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PROPOSING A DIGITAL TWIN DATADOSE FRAMEWORK FOR ASSET MANAGEMENT IN STATE DEPARTMENTS OF TRANSPORTATION

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SUMMARY: *The economic competitiveness, quality of life, and travel safety of a state hinge on the effective management of its transportation assets as overseen by the state and local jurisdictional Departments of Transportation (DOTs). To operate, maintain, upgrade, and expand assets, Transportation Asset Management (TAM) was developed as a strategic and systematic data-driven decision-making process that relies on quality asset data to guide decision-making. However, within state DOTs, every division that interacts with an asset documents parts of its history, resulting in data fragmentation. This shifted the focus of state DOTs to digital project delivery and Digital Twins to close the gap in capturing data and leverage the effectiveness of TAM. The following paper contributes to the data discourse withing state DOTs and proposes the DataDOSE framework that is data- and user-centered to support successful data-driven asset management decision-making in state DOTs. The framework is a middle-out approach that does not rely solely on top-down directives, but rather fosters a collaborative culture where ideas flow both upward and downward in the agency, empowering all stakeholders to contribute their valuable insights. DataDOSE encompasses four steps: Defining assets through the lens of data, Organizing asset data into the Asset Data Structure, Strategizing with a Data Governance Plan, and Executing with a Data Management Plan. This paper discusses the elements that state DOTs need to consider in answering why data is important, what data is needed, and how to govern and manage data. This paper builds the foundation for multiple future directions including developing a user-friendly digital tool based on the DataDOSE framework, establishing appropriate Key Performance Indicators (KPIs) to measure the framework's effectiveness, and ultimately creating guidance documents and training materials to facilitate the adoption of the DataDOSE framework across state DOTs.*

KEYWORDS: *Asset Data Management, Digital Project Delivery, Digital Twin, Data Framework.*

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1. INTRODUCTION AND BACKGROUND

1.1 Transportation Asset Management

The transportation network serves a vital role in the development of any state, and thus, the successful management of the state's transportation assets is key for the state's economic competitiveness, quality of life, and travel safety (Arizona Department of Transportation, 2021). Transportation assets include all components necessary for the operation of a transportation system including pavements, highway bridges, tunnels, ancillary structures, and other physical components of a transportation system (National Archives, 2023). To manage such assets, the Transportation Asset Management (TAM) is defined by the American Association of State Highway Transportation Officials (AASHTO) as a "strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their life cycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision making based upon quality information and well-defined objectives" (Federal Transit Administration, 2022). TAM helps state Departments of Transportation (DOTs) set priorities and encourages data-driven, performance-based decision-making (National Archives, 2023).

Following the enactment of the Moving Ahead for Progress in the 21st Century Act (MAP-21) in 2012, state DOTs were required to develop a risk-based Transportation Asset Management Plan (TAMP) for the National Highway System (NHS) to improve or preserve the condition of the assets and the performance of the system, as stated under 23 U.S.C. 119(e) (Federal Highway Administration, 2023c). While state DOTs are required to address pavements and bridges in their TAMP, the legislation encouraged state DOTs to include other infrastructure assets within the highway right-of-way (Federal Highway Administration, 2022b). The Louisiana, Minnesota, and New York state DOTs were the three pilot states to create a TAMP. The Federal Highway Administration (FHWA) first gave state DOTs full certification of their TAMP in 2018 and must certify at least every four years that the state DOT's processes for developing its TAMP meet applicable requirements (Federal Highway Administration, 2022d). Most recently, and according to the Bipartisan Infrastructure Law (BIL) in 2022, state DOTs are required to include extreme weather and resilience as part of the life-cycle planning and risk management analysis within their TAMP (Federal Highway Administration, 2022a).

Effective TAM relies on good asset data to guide effective decision-making (Federal Highway Administration, 2023c). Quality data regarding the asset history, inventory, current condition, and functional performance is needed to inform decisions regarding the development, maintenance, improvement, and rehabilitation of assets during their service lives (Hagedorn et al., 2023; Spy Pond Partners, LLC, 2021). Given the data- and analysis-intensive nature of TAM (Spy Pond Partners, LLC, 2021), a TAMP cannot be developed in silos and requires input from across the agency (Federal Highway Administration, 2023c). However, state DoTs face unique challenges in maintaining a comprehensive asset inventory and data. Within an agency, changes to the asset condition and physical properties occur in a variety of ways and are documented by different departments within the agency, making it difficult to maintain a current inventory (The National Academy of Sciences, Engineering and Medicine, 2022). Subsequently, asset data is scattered across various departments, systems, and databases, which leads to fragmented asset data that is both time-consuming and challenging to collect, verify, and analyze when needed making it difficult for state DoTs to maintain a comprehensive and up-to-date asset inventory (The National Academy of Sciences, Engineering and Medicine, 2022). The integration challenge is further compounded by the sheer scale and geographic extent of transportation assets under state DOT jurisdiction. State DOT asset portfolios may contain thousands of miles of pavements, bridges, culverts, signs, signals, and other infrastructure that are geographically dispersed over very large areas. Collecting and consolidating data on the condition and performance from such dispersed assets is an enormous logistical task. Moreover, another major challenge is the lack of standardization and interoperability of data across state DOTs and their information systems. This, in turn, entails different formats, methods of collection, and storage systems within state DOTs that hinder seamless sharing and integrated analysis of asset data (Girard, 2020). Thus, state DoTs require innovative approaches to transportation asset management that can overcome the fragmentation, integration, and other abovementioned challenges inherent in their data environments.

1.2 Digital Project Delivery

Fueled by the rapid technological advancements in the construction industry, digital project delivery, which is a way of working where projects are conceived, planned, designed, built, and operated in an interactive digital space that all stakeholders can access, has become the focus of state DOTs, creating the impetus to close the gap in capturing data. FHWA noted the rapid evolution of digital technologies presents state DOTs with new opportunities for improved data collection and utilization in asset management (Federal Highway Administration, 2022c). FHWA began its Everyday Counts (EDC) program as a joint effort between FHWA and AASHTO to push innovations. EDC Rounds 2 (2013-2014) and 3 (2015-2016) involved 3D models in construction, where one EDC-2 activity encouraged "3D Engineered Models for Construction", and EDC-3 expanded the scope to a topic of "3D Engineered Models: Schedule, Cost, and Post-Construction". EDC Round 4 (2017-2018) included e-construction and partnering, and EDC Round 6 (2021-2022) included e-ticketing and digital as-builts (DAB).

Additionally, FHWA established a national strategic roadmap to provide state DOTs with a comprehensive and coordinated approach to implementing Building Information Modeling (BIM) for Infrastructure (Mallela & Bhargava, 2021; Pavard et al., 2023). Most recently, FHWA launched the BIL's Advanced Digital Construction Management Systems (ADCMS) Grant Program to provide federal funds to "promote, implement, deploy, demonstrate, showcase, support, and document the application of advanced digital construction management systems, practices, performance, and benefits" (Federal Highway Administration, 2023a). These various FHWA efforts aim to help agencies better utilize data created during design and construction for business needs during operations and maintenance (Federal Highway Administration, 2022c). Below are highlights of some state DOTs with their digital project delivery journey.

The Florida Department of Transportation's (FDOT) digital delivery guide aims to equip design professionals with the necessary skills to utilize digital certificates for signing and validating contract documents (Florida Department of Transportation, 2016). The digital certificates eliminate the need to scan paper documents for signature approvals and securely streamline the entire contract document process from concept to construction. Overall, the guide aims to modernize and optimize document handling procedures, enhancing efficiency and reducing reliance on traditional paper-based workflows (Florida Department of Transportation, 2016).

The Minnesota Department of Transportation (MnDOT) integrated its DABs program with its asset management plan, encompassing around 75 asset classes, where contractors are required to collect DABs for 12 asset classes that are part of its TAMP (Minnesota Local Technical Assistance Program, 2022). Their geospatial location data format ranges from 2D latitude/longitude spreadsheets to 3D survey files, all adhering to specific formats to facilitate integration into statewide or regional asset tracking tools. As a result of this implementation, MnDOT has seen a 30% increase in data collection efficiency. Additionally, MnDOT is piloting the use of digital delivery with DAB information on a construction project, incorporating 3D model-based project delivery with their Construction Manager/General Contractor (CM/GC) project delivery approach. The 3D model-based project delivery combined with CM/GC contracting helped refine project design and estimates leading to a documented savings of $15 million out of the $130 million guaranteed maximum price for the project (Minnesota Local Technical Assistance Program, 2022).

The Michigan Department of Transportation (MDOT) has embraced digital workflows for project delivery, particularly engineering data models (Federal Highway Administration, 2019). Since 2012, MDOT has provided 3D digital models as part of reference information documents, which enables contractors to estimate bids, compare against contract plans, and prepare files for automated machine guidance (AMG) equipment. MDOT continues to collaborate with local consultant and contractor associations to achieve their goal of making digital data part of the contract documents (Federal Highway Administration, 2019). The Digital Delivery Work Group was established in June 2016 seeking to advance digital delivery concepts through collaboration between MDOT, the Michigan Infrastructure and Transportation Association (MITA), and the American Council of Engineering Companies (ACEC). Ultimately, MDOT aims to instill a culture of collaboration which is a critical component for partnering, empower technical champions to keep innovation at the forefront, and use programmatic partnering that enables agencies to scale their current and future technology capabilities (Federal Highway Administration, 2019).

