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Towards a Centralized BIM Transportation Library

Summary of Available Resources and Technical Requirements

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16. Abstract

This report provides a comprehensive assessment and availability of the technical resources required in the development of a Central Building Information Modeling (BIM) Transportation Library (CBTL), outlining its foundational requirements based on past research, related projects, and stakeholder engagement. The CBTL is envisioned as a nationally accessible digital repository that enables standardized, version-controlled BIM artifact management for transportation infrastructure projects, enhancing interoperability, efficiency, and data-driven decision-making across agencies. The secure and access-controlled environment enables individual transportation agencies and other users the ability to keep their data private and secure, while maintaining the ability to share and access open data standards.

The report synthesizes findings from research conducted by the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), related Transportation Pooled Fund (TPF) projects, and other federal and state agencies towards best practices and aligns with national digital delivery goals. Key sources include evaluations of existing repositories, assessments of BIM workflows, and insights from stakeholder engagement efforts.

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Executive Summary

This report provides a comprehensive assessment and availability of the technical resources required in the development of a Central Building Information Modeling (BIM) Transportation Library (CBTL), outlining its foundational requirements based on past research, related projects, and stakeholder engagement. The CBTL is envisioned as a nationally accessible digital repository that enables standardized, version-controlled BIM artifact management for transportation infrastructure projects, enhancing interoperability, efficiency, and data-driven decision-making across agencies. The secure and access-controlled environment enables individual transportation agencies and other users the ability to keep their data private and secure, while maintaining the ability to share and access open data standards.

The report synthesizes findings from research conducted by the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), related Transportation Pooled Fund (TPF) projects, and other federal and state agencies towards best practices and aligns with national digital delivery goals. Key sources include evaluations of existing repositories (e.g., the Secure Data Commons (SDC) platform and buildingSMART Data Dictionary (bSDD)), assessments of BIM workflows, and insights from stakeholder engagement efforts.

Core Project Objectives

The primary tasks and objectives of this project were to:

1. Conduct Literature Review of the BIM State of Practice in DOTs
    - A scan of technical resources available for the CBTL
    - A scan of USDOT Databases, repositories, and libraries
    - A technical assessment of Building Information Modeling (BIM) Workflows and Centralized BIM Transportation Library for Bridges and Roadways FHWA-HIF-24-004
    - A technical assessment of Secure Data Commons (SDC) platform
    - A technical assessment of buildingSMART Data Dictionary (bSDD)
    - A technical assessment of The Open Group Architecture Framework (TOGAF)
    - A technical assessment and considerations for the CBTL
2. Summarize Requirements for the CBTL
    - Review and consolidate existing research on BIM workflows, metadata governance, interoperability frameworks, and federated data models.
    - Identify critical technical and operational components necessary for a scalable, secure, and user-centric CBTL architecture.
    - Establish a structured governance framework based on TOGAF and other enterprise architecture models.
3. Facilitate Stakeholder Engagement
    - Facilitate stakeholder engagement via online peer exchanges, focused workshops, one-on-one technical talks, and quick polls.
    - Identify stakeholder needs and capacity to adopt and contribute to a shared CBTL.
    - Assess how stakeholders utilize the industry foundation classes (IFC) and related standards, along with current software tools that support model organization and delivery of digital data.
    - Solicit evaluation and feedback of the CBTL architecture, data models, application programming interfaces (API), and governance workflows to confirm its technical feasibility, scalability, and alignment with DOT requirements.
    - Conduct a CBTL roundtable to evaluate the results and findings.

Key Findings

The project has conducted systematic literature reviews, technical assessments, and stakeholder engagements to identify and address the challenges and opportunities in implementing BIM for transportation infrastructure. Establishing a centralized repository for BIM artifacts is a step toward standardizing and enhancing data management, interoperability, and collaboration among various stakeholders, including state DOTs, the FHWA, and industry partners. Key findings emphasize the importance of adopting open data standards, leveraging existing technical solutions, and fostering a collaborative environment to support the widespread adoption of BIM.

The review of state DOTs current practice revealed varying levels of BIM adoption, with some agencies leading digital delivery efforts, while others remain in early exploratory stages. Key challenges include data standardization, workforce training, interoperability across platforms, and integration with existing asset management systems. State DOTs expressed the need for flexible solutions that accommodate state-specific workflows while maintaining alignment with national BIM standards. Additionally, stakeholder engagement highlighted concerns about scalability, governance structures, and long-term sustainability of BIM implementations. One finding was the lack of awareness of available resources, which hinders stakeholders' ability to fully utilize support systems, and consequently limited the overall effectiveness of the ongoing research to support BIM-based delivery. The findings emphasize the importance of collaboration, knowledge sharing, and tailored technical solutions to support widespread adoption of the CBTL. The CBTL Leadership Roundtable held in January 2025 provided important insights into the needs for, and potential value of, the CBTL. More information about the roundtable can be found in the Stakeholder Engagement section of the report.

The review of relevant projects and reports identified several ongoing initiatives that align with the objectives of this project, including *TPF-5(523) BIM for Bridges and Structures – Phase II*, *TPF-5(480) BIM for Infrastructure*, and the *FHWA-HIF-24-004 BIM Workflows and Centralized BIM Transportation Library for Bridges and Roadways.* These projects provide valuable BIM artifacts, workflow models, data exchange standards, and governance frameworks that can inform the CBTL's development. The findings underline the importance of leveraging existing BIM resources, ensuring interoperability with national repositories, and addressing technical gaps in data integration and standardization. Additionally, engagement with *FHWA's CBTL Demonstration Project* presents opportunities for collaboration to refine data management strategies and enhance national adoption of BIM-based workflows in transportation infrastructure. The FHWA through creating and funding these and prior research projects has supported the development of the CBTL as a solution to information access, management, and utilization challenges faced by states. Ultimately, the CBTL will need to be adopted and implemented by the states and industry.

The review of existing technologies for supporting a CBTL identified several mature and scalable solutions that can be leveraged, including SDC platform, bSDD, and the National Transportation Library (NTL). These platforms offer capabilities for structured data storage, metadata management, and interoperability with open data standards such as IFC and COBie. However, gaps remain in version control, API integration, and file format support for BIM artifacts, necessitating enhancements to existing repositories or the development of custom solutions. Cloud-based databases, Web-based APIs, and open-source DevOps platforms were also evaluated for their potential to facilitate secure access, efficient querying, and both role-based and attribute-based data management, ensuring that the CBTL can provide a centralized, accessible, and standardized BIM resource for transportation infrastructure stakeholders.

An important concern raised during stakeholder engagements was the perception that a centralized CBTL might impose federal control over state-managed data, leading to hesitancy among State DOTs about sharing sensitive information. In response to this concern, it is important to note that the CBTL is envisioned as a *federated platform*—developed once as a standardized technology foundation but designed to support multiple state-specific instances with configurable access controls and governance policies. This approach allows each State DOT to maintain ownership and control over their data while still participating in a nationally coordinated system that ensures interoperability and shared best practices. The governance framework will define clear roles, responsibilities, and access boundaries, enabling states to securely manage their data contributions within a unified architecture. This strategy fosters trust, transparency, and collaboration, ensuring that the CBTL supports both national consistency and state-level flexibility.

Ultimately, it is clear that a one-size-fits-all solution will not work. State DOTs operate at varying levels of BIM maturity, with diverse data management requirements shaped by legacy systems, funding constraints, and regulatory environments. Despite these differences, the core technologies needed to support the CBTL concept are readily available. The challenge lies in developing a solution that is both adaptable to individual state needs and structured enough to promote national standardization. To achieve this, the CBTL must adopt a modular, scalable approach, enabling states to seamlessly integrate existing workflows while gradually implementing standardized BIM artifacts, processes, and data structures. This phased adoption strategy will ensure that states progress at their own pace while maintaining alignment with broader national objectives. Success will hinge on strong stakeholder engagement, a well-defined governance framework, and robust technical solutions that prioritize interoperability, security, and long-term sustainability.

Recommendations and Next Steps

To build on the progress achieved and outline the path forward, the following recommendations detail the next steps, leveraging research findings, existing solutions, and best practices:

1. A Federated Approach:

The CBTL should function as a federated system, meaning the data is not located in one centralized repository but rather connects various existing sources. This ensures interoperability while allowing agencies to retain control over their data, avoiding duplication and enhancing accessibility through standardized APIs and metadata structures.

2. Robust Metadata Management and Version Control:

Establishing structured metadata governance, attribute-based access controls, and automated version tracking will be critical for ensuring data integrity. Artificial Intelligence (AI)-enhanced search functionalities can improve retrievability and usability, enabling users to efficiently locate and validate BIM artifacts across multiple repositories.

3. Scalability and Future-Proofing:

The CBTL should be cloud-native and API-driven, allowing for seamless scalability to accommodate growing datasets, evolving BIM standards, and expanding state DOT adoption. The architecture should support containerized microservices, advanced caching mechanisms, and real-time data synchronization to ensure adaptability as digital delivery practices evolve, while helping maintain interoperability with legacy systems.

4. Continuous Stakeholder Engagement:

Ongoing, structured engagement with stakeholders including state DOTs, FHWA, AASHTO, and industry partners will be essential to ensure the CBTL meets user needs and remains aligned with evolving practices. The CBTL should actively leverage insights and outcomes from key initiatives to inform both development and adoption strategies. Specifically, the TPF-5(372) project's Model View Definitions (MVD), Information Delivery Manuals (IDM), Information Delivery Specifications (IDS), and data dictionaries will serve as foundational reference artifacts. The TPF-5(523) project's standardized data exchange and management methods will shape the CBTL's data governance and interoperability framework. Additionally, the collaborative strategies and digital workflows refined in the TPF-5(480) initiative will be integrated to maintain robust stakeholder collaboration, transparent communication channels, and effective data management practices throughout the CBTL's life cycle.

5. Governance, Compliance, and Policy Development:

A national governance framework should be established to ensure CBTL adoption, interoperability, data security, and compliance with federal and state policies. This framework will define roles, responsibilities, and processes for managing the CBTL, which will ensure accountability and continuous improvement. This includes:

a. A CBTL Advisory Board comprising FHWA, AASHTO, state DOTs, and industry stakeholders to oversee policy implementation and metadata governance.
b. Alignment with National BIM and Digital Delivery Policies, including FHWA's BIM Strategic Roadmap, International Organization for Standardization (ISO) 19650 and other relevant industry standards, and federal cybersecurity guidelines.
c. Attribute-based access management and compliance oversight to standardize data stewardship, version control, data security, protection of sensitive infrastructure data, and content contribution protocols across agencies.
d. Ensure that the governance model explicitly supports state and local agency data ownership and control, addressing concerns about centralized authority by establishing clear data access boundaries, permissions, and opt-in mechanisms. This approach promotes national coordination while safeguarding state-specific interests and sensitive infrastructure information.
e. Change-management strategies and training programs to ensure workforce readiness and smooth adoption of BIM-based workflows.

6. Capacity Building, Training, and Leadership Engagement:

Comprehensive training programs need to be developed to build capacity among DOTs and other key stakeholders, drawing on best practices and lessons learned from previous projects to ensure effective adoption of BIM practices. Training should be modular and scalable, addressing technical skills, data governance, and the use of CBTL tools and workflows. In parallel, pilot projects and case studies will be used to demonstrate the practical value and benefits of the CBTL, fostering leadership commitment and securing long-term support for widespread implementation.

I. Introduction

1. Introduction

In the US national advancement of Building Information Modeling (BIM) for bridges, structures, and infrastructure, there have been many research efforts by the Federal Highway Administration (FHWA) and state departments of transportation (DOT). For development and administration of these BIM artifacts to support collaboration and alignment, the need exists for creating a Central BIM Transportation Library (CBTL). Deployment of an open, standards-based repository allows stakeholders in the public and private sector, including BIM standard development organizations (SDO) and transportation organizations at the regional, state, and national level, to use the content in the repository and contribute to its development promoting the interoperability objective of BIM.

The CBTL is envisioned as a federated repository that will be used to maintain open standards-based BIM artifacts in a version-controlled environment that supports the FHWA's *Advancing BIM for Infrastructure: National Strategic Roadmap* (Mallela et al., 2021) by providing a centralized, open standards-based repository of BIM artifacts tailored to the needs of transportation infrastructure. The purpose of creating these requirements is to ensure that CBTL implementers (whether at national, state, or local level) can use and implement the system consistently. Aligned with the roadmap's goals, the CBTL promotes life cycle data integration, interoperability, and collaboration among public and private stakeholders. It facilitates the transition to BIM-based workflows, strengthens data governance, and addresses the specific requirements of horizontal construction—ensuring a scalable, future-ready foundation for digital project delivery and asset management across the national highway system.

The CBTL was initially conceptualized in *BIM Workflows and Centralized BIM Transportation Library for Bridges and Roadways* (Bhargava et al., 2024). The CBTL concept is architected as a federated, version-controlled metadata repository structured to support the full life cycle of transportation infrastructure data modeling and management. Built on principles aligned with The Open Group Architecture Framework (TOGAF)[1], it aims to serve as a centralized digital environment for storing, curating, and provisioning BIM artifacts, including Object-Type Libraries (OTL), Data Dictionaries, Information Delivery Manuals (IDM), Information Exchange Specifications (ILS), and Model View Definitions (MVD). These artifacts are structured around open standards such as the Industry Foundation Classes (IFC), and International Organization for Standardization (ISO) 19650[2], enabling semantic consistency and interoperability across disciplines and platforms.

The CBTL concept is also integrated with an Application Programming Interface (API) framework that supports automation, querying, and federated access to content, and allows external systems—such as state DOT platforms—to interact programmatically with its datasets. This architecture includes granular administrator controls for content segmentation, scaffolding management, and collaborative contributions, making it not only a repository but also a dynamic platform for BIM standardization and deployment at national and state levels. The draft plan envisions an ambitious BIM ecosystem, yet several hidden snags threaten to slow its momentum. At the code level, the decision to build APIs in Azure API Management while the user interface lives in Next.js creates a split-brain stack—demanding two skill sets, duplicating effort, and driving costs upward. Meanwhile, the team proposes to park vast BIM files in GitHub or GitLab, but these platforms excel at source code, not at hundred-megabyte geometry models; shoe-horning them in with Git LFS will make branching, differencing, and storage management

[1] https://www.opengroup.org/togaf

[2] https://www.iso.org/standard/68078.html

increasingly unwieldy. Scalability is another blind spot: without explicit cloud auto-growth, indexing, caching, and performance telemetry, query times will balloon as the library expands. Quality assurance (QA) is equally fragile; there is no automated checkpointing or shared vocabulary to catch errors as data travels between tools, leaving integrity to chance. Misunderstandings also linger around the buildingSMART Data Dictionary (bSDD)—bSDD stores definitions, not actual three-dimensional (3D) geometry—so geometric content still needs its own object-type library. Security has yet to move beyond aspiration; robust encryption, role-based access control, penetration tests, and audit trails are essential when safeguarding sensitive transportation data. On the human side, the single portal must satisfy both non-technical users and power data architects, but little has been done to reconcile those divergent needs. Artificial intelligence (AI) features are name-checked without any concrete use-case or model choice, leaving stakeholders unsure how Natural Language Processing (NLP) or AI-assisted querying will function. Finally, the project's success hinges on people: without formal incentives, change-management, hands-on training, and a phased roadmap studded with clear Key Performance Indicators (KPI) and a feedback loop, even the best technology may languish from lack of engagement and measurable progress.

Despite these architectural and operational challenges, the foundational technologies needed to support the CBTL are already available and proven in other domains. From robust API management platforms and scalable cloud infrastructures to interoperable open data standards and advanced metadata management frameworks, the essential components for a CBTL are within reach. What remains is to strategically align these technologies, mitigate implementation risks, and establish a clear execution framework tailored to the unique demands of transportation infrastructure. This report will outline how to leverage existing capabilities to build a resilient, standards-compliant, and future-ready CBTL, transforming a promising concept into a practical, scalable solution for national deployment.

1.1. Research Approach

The technical approach for the development of the CBTL is structured to seamlessly integrate the expertise and insights of the transportation industry. The aim is to identify existing repositories that can be leveraged that addresses the industry's needs and limitations through a collaborative and systematic process. The goal of this approach is to foster integration, collaboration, and innovation. By engaging with industry resources, aligning with standards, and considering potential risks, the approach aims to create a robust and impactful CBTL that not only addresses limitations but also paves the way for a more connected and efficient transportation industry.

The initial phase of the approach involved a comprehensive analysis of available resources, such as the Secure Data Commons (SDC)[3] and the bSDD[4]. Each was evaluated based on its capabilities and limitations, ensuring that the chosen resources aligned with the CBTL's objectives. By understanding these resources, they can be leveraged effectively to enrich the CBTL's content and functionality.

The approach extends to evaluating and integrating existing databases, repositories, and libraries like the National Transportation Library (NTL)[5] and the Repository and Open Science Access Portal (ROSA P)[6]. By identifying synergies between these repositories and the CBTL, the overall effectiveness of the library's content and impact can be enhanced. Furthermore, open data standards, such as those provided by

[3] https://www.transportation.gov/data/secure

[4] https://www.buildingsmart.org/users/services/buildingsmart-data-dictionary/

[5] https://ntl.bts.gov/ntl

[6] https://rosap.ntl.bts.gov/

buildingSMART International, were explored to ensure seamless data interoperability and exchange within the CBTL, while also assessing the suitability of SDC for secure content hosting and sharing.

The heart of the approach lies in defining clear goals and objectives for the CBTL through a meticulous sequence of steps, tasks, and activities to achieve these objectives. This includes defining the technical requirements, identifying ownership and management criteria, establishing data governance and management plans, and developing strategies for scalability and future improvements. Through active industry participation, feedback incorporation, and validation, it has been assured that these goals align with the industry's needs.

1.2. CBTL Overview

1.2.1. Concept and Vision

The CBTL envisions becoming the national cornerstone for open, standardized, and interoperable digital infrastructure data that enables transformative collaboration, efficiency, and innovation across the entire life cycle of transportation infrastructure assets.

As a centralized, version-controlled repository, the CBTL will empower stakeholders—from federal and state agencies to technology vendors and engineering professionals—to create, manage, and share Building Information Modeling (BIM) artifacts rooted in open standards. These artifacts will support evolving workflows for design, construction, inspection, maintenance, and asset management of highway infrastructure including roads, bridges, and tunnels.

The CBTL should be designed to:

- Support the advancement of BIM for transportation infrastructure.
- Close the gap between vertical and horizontal construction needs by enhancing and expanding the BIM and open data standards to better accommodate the geospatial and infrastructure-specific demands of transportation assets.
- Provide a consistent and collaborative framework by offering a curated collection of technical resources such as object-type libraries, comprehensive data dictionaries, Model View Definitions (MVD), and standardized information exchange specifications.
- Deliver a scalable, open-access digital platform, structured around established standards and principles to maintain metadata quality, ensure semantic alignment, and enable future scalability and evolution.
- Enable a centralized system that facilitates secure information sharing across different DOTs and transportation agencies, while maintaining robust user-defined access controls to protect sensitive data and ensure data security.
- Foster integration and public-private collaboration through robust APIs, community engagement portals, and transparent data governance practices, ensuring the CBTL can be seamlessly adopted within agency workflows and existing Information Technology (IT) ecosystems.

Ultimately, the CBTL can serve as the digital backbone of a national transportation infrastructure ecosystem that is data-centric, interoperable, future-ready, and aligned with global best practices, driving smarter infrastructure delivery and life cycle management.

1.2.2. BIM Artifacts

While it has yet to be formally defined, *BIM Workflows and Centralized BIM Transportation Library for Bridges and Roadways* presents BIM artifacts as structured digital resources that enable the development, deployment, and standardization of BIM-based workflows across the transportation asset life cycle (Bhargava et al., 2024). They are essential for supporting data modeling, data exchange, and consistent process implementation in BIM-enabled environments, and include components such as OTLs, data dictionaries, MVDs, and information exchange specifications. The six previously identified artifacts include BIM processes, workflows, terms, and definitions; BIM information needs; BIM OTL and Data Dictionary; BIM Information Delivery Manuals (IDM); BIM Information Exchange Specification; and BIM MVDs.

BIM artifacts are the foundational elements required to support a robust digital exchange environment across the infrastructure life cycle. They encompass standardized processes, structured data, and interoperable formats that guide digital project delivery and asset management. These resources collectively underpin a data-driven approach to digital delivery, enhancing interoperability, clarity, and consistency across infrastructure and building projects. The following list provides an expansion of the previously defined BIM artifacts with additional details including the description, an example of its application, and typical file types used for its development or exchange.

1. BIM Processes, Workflows, Terms, and Definitions

- Description: Standardized procedures, language, terminology, and semantics for BIM implementation and coordination.
- Example: TPF-5(372) developed a glossary of terms and the “Bridge Lifecycle Management Overview Map” to define and align BIM terms and processes for consistent digital information exchange.
- File Types:
    - Text Documents: .docx, .pdf, .txt
    - Diagrams/Workflows: .vsdx, .png, .svg, .pptx

2. BIM Information Needs

- Description: Requirements for information to be captured at different stages of the asset life cycle.
- Example: TPF-5(480) published the *Building Enterprise Asset Inventories* report that defines information needs for facility assets across planning, design, construction, and operations, including minimum data fields, spatial requirements, and modeling expectations based on asset type and life cycle phase.
- File Types:
    - Text Documents: .docx, .pdf
    - Structured Data: .xlsx, .csv, .xml

3. BIM Models, Object-Type Library (OTL), 3D Cell, and Parametric Object Library

- Description: Structured collection of standardized digital representations, including object-type and parametric libraries, of building components and systems used in BIM software.
- Example: A transportation-focused parametric object library includes 3D cells of components like guardrails, culverts, and roadway signs, each embedded with attributes such as material, dimensions, installation standards, and asset classification, allowing direct import into roadway or bridge BIM models.

- File Types:
    - 3D BIM Models: .rfa,.dwg, .dgn, .skp, .obj, .rvt , .nwd, etc.
    - Data Exchange: .xml, .json, .csv, .ifc

4. Data Dictionary

- Description: A centralized repository of information about data (e.g., metadata), which describes the content, format, and structure of a database and the relationship between its elements.
- Example: TPF-5(372) developed the US Bridge Data Dictionary that standardizes the definitions, attributes, and relationships of bridge-related data elements to support consistent information exchange and interoperability across BIM systems.
- File Types:
    - Text-Based Files: .json, .xml, .txt
    - Spreadsheet Files: .xlsx, .cvs
    - Linked Data Formats: .rdf

5. Information Delivery Manuals (IDM)

- Description: Standardized methodology and guidelines for the delivery and exchange of BIM information to clearly specify who needs to send what information, when, and how it must be formatted to enable reliable, software-interpretable BIM data exchange throughout a facility's life cycle.
- Example: AASHTO published the *Information Delivery Manual for the Design-to-Construction Data Exchange for Highway Bridges* to define a standardized information exchange to support interoperable, model-based construction workflows using IFC 4.3.
- File Types:
    - Documents: .pdf, .docx
    - Workflows: .bpmn, .vsdx, .xml

6. Information Exchange Specifications

- Description: Standards for how data is structured, shared, and validated across platforms, ensuring clarity on detail levels, tolerances, and reference datasets.
- Example: TPF-5(480) published *Utilizing Digital Information for Design to Construction and Fabrication: Information Requirements to Establish Data Exchange Models* that defines a structured process to capture and exchange the road asset information required from design through construction and fabrication phases.
- File Types:
    - Industry Standards: .ifc, .xml,
    - Common Data Environment (CDE) Outputs: .bimcollab, .bcf
    - Spreadsheets: .xlsx, .csv

7. Model View Definitions (MVD)

- Description: Specifications defining which data from IFC should be included in a model for specific use cases.

