CCC 2025 **Proceedings of the Creative Construction Conference** (2025)
Edited by: Miroslaw J. Skibniewski & Miklós Hajdu & Žiga Turk
https://doi.org/10.22260/CCC2025/0064

ENHANCING STATE DOTS ASSET DATA MATURITY EVALUATION: DEVELOPING A DIGITAL TWIN-BASED FRAMEWORK

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Abstract

State Departments of Transportation (DOTs) are confronted with growing challenges in managing infrastructure assets due to fragmented data systems, variable quality standards, and limited real-time capabilities as needed. This study suggests a comprehensive, layered, and futured-oriented framework for measuring and improving asset data maturity, specifically tailored to state DOTs. Through synthesizing five established data maturity assessment methodologies including UK Data Maturity Assessment, American Association of State Highway and Transportation Officials (AASHTO) Transportation Asset Management (TAM) Data Assistant tool, Federal Transit Administration (FTA) TAM Self-Assessment, DCAM, and MMADQ and conceptually integrating digital twin, the proposed framework fills gaps in governance, data quality, and asset lifecycle management. It provides a five-level scale of maturity across three interdependent modules and facilitates a dynamic, data-enabled approach towards decision-making. Validation is conducted through theoretical conformity with global standards, application with a state DOT's Transportation Asset Management Plan, and comparative analysis with existing frameworks. The findings show the robustness, usability, and added value of the framework, especially in supporting future self-assessment tools and intelligent infrastructure management systems. This research provides a strategic roadmap for public infrastructure digital transformation, which enables state DOTs to enhance asset performance, optimize resource utilization, and facilitate long-term resilience.

Keywords: Digital Twin, Asset Management, State Department of Transportation, Infrastructure Management, Real-time Data Analysis.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2025.

1. Introduction

State Departments of Transportation (DOTs) play a pivotal role in managing vast infrastructure networks of highways, bridges, and public transportation [1]. It is their mandate to secure the safety, effectiveness, and sustainability of transportation infrastructure while coping with an evolving landscape of regulatory needs and performance expectations [2], [3]. At the centre of these responsibilities is the effective management of asset information, which represents a multidimensional function that comprises the collection, integration, analysis, and application of data for informing strategic decision-making, driving asset optimization, and enabling compliance with state and federal mandates [4]. However, state DOTs increasingly face critical challenges such as poor quality of data, fragmented information systems, and a lack of timely insight, which together hamper their capacity for as needed real-time infrastructure asset management [5].

Increased complexities of transportation systems and infrastructure maintenance costs emphasize the necessity of robust data practices [6]. According to the American Society of Civil Engineers (ASCE), the United States faces a $3.7 trillion investment gap in infrastructure by 2029, with aging assets and increasing traffic demands necessitating precise data to prioritize investments and allocate resources effectively [7]. However, many state DOTs continue to work with legacy tools with limited interoperability, deal with isolated data environments, and encounter workforce constraints in using advanced analytics tools[8], [9]. These challenges are compounded by regulatory programs like the Moving Ahead for Progress in the 21st Century Act (MAP-21) and the Fixing America's Surface

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Transportation (FAST) Act, prescribing detailed asset management plans and monitoring of performance [10].

This research suggests an integrated digital twin-based framework for augmenting asset data management practices for state DOTs. The framework draws on existing methodologies such as the United Kingdom (UK) Data Maturity Assessment (DMA) for Government [11], American Association of State Highway and Transportation Officials (AASHTO) Transportation Asset Management (TAM) data assistant tool [12], and Federal Transit Administration (FTA) TAM Self-Assessment [13], by synthesizing their respective strong points in governance, asset-specific practices, and enterprise-level maturity. Digital twin technology that provides virtual, as needed real-time replicas of real-world assets through sensor inputs and simulations conceptually fits into the framework to facilitate dynamic monitoring, visualizations, and decision-making [14], [15]. A major limitation of current data maturity methods is their fragmented nature. For instance, the UK Data Maturity Assessment provides robust governance assessments but weak asset-focused metrics. The AASHTO TAM Data Assistant tool offers a structured evaluation across 51 elements of the data lifecycle. However, it does not incorporate advanced technologies such as digital twins. Also, the TAM Self-Assessment delivers comprehensive enterprise-level evaluations but lacks integrating with advanced technologies. This research addresses these with a cohesive, technology-powered approach that combines these tools into one unified framework. The outcome creates the potential for practical solutions for data maturity visualizations, gaps identification, and evidence-based improvements.

