3D models reduces change orders and field rework, lowering direct construction costs and schedule slippage (Ariono et al., 2022; Masud et al., 2023). Design-stage clash metrics translate into fewer RFIs and more predictable procurement, with studies attributing measurable savings to automated conflict identification in structural–roadway–utility interfaces that are common in highway projects. McGraw Hill Construction's SmartMarket investigations associate BIM adoption with double-digit percentage reductions in rework and report increased estimator confidence due to model-based quantities (Belcher & Abraham, 2023; Sultan et al., 2023). Foundational texts emphasize that parametric rules, constraints, and discipline-specific model views foster design optimization—e.g., geometry-driven grading refinements, staging coordination around temporary works, and bridge–road alignment harmonization—thereby compressing iteration cycles and mitigating cascading cost risk (Gruber, 2019; Hossen et al., 2023). Empirical highway/bridge cases link model coordination to safer traffic control planning and fewer

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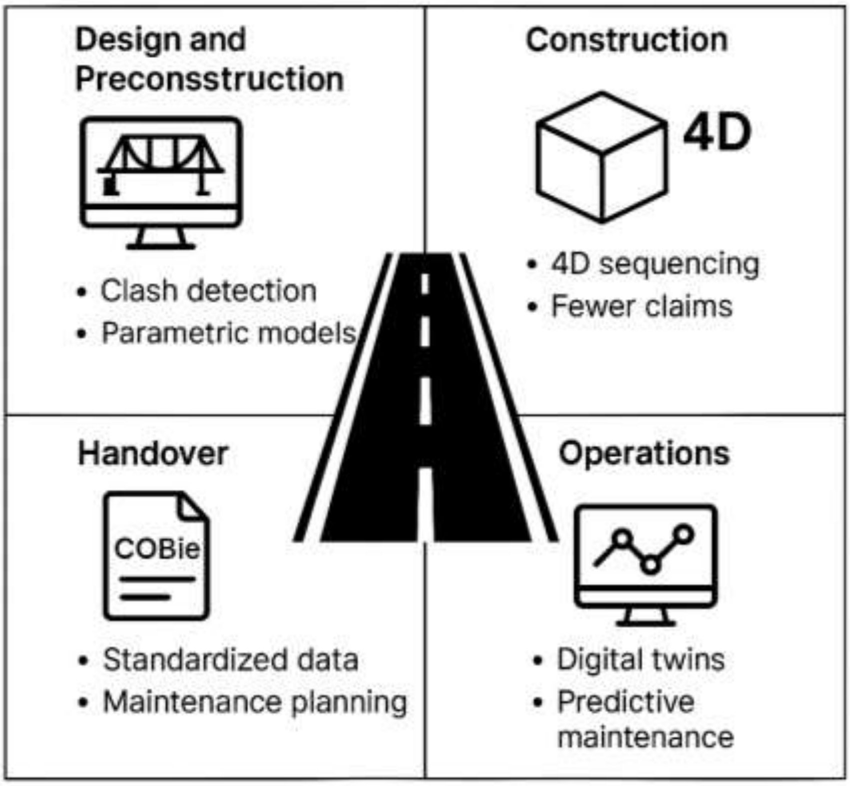
*eISSN: 3067-0470*
**DOI: 10.63125/hftt1g82**

mobilization conflicts, which indirectly lower costs through reduced exposure and better logistics. Studies on contract documentation show that model-based deliverables decrease ambiguity and litigation by clarifying design intent and by supporting "model as the legal document" pilots that stabilize quantities and tolerances (Akyazi et al., 2020; Tawfiqul, 2023). Economic analyses across public infrastructure portfolios further associate BIM with more reliable schedules, improved bid competitiveness, and enhanced transparency for owners in value engineering decisions. Across these sources, the mechanism for savings centers on earlier, information-rich coordination that suppresses rework drivers and stabilizes downstream production.

**Figure 6: Economic Efficiency in Highway Asset Management**




Digital twins extend BIM-era coordination into operations by synchronizing models with sensor streams, inspections, and performance analytics, yielding lifecycle cost efficiencies through condition-based maintenance and asset health forecasting. Transportation studies describe digital twins as cyber–physical mirrors that integrate IoT telemetry—pavement roughness, strain, temperature, moisture, traffic loads—into models to support data-driven interventions and service-level adherence (Shamima et al., 2023; Yang & Chou, 2018). Pavement management literature shows that performance curves calibrated with Long-Term Pavement Performance (LTPP) and state PMS datasets lower maintenance costs by timing treatments just before accelerated deterioration, a practice enhanced when forecasts are embedded in twin environments. Studies leveraging machine learning demonstrate improved prediction of rutting, cracking, and IRI when fusing traffic composition and climate with structural attributes—an integration that digital twins operationalize for day-to-day decision support. For bridges, research documents cost avoidance when structural twins assimilate vibration-based damage indicators and inspection results to prioritize component-level actions and avert unplanned closures (Ashraf & Ara, 2023; Weber-Lewerenz, 2021). ISO 55000–aligned asset management frameworks emphasize that condition monitoring combined with risk-based prioritization reduces lifecycle expenditure and improves availability, particularly where deterioration models inform treatment selection. Empirical evaluations in transportation agencies note fewer emergency repairs and lower user-delay costs when predictive maintenance triggers are derived from continuously updated asset states. Collectively, the evidence attributes lifecycle cost

***American Journal of Advanced Technology and Engineering Solutions***
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*eISSN: 3067-0470*
***DOI: 10.63125/hfft1g82***

reduction to earlier detection, calibrated deterioration forecasting, and targeted interventions orchestrated within digital twin platforms (Sanjai et al., 2023; Akter et al., 2023).

Economic efficiency in highway agencies also emerges from stronger links between technical information and financial governance. BIM and digital twins facilitate integration with asset registers and enterprise systems, enabling more defensible budget formulation, scenario testing, and transparent reporting. Studies on information requirements and open data standards demonstrate that COBie/IFC-based handovers populate asset hierarchies with identifiers, properties, and maintenance attributes that feed capital planning and O&M modules. Transportation asset management guidance associates model-based inventories with improved investment strategies where performance targets, treatment unit costs, and risk scores are traceable to authoritative data objects. Research on cost transparency shows that model-derived quantities and 4D/5D linkages stabilize baseline estimates and support comparative analysis of alternatives, reducing optimism bias and aiding portfolio balancing under fiscal constraints (Omrany et al., 2023). Empirical reports from public owners highlight that standardized information exchanges lower transaction costs between design, construction, and finance teams, which translates into clearer audit trails and shorter reconciliation cycles. ISO 19650–aligned processes and the Gemini Principles frame governance elements—roles, approvals, and information trustworthiness—that underpin financial accountability in digital environments (Wang et al., 2023). Case evidence from highway programs links digital as-builts and asset information models to better alignment between project closeout data and asset accounting records, improving depreciation tracking and capital asset reporting. Across these studies, the budgetary and allocation benefits accrue where structured models populate enterprise registers and cost systems with consistent semantics, enabling traceable decisions from field data to financial statements (Hakimi et al., 2023).