- Example: The Alignment-based View (AbV) MVD defines the specific IFC 4.3 elements, such as alignments, linear structures, and associated attributes, required to support data exchange for most horizontal infrastructure projects like roads and bridges.
- File Types:
    - Data Standards: .ifcxml, .ifc
    - Schema Formats: .json, .xml

8. Information Delivery Specification (IDS)

- Description: a buildingSMART standard for defining information requirements in a computer-interpretable form. It allows for automatic compliance checking of IFC models, which increases quality control and fidelity of data.
- Example: An IDS that outlines the specific data requirements, formats, delivery timelines, and responsibilities for exchanging detailed 3D bridge models, structural analyses, material specifications, and maintenance schedules between architects, engineers, contractors, and facility managers throughout the project life cycle.
- File Types:
    - Open BIM Standards: .ifc, .xml, .json
    - Spreadsheet Formats: .xlsx, .csv

9. Geospatial Data

- Description: Standardized geospatial data formats used to represent infrastructure assets, terrain models, and spatial relationships in transportation projects. These formats enable the integration of Geographic Information Systems (GIS) with BIM workflows for enhanced spatial analysis, asset management, and validation of existing structures modeled from as-built plans.
- Examples: Geospatial data is used to verify the location and accuracy of existing bridges and roadways modeled from as-built plans, ensuring alignment with real-world terrain and asset records in transportation projects.
- File Types:
    - GIS Data Formats: .gml, .shp, .geojson, .kml, .gpkg
    - Point Cloud and LiDAR Data: .las, .laz, .e57, .xyz
    - Database and Web GIS Formats: .sqlite, .gdb, .wfs, .wms, PostGIS

1.2.3. CBTL Implementation Approaches

Because BIM artifacts encompass a wide range of data types, formats, and structures, accessing and managing this information requires flexible approaches tailored to different user needs and system capabilities. There are three primary implementation approaches: directory, gateway, and repository (Figure 1). Each approach offers a different level of integration, control, and functionality ranging from lightweight linkage to full data management based on the type of content needing to be accessed. Thus, the CBTL must adopt a hybrid implementation using all three. This multi-tiered strategy provides flexibility for stakeholders at different stages of BIM adoption and supports a scalable path toward nationwide digital infrastructure standardization.

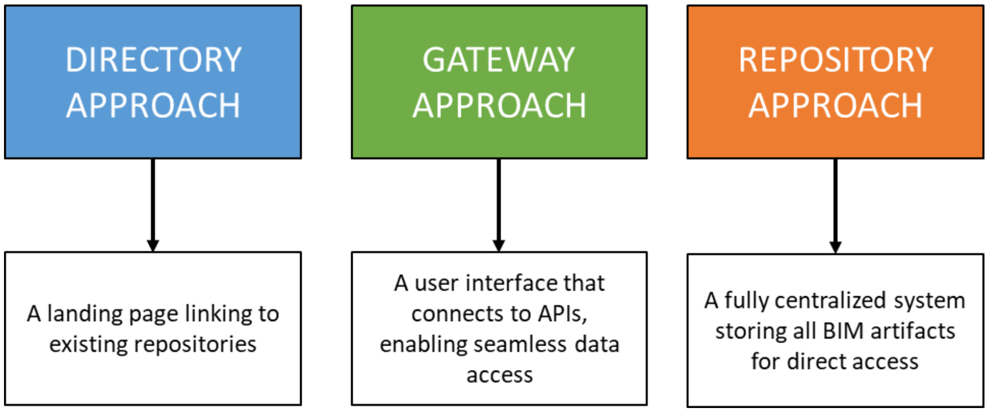

Figure 1: Central BIM Transportation Library (CBTL) Implementation Approaches

1. Directory Approach: A Central Landing Page for Discovery

The Directory Approach positions the CBTL as a curated entry point—a centralized Web interface that aggregates and links to existing BIM artifact repositories maintained by various organizations (e.g., FHWA, AASHTO, state DOTs, buildingSMART). Ideal for quick access and discovery, this approach minimizes content duplication while providing a national-level directory for locating authoritative resources in a federated environment. Key features include:

- Categorized indexing of external BIM resources.
- Metadata-driven navigation and filtering.
- Guidance on artifact usage and source authority.

2. Gateway Approach: Seamless Connectivity via APIs

The Gateway Approach enables the CBTL to act as an integration layer, facilitating real-time data access through standardized Application Programming Interfaces (API). This enables technical users to retrieve, transform, and integrate content into their own systems or workflows. This approach supports automated, system-to-system interaction, ideal for software vendors, developers, and agencies looking to embed BIM content directly into design tools, asset management systems, or analysis platforms. Key features include:

- API management platform for secure, scalable access.
- Developer tools and documentation for system integration.
- Dynamic querying and real-time data services.

3. Repository Approach: A Centralized BIM Content Library

The Repository Approach represents a fully centralized solution, where all BIM artifacts—such as data dictionaries, object libraries, IDMs, and MVDs—are stored, curated, versioned, and governed within the CBTL itself. This approach is ideal for national standardization, centralized governance, and life cycle management of BIM artifacts. It ensures all users access a consistent, validated set of content from a trusted source. Key features include:

- Central storage and authoritative version control.
- Contributor workflows with permissioned roles and quality review.
- Collaborative editing, discussion, and publication tools.

1.2.4. Core Technology

The CBTL requires a well-structured technical foundation to support efficient management, retrieval, and exchange of BIM artifacts. This includes:

- **Database Infrastructure:** Incorporate a scalable, cloud-based database system capable of storing and managing BIM artifacts efficiently. The system should support structured and unstructured data storage, ensuring compatibility with diverse data formats such as Computer-Aided Design (CAD) files, GIS layers, and metadata standards.
- **Interoperability:** Integrate with existing platforms, such as the SDC and industry systems such as the bSDD, ensuring interoperability across various systems. However, challenges remain in harmonizing different data formats and managing metadata across multiple agencies that often use legacy systems.
- **Standardized Data Formats:** Support a broad set of open and proprietary standards to ensure interoperability and life cycle coverage. This includes BIM standards such as IFC, MVDs, and IDS; web and geospatial standards like JSON, GeoJSON, and XML (W3C, OGC); and widely used proprietary formats such as DGN, DWG, and GDB. These formats are essential for enabling data exchange, metadata extraction, and validation across planning, design, construction, and asset management phases.
- **Metadata and Classification:** Implementation of a structured metadata model leveraging standards such as the Open Group Architecture Framework (TOGAF) for categorizing and managing BIM artifacts. Metadata should capture key attributes such as data editor, accuracy, resolution, and update history to ensure high-quality information exchange.
- **Data Storage Efficiency:** Use of optimized file storage mechanisms that can efficiently manage and query large datasets, including 3D models and GIS layers. The repository should integrate with federated data storage and indexing solutions for rapid retrieval of large-scale infrastructure datasets.
- **Data Security and Privacy**: Implement robust data security protocols and privacy safeguards to protect sensitive transportation infrastructure information. This includes implementing encryption for data at rest and in transit, role- and attribute-based access controls, audit logging, and compliance with federal cybersecurity standards such as NIST and FISMA. Security measures must also address cross-agency data sharing and the protection of proprietary and personally identifiable information (PII).

1.2.5. Data Governance and Management

Effective data governance ensures security, validity, and reliability of BIM artifacts within the CBTL:

- **Access Control:** Establish role-based access mechanisms to ensure data security and controlled data sharing among stakeholders. This should include fine-grained permission settings that allow different levels of access based on user roles and agency requirements. This enables specific users (e.g., state DOTs) to keep specific data private and secure.
- **Version Control:** Implement a robust version control system to track updates and changes to BIM artifacts over time, ensuring historical integrity and rollback capabilities. Ensuring that versioned data is interoperable across multiple platforms is critical for sustained data usability.
- **Data Validation and Quality Assurance (QA):** Define a comprehensive QA/Quality Control (QC) framework to standardize the validation process for BIM artifacts before inclusion in the CBTL. Automated validation routines and AI-driven anomaly detection should be implemented to enhance data reliability.

- **Integration with Existing Repositories:** Leverage data governance and management practices from national, state, and local repositories to inform CBTL policies on metadata standards, access control, and quality assurance. Establishing API-based interoperability with these systems will support dynamic updates, alignment of governance protocols, and consistent data stewardship across federated sources.

1.2.6. Stakeholder Engagement and Collaboration

The success of the CBTL depends on active participation and collaboration between different stakeholders:

- **DOT Participation:** Involve state DOTs to align CBTL with their specific needs, ensuring usability and adoption. Each DOT should have a mechanism to contribute localized data while maintaining national interoperability.
- **Industry Collaboration:** Partner with standards organizations such as buildingSMART International and National Institute of Building Sciences (NIBS), as well as technology providers, to align CBTL with industry-wide best practices. Regular stakeholder workshops should be conducted to address ongoing challenges in data standardization.
- **Training and Support:** Develop training programs and user guidelines to promote effective utilization of the CBTL. Training should focus on both technical implementation (e.g., BIM software integration) and governance practices (e.g., data submission and validation workflows).
- **User Feedback and Iterative Development:** Establish a continuous improvement loop where feedback from DOTs, contractors, and consultants is systematically incorporated into CBTL updates. A structured feedback mechanism should be implemented, ensuring that end-users' insights contribute to enhancements.
- **Collaborative Contribution Platform:** Establish a transparent, open-source-inspired environment—such as GitHub or an equivalent platform—to support issue tracking, discussions, and user-submitted enhancements. This mechanism will empower engaged stakeholders to propose changes, document ideas, and track progress collaboratively, ensuring a responsive and evolving CBTL ecosystem that values and incorporates community contributions.

1.2.7. Emerging Technologies That Can Enhance CBTL

While past research has primarily focused on foundational BIM technologies, several emerging technologies offer opportunities to further strengthen CBTL's capabilities. These include advancements in artificial intelligence, blockchain, digital twins, immersive visualization, graph databases, and edge computing, each of which can play a role in improving efficiency, reliability, and usability. *The following tools are listed as illustrative examples only and do not represent endorsements or a comprehensive listing of available solutions*:

- **AI and Machine Learning for Data Categorization:** Automating metadata tagging and improving searchability of BIM artifacts.
    - **Tools:** Google AutoML, IBM Watson AI, and OpenAI Codex can assist in intelligent data categorization and search optimization.
- **Blockchain for Data Integrity:** Ensuring immutability and secure traceability of version-controlled BIM artifacts.

  - **Tools:** Hyperledger Fabric and Ethereum-based smart contracts can facilitate data security and transaction validation.
- **Digital Twin Integration:** Enabling real-time updates by connecting CBTL with live infrastructure data from Internet of Things (IoT) sensors.
  - **Tools:** Bentley iTwin, Dassault Systèmes 3DEXPERIENCE, and Siemens MindSphere support digital twin modeling and analysis.
- **Augmented Reality (AR) and Virtual Reality (VR):** Supporting visualization and interactive training for BIM users.
  - **Tools:** Unity Reflect, Autodesk Revit Live, and Trimble XR10 enhance immersive visualization for BIM data.
- **Graph Databases:** Enhancing data relationships for better querying of interconnected BIM objects and workflows.
  - **Tools:** Neo4j and Amazon Neptune provide advanced querying capabilities for structured BIM data.
- **Edge Computing for Remote Access:** Improving data processing capabilities for field engineers accessing BIM data on-site.
  - **Tools:** Microsoft Azure IoT Edge and AWS Greengrass allow processing and analytics on remote devices.

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II. Literature Review and Related Projects

2. Literature Review and Related Projects

2.1. Literature Review Methodology

The purpose of the literature review was to provide a comprehensive state-of-practice review on the application of Building Information Modeling (BIM) for transportation infrastructure for the development of the CBTL in the United States. A systematic literature review was conducted to pinpoint relevant research projects and literature. Such reviews are guided by clearly defined questions, scope, parameters, and methodologies to identify, select, and critically assess pertinent material. Systematic reviews incorporate both qualitative and quantitative approaches. Additionally, a scan of related industry projects and technologies was performed to identify additional literature for this task.

The scope was limited to existing research conducted by the FHWA and state DOTs, aiming to pinpoint key barriers to successful adoption and to explore methods that can be developed to support the development of the CBTL. Traditional literature reviews typically utilize academic databases as the primary source of published literature. However, given the focus on state DOTs for this review, it was anticipated that most relevant documents would be white papers, reports, and guidance documents, which are not commonly found in academic databases. Therefore, this review employed a mixed-method approach, searching academic databases, federal and state transportation databases, Google Scholar, and individual state DOT Web pages. Additionally, a depth-first search strategy was applied to explore the references within each article and the articles citing them.

BIM for transportation encompasses a wide array of topics, so a variety of keywords and variations was employed. The search queries combined terms like ["BIM" AND "state" AND "DOT"] and [("BIM" OR "Building Information Modeling") AND "State Departments of Transportation"]. The search began with broader themes of digital delivery and was progressively refined for more detailed results. Due to the vast number of sources and Web pages, which varied in design, it was not feasible to quantify the total results based on keyword queries.

During the search and collection process, it was important to prescreen the articles to avoid excluding any relevant ones. When a publication was found, its title, abstract, and keywords were reviewed to determine its relevance to the review. If deemed relevant, the publication's metadata was recorded and stored for future retrieval and analysis. This metadata included the Digital Object Identifier (DOI), and Uniform Resource Identifier (URI), authors, publication information, keywords, and abstract. Due to restrictions and permissions on some articles, not all publications could be stored.

2.2. Results and Findings

The review resulted in 58 relevant articles, including technical reports, journal articles, conference proceedings, and case studies. Additionally, the scan provided information regarding industry research and available technologies. A high-level review is detailed below, including common themes, BIM state of practice in DOTs, and related projects.

2.2.1. Common Themes

The transportation sector is undergoing a significant transformation, driven by advances in technology and digital workflows. Figure 2 displays the common themes identified from the literature review. As the industry nears the peak of the technology adoption curve, it faces critical challenges in implementing tools that support full life cycle integration, particularly in the adoption of BIM and associated processes. While BIM has seen substantial success in the vertical construction industry, its application in transportation infrastructure remains limited. This is largely due to the sector's inherent complexity, where planning, design, construction, and maintenance phases are deeply interdependent and require highly coordinated digital solutions (Costin et al., 2018).

Although some transportation agencies and contractors have begun to integrate digital delivery methods within Alternative Contracting Models (ACM) such as design-build and public-private partnerships, the degree of implementation and integration into broader project management systems varies considerably (U.S. Department of Transportation, 2022). Furthermore, ongoing concerns around data governance, institutional readiness, and legal implications continue to hinder widespread and consistent adoption across the industry.

3D Modeling and BIM Implementation	•Growing adoption of 3D data and BIM in transportation. •Case studies highlight early successes but expose gaps in workflows and standards. •Increasing use of 3D for asset life cycle management, beyond design/construction.
Technological Advancements	•Expansion of advanced data capture technologies (LiDAR, UAVs, IoT sensors). •Rising emphasis on API-driven ecosystems and cloud-native infrastructures. •Need for system interoperability across legacy asset management platforms.
Governance, Collaboration, and Change Management	•Metadata standardization, data dictionary development, and governance frameworks emerging as critical priorities. •Change management, stakeholder engagement, and workforce training needed to enable digital delivery transitions. •Ongoing challenges in establishing ownership and stewardship models for BIM data.
Challenges and Benefits	•Benefits: Efficiency, collaboration, and data integration. •Challenges: Technical, organizational, and regulatory issues. •Real-world implementation analysis.
Gaps, Risks, and Future Directions	•Inconsistent BIM adoption maturity across state DOTs; need for flexible, scalable solutions. •Lack of standardized QA/QC for BIM artifacts across project life cycles. •Future directions point toward federated repositories, stronger AI-supported querying, and national data-sharing protocols.

Figure 2: Common Themes

2.2.1.1. 3D Modeling and BIM Implementation

National BIM Initiatives and Programs

The FHWA has promoted several initiatives under its Every Day Counts (EDC) program to accelerate the adoption of innovative technologies, including BIM, digital project delivery, and digital twins. Through EDC rounds such as EDC-3[7] and EDC-6[8], FHWA has emphasized the use of 3D-engineered models for construction, which serve as the foundation for digital project delivery and eventual digital twin development. These initiatives encourage state DOTs to transition from paper-based to model-based workflows to improve accuracy, efficiency, and data integration across the project life cycle. FHWA's efforts aim to enhance project visualization, support automated machine guidance, and enable more effective asset management by fostering a connected data environment. The overarching goal is to modernize transportation infrastructure delivery through digital innovation, improving decision-making and long-term performance.

Productivity Improvements in Project Delivery

The integration of digital workflows, such as BIM and 3D modeling, offers significant potential to enhance productivity in transportation project delivery. These technologies streamline coordination across project phases, reduce delays, and help control costs by improving design accuracy and facilitating proactive decision-making.

A notable example is the Downtown Links project in Tucson, where BIM was used to unify design and construction workflows. This enabled project stakeholders to visualize the infrastructure in advance, anticipate potential conflicts, and minimize costly design changes during execution — ultimately reducing overall project costs (Kittelson & Associates, 2021). Similarly, the Chicago Transit Authority’s Red and Purple Line Modernization Program leveraged 3D modeling to strengthen stakeholder coordination and improve design fidelity. This approach led to fewer construction errors and measurable cost savings (Barone, 2021). These cases illustrate how digital tools, when effectively implemented, can significantly boost efficiency and mitigate risk in complex transportation projects.

Project Management and Controls

Digital integration presents new opportunities to strengthen project management practices across transportation infrastructure, particularly in the areas of safety, scope management, and QA. By embedding digital tools into project controls, agencies and contractors can achieve greater transparency, predictability, and accountability throughout the delivery life cycle.

A compelling example is the Pecos Street over I-70 Bridge Replacement Project in Colorado, which utilized BIM to improve stakeholder coordination, enhance schedule reliability, and deliver precise cost estimates. This integration of digital project controls enabled more efficient workflows, rigorous quality oversight, and effective risk mitigation, ultimately contributing to the project's timely and successful completion (Clevenger et al., 2014). Such frameworks demonstrate how digital methodologies can elevate the standards of project delivery, ensuring both operational efficiency and adherence to defined performance goals.

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[7] https://www.fhwa.dot.gov/innovation/everydaycounts/edc-3.cfm

[8] https://www.fhwa.dot.gov/innovation/everydaycounts/edc_6/

2.2.1.2. Technological Advancements

DOTs are leveraging a suite of advanced digital technologies to modernize transportation infrastructure delivery, improve asset management, and enhance operational efficiency. These technologies support data-driven decision-making, cross-discipline collaboration, and life cycle project integration.

- Advanced Traffic Management Systems (ATMS) are employed to optimize traffic flow and increase safety through real-time data collection, predictive analytics, and adaptive signal controls. These systems integrate sensors, cameras, and communication technologies to monitor and respond to traffic conditions dynamically.
- Geographic Information Systems (GIS) are widely adopted by DOTs. GIS enables spatial data visualization, analysis, and integration for tasks such as asset inventory, environmental assessments, and infrastructure planning. These systems provide geospatial intelligence that supports strategic investments and maintenance decisions.
- Automated Vehicle Location (AVL) Systems enhance fleet management by providing real-time location tracking and operational data for maintenance vehicles, transit fleets, and emergency response units. This helps improve dispatch efficiency, route optimization, and overall service reliability.
- Intelligent Transportation Systems (ITS) integrate technologies such as dynamic message signs, surveillance systems, and vehicle detection sensors. DOTs apply ITS to manage congestion, monitor traffic incidents, and streamline travel through coordinated control systems and connected vehicle communication.
- Digital Twin Technology is emerging as a transformative approach for infrastructure management by enabling real-time, data-rich virtual representations of physical assets. Several DOTs are exploring or piloting digital twins to integrate live sensor data, 3D models, and operational systems for predictive maintenance, enhanced asset monitoring, and performance optimization. By bridging physical infrastructure with its digital counterpart, digital twins support proactive decision-making across the asset life cycle.
- API-Driven Systems are increasingly necessary to ensure seamless data exchange between disparate systems and applications. By adopting open APIs, DOTs can achieve greater interoperability across design, asset management, construction inspection, and GIS platforms. This approach enables real-time data sharing, automates workflows, and supports more agile and scalable digital ecosystems.
- Cloud-Based Solutions are becoming essential to support remote collaboration, scalability, and centralized data access. DOTs are adopting cloud-based platforms to manage large datasets, enable real-time collaboration among geographically dispersed teams, and provide secure, centralized repositories for project information. These solutions also facilitate integration with other technologies such as BIM, GIS, IoT sensors, and AI-driven analytics tools, enhancing overall system responsiveness and decision-making.

Collectively, these technologies signify a paradigm shift in how state DOTs approach infrastructure planning, delivery, and management. By adopting integrated, cloud-enabled, and API-driven solutions, agencies are laying the groundwork for more intelligent, resilient, and connected transportation systems.

2.2.1.3. Governance, Collaboration, and Change Management

Digital Transformation and Organizational Development

Driving digital transformation in transportation infrastructure requires more than adopting new technologies—it demands deliberate strategies that foster organizational adaptability, promote stakeholder buy-in, and build a culture of continuous innovation. Agencies across the US are responding with structured programs and strategic plans to institutionalize digital delivery and accelerate the adoption of model-based workflows.

The State of California recently enacted Assembly Bill No. 1037 (AB-1037) that mandates the California DOT (Caltrans) to develop and implement a plan for integrating digital construction management technologies (DCMT) into transportation infrastructure projects. Thus, Caltrans established *Building Information Modeling for Infrastructure (BIM4I) Initiative Implementation Plan* (Value Management Strategies, 2023) that underscores the importance of common data environments, open standards, and cross-disciplinary collaboration. Complementing this vision, the *Digital Construction Management Technology (DCMT) Implementation Plan* (Caltrans, 2023) focuses on modernizing construction contract administration systems, and identifying priority tools and workflows to digitize inspection, documentation, and payment processes.