The Pennsylvania DOT (PennDOT) Digital Delivery Directive of 2025 (3D2025) aims to modernize PennDOT's project delivery processes to include 3D technology and deliver contractual information in digital formats (Pennsylvania Department of Transportation, 2023). The benefits of using 3D models have been documented at length (Dadi et al., 2022; Ramadan et al., 2023). By 2025, construction project designs for bids will include 3D models and other digital data, and contract documents will transition from traditional 2D PDF plans to 3D models (Nnaji et al., 2023). This shift will enable PennDOT to streamline processes and effectively manage asset information as the assets evolve throughout project development. The objective of this plan is to use 3D technology to create high-quality, data-rich models of the assets affected by construction projects; use accessible digital processes and tools to support all project development functions by all stakeholders; and develop and implement new information management processes for capturing asset information from projects and using the information to improve inspections and asset management (Kovacic & Honic, 2021). Such benefits will allow PennDOT to improve the design quality, reduce risks and project costs, control delays, increase construction efficiency, and improve as-built records (Pennsylvania Department of Transportation, 2023). The benefits of as-built records have been documented at length (Nassereddine et al., 2023; Patel et al., 2023).

The Utah Department of Transportation (UDOT) is aiming to transform the way it manages and delivers projects, offering new ways to view, understand, and use digital project design data in the field. UDOT aims to compile data digitally from each stage in the lifecycle of the project, thus reducing the need for paper, capturing as-built information, and aiding decision-making by downstream users. In 2019, UDOT published its Model-Based Design and Construction (MBDC) Guidelines for digital delivery and was the first agency to create detailed modeling standards. The guidebook provides project teams with the guidance needed to execute MBDC for digital delivery. The document contains the current progress, lessons learned, and best practices to date, yet they acknowledge that the technology is constantly advancing and there is a need to continuously update their guidelines (Utah Department of Transportation, 2019).

The Iowa Department of Transportation (Iowa DOT) created a strategic plan for integrating digital delivery across their agency (Sharp, 2022). Iowa DOT has made progress towards digital delivery by including systems for e-ticket tracking (providing all stakeholders with an electronic means to produce, transmit, and share materials data and track and verify materials deliveries enhances safety, streamlines inspections, and improves contract administration processing), as-built records, asset maintenance data, and right-of-way inventory management. Their plan seeks to develop consistent digital deliverables, support new tools, manage assets using digital models, and implement data management processes aligned with Iowa DOT's enterprise goals. Such a digital transformation potentially enhances information sharing and asset management, and can provide a greater value to external users like contractors and suppliers (Sharp, 2022).

The power of digital project delivery has also been highlighted internationally. Notably, England has laid out its new visionary plan for a digital revolution that will transform the management and operations of the country's national highways and roads to bring significant changes in the transportation sector (National Highways, 2021). This plan focuses on five key themes: a digitally enabled network, connected vehicles, customer-centered services, a data-driven approach, and a transformative culture. To implement the plan, England is attempting to incorporate cutting-edge digital solutions to create a smarter, safer, and more efficient transportation sector (National Highways, 2021). The plan aims to improve the design, construction, operation, and user experience of the transportation industry. This plan seeks will leverage technologies to introduce repeatable, modular designs and digital twins to expedite the design process, improve efficiency, and reduce waste and carbon emissions (Drinkwater, 2021). Additionally, data will be used to enhance digital operation and decision-making in managing traffic flows to improve road performance and safety. To drive this digital transformation, National Highways plans to invest £27.4bn in the Strategic Road Network between 2020 and 2025. They will launch two new IT frameworks—the £1.5bn Information and Technology Commercial Framework (ITCF) and the £500m Operational Technology Commercial Framework (OTCF)—to provide the necessary technology for the strategic road network, opening opportunities for both large and small suppliers (Drinkwater, 2021). Australia is another country leading digital delivery initiatives. An industry-wide paradigm shift in digital project delivery is largely being driven by the Australian transport authorities (Hamid, 2021). While change is difficult as it has taken a long time to make progress, they are now at the point of exponential growth for the requirements around digital engineering and the collection and use of digital data throughout an asset's lifecycle, including and throughout the project delivery phase. The government has been proactive in articulating why the industry needs to take a digital engineering approach. Most recently, industry stakeholders have been focused on defining how to create, capture, deliver, and use digital data in a manner that is easily consumable by all project stakeholders (Hamid, 2021; Samuelson & Stehn, 2023).

1.3 ISO 19650

The international community has united behind the ISO 19650 approach to construction information management, which is a set of comprehensive standards developed by the International Organization for Standardization (ISO) used for the management of information throughout the lifecycle of a built asset using BIM (Maier, 2020; Plannerly, 2022). The ISO 19650 consists of five parts related to the organization and digitization of information about buildings and civil engineering works, including building information modeling, and information management using building information modeling, which are (British Standards Institution, 2022):

- ISO 19650-1: Concepts and principles;
- ISO 19650-2: Delivery phase of the assets;
- ISO 19650-3: Operational phase of the assets;
- ISO 19650-4: Information exchange;
- ISO 19650-5: Security-minded approach to information management.

ISO 19650-1 establishes a framework for business processes that support creating and managing information using BIM. It covers various aspects such as project and asset information management perspectives, defining information requirements and resulting models, information delivery cycles aligned with the asset lifecycle, project and asset information management functions, collaboration through information containers, information delivery planning, collaborative information production, and the use of a Common Data Environment (CDE) solution and workflow (International Standard for Organization, 2018a; Maier, 2020). On the other hand, ISO 19650-2 describes high level processes for quality management for data and information. It requires tasks to undergo quality assurance checks according to project procedures and methods. Successful checks lead to reporting the outcome, while unsuccessful checks result in rejection, with the author receiving comments on required corrective action. Before information is shared in a common data environment for collaboration, it must undergo independent review to ensure it meets all data requirements, the necessary information level, and coordination needs with other task teams. An "Information management matrix" is recommended by ISO 19650 to organize quality checks and reviews for each task and ensure the successful completion of this process (International Standard for Organization, 2018b).

Examples of BIM studies that used ISO 19650 include developing a BIM Enterprise framework that can support asset management (Godager et al., 2022a, 2022b), designing a BIM-based plug-in solution that automates and standardizes naming project files (Ajayi et al., 2023), integrating BIM with the environmental product declaration (Almeida et al., 2023), and enhancing BIM for sustainability and energy modeling (Pan et al., 2023). Overall, ISO 19650 aims to standardize and improve BIM processes, enhance collaboration, and remove barriers to working across international borders in the construction industry.

1.4 Digital Twins: The Future of TAM

Recognizing the need to overcome data-related challenges, state DOTs recently began exploring the potential of Digital Twins as a scalable information management strategy that leverages the benefits of digital delivery and supports asset management (Federal Highway Administration, 2021b; Utah Department of Transportation, 2021). The Digital Twin of transportation assets is defined by (Ammar et al., 2023) as the "digital representation of an actual physical asset or system of assets (i.e., existing or to-exist asset/or system of assets) connected bi-directionally through geometric and semantic data integrated with layers of spatial data of the surrounding environment, and linked with real-time data." In (Kritzinger et al., 2018), research on Digital Twins was classified into three subcategories, each having a specific level of data integration. The Digital Model is the digital representation of the physical space that does not involve any automated data exchange between the physical and virtual space. Digital Shadow builds on the Digital Model subcategory and enables an automated one-way data flow between the physical and virtual space. Digital Twin takes Digital Shadow a step further where the physical and virtual space are fully integrated in both directions (Jahangir et al., 2024). A study on Digital Twins in the construction industry showed that the industry is mostly in the Digital Model subcategory with an intensive research stream on Building Information Modeling (BIM) (El Jazzar et al., 2020; Khoshkenar & Nassereddine, 2024a). The results of the study also suggested that the industry is moving toward Digital Twin which is fueled by the increased interest in Digital Shadow (El Jazzar et al., 2020). UDOT, for instance, shared its Digital Twin

Strategic Plan that establishes the overarching vision to link its various investments in digital asset information through the concept of Digital Twin (Utah Department of Transportation, 2021). FDOT announced new holographic Digital Twin technology for three counties to better enable utility infrastructure planning and decision-making (Khoshkenar & Nassereddine, 2024b; Latief, 2022). Minnesota DOT leveraged integrated technology applications to create a digital model early in the engineering process of a pilot project to provide a true virtual representation of what will be built, allowing stakeholders to easily review the project impact (Smart Industry, 2022).

The implementation of Digital Twins in the infrastructure industry to support asset management requires the availability of quality asset data (Ammar et al., 2023) as well as a data structure to limit data gaps and contextualize the vast amounts of available and future data (Saroj et al., 2023). UDOT highlights in their Digital Twin Strategic Plan that the ideal Digital Twin solution has two critical elements: 1) the business architecture that automates the collection of the enterprise component of transactional data; and 2) a data governance framework to ensure a single source of relevant information is accessible, current, and of transparent provenance and quality (Utah Department of Transportation, 2021).