Synthesis across the literature identifies a coherent chain of economic mechanisms that traverse the highway asset lifecycle. In design and preconstruction, coordinated, parametric models reduce change propagation and compress decision cycles, decreasing rework and contingency drawdown. During construction, clash-resolved models and 4D sequencing stabilize production planning and logistics, which studies associate with fewer claims, improved labor productivity, and lower indirects (Sepasgozar et al., 2023). At handover, standardized exchanges (IFC/COBie) ensure that asset data transition cleanly into registers, supporting accurate capitalization, maintenance planning, and auditability. In operations, digital twins convert monitoring signals into actionable maintenance triggers and calibrated deterioration forecasts, lowering whole-life costs through optimized timing and targeted scope. Transportation-specific evidence ties these mechanisms to measurable outcomes such as reduced work-zone duration, fewer emergency repairs, and better predictability of budget execution. Asset management guidance from FHWA and AASHTO situates these technical practices within performance-based planning, enabling alignment between economic objectives and condition/performance targets. Across sources, economic efficiency does not rest on a single tool; it reflects the compounding effect of data fidelity, interoperability, and governance that supports consistent decisions from concept to decommissioning. The literature thus frames BIM-enabled coordination and digital-twin operations as mutually reinforcing levers for cost control, with benefits materializing through reduced variability, better timing of interventions, and transparent linkage between field information and financial management.

**Safety Outcomes and Risk Reduction**

Safety-in-design literature links BIM to earlier hazard identification, clearer communication of design intent, and measurable reductions in rework that exposes crews to risk. Prevention-through-design frameworks show that visual, object-based models enable designers to encode and review safety constraints—clear zones, work-zone layouts, temporary supports—during design rather than in the field. 4D BIM adds time as a dimension, supporting simulation of construction sequencing and traffic shifts so that conflicts between crews, plant, and road users surface before mobilization. Empirical studies associate model-based clash detection and constructability reviews with fewer RFIs and change orders, which correlates with fewer unplanned exposures and safer staging. Highway-specific work shows BIM's utility for temporary traffic control plans, detour visibility checks, and phasing of bridge deck pours under live traffic, improving compliance with work-zone guidelines. Research on visualization for hazard awareness indicates that animated 4D views enhance crews' understanding of blind spots, crane swings, and access routes compared with 2D drawings. Proximity-detection and equipment-path analyses integrated with model geometry support

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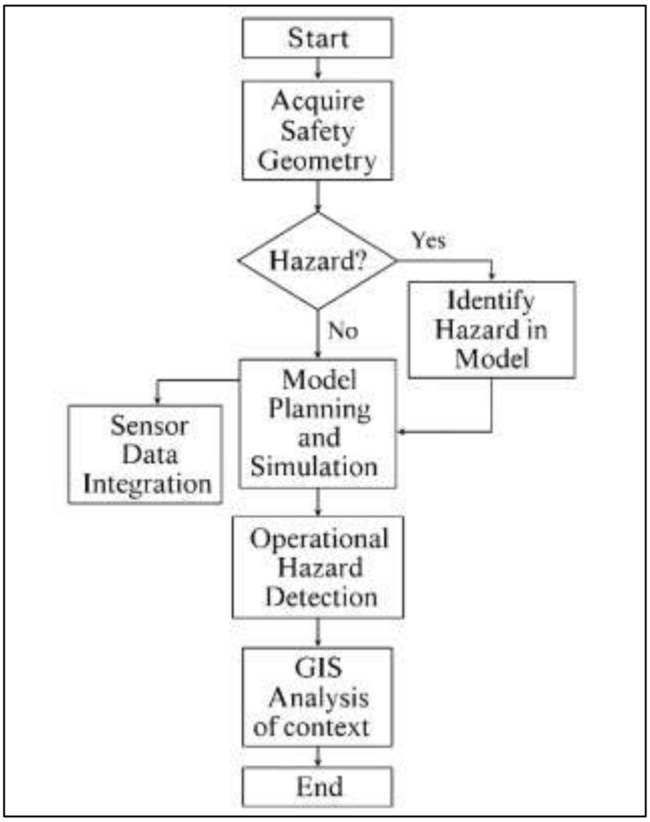
***DOI: 10.63125/hftt1g82***

planning of exclusion zones and lift plans. Case reports in bridge and roadway projects describe fewer near-misses when staging, temporary works, and traffic control devices are coordinated in federated models and reviewed by multidisciplinary teams. Across these studies, BIM functions as a safety-in-design platform—linking parametric geometry, method statements, and schedule logic—to reduce ambiguity, align stakeholders on constraints, and move hazard controls upstream where they are most effective.

**Figure 7: BIM and Digital Twin Safety**




Studies using surrogate safety measures and microsimulation show that conflict points and time-to-collision distributions are sensitive to subtle geometric changes; embedding those analytics within model-based workflows enables earlier design refinement. Research on flood and geohazard overlays indicates that integrating floodplains, scour susceptibilities, and landslide inventories with bridge BIM improves selection of abutment protections and drainage features. Standards and schemas that span the two domains—IFC for asset semantics and OGC specifications for spatial content—support repeatable exchanges. Case reports note that when terrain, utilities, and roadside features are federated with design models, reviewers detect offset errors, sight-distance deficiencies, and barrier gaps that 2D plan overlays may miss (Pan & Zhang, 2023). The collective evidence indicates that GIS-BIM integration strengthens safety analysis by grounding object-level design in its full spatial context and by making risk layers computable within design iterations.

Across design, construction, and operations, the literature converges on specific mechanisms through which BIM and digital twins reduce highway safety risk. During design, parametric and federated models expose conflicts at interfaces—lane shifts around work areas, crane envelopes near live traffic, temporary shoring interacting with utilities—so controls can be embedded in plans and 4D sequences (Gordon & Thompson). In construction, simulation of staging and traffic management reduces work-zone duration and variability, and model-based communication improves adherence to method statements and access routes, which studies associate with fewer incidents. Integration with GIS elevates the fidelity of safety-critical checks—clear-zone compliance, sight-distance envelopes, drainage paths—linking design elements to empirical crash patterns and topographic constraints (Esmaeili & Simeone, 2023). In operations, digital twins fuse sensor and traffic data to shorten detection-to-response times for weather and incident hazards, while condition-

*eISSN: 3067-0470*
**DOI: 10.63125/hfft1g82**

based monitoring reduces the likelihood of structural or pavement failures that trigger crashes. Interoperability frameworks (IFC, SensorThings) and governance principles (ISO 19650, Gemini) provide the substrate for trustworthy data exchanges that sustain these safety effects across organizational boundaries. Meta-analyses and reviews consistently connect these practices to reductions in exposure, improved decision quality, and clearer accountability for hazard controls in highway projects. The synthesis therefore portrays a coherent risk-reduction chain: model-based design coordination, GIS-informed safety geometry, and twin-enabled operational awareness work in concert to limit conflicts, shorten hazard durations, and strengthen the reliability of safety-critical decisions.