The Utah DOT (UDOT), for instance, has developed a Digital Delivery Guide as part of its broader Digital Twin Strategic Plan, offering a roadmap for integrating advanced digital tools across the asset life cycle (Hjelm & Lukes, 2021). Similarly, the Pennsylvania DOT (PennDOT) launched its Digital Delivery Directive 2025, establishing standards and procedures to prepare for Model as the Legal Document (MALD) and advance digital practices statewide (HDR Inc., 2020).

Texas DOT (TxDOT) has created a comprehensive Digital Delivery Program, which includes formal guidance and outreach strategies, most notably its statewide “Road Show” initiative aimed at educating and engaging staff across all districts (Texas Department of Transportation (TxDOT), 2025). In parallel, Ohio DOT has crafted a BIM Strategic Plan to standardize the use of BIM for Infrastructure, signaling a long-term commitment to digital integration (Ohio Department of Transportation (ODOT), 2024).

A particularly impactful example comes from the Iowa DOT (Iowa DOT), which implemented a Digital Delivery and Digital Twin Initiative involving a fundamental transformation in workflows, technologies, and organizational culture. By shifting from paper-based processes to model-centric designs, Iowa DOT enhanced data accessibility, collaboration, and decision-making. The agency also introduced robust training programs, adopted open data standards, and utilized a phased approach to ease resistance and ensure internal alignment. This comprehensive strategy has not only increased project efficiency but also embedded digital innovation into the organizational fabric (Iowa Department of Transportation (Iowa DOT, 2022). These examples illustrate how targeted organizational development strategies are critical to the success of digital delivery, ensuring agencies are equipped to lead and sustain technological change.

Change and Knowledge Management for Digital Delivery

Digital delivery represents a fundamental shift in how transportation agencies design, deliver, and manage infrastructure. But while technology plays a central role, long-term success hinges equally on the ability of organizations to manage change and institutional knowledge effectively. Without these foundational elements, even the most promising digital initiatives are at risk of failure. Indeed, research shows that up to 70% of organizational change initiatives fail to result in sustained transformation, often due to inadequate support for people, processes, and cultural adaptation (Ketterl et al., 2024).

Change management in the context of digital delivery focuses on implementing structured processes to assess, coordinate, and drive transformation across project and organizational levels. This includes clarifying task ownership, ensuring accountability, and fostering agency-wide alignment on digital practices. It is not enough to introduce new tools—agencies must address institutional resistance, streamline workflows, and clearly communicate the value of innovation to internal stakeholders. When done well, change management efforts reduce implementation errors, improve adoption rates, and unlock broader efficiencies across the project life cycle.

In parallel, Knowledge Management (KM) plays a critical role in sustaining and scaling digital transformation. As agencies implement new technologies and data systems, including advanced digital libraries or model-based environments, maintaining continuity of knowledge becomes essential. A strong KM approach supports the long-term maintenance, adoption, and evolution of these systems, particularly when integrating with legacy processes or collaborating across agencies.

While there is no single blueprint for KM, successful approaches typically include:

- **Capturing and sharing institutional knowledge**, such as case studies, technical standards, and lessons learned.
- **Providing structured support mechanisms**, including training, user feedback loops, and troubleshooting resources.
- **Fostering a culture of learning**, where teams are empowered to explore, iterate, and improve.
- **Ensuring data and system interoperability**, enabling seamless information flow across tools, departments, and project phases.

Taken together, change management and knowledge management provide the scaffolding for lasting digital transformation. They help agencies navigate cultural and institutional barriers, build resilience, and fully leverage digital delivery to improve infrastructure outcomes.

2.2.1.4. Challenges and Benefits

Cost Implications and Long-Term Value Creation

While the shift to digital delivery requires substantial initial investment in tools, training, and organizational infrastructure, it also offers significant long-term returns in efficiency, accuracy, and asset performance. Strategic digital investments can reduce rework, minimize delays, and support life cycle-based asset management, ultimately generating cost savings and improving delivery outcomes.

One example is the Montana DOT's (MDT) Digital Delivery Initiative, which integrated BIM and CAD technologies into its project workflows. This investment proved particularly effective during the expedited replacement of the Wolf Creek Bridge, which had been destroyed by wildfire. Through streamlined digital workflows and enhanced collaboration, MDT completed the replacement in just six months—a timeline that would have been difficult to achieve using traditional methods. The approach reduced design and construction errors, improved stakeholder coordination, and enhanced long-term asset management planning (Racewicz, 2023).

This case highlights how up-front digital delivery costs can be offset by downstream savings in time, materials, and maintenance. By focusing on the total life cycle value of infrastructure projects, agencies can position digital delivery not as an expense, but as a high-impact investment in resilience, efficiency, and performance.

Risk Management in Digital Project Delivery

As transportation agencies increasingly adopt digital delivery methods, proactive risk management frameworks are becoming essential for ensuring project success. These frameworks support the early identification, analysis, and mitigation of potential risks throughout the infrastructure life cycle, enabling more resilient and adaptive project execution.

The Kentucky Transportation Cabinet's (KYTC) Digital Project Delivery (DPD) Initiative exemplifies this shift, as it transitions to paperless plan sets while instituting necessary legal and procedural safeguards to ensure compliance, secure data governance, and maintain effective stakeholder collaboration (Gibson et al., 2022). Similarly, the TxDOT held a Risk Management Workshop as part of its Digital Delivery Program, gathering insights from stakeholders across the state to develop a comprehensive risk register, which is a foundational tool for managing uncertainty throughout project development.

Another exemplary case is the I-95 New Haven Harbor Crossing Corridor Improvement Program in Connecticut, where 4D modeling was used to integrate time-based data with 3D designs. This enabled the Connecticut DOT (CTDOT) to simulate construction sequences, identify scheduling conflicts along the critical path, and implement preemptive mitigation strategies. The use of 4D modeling not only improved scheduling accuracy and reduced delays, but also enhanced stakeholder communication and real-time decision-making, contributing to the project's on-time and on-budget delivery (Federal Highway Administration (FHWA), 2017).

Security and Privacy Concerns

As digital delivery and data integration become central to transportation infrastructure, safeguarding sensitive information is a critical priority. Expanding reliance on model-based design, cloud-based collaboration, and interconnected systems introduces new vulnerabilities, particularly in areas of data integrity, access control, and cybersecurity. Ensuring the confidentiality, availability, and security of digital assets is essential to maintaining public trust and operational resilience.

A leading example comes from the Pennsylvania Turnpike Commission (PTC), which implemented a comprehensive cybersecurity transformation initiative to protect its highway operations from emerging cyber threats. This effort involved the deployment of advanced encryption protocols, tiered access controls, and organization-wide cybersecurity training to instill a culture of awareness and accountability. These measures significantly bolstered the protection of critical infrastructure data and enhanced the agency's ability to respond to and recover from potential attacks (Deloitte, 2024).

As transportation agencies continue to modernize their digital ecosystems, addressing cybersecurity and privacy concerns must be treated as a foundational component of digital delivery, not as a parallel or secondary task. This includes proactively designing systems with security in mind, enforcing compliance with industry standards, and preparing personnel to manage risks in an increasingly connected environment.

Legal and Liability Issues

As transportation agencies transition toward digital project delivery, they must navigate an evolving legal landscape shaped by questions of data ownership, intellectual property rights, liability, and contractual frameworks. The use of digital models—particularly as contractually binding instruments—requires new legal definitions and protocols to ensure clarity, accountability, and compliance across all project phases.

The Iowa DOT Digital Delivery and Digital Twin Initiative has emerged as a national precedent in addressing these challenges. Through the adoption of Model as a Legal Document (MALD), Iowa DOT has redefined the role of digital models in contract documentation, shifting from static plan sets to dynamic, data-rich design environments. This transition has required careful consideration of data governance policies, including the allocation of data ownership rights and the delineation of responsibilities among project stakeholders (Iowa DOT, 2022).

Central to Iowa DOT's approach is the implementation of open data standards, which promote interoperability and transparent information exchange while minimizing legal ambiguities. This strategy has improved coordination, streamlined asset management practices, and most importantly, provided greater clarity around liability and accountability, which are key factors in building stakeholder trust and supporting collaborative delivery models. As more agencies follow suit, addressing legal and liability concerns will be essential to unlocking the full potential of digital delivery while safeguarding institutional and stakeholder interests.

2.3. Related Projects

2.3.1. Building Information Modeling (BIM) Workflows and Centralized BIM Transportation Library for Bridges and Roadways FHWA-HIF-24-004

Summary. This project provides a comprehensive overview of the implementation of BIM in transportation infrastructure. The report focuses on transitioning traditional workflows to BIM-based workflows to enhance efficiency and productivity. It includes a detailed analysis of ten process workflows spanning planning, survey, design, construction, and asset management. The report identifies key artifacts necessary for deploying BIM-based workflows, such as business process models, data terminology, classification systems, information delivery manuals, and model view definitions. The report also proposes the establishment of a Central BIM Transportation Library (CBTL) as a centralized repository for maintaining open standards-based BIM artifacts, with the goal of improving data management and fostering collaboration among stakeholders. The CBTL would provide a version-controlled environment to ensure data integrity and facilitate the development of state-specific BIM transportation libraries. The project resulted in several key findings:

1. **BIM Components and Objectives**: The document outlines the components necessary for BIM development, including data and process specifications, tools and technology, capacity-building activities, and leadership collaboration and policies. The objectives focus on identifying business processes across the asset life cycle (planning, survey, design, construction, and asset management) and enhancing BIM maturity to improve efficiency and productivity.
1. **BIM Workflows**: Four main BIM workflows are identified:
   - 1.1. Planning, Survey, and Design (PSD): Involves initial project development activities leading to a Project Information Model (PIM).
   - 1.2. Design and Analysis (DA): Focuses on creating detailed design models for various disciplines and integrating them into a final design model for construction.
   - 1.3. Design and Construction (DC): Covers developing final design models, fabrication, construction, and as-built models.
   - 1.4. Design, Construction, and Asset Management (DCA): Integrates data models from design and construction into an Asset Information Model (AIM) for asset management.
2. **BIM Artifacts:** The document details various BIM artifacts needed for workflow deployment, such as business process models, data terminology, classification systems, OTLs, information needs, IDMs, information exchange specifications, and MVDs.
3. **CBTL**: Proposes creating a CBTL as a repository for maintaining open standards-based BIM artifacts. The CBTL aims to facilitate content sharing and development among stakeholders, with recommendations for architecture and deployment.
4. **Implementation and Administration**: Discusses the technical aspects of developing, deploying, and administering a CBTL, including people, roles, responsibilities, database management, version control, and APIs.
5. **Case Studies and Examples**: Provides examples and case studies from various state departments and international practices to illustrate the implementation and benefits of BIM in transportation.

Benefits for the CBTL. This report provides valuable information regarding the creation of the CBTL, including a CBTL framework, industry use cases, technical requirements, example of BIM artifacts, and a governance model. The report addresses the critical aspects of BIM implementation in transportation infrastructure, providing a clear pathway for transitioning from traditional to BIM-based workflows. The identification of specific workflows and use cases highlights practical areas where BIM can bring substantial improvements. The proposed CBTL is a significant step toward standardizing and managing BIM artifacts, promoting interoperability, and supporting the overall goal of enhanced data management across the asset life cycle. The detailed discussion on data modeling, data management, and data use underscores the importance of a holistic approach to BIM implementation, ensuring that all relevant data is captured, validated, and utilized effectively. The report's emphasis on stakeholder engagement and the integration of various data sources reflects a comprehensive understanding of the complexities involved in transportation projects. Overall, the findings and recommendations in the report provide a solid foundation for advancing the CBTL concept.

2.3.2. TPF-5(372) Building Information Modeling (BIM) for Bridges and Structures

Summary. The TPF-5(372)[9] study aimed to develop a standard for exchanging 3D models and digital data for bridges using an open, nonproprietary format. This multi-year project focused on creating an open data standard for software developers to enhance interoperability within the US bridge industry. The final report outlines the study's direct outcomes, including the development of the data standard, and indirect outcomes, such as industry impact. It also discusses the next steps for continuing the project's work.

Benefits for the CBTL. The TPF-5(372) study was a critical step forward in standardizing BIM for the bridge and structures sector, addressing a significant need for interoperability and consistency in data exchange. The development of an open, nonproprietary format ensures that various software products can seamlessly integrate, facilitating better collaboration and efficiency within the industry. The project's outcomes, both direct and indirect, highlight its comprehensive approach and significant impact. The emphasis on next steps ensures continuity and sustained progress in the adoption and implementation of BIM standards across the industry, promoting long-term benefits. This project resulted in many artifacts that can be hosted on the CBTL, such as the MVD, IDM, IDS, and data dictionary.

2.3.3. TPF-5(523) Building Information Modeling (BIM) for Bridges and Structures-Phase II (Ongoing)

Summary. The TPF-5(523)[10] project is a continuation of the TPF-5(372) that kicked off in February 2024. This project builds on the outcomes of the earlier TPF-5(372) project, aiming to establish national openBIM data standards, support model-based data exchanges, and provide training and implementation support for state DOTs. Key goals include developing standardized data requirements, offering technical support and workshops, enabling secure model-based deliverables, and collaborating with industry groups such as buildingSMART International (bSI). Through these efforts, the initiative seeks to streamline project workflows, promote interoperability, and lay the groundwork for more efficient digital project delivery methods.

Benefits for the CBTL. The CBTL will be able to capitalize on the deliverables and best practices from the project, specifically the major BIM artifacts of the MVD, IDM, Data Dictionary, and Process maps. Additionally, TPF-5(523) is working closely with buildingSMART International (bSI) in the methodology development, which will optimize the development and utilization of bSI’s technical solutions that can be leveraged.

2.3.4. TPF-5(480) Building Information Modeling (BIM) for Infrastructure (Ongoing)

Summary. The BIM for Infrastructure Transportation Pooled Fund Clearinghouse (TPF-5(480))[11] is a collaborative initiative aimed at advancing BIM for transportation infrastructure. This project seeks to leverage BIM and open data standards to enhance information management across all phases of the asset life cycle in transportation infrastructure. The initiative focuses on breaking down data silos and improving data accessibility for real-time decision-making in managing highway assets. The objectives include: 1) provide technical guidance on leveraging BIM concepts and open data standards, 2) develop a comprehensive guide for information management covering all project phases, including development,

[9] https://bimforbridgesus.com/

[10] https://pooledfund.org/Details/Study/755

[11] https://www.bimclearinghouse.com/about/

construction, operations, maintenance, and strategic asset management, and 3) increase coordination and awareness of BIM technologies and activities, building on foundational work from the National Strategic Work Plan. Initial findings include:

- Document Library
  - A well-organized and searchable collection of reports offering detailed information to support BIM for transportation infrastructure.
- 3D Cell and Parametric Object Library
  - A searchable repository of custom-built 3D cells and parametric objects that can be incorporated into software.
- BIM deployment Tools
  - BIM Data Models Catalog and Data Assets Catalog
  - BIM Model Elements Breakdown–Object Type Library (OTL) and Data Dictionary
  - BIM Asset Information Requirements (AIR)
  - BIM Information Exchanges for Information Delivery Manual
  - BIM Software Applications Catalog and Applications Communication Diagram
- Data Artifacts
  - *Terms and Definitions*–A glossary of all BIM-related terms and definitions.
  - *Data Models Catalog*–A catalog of information about the data models created in the digital delivery process.
  - *Data Assets Catalog*–A catalog of information about the data assets captured in the data models.
  - *Information Exchanges Catalog*–A catalog of information about all the data exchanges between data models and digital workflow process steps.
  - *Object Type Library (OTL)*–A library of object types that are part of the BIM data model. They are also referred to as “model elements” and the American Association of State Highway and Transportation Officials (AASHTO) Joint Technical Committee on Electronic Engineering Standards (JTCEES) Model Element Breakdown will be used as the starting point for defining these object types.
  - *Data Dictionary*–The BIM data dictionary describes the attributes that are captured in a data model corresponding to each of the object types in the model.

Benefits for the CBTL. Overall, the TPF-5(480) initiative represents a significant advancement in the field of transportation infrastructure, promising substantial improvements in project delivery, asset management, and real-time decision-making capabilities. The creation of a BIM communication hub and training programs ensures that all stakeholders are well-equipped to adopt and implement BIM technologies effectively. The BIM Clearinghouse is expected to be an online searchable platform designed to communicate TPF-5(480) research findings and guidance. The creation of the clearinghouse, BIM communication hub, BIM data artifacts, and training programs are in line with the vision of the CBTL.

2.3.5. The Semantic buildingSMART Data Dictionary (bSDD) (Ongoing)

The Semantic buildingSMART Data Dictionary (bSDD)[12] project aims to enhance data interoperability and quality in the Architecture, Engineering, Construction, and Operations (AECO) industry by improving the structure and accessibility of construction-related data through advanced APIs like GraphQL, JavaScript Object Notation (JSON), and Resource Description Framework (RDF).

Findings:

- **Improved Data Structure:** The data and schema were refactored for better structuring and interconnectivity.
- **Enhanced Access Methods:** Provided SPARQL and GraphQL endpoints for easier data querying.
- **Consistency Issues:** Identified discrepancies in data returned by different APIs.
- **Statistics:** Detailed statistics on data usage and structure were provided, revealing underused features and inconsistencies.

Recommendations:

- **Standardize Data Across APIs:** Ensure consistent data returns across GraphQL, JSON, and RDF APIs.
- **Improve Property Names and Uniform Resource Locators (URL):** Conform to naming conventions and use uniform URLs.
- **Enhance Entity Relations:** Convert string attributes to object properties to improve graph navigation.
- **Model Complex and Dynamic Properties:** Clarify the use of complex properties and dynamic property calculations.
- **Add New Entities:** Introduce new entities like *CountrySubdivision* and *DomainVersion* to better structure the data.

Benefits for CBTL. The bSDD can be integrated into the CBTL.

2.3.6. Demonstrating the Creation and Use of a Central BIM Transportation Library (CBTL) (Ongoing)

FHWA initiated the CBTL Demonstration Project in parallel with this CBTL project. It has the following objectives:

- House sample BIM data artifacts in a nationally accessible repository.
- Demonstrate governance structure and control to manage artifacts.
- Demonstrate CBTL's functionality and utility at project level for consistent, national adoption and implementation of BIM data and process standard.
- Develop people and infrastructure requirements for a CBTL data management tool.

Benefits for CBTL. This project is intended to use a Commercial Off-the-Shelf (COTS) application at several state DOTs to demonstrate the use and development of selected components of the CBTL. Collaboration between these two projects has just begun and as it progresses, this section will be further developed including designation of benefits.

[12] https://bsdd.ontotext.com/

2.4. Summary of Literature Review Findings

The CBTL plays a pivotal role in advancing the adoption and institutionalization of standardized BIM practices across the transportation sector. This chapter reviewed the current state of practice, industry trends, technological advancements, organizational change efforts, and ongoing national projects that collectively shape the digital transformation landscape for transportation infrastructure. Through a systematic literature review and examination of related initiatives, several critical themes emerged, including the growing importance of data interoperability, life cycle information management, stakeholder collaboration, and digital delivery integration. The findings highlight that many transportation agencies are still navigating early phases of BIM implementation, with varied maturity levels across states. Barriers such as institutional resistance, legal ambiguity, and lack of standardization persist, yet there is clear momentum driven by federal programs (e.g., FHWA's EDC initiatives), statewide strategic plans (e.g., UDOT, Caltrans, PennDOT), and innovative pilot projects (e.g., MDT, CTDOT). These efforts underscore a national shift toward model-based workflows and integrated project delivery methods. Success stories from states like Utah, California, and Pennsylvania, as well as pilot implementations in Montana and Connecticut, demonstrate the practical benefits and growing traction of BIM across diverse transportation contexts.

The CBTL initiative directly benefits from these developments by aligning its mission with the core outcomes of major BIM research and pooled fund studies, particularly those focused on openBIM standards, data exchange protocols, and MVDs. Projects such as TPF-5(372), TPF-5(523), and TPF-5(480) have yielded essential BIM artifacts and data governance structures that CBTL can adopt, curate, and disseminate. Moreover, initiatives like the FHWA Demonstration Project and the Semantic bSDD provide critical technical and procedural frameworks that inform the design, functionality, and extensibility of the CBTL platform.

By incorporating training materials, implementation guides, model-based workflows, and standardized terminology from these efforts, the CBTL strengthens its capacity to serve as a trusted and centralized resource for state DOTs and industry stakeholders. Its role is not only to house data artifacts, but to provide a version-controlled, governance-driven, and nationally accessible environment that promotes consistent use, continuous improvement, and cross-agency collaboration. Ultimately, this literature and project review validates the need for a unified infrastructure to manage and standardize BIM data practices in transportation. The CBTL is positioned to become that foundation, empowering agencies with the tools, guidance, and shared knowledge necessary to transition from isolated digital efforts to coordinated, resilient, and interoperable digital delivery ecosystems.

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III. Stakeholder Engagement

3. Stakeholder Engagement

3.1. Stakeholder Engagement Methodology

An extensive stakeholder engagement initiative was undertaken to guide the development of the CBTL. This effort employed a variety of channels and touchpoints to gather input from a diverse array of stakeholders across the transportation sector. Perspectives were captured from state and local transportation agencies, federal agencies, contractors, engineering and design consultants, software vendors, technology solution providers, and standards development organizations. This broad outreach ensured that the CBTL would be informed by the practical needs, challenges, and innovations identified by end users, industry experts, and technology partners alike. Stakeholder engagement was broken into two categories: 1) End Users, including state DOTs, local transportation agencies, transit authorities, contractors, and engineering consultants who would utilize the system for planning, design, construction, and asset management; and 2) Solution Providers, encompassing software vendors, technology developers, data service providers, and standards organizations contributing tools, platforms, and expertise to enable system functionality and interoperability. Finally, the stakeholder engagement process culminated in the CBTL roundtable, where a representative group of stakeholders convened to provide real-time feedback and help refine the project's key research outcomes and future directions.

The engagement approach included:

- In-person and virtual meetings with stakeholders.
- Participation in peer events such as the Transportation Research Board (TRB) Annual Meeting, International Highway Engineering Exchange Program (IHEEP), BIM for Infrastructure Week (BIM Week), and additional regional conferences.
- 1:1 interviews, surveys, and structured discussions with state DOTs, industry consultants, technology providers, and academic researchers.
- Utilization of insights from prior contracted research engagements with state DOTs and industry initiatives.
- Active participation in the BIM Roundtable held January 9, 2025, after TRB, which served as a key forum for gathering live feedback and refining key research findings.

In addition to primary engagements, secondary research from existing industry reports, prior FHWA initiatives, state DOT research, pooled fund studies, and related federal programs were synthesized to ensure findings were comprehensive and reflected the most current state of practice. This multifaceted approach provided a robust basis to assess the current landscape, barriers, opportunities, and success criteria needed to support the development and deployment of a centralized BIM library for transportation infrastructure.