2. GAP AND OBJECTIVES

In the realm of Digital Twins and digital project delivery, data is the engine of digital transformation (Bou Hatoum et al., 2023). However, it has been well documented that almost every organization faces challenges in establishing a single, reliable source of truth for their asset data. The fragmentation of the vast amounts of data, the inability to identify and isolate data that is of interest for the enterprise vs data that is of interest for current needs, and the accumulation of diverse quality issues and inconsistencies across various systems within state DOTs is a significant challenge for implementing Digital Twin and making informed asset management decisions. The objective of this paper is to contribute to the ongoing data discourse within the transportation industry by developing a data and user-centered framework to support state DOTs through their Digital Twin journey and support data-driven decision-making for asset management.

3. LITERATURE REVIEW

3.1 Enterprise Architecture

Architecture at the level of a whole organization is widely known as Enterprise Architecture (EA). EA represents a coherent set of principles, methodologies, and models utilized in conceiving and realizing an organization's organizational structure, business processes, information systems, and infrastructure in past, current, and future states (Niemann, 2006). EA captures the fundamental aspects of the business, Information Technology (IT), and their evolution. The underlying premise is that these fundamental elements exhibit greater stability compared to the specific solutions that are used to address current challenges. Thus, architecture plays a crucial role in safeguarding the essentials of the business while preserving maximal flexibility and adaptability. EA serves as the systematic 'blueprint' for defining an organization's current or future environment, coupled with a process for development and maintenance. EA also functions as a pivotal planning discipline that guides and optimizes an organization's IT investments, translating business strategies into practical and implementable technological solutions (Jonkers et al., 2006). Moreover, EA offers a long-term vision of an organization's processes, systems, and technologies to ensure that individual projects can build their capabilities, and not merely fulfill current demands (Ross et al., 2006).

A well-defined architecture plays a crucial role in positioning new developments within the framework of existing processes, IT systems, and other assets of an organization, and aids in identifying necessary changes. Consequently, effective architectural practices not only foster innovation and change, but also provide a balance between stability and flexibility for a company. The insights derived from enterprise architecture are essential for determining business needs and priorities for change while also evaluating the potential benefits of technological innovations. Furthermore, in an increasingly interconnected world, no enterprise can afford to focus solely on its internal operations. An enterprise architecture becomes a valuable asset in comprehending the interconnections with customers, suppliers, and other partners (Jonkers et al., 2006).

Several frameworks for EA have been discussed throughout the literature. The Zachman Framework is a two-dimensional classification scheme for descriptive representations of an Enterprise (Jonkers et al., 2006). In this framework, different perspectives are being represented over the process of engineering and manufacturing complex products (Zachman, 2003). The main perspectives are identified as follows: The Planner's role is to define the enterprise's direction and business purpose, establishing a contextual framework for development. The Owner takes a conceptual stance, utilizing the business model to articulate the nature, structure, function, and organization of the business, with a strong focus on deliverables. Shifting to a logical perspective, the Designer employs the system model to describe the business in terms of information architecture concepts, concentrating on specifications and meeting owner expectations. The Builder's physical perspective is represented by a technological model, defining the technology for information processing, including relational databases, programming languages, structures, and user interfaces while focusing on production and assembly. Lastly, the Subcontractor is closely focused on creating reusable components based on the constructor's specifications, providing detailed perspectives on programs, databases, and network requirements in a particular programming language (Zachman, 2003). The Zachman framework aims to address six fundamental questions that progress towards distinct abstractions. These six questions are systematically correlated and are visually represented in the columns of the framework matrix. Every perspective addresses these questions from its unique viewpoint, resulting in diverse descriptive representations. The questions include: What (inventory sets), how (process flows), where (distribution networks), who (responsibility assignments), when (timing cycles), and why (motivation intentions) (Zachman, 2003).

The Open Group Architecture Framework (TOGAF) is a framework for enterprise architecture. The Architecture Development Method (ADM) constitutes the central component of TOGAF, which describes a systematic approach for developing and overseeing the life cycle of enterprise architecture (Dedic, 2020). ADM is an iterative cyclic process that requires checks and validation through every step. TOGAF is structured on four interconnected areas of expertise known as architecture domains: Business Architecture focuses on defining the organization's business strategy, governance, organizational structure, and key business processes. Data Architecture focuses on the logical and physical aspects of the organization's data assets, detailing their structure and associated data management resources. Applications Architecture provides a comprehensive blueprint for individual systems, illustrating interactions between application systems and their relationships to core business processes. It also establishes frameworks for exposing services as business functions for integration. Lastly, Technical Architecture, or technology architecture, outlines the necessary hardware, software, and network infrastructure to support the deployment of core, mission-critical applications. These architecture domains collectively form the foundation for the systematic development and management of enterprise architecture within the TOGAF framework (Josey, 2011).

The Federal Enterprise Architecture Framework (FEAF) is the enterprise architecture of the US federal government. It offers a common approach for the integration of strategic, business and technology management as part of organization design and performance improvement(The White House, 2013). The Consolidated Reference Model within the FEAF provides federal agencies with a unified language and framework for analyzing and assessing investments. These reference models collectively form a structured framework for depicting essential elements of federal agency operations in a standardized manner. By employing the FEAF and its associated vocabulary, effective management of IT portfolios is facilitated, promoting collaboration and driving transformative initiatives throughout the Federal government. The FEAF includes several reference models designed to support the different aspects of enterprise architecture(The White House, 2013). The Performance Reference Model (PRM) facilitates architectural analysis and reporting in the strategy sub-architecture view, linking agency strategy, business components, and investments to measure their impact on strategic outcomes. The Business Reference Model (BRM) combines business and service component reference models, promoting collaboration by describing an organization through a taxonomy of common mission and support service areas. The Data Reference Model (DRM) aids in discovering existing data holdings and understanding their meaning to support performance results. The Application Reference Model (ARM) categorizes system- and application-related standards, enabling the sharing and reuse of common solutions. The Infrastructure Reference Model (IRM) categorizes network and cloud-related standards to support the delivery of service capabilities. Finally, the Security Reference Model (SRM) provides a common language and methodology for discussing security and privacy in the context of federal agencies' business and performance goals. Each reference model contributes to the overall effectiveness of the FEAF by addressing specific aspects of enterprise architecture (The White House, 2013).

Enterprise Architecture Planning (EAP) within the field of EA involves the strategic planning process of defining information architectures to support business operations and outlining the implementation plan for these architectures (Budiman et al., 2018; Spewak & Tiemann, 2006). The EAP model is structured into four levels. The first level, "Getting Started," focuses on initiating the planning process by creating an EAP workplan and emphasizing the importance of securing high-level management commitment. It includes the Planning Initiation component, involving decisions on methodology, stakeholders, necessary support, and toolset selection. Moving to the second level, "Where We Are Today," this layer establishes a baseline for defining the eventual architecture and the long-term migration plan. It includes Business Process Modeling, which is a compilation of the knowledge base about business functions and information used in processes, and Current Systems and Technology, defining existing application systems and supporting technology platforms. The third level, "The Vision of Where We Want to Be," outlines the fundamental definition process flow, covering Data Architecture, Applications Architecture, and Technology Architecture. Finally, the fourth level, "How We Plan to Get There," involves creating Implementation/Migration Plans, specifying the sequence for implementing applications, a schedule for implementation, a cost/benefit analysis, and a clear migration path (Budiman et al., 2018; Spewak & Tiemann, 2006).

A systematic literature review on EA implementation methodologies identified 28 effective practices recommended for use in EA implementation methodology that were discussed and analyzed in the existing literature (Rouhani et al., 2015). These practices are: governance, alignment, interoperability and communication, modeling, continuum, design creation, repository management, change management, quality management, architectural design, integration, specification document, security, initiation, institutionalization, transition plan, management, prioritizing, gap analysis, conceptualization, designing target architecture, defining baseline architecture, requirement management, supply chain, optimization, business strategy, evaluation, and references model. Each factor is backed by relevant studies, providing a comprehensive references for detailed discussion on each practice into enterprise architecture practices (Rouhani et al., 2015). Additionally, this systematic literature review identified 19 factors that make EA implementation methodology effective. Those factors are: effective communication, optimal alignment, continuous improvement, selecting effective process, effective collaboration, agility, efficiency, consistency, adaptability, step by step guidelines, abstraction levels standardization, structured analysis and design, holistic scope, value driven, appropriate governance mechanisms, clear scope and purpose, appropriate management practices, adequate EA tool support, and flexibility (Rouhani et al., 2015).

3.2 Data Architecture

The overview of the existing work on data frameworks shows that “data” is a broad concept that encompasses a wide range of interconnected functionalities that collectively enable organizations to effectively leverage their asset data. At a high level, the reviewed work highlights data concepts that focus on understanding assets and their data and stakeholders, governing data, and managing data. Understanding these terms is important when creating a data framework to ensure that the framework encompasses all data-related activities.