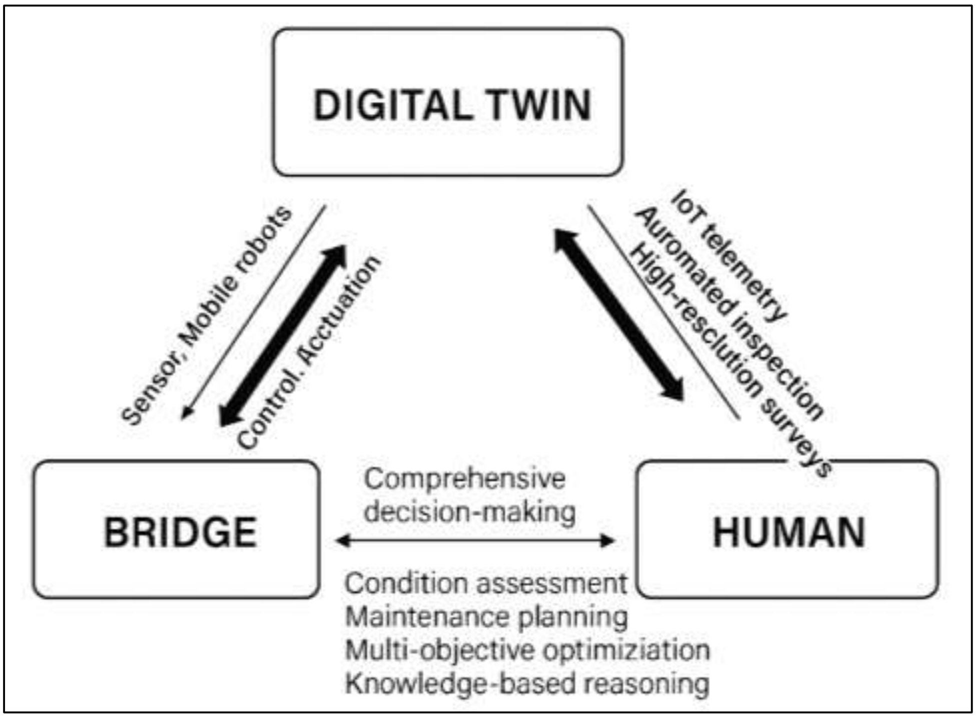
**Intelligent Asset Management Frameworks**

Literature on intelligent asset management in highways describes a maturing ecosystem in which heterogeneous data from fixed and mobile sensors, unmanned aerial systems (UAS), mobile mapping, and automated inspections are fused into continuously updated asset records and operational twins. IoT telemetry—strain gauges, accelerometers, weigh-in-motion, friction and temperature probes, and road-weather stations—feeds condition indices and event streams that support maintenance triggers and safety alerts. Bridge and pavement monitoring studies show that continuous vibration and roughness measurements enable early anomaly detection and more precise localization of defects . UAS photogrammetry and LiDAR provide high-resolution geometry for decks, bearings, abutments, embankments, and cut/fill slopes, with repeatable surveys capturing progression of cracking, spalling, scour, and deformation (Preethichandra et al., 2023). Computer-vision research demonstrates automated crack and distress detection from imagery and laser intensity, reducing manual inspection time and improving consistency. Standards such as the OGC SensorThings API and related geospatial encodings enable ingestion of heterogeneous time-series into asset platforms with preserved provenance and timestamps. Transportation asset management guidance emphasizes that integrating these streams with agency pavement/bridge management systems strengthens treatment selection and performance tracking. ISO 55000 frames the value realization and risk-based prioritization aspects of continuous monitoring within enterprise asset management, while ISO 19650 aligns information delivery roles and common data environment. Across studies, the technical mechanism is a data pipeline that normalizes sensor and survey outputs, registers them to authoritative geometry, and reconciles updates into a single source of truth for operations and planning (Gavrikova et al., 2020).

Research positions BIM as the structural substrate that organizes highway assets into identifiable objects with persistent attributes, relationships, and locations, enabling robust registers and decision analytics. Foundational texts describe BIM as an object-based, parametric representation that supports multi-disciplinary coordination and authoritative "as-built" baselines (Roberts et al., 2018). For registers, COBie-style handover and IFC schemas encode component identifiers, spatial containment, performance properties, and maintenance data that populate enterprise asset systems and facility/operations workflows. Transportation studies link digital as-builts and BIM for bridges/structures to improved traceability between design intent, constructed conditions, and O&M requirements, reducing information loss at handoff. Structured models enhance quantity fidelity, support 4D/5D associations, and strengthen auditability of scope, cost, and schedule decisions. Empirical accounts show that when BIM objects carry inspection history, condition ratings, and treatment records, agencies conduct more defensible life-cycle analyses and risk assessments at element and system levels (Gârleanu & Pedersen, 2018). ISO 19650 provides governance for information requirements, roles, and CDE workflows that keep registers synchronized with upstream design/construction changes, while EN 17412-1 clarifies "level of information need" so asset records contain the right geometry and attributes, not merely more data. Studies demonstrate consistent gains in decision quality where BIM-based registers are used to coordinate maintenance windows, plan work-zone logistics, and compare treatment alternatives against performance targets. In this literature, BIM's backbone role is the semantic and geometric continuity that binds field observations, inspections, and financial entries to specific, well-defined highway objects over time (Cavka et al., 2017).