3.2. End-User Stakeholder Engagement

Drawing from the research foundation and direct outreach activities, structured feedback was gathered from key DOT stakeholders and solution providers. These conversations helped validate early findings, uncover critical challenges and opportunities, and inform recommendations for next steps for the CBTL's design and deployment.

3.2.1. Feedback from State DOTs

A consistent theme across states was the challenge of achieving collaboration and data standardization. While most agencies recognize the need for a unified environment to support BIM and digital project delivery, significant variability in practices, technologies, and organizational structures exists.

Although a national BIM standard is broadly seen as desirable, practical considerations—including legacy systems, differing levels of digital maturity, and jurisdictional requirements—complicate adoption. State DOTs emphasized the need for a flexible framework that enables cross-state collaboration without imposing rigid, one-size-fits-all requirements. The following are highlights based on early feedback:

- Data Structure & Management:
  - Lack of centralized data collection; data often resides in separate GIS databases or with individual stewards.
  - Preference for flexible, cross-platform data solutions.
  - Standardization of data, processes, and technology emphasized to maintain continuity despite staff turnover.
- Technology & Tools:
  - Adoption of advanced digital modeling and exploration of next-generation tools beyond traditional standards.
  - Use of open APIs to improve data exchange, accuracy, and interoperability.
- Workforce & Change Management:
  - Importance of aligning people, processes, and technology for digital delivery.
  - Change management planning (leadership engagement, staff training, internal communication) identified as critical.
  - Concerns about workforce readiness and insufficient digital training in education programs.
- Pilots & Adoption:
  - Piloting digital tools while managing resistance from contractors.
  - Continued reliance on paper deliverables alongside digital workflows.
  - Organizational readiness is seen as equally important as technical solutions for long-term BIM adoption.

3.2.2. Key Themes:

- **Workforce Training and Change Management**: A strong focus emerged on the need for change management and workforce training to ensure the adoption of new digital tools. States like Ohio, Michigan, and Minnesota are struggling with workforce turnover, making it difficult to retain knowledge and skills related to digital delivery.

- **Data Standardization**: Several states emphasized the importance of data standardization, but also the reality that every state has its own unique data needs. This raises questions about whether a national standard is realistic or whether there is a better solution in creating a "translator" for data that can work across different platforms.

- **Technology and Tool Integration**: A few states have made strides with digital tools, piloting them in projects and seeing measurable improvements in project duration and data accuracy. However, interoperability between tools remains a challenge, and many states are still in the piloting phase to determine the best tools for digital delivery.

- **Collaboration and Consultant Involvement**: There is growing recognition that the consultant community holds valuable insights into best practices across multiple states and platforms. Their broader view of DOT operations offers key opportunities for collaboration as states work toward common solutions.

3.3. Solution Provider Stakeholder Engagement

To further align the CBTL with existing standards and infrastructure, engagement was conducted with technical leads from bSI and the SDC. These sessions aimed to:

1. Understand how current technical resources and platforms could integrate with or inform the CBTL design.
2. Assess API access, interoperability challenges, and scalability considerations.
3. Identify available artifacts, metadata schemas, and open data standards that could be leveraged during the CBTL's initial development phase.

This outreach helped validate the feasibility of integrating the CBTL with existing national and international frameworks and identified potential technical gaps that must be addressed during deployment.

3.3.1. buildingSMART international (bSI) buildingSMART Data Dictionary (bSDD)

1. CBTL Integration

The bSDD can be utilized by the CBTL as a service to host data dictionaries containing classifications, their properties, allowed values, and other associated information.

2. bSDD API Access and Technical Considerations

The bSDD API[13] provides programmatic access to this rich dataset, enabling developers to integrate standardized information into their applications. Key features of the bSDD API include:

- **Standardized Definitions:** Access detailed definitions of industry terms, properties, and classifications to ensure consistency in data usage.
- **Multilingual Support:** Retrieve information in multiple languages, supporting global collaboration and communication.
- **Classification Systems Integration:** Work with various classification systems like IFC, OmniClass, and UniClass to enhance interoperability.
- **Search Functionality:** Perform advanced searches to find specific terms or concepts within the data dictionary.
- **Semantic Relationships:** Understand and utilize the relationships between different building elements and properties.

[13] https://app.swaggerhub.com/apis-docs/buildingSMART/Dictionaries/v1

- The API is "RESTful" and utilizes standard HTTP methods (GET, POST, PUT, DELETE) for interaction. It supports data formats such as JSON and XML, making it versatile for integration with various programming languages and platforms. By leveraging the bSDD API, developers and industry professionals can:
- **Enhance Data Consistency:** Reduce discrepancies in terminology and classifications across different systems.
- **Improve Interoperability:** Facilitate seamless data exchange between software applications, improving collaboration efficiency.
- **Streamline Workflows:** Integrate standardized data directly into applications, reducing the need for manual data entry and minimizing errors.

3. Key Features and Functionalities:

- Authentication and Access:
  - The bSDD API requires authentication via **API keys**.
  - API keys are included in the Authorization header as a Bearer token: Authorization: Bearer YOUR_API_KEY.
  - Access levels vary:
    - **Public Access**: Limited to basic data.
    - **Registered User**: Access to more comprehensive data and endpoints.
    - **Contributor/Administrator**: Extended permissions, including data modification.
  - API keys can be obtained by registering on the buildingSMART Website or bSDD portal.
- API Endpoints:
  - **Concepts** (/api/Concepts): Retrieve, create, update, or delete concepts like terms, properties, units.
  - **Classifications** (/api/Classifications): Access available classification systems.
  - **Languages** (/api/Languages): List supported languages and their details.
  - **Search** (/api/Search): Perform advanced searches with filtering options.
  - **Units and Properties** (/api/Units, /api/Properties): Retrieve measurement units and properties associated with building elements.
- Data Filtering, Sorting, and Pagination:
  - **Filtering**: Use query parameters (name, type, language, classification) to refine results.
  - **Sorting**: Apply sortBy and sortOrder parameters.
  - **Pagination**: Control results with page and pageSize parameters.
- Multilingual Support:
  - Retrieve information in multiple languages to support global collaboration.
- Error Handling:
  - Common error codes include:
    - **400 Bad Request**: Malformed request.
    - **401 Unauthorized**: Authentication failure.
    - **403 Forbidden**: Insufficient permissions.
    - **404 Not Found**: Resource doesn't exist.
    - **429 Too Many Requests**: Rate limit exceeded.
    - **500 Internal Server Error:** Server-side issue.
  - A detailed error reference guide is available in the documentation.

- Limitations and Constraints:
    - **Rate Limits**: Restrictions on the number of requests per time period.
    - **Data Licensing**: Be aware of usage rights and restrictions.
    - **Access Levels**: Higher permissions may be required for certain data or actions.
    - **Language Availability**: Some data may not be available in all languages.
    - **Data Currency**: Update frequency may affect data freshness.
- Resources for Getting Started:
    - **Documentation**: Comprehensive API docs with examples are available on SwaggerHub and the bSDD GitHub.
    - **Tutorials and Sample Projects**: Available on the buildingSMART Website and GitHub repositories.
    - **Community Support**: Forums and discussion boards for developer support.

3.3.2. Secure Data Commons (SDC) Platform

1. CBTL Integration

The SDC can serve as the main platform to host the CBTL, and provides the service of developing, onboarding, hosting, and analyzing various data. The SDC is built on Amazon Web Services (AWS), which is a comprehensive cloud-computing platform provided by Amazon. Since AWS offers a wide array of services that include computing power, storage solutions, networking, databases, analytics, and application development, the SDC is a customizable and flexible solution to meet the needs of the CBTL.

2. SDC API access and technical considerations

Currently the SDC is available only to USDOT-approved projects. Therefore, future projects will need to request access.

Resources for Getting Started:

- **Documentation**: Comprehensive documents on how to get started are on the SDC Web site.
- **Tutorials and Sample Projects**: Available on the SDC Web site and possibly GitHub repositories.
- **Community Support**: There is a dedicated technical team to provide support.

3.4. CBTL Leadership Roundtable

On January 9, 2025, industry leaders at the Washington Convention Center for the CBTL Leadership Roundtable convened. The event brought together representatives from state Departments of Transportation (DOT), contractors, technology providers, and industry organizations to collaborate on shaping the CBTL.

The roundtable centered on defining the objectives, priorities, and structure for the CBTL. Participants confirmed the need for a centralized, secure resource to access, standardize, and share digital data critical to transportation infrastructure management. The discussion emphasized the dual importance of robust technical design, including interoperability, metadata standards and data security, and organizational change management such as leadership buy-in, workforce training, and governance development.

Key outcomes included strong support for a progressive development model, combining a Directory, Gateway, and Repository structure, and consensus on aligning CBTL efforts with broader federal initiatives like FHWA's BIM Level 2 targets by 2030. The group also highlighted challenges around data access, standardization, and cross-state collaboration, and identified pilot programs and iterative engagement as next steps to move the initiative forward.

This roundtable marked an important milestone in building a shared vision for the CBTL, one that balances technical excellence with organizational readiness to advance digital project delivery across the transportation industry. Details of the roundtable content, participants, and findings are in Appendix A.4. CBTL Leadership Roundtable.

3.5. Stakeholder Engagement Summary

The stakeholder engagement process, particularly the CBTL Leadership Roundtable, established a strong foundation for the CBTL by convening a diverse group of experts across state DOTs, industry, academia, and standards organizations. This dialogue clarified the structure, purpose, and potential of the CBTL, while also highlighting the critical challenges and opportunities that must be addressed for successful implementation.

A clear consensus emerged that states not only need—but are actively requesting—a centralized resource like the CBTL to facilitate digital project delivery, data standardization, and interoperability. Advanced Digital Construction Management Systems (ADCMS) grant recipients and other state initiatives are already producing valuable artifacts that would benefit from a shared repository, underscoring the CBTL's role as a national clearinghouse for BIM data and standards.

The discussions emphasized that both technical implementation and organizational change management are essential to the CBTL's success. Technical priorities include secure data access, robust governance models, and flexible interoperability solutions, such as combining directory, gateway, and repository models. Equally important are leadership engagement, workforce training, internal communication strategies, and cross-agency collaboration to build a culture of digital adoption.

Participants identified key functional priorities for the CBTL, including support for standardized data formats, real-time tracking of state progress, clear interoperability policies, and accessible user support. AI-enabled tools and metadata structuring were identified as promising areas for future exploration to improve data usability and retrieval.

A key point of concern regarding a centralized repository was the perception that it would function as a "national" system, implying federal government control. This raised concerns among State DOTs about granting access to their sensitive data. While the technology behind the CBTL is designed to offer a shared platform with robust security and access controls, these concerns highlight the critical need for well-defined governance and access policies. There was also discussion about establishing a National CBTL alongside independently developed State CBTLs. The CBTL concept outlined in this report is intended to provide a centralized repository framework eliminating the need for individually developed CBTLs while still allowing for state-specific data management and access controls within a unified system.

Looking forward, integration with existing platforms will be a major focus. In particular, close coordination with the bSDD and the SDC is recommended. The bSDD offers structured semantic relationships and classification systems that CBTL can leverage to enhance interoperability. Meanwhile, SDC offers a secure, cloud-based infrastructure via AWS that may be suitable for CBTL hosting, pending formal access requests and clarification of any associated costs or technical constraints.

Additional collaboration with solution providers, ongoing demonstration projects, and pooled fund initiatives will inform the CBTL's phased development. A pilot-based, iterative rollout, supported by continuous stakeholder feedback, is key to building a resilient, scalable, and nationally adopted BIM resource. By continuing to engage with DOTs and key stakeholders, the CBTL development strategy will focus on balancing the benefits of national standardization with the flexibility needed to accommodate the unique requirements of individual states. Collaboration, innovation, and adaptability will be crucial in the move toward a future of digital delivery. Building on stakeholder input, several strategies have been identified to guide the continued development of the CBTL:

- Focused Stakeholder Engagement:
  Conduct targeted discussions with additional DOTs to further refine technical and operational requirements, ensuring alignment with real-world workflows and challenges.
- Customization Versus Standardization:
  Explore the development of modular translation tools and AI-driven interfaces that support both state-specific flexibility and broader data alignment.
- Governance Framework and Data Access Policies:
  Develop a comprehensive governance structure that addresses data ownership, security, and access controls, ensuring State DOTs retain authority over their sensitive data while participating in a nationally coordinated CBTL environment. The framework should define clear roles, responsibilities, and access boundaries to maintain trust and protect state-specific interests.
- Cross-Sector Collaboration:
  Foster partnerships not only among DOTs but also with consultants, vendors, and academic institutions to strengthen the CBTL's ecosystem and innovation pipeline.
- Pilot Programs and Iterative Testing:
  Continue to support pilot programs and incremental rollouts, learning from states that have demonstrated successful phased adoption models.
- Exploration of Emerging Technologies:
  Monitor and evaluate new technologies, such as drone-based asset capture and real-time model integration (e.g., Omniverse), for future incorporation into the CBTL.
- Phased Implementation Approach:
  Structure the CBTL roadmap around phased deployment, beginning with current technologies while embedding scalability for emerging capabilities. Establish a governance framework to support life cycle management, data QA, and system adaptability.

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IV. Technical Solutions Available for the CBTL

4. Technical Solutions Available for the CBTL

4.1. Overview

This section focuses on identifying software solutions that support multi-application integration and open data exchange, which are critical to the technical development of the CBTL. The scan also includes project management and design systems commonly used by state DOTs. The resulting list includes software and platforms that may be suitable for integration into the CBTL. These tools will need to be further evaluated in later CBTL project tasks to determine their compatibility and applicability. The following provides definitions for the types of software and platforms included in the scan.

4.1.1. Terminology

Authoring Tool: An application or service utilized by industry to create information, such as BIM software.

Common Data Environment (CDE): A central repository where project information is stored and managed. It serves as a collaborative workspace for all stakeholders involved in a project, ensuring that everyone has access to the latest data and documents.

Collaboration Environment: A central platform designed to facilitate the sharing of content among multiple users, enhancing teamwork and communication.

DevOps: DevOps is a combination of practices, tools, and a cultural philosophy that aims to integrate and automate the processes between software development (Dev) and IT operations (Ops) teams.

Data Dictionary: A centralized repository of information about data, including meaning, relationships, origin, usage, and form. The data dictionary describes the attributes that are captured in a data model corresponding to each of the object types in the model.

Open BIM: A universal approach to the collaborative design, realization, and operation of buildings, based on open standards and workflows, aimed at improving the interoperability of BIM data across different software platforms and stakeholders in the construction industry. Note that "openBIM" is the branded initiative by buildingSMART International (bSI) that emphasizes the formal program and standards set by bSI’s frameworks and guidelines.

Open Source: A type of software development model where the source code of a program is made available to the public, allowing anyone to view, modify, and distribute the code. This approach promotes collaborative development and transparency, enabling a community of developers to contribute to the software's improvement and evolution.

Repository: A location where you can store data, files, code, and other digital elements.

4.1.2. Summary of Software and Platforms

As part of the literature review and technology scan conducted for this project, an inventory of software solutions and digital platforms relevant to the CBTL was compiled. This scan focused on tools that support multi-software integration, open data exchange, and digital project delivery workflows commonly used by state DOTs and industry stakeholders. The results encompass a wide range of technologies, including openBIM-compliant applications, open-source tools, CDEs, DevOps platforms, and pertinent repositories that collectively represent the technical ecosystem in which the CBTL must operate. These findings will guide the evaluation and selection of candidate technologies for integration into the CBTL architecture in future project phases (see Appendix Software and Platforms for the full list).

- **openBIM**: An extensive collection of software tools that align with IFC-based openBIM principles, providing a foundation for seamless model data exchange across diverse platforms. The CBTL development can identify common open standards and interoperable workflows to be leveraged, ensuring consistent access to standardized BIM artifacts for state DOTs and industry partners.
- **Open-Source BIM tools:** A diverse set of open-source software supporting geometry processing, BIM modeling, simulation, and project collaboration. The CBTL can help facilitate these tools to foster transparency, customization, and community-driven enhancements, reducing vendor lock-in while supporting the development of flexible, cost-effective solutions. This includes:
    - CAD/BIM Design and Development Analysis and Simulation
    - Geometry Scanning and Processing
    - Analysis and Simulation
    - Project Management and Collaboration
- **Common Data Environments (CDE)**: Cloud-based platforms that centralize data management, project communication, and workflow coordination. The CBTL facilitates integration with these CDEs to provide state DOTs with streamlined access to project documentation, fostering real-time collaboration and version control across the asset life cycle.
- **DevOps Tools and Platforms:** A comprehensive landscape of tools that enable automation, scalability, collaboration, and operational excellence for developing and maintaining the CBTL platform. This includes:
    - Continuous Integration and Continuous Delivery (CI/CD)
    - Frontend CI/CD Platforms
    - Frontend Frameworks & Libraries
    - Build Tools & Package Managers
    - Configuration Management & Infrastructure as Code (IaC)
    - Container Management & Orchestration
    - Monitoring and Logging
    - Deployment Automation
    - Source Control Management (SCM)
    - Testing & Quality Assurance Tools
    - Collaborative Platforms & Project Management
    - Frontend Monitoring & Analytics
    - UX/UI Design & Prototyping Platforms
    - Database Management & Backend-as-a-Service (BaaS)
    - Security (DevSecOps) Tools
    - Release Management & Feature Flags
    - Service Mesh & API Gateways
    - Documentation as Code & Knowledge Management
    - Observability Pipelines & Chaos Engineering
    - Edge Computing Platforms
- **Digital Libraries and Repositories:** Foundational platforms providing access to research reports, technical publications, and standards references essential for CBTL documentation and repository alignment.

- **Data Inventories and Geographic Databases:** Structured databases offering classification schemas, geospatial referencing, and condition assessments that can be integrated with the CBTL's object libraries and templates.
- **Materials Research and Performance Repositories:** Centralized sources of standardized materials testing data and evaluation reports.
- **Safety and EMS Data Systems:** Databases that provide critical safety performance metrics to inform risk modeling and infrastructure safety workflows.
- **Transportation Management and Engineering Tools:** Platforms supporting asset management, performance monitoring, and process integration for life cycle workflows.
- **BIM Metadata and Data Repositories:** Core repositories managing BIM classification systems, use cases, and standardized data exchanges.

4.2. Required Technologies

The technologies to create the CBTL are mature and readily available, but the usage and application of these specifically aimed at BIM artifacts will require proper organization, collaboration, and management. To fully support the complexity and variety of the BIM artifacts, the creation of the CBTL will require three main components for successful deployment: 1) a database that defines and manages information; 2) a backend server that enables access control to the data (querying, saving, editing); and 3) a front-end user interface to provide access to the information in a controlled and easy-to-use way. Each component also requires information exchanges to transfer the data. There are various technologies that can be selected for each, and this section briefly discusses some of them.

Database: The main component of this proposal that requires investigation is the database and corresponding information exchanges. Structured vocabularies are important means of defining and organizing the meaning of concepts and terms used to ensure their consistent use by all stakeholders over the life cycle of an asset. They offer an efficient way to organize knowledge for subsequent retrieval, such as Web interfaces and querying over the internet (i.e., the Semantic Web.) Databases require specific development to tailor to the specific use case--in this case a BIM-based transportation library. Since BIM is becoming more Web-based, traditional desktop databases such as Microsoft Access are becoming less widely useful with Cloud-based databases such as Microsoft Azure SQL Database, Amazon RDS, and MongoDB Atlas gaining prominence.

Backend Servers: Backend servers are responsible for storing and organizing data and ensuring everything on the client side works. The backend communicates with the front end (i.e., the user interface), sending and receiving information to be displayed as a Web page. Examples include Google Cloud, Amazon AWS, and Microsoft Azure. Open-source servers include Node.js and Express.

Front-end User Interface: Frontend user interface provides the means for the user to interact with the data and Web pages. The latest Web technologies include HTML5, CSS3, JavaScript (ES6+), and React. A backend Web service, such as Drupal, is required for the front-end users to access the data in a controlled and secure fashion, including role-based access.

4.3. Repository Resources

AASHTO Transportation Management Hub

The American Association of State Highway and Transportation Officials (AASHTO) Transportation Management Hub[14] serves as a centralized portal offering access to a trio of specialized AASHTO resources devoted to key aspects of transportation administration: performance, asset, and risk management. Each portal—namely the Transportation Performance Management Portal, Transportation Asset Management Portal, and Enterprise Risk Management Portal—provides tools, resources, databases, and documentation tailored to those focus areas.

Federal Highway Administration (FHWA) InfoHighway Web Portals

The Federal Highway Administration (FHWA) maintains a suite of web-based "Info" portals, each tailored to provide access to specialized infrastructure datasets, analytical tools, and decision-support resources. InfoHighway[15] serves as the central gateway that connects these platforms, offering an entry point for users to explore bridges, pavement, materials, and technology performance data. It integrates and directs users to domain-specific portals such as InfoBridge for bridge performance and forecasting, InfoPave for pavement life cycle analysis, InfoMaterials for lab-scale and construction materials testing results, InfoTechnology for non-destructive evaluation (NDE) methodologies and tools, and InfoPTF for full-scale accelerated pavement testing data. Beyond linking these specialized resources, InfoHighway also supports network-level visualizations, dashboard analytics, and cross-platform exploration, ensuring that transportation professionals, researchers, and asset managers have streamlined access to comprehensive, data-driven insights across all aspects of infrastructure asset management.

Long-Term Bridge Performance (LTBP) InfoBridge[16]: Provides comprehensive bridge performance data, integrating the National Bridge Inventory (NBI), National Bridge Element (NBE) data, NASA-sourced climate variables, and Long-Term Bridge Performance (LTBP) research outputs—including nondestructive evaluation, structural health monitoring, and material testing data from a representative sample of US bridges. Through a user-friendly web interface, InfoBridge supports advanced search capabilities via "Find Bridges," "Advanced Find," and "Map Find," allowing users to filter by various attributes, draw geographic query shapes, and view selected bridges in customizable tabular or map-based layouts. The platform features robust analytics tools, including interactive charts, condition summaries by state, and asset valuation modules that estimate replacement, existing, and remaining values based on deck area and unit cost data. Embedded forecasting tools generate condition transition predictions using FHWA-developed base models, survival analysis, and machine learning techniques, regularly updated to reflect the latest NBI data. Additionally, InfoBridge provides a comprehensive Library section offering documentation, update notes, historical specification changes, and LTBP program reports to support in-depth bridge performance analysis and research.