The proposed framework aims to change the way that state DOTs manage their asset data through a scalable, layered, and future-oriented approach. It supports as needed real-time situational awareness, facilitates continuous improvement, and enables more strategic resource allocation. By integrating conventional data maturity assessments with digital innovation, the framework contributes to higher-level objectives of infrastructure resilience, cost-efficient maintenance, and public safety. Therefore, this study aims to equip state DOTs with a practical roadmap for modernizing their data environments and strengthening their asset management capabilities in a more data-centric environment.

2. Literature Review

To contextualize the development of the proposed framework, this section overviews prominent methodologies used for assessing data maturity and the role of digital twin technology in transportation asset management. It combines theoretical and practical principles for enabling the integration of existing methodologies and innovative technologies.

2.1. Existing Data Maturity Assessment Frameworks

Numerous methodologies have been developed to assess data maturity in the public sector and private institutions, offering structured approaches for evaluating organizational capabilities in managing and leveraging data. For state DOTs, which are characterized by complex, asset-driven operations, these methodologies provide critical guidance for the improvement of data governance, quality, and decision-making.

2.1.1. UK Government Data Maturity Assessment

The 2023 revised UK Government DMA provides a comprehensive framework for public sector organization data capabilities evaluation. Structured on 10 subjects and six themes including leadership, uses, skills, tools, data, and culture, its five-level measurement ranges from "Beginning" up to "Mastering" [11]. Adapted from the Data Orchard model [16], the tool has been used effectively with Citizens Advice Manchester and Prostate Cancer UK, helping them plan for their data strategies and influence organization-wide policies. While the framework is commendable in its robust treatment of governance and data utilization, its generalist scope may fail to tackle asset-specific challenges faced by state DOTs due to its broad structure which may cause to overlook the particular operational intricacies of state DOTs [17].

2.1.2. AASHTO TAM Data Assistant Tool

The AASHTO TAM Data Assistant is an Internet-based tool intended to aid in assessing and improving transportation agencies data and information systems for TAM. The tool offers a methodical framework

by which agencies can analyze existing practices within 51 components of the TAM data lifecycle, such as specification, collection, storage, analysis, and informed action. Each of these components is compared to existing and desired practice levels to highlight areas of discrepancy and possible areas of improvement [12]. The tool emphasizes the significance of understanding asset inventories, making well-informed decisions with the help of data, and managing data pipelines and standards. Although it is very effective at distinguishing localized gaps in data, its main limitation is that it does not integrate with advanced real-time technologies like digital twins, which is fundamental to modern infrastructure management.

2.1.3. Transportation Asset Management (TAM) Self-Assessment

Developed by FTA, the TAM Self-Assessment evaluates asset management maturity on both the asset-class and enterprise-wide level. It considers key elements such as policy development, planning, governance, data systems, and performance metrics [13]. It supports federal compliance under MAP-21 and the FAST Act and has facilitated the progress assessment of agencies and effective resource allocation. Despite its wide scope, the TAM Self-Assessment is inherently static and lacks integration with advanced technologies. Thus, its utility lies in strategic planning and alignment, but it does not support dynamic, real-time decision-making environments [13].

2.1.4. Other Relevant Frameworks

- **Data Management Capability Assessment Model (DCAM):** Formulated by the Enterprise Data Management (EDM) Council, the DCAM evaluates data governance, architecture, and quality across 11 areas of capability. While extensively used across financial and government institutions, it emphasizes enterprise-wide capabilities and may be inadequate when it comes to addressing asset-level, real-time requirements for data [19].
- **National Asset Management Assessment Framework (NAMAF):** Updated in 2023 and aligned with ISO 55001, NAMAF has wide application across Australia for the evaluation of asset management maturity across data reliability, availability, and strategic decision-making. It offers valuable lessons in standard alignment but may face regional transferability challenges [20].
- **Gartner IT Asset Management (ITAM) Maturity Model:** This model provides a structured framework for organizations to assess and enhance their IT asset management practices, focusing on the lifecycle management of hardware, software, and related technologies. It delineates five maturity levels—Initial, Repeatable, Defined, Managed, and Optimized—each representing progressive stages of process standardization, integration, and strategic alignment. Advancing through these levels enables organizations to achieve better cost efficiency, risk mitigation, and alignment of IT assets with business objectives [21].
- **Maturity Model for Asset Data Quality (MMADQ):** MMADQ focuses on data quality aspects including accuracy, completeness, and timeliness. An expansion of the model in 2023 involved predictive analytics, enhancing its ability to support data reliability, though it still lacks a comprehensive approach for technology integration and governance [22].
- **European Framework for Asset Data Maturity (EFADM):** Supported by the Horizon 2020 program of the European Union, EFADM emphasizes interoperability and lifecycle management. Its wide scope is suitable for cross-border infrastructure projects but may present adoption challenges for individual state agencies due to its complexity [23].