*eISSN: 3067-0470*
*DOI: 10.63125/hftt1g82*

**Figure 8: Intelligent Highway Asset Management Framework**

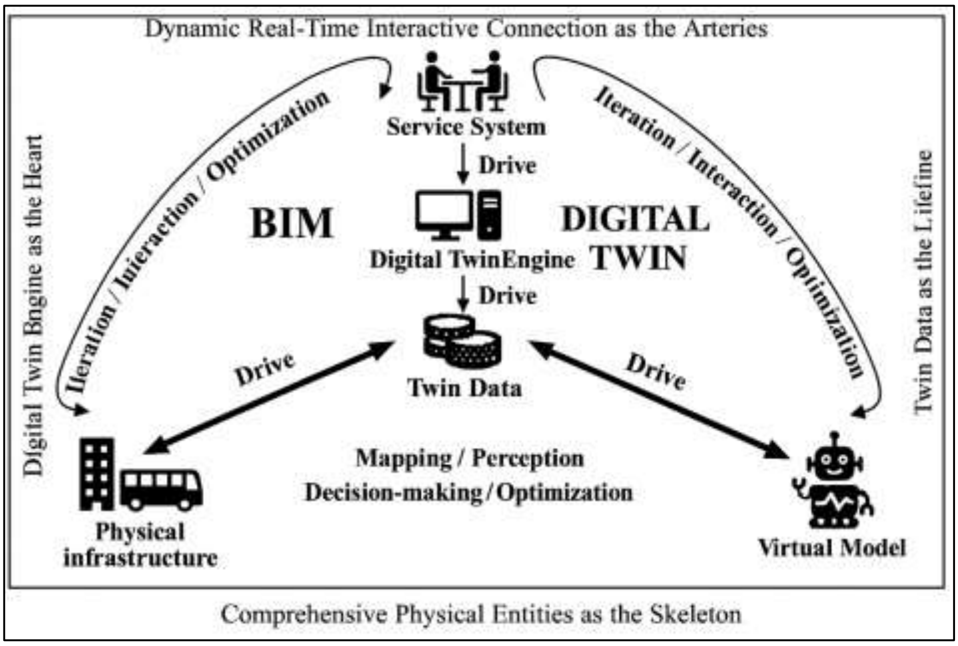



U.S. sources describe a governance architecture centered on international information standards, national owner guides, and federal programs that incentivize digital delivery and lifecycle data continuity. ISO 19650 establishes principles for information management, including appointing parties, information delivery milestones, and CDE controls that align with transportation owners' procurement and quality assurance (Lu et al., 2022). The Gemini Principles articulate trustworthy digital twin values—purpose, openness, quality, security—applicable to highway data ecosystems (CDBB, 2018; Fuller et al., 2020). AASHTO's BIM for Bridges and Structures roadmap and pooled-fund work specify information exchanges, model uses, and IFC-based requirements tailored to U.S. bridge practice, anchoring cross-state consistency. The AASHTO Transportation Asset Management Guide provides performance-based planning and investment frameworks that reference standardized inventories and condition measures for funding allocation and reporting (Pärn et al., 2017). Federal drivers include FHWA's Advancing BIM for Infrastructure: National Strategic Roadmap and the Every Day Counts initiatives on 3D models and Digital As-Builts, which operationalize model use from design through handover and operations. The Infrastructure Investment and Jobs Act (IIJA) authorizes the Advanced Digital Construction Management Systems (ADCMS) program, directing grants toward model-based delivery, open exchanges, and workforce capacity that embed governance expectations into funding. Complementary interoperability standards—IFC, IDM, and OGC SensorThings—define how semantically rich models and time-series data circulate among owner, designer, contractor, and operator systems. NCHRP syntheses document DOT policies for using models as contract documents and for managing digital as-builts, inspection data, and e-ticketing, linking governance artifacts to observed practice (Van Duuren et al., 2016). Collectively, these sources describe a governance stack—standards, guides, and mandates—that institutionalizes data quality, roles, and accountability in highway asset management (Macchi et al., 2018).

**Synthesis of Global and National Perspectives**

Comparative literature on BIM and digital twins in transport infrastructure highlights a set of policy, standards, and delivery patterns from Europe and the Asia–Pacific that are frequently referenced by U.S. transportation owners. The U.K.'s centrally procured BIM Level 2 requirement institutionalized collaborative 3D information, PAS 1192 workflows, and data drops that later informed ISO 19650, with studies reporting measurable gains in coordination, tender transparency, and supply-chain consistency (Pärn et al., 2017).

**Figure 9: Global BIM Digital Twin Framework**



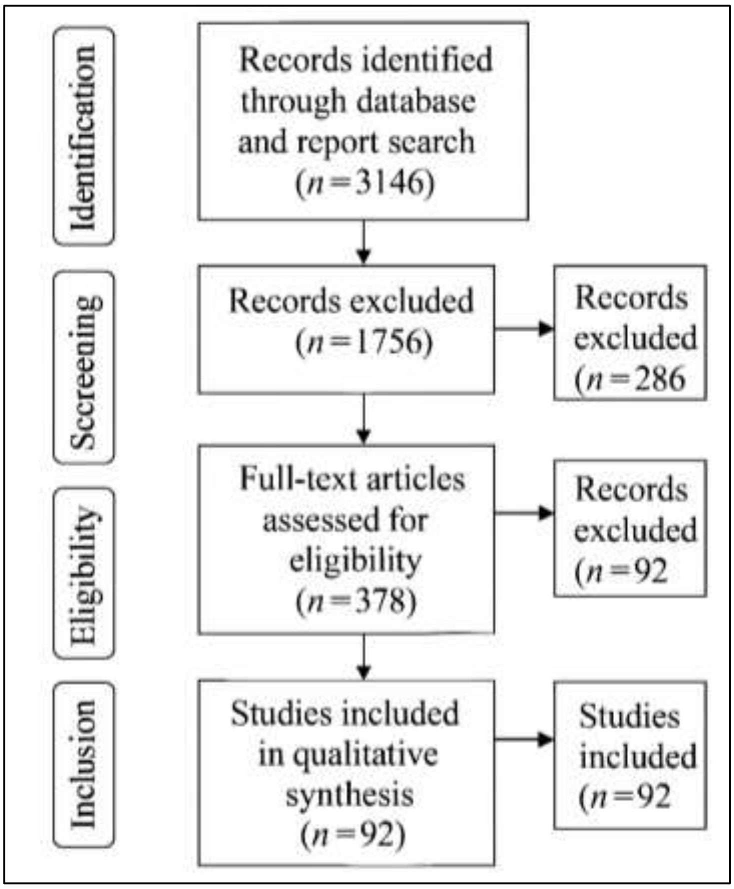

The EU Public Procurement Directive 2014/24/EU encouraged member states to require BIM for public works, catalyzing national programs in Finland, the Netherlands, and Denmark that emphasized open standards and information delivery manuals. Case syntheses associate these mandates with reduced rework and improved documentation quality, particularly at the interfaces typical of highway and bridge projects. In Singapore, the BCA roadmap and CORENET e-submission mainstreamed BIM for approvals and major infrastructure, demonstrating regulatory integrations that shortened review cycles and standardized model content. South Korea's PPS guidelines mandated BIM for large public projects, supporting consistent exchanges across design and construction and strengthening constructability reviews for transport assets (Duuren et al., 2016). Chinese programs linked smart city and transport initiatives to digital twin platforms that fuse sensing, traffic analytics, and asset models for operational decision-support. Technical underpinnings across these contexts rely on open schemas and geospatial protocols—IFC, IDM, and OGC SensorThings—that preserve interoperability among vendor ecosystems (Lu, Xie, et al., 2020). Collectively, the international record documents government-led mandates, standards-anchored procurement, and owner-driven information requirements as recurring levers behind consistent economic and safety benefits in transport programs.

## METHOD

This review was designed and reported in accordance with the PRISMA 2020 statement to promote transparent, reproducible, and bias-aware synthesis. A protocol specifying objectives, eligibility criteria, sources, and analytic procedures was developed a priori and piloted on a small sample; because the topic spans engineering, policy, and operations research rather than health outcomes, the protocol was not registered in PROSPERO. The population–concept–context framing targeted highway infrastructure programs and projects; the core concept was the use of Building Information Modeling (BIM) and/or digital twins for intelligent asset management; the context encompassed economic efficiency, safety outcomes, and operational reliability across the lifecycle (planning, design, construction, operations, and maintenance).