Long-Term Pavement Performance (LTPP) InfoPave[17]: Serves as the public, web-based gateway to the Long-Term Pavement Performance (LTPP) program's comprehensive Information Management System (IMS), which includes the Pavement Performance Database, Ancillary Information Management System (AIMS), and Traffic Analysis Software database. It offers powerful tools for locating and filtering LTPP test

[14] https://www.transportationmanagement.us/

[15] https://infohighway.fhwa.dot.gov/

[16] https://infobridge.fhwa.dot.gov/

[17] https://infopave.fhwa.dot.gov/

sections through geospatial mapping, advanced keyword- and criteria-based searches, and interactive section timelines. Visualization features include pavement cross-section viewers, virtual walkthroughs of test sections, transverse profile displays, and access to inspection imagery and videos. InfoPave streamlines data extraction via a Data Selector, Section Summary, and State/Province Summary reports, and supports export in formats such as SQL, Excel, and Access. The platform also provides built-in analytical tools, including trend and correlation analysis, data availability dashboards, mechanistic-empirical design modules like dynamic modulus prediction and weigh-in-motion (WIM) cost analysis, and national performance measure calculators. A comprehensive Reference Library offers program documentation, technical reports, user guides, newsletters, and contest materials, while integrated help tours and SQL code samples assist users in navigating and utilizing the system effectively.

InfoMaterials[18]: Provides storage, retrieval, and visualization capabilities for infrastructure research and materials testing datasets collected through FHWA programs and partner efforts. It hosts structured and unstructured data including asphalt and concrete characterization, pavement testing results, and material performance studies, all supplemented with extensive metadata, dataset documentation, and visualization tools. Users can browse and extract datasets via guided data selectors, with downloadable output formats such as Excel, Access, or SQL. The platform also includes a Library section offering update notes, technical documentation, FAQs, and student data contest resources. InfoMaterials enables both high-level and granular assessment of materials performance, facilitating research, data reuse, and innovation in infrastructure management.

InfoTechnology[19]: Bridges the gap between nondestructive evaluation (NDE) technology research and practical use by transportation engineers and infrastructure asset managers. It offers clear, asset-centric guidance on selecting and applying NDE methods—such as ground-penetrating radar, automated sounding, sand patch testing, and electrical resistivity—by filtering options based on asset type (bridge, pavement, or tunnel), material, structural element, and investigative target (e.g., rebars, delamination). The portal presents concise descriptions of each technology's underlying engineering principles, applications, limitations, and benefits, complemented by diagrams, tables, and imagery to support user understanding. Interactive filters enable quick navigation to relevant NDE tools, while a built-in library provides definitions for acronyms and technical terms to aid comprehension. InfoTechnology empowers users to make well-informed assessment decisions by facilitating access to both high-level overviews and detailed technical specifications in an intuitive, searchable format.

InfoPTF[20]: Provides visualization and documentation of data collected from the Federal Highway Administration's Pavement Testing Facility (PTF) at the Turner-Fairbank Highway Research Center. The portal offers detailed access to full-scale accelerated pavement testing results, including construction records, material testing data such as asphalt mixes and geotechnical materials, nondestructive evaluation outcomes, onsite weather station measurements, and soil moisture sensor readings. InfoPTF is designed to help users explore experimental configurations and performance metrics at scale through intuitive navigation tools linked to the Pavement Testing Facility's instrumentation and test protocols. By centralizing these comprehensive datasets, InfoPTF supports research, innovation, and data-driven decision-making in pavement design, materials performance evaluation, and infrastructure durability studies.

[18] https://infomaterials.fhwa.dot.gov/

[19] https://infotechnology.fhwa.dot.gov/

[20] https://infoptf.fhwa.dot.gov/

National Transportation Library (NTL), Bureau of Transportation Statistics

The NTL[21] is “the permanent, publicly accessible home for research publications from throughout the transportation community; the gateway to all DOT data; and the help line for the Congress, researchers, and the public for information about transportation.” The NTL is one of the few products available under the Bureau of Transportation Statistics (BTS). The BTS and NTL host a plethora of articles, data, and knowledge regarding many aspects of US transportation.

NTL’s Repository and Open Science Access Portal (ROSA P)[22] hosts tens of thousands of publicly available publications, datasets, and other resources. A major feature of the ROSA P is that each document is a digital object identifier, or DOI, which is a permanent and immutable Web link. This is significant for BIM artifacts (and any other digital object), allowing things to be uniquely identified and accessed reliably. Content types found in ROSA P include textual works, datasets, still image works, moving image works, other multimedia, and maps. Table 1 **Table 1 : File Formats Hosted by the National Transportation Library Digital Repository (ROSA P)**displays all the permissible data types.

Table 1 : File Formats Hosted by the National Transportation Library Digital Repository (ROSA P)

Text	Dataset	Image	Multimedia	Maps	Metadata	Collections
TXT	CSV	TIFF	WARC	TIFF	XML	ZIP
PDF	XLS	PNG	WMV	PNG	JSON	
XML	XLSX	JPEG	SWF	Shapefiles		
WARC			WMA			
RTF			MPEG			
			PPT, PPTX			

Upon initial inspection, the NTL and BTS have two limitations regarding BIM artifacts. First, BIM artifacts have more data formats, such as native software formats (e.g., RVT, NWD, DWG), than what is able to be uploaded into the ROSA P. Second, “BIM” and “3D” are not topics currently available in the BTS.

BTS Data Inventory, Bureau of Transportation Statistics (BTS)

The BTS Data Inventory[23] is the official data portal of the Bureau of Transportation Statistics (BTS), which is part of the USDOT. This portal provides access to a wide range of transportation-related data, statistics, and visualizations for the public, researchers, policymakers, and anyone interested in transportation information. The data available on this portal covers various modes of transportation, including aviation, rail, road, maritime, and more. It encompasses information about freight, passenger travel, safety, infrastructure, economics, and other transportation-related topics. There are user guides and videos available to assist users on how to use the tools and features on this site, such as interacting with datasets, creating visualizations, and more.

[21] https://www.bts.gov/about-BTS

[22] https://rosap.ntl.bts.gov/

[23] https://data.bts.gov/

The BTS Data Inventory is also publicly available to software developers and data providers by using the Socrata platform,[24] which offers tools and resources for developers to work with data and create applications using the Socrata Data API. The Socrata platform specializes in open data solutions and helps governments and organizations manage, analyze, and share their data more effectively.

The Socrata Open Data API (SODA) is a set of tools and protocols that allows developers to access, retrieve, and manipulate data from datasets hosted on the Socrata platform. It provides a standardized way for developers to programmatically interact with data, enabling them to create custom applications, visualizations, analytics, and other solutions that leverage the data available on the Socrata platform.

Secure Data Commons (SDC) Platform

The SDC[25] is a platform designed for collaborative and controlled data integration and analysis in the transportation field. It serves as a hub for working with moderate sensitivity data, including Personally Identifiable Information (PII) and Confidential Business Information (CBI). This environment is designed to facilitate secure data-sharing and collaboration within the transportation community. It offers a controlled space for authorized users to access, analyze, and exchange sensitive transportation-related data. The SDC supports research, analysis, and decision-making by providing a platform that ensures data privacy, security, and compliance with legal and regulatory requirements. This initiative reflects the DOT's commitment to enhancing data-driven insights while safeguarding the confidentiality and integrity of sensitive transportation data. The SDC offers three types of data transfer updates: real-time (streaming), batch (daily, weekly), and ad-hoc (occasional). More information can be found in Secure Data Commons 101[26].

The SDC has a GitHub repository, which is a collection of code, tools, and resources related to the SDC project. The repository contains various software components, scripts, documentation, and configurations that are utilized within the SDC environment. As it is a public repository, the content is accessible to the broader community, including developers, researchers, and stakeholders interested in transportation data analysis and collaboration. The repository serves as a collaborative space where contributors both from within the USDOT and the wider developer community can collaborate on improving and maintaining the tools and infrastructure associated with the SDC. This collaboration can include developing data processing pipelines, creating analysis tools, enhancing security measures, and addressing any other aspects relevant to the SDC's goals and functionalities.

Importantly, the GitHub repository contains 1) the SDC's infrastructure resources that are used to build the base platform, such as the Web portal; 2) the SDC's operational resources that are used to support data providers and research teams; and 3) the SDC’s Primary Public Project, which are the instructions and template for creating an SDC project.

Based on a preliminary review, the SDC supports the following data types; however, in a general context, data file structures can take various forms:

- **Tabular Data:** One of the most common structures, where data is organized in rows and columns, much like a spreadsheet. Each row represents a record, and each column represents a field or attribute.

[24] https://dev.socrata.com/

[25] https://www.transportation.gov/data/secure

[26] https://www.transportation.gov/sites/dot.gov/files/2021-12/SDC101F202112.pdf

- **Hierarchical Data:** Data is organized in a hierarchical structure, such as XML or JSON files. This is suitable for representing nested or complex relationships.
- **Relational Databases:** Data is organized using tables with relationships defined by keys. This is a structured and efficient way to manage large datasets.
- **Time Series Data:** Organized by timestamps, suitable for temporal data like sensor readings, financial data, or any data collected over time.
- **Geospatial Data:** Organized to represent geographic information, such as points, lines, and polygons, often stored in formats like Shapefiles, GeoJSON, or Geodatabases.
- **Binary Data:** Unstructured or semi-structured data stored in binary formats, such as images, audio files, video files, and proprietary data formats.
- **Textual Data:** Unstructured data like text documents, Web pages, or logs, often stored in plain text, CSV, or other formats.
- **Graph Data:** Data is organized as nodes and edges, suitable for representing complex relationships and networks.

The SDC platform allows the following dataset formats[27]:

- "Raw datasets: The data stored in its native or original format are referred to as Raw datasets. These datasets could be in structured (databases, logs, financial data etc.), semi-structured (HTML, XML, RDF, CSV) and un-structured (images, PDF, docs). This data is unaltered and stored in as-is format. The data can be received through continuous streaming sources (APIs, sensors) or one-time load from external sources
- Curated datasets: Data curation is a process of integrating the raw data collected from various sources, annotating the data and presenting it in such a way that the value of the data is maintained overtime and the data remains available for reuse and preservation. Curated datasets enable data discovery and retrieval, maintain quality, add value and provide for re-use over time, for researchers and data scientists. The curation process includes data transformations from unstructured and semi structured formats to a structured format, deduplication of data, data obfuscation, data cleansing etc. thus providing high quality of data for researchers to create meaningful insights.
- Published datasets: Published datasets are created by researchers to disclose their research for other users to verify and reuse them beyond the original purpose for which they were collected. Published datasets are a result of combining analysis on curated datasets available in SDC platform along with other datasets or algorithms that is owned/created by a researcher or data scientist".

Although there are existing DOT repositories, the SDC is a recent solution that provides more features. Figure 3 displays the comparison of the SDC and the other repositories.

[27] https://portal.sdc.dot.gov/datasets

	SECURE DATA COMMONS	DOT MANAGED CLOUD	CLOUD.GOV
Analytics Platform	Analytical Tools, data pipelines, workstations, etc. are ready	Build/Install your own Analytical Tools, data pipelines	Used for Web sites and applications.
Data Set Availability	Bring your own data, and combine with existing datasets (e.g., Waze)	Bring your own data. Transportation data is not pre-loaded	Bring your own data. Transportation data is not pre-loaded.
Data Export	Already established Data Export process	Manual or build your own	Manual or build your own
Security	Already established security controls with DOT and Login.gov	Leverage DOT User authentication	Leverage existing authentication
Authorization to Operate (ATO)	ATO Approved	Not ATO Approved	Provisional ATO

Figure 3: SDC Platform vs. Other Cloud Platforms[28]

In the preliminary review, the SDC does appear to be a suitable solution to hold some types of BIM artifacts, although more investigation is needed on which file types are still needed and what extensions are needed to host the additional file types.

Federal Highway Administration (FHWA) Research Library

The FHWA Research Library[29] is a resource provided by the USDOT's FHWA. This library is a collection of research materials, documents, reports, and resources related to various aspects of highway and transportation research. The library contains a wide range of materials, including research reports, technical documents, studies, guidelines, and other publications related to highway engineering, infrastructure, safety, sustainability, planning, and more. It aims to promote informed decision-making, innovation, and best practices within the field of transportation. An online FHWA Research Library Catalog and Subscription Databases are also available. Materials include:

- Federal Highway Administration Office of Research, Development, and Technology reports (HRT, IP, RD, and TS series) and reports from other FHWA offices
- State departments of transportation (DOT) and University Transportation Center research reports
- Transportation Research Board (TRB) and American Association of State Highway and Transportation Officials (AASHTO) publications
- Proceedings, seminal works, international reports, dissertations, and reference books
- Journals and magazines, including Public Roads, beginning with the first issue (May 1918)
- Historical materials on FHWA and its predecessor agencies

One limitation, as stated, "The FHWA Research Library exists to serve the information needs of FHWA employees by providing materials, reference/research assistance, and other support services. The FHWA Research Library will answer questions from the general public as time permits."

[28] https://www.transportation.gov/data/secure/about

[29] https://highways.dot.gov/research/resources/research-library/federal-highway-administration-research-library

4.4. Open BIM Data Resources

buildingSMART Data Dictionary (bSDD), buildingSMART International

The buildingSMART Data Dictionary (bSDD) is an online service that hosts classifications and their properties, allowed values, units, and translations. The bSDD allows linking between all the content inside the database and provides a standardized workflow to guarantee data quality and information consistency. Essentially, the dictionary works as a semantic mapping tool that connects like-terms based upon their meaning as it pertains to construction. Once the content is uploaded, software systems can access the bSDD via an API to have easy and efficient access to all kinds of standards to enrich their model. Some examples include BIM Managers using the bSDD to check BIM data for validity, advanced users providing compliance checks against the contents from the bSDD, and automatically identifying manufacturers' products. A significant benefit of the bSDD is the mapping of the defined classifications, definitions, and properties to the Industry Foundation Classes (IFC) and other data dictionaries. Furthermore, the information specifications defined in the Information Delivery Specifications (IDS)[30] can reference the content in the data dictionary. The bSDD can, in fact, support horizontal as well as vertical construction. The bSDD is simply an open-source repository that enables users to define custom objects and their associated meta data. The bSDD contains the current offerings of IFC 4.3 entities, relationships, and attributes. While these are limited to common bridge applications, these will be continually added over time. Technically speaking, it is the IFC 4.3 that is currently limited in support for horizonal construction, but the continued expansion is ongoing. Furthermore, the buildingSMART International Standards Implementation Database[31] contains the listing of all software products that claim to support buildingSMART International standards, including IFC, BIM Collaboration Format (BCF)[32], and bSDD and eventually including IDS and openCDE APIs.

Limitations: While bSDD plays a valuable role in standardizing terminology and data definitions, it must be complemented by other tools and standards to fully support the needs of horizontal construction projects, particularly those involving geometry, real-time data, and project-specific details. The following are key limitations of the data types that the bSDD cannot store:

1. No Geometric or Model Data: The bSDD does not store any geometric data or model elements. It serves solely as a repository for classifications, definitions, properties, and property sets, which must be referenced by external modeling environments for visualization and spatial representation.
2. Proprietary Information: The bSDD is not intended to store proprietary, confidential, or project-specific data.
3. Real-Time Data: bSDD is not designed to manage dynamic, real-time data such as sensor inputs, construction progress updates, or other time-sensitive information.
4. Highly Detailed Specifications: The bSDD does not accommodate detailed engineering calculations, CAD drawings, or other highly specific technical documentation.

[30] https://www.buildingsmartusa.org/standards/bsi-standards/information-delivery-specification-ids/

[31] https://technical.buildingsmart.org/resources/software-implementations

[32] https://www.buildingsmart.org/standards/bsi-standards/bim-collaboration-format-bcf/

National Institute of Building Sciences (NIBS) Whole Building Design Guide (WBDG)

The NIBS WBDG is a comprehensive, Web-based portal providing a vast array of resources for the design, construction, and operation of buildings. It is aimed at integrating and optimizing all major building attributes, including sustainability, accessibility, functionality, productivity, and aesthetics. Key aspects include:

1. Guidance and Criteria: Offers extensive design guidance and criteria from various federal agencies and private organizations, including building codes, standards, and best practices.
2. Project Management: Provides tools and strategies for project management, encompassing project planning, execution, and post-construction phases to ensure successful building projects.
3. Resource Library: Contains a wealth of resources, including case studies, technical reports, and links to additional information sources to assist professionals in staying updated with the latest industry developments.
4. Sustainable Design: A significant focus is placed on sustainable design principles, promoting environmentally responsible building practices to enhance energy efficiency and reduce the ecological footprint of buildings.
5. Interdisciplinary Approach: Encourages an interdisciplinary approach to building design and operation, fostering collaboration among architects, engineers, builders, and owners to achieve holistic and high-performing buildings.

The WBDG was created and continues to evolve as the only online portal providing built environment practitioners access to relevant building-related guidance, up-to-date federal criteria, new technology information, and workforce development training from a “whole building” perspective. Using Drupal as its foundation, the WBDG houses more than 6,000 federal facility design criteria, 300 subject-matter written guidance pages, 200 continuing education courses, and other dynamic online data-dictionary or application resources. For more than two decades, the Department of Defense (DoD), the Department of Veterans Affairs (VA), the Department of Energy (DOE), the US General Services Administration (GSA), and the Department of State (DOS) Bureau of Overseas Buildings Operations (OBO) has supported the WBDG as it represents a collaborative effort among not only government agency Subject Matter Experts (SME), but also those from private sector companies, non-profit organizations, and educational institutions, all contributing their knowledge and experience to better serve the building community.

Limitation. Currently, the WBDG only contains information regarding buildings. However, the architecture can support a range of resources supporting the use of BIM in US transportation infrastructure projects.

The Open Group Architecture Framework (TOGAF)

TOGAF is a widely used framework for enterprise architecture that provides a comprehensive approach for designing, planning, implementing, and governing an enterprise information architecture. Developed by The Open Group, TOGAF aims to help organizations create an architecture that aligns with business goals and facilitates the efficient and effective use of IT resources. Key aspects of TOGAF include:

1. Architecture Development Method (ADM): The ADM is the core of TOGAF, providing a step-by-step approach to developing an enterprise architecture. It includes phases such as Preliminary, Vision, Business Architecture, Information Systems Architectures, Technology Architecture, Opportunities and Solutions, Migration Planning, Implementation Governance, and Architecture Change Management.

2. **Content Framework:** TOGAF provides a detailed content framework that includes guidelines and templates for creating architectural artifacts and deliverables. This helps ensure consistency and completeness in the architecture development process.
3. **Enterprise Continuum**: This concept helps organizations categorize and store architectural assets. It includes the Architecture Continuum and the Solutions Continuum, which provide a repository for reusable architecture assets and solutions.
4. **Reference Models:** TOGAF includes several reference models, such as the Technical Reference Model (TRM) and the Integrated Information Infrastructure Reference Model (III-RM), which provide standard templates and guidelines for developing specific components of the architecture.
5. **Governance:** TOGAF emphasizes the importance of governance in the architecture development process. It provides guidelines for establishing an Architecture Board and processes for architecture compliance, ensuring that the architecture aligns with business objectives and complies with organizational standards.
6. **Stakeholder Management:** The framework includes techniques for identifying and managing stakeholders, ensuring that their concerns and requirements are addressed throughout the architecture development process.
7. **Capability Framework:** TOGAF helps organizations assess their maturity in various capabilities related to enterprise architecture, providing a structured approach for continuous improvement.
8. **Tools and Techniques:** TOGAF provides a variety of tools and techniques, such as architecture patterns, checklists, and guidelines, to support the architecture development process.

Limitations. TOGAF's extensive methodology can be overwhelming and resource-intensive, posing challenges in understanding and application, particularly for organizations new to enterprise architecture. Tailoring the generic framework to specific needs requires significant customization and expertise, which can be difficult to find or develop. Cultural resistance from employees and stakeholders, integration with other frameworks, scalability issues, and ensuring effective governance and compliance are additional hurdles. Continuous stakeholder engagement is crucial, but challenging and demonstrating tangible value and Return on Investment (ROI) from TOGAF initiatives can be complex and time-consuming.

4.5. Assessment of Current Solutions for Hosting BIM Artifacts

Preliminary findings suggest that several existing platforms have the potential to support the hosting of BIM artifacts, though limitations and gaps remain. The NTL's ROSA P platform can accommodate a variety of document-based file types, including PDFs, Word documents, text files, PowerPoint presentations, spreadsheets, and multimedia formats. This makes it suitable for hosting reports, articles, white papers, and related supporting materials.

In addition, both the BTS Data Inventory and the SDC platforms can store a broader array of data formats and structures. These include tabular, geospatial, hierarchical, and time-series data, among others. Both platforms also support open data standards and offer integration capabilities through developer tools such as Software Development Kits (SDK) and APIs, enabling the development of custom portals and applications for data access and analysis.

However, initial review indicates that these platforms currently do not support native BIM file formats (e.g., RVT, DWG, NWD) directly. A viable interim solution is to export BIM model data into open, standards-based formats such as IFC, RDF, or COBie, which use widely supported file types like .TXT, .XML, and .CSV. These can be supplemented by including additional BIM artifacts in compressed (.ZIP) packages for upload.

To move forward effectively, further investigation is needed in the following key areas:

- Integration Pathways–Evaluate how these platforms can be integrated into the CBTL framework, including governance and access coordination.
- BIM Artifact Inventory–Define the specific types of BIM artifacts that need to be hosted in the CBTL to determine exact file format requirements.
- Hosting Suitability–Map artifact types to the platform(s) best suited to host them, based on format support, storage capabilities, and accessibility.
- User Experience and Access–Assess which platform offers the most efficient, secure, and user-friendly access interface for stakeholders.

Overall, while foundational capabilities exist, a tailored strategy that combines data transformation, system interoperability, and user-centric design will be essential to ensure BIM artifacts are both technically supported and meaningfully accessible through the CBTL.

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V. Core Technical Framework for the CBTL

5. Core Technical Framework for the CBTL

The CBTL requires a well-structured framework that ensures scalability, interoperability, security, and usability for managing BIM artifacts effectively. The requirements are categorized into technical architecture, governance, data management, and user engagement. This section builds upon insights from FHWA, AASHTO, USDOT, and various pooled fund projects that were detailed in Interim Report 2. These findings also align with industry best practices and stakeholder feedback.

To function as a national repository for BIM artifacts, the CBTL must be technically robust, interoperable with existing systems, scalable to meet future demands, and secure against evolving threats. This section details the essential technical architecture, data integration strategy, security framework, and interoperability mechanisms that will shape the CBTL into a powerful and sustainable digital asset.

5.1. System Architecture: A Cloud-Based, Scalable Platform

A robust system architecture is the foundation of the CBTL, ensuring its ability to support the storage, retrieval, and management of BIM artifacts at a national scale. Key architectural components include 1) a Cloud-based platform, 2) a database infrastructure, 3) application programming interfaces (API) for data exchange between the various services and solutions that CBTL integrates, and 4) containerized microservices.