Data Architecture is defined as “a discipline that documents an organization's data assets, maps how data flows through its systems and provides a blueprint for managing data, with the goal is to ensure that data is managed properly and meets business needs for information” (Doe et al., 2024; Stedman, 2022). According to The Global Data Management Community (DAMA), Data Architecture is defined as “designing and maintaining the data infrastructure to support data integration, data quality, and data accessibility” (Earley et al., 2017). In (Knight, 2023a), Data Architecture is defined as what “describes the infrastructure that connects a Business Strategy and Data Strategy with technical execution. Ideally, Data Architecture happens within a systematic framework, providing a foundation for people and systems to work with data”.

Businesses strategically choose technologies based on prevalent Data Architecture patterns (Knight, 2023a). Centralized data architectures, such as Data Warehouses, consolidate data storage in a single repository, offering a unified view of business data. Data Marts, which are subsets of data warehouses, are tailored to specific business lines, and Data Lakes, which are flexible undefined structures that can hold vast types of data. (Knight, 2023a).

A well-constructed data architecture offers crucial benefits for businesses and enterprises (IBM, 2024). For instance, modern data architectures break down silos, facilitating integration across domains and providing a more consistent understanding of metrics, customers, and products. Finally, these architectures address data management across its lifecycle, allowing for the migration of aging data to cost-effective storage options without compromising accessibility for reports and audits. In essence, a robust data architecture enhances data quality, facilitates integration, and optimizes data management over time, contributing significantly to informed decision-making (IBM, 2024).

The FHWA Enterprise Data Architecture aims to strategically prepare for technological advancements by implementing effective data modeling and designing efficient information exchange between systems (Federal Highway Administration, 2017). The FHWA's objectives include categorizing and cataloging FHWA data containers, managing duplicate or overlapping data sources, integrating data containers into the target environment for improved business intelligence analytics, maintaining the legacy data environment until a complete transition, and providing Application Program Interfaces (APIs) for both public consumers and trusted internal data exchanges (Federal Highway Administration, 2017). The current FHWA data environment operates through segmented data sources across functional units such as FHWA Headquarters, Federal Lands, Turner Fairbanks, and more. These units host data in diverse locations with varying structures, often as silos without standardized formats. Data exchange is divided into four tiers: Bulk Data involves collecting plain text or XML data from providers like Delphi and State Partners; Data Ingestion utilizes Extract Transform Load (ETL) tools for complex transformations, incorporating optimized processes like ELT for staging databases; Data Processing manages data quality and availability, storing structured data in relational databases and unstructured data in file servers; and Information Delivery which provides data through extractions, reports, websites, and limited BI services to consumers, with read-only access by default, and special permissions required for full data access (Federal Highway Administration, 2017; Harode et al., 2023). The FHWA plans to adopt an incremental approach for transitioning into the "Target" Enterprise Data Environment (T-EDE), concurrent with the development of a near-term FHWA Cloud Implementation Plan with the goal of mitigating risks by gradually releasing data operations into the T-EDE. The FHWA T-EDE envisions a services-based infrastructure hosted on the Cloud, highlighting its improved network capacity. Major components of the T-EDE include data sources, extract and commit processes, a data access and transformation API, public and trusted zones, data hubs, communication connectors, and business applications and platform services. Data sources consist of repositories with varied formats and interconnections, while the extract and commit activities facilitate event-driven data transfer for transformation. The Data Access and Transformation API ensures data transformation before entering designated zones. The public zone handles open data, and the trusted zone manages restricted data. Data hubs serve as logical segments for data consumption and preparation. Finally, communication connectors enable the exchange of formatted data, and business applications utilize data for various purposes at the application tier (Federal Highway Administration, 2017).

3.3 Data Governance and Data Management

According to the Data Governance Institute, Data Governance is "a system of decision rights and accountabilities for information-related processes, executed according to agreed-upon models which describe who can take what actions with what information, and when, under what circumstances, suing what methods" (Halttula et al., 2020; The Data Governance Institute, 2022). DAMA , defines Data Governance as "the exercise of authority and control (planning, monitoring, and enforcement) over the management of data assets" (Earley et al., 2017). The FHWA defines Data Governance as "the discipline that establishes the criteria and requirements for data; their quality, management, policies, business process; and risk management for handling of data within FHWA" (Federal Highway Administration, 2021a). In (Knight, 2023b), Data Governance is defined as a "a business program and bedrock that supports harmonized data activities across the organization. It accomplishes this goal as a formalized framework implemented to the specifications of a corporate Data Strategy". The common thread in these definitions is that data governance is about enforcing the rules for controlling and managing data allowing for effective decision making.

According to DAMA, Data Management is "the development, execution, and supervision of plans, policies, programs, and practices that deliver, control, protect, and enhance the value of data and information assets throughout their lifecycles" (Earley et al., 2017). In (Kakarlapudi & Mahmoud, 2021), Data Management is defined as "Obtaining, processing, safeguarding, and storing information about an organization to aid with making better business decisions". In (Zide & Jokonya, 2022). Data Management is defined as a "A group of activities relating to the planning, development, implementation, and administration of systems for the acquisition, storage, security, retrieval, dissemination, archiving and disposal of data". The common theme across all these definitions is that Data Management describes the processes and activities for the practice of collecting, safeguarding, organizing, and accessing data to support effective data-driven decision-making processes (Vestin et al., 2023).

DAMA created a framework that defines 11 functional areas of data management, also known as the DAMA Wheel (Earley et al., 2017). At the heart of the wheel is data governance that provides direction and oversight for data management to ensure the secure, effective, and efficient use of data within the organization. Surrounded by Data Governance is the 10 other functional areas: data architecture; data modelling and design; data storage and operation; data security; data integration and interoperability; document and content management; reference and master data; data warehousing and business intelligence; metadata; and data quality. All these interconnected components collectively contribute to a robust and efficient data management framework, facilitating optimal utilization and governance of an organization's valuable data assets (Earley et al., 2017).

3.4 Existing Data Frameworks

While this paper aims to present the DataDOSE framework, plenty of data frameworks are discussed in the existing body of work. This section offers a brief overview of the most relevant data frameworks in the available literature. For example, the authors (Bou Hatoum et al., 2023) explored the interconnectivity between people, processes, and data as the three pillars of the construction project digital thread. A three-dimensional Digital Thread Infrastructure was proposed for the fundamental elements of the digital thread, i.e., asset lifecycle, asset stakeholders, and asset data sources. The authors also noted that quality data is what prevents a broken digital thread and highlighted the importance of proper data management which depends on the understanding of how data is produced, obtained, and used (Bou Hatoum et al., 2023). Additionally, the authors in (Huck et al., 2005) developed a Performance Data Management Framework (PerfDMF) that focuses on integrating, interconnecting, and reusing performance tools by offering a unified infrastructure for storing, accessing, and analyzing parallel performance profiles. PerfDMF encompasses an adaptable parallel profile data schema and relational database schema, along with a programming interface for querying and analyzing profiles. .

In the transportation industry, NCHRP 08-115 proposed a technical framework developed around the data life-cycle, which has been broken down into five areas: 1) specifying and standardizing data, which aims at understanding the needs and full costs of asset inventory, condition and performance, treatment, and work history data; 2) collecting data, which explores TAM-related data collection processes and practices, tools and technologies, and quality as delivered with respect to existing data standards; 3) storage, integration and data access, which addresses data availability across the enterprise and the elimination of redundant and duplicative data; 4) analyzing data, which examines decision-support tools, techniques, and practices that facilitate the development of actionable information and insights to support decision-making; and 5) acting as informed by data, which is the area that covers data-informed TAM practices, exploring asset life-cycle management through resource allocation and prioritization; project planning, scoping, and design; and maintenance decision-making (Spy Pond Partners, LLC, 2021).

The Florida Department of Transportation (FDOT) has implemented a data governance plan to manage data effectively for strategic planning and decision-making. Data, as a valuable corporate asset, is managed throughout its lifecycle to ensure its continued relevance and usefulness. FDOT's March 2015 initiative, ROADS, which aims to promote agency-wide adoption of data governance and master data management, is streamlining information flow, removing barriers to data sharing, and facilitating better decision-making. This initiative is currently supported by FDOT Transportation Technology, seeking to establish a comprehensive Enterprise Information Management Structure for improved data reliability and accessibility across the organization (Florida Department of Transportation, 2023; Ghorbani & Messner, 2024). The Ohio Department of Transportation (ODOT) Data Governance (DG) Program ensures alignment of agency data with its mission. By collaborating with various departments, it ensures high-quality accessible data for decision-makers. The DG program works with IT and the Project Management Office to implement data standards for new systems. ODOT is investing in searchability and data quality tools that are expected to be made available agency-wide. The DG Office ensures compliance with ORC 1347.01 regarding Personal Identifiable Information, collecting and storing only necessary data, with a defined process for removing confidential information appropriately (Ohio Department of Transportation, 2023). Indiana DOT (INDOT) has a specified data governance structure that aims to implement a standardized method of structuring and improving data across the asset classes and INDOT’s different divisions. This data governance model defines the roles and responsibilities for entering, processing, and managing data as follows: The Data Governance Council sets strategy and policy. Data Trustees oversee data domains and define function-specific policies, processes, and tool decisions. Data Stewards monitor data quality, enforce policies, and manage inquiries. System Custodians implement system policies within systems, control access, and manage data flows. Finally, Data Producers and Data Consumers follow policies and procedures, report integrity issues, and attend training (Federal Highway Administration, 2023b; Reyes-Veras et al., 2021). Iowa DOT has a comprehensive data governance and management strategy that has resulted in better decision-making as well as financial benefits that translate into hundreds of millions of dollars over the next decade. Despite the challenges of data duplication, underutilization, inefficient integration, inefficient use of resources, and a gap in required skill sets, Iowa DOT remains committed to raising awareness of the data collected across the agency, improving transparency, and allowing them all to improve their work, which should lead to reduced duplication and more cohesive decision-making between business units especially with fuller data integration to represent the current status quo (Iowa Department of Transportation, 2021).