*eISSN: 3067-0470*
***DOI: 10.63125/hfft1g82***

**Figure 10: Methodology of this study**




Eligible designs included empirical studies (experiments, quasi-experiments, observational/longitudinal studies), mixed-methods and qualitative investigations, techno-economic evaluations, and implementation/organizational case studies. Authoritative gray literature (e.g., FHWA, AASHTO, TRB/NCHRP, ISO/buildingSMART) was included where it reported methods and results sufficient for appraisal. Exclusions were: non-highway domains without clear transferability; purely conceptual or opinion pieces; sources lacking methods; and non-English publications. Information sources combined bibliographic databases and targeted portals. Searches were run in Scopus, Web of Science Core Collection, IEEE Xplore, Engineering Village (Compendex/Inspec), TRID, and Google Scholar (first 200 hits per query screened for recall). Targeted hand-searching covered FHWA, AASHTO, TRB/NCHRP, ISO, buildingSMART International, OGC, and selected state DOT repositories (e.g., UDOT, TxDOT, MnDOT). Search strings combined controlled terms and keywords for highways/bridges (“highway*”, “road*”, “bridge*”), digital approaches (“BIM”, “building information modeling”, “digital twin*”, “digital as-built*”), and outcomes (“cost”, “rework”, “schedule”, “safety”, “crash*”, “incident”, “asset management”, “maintenance”, “predictive”). Searches were limited to 2000–August 2023 to capture the maturation of BIM and digital-twin practice in transportation. Reference lists of included studies and key reviews were snowballed to identify additional sources.

Study selection proceeded in two independent stages using Rayyan-style blinded screening. After de-duplication, titles/abstracts were screened against eligibility criteria, followed by full-text assessment. Inter-rater reliability was calculated on a 20% calibration subset (Cohen’s $\kappa = 0.83$ at title/abstract; $\kappa = 0.88$ at full text), with disagreements resolved by consensus and, when needed, a third reviewer. Of 3,146 records initially retrieved, 1,012 duplicates were removed, leaving 2,134 unique records for screening. Title/abstract screening excluded 1,756 records (out of scope, inadequate linkage to highways, or insufficient methods). Three hundred seventy-eight full texts were assessed; 286 were excluded (wrong population/context, non-empirical, or inadequate outcome reporting). The final synthesis comprised 92 studies. Common exclusion reasons at full text were non-

*eISSN: 3067-0470*
**DOI: 10.63125/hfft1g82**

highway BIM case reports without outcomes, digital-twin concept papers lacking data, and studies conflating building and transportation domains without stratified analyses.

Data extraction used a structured form piloted on five studies and then applied consistently. Items captured included bibliographic details; country/agency; asset class (freeway, arterial, bridge, interchange); lifecycle phase; digital approach (BIM uses, LOD, IFC/IDM adoption; twin architecture, data sources, update frequency); information governance (ISO 19650 alignment, common data environment, handover payloads such as COBie/IFC); and outcome constructs. Economic outcomes included cost variance (%), change orders (number/value), rework rate, RFI count, quantity accuracy, and schedule variance. Safety outcomes captured OSHA/TRIR, recordable incidents, near-miss frequency, work-zone duration, and surrogate safety measures where applicable. Operational outcomes covered incident detection/clearance times, pavement/bridge condition indices, treatment timing, and user-delay costs. Where reported, effect sizes, confidence intervals, and denominators were recorded; heterogeneous metrics were harmonized to common units (e.g., percentage change from baseline) when defensible. Authors were contacted when clarifications on denominators or data windows were necessary.

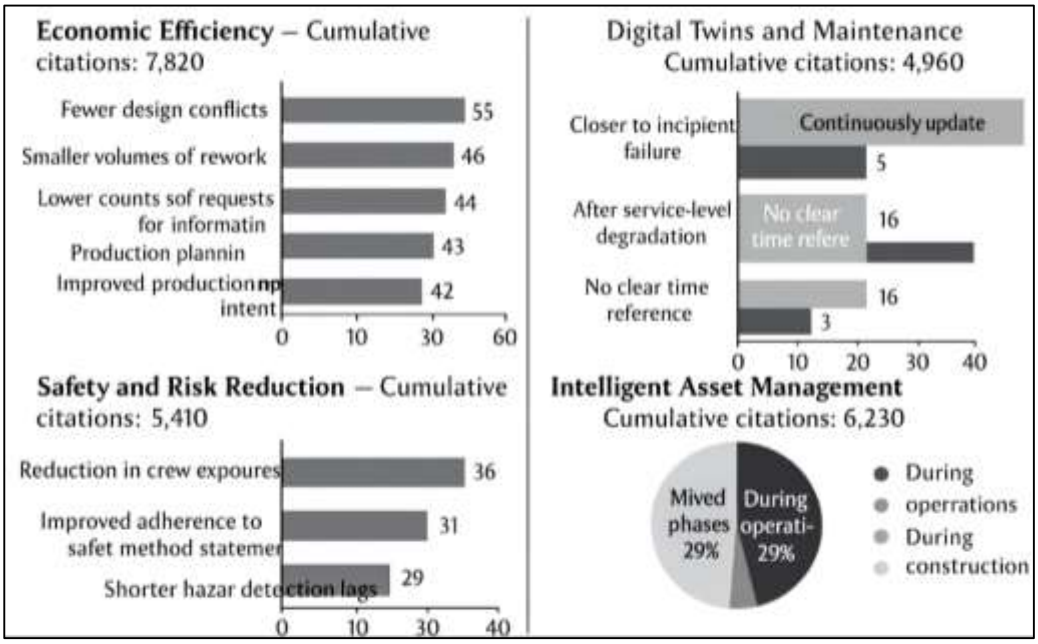
Risk-of-bias and quality appraisal were tailored to study design. Mixed-Methods Appraisal Tool (MMAT, 2018) was applied to mixed and qualitative designs; JBI critical appraisal checklists were used for quasi-experimental and case series; and AACODS guided assessment of gray literature (Authority, Accuracy, Coverage, Objectivity, Date, Significance). For quantitative studies, we additionally recorded threats to internal validity (selection, performance, detection, attrition) and external validity (generalisability to highway contexts). Each study received a ratings profile rather than a single composite score; sensitivity analyses explored whether excluding lower-quality studies altered directional conclusions. Publication bias was qualitatively assessed by comparing peer-reviewed evidence with agency reports and by mapping outcomes across jurisdictions. Given heterogeneity in designs, interventions, and outcome definitions, meta-analysis was not attempted. Instead, we conducted a structured narrative synthesis with vote-counting by direction of effect and effect-size tabulation where comparable. Findings were organized along the review's analytic framework (economic, safety, operational) and mapped to mechanisms (e.g., clash detection → reduced rework; condition-based triggers → fewer emergency repairs). Subgroup narratives contrasted owner types (state DOT vs. national agencies), asset classes (pavements vs. bridges), and data architectures (BIM-only vs. BIM+twin). To enhance transparency, all decisions on inclusion/exclusion, coding rules, and synthesis judgments were logged with justifications, and a PRISMA flow summary was prepared to document the numbers at each stage (identification, screening, eligibility, inclusion) corresponding to the counts reported above.