Figure 4 depicts the basic access model and architecture required for the CBTL, which is a streamlined Open Authorization (OAuth)-style flow and its supporting infrastructure. As shown on the left, users provide credentials (e.g., username/password) to the main system (the Client). The Client then contacts an Authorization Server to validate these credentials. If they are correct, the Authorization Server issues an access token, which grants the user secure access to system resources. With this token in hand, the user (or Client on their behalf) can now interact with two main sets of resources: 1) system resources stored within the CBTL system via a Resource Server, which reads from or writes to a Relational Database, or 2) external resources that the CBTL integrates, which are stored in third-party (External Entity) databases and accessed via an API.

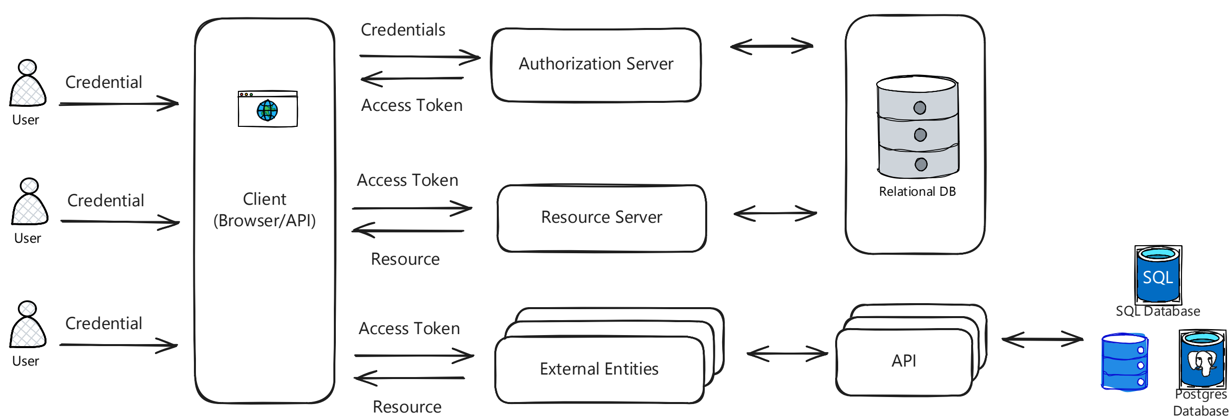

Figure 4: System Access Model

Table 2: CBTL Architecture Layers and Functions

Layer	Function	Key Technologies
User Interface & Gateway	Web portal for discovery, secure access, NLP-powered search, and API console	Web frameworks (e.g., React), OAuth 2.0 / OpenID Connect, OpenAPI
APIs & Middleware	Validation, schema mapping, governance, and rate-limiting of data exchanges	API management tools; REST & GraphQL
Artifact Repository	Version-controlled storage and metadata management for BIM artifacts	Cloud object storage + relational DB; Git-style versioning
External Integrations	Live connections to authoritative repositories and standards (e.g., bSDD, SDC, NTL)	APIs and linked data services (e.g., GraphQL, Socrata)

The CBTL architecture combines four layers (Table 2): a user interface and gateway for discovery, secure access, and search; API and middleware services that validate, normalize, and manage data exchanges; an artifact store that provides version-controlled storage of BIM files and metadata; and standards integrations that connect directly to authoritative sources like bSDD and USDOT repositories. Together these layers provide scalable access, strengthen interoperability, and ensure compliance across the transportation sector.

The CBTL must operate as a cloud-native infrastructure, allowing seamless scalability, high availability, and real-time accessibility. Traditional on-premise solutions lack the flexibility required to support evolving data demands, making cloud-based solutions such as Amazon Web Services (AWS), Microsoft Azure, or Secure Data Commons (SDC) essential for its development.

The architecture must facilitate redundant data storage, ensuring high availability and disaster recovery capabilities. Additionally, containerized microservices should be employed to support modular and incremental system updates without disrupting ongoing operations. Containerized microservices are a modern software architecture approach that breaks down a large, monolithic application into small, independent, and loosely coupled services, each running inside its own lightweight, isolated environment called a container. This design enables the CBTL to function as a federated repository, allowing seamless integration with existing state and federal transportation data systems.

5.1.1. Cloud-based Platform

- Hosted on a secure and scalable cloud infrastructure, integrating services like AWS, Microsoft Azure, or SDC.
- Provides a distributed, redundant storage system that prevents data loss and ensures high-speed retrieval.
- Elastic scalability, allowing the CBTL to accommodate growing data volumes without performance degradation.
- Role-based authentication and multi-tiered access control to protect sensitive transportation data from unauthorized access.

5.1.2. Database Infrastructure

- Supports structured and unstructured data formats, including IFC, RDF, JSON, XML, and CSV.
- Allows version-controlled schema for artifact updates.

5.1.3. APIs for Data Exchange

- RESTful APIs to facilitate integration with bSDD, SDC, FHWA research repositories, and BIM authoring tools.
- Support for graph-based queries and semantic linking for efficient data retrieval.
- Federated authentication protocols to allow agencies to use their existing credentials (e.g., Single Sign-On with FHWA).

5.2. Seamless Data Exchange and Interoperability

For the CBTL to function as a successful national repository, it must be capable of seamless integration with existing transportation data repositories at the federal, state, and local levels. Given the fragmented nature of BIM adoption across agencies, achieving standardized data exchange mechanisms and open-source integration frameworks is critical. The CBTL must provide a flexible, technology-agnostic infrastructure that supports multiple BIM formats, metadata standards, and data governance models, ensuring interoperability with diverse digital systems already in use across the transportation sector.

Currently, repositories exist within agencies, but they largely operate in siloed environments with limited cross-agency collaboration. These siloed repositories hinder data sharing, version control, and standardized metadata management, resulting in duplicated efforts, inconsistencies in BIM workflows, and inefficiencies in project execution.

By establishing a common integration framework, the CBTL will serve as a centralized digital hub, ensuring that BIM artifacts are easily accessible, reusable, and consistently classified across agencies and industry stakeholders. This harmonized ecosystem will enable state DOTs, contractors, researchers, and policymakers to leverage a single source of truth for transportation infrastructure data, ultimately enhancing decision-making, cost efficiency, and project coordination on a national scale.

Figure 5 illustrates the data flow between the bSDD, SDC/BTS, and the CBTL, detailing how state DOTs can access standardized BIM object definitions and metadata directly through the CBTL. The integration leverages secure API connections to enable seamless data retrieval from the bSDD, ensuring that DOTs can utilize up-to-date classifications, properties, and terms within their BIM workflows.

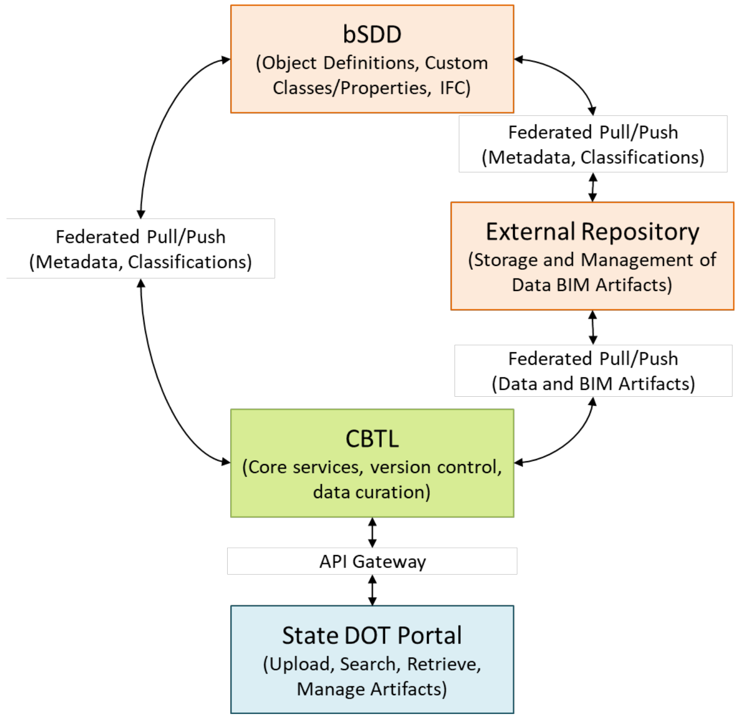

Figure 5: bSDD to CBTL Data Flow

This federated approach supports real-time data synchronization while maintaining version control and metadata consistency within the CBTL. By serving as a centralized access point, the CBTL reduces redundancy, streamlines data management processes, and enhances interoperability across platforms. The diagram also highlights user interaction flows, showcasing how DOTs can query the bSDD through the CBTL's user interface without directly interacting with the external service, simplifying access and strengthening data governance.

5.2.1. Interoperability Features

To ensure seamless data exchange between BIM software platforms, agencies, and contractors, the CBTL will implement:

- RESTful APIs that allow direct integration with BIM tools enabling real-time querying and retrieval of BIM artifacts.
- Real-time data synchronization between federal, state, and local repositories, ensuring that BIM models remain up-to-date and version-controlled across multiple agencies.
- Support for Industry Foundation Classes (IFC), a widely adopted open BIM standard, allowing interoperability between different BIM authoring and analysis platforms without requiring proprietary software.
- Advanced querying capabilities enabling users to:
    - Perform context-aware searches on BIM objects and metadata.
    - Query project-specific artifacts across multiple repositories with structured ontology-based filtering.
    - Retrieve historical versions of BIM models to track design modifications, version histories, and compliance with evolving regulations.

5.2.2. Federated Access and Data Governance

Given the complexity of multi-agency collaboration, the CBTL must balance data accessibility with security and governance policies. To achieve this, the CBTL will:

- Implement federated access control mechanisms, allowing:
    - State DOTs to maintain localized BIM repositories that remain synchronized with national standards, ensuring state-specific flexibility without compromising national interoperability.
    - Transportation agencies to access shared datasets while preserving proprietary data integrity, ensuring that sensitive infrastructure data remains protected.
- Utilize Single Sign-on (SSO) authentication protocols (e.g. Login.gov) to streamline user access while maintaining secure authentication standards.
- Enforce data-sharing policies aligned with federal cybersecurity guidelines, ensuring compliance with ISO 19650, National Institute of Standards and Technology (NIST) Cybersecurity Framework, and agency data governance best practices.

By embedding these data exchange and interoperability strategies, the CBTL will foster a collaborative, data-driven transportation infrastructure ecosystem, eliminating redundant data storage, enhancing efficiency, and supporting the national adoption of BIM-based workflows.

5.3. Robust Security Framework and Compliance

Given the sensitive nature of transportation infrastructure data, ensuring strong cybersecurity and regulatory compliance is paramount for the CBTL. The repository will store critical digital assets, including BIM artifacts, infrastructure models, and metadata that are essential for design, construction, and asset management across federal and state agencies. Unauthorized access, data breaches, or cyberattacks could pose significant risks to infrastructure security, operational continuity, and public safety.

To mitigate these risks, the CBTL will be built upon multi-layered security controls, integrating advanced encryption, authentication, access management, and audit mechanisms. These measures will protect against data tampering, unauthorized modifications, and cyber threats while ensuring compliance with federal cybersecurity mandates.

5.3.1. Zero Trust Security Model

To strengthen protection against cyber threats, the CBTL will adopt a Zero Trust security model, which assumes that no user, device, or system should be inherently trusted. Under this framework:

- All access requests are continuously verified before granting permissions.
- Multi-factor Authentication (MFA) and identity verification are enforced for system users.
- Least-privilege access policies restrict user permissions to only necessary functions.
- Real-time monitoring and anomaly detection identify and mitigate potential cyber threats.

5.3.2. Regulatory Compliance and Cybersecurity Standards

To ensure the CBTL aligns with national cybersecurity policies, it will adhere to:

- **NIST Cybersecurity Framework (CSF):** Establishes best practices for risk management, continuous monitoring, and incident response.
- **ISO 19650:** Provides secure digital information management guidelines for BIM workflows and federated data systems.
- **Federal Information Security Modernization Act (FISMA):** Mandates security protocols for government-managed data repositories.
- **Controlled Unclassified Information (CUI) Compliance:** Ensures sensitive transportation data remains protected in compliance with federal regulations.

5.3.3. Key Security Measures

Attribute-Based Access Control (ABAC):

- Restricts access based on user through a mix of roles, responsibilities, and permissions (e.g., State DOTs, consultants, FHWA officials).
- Enforces granular permissions, preventing unauthorized access to sensitive BIM data.
- Supports federated authentication for agency credential reuse (e.g., FHWA SSO).

Encryption Protocols:

- Implements AES-256 encryption for data at rest, ensuring stored information is protected against breaches.
- Enforces Transport Layer Security (TLS) 1.3 encryption for data in transit, securing data transfers between users, repositories, and external systems.
- Uses cryptographic hashing to validate data integrity and prevent tampering.

Automated Audit Logs and Monitoring:

- Tracks all data modifications, providing full traceability of who accessed or altered BIM artifacts.
- Implements real-time anomaly detection and Intrusion Prevention Systems (IPS) to detect and mitigate cyber threats.
- Ensures full compliance with federal auditing requirements, enabling forensic investigations and incident response.

Secure Data Sharing and Governance:

- Establishes federated security policies to govern data access and interoperability across state and federal agencies.
- Uses data classification standards to categorize information based on sensitivity and accessibility requirements.

To maintain data integrity, security, and compliance within the CBTL, an ABAC framework is employed. Rather than assigning permissions solely based on predefined roles, ABAC dynamically evaluates a combination of user, resource, and contextual attributes (e.g., job function, project affiliation, data sensitivity level). By tailoring permissions based on these attributes, sensitive data remains protected while authorized stakeholders can collaborate efficiently. Table 3 illustrates how attributes might be grouped to form typical "roles" within the CBTL, helping stakeholders understand the kinds of permissions generally assigned. However, in practice, the ABAC model can flexibly adjust permissions to suit evolving project needs and individual user attributes:

Table 3: Example of CBTL User Attribute Groupings and Associated Permissions

User Attribute Group	Read	Upload	Edit Metadata	Approve/Publish	Delete
Administrator	✓	✓	✓	✓	✓
Data Curator	✓	✓	✓	✓	✗
User	✓	✓	✓	✗	✗
External Viewer	✓	✗	✗	✗	✗
Public Guest	✓	✗	✗	✗	✗

Key Advantages of ABAC in CBTL:

- **Granular Permissions:** Instead of a one-size-fits-all role, access decisions are made by evaluating user attributes, minimizing the risk of unauthorized data manipulation.
- **Data Integrity:** By precisely controlling who can modify or delete data, ABAC ensures data consistency, accuracy, and accountability.
- **Transparency and Accessibility:** Public and external stakeholders can have read-only attributes assigned, safeguarding data integrity while promoting transparency.

The CBTL's governance framework continues to align with national data security standards, including NIST CSF, ISO 19650, and FISMA compliance. By implementing these robust, attribute-driven security controls, the CBTL ensures digital transportation assets remain secure, accessible, and compliant with federal regulations. This approach fosters trust and collaboration among stakeholders while protecting critical infrastructure data against evolving cyber threats.

5.4. Advanced Data Management and Version Control

Managing BIM artifacts at scale requires a structured and systematic approach to version control, data validation, and metadata integrity. Given the complexity of transportation infrastructure projects, the CBTL must ensure that BIM artifacts remain accurate, up to date, and fully traceable throughout their life cycle. Without a robust version control system, agencies risk data inconsistencies, conflicting modifications, and loss of historical records, which could compromise design integrity, compliance, and interoperability.

A well-implemented version control system enables stakeholders to track changes, revert to previous versions, and maintain data consistency across projects. This is especially important in multi-agency collaborations, where numerous stakeholders (e.g., state DOTs, contractors, federal agencies) contribute to and modify BIM artifacts over time.

In addition to version tracking, the CBTL must implement automated data validation mechanisms to ensure that BIM artifacts comply with industry standards and metadata structures. By leveraging Machine Learning (ML) and AI-driven anomaly detection, the system can flag inconsistencies, enforce quality standards, and reduce human errors in classification and file management.

5.4.1. Importance of Version Control in CBTL

The lifespan of transportation infrastructure projects extends for decades, requiring accurate, well-maintained digital records of BIM artifacts to support planning, construction, maintenance, and asset management. Without a structured version control system, agencies risk data fragmentation, conflicting file versions, and loss of historical records, leading to design inconsistencies and compliance issues. Version control is especially critical for:

- Managing evolving infrastructure models as projects progress through design, construction, and operations phases.
- Ensuring regulatory compliance by maintaining an accurate audit trail of modifications.
- Facilitating inter-agency collaboration while preventing data overwrites and version conflicts.
- Supporting data-driven decision-making by allowing users to compare previous versions and revisions.

- Ensuring data integrity by maintaining a structured history of changes to BIM artifacts.
- Improving accountability by tracking who made what changes and when.
- Facilitating regulatory compliance with FHWA, USDOT, and ISO 19650 standards for digital project delivery.
- Enabling collaboration across multiple agencies while preventing conflicting edits and data corruption.
- Reducing data duplication and ensuring all stakeholders work from the latest, authoritative version of BIM models.

5.4.2. Key Version Control Features

To support efficient and standardized data governance, the CBTL must implement key version control mechanisms that allow users to track, compare, and manage changes to BIM artifacts over time. These features must be seamlessly integrated into the CBTL's infrastructure, ensuring that all stakeholders work from the most current and accurate version of BIM data, while preserving historical records for auditing, compliance, and future reference.

Version-Controlled Schema:

- Each BIM artifact is assigned a unique identifier with a fully traceable version history.
- Users can review, compare, and revert to previous versions when necessary, ensuring design continuity.
- Supports differentiated versioning for minor edits vs. major revisions, helping agencies manage changes efficiently.
- Versioned metadata fields enable structured querying, allowing users to retrieve specific artifact states based on timestamps, contributors, or project milestones.

Hybrid Git-Based Version Control:

- Utilizes Git-based repositories (GitHub/GitLab) for metadata versioning, ensuring structured tracking of modifications while avoiding performance bottlenecks with large files.
- Integrates with structured databases to store BIM artifacts efficiently, allowing for faster queries, structured metadata retrieval, and optimized storage.
- Branching workflows allow different teams to work on separate features or asset versions without overwriting existing models, preventing conflicts in multi-agency collaborations.
- Automated conflict resolution mechanisms reduce the risk of data corruption when multiple users update the same artifact, ensuring data integrity.
- Cloud-based storage (e.g., AWS S3, Azure Blob Storage) handles large BIM models, while Git tracks changes in metadata, dependencies, and relationships between artifacts.

Data Version Control and Pipeline Orchestration:

- Enables structured, scalable version control for large BIM datasets that exceed Git's storage capabilities.
- Tracks every modification to BIM artifacts while supporting parallelized, automated workflows for processing infrastructure data.
- Integrates with cloud-based storage solutions like Delta Lake, Apache Iceberg, and AWS S3, ensuring efficient long-term BIM data management.

- Leverages specialized tools such as Data Version Control (DVC) and Pachyderm to manage complex BIM datasets across distributed repositories.
- Supports federated data synchronization, allowing state DOTs, contractors, and agencies to maintain independent yet synchronized BIM repositories.

Automated Data Validation:

- QA/QC processes ensure BIM artifacts adhere to established metadata and file format standards, reducing format inconsistencies and structural errors.
- AI-driven anomaly detection flags inconsistencies, missing metadata, and non-compliant files, improving data reliability.
- Implements automated metadata tagging, reducing human effort in file classification, retrieval, and searchability.
- ML algorithms predict inconsistencies in metadata classification, ensuring uniform artifact descriptions and compliance with industry standards.
- Validation scripts enforce IFC, ISO 19650, and NIST standards, preventing invalid data entries or incorrect version assignments.

5.4.3. Ensuring Compliance and Long-Term Data Management

As a national repository for BIM artifacts, the CBTL must adhere to data governance regulations, cybersecurity policies, and industry standards to ensure data integrity, accessibility, and compliance across transportation agencies. Given the long life-cycle of infrastructure projects, maintaining accurate, versioned records of BIM artifacts is essential for regulatory audits, historical reference, and long-term digital asset management. Failure to implement structured compliance frameworks and retention policies could lead to:

- Data loss or corruption, impacting project continuity and infrastructure planning.
- Regulatory non-compliance, resulting in legal liabilities.
- Inefficiencies in digital project delivery, reducing interoperability and decision-making capabilities.

To mitigate these risks, the CBTL must integrate federated governance policies, long-term archival strategies, and compliance tracking mechanisms. These safeguards will ensure that:

- All BIM artifacts remain accessible, accurate, and version controlled.
- Agencies can retrieve historical project data for audits, maintenance, and legal documentation.
- The repository aligns with ISO 19650, NIST, and other existing standards, supporting consistency across transportation systems.

By implementing these advanced version control and data validation features, the CBTL will ensure high-quality, reliable, and interoperable BIM workflows, enabling a standardized digital foundation for transportation infrastructure management.

5.5. User Interface (UI) and Accessibility

A robust, intuitive User Interface (UI) is essential for making the CBTL an efficient and accessible platform for a diverse range of users, including engineers, planners, policymakers, researchers, and contractors. The effectiveness of CBTL depends not just on data availability but also on how easily users can interact with, retrieve, and interpret BIM artifacts.

Since BIM workflows often require complex data navigation, cross-referencing multiple artifacts, and handling 3D model visualization, the UI must be designed to streamline these processes, reduce complexity, and enhance user productivity. Without an intuitive interface, adoption rates could be hindered, usability challenges may arise, and the overall efficiency of digital project delivery could suffer.

By implementing role-specific dashboards, AI-enhanced search functionalities, and seamless model visualization tools, CBTL can bridge the gap between technical and non-technical users, ensuring that all stakeholders can effectively access, analyze, and utilize transportation BIM data.

5.5.1. The Importance of an Intuitive UI in CBTL

- Increases user adoption and engagement, ensuring seamless integration into existing workflows.
- Reduces training time for new users, making BIM artifacts more accessible to a broader range of stakeholders.
- Enhances decision-making and project efficiency, enabling faster retrieval, comparison, and analysis of BIM data.
- Supports interoperability, allowing users to interact with BIM artifacts from multiple agencies and software platforms within a unified interface.

5.5.2. Key UI Features

Dashboard-Based Navigation:

- Users should have customizable, role-specific dashboards tailored to their specific workflows and access privileges.
- Engineers, planners, and policymakers will be presented with only the most relevant BIM artifacts, workflows, and tools, minimizing information overload.
- Interactive visualizations will allow users to track project progress, review version histories, and access geospatial data layers in real time.

Advanced Search and AI-Assisted Queries:

- Natural Language Processing (NLP) integration will allow users to search for BIM artifacts using everyday language, making complex queries more accessible.
- AI-driven semantic search will enable intelligent filtering and contextual recommendations, helping users find the most relevant models, metadata, and historical records.
- Search functions will be optimized for metadata-based retrieval, allowing users to query BIM artifacts based on object types, construction phases, geographic locations, and compliance standards.