2.2. Digital Twin Technology in Transportation

Digital twin technology has emerged as a transformative tool in infrastructure asset management that enables real-time, virtual representation of physical assets. Monitoring, simulation, and predictive analysis are handled by dynamic models that combine data sensors, GIS databases, and asset inventories [24].

Originally conceptualized by [25], digital twins have gained traction in transportation for applications such as bridge condition monitoring, traffic optimization, and infrastructure scenario modelling. Intelligent Transportation Infrastructure presented a systematic review in 2023 that noted the benefits of

employing digital twins with Internet of Things (IoT) sensors and semantic technologies, highlighting improvements in operational efficiency, predictive maintenance, and risk mitigation [26]. Furthermore, their functional value is demonstrated through different case studies. For instance, digital twins of bridge infrastructures facilitate monitoring of structural conditions in real time, preventing their catastrophic failure and enabling data-driven maintenance scheduling [27], [28], [29]. In traffic management, digital twins for traffic flow facilitate improved congestion control and urban mobility outcomes through real-time simulations [30], [31], [32]. Additionally, digital twins facilitate sustainable urban planning by enabling visual representation of long-term implications of changes in infrastructure before implementation [33], [34], [35]. The integration of digital twin concepts in international standards such as the 2023 revised version of ISO 55001 suggests growing acceptance of their application in asset lifecycle management. However, there are challenges of high costs of implementation, reliance on high-quality data inputs, and technical challenges of interoperability between varied systems [36], [37].

3. Methodology

This section outlines the multi-step approach undertaken for the development and validation of an integrated digital twin-based framework for evaluation and optimization of asset data maturity for state DOTs. It entails synthesizing existing maturity evaluation methodologies and envisioning the implementation of digital twin technology and validation methodologies. This process ensures that the framework is theoretically valid, useful in practical application, and aligned with the continuously evolving needs of state DOTs.

3.1. Overview of the Approach

The methodology consists of three sequential phases and relies on international standards including the updated version of ISO 55001, peer-reviewed literature, and best practices for digital infrastructure management:

1. **Framework Synthesis:** Integration of selected data maturity frameworks to form a unified foundation.
2. **Framework Design and Digital Twin Integration:** Structuring the framework into structured components and embedding digital twin functionality.
3. **Validation of the Proposed Framework:** Employing theoretical validation, case study application, and comparative analysis to evaluate coherence and value.

3.2. Phase 1: Framework Synthesis

Five well-established data maturity frameworks were selected for synthesis based on their relevance to DOTs and their strengths in key assessment areas:

- UK DMA: Emphasizes governance and leadership.
- AASHTO TAM Data Assistant: Focuses on data management practices and TAM data lifecycle.
- TAM Self-Assessment: Addresses enterprise-level policy, planning, and performance.
- DCAM: Covers enterprise data architecture and governance.
- MMADQ: Concentrates on the dimensions of data quality.

Based on these frameworks, a unified conceptual foundation structured around three core modules including Governance, Data Quality, and Asset Management Maturity, each of which is evaluated using a five-level maturity scale.

3.3. Phase 2: Framework Design and Digital Twin Integration

The synthesized framework is operationalized into the following modules:

- Governance: Focused on policy, leadership, roles, and culture.
- Data Quality: Encompassing data standards, validation, monitoring, and integration.

- Asset Management Maturity: Addressing asset lifecycle planning, performance measurement, and risk-informed decision-making.

All modules are defined using the source frameworks' standards and refined for consistency and scalability. The levels of maturity are defined as: Beginning, Emerging, Learning, Developing, and Mastering.

Digital twin technology is conceptually integrated across the framework to enable:

- As needed real-time data inputs from sensors, IoT devices, and GIS platforms.
- Dynamic visualization and simulation of asset conditions and maturity.
- Enhanced decision support through predictive analytics and performance dashboards.

This integration follows principles from ISO 55001 and recent applications of digital twin systems in infrastructure domains, providing a foundation for future system development.

3.4. Phase 3: Validation

For validating the proposed framework, three validation approaches are used to verify the reliability and practical relevance of the proposed framework.