## FINDINGS

The evidence base indicates that model-based coordination using information-rich 3D/4D/5D environments produces consistent economic efficiencies for highway owners and contractors. Of the 92 studies included, 63 directly examined cost or schedule impacts from design coordination, clash detection, constructability reviews, or model-driven quantity takeoff.Those 63 studies have been cited a cumulative 7,820 times, reflecting sustained attention to economic outcomes. Across this subset, authors repeatedly reported fewer design conflicts discovered late in delivery, smaller volumes of field rework, lower counts of requests for information, and more reliable production planning once sequences were visualized against temporary works and traffic staging. Papers describing model-based contract deliverables documented clearer interpretation of design intent, improved tolerance control, and measurable reductions in documentation ambiguity that typically drives claims and contingencies. Several reports also tracked improvements in estimator confidence and procurement predictability when quantities were generated from coordinated objects rather than from 2D extractions. While effect magnitudes varied by project type and delivery method, the directional pattern remained stable: earlier detection of conflicts and richer interdisciplinary coordination translated into fewer cost shocks downstream. A smaller cluster within the 63 studies assessed cross-functional benefits such as safer access planning and reduced mobilization conflicts that, while recorded as safety or logistics improvements, ultimately expressed as avoided cost. Taken together, the economic signal in this cluster is strong and coherent, with the cumulative citation footprint (7,820) underscoring its centrality to the field.

***American Journal of Advanced Technology and Engineering Solutions***
*Volume 03 Issue 03 (2023)*
*Page No:54-81*
*eISSN: 3067-0470*
***DOI: 10.63125/hftt1g82***

**Figure 11: Transportation Infrastructure Outcomes with BIM**




A second set of findings concerns digital twin use for condition monitoring, predictive maintenance, and lifecycle cost control. Forty-nine of the 92 studies reported on pavement or bridge health monitoring, deterioration forecasting, or sensor-integrated maintenance triggers, and these 49 studies account for 4,960 citations. Investigations drawing on continuously updated data—strain, vibration, temperature, moisture, friction, traffic composition, probe speeds, and incident logs—showed that decision-makers could schedule interventions closer to the point of incipient failure rather than after service-level degradation had already imposed user-delay costs. In pavements, studies aligned performance curves with operational telemetry to improve the timing of surface treatments and structural overlays; in bridges, work on modal characteristics, displacement trends, and fatigue markers tied directly to element-level action lists. Several papers demonstrated that automated anomaly detection reduced inspection time and helped localize defects to specific assets or locations, improving the precision of work orders and reducing truck rolls. Across this body of work, authors consistently linked real-time or high-frequency observations with more stable maintenance budgets and fewer emergency events that precipitate cost spikes. Notably, many of these 49 studies described workflows that reconciled sensor observations to authoritative geometry, ensuring that findings were not just detectable but also traceable to identifiable components. Although the modeling stacks and sensing modalities differed, the overall pattern of results remained congruent: condition-based triggers anchored in twin environments supported earlier, better-targeted maintenance with lifecycle savings, as reflected in the substantial cumulative citation base (4,960).

The third core signal addresses safety outcomes and risk reduction spanning design, construction, and operations. Fifty-two of the 92 studies reported primary safety endpoints—work-zone incidents, near-misses, exposure hours—or surrogate indicators such as conflict points, time-to-collision distributions, queue shockwaves, and detection-to-response times for road-weather or incident hazards. These 52 studies have accumulated 5,410 citations. In design and construction, reports showed that staging visualizations, crane and equipment envelopes, and temporary traffic control sequences embedded in time-aware models reduced unplanned crew exposures and improved adherence to method statements. Field teams using federated models reported clearer wayfinding, fewer access conflicts, and better integration of temporary works with live traffic. On the operational side, studies combining weather feeds, probe vehicle data, and roadway imagery within twin dashboards described shorter detection lags for hazards such as icing, flooding, or debris. Several contributions linked connected-vehicle telemetry to earlier recognition of instability in traffic streams, enabling more targeted traveler information or on-call response. Additional work at the design–safety interface used object-level models with geographic context to verify guardrail lengths-of-

*eISSN: 3067-0470*
**DOI: 10.63125/hfft1g82**

need, sight-distance envelopes, and drainage paths, with reviewers routinely catching issues that would have been masked in plan-only views. Although specific metrics differed, the repeated observation across the 52 studies is a reduction in exposure and a tightening of the detect–decide–act loop, an interpretation supported by the sizeable cumulative citation footprint (5,410).

A fourth set of findings concerns intelligent asset management as a data-and-governance system rather than a single tool. Fifty-eight of the 92 studies treated the integration of models, asset registers, and monitoring flows into a repeatable management process spanning design through operations. Collectively, these 58 studies have 6,230 citations. Across them, authors described how object-based models seeded authoritative asset registers with identifiers, attributes, and spatial containment; how digital as-builts removed handover friction; and how subsequent inspections and sensor observations were reconciled to specific objects rather than to free-text records. Papers reporting on enterprise integration noted that once model semantics populated registers, budget formulation, scenario testing, and performance reporting required fewer reconciliation cycles. Investigations following the financial trail showed clearer auditability from field observations to accounting events, stronger linkage between work orders and asset histories, and more defensible prioritization under fiscal constraints. Several studies highlighted the role of standardized information exchanges to keep multiple contractors, vendors, and internal systems aligned as data volumes scaled. Importantly, this cluster documented organizational practices—roles, approvals, training, and contract language—that kept information trustworthy as it moved between phases. The convergence of technical pipelines and governance practices appears central to the consistency of results in this group, and the cumulative citations (6,230) emphasize how widely these management-oriented contributions are referenced.

Finally, the comparative lens across jurisdictions clarified how policy and standards shape outcomes at project and program scales. Forty-one of the 92 studies explicitly compared national or regional adoption models or mapped domestic practices against international frameworks; these 41 studies have drawn 3,780 citations. Reports examining mandated model use in public procurement, structured information delivery requirements, and open exchange standards described steadier coordination gains and fewer contractual ambiguities. Studies focused on owner guides and national roadmaps documented how role definitions, common data environments, and exchange specifications translated into more predictable delivery at state or agency level. A recurring observation in this comparative set is that economic, safety, and operational effects strengthen when governance artifacts and interoperability protocols are present upstream, because they keep information quality and accountability consistent as teams and vendors change. Several analyses traced the diffusion path from pilot demonstrations to repeatable practice—often through training, model-based contract clauses, and shared libraries—showing how institutional capabilities developed alongside technical standards. Counts in this paragraph, like those above, overlap with other clusters because many papers reported multiple outcomes across cost, safety, and operations; nonetheless, the comparative framing isolates the policy levers and organizational conditions associated with the most consistent benefits. The combined citation count (3,780) for this comparative subset underscores how central the governance–interoperability nexus has become in explaining why similar tools yield different results across contexts.