The overview of the existing work on data frameworks shows that "data" is a broad concept that encompasses a wide range of interconnected functionalities that collectively enable organizations to effectively leverage their asset data. At a high level, the reviewed work highlights data concepts that focus on understanding assets and their data and stakeholders, governing data, and managing data.

4. THE DATADOSE FRAMEWORK

The proposed DataDOSE framework, depicted in Figure 1, builds on the existing body of knowledge and presents state DOTs with a holistic approach that is both data- and user-centered to support successful data-driven asset management decision-making. Unlike existing standards and frameworks such as ISO 19650 and TAM Guide produced by NCHRP 08-115, the DataDOSE framework is a middle-out approach that does not rely solely on top-down directives, but rather fosters a collaborative culture where ideas flow both upward and downward in the agency, empowering all stakeholders to contribute their valuable insights. By embracing a middle-out perspective, the first two steps of the framework empower asset owners to take the lead in establishing their data and performance models, initiating the groundwork for effective data-driven strategies. The significance of top-down implementation becomes apparent in the third and fourth steps of the framework as the establishment of robust governance and management plans necessitates a top-down approach to ensure consistency, compliance, and scalability. This inclusive approach ensures that needed levels of the agency play a crucial role in shaping asset management strategies.

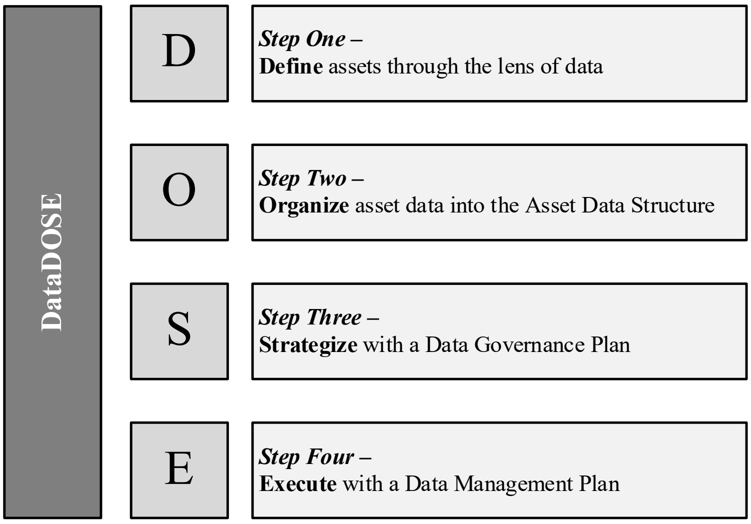

Figure 1: The proposed DataDOSE Framework.

4.1 Define Assets through the Lens of Data

A comprehensive assessment of the assets themselves can demonstrate the potential of asset data to add value to decisions over the lifecycle of the asset. This section delves into the importance of the first step in the proposed framework that guides state DOTs toward transforming asset data into actionable insights. The interconnected system of assets that make up the transportation network represents an enormous and ongoing public investment. It is imperative for state DOTs to delve deeper into assets-specific knowledge to uncover key data points that are most relevant and valuable to support decisions to optimize how public funds are spent. This first step of the DataDOSE framework aligns with the first principle of ISO 19650 which states that "information is needed for decision-making during all parts of the asset lifecycle […]".

To understand the assets themselves, it is important to learn about the asset-related decision from the subject matter experts who possess specialized knowledge. Thus, the initial priority becomes identifying and engaging the individuals within the state DOT who are responsible for the overall performance of the asset, referred to as Asset Owners . ISO 19650 also states that information requirements need to be defined to address the questions that have to be answered to make key asset-related decisions at different points during the asset lifecycle. Therefore, the identified Asset Owners with their domain expertise take charge of determining how asset data could be used to make asset-related and data-driven decisions. To achieve this, Asset Owners should contemplate questions that elucidate how asset data can lead to well-informed decisions. Some questions that Asset Owners can consider are:

- Are there regulatory requirements (at the Federal or State level) that should be monitored?
- Are there safety requirements that should be mentioned?
- Are there specific failure modes or deterioration patterns that can be monitored?
- Does asset reliability need to be tracked?
- What is the time step needed to refresh data?

This understanding of what asset data can enable about the asset itself reinforces an important habit of "beginning with the end in mind" and enables state DOTs to define their data requirements accurately and design effective data collection processes. Data requirements include data models, refresh interval, quality measures, metadata, formats, and type of storage. It is important to note, however, that data does not possess equal value for all asset classes. The value assessment of asset data in action allows state DOTs to prioritize their assets based on the potential impact of data-driven decision-making. By evaluating the value that can be derived from each asset, state DOTs can allocate resources efficiently, focusing on managing and utilizing data for high-value and high-risk assets. This prioritization enhances the overall effectiveness of the data-driven approach, maximizing the return on investment.

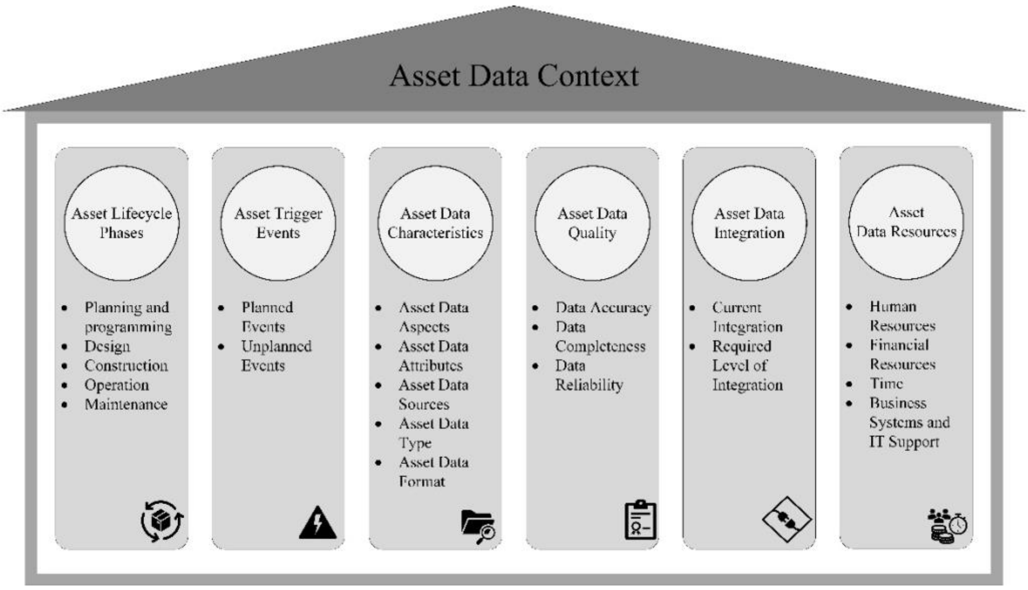

Figure 2: Asset Data Context Pillars.

4.2 Organize Asset Data into the Asset Data Structure

Once transportation assets have been defined and understood through the lens of their data, the next step is to understand asset data, particularly how it fits within the data architecture of the enterprise, as well as the type, completeness, and quality level of available data. Understanding asset data enables the development of data models that align with the enterprise's business goals, which is fundamental for effective data management and governance. This step is crucial before a state DOT can effectively govern and manage its data as it aims to identify data gaps, redundancies, and inconsistencies which are essential for effective data governance and management. A six-pillar approach for Asset Data Context (illustrated in **Error! Reference source not found.**) is proposed to comprehensively map asset data at different levels of granularity. It is important to note that the first two pillars are both context that prompts the production and use of data. This exercise should be a collaborative effort that involves not only the Asset Owners but also key internal and external stakeholders who are closely engaged with the asset of interest.

Pillar 1 — Asset Lifecycle Phases. The lifecycle of an asset is defined in ISO 19650 as "the life of an asset from the definition of its requirements to the termination of its use, covering its conception, development, operation, maintenance support, and disposal" (International Standard for Organization, 2018a). For transportation assets, this pillar encompasses the following five phases: planning and programming (short- and long-term), design, construction, operation, and maintenance.

Pillar 2 – Asset Trigger Events. A trigger event is defined in ISO 19650 as "a planned or unplanned event that changes as an asset or its status during the lifecycle, which results in information exchange." Triggering events can happen during any phase of the asset lifecycle.