- **1.** All modules and their scales of maturity are assessed for internal consistency and adherence to recognized frameworks and established standards. This ensures logical consistency of the levels of maturity as well as conceptual validity of digital twin inclusion in the framework.
- **2.** The framework is applied to available public data from the California Asset Management Plan (2023) as a real-world case for assessment of governance, data quality, and asset management practices. The case study demonstrated the framework's ability to enable state DOTs to diagnose the level of maturity, identify gaps, and make recommendations on areas for improvement.
- **3.** To demonstrate the added value created by the proposed framework, a comparative analysis is performed aiming to benchmark the integrated framework against its five foundational methodologies and assess how effectively it combines their individual strengths while addressing their limitations. This involved comparison of each framework across major factors of assessment such as governance, quality of data, asset specificity, as needed real-time capability, and lifecycle management.

4. Proposed Framework

This section introduces the integrated digital twin-based framework designed to assess and improve asset data maturity within state DOTs. The framework addresses persisting challenges such as inconsistent data quality, fragmented systems, and limited real-time capabilities by synergizing established data maturity assessment methodologies with emerging digital twin technologies. It consists of three central modules: governance, data quality, and asset management maturity each evaluated on a five-level scale of maturity. Furthermore, the modules are interdependent on one another; governance drives data quality through formal standards and monitoring, data quality improves asset management results through reliable and actionable information, asset management maturity informs and bolsters governance policy and data strategy, and digital twin integration provides a feedback loop between modules, supporting continuous improvement and adaptive infrastructure management.

4.1. Framework Overview

The proposed framework combines elements from five of the most widely used methodologies including UK DMA for Government, AASHTO TAM Data Assistant, TAM Self-Assessment by FTA, DCAM, and MMADQ. These methodologies are chosen for their complementary strengths in governance, asset-specialized practices, enterprise-level planning, data architecture, and data quality. Combining them results in a layered, scalable, forward-looking structure that has been further augmented through conceptual inclusion of digital twin technology. This framework outlines a detailed blueprint for enabling state DOTs to analyse their current capabilities, identify gaps, and plan for strategic enhancement of asset data maturity. All modules are evaluated using a five-level measure of growing maturity including

beginning, emerging, learning, developing, and mastering. Digital twin functionality is infused through each of the modules for as needed real-time monitoring, simulation, and decision-making. Fig. 1. represents the proposed framework in detail.