Mobile-Friendly Design:

- The UI should be fully responsive and optimized for tablets and mobile devices, allowing field engineers, surveyors, and inspectors to access BIM data on-site.
- Offline mode capabilities will ensure that BIM models and metadata can be accessed in low-connectivity environments, critical for on-site inspections and remote infrastructure assessments.
- Gesture-based controls for mobile users will provide a streamlined experience for navigating large datasets, rotating 3D models, and inputting field data efficiently.

5.5.3. Key Considerations for CBTL UI Design

User Experience (UX) and Tailored Interfaces:

- Different user groups require different UI complexity levels:
  - Non-technical users (e.g., policymakers, planners) need a simple, intuitive UI with guided workflows.
  - Technical users (e.g., engineers, developers, data architects) require advanced features, API access, and model interaction tools.
- In an ABAC model, interfaces should present only those tools and data that align with a user's attributes, ensuring relevance and preventing information overload.

NLP-Enabled AI Queries:

- NLP integration will allow users to search for BIM artifacts using conversational language rather than complex queries.
- AI-driven search can extract contextually relevant BIM models based on project requirements.

Stakeholder Engagement and Training Integration:

- The CBTL UI should include embedded tutorials, tooltips, and onboarding workflows to assist users in learning the system.
- A help center or chatbot-style support could address common questions and troubleshooting needs.
- Comprehensive training programs should be accessible directly from the UI to improve user adoption.

Community Engagement and Feedback Loop:

- Users should be able to submit feedback directly through the UI, enabling continuous improvement.
- Incentive mechanisms (badges, points-based recognition) could encourage engagement and contributions.
- A discussion forum or community portal could foster collaboration among state DOTs, researchers, and consultants.

Interoperability and Emerging Technologies:

- The UI should allow for direct integration with IoT, AR, and VR tools, enabling enhanced BIM visualization and data monitoring.
- Future-proofing for AI-driven insights and real-time BIM updates should be considered in UI design.

API and Developer Access Portal:

- The UI should include a dedicated API management section, enabling technical users to integrate BIM data into external applications.
- API documentation should be interactive and support live testing to simplify third-party development.

By prioritizing usability, accessibility, and performance, the CBTL UI will empower engineers, policymakers, and field personnel to seamlessly interact with transportation BIM data, enhancing decision-making efficiency and infrastructure planning. Additionally, by integrating stakeholder-driven enhancements, such as role-based dashboards, AI-powered search, mobile accessibility, and real-time collaboration tools, the CBTL will maximize user engagement, streamline workflows, and drive widespread adoption across federal, state, and industry stakeholders. These improvements will foster cross-agency collaboration, encourage continuous feedback-driven refinements, and future-proof the system for emerging technologies such as IoT, AR/VR, and AI-driven insights.

5.6. Example – Inspection Update

The following example is to provide a simple demonstration of the technical aspects of the CBTL and how it integrates with other systems. NOTE: this example is for demonstration purposes in simple terms and is not intended to be asserted as an actual use case. In this example, the CBTL serves as a gateway linking an inspector (user) to a local asset management system (AMS). This assumes that the asset management system has previously been integrated with the CBTL through the API integration services. It is important to note that, unless configured and authorized to do so, the CBTL will not store the bridge inspection data, but rather in this example acts as the intermediary to connect to the local asset management system.

This example illustrates how the CBTL could support user requirements, in which an inspector inspects a bridge and logs into the CBTL to submit updates. In this case, once construction is complete, the model is integrated into the local AMS. AMS. Inspection teams equipped with tablets or AR devices can overlay the digital BIM model onto the physical structure during on-site evaluations. This allows inspectors to pinpoint specific components, compare current conditions to original design specifications, and record defects directly onto the model. For example, if an inspector identifies a crack in Beam #2 of a bridge, they can immediately document the defect within the BIM artifact, attach relevant photographs, assess severity, and synchronize the update with the central AMS.

Figure 6 displays the flowchart of the inspector's interaction with the CBTL to update the bridge model data into the local AMS. After logging into the CBTL, the user selects the project that they want to update and submits inspection data to the ASM, where it undergoes validation through middleware services. The request passes through middleware for validation before updating the ASM. Successful updates trigger event-driven notifications through a message broker, ensuring all downstream systems remain synchronized. Example API calls can be found in Appendix B.

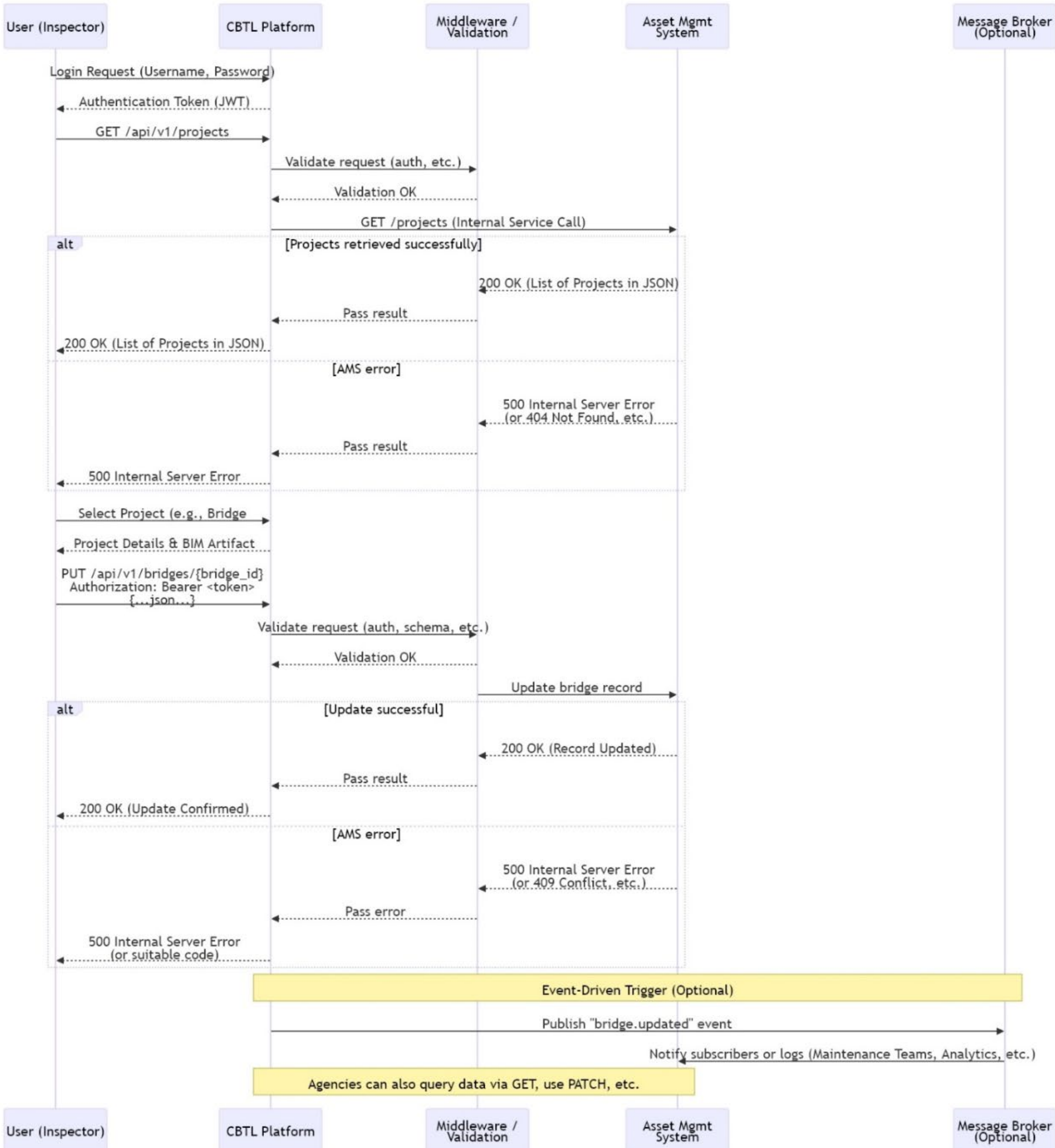

Figure 6: Diagram of Inspector Updating BIM Model

Diagram Breakdown:

1. User Login to CBTL:

- The Inspector logs into the CBTL platform using their credentials.
- The CBTL validates the user and returns an authentication token, typically a JSON Web Token (JWT).
- If authentication fails (invalid credentials or unauthorized user), the CBTL returns a 401 Unauthorized Error, and the user cannot proceed.

2. Requesting Projects:

- The user calls the CBTL (GET /api/v1/projects) to retrieve a list of available projects.
- The CBTL internally queries the AMS (GET /projects).

3. Validation Success:

- If the update is successful, the API responds with a 200 OK.
- Upon successful validation, the CBTL retrieves the list of projects from the AMS.

4. Validation Failure:

- If there is an error, the API returns a relevant error code. Potential error codes here include:
    - 400 Bad Request for malformed queries
    - 401 Unauthorized if the JWT is invalid or missing
    - 404 Not Found
    - 403 Forbidden
    - 500 Internal Server Error if the AMS is unable to process the request

5. Project Selection:

- From the list provided, the user then selects the specific project (e.g., Bridge #6789) they wish to update.
- The CBTL displays the BIM artifact and related project details (usually by calling the AMS internally).
- If the AMS fails to retrieve project details, the CBTL will return the corresponding error.

6. Submitting an Update:

- The user submits an update to the bridge using the API Gateway.
- CBTL issues a PUT request (PUT /api/v1/bridges/{bridge_id}) to update the chosen resource, including their JWT in the Authorization header.
- The API forwards the request to Middleware for validation (again checking authorization, data schema, etc.).

7. Event-Driven Data Propagation:

- Upon successful update, the API publishes a “bridge.updated” event to a Message Broker.

8. Real-Time Updates:

- The event-driven data propagation triggers downstream updates, notifying maintenance teams, analytics dashboards, or compliance systems.
- Subscribed and authorized stakeholders received real-time alerts

These updates are facilitated through standardized APIs that ensure data consistency and integrity across systems. Real implementations may vary, but the general structure remains similar. Again, these are system-generated encodings automatically done by the CBTL.

These API calls enable the user to interact with the AMS directly through the CBTL. In this example, the CBTL does not directly store any bridge data, but rather is used to retrieve and submit data to the AMS. It is important to emphasize that the CBTL automatically generates these API calls based on the user's interactions within the platform. This means that users, such as inspectors or asset managers, do not need to manually write or format API requests. Instead, as users navigate the CBTL—selecting projects, entering inspection results, or updating asset conditions—the platform handles the backend processes required to structure, authenticate, and transmit the data securely. The middleware service plays a crucial role in this process, ensuring that all submitted data complies with established schemas, business rules, and security protocols before it is integrated into the AMS. This step prevents malformed or unauthorized data from entering the AMS, maintaining data integrity and consistency across the platform.

Once the data passes validation and is successfully stored in the AMS, it triggers an event within an event-driven architecture. For example, a "bridge.updated" event can be published to a message broker, such as Kafka or RabbitMQ, which then distributes this update to all relevant stakeholders and connected systems. This real-time propagation can 1) Notify maintenance teams of required repairs or inspections, 2) Update real-time dashboards used by decision-makers and public agencies, and 3) Alert public safety agencies if the update indicates any structural risks or immediate hazards.

5.7. Summary of Core Technical Framework for the CBTL

This chapter defines the foundational technical architecture required to implement the CBTL as a scalable, secure, and interoperable national repository for BIM artifacts. Building on guidance from FHWA, USDOT, AASHTO, and pooled fund research, the proposed framework outlines the system components, integration strategies, data governance models, and security mechanisms necessary to ensure effective deployment and long-term viability. The CBTL is envisioned as a cloud-native, containerized platform capable of integrating with diverse data sources and tools across federal and state agencies. The core system architecture includes a cloud-hosted environment (e.g., AWS, Azure, SDC), a relational database for storing and retrieving BIM artifacts, RESTful APIs for system integration, and OAuth-based authorization for secure access. A microservices architecture will support modular updates and redundancy while enabling scalable performance.

A major priority is seamless interoperability, allowing the CBTL to integrate with external systems such as FHWA repositories, BIM authoring tools, and the buildingSMART Data Dictionary (bSDD). Using open standards (e.g., IFC, RDF, JSON), the CBTL will support real-time data synchronization, metadata alignment, and federated access to state and national repositories. Federated governance models will allow state DOTs to maintain autonomy while aligning with national standards.

To protect sensitive transportation data, the CBTL will implement a Zero Trust security model, incorporating multi-factor authentication, least-privilege access, encryption protocols, and automated audit logs. The system will comply with federal regulations, including NIST CSF, FISMA, ISO 19650, and CUI policies, to ensure data integrity and cybersecurity.

Robust version control and data validation are central to CBTL's functionality. Features include Git-based tracking, structured metadata querying, conflict resolution, and AI-driven anomaly detection. These capabilities ensure consistent and reliable management of BIM artifacts throughout the asset life cycle, supporting audits, compliance, and historical reference.

A strong emphasis is also placed on user interface (UI) design, prioritizing accessibility and usability for a wide range of users—from engineers and inspectors to planners and policymakers. Key features include role-based dashboards, AI-powered search, mobile accessibility, and support for real-time collaboration and feedback.

Finally, this chapter presents an illustrative scenario designed to demonstrate the core technical functionalities of the CBTL in action. While the use case itself is arbitrary and not intended to be a recommended use case, it effectively showcases how the CBTL operates as an integration hub, connecting users to external systems such as a state DOT's AMS. In this demonstration, the CBTL facilitates secure user authentication, project selection, and data submission through automated API calls. Middleware services validate the data against pre-defined schemas before it is transmitted, while event-driven architecture ensures that updates propagate to all connected systems in real time. This example illustrates CBTL's role in enabling seamless, secure, and standards-compliant interactions across decentralized data environments without requiring users to manage the technical complexity of backend processes.

VI. Conclusion and Next Steps

6. Conclusion and Next Steps

The CBTL initiative represents a pivotal step toward national alignment on digital delivery, BIM standardization, and life cycle asset management in the transportation sector. Through comprehensive stakeholder engagement, a structured review of related projects, and an extensive scan of current technologies, this report has established a foundation for the CBTL as a scalable, interoperable, and secure digital platform. Its overarching purpose is to support state and federal agencies in transitioning to model-based workflows by providing a centralized resource for validated BIM artifacts, metadata standards, and technical integration frameworks.

In addition to these technical elements, there is a lot more to CBTL implementations—the workflows, governance, organizational change management, inter-agency/stakeholders collaboration, prototyping/piloting, etc. Following on the conceptualization of the CBTL, this report takes the concept further by laying out detailed technical requirements associated with CBTL implementation so that implementers can discuss what it takes to implement the CBTL.

6.1. Insights from Stakeholder Engagement

Engagement with stakeholders—including state DOTs, federal agencies, industry consultants, technology providers, and standards organizations—was instrumental in shaping the CBTL's vision and functionality. Input was gathered through roundtables, interviews, peer exchanges, and major conferences such as TRB, BIM for Infrastructure Week, and IHEEP. This engagement uncovered both barriers and opportunities, offering practical insights into real-world needs and expectations.

Key takeaways include:

- A strong desire for a federated, flexible framework that supports national goals without compromising state-level autonomy.
- The need for workforce training, change management, and clear governance models to ensure adoption and sustainability.
- Broad support for interoperability, metadata standardization, and the use of AI and NLP tools to enhance platform usability.

Stakeholders consistently affirmed the value of a national CBTL platform that serves as a trusted, authoritative repository for BIM resources while enabling integration with existing systems.

6.2. Leveraging Existing Solutions

The report identified and assessed numerous existing repositories, data frameworks, and open standards—both domestic and international—that can inform CBTL's technical development. Rather than creating a stand-alone solution from scratch, the CBTL is envisioned as a federated platform that integrates with complementary systems such as:

- Secure Data Commons (SDC)
- buildingSMART Data Dictionary (bSDD)
- FHWA and state DOT repositories
- AASHTO and NIBS digital initiatives

This approach promotes interoperability and reduces duplication, enabling CBTL to serve as both a hub and a gateway for access to BIM data, workflows, and metadata resources. Recommendations for implementation include:

- **Integration with National Digital Delivery Goals:** The CBTL should align with FHWA's BIM strategic roadmap and supports national efforts toward the adoption of BIM-based workflows for digital project delivery, asset management, and life cycle cost optimization.
- **Federated Data Model:** The CBTL should integrate with existing repositories such as SDC, the bSDD, and state DOT digital libraries through API-driven architecture. Rather than a monolithic central repository, a federated approach ensures seamless interoperability while allowing organizations to retain control over their data.
- **Version Control and Governance**: BIM artifacts should be managed with structured metadata, version tracking, and role-based access controls. Drawing from TOGAF principles, the CBTL governance model will emphasize data integrity, access management, and structured collaboration.
- **RESTful APIs and federated authentication**: The CBTL should leverage RESTful APIs and federated authentication mechanisms as core enablers of its technical infrastructure to enable seamless data exchange between CBTL and external systems while allowing users to log in with existing agency credentials (e.g., FHWA or state DOT SSO). This approach streamlines access, enhances security, supports interoperability, and reduces administrative overhead.
- **User-Centric Design and Accessibility:** The CBTL should strike a balance between technical depth and usability. Engineers, planners, policymakers, and non-technical users should be able to navigate and utilize the platform effectively. AI and NLP capabilities will be explored to enhance metadata structuring, automated tagging, and improved search functionalities.

6.3. Addressing Key Challenges and Opportunities

The transition to a national CBTL platform should overcome several challenges while capitalizing on clear opportunities:

- **Interoperability**: The CBTL needs to integrate with a wide range of proprietary and open-source tools through open standards like IFC, RDF, and COBie.
- **Security and Compliance**: Given the sensitivity of infrastructure data, the platform must implement a robust cybersecurity framework including Zero Trust principles, encryption, and NIST-aligned practices.
- **Scalability and Flexibility**: The cloud-native architecture ensures CBTL can evolve alongside growing data needs and emerging technologies.
- **Change Management**: Broad adoption requires a clear strategy to support training, organizational readiness, and stakeholder communication

These challenges are addressable through the technical framework proposed in this report, which includes cloud infrastructure, microservices, automated validation, and role-based access.

6.4. Demonstrating CBTL Functionality

To demonstrate how the CBTL would operate in practice, a conceptual use case was developed showing how an inspector could log into CBTL and submit bridge inspection updates to a state DOT's AMS. Though the use case is illustrative, it effectively highlights CBTL's technical capabilities, including:

- API-driven integration with external systems.
- Automated validation and security screening via middleware.
- Real-time data propagation through event-based architecture.
- Role-based user access and simplified front-end interaction.

This example reinforces the CBTL's potential to function as a dynamic integration layer between users and external systems, streamlining complex workflows while preserving data integrity and compliance. It illustrates how CBTL's API-driven architecture, automated validation processes, and event-based data propagation can simplify user interactions and ensure consistent, real-time updates across platforms. By enabling secure, role-based access and intuitive data entry, the CBTL can support a wide range of operational scenarios, making it a practical and scalable solution for digital project delivery in transportation.

6.5. Looking Ahead: Next Steps in the CBTL Development

With the research phase complete, the CBTL initiative now turns toward prototyping and implementation. The following next steps are recommended to ensure successful deployment:

Technical Development and Hosting:

- Develop the CBTL on a cloud-native platform such as AWS, Azure, or SDC.
- Implement backend servers, structured databases, and secure API gateways.
- Identify funding and business model for long-term development, management, and maintenance of the CBTL.
- Prioritize CBTL functions to be developed and deployed.

Pilot Testing with Select State DOTs:

- Implement small-scale CBTL test cases with partner agencies to refine functionality, governance structures, and interoperability.
- Launch pilots with select state DOTs to validate workflows, identify integration challenges, and refine UI/UX features.
- Use pilots to test scalability, performance, and governance alignment.
- Evaluate data integration workflows and identify potential bottlenecks.
- Coordinate with and get input from the ongoing FHWA Demonstrating the Creation, Use, and Management of Central BIM Transportation Library (CBTL) project.

Formalizing Governance and Metadata Standards:

- Define policies for metadata structuring, user roles, and data contribution protocols.
- Establish a multi-agency governance committee to guide long-term oversight and compliance.

Broader Collaboration and Standards Alignment

- Deepen partnerships with FHWA, AASHTO, bSI, NIBS, and other standards bodies.
- Align CBTL goals with FHWA's BIM roadmap and digital delivery objectives.

Workforce and Change Management

- Develop comprehensive onboarding, training, and support resources.
- Promote engagement through feedback mechanisms, tutorials, and role-specific dashboards.

The CBTL is positioned to become a cornerstone of digital transformation in transportation infrastructure. By providing a national framework for BIM data management rooted in open standards, user accessibility, and secure interoperability, the CBTL will help agencies improve coordination, reduce inefficiencies, and deliver better infrastructure outcomes. With the support of ongoing research, strong stakeholder collaboration, and strategic technical implementation, the CBTL can evolve from vision to reality, setting the national standard for model-based project delivery in the years ahead.

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IIX. Appendices

Appendix A. Stakeholder Engagement

A.1. End-User Engagement

Following extensive secondary research and initial feedback from stakeholder engagement, a set of questions has been developed to gather insights on the potential adoption and implementation of the Central Building Information Modeling (BIM) Transportation Library (CBTL) for managing BIM artifacts and BIM administration for highway infrastructure projects. This inquiry aims to understand the utility, vision, and readiness for the CBTL within the Department of Transportation (DOT). The responses will help identify existing initiatives, resources, and skills, as well as potential challenges and opportunities associated with the deployment of this tool. Additionally, the questions seek to understand the importance of workforce training, leadership buy-in, and funding considerations in the successful adoption of this technology. The ultimate goal is to ensure that the deployment of the CBTL is aligned with the DOT's strategic objectives and that it addresses critical needs in project management and information sharing.

1. BIM Artifacts:
    - 1.1. Are the artifacts we've summarized the right artifacts to capture? Is there something missing, or needed in the repository?
    - 1.2. What other types of BIM artifacts exist?
    - 1.3. How do you envision using these?
    - 1.4. What resources do you have/need to support the artifacts?
2. Tool Utilization and Vision:
    - 2.1. Would you use this tool?
    - 2.2. How do you envision using it to share information?
3. State-Specific Initiatives and Development:
    - 3.1. Is there a state-specific initiative to develop something similar? If so, describe the tool.
    - 3.2. How far along in the process are you?
    - 3.3. What have been some early learning (challenges/opportunities)?
4. Resources and Skills:
    - 4.1. Do you have the resources and skills to leverage this tool across your DOT?
    - 4.2. If not, what are the biggest limitations to the successful adoption of this tool(s)?
5. Deployment and Governance:
    - 5.1. When we talk about the deployment of any new system or process, change management (the process of deploying the change) and proper governance (structure around people, process, and technology) are critical to the tool's success. Are there any key challenges you anticipate in the deployment and adoption of this tool?
    - 5.2. What problems do you think it'll solve for your DOT?
6. Workforce Training and Communication:
    - 6.1. How important is workforce training and communication to the successful adoption of this tool?
    - 6.2. What training programs do you have for similar initiatives? How well do they work?
    - 6.3. Are they aligned to a centralized digital delivery program and strategy?
7. Leadership and Readiness:
    - 7.1. Does your DOT have the leadership buy-in to deploy this tool across the enterprise?
    - 7.2. What barriers to adoption at the leadership level do you anticipate?