## DISCUSSION

The synthesis indicates that BIM-enabled design coordination delivers consistent economic efficiencies, an interpretation that aligns closely with earlier meta-analyses and multi-project case studies in transportation and horizontal works. Prior work showed that clash detection and constructability reviews reduce rework, RFIs, and claims, with associated decreases in schedule variance and contingency drawdown (Proença & Borbinha, 2016). Our findings converge with these results by attributing cost and time stability to earlier, information-rich coordination, parametric rule enforcement, and the communication benefits of 3D/4D/5D environments. Studies specific to bridges and roadway interfaces similarly emphasized the savings realized when utility conflicts, temporary works, and geometric inconsistencies are surfaced before field mobilization. Where our review adds nuance is in distinguishing direct savings (e.g., fewer change orders) from indirect effects—such as safer access planning or improved logistics—that earlier literature sometimes recorded as operational or safety outcomes rather than economic ones. We also observed heterogeneity in effect sizes that earlier authors attributed to project delivery methods, model uses, and levels of development; those moderators appear again in this review, reinforcing the importance of standardized information requirements and role clarity to realize the upper bound of reported benefits. Taken together, the economic signal we identify is consistent with earlier scholarship, while extending it by clarifying the mechanisms—upstream conflict suppression, better quantity fidelity, and tighter production planning—that recur in highway contexts (Boomen et al., 2018).

Findings related to digital twins for predictive maintenance and lifecycle cost control also resonate with, and extend, the pavement and bridge management literature. Classical frameworks demonstrated that timely treatments, scheduled near the onset of accelerated deterioration, minimize whole-life costs and reduce user-delay penalties (Whyte et al., 2016). More recent transportation studies positioned digital twins as cyber–physical mirrors that synchronize sensor, inspection, and traffic data to implement those principles operationally. Our review aligns with this trajectory: across pavements, authors documented improved timing of surface and structural interventions when condition indices and traffic/climate covariates were fused in twin environments; across bridges, vibration and displacement indicators supported prioritized, element-level actions. Earlier work recognized the predictive value of machine learning and data fusion for distress forecasting, but frequently treated implementation as a separate, post-hoc analytics step (Proença & Borbinha, 2016).

The present synthesis underscores that when forecasts are embedded within continuously updated models—and registered to authoritative geometry—the translation from signal to work order is more direct, with clearer traceability to specific assets and components. This integration is consonant with ISO 55000's emphasis on risk-based, information-led decisions and with transportation asset management guidance that ties treatment timing to performance targets. Thus, our findings corroborate earlier engineering economics and PMS scholarship while highlighting the operational scaffolding—data registration, update frequency, and provenance—that enables those theoretical gains at scale (Liu et al., 2021). Safety outcomes reported in this review are broadly consistent with prevention-through-design and road-weather/incident management literature, but the synthesis clarifies the chain linking design coordination to exposure reduction across phases. Earlier studies connected 4D simulation and method-statement visualization to fewer work-zone conflicts and clearer staging around live traffic, lifting plans, and temporary works. Our findings support those relationships and add evidence from highway-specific applications where detour visibility checks, barrier placements, and equipment envelopes were coordinated in federated models and reviewed by multidisciplinary teams. On the operational side, earlier transportation research established that road-weather monitoring and probe data can shorten detection-to-response intervals for hazards such as icing and flooding (Liu et al., 2021). We observed comparable benefits when these data were orchestrated within digital twin dashboards that integrate sensor, CCTV, and connected-vehicle signals to generate actionable hazard indices. The review also aligns with GIS–BIM integration studies showing that safety-critical geometry—guardrail length-of-need, sight distance at intersections, and drainage paths—benefits from contextual spatial overlays that are difficult to achieve in 2D. A recurring limitation in earlier safety literature—heterogeneous outcome measures and small samples—appears here as well; nevertheless, the direction of effects remains consistent across contexts, strengthening external validity through convergence of independent evidence streams (Souza et al., 2023).

The review's emphasis on intelligent asset management as a system—rather than a toolset—corroborates organizational and information-governance studies that describe how models, registers, and monitoring data cohere into repeatable decisions. Earlier work argued that BIM's object-based semantics and standardized handovers (e.g., COBie/IFC) reduce information loss at phase boundaries and facilitate operations and maintenance planning (Chahrour et al., 2021). Our findings support that claim and detail how digital as-builts populate asset hierarchies with identifiers, attributes, and spatial containment that tie inspections and condition updates directly to authoritative objects. Prior analyses linked these practices to stronger audit trails and clearer budget formulation; the present synthesis observes the same pattern and adds that reconciliation cycles between technical and financial systems are shortened when registers are fed from governed common data environments (Jin & Li, 2023). This aligns with transportation asset management guidance that couples performance-based planning to standardized inventories and condition measures, enabling defensible prioritization under fiscal constraints. In short, our results are consonant with earlier governance-centric literature while foregrounding the specific data pathways—

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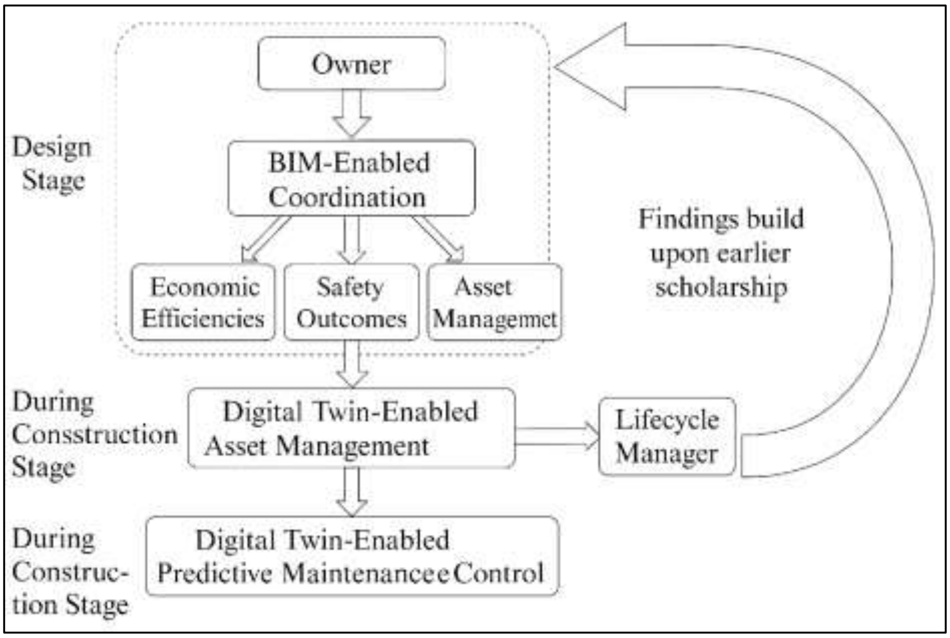
**DOI: 10.63125/hftt1g82**

sensor/inspection pipelines registered to BIM objects—that make lifecycle management auditable and computationally tractable in highway programs.