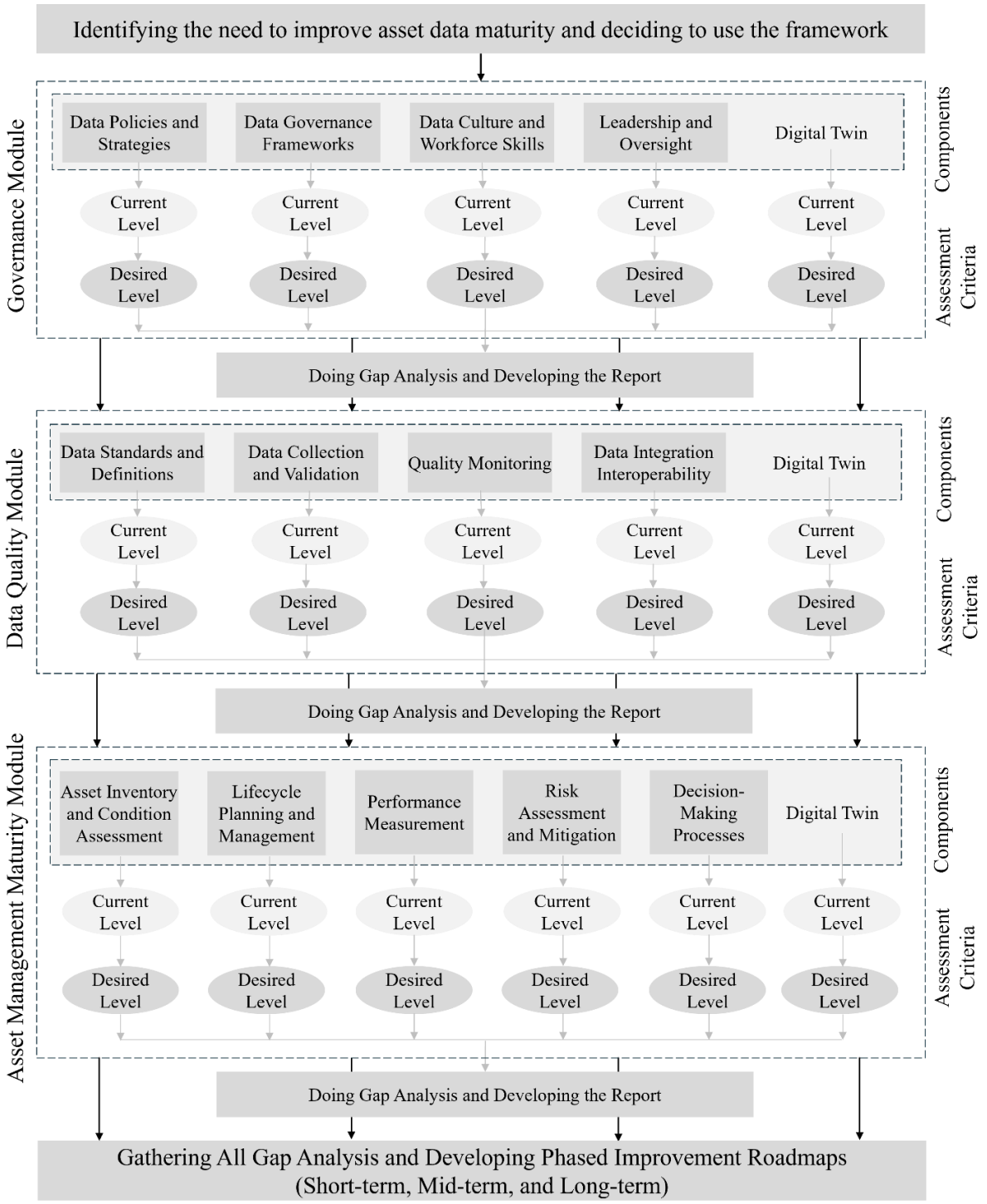

Fig. 1. Proposed framework and its components

4.2. Governance Module

The governance module establishes the institutional foundation for effective asset data management. It ensures that policies, organizational structures, and leadership practices support consistent, high-quality data management aligned with strategic goals (Table 1).

Table 1. Governance module components and details.

Purpose: This module ensures that asset data governance is not fragmented or ad hoc, but rather systematically managed and institutionally supported.	
Key Components and Definitions	
Components	Explanation
Data Policies and Strategies	Clearly defined policies for data collection, storage, access, and use, aligned with federal regulations such as MAP-21 and the FAST Act.
Data Governance Frameworks	Designated roles (e.g., data stewards), oversight committees, and accountability structures.
Data Culture and Workforce Skills	Initiatives to foster a data-driven culture and enhance staff competencies in analytics and data management.
Leadership and Oversight	Executive-level commitment to data governance, with performance audits and continuous feedback mechanisms.
Assessment Criteria	
Criteria	Definition
Beginning	Absence of formal governance or policies.
Emerging	Basic policies exist, but roles and enforcement are limited.
Learning	Governance framework established; basic training and compliance mechanisms implemented.
Developing	Formal roles and cross-departmental coordination present; oversight mechanisms active.
Mastering	Governance is fully integrated, with continuous improvement and proactive leadership engagement.

4.3. Data Quality Module

The Data Quality Module ensures that the data underlying asset management activities is accurate, complete, timely, and reliable. This is essential for informed decision-making and effective resource allocation (Table 2).

Table 2. Data quality module components and details.

Purpose: High data quality enables more reliable forecasting, planning, and maintenance, ensuring that asset-related decisions are grounded in trustworthy information.	
Key Components and Definitions	
Components	Explanation
Data Standards and Definitions	Common data formats and terminologies across asset classes.
Data Collection and Validation	Mechanisms for capturing and verifying data from diverse sources (e.g., sensors, GIS, manual inspections).
Quality Monitoring	Tools and dashboards to track data completeness, accuracy, and consistency over time.
Data Integration and Interoperability	Processes for linking data across systems and departments.
Assessment Criteria	
Criteria	Definition
Beginning	Data collection is inconsistent and lacks quality control.
Emerging	Some validation practices exist, but standards are informal.
Learning	Standardized processes implemented; periodic data reviews conducted.
Developing	Automated validation and integration across systems.
Mastering	As needed real-time quality monitoring with advanced analytics and predictive data assessment.

4.4. Asset Management Maturity Module

The Asset Management Maturity Module evaluates the agency's ability to use data across the full asset lifecycle, from planning and construction to maintenance and decommissioning (Table 3).

Table 3. Asset Management Maturity module components and details.