Pillar 3 – Asset Data Characteristics. For each asset trigger event, the various data characteristics need to be identified as this information influences how data is collected, stored, processed, and utilized. This pillar must consider the characteristics of both enterprise and transactional data. Not every element of transactional data will be of value to the enterprise (Utah Department of Transportation, 2021). Thus, it is important to differentiate between transactional and enterprise data. Transactional data is the information collected from transactions that include all the details necessary to define each transaction as a unique event at a specific date and time (Sheldon, 2024), while enterprise data is data that is shared by the users of an organization, generally across departments and/or geographic regions (Rouse, 2017). Additionally, this pillar builds on the data taxonomy concept, which refers to the classification of data into hierarchical groups to create structure, standardized terminology, and popularize a dataset within an organization (Gomez, 2024), and aims to present a process for state DOTs to understand and organize their asset inventory data to retain needed information and to effectively plan to collect future data.

Identifying the asset data characteristics follows a cascading approach where the asset data description starts from a high-level perspective and gradually becomes more detailed and specific as it moves down the hierarchy of data characteristics. Consequently, pillar 3 consists of five sub-pillars:

Sub-Pillar 3.1 – Asset Data Aspects. For each asset trigger event, the various data dimensions need to be defined, as applicable. Data levels could include programming data, permits data, safety data, operations data, inventory data, performance data, legal data, maintenance data, and condition data.

Sub-Pillar 3.2 – Asset Data Attributes. For each asset data aspect, the data attributes need to be outlined. Data attributes refer to the specific characteristics or properties that describe the asset data. These data attributes provide important information and context about the asset itself, its characteristics, and its associated data. Examples of attributes include the location (i.e., the geographical coordinates or physical address of the asset), dimensions (i.e., the physical size, shape, or spatial dimensions of the asset), load capacity (i.e., the maximum load or weight that the asset can bear or support), etc.

Sub-Pillar 3.3 – Asset Data Sources. For each data attribute identified in the second sub-pillar, the asset data source(s) need to be identified. Data sources refer to the internal and external systems, applications, databases, and entities where data is located. Examples of data sources include plans, specifications, permits, 3D models, manuals, picture logs, scans, GIS databases, sensors, and maintenance work orders in the Asset Maintenance Management System. Along with identifying the data sources, the reliability of these sources must also be assessed, and the collection method should be discussed.

Sub-Pillar 3.4 – Asset Data Type. The type of data in each data source must be specified. Data type represents the categorization of data based on its characteristics, structure, and intended use. Common data types include structured data (organized in tables with predefined schemas), unstructured data, semi-structured data, time series data, geospatial data, and more.

Sub-Pillar 3.5 – Asset Data Format. For each data type, the format is specified. Data format defines the structure and encoding of data, specifying how data is represented and stored. Data could be stored in proprietary or open file formats.

Pillar 4 – Asset Data Quality. The better the quality of the data, the better state DOTs can make decisions and take effective actions. Moreover, asset data quality impacts directly the level of trust users have in the data. This pillar aims to answer the following question: What is the actual quality of the data and is it at the level needed? Data quality assessment encompasses evaluating the accuracy, completeness, and reliability of the data.

Pillar 5 – Asset Data Integration. After identifying the asset data characteristics, evaluating the current and needed level of data source integration across various asset trigger events is vital for state DOTs aiming to transform asset data into actionable insights. The integration status determines how well data from different sources are interconnected and synchronized during significant asset trigger events.

Pillar 6 – Asset Data Resources. This pillar lays the foundation for successful data initiatives and ensures that state DOTs allocate the necessary resources to effectively sustain these efforts. Resources that should be considered include:

- Human resources: Data governance requires a dedicated team of skilled professionals (in-house and outsourced) to collect, manage, analyze, and maintain data. Additionally, state DOTs must recognize the importance of executive-level sponsorship to champion the initiative and gain support from all divisions.
- Financial resources: State DOTs need to invest in data management tools, data integration platforms, data security measures, data storage solutions, and consulting services. Furthermore, budget allocation is required to facilitate data training programs for employees, ensuring data literacy across the agency.
- Time resources: Time is a critical resource in any data initiative. Careful planning, training, and gradual implementation are required. Additionally, allocating sufficient time for data quality assessments, data integration, and the development of data policies is essential for long-term success.
- Business systems and IT Support: Data initiatives should align with existing systems and processes to achieve seamless integration and avoid redundancy. The IT department plays a critical role in ensuring existing resources and infrastructure are leveraged where possible.

In addition to the above-mentioned resources, it is important to emphasize the significance of fostering a data-driven culture within the state DOT. Leadership must communicate their data plan to all employees across all levels to better understand the value of data, embrace data-driven decision-making, and actively participate in the data initiatives.

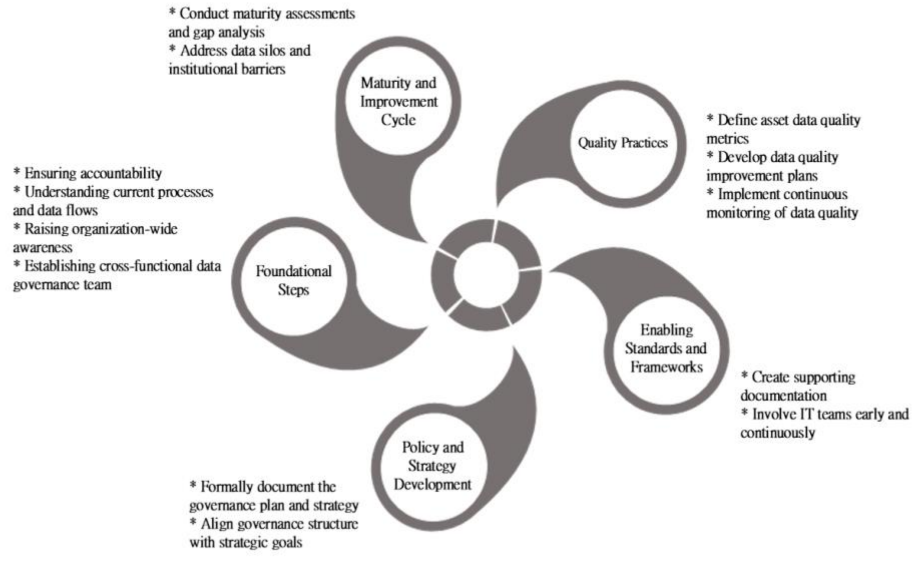

Figure 3: Data Governance Plan groups and components.

4.3 Strategizing with a Data Governance Plan

As state DOTs increasingly rely on data-driven decisions for asset management, the need for robust data governance grows imperative. A sound Data Governance Plan (DGP) establishes policies, standards, and procedures to effectively manage transportation asset data. As the third step of the DataDOSE framework, this step represents a comprehensive DGP methodology for DOTs to elevate data quality, access, security, and analytics capabilities required for strategic asset management. The methodology categorizes necessary DGP components into five groups as represented in Figure 3 and discussed afterwards, including foundational steps, establishing accountability and process understanding, developing policy and strategy to align the governance framework; enabling standards and frameworks for execution; implementing maturity and improvement cycle assessments; and embedded quality practices. By methodically addressing each area, state DOTs can implement holistic DGPs that transform transportation asset data into an enterprise-wide capability for informed decision making and planning. The categorized methodology serves as a model for state DOTs to strategize, gain stakeholder alignment, and incrementally strengthen data governance for advanced transportation asset management.

4.3.1 Foundational Steps

- Ensuring accountability: Clear governance establishes transparent data accountability (Janssen et al., 2020) across all transportation assets through defined data owners, administrators, and trustees steering usage protocols and excellence. Downward chains for usage are developed around localized data stewards that supplement the centralized governance council and flow upward to be responsible from a field level to the executive tier.
- Understanding the current business processes and data flows: Critical to strategic data governance will be to develop comprehensive, fully detailed documentation of the current transportation asset management processes and their information flows using visualizations prescribed by Unified Modeling Language (UML) (Le & David Jeong, 2016). The enterprise-wide input gives one the optimal opportunity once there is such cross-departmental tracing of decision nodes and systems. Also, the process chokepoints and governance vulnerabilities need to be addressed by sequential gap remediation at this point.
- Raising organization-wide awareness: Actions for building organization-wide awareness of the value that a DGP offers can include special communication campaigns such as executive workshops aimed at expressing strategic merit and staff training aimed at quality improvement in asset information. It is furthered by establishing communities of practice, providing training, and providing proper time allocation.
- Establishing a cross-functional data governance team: This process of creating holistic governance plans requires a multidisciplinary team to merge business and technology expertise with legal, data, and asset management perspectives. Herein, the group needs the authority to compel the adoption by stakeholders, a move that defines the governing body as a change leader (Glatter et al., 2003). Constructing the team with a collaborative governance vision and roadmaps ensures coherence in all organization aspects.