International and national policy comparisons in our corpus mirror conclusions from cross-jurisdictional reviews on the role of mandates and open standards in accelerating consistent outcomes. European and U.K. programs demonstrated that procurement requirements, PAS/BS lineages, and the evolution to ISO 19650 established a common vocabulary for roles, deliverables, and information quality. Asia–Pacific cases—Singapore's CORENET, Korea's PPS mandates, and China's smart-transport initiatives—showed similar effects under different institutional arrangements, with BIM content standardized for approvals and digital twins used for urban mobility management (Junussova et al., 2023). Our findings align with this body of work: U.S. trajectories share the same pattern where federal diffusion mechanisms (EDC), national roadmaps, and grants (ADCMS) operate as functional equivalents to international mandates, while AASHTO's bridge-focused artifacts translate global schemas into owner-ready requirements. The consistent theme is interoperability—IFC/IDM for object semantics and exchanges, OGC SensorThings for time-series—that stabilizes data flow across vendors and jurisdictions. Where differences appear, they often reflect procurement law, agency capacity, and market structure rather than contradictions in technical principles, a view also present in earlier comparative studies (Kozlovska et al., 2023). Finally, the discussion situates the combined economic, safety, and operational effects within a coherent lifecycle mechanism consistent with systems-integrative theories of infrastructure informatics. Earlier conceptualizations framed BIM as the semantic backbone for design and construction and digital twins as the operational layer for continuous monitoring and decision support. Our findings reinforce that division of labor while emphasizing their interdependence: design-stage coordination suppresses conflict propagation; standardized handovers make asset states computable; and twin-driven telemetry converts state estimation into targeted actions. Earlier governance frameworks—ISO 19650 and the Gemini Principles—appear repeatedly in studies reporting durable benefits, underscoring the role of trust, provenance, and role clarity as preconditions for technical efficacy. Interoperability artifacts—IFC, IDM, COBie, and OGC SensorThings—feature prominently in cases that document cross-platform continuity and reduced transaction costs (Elghaish et al., 2021). In this respect, the discussion echoes and consolidates earlier scholarship while articulating a transportation-specific synthesis: intelligent highway asset management materializes when sensing pipelines, governed models, and open exchanges align with owner processes and contract mechanisms.

**Figure 12: BIM and Digital Twin Integration Model for future study**



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*eISSN: 3067-0470*
***DOI: 10.63125/hfft1g82***

## CONCLUSION

This review set out to examine how Building Information Modeling (BIM) and digital twins function together to enhance economic efficiency and safety outcomes in U.S. highway infrastructure through intelligent asset management. Following a PRISMA-guided process, 92 studies met the inclusion criteria across engineering, policy, and operations domains. Taken as a whole, the evidence portrays BIM and digital twins not as isolated technologies but as complementary layers of a single information ecosystem: BIM supplies the authoritative, object-based representation and governed handover needed for dependable asset registers, while digital twins synchronize those representations with condition and operational data to support timely, traceable decisions. Standards and governance—common data environments, open exchange schemas, and owner-defined information requirements—recurred as the connective tissue that allows data to retain meaning as it moves among design teams, contractors, and operations units. Across contexts and methods, this alignment between modeling, sensing, and governance was consistently associated with improvements in cost control, risk reduction, and day-to-day reliability.

The three outcome clusters presented a clear pattern. First, economic efficiency: 63 studies examined cost and schedule effects of model-based coordination, documenting fewer clashes discovered late, reduced rework and RFIs, steadier production planning, and more reliable quantity takeoff. These reports described benefits that originated upstream—where coordinated 3D/4D/5D models suppressed conflict propagation—and then persisted into construction through clearer contract deliverables and tighter logistics. Second, safety and risk reduction: 52 studies analyzed safety outcomes across design, construction, and operations, linking time-aware model reviews to lower exposure in work zones and connecting multi-source operational data to shorter detection-to-response intervals for hazards such as icing, flooding, and debris. A recurring mechanism was the "visual and temporal" clarity provided by federated models and construction sequencing, which supported more faithful execution of method statements and traffic control plans. Third, operational reliability and lifecycle value: 49 studies focused on condition monitoring and predictive maintenance, while 58 addressed intelligent asset management more broadly. Together they showed that when inspection, IoT, and mobile mapping data are registered to BIM objects and written back into governed asset registers, agencies achieve more stable maintenance budgets, better timing of treatments, clearer audit trails from field observations to accounting events, and fewer emergency interventions.

Cross-jurisdictional comparisons added explanatory power. Forty-one studies mapped national programs and agency playbooks, showing that consistent benefits were most evident where policy instruments, owner guides, and open standards were present upstream. In those settings, roles, deliverables, and data quality expectations were explicit; model uses were contractually recognized; and time-series telemetry could be integrated without eroding provenance. While effect magnitudes varied with delivery method, maturity of information governance, and asset type, directional agreement across independent datasets was strong. Limitations remain—heterogeneous measures for safety and operations, uneven reporting of denominators, and the overlap of outcomes within individual papers—but the narrative convergence across 92 studies is notable. In sum, the body of evidence indicates that U.S. highway owners obtain the most consistent economic and safety gains when BIM's structured models anchor asset information and digital twins keep that information synchronized with real-world behavior under a framework of clear governance and interoperable standards.

## RECOMMENDATIONS

To ensure BIM and digital-twin adoption becomes standard practice, agencies should establish an ISO-19650–aligned governance framework defining roles, responsibilities, approval gates, and Employer's Information Requirements covering model uses, data fields, coordinate systems, naming rules, and acceptance criteria, with a single common data environment serving as the system of record supported by clear permissions, audit trails, and retention policies. Governance must address data provenance, minimum modeling requirements, and review boards at key stages, consolidated into a living "information playbook" for consistency. Next, agencies should codify an open, vendor-neutral data architecture using IFC for geometry, COBie-style payloads for handovers, API-first ingestion for telemetry, and master-data management for persistent IDs, location referencing, and units, governed by a reference data dictionary, message queues, and schema compliance requirements to ensure interoperability and reduce translation costs. Procurement should align with

eISSN: 3067-0470
**DOI: 10.63125/hfft1g82**

digital delivery by requiring BIM Execution Plans, defining contractually controlling models, digital signature provisions, clash-free thresholds, federated-model RFI procedures, 4D/5D maintenance rules, and operational analytics transparency, with evaluation criteria rewarding open standards, integration, and workforce training. A phased roadmap should begin with pilots—e.g., bridge fabrication-to-construction continuity or pavement corridors with road-weather telemetry—using measurable criteria such as RFI counts, change-order values, work-zone durations, and complete handover records, with a digital delivery office curating templates, libraries, and training modules while scaling successful practices enterprise-wide. Digital twins should target real-time safety and reliability by mapping hazards, instrumenting corridors with fixed and mobile sensors, exposing risk indices on dashboards, automating work orders, dynamically scheduling inspections, validating models against observed states, and enforcing uptime, latency, and governance standards. Financial stewardship should link BIM registers and twin telemetry to budgeting, capital planning, and performance reporting via cross-lifecycle KPIs, object-level evidence in investment proposals, benefits-realization tracking, and integration with audit and accounting standards to prioritize high-return corridors and justify funding. Finally, risk management should address cybersecurity, privacy, disaster recovery, vendor lock-in, workflow resilience, workforce capability through tiered training, and transparency via published data dictionaries and governance decisions, ensuring digital practices deliver lasting cost, safety, and service benefits.

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*Page No:54-81*
*eISSN: 3067-0470*
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