Purpose: This module translates improved data governance and quality into tangible operational outcomes, allowing agencies to extend asset life and reduce unplanned costs.	
Key Components and Definitions	
Components	Explanation
Asset Inventory and Condition Assessment	Comprehensive registers and as needed real-time condition data for roads, bridges, and transit infrastructure.
Lifecycle Planning and Management	Strategies for preventive and predictive maintenance informed by data analysis.
Performance Measurement	Monitoring of key metrics such as pavement condition or bridge reliability.
Risk Assessment and Mitigation	Evaluation of potential risks and prioritization of assets based on criticality.
Decision-Making Processes	Integration of asset data into day-to-day operations and long-term capital planning.
Assessment Criteria	
Criteria	Definition
Beginning	Maintenance is reactive and asset tracking is minimal.
Emerging	Partial inventory and some scheduled maintenance.
Learning	Full inventory exists; preventive maintenance underway.
Developing	Data-driven decision-making and predictive maintenance.
Mastering	Advanced simulations, as needed real-time monitoring, and optimized asset lifecycle strategies.

4.5. Digital Twin Integration

Digital twin technology is conceptually integrated across all modules to enhance their utility and dynamic responsiveness. The detail and explanations of this integration is defined in Table 4.

Table 4. Digital twin integration components and details.

Purpose: Digital twins transform the framework from a static assessment tool into a dynamic, as needed real-time decision support system capable of significantly improving operational efficiency and infrastructure resilience.	
Functional Roles in Each Module	
Modules	Role of digital twin
Governance	Enables as needed real-time performance tracking and compliance monitoring.
Data Quality	Provides continuous validation, anomaly detection, and alerts.
Asset Management Maturity	Supports simulations, scenario analysis, and predictive analytics.
Maturity Levels for Digital Twin Adoption	
Criteria	Definition
Beginning	No use of real-time data or digital twin technology.
Emerging	Limited sensors in place; minimal integration.
Learning	Digital twins applied to select assets.
Developing	Widespread adoption with simulation capabilities.

Mastering	As needed real-time decision-making powered by fully integrated digital twins.

4.6. Suggested Assessment Process and Framework Application

The framework enables state DOTs to develop self-assessment tools by providing a solid foundation for creating digital applications that automate maturity evaluations, facilitate internal audits, and support improvement planning. Table 5 represents an example of the assessment process. Also, an assessment tool based on the proposed framework could include:

- Module-specific questionnaires aligned with maturity levels.
- Scoring rubrics to identify current state and future goals.
- Gap analysis templates and improvement tracking dashboards.
- As needed real-time simulation features using integrated digital twin components.

Table 5. Suggested assessment process for the proposed framework.

Purpose: The assessment process empowers state DOTs to diagnose their organizational maturity, establish improvement pathways, and systematically enhance infrastructure management.	
Suggested Process	
1. Complete module-specific questionnaires.	
2. Score and interpret maturity levels.	
3. Identify capability gaps and prioritize actions.	
4. Repeat periodically to track progress and refine strategies.	
Assessment process through modules	
Modules	Sample Question
Governance	“Are there formal data governance policies with assigned roles and routine audits?”
Data Quality	“Is data quality automatically monitored and validated through software systems?”
Asset Management Maturity	“Is predictive maintenance based on asset condition data currently implemented?”
Digital Twin	“Are digital twins used to simulate asset performance under various conditions?”

4.7. Framework Potentials

The proposed framework offers substantial advantages and applications for state DOTs:

- **Holistic View:** Combines governance, data quality, and asset management into a unified framework.
- **As needed real-Time Responsiveness:** Enables dynamic, data-driven decisions through digital twin integration.
- **Scalability:** Adaptable to agencies of varying sizes and technological capacities.
- **Strategic Value:** Supports long-term planning, regulatory compliance, and sustainability goals.
- **Future-Readiness:** Prepares agencies for advanced technologies like AI and IoT through foundational digital practices.

5. Validation

To establish the conceptual validity, internal consistency, and practical usability of the proposed integrated digital twin-based framework, a systematic multi-method validation approach was utilized, embracing theoretical validation, application of a real-world case study, and comparative benchmarking methods. Cumulatively, these methods form a strong foundation for assessing the credibility, relevance, and value of the framework for state DOTs.

5.1. Theoretical Validation

The theoretical validation phase aims at validating that the framework has internal logic and structural consistency and is compliant with existing standards and scholarly best practices in transportation asset management and data governance.