4.3.2 Policy and Strategy Development Steps

- Formally documenting the data governance plan and strategy: Resulting in policies getting embedded around access privacy, security, and retention within the TAM. Guidelines for proper use of data and formats should be specified at this stage, while collection, storage, integration, and quality standards must be baked into the governance strategy, along with a requirement for cataloging metadata (Bönisch, 2023). At this stage, outlining audits and controls promotes further searchability and interoperability. This feature contributes to an ideal policy apparatus by escalating procedures for non-compliance scenarios.
- Aligning the governance structure to strategic goals: Ensuring that governance priorities are linked to the overarching objectives of asset management creates integrity, which is essential for mapping out roles and responsibilities, and thus, informing decision-making systems (Dawood & Rahimian, 2021; Janssen et al., 2020). Moreover, integrating insights from behavioral economics highlights the importance of policies and procedures aligning with enterprise needs. For instance, updating key

performance indicators (KPIs) for individual business units is vital. Constructing achievement roadmaps for strategic targets through governance initiatives to maintain line-of-sight, and developing mechanisms for validating governance outputs empirically support business goals (Eweje et al., 2021). Moreover, it sustains coordination through the formation of feedback loops that connect the objectives of the asset with the policies and standards of data, ensuring that KPIs are updated to facilitate and prioritize the DG functions.

4.3.3 Enabling Standards and Frameworks Steps

- Creating the supporting data documentation: Standardization of taxonomy and glossaries makes uniform usage of asset terminology a possibility, which is an important part of governance. Defining exact metadata that specifies key attributes, location identifiers, and asset hierarchy mappings allows the combining of different data elements across the enterprise. Additionally, published data dictionary structures accelerate systems modeling. Creation of governance certified standards leads to interchangeable formats which then foster cross platform data movements and allow for maximum interoperability (Girard, 2020; Khoshkenar & Nassereddine, 2024c).

- Involving IT teams early and continuously or as needed: Involving IT teams early, when establishing governance frameworks, with central and departmental members included in the governance structure itself, to direct integration of standards, architectures, and interchange formats leverages existing technical leadership. IT experts also possess expertise in the legal aspects of data that need to be included in a DGP. Moreover, while engaging IT groups in compiling official metadata catalogs and taxonomy repositories taps niche skills, collaborating on policy drafting provides balanced security and access (Hassani & MacFeely, 2023). Above all, coordination must continue systematically on enhancement requests to ensure responsive data and technology governance.

4.3.4 Maturity and Improvement Cycle Steps

- Conducting maturity assessments and gap analysis: Surveying stakeholder needs, auditing existing governance capabilities across technology, processes, and people, beside evaluating resultant data quality, accessibility, and reporting effectiveness are vital requirements at this stage. Additionally, taking the current governance processes, measuring them against capability maturity models, and identifying shortfalls that inhibit analytics-based decision making allow plotting out incremental roadmaps to address systematically assessed gaps over time.

- Addressing data silos and institutional barriers: While transactional data silos could be acceptable or efficient for some purposes within operations, siloed enterprise data can nevertheless serve as really inhibiting factors to enterprise-wide asset data aggregation, integration, and its utilization toward decision-making (Zorrilla & Yebenes, 2022). This can only be further complicated by institutional barriers such as policies, political constraints, and cultural tendencies towards data hoarding. To overcome this, there has to be continuous effort in pinpointing information silos, supporting cultural change towards data sharing, and implement additional methodologies such as mobile LiDAR to capture the changes or gaps in respect of asset data that cannot be fully captured in the transactional systems (Shah-Nelson, 2020). Thus, it is vital to overcome such practical barriers in reaching higher levels of data governance maturity, which makes effective analytics-based asset management possible.

4.3.5 Quality Practices Steps

- Defining asset data quality metrics: Relevant dimensions are defined to customize quantitative data quality gauges according to accuracy, completeness, and consistency which are considered as asset management priorities (Georgiev & Valkanov, 2024). Standards that are relevant to trends, thresholds, and goals that are monitored through governance reviews are instituted to derive custom-tailored diagnostics. Comparison of measurable quality against benchmarked quality indicators is encouraged to drive empirical assessments of continuous excellence.

- Developing data quality improvement plans: Performing root cause analysis on critical asset data issues is one of the vital plans to improve the data quality outlining corrective actions such as data scrubs or process reviews for accountability (Patacas et al., 2020). Additionally, preventive controls safeguard quality while formalizing continual enhancement plans for priority metrics enables sustained capabilities and this loop will be closed by tracking remediation and control effectiveness over time.

- Implementing continuous monitoring mechanisms: Automating identification of deviations and anomalies in key data systems flagging attention needs is considered as the foundation of this stage fortified by establishing feedback channels across producers and consumers to reveal perceptions and developing structured data quality scorecard reporting to sustain stakeholder vigilance. Also, tiered quality metrics fostering individual data domain accountability further motivates data excellence.

4.4 Executing with a Data Management Plan

As the final phase of the DataDOSE framework, an executive Data Management Plan (DMP) enables the systematic leveraging of data to drive optimal decision-making, financial stability, sustainable lifecycle management, efficiency through technology, and proactive safety maintenance (Akanmu et al., 2021). In addition, robust data strategies along with governing data collection, storage, analysis, and application, enhance the efficacy of asset management methodologies (Baduge et al., 2022; Jafari et al., 2023) and enable state DOTs to navigate complex problems with increased insight.

As shown in Figure 4, an eight-step procedure is proposed to systematize transportation data as an indispensable asset itself. This comprehensive, cross-functional data focus facilitates simulation for evidence-based planning, detects early warning signs of disruption, balances short and long-term objectives, and fosters accountability through transparency. As networks grow more multifaceted, embracing data-optimization across assessment and decision prioritization steer state DOTs toward stable, sustainable, and secure transportation ecosystems. The eight steps in Figure 4 are:

1. Engage department stakeholders to align organizational objectives for TAM with department-specific objectives related to policies, governance, and requirements for access procedures.
2. Establish the critical asset data governance and quality assurance protocols based on stakeholder requirements and organization goals for collection, storage, security, lifecycle, and interoperability. Also, data monitoring procedures should be established at this stage.
3. Integrate data management systems with existing asset data repositories to centralize storage, govern lifecycles, ensure quality assurance, and enable self-service analytics through automated workflows and unified reporting tools.
4. Develop a cross-functional infrastructure for data analytics that will provide safe, controlled access to data assets supporting planning and decision making. Also, self-service access to insights via business intelligence platforms should be provided at this stage.
5. Embed data-driven optimization, simulation, and predictive modeling within the planning workflows to guide investment and maintenance prioritization leveraging risk models, lifecycle cost analysis, and infrastructure performance forecasting.
6. Continually integrate advanced sensors, AI/ML data processing, cloud infrastructure by working cross-functionally to enhance data collection, analytics velocity and risk mitigation based on periodic risk assessments.
7. Develop organizational capabilities on data management through training programs to drive data literacy, adoption of analytics, governing best practices, and emerging technologies.
8. Institutionalize a series of iterative cycles of quarterly reviews to actively revisit data policies, system integrations, utilization barriers, and training needs and address any changes through updated procedures, configurations, and capability building.

5. CASE STUDY: CONNECTICUT DOT'S ASSET MANAGEMENT APPROACH

This case study demonstrates how the DataDOSE framework can be effectively utilized by state Departments of Transportation (DOTs) to develop a more efficient, data-driven approach to asset management. It specifically highlights the Connecticut Department of Transportation (CTDOT) as an example of how a state DOT can evolve to become more data-centric and efficient. This apper provides an overview of how CTDOT's data practices align with the DataDOSE steps.

CTDOT began its journey toward integrated asset management in 2012 with the development of their Transportation Asset Management (TAM) dedicated unit in Engineering. Recognizing the importance of a robust data infrastructure, CTDOT gradually expanded their capabilities over the years. In 2015, they implemented a digital Linear Reference System (LRS) to better manage their road network data. Building on this foundation, they launched the Transportation Enterprise Data (TED) initiative (data awareness) in 2016, which centralized data from various sources to support more comprehensive analysis and decision-making. To further strengthen their data management and utilization, CTDOT established the position of Chief Data Officer in 2020, underscoring their commitment to a data-driven approach.

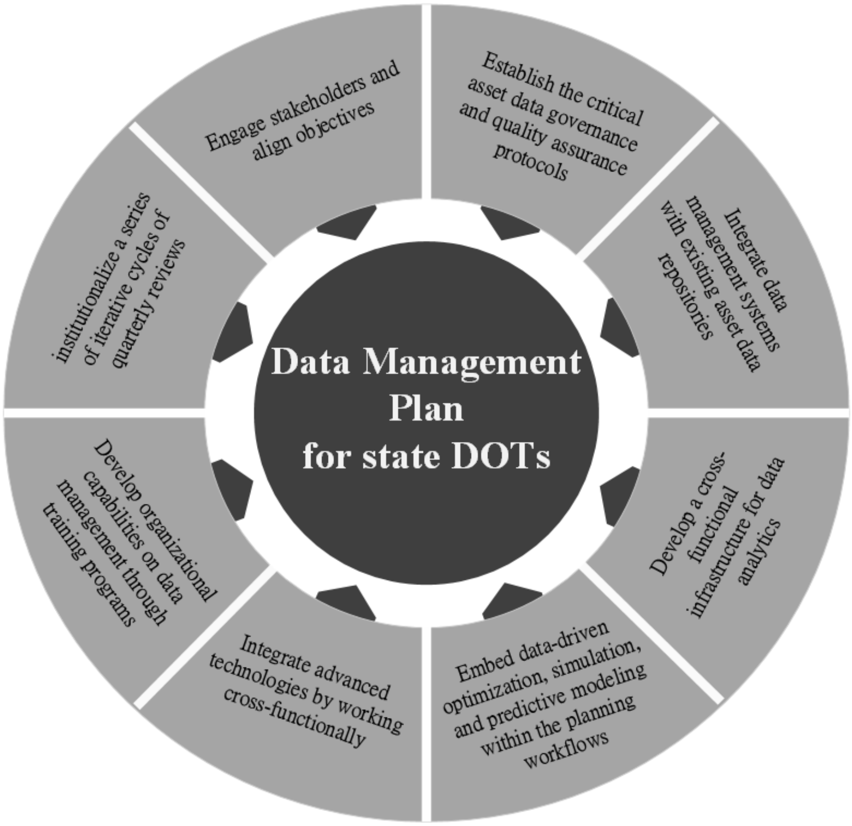

Figure 4: Data Management Plan steps.