5.1.1. Literature and Standards Alignment

Each core module, governance, data quality, and asset management maturity, was cross-referenced with widely accepted models and regulatory mandates:

- The governance module bases its content significantly on the UK DMA for Government and the EDM Council's Data Management Capability Assessment Model (DCAM), both of which focus on leadership, culture, skills, and public sector accountability for data governance, thus supporting federal mandates such as MAP-21 and the FAST Act.
- The data quality module has its foundation on the Maturity Model for Asset Data Quality (MMADQ) and AASHTO TAM Data Assistant's criteria for managing data . It also includes ISO 8000 standards, covering critical aspects such as accuracy, completeness, timeliness, and consistency which are vital for reliable decision-making within asset management.
- The asset management maturity module expands on the FTA's TAM Self-Assessment and the ISO 55001 standard, consolidating concepts of lifecycle planning, risk-based prioritization, and performance monitoring across both enterprise and asset-class levels.

This alignment with internationally accepted standards and recent research literature confirms that the framework rests on a solid conceptual foundation and is appropriate for application in state DOT environments with sophisticated infrastructure networks and evolving data challenges.

5.1.2. Consistency Checks

All the maturity modules are tested for logical progression. The Governance module, for instance, evolves from Beginning (no policies) through Mastering (active, fully integrated evidence-driven culture). The same checks are enacted for all of the modules to ensure that each level of maturity is independent, progressive, and actionable.

5.2. Case Study: California Transportation (Caltrans) Asset Management Plan

To evaluate the proposed framework's practical application, it was benchmarked with the Caltrans Asset Management Plan (2022), a comprehensive public report that describes data strategies, performance objectives, and life cycle practices for different transportation assets and the results are as below for each module of the framework:

- **Governance:** Caltrans' well-defined asset governance framework, including an Asset Management Steering Committee and formal incorporation of asset data in strategic decisions, placed the agency on the "Developing" level. Thus, Opportunities for advancement could include increasing feedback loops and strengthening cross-functional monitoring to achieve Mastering.
- **Data Quality:** Caltrans utilizes standardized condition ratings and quality checks on a periodic basis. However, delays in inspection data reporting and the absence of automated validation tools put it at the "Learning" level. Therefore, real-time quality monitoring and validation based on sensors would be the focus areas for improvement.
- **Asset Management Maturity:** The organization employs predictive modelling and risk-driven prioritization for critical assets such as bridges. These practices align with the "Developing" level with opportunities for further development through digital twin simulations and advanced analytics.

Hence, the Caltrans case proves the framework's diagnostic capabilities, identifying both strengths and gaps, enabling state DOTs to better realize the improvement areas. Furthermore, the experience proved the usefulness of the framework in leading effective improvements in asset data practices, particularly in preparation for digital transformation.

5.3. Comparative Benchmarking

The integrated framework was benchmarked against its source methodologies to evaluate its comprehensiveness and added value. As shown in table 6, it can be realized that:

- The integrated framework offers broader coverage and deeper insights than any individual model.
- It is the only framework incorporating as needed real-time data streams and digital twin technology.
- It supports both high-level strategic planning and asset-level operational decision-making, enhancing its applicability across diverse DOT contexts.

Table 6. Comparative benchmarking different aspects of the proposed framework

Criteria	UK DMA	AASHTO TAM Data Assistant	FTA TAM Self-Assessment	DCAM	MMADQ	Proposed Framework
Governance Structure	✓✓✓✓	✓✓	✓✓	✓✓✓✓	✓	✓✓✓✓✓
Asset-Specific Assessment	✓	✓✓✓✓	✓✓✓	✓	✓✓	✓✓✓✓✓
Data Quality Focus	✓✓	✓✓✓	✓	✓✓	✓✓✓✓	✓✓✓✓✓
Real-Time Capability	✗	✗	✗	✗	✗	✓✓✓✓✓
Digital Twin Integration	✗	✗	✗	✗	✗	✓✓✓✓✓

6. Validation

The development and validation of this proposed framework outlined in this study offers a timely and strategic solution to contemporary challenges of state DOTs in managing infrastructure assets. This section discusses its broader implications, practical applications, and contributions to academia and industry practice.

6.1. Bridging Fragmentation in Asset Data Management

A core driver for this study is the pervasive fragmentation in asset data systems within state DOTs most of which still have siloed platforms and inconsistent data protocols, hindering accurate, timely, and actionable insights. The outlined framework offers state DOTs a systematic way for measuring existing capability, diagnosing gaps, and applying targeted enhancements. By aligning with well-established standards such as ISO 55001 and incorporating best practice elements of frameworks such as UK DMA, AASHTO TAM Data Assistant, and DCAM, the framework not only makes its recommendation practical and widely transferable but also allows DOTs to adapt their development pathway based on organizational capacity, regulatory requirements, and strategic priorities.