A significant advancement in their data-driven approach came with the development of the COMPASS system (shown in Figure 5), a second-generation Common Data Environment (CDE) launched to integrate CTDOT's data and asset management systems seamlessly. COMPASS, in collaboration with Esri's ArcGIS and Microsoft's SharePoint, allows for comprehensive project planning, data visualization, and real-time updates on project status. This system enables CTDOT to manage both active and legacy projects efficiently, offering a digital repository that supports project developers, engineers, and planners in making informed decisions. This cloud-based transportation project management solution exemplifies the holistic, data-centric approach advanced by the DataDOSE framework:

1. Define assets through the lens of data: COMPASS facilitates this step by providing a unified platform that integrates multiple data sources, enabling CTDOT to define and visualize assets using geographic information systems (GIS) data. This comprehensive view ensures all asset-related information is easily accessible and well-defined.
2. Organize asset data into the Asset Data Context: COMPASS consolidates project and asset data comprising staff management, environmental permits, rights-of-way tracking, schedules, financial

information, and geospatial data and utilizes a digital repository and a common data environment to organize asset data efficiently. This kind of organization creates a unified Asset Information Model (AIM) and Project Information Model (PIM).

3. Strategize with a Data Governance Plan: CTDOT's strategy incorporates explicit data governance with clearly defined hierarchies of authority across various asset types and environmental conditions. The integration between COMPASS and ATLAS 2.0 (CTDOT's Asset Tracking and Location System) ensures data consistency and facilitates automated updates to asset inventories, streamlining data management, and improving accuracy.
4. Execute with a Data Management Plan: CTDOT has implemented a comprehensive data management plan comprising:
    - Integrating CAD systems like OpenRoads Designer, OpenRail Designer, and OpenBridge Modeler with SharePoint/COMPASS for efficient design file management.
    - Automating the conversion of CAD data to GIS for assets such as guiderails, traffic signals, and ROW parcels.
    - Establishing data validation processes to ensure the accuracy and quality of data posted to the central database.
    - Utilizing a versioned database approach to manage updates and ensure quality assurance.

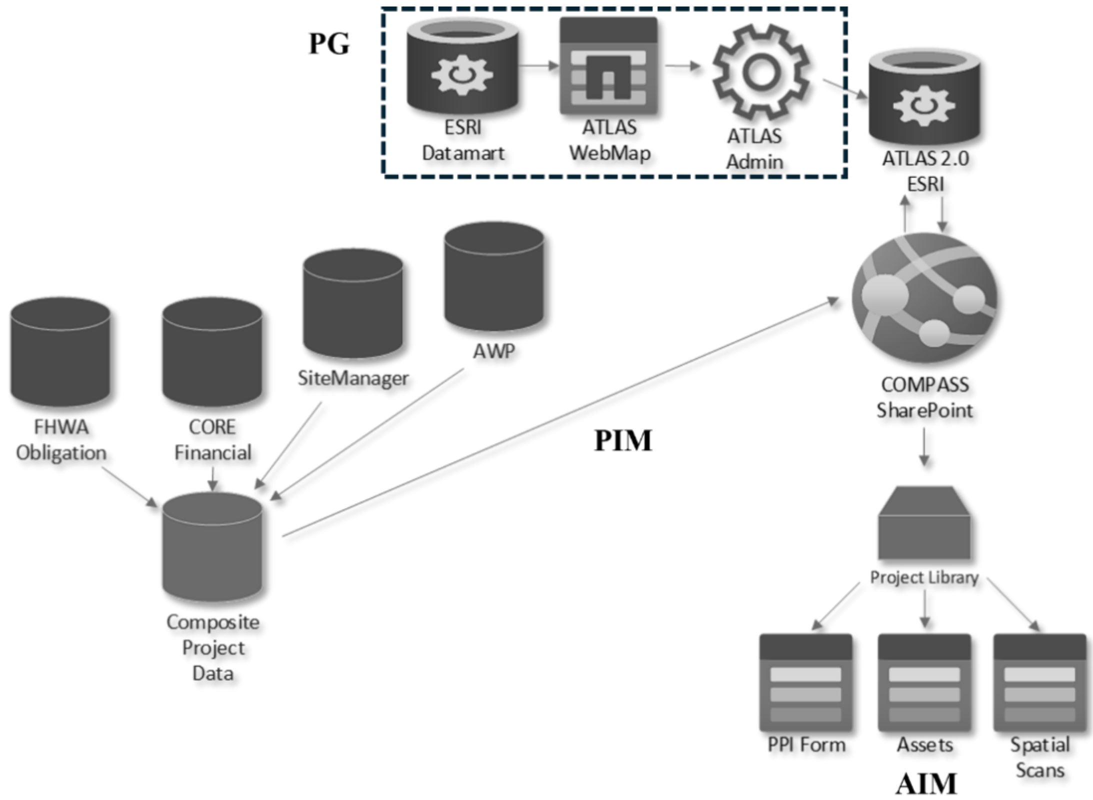

Figure 5: CTDOT's COMPASS solution for transportation asset and project management.

It is important to note that the architecture shown in Figure 5 emphasizes the seamless information exchange between COMPASS and ATLAS 2.0, which is a key component of CTDOT's asset management strategy. The integration focuses on the Project Generator (PG), which connects geospatial data from ATLAS 2.0’s ESRI system with project management data in COMPASS, based on SharePoint. This integration enables:

- Spatial scanning of project areas to identify relevant assets.
- Populating the Project Proposal Information (PPI) form with asset data.
- Developing and maintaining project libraries within COMPASS.
- Synchronizing project and asset data across systems.

This integrated approach ensures continuous data flow between assets and projects, supporting accurate planning, better decision-making, and effective asset tracking throughout the project lifecycle. This aligns with the DataDOSE framework's emphasis on organizing asset data and implementing efficient data management strategies.

Additionally, the relationship between OpenRoads/OpenBridge Designer and the ESRI asset data demonstrates how CTDOT facilitates a seamless flow of information from project design to asset inventory. This enables contract pay items and asset information to be generated directly from CAD models and transferred into GIS systems for comprehensive asset management.

CTDOT's success in implementing this integrated system can be attributed to several key factors that align with the middle-out approach of the DataDOSE framework:

- Strong support from top-level management.
- Alignment between IT and business units to avoid "shadow IT."
- Flexibility in adapting processes to leverage technological capabilities.
- Measurement of current costs to assess ROI for new initiatives.
- Formation of multi-discipline committees to address diverse asset management needs.

6. CONCLUSION

Transportation Asset Management (TAM) relies heavily on data. This paper proposed a holistic framework called DataDOSE that provides state Departments of Transportation (DOTs) with an approach to overcome data-related challenges. The DataDOSE framework adopts a middle-out approach, holistically incorporating both data-centric and user-centric aspects, with the goal of supporting successful data-driven asset management decision-making. The framework comprises four key steps: Define assets through the lens of data, Organize asset data into the Asset Data Context, Strategize with a Data Governance Plan, and Execute with a Data Management Plan. Unlike existing top-down standards and frameworks, DataDOSE fosters a collaborative culture in which ideas flow both upward and downward. This enables the asset owners to take the lead in defining their data and performance models in the first two steps while the third and fourth steps necessitate a top-down approach to ensure consistency, compliance, and scalability across the organization.

This paper has outlined the critical considerations for state DOTs in recognizing the importance of data and defining the specific data required for their asset management processes. It also introduced models for establishing a Data Governance Plan and Data Management Plan, providing valuable insights for practitioners and policymakers to understand the benefits of a middle-out approach. This approach addresses data fragmentation and silos within state DOTs, emphasizing the need for both bottom-up engagement and top-down support in implementing effective data governance and management.

To further advance this paper and offer state DOTs actionable insights, the following future work is proposed:

- Conduct interviews with state DOTs that lead in data initiatives to refine and validate the DataDOSE framework.
- Apply the framework in interested state DOTs, documenting case studies and lessons learned.
- Develop a user-friendly digital tool based on the DataDOSE framework to assist state DOTs in planning, implementing, and optimizing data-driven TAM practices.
- Establish appropriate Key Performance Indicators (KPIs) to measure the framework's effectiveness in improving asset data quality, integration, and utilization.
- Create guidance documents and training materials to facilitate the adoption of the DataDOSE framework across state DOTs.

By pursuing these next steps, the DataDOSE framework can continue to evolve and provide practical solutions for state DOTs to enhance their asset management strategies and data practices.

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