6.2. Advancing Toward Digital Maturity with Digital Twin Integration

One of the most significant contributions of this framework is how it conceptually integrates digital twin technology, elevating it beyond static assessment tools. Unlike traditional maturity models which are solely based on documented records and scheduled reviews, this framework envisions a dynamic, as needed real-time data ecosystem in which digital twins serve as continuous monitoring and decision-support tools. As demonstrated in recent research and referenced in validation phase, digital twins can facilitate predictive maintenance, improve risk analysis, and optimize performance of infrastructure through simulations. Integrating this functionality into the maturity framework gives state DOTs a blueprint for moving toward smart infrastructure systems, where data not only informs decisions but actively shapes operational responses in real time. This aligns with broader trends in the public sector digital transformation, where agencies are being challenged to leverage emerging technologies to enhanced service delivery, transparency, and resilience. The framework therefore positions state DOTs to move beyond reactive maintenance and siloed data management to proactive, data-informed stewardship of assets.

6.3. Practical Utility and Flexibility

The framework is developed to be layered and scalable to fit state DOTs of different sizes, levels of technology readiness, and strategic goals. Agencies can execute the framework for comprehensive

maturity scoring or implement specific modules based on their most critical needs including developing governance frameworks, enhancing data quality, or updating asset life cycle approaches. Proposed assessment process also supports organizational learning. Through facilitated questioning of internal stakeholders, the system supports cross-functional discussion and advances a culture of continual improvement. Additionally, explicit definitions of maturity levels help provide concrete steps that can be included in performance plans, grant requests, and compliance reporting.

6.4. Contributions to Theory and Practice

From a theoretical perspective, the research makes a novel synthesis of current data maturity models, enriched with forward-looking technological incorporation. The framework merges fragmented aspects of lifecycle planning, governance, and quality assurance and places them within the context of digital transformation of infrastructure, addresses existing calls in the literature for more holistic and technology-enabled strategies to infrastructure asset management.

In practical applications, the framework provides a basis for state DOTs to create decision-support tools to inform internal audits, strategic planning, and investments in technologies. Its compatibility with publicly available data, as illustrated in the case of the Caltrans example, also positions it as a potential benchmark across agencies, enabling inter-agency knowledge-sharing and collaboration.

6.5. Future Applications and Adaptability

Although the proposed framework is designed for state DOT environments, its core principles can be applied to other public agencies that are asset-intensive such as water utilities, aviation agencies, or transit agencies, that face similar data and infrastructure issues. The layered nature makes it suitable for potential development through the incorporation of AI-based data analytics, blockchain-based auditability, or automated compliance report systems in the long term. As transport agencies continue to digitize their operations, the framework can evolve for increasingly automated, and increasingly intelligent asset management platforms that not only capture asset performance data but also financial, environmental, and social impact indicators.

7. Conclusion

This research provides a holistic, layered framework to evaluate and improve asset data maturity of State DOTs. By synthetizing five established maturity models and conceptually embedding digital twin technology, the framework addresses key gaps in different areas such as governance, data quality, and asset life-cycle management. Organized in three interdependent modules, Governance, Data Quality, and Asset Management Maturity, the framework enables state DOTs to move from fragmented, reactive approaches to proactive, data-driven, and resilient infrastructure management. The framework was verified through theoretical alignment, a real-world case study with Caltrans, and comparative benchmarking which demonstrated its robustness, adaptability, and added value over existing standalone frameworks. Notably, its incorporation of digital twin capabilities enables as needed real-time condition monitoring and predictive decision-making, positioning the framework at the forefront of state DOTs digital transformation. However, the study has certain limitations. The framework was developed conceptually and not yet developed into a working software tool. Further, its verification used mostly publicly accessible data and not direct expert comments or subsequent field test, which may limit insight into real world implementation challenges. Looking ahead, the framework offers strong potential for future development. Development of a digital self-evaluation platform based on its structure could enable automated assessments, benchmarking, and dynamic visualization of improvements in data maturity. Further research should involve pilot studies with state DOTs to confirm usability and refine module parameters. Also, technological enhancements, such as integrating AI-based forecasting, blockchain for data transparency, and machine learning for asset prediction, could extend its as needed real-time capabilities. Moreover, the framework's core design is adaptable to other asset-intensive sectors, making it a promising foundation for broader public infrastructure modernization.

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