   7.3. What is your DOT's level of readiness to leverage a fully integrated cloud-based repository?
8. Funding Considerations:
   8.1. What funding considerations should we keep in mind as we look at deploying the tool? (I.e., technology, training, staff, etc.)
9. Development and Deployment Plan:
   9.1. What are the most important considerations we should have, as we develop our work plan for creating and deploying an CBTL for hosting BIM artifacts and BIM administration of highway infrastructure projects to complement the bSI Data Dictionary?

A.2. Solution Provider Engagement

Following extensive secondary research and initial feedback from stakeholder engagement, a set of questions has been developed to gather detailed insights on the access, functionality, development, and support aspects of integrating with the CBTL. These questions are designed to help us understand the requirements and best practices for leveraging various integration methods, including but not limited to APIs, to effectively utilize the CBTL within the organization. Additionally, when reaching out to different platform teams about developing an app or integrating with their systems, it is important to ask questions that will help understand their capabilities, limitations, and best practices. The inquiry aims to cover various areas, including general access and authentication methods, technical details about endpoints and error handling, development environment setup, support resources, and specific use case recommendations. The ultimate goal is to ensure that all integration methods are utilized efficiently, securely, and in alignment with the organization's objectives.

1. General Questions
   1.1. Access and Authentication:
      1.1.1. What are the authentication methods required to access the API? Is there a need for API keys, OAuth tokens, or other authentication mechanisms?
      1.1.2. How do we obtain access credentials, and are there different access levels?
   1.2. Rate Limits and Usage:
      1.2.1. Are there any rate limits or usage quotas for the API? If so, what are the limits, and how can we monitor our usage?
      1.2.2. What happens if we exceed the rate limits?
   1.3. Data Formats:
      1.3.1. Are there any constraints on the data, such as data retention periods or frequency of updates?
2. Technical Questions
   2.1. Endpoints and Functionality:
      2.1.1. Can you provide detailed information on the available API endpoints and their respective functionalities?
      2.1.2. Are there any tutorials or sample projects available to help us get started?
   2.2. Data Filtering and Pagination:
      2.2.1. Does the API support data filtering, sorting, and pagination?
   2.3. Error Handling:
      2.3.1. What are the common error codes returned by the API, and how should they be handled?
      2.3.2. Is there a detailed error message reference guide available?
3. Development and Support Questions

- 3.1. Development Environment:
  - 3.1.1. Are there any development or sandbox environments available for testing purposes before accessing the production API?
  - 3.1.2. What are the best practices for setting up a development environment to work with the API?
- 3.2. Support and Resources:
  - 3.2.1. What kind of support is available for developers using the API? Is there a dedicated support team or community forum?
  - 3.2.2. Are there any example projects, SDKs, or libraries available to help with integration?
- 3.3. Versioning and Updates:
  - 3.3.1. How is the API versioned, and how are updates or changes communicated to users?
  - 3.3.2. What is the policy on backward compatibility for different versions of the API?
- 3.4. Security and Compliance:
  - 3.4.1. What security measures are in place to protect the data transmitted through the API?
  - 3.4.2. Are there any compliance requirements or guidelines we should be aware of when using the API?

4. Specific Use Case Questions
   - 4.1. Use Case-Specific Queries:
     - 4.1.1. Based on our intended use case are there any specific recommendations or best practices for using the API?
     - 4.1.2. Are there any limitations or constraints that we should be aware of for our specific use case?

A.3. Open Roundtable Peer-Exchange

A peer-exchange was organized for industry leaders and stakeholders to come together and collectively provide a dialogue in shaping the CBTL. The aim was to engage stakeholders on best practices, governance, and priorities for managing BIM artifacts and advancing infrastructure projects.

The objective was to create a "roundtable" experience, in which everyone involved had a literal seat around the table to have an open dialogue and share their opinions based on a set of pre-defined prompts formulated from the research. The goals included:

1. Share insights into how a CBTL should address your needs.
2. Align on best practices, requirements, expectations, and priorities.
3. Explore the tools, resources, and governance needed in the CBTL.

The roundtable featured a diverse representation from DOTs, contractors, and technology providers, ensuring a collaborative discussion across multiple perspectives. This wide representation facilitated a comprehensive discussion on how a CBTL can serve the transportation industry effectively.

A.4. CBTL Leadership Roundtable

The roundtable held at the Transportation Research Board (TRB) Annual Meeting in January 2025 convened a cross-section of stakeholders from Departments of Transportation (DOT), contractors, technology providers, standards organizations, and research entities to facilitate a comprehensive and collaborative dialogue on the development of a CBTL.

Given the complexity and scale of digital transformation in transportation infrastructure, it is critical to engage a wide range of perspectives to ensure that any proposed solution is operationally viable, technically robust, and responsive to the diverse needs of the industry. Cross-sector collaboration enables a deeper understanding of the barriers and opportunities associated with implementing a centralized BIM repository, while fostering consensus on priorities such as data interoperability, governance structures, workforce development, and long-term system sustainability.

The roundtable provided an open forum for identifying practical challenges, sharing lessons learned, and exploring strategies for successful adoption at both the state and national levels. The diversity of participants reflected the broad stakeholder base that a CBTL must ultimately support, and underscored the importance of ongoing multi-stakeholder engagement throughout its development.

Organizations represented included:

- Researchers and Roundtable Moderators: NIBS, S3, and CRAFT
- Departments of Transportation (DOT): Iowa, Montana, Ohio, Florida, Minnesota, Connecticut, Texas, Michigan, Utah, and Pennsylvania)
- Standards Organizations: buildingSMART International (bSI), NIBS
- Technology Providers: Infotech
- Contractors and Consultants: HDR, Michael Baker International, Cliff, Gannet Fleming Inc., Kimley-Horn, CRAFT, and S3

A.4.1. Agenda:

1. What is the CBTL?

To open the discussion, NIBS presented an overview of the CBTL, summarized as:

- A centralized location for securely accessing multiple data sources.
- A tool to standardize terminology and promote a common language within the industry.
- A resource to facilitate interoperability and data sharing across agencies and contractors.
- A structured approach to support digital project delivery and infrastructure life cycle management.

With the fundamentals established, discussion moved into the following categories. Summaries and conclusions from these discussions are provided in subsequent sections. A Mentimeter poll was also conducted periodically, with excerpts included in this document.

2. Priorities of Discussion

- Resources and Skills
- Workforce Training and Communication
- Development and Deployment
- Deployment and Governance
- Leadership Buy-in and Readiness

- Tool Utilization
- BIM Artifacts
- State-Specific Initiatives
- Funding Considerations

3) Discussion Questions

1. What digital data do you use today? (Be specific.)
2. What are you doing to manage your digital data?
3. What works well with your current approach?
4. What challenges do you face?
5. How can the CBTL serve you? What would you need it to do?

A.4.2. Key Themes and Outcomes

A.4.2.1. What is the CBTL?

- A centralized location for accessing multiple data sources securely.
- A tool to standardize terminology and help ensure a common language within industry.
- A resource to facilitate interoperability and data sharing across agencies and contractors.
- A structured approach to support digital project delivery and infrastructure life cycle management.

With the basics of the CBTL established, discussion proceeded in the following categories. Summaries/conclusions from the discussions are captured here. A Mentimeter poll was also taken periodically, excerpts of which are included here, and the full results of which are also provided with this report.

A.4.2.2. Digital Data Priorities

- Participants shared insights on key digital data sources, including Open Bridge Designer, ArcGIS, Drone capture data, Light Detection and Ranging (LiDAR), video, and asset data for roads and bridges.
- The need for a standardized data dictionary and metadata structure that would allow disparate systems to interoperate on data was emphasized.
- Integration with existing pooled fund efforts and federal initiatives should be considered to maximize efficiency.

Priorities

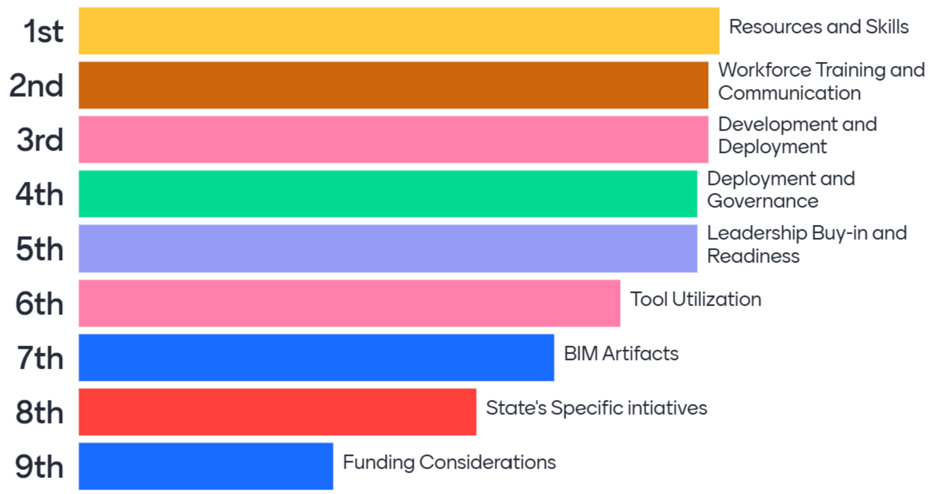

Figure 7. Digital Data Priorities

A.4.2.3. Key Challenges Identified

- **Signage Data Variability:** Different perspectives and needs make standardization difficult.
- **3D Cell Libraries:** States develop and maintain these libraries independently currently and they have many shared components that could be leveraged if readily available in a common location.
- **Data Access and Security:** Ensuring proper access while maintaining data integrity.
- **Governance and Data Stewardship:** Establishing responsible data ownership within agencies. Sharing organizational models, best practices, and lessons learned was of interest.
- **Interoperability of Multiple Systems:** Ensuring seamless integration of diverse datasets.
- **Common Data Formats and Metadata:** Need for a standardized data dictionary.
- **Leveraging Pooled Fund and Advanced Digital Construction Management Systems (ADCMS) Grant Initiatives:** Opportunities to build upon existing state-level funding and projects.

A.4.2.4. Envisioned Functionalities of the CBTL

- **Standardized Formats**: What data are we capturing, and what metadata should be included?
- **Tracking DOT Progress:** How do we monitor updates and advancements effectively?
- **Data Interoperability Policies:** What guidelines ensure seamless data exchange?
- **Sustaining Outcomes:** Ensuring that results from various initiatives remain active and utilized.
- **Accessible Support:** Providing a simple and efficient way for users to ask questions and receive assistance.

A.4.2.5. Technical Implementation Approach

- CBTL development should follow a **progressive structure:**
    - **Directory Model:** A landing page linking to existing repositories.
    - **Gateway Model:** A user interface that connects to APIs, enabling seamless data access.
    - **Repository Model:** A fully centralized system storing all BIM artifacts for direct access.
- AI-driven solutions should be explored to enhance querying and metadata structuring.
- Security measures must be robust, considering inter-state data sharing and governance policies.
- A high-level as well as drill-in structure should be established.
- Agencies must evaluate different technological solutions for managing CBTL functions, including cloud-based infrastructure and decentralized data storage approaches.

A.4.2.6. Change Management Considerations

- Leadership buy-in is crucial for ensuring the adoption of CBTL.
- Workforce training, program marketing, and stakeholder engagement are necessary to drive participation.
- Organizational structure and governance models must support sustainable implementation.
- Change management strategies should account for potential resistance and provide clear pathways for integration.
- Agencies must address data ownership concerns and clearly define roles and responsibilities for data stewardship.

A.4.3. Next Steps and Implementation Considerations

- **Define a Clear Vision and Regulatory Alignment:** Ensure alignment with the Federal Highway Administration (FHWA)'s BIM Level 2 by 2030 objectives.
- **Pilot Programs:** Launch small-scale implementations to test feasibility and refine standards.
- **Structured Follow-Ups:** Engage with DOTs and stakeholders for iterative feedback.
- **Cross-State Collaboration:** Address multi-state data sharing, governance, and standardization.
- **Lessons Learned from Existing Initiatives:** Incorporate insights from pooled fund projects, ADCMS grants, and best practices from leading agencies.
- **Integration with Change Management Strategies:** Ensure that technical implementation is paired with effective organizational readiness efforts.

Appendix B. Software and Platforms

B.1. Open BIM

The following are openBIM platforms that are self-reported to be compliant with one or more of the Industry Foundation Classes (IFC) openBIM standards[33]. While these claims have not been formally verified by buildingSMART International (bSI), they represent a significant portion of the market ecosystem promoting open data exchange and interoperability. Open BIM platforms are essential to the Central BIM Transportation Library (CBTL) as they enable seamless collaboration across different software environments, reducing data silos and supporting standardized workflows for design, construction, and asset management. Identifying these platforms provides a starting point for evaluating software tools that can integrate with the CBTL's open, federated data architecture).

12d Model (12d Solutions Pty Ltd.)

3D Repo (3D Repo Ltd.)

3DEXPERIENCE Platform (DASSAULT SYSTÈMES)

3rd Party Addin IFC Export and Enhanced Import for Autodesk Navisworks (GeometryGym)

3rd Party Addin IFC Import and Enhanced Export for Autodesk Revit (GeometryGym)

3rd Party Plugin IFC Export and Import for McNeel Rhino3d and Grasshopper3d (GeometryGym)

4M Fine4RATE (4M SA)

4M FineELEC (4M SA)

4M FineGREEN (4M SA)

4M FineHVAC (4M SA)

4M FineSANI (4M SA)

4M IDEA Architecture (4M SA)

4M STRAD (4M SA)

4MCAD (4M SA)

Abisplan 3d ()

abstractBIM generator (abstract ag)

Aconex (Oracle)

AcoubatBIM by CYPE (Centre Scientifique et Technique du Batiment (CSTB) & CYPE Ingenieros, S.A.)

ACTIVe3D (Sopra Steria)

Adoddle (Asite Solutions Ltd.)

Adomi (Arkey Systems B.V.)

Advance Design (GRAITEC SA)

Advance Steel (Autodesk, Inc.)

AI-driven BIM collaboration & progress monitoring (Bimefy)

Allplan Architecture (ALLPLAN GmbH (Nemetschek Group))

Allplan Bimplus (ALLPLAN GmbH (Nemetschek Group))

Allplan Bridge (ALLPLAN GmbH (Nemetschek Group))

Allplan Engineering (ALLPLAN GmbH (Nemetschek Group))

Allplan Precast (ALLPLAN GmbH (Nemetschek Group))

AnTherm (Kornicki Dienstleistungen in EDV und Informationstechnologie)

ArcGIS CityEngine (Esri)

ArcGIS GeoBIM (Esri)

ArcGIS Pro (Esri)

ArchiBIM Analyzer (Solideo Systems Co., Ltd)

ArchiBIM Server (Solideo Systems Co., Ltd)

ArchiBIM Viewer (Solideo Systems Co., Ltd)

Archicad (GRAPHISOFT (Nemetschek Group))

ArchiFMS (Solideo Systems Co., Ltd)

Archilogic (Archilogic AG)

ArchiWIZARD (GRAITEC SA)

[33] https://technical.buildingsmart.org/resources/software-implementations/

ARCHLine.XP (CadLine Ltd)

ARCHLine.XP (CadLine Ltd.)

Areddo (Arkey Systems B.V.)

Areo (Areo AS)

ARES Commander 2020 (Graebert GmbH)

Assimp (Open Asset Import Library) (*open source (BSD))

Asta Powerproject BIM (Elecosoft UK Ltd)

AtomIFC (Qonic)

AutoBid SheetMetal (Trimble MEP (Trimble, Inc.))

AutoCAD Architecture (Autodesk, Inc.)

AutoCAD MEP (Autodesk, Inc.)

Autodesk Construction Cloud (ACC) (Autodesk)

AUTOFLUID (TracéoCAD)

AutoPISTE (GEOMEDIA)

Autosign (CGS Labs)

AutoVue 3D Professional Advanced (Oracle)

AVEVA Bocad (AVEVA Group plc)

AxeoBIM (Axxone System)

AxisVM (InterCAD Kft.)

Bausoft Haustech-CAD (Bausoft Informatik AG)

BC Enterprise (Business Collaborator Ltd.)

BCF Manager (KUBUS)

BCFier (*open source (GNU GPL3))

bcfplugin (*open source (GNU LGPL2.1))

Benchmark (ITI International Training Institute)

Bentley Map (Bentley Systems, Inc.)

Bentley Navigator (Bentley Systems, Inc.)

Bentley View (Bentley Systems, Inc.)

Bexel Manager (Bexel Consulting)

BIM 360 (Autodesk, Inc.)

BIM Assure (Invicara)

BIM BEAVER (BIM VILLAGE)

BIM Energy (StruSoft AB)

BIM Handover (Digital Alchemy)

BIM HVACTool (Tian Building Engineering UG)

Bim Leader (Cadline Software s.r.l.)

BIM Track (BIM Track)

BIM&CO (BIM&CO)

BIM.permit (VSK Software GmbH)

BIM.works (BIM Base B.V.)

BIMcollab (KUBUS)

BIMcollab Nexus (KUBUS)

BIMcollab Zoom (KUBUS)

BIMData Viewer (BIMData.io)

BIMData.io API (BIMData.io)

BIMData.io Platform (BIMData.io)

BIMEYE (Tribia AS (Addnode Group))

BIMobject (BIMobject)

BIMQ (AEC3 Deutschland GmbH)

BIMReview (StruMIS Ltd.)

BIMscript (BIMobject)

BIMserver (BIMserver.org)

BIMserver.center (CYPE Ingenieros, S.A.)

bimspot (bimspot GmbH)

BIMsurfer WebGL viewer (*open source (MIT))

Bimsync API (Catenda AS)

Bimsync Arena (Catenda AS)

Bimsync Boost (Catenda AS)

BIMTester (*open source)

BIMvision (Datacomp Sp. z o.o.)

BIMxBEM (EPFL Laboratory of Numeric Cultures for Architectural Projects (CNPA))

Bloc in Bloc API (Bloc in Bloc, SAS)

Bloc in Bloc App (Bloc in Bloc, SAS)

Bloc in Bloc Platform (Bloc in Bloc, SAS)

Bonsai (IfcOpenShell Contributors)

Bricks (Bricks)

BricsCAD BIM (Bricsys NV (Hexagon AB))

BricsCAD Pro (Bricsys NV (Hexagon AB))

BricsCAD Ultimate (Bricsys NV (Hexagon AB))

Bricsys 24/7 (Bricsys - Hexagon)

bSDD Revit plugin (VolkerWessels, Heijmans, ASRR and other Contributors)

CAD Exchanger (CADEX)

CAD/TQS (TQS Informatica Ltda.)

CADMATIC Building (CADMATIC EAC Oy)

CADMATIC Drawing Viewer (CADMATIC EAC Oy)

CADMATIC Electrical (CADMATIC EAC Oy)

CADMATIC HVAC (CADMATIC EAC Oy)

cadwork 3D (cadwork)

CADWorx Design Review (Hexagon AB)

card_1 (IB&T Software GmbH)

Catenda Boost (Catenda AS)

Catenda Duo (Catenda Duo)

Catenda Hub (Catenda AS)

Catenda Site (Catenda AS)

Causeway BIMMeasure (Causeway Technologies Ltd.)

CerTus HSBIM (ACCA Software S.p.A.)

CerTus SCAFFOLDING (ACCA Software S.p.A.)

CET Designer (Configura Sverige AB)

Civil 3D (Autodesk, Inc.)

CMDBuild READY2USE (*open source (GNU AGPL))

CMS IntelliCAD (CAD-Manufacturing Solutions, Inc.)

Cobuilder Link (Cobuilder)

CostOS (Nomitech Ltd.)

CostX (Exactal Group Ltd)

COVADIS (GEOMEDIA)

Creating IDS for projects (ILS Configurator)

Creo to IFC Exporter (BIMDeX (SrinSoft Inc.))

CrossCad/Plg (Datakit)

CrossCad/Ware (Datakit)

CrossManager (Datakit)

CSiBridge (Computers and Structures, Inc. (CSi))

Cubicost (Glodon Company Limited)

Cubit Pro + BIM (BUILDSOFT (MiTek))

Cyclone 3DR (Leica Geosystems)

Cype Architecture (CYPE Ingenieros, S.A.)

CYPECAD (CYPE Ingenieros, S.A.)

CYPECAD MEP (CYPE Ingenieros, S.A.)

CYPEFIRE Design (CYPE Ingenieros, S.A.)

CYPEFIRE Hydraulic Systems (CYPE Ingenieros, S.A.)

CYPEHVAC Hydronics (CYPE Ingenieros, S.A.)

CYPELEC Networks (CYPE Ingenieros, S.A.)

CYPELUX (CYPE Ingenieros, S.A.)

CYPEPLUMBING Sanitary Systems (CYPE Ingenieros, S.A.)

CYPEPLUMBING Water Systems (CYPE Ingenieros, S.A.)

CYPETHERM Eplus (CYPE Ingenieros, S.A.)

Dalux BIM Viewer (Dalux)

Dalux Box (Dalux)

Dalux Field (Dalux)

DaluxFM (Dalux)

DATAflor BIM-Manager (DATAflor AG)

DDS-CAD Architect (Data Design System ASA (Nemetschek Group))

DDS-CAD Building (Data Design System ASA (Nemetschek Group))

DDS-CAD Construction (Data Design System ASA (Nemetschek Group))

DDS-CAD Electrical (Data Design System ASA (Nemetschek Group))

DDS-CAD Mechanical (Data Design System ASA (Nemetschek Group))

DDS-CAD Plumbing (Data Design System ASA (Nemetschek Group))

DDS-CAD PV (Data Design System ASA (Nemetschek Group))

DDS-CAD Viewer (Data Design System ASA (Nemetschek Group))

Define (Cobuilder)

DESITE BIM (thinkproject (Reseller: IB&T Software GmbH))

DIALux evo (DIAL GmbH)

Dietrich's (Datenverarbeitungsgesellschaft für Handel und Produktion AG)

Digital Project (Digital Project, Inc.)

Dimension10 (Dimension 10 AS)

Documentación Técnica de Proyectos DTP POK (PLANOK SA)

dRofus (dRofus (Nemetschek Group))

DuctDesigner 3D (Trimble MEP (Trimble, Inc.))

EcoDomus FM (EcoDomus)

EcoDomus PM (EcoDomus)

Edificius (ACCA Software S.p.A.)

Edificius MEP (ACCA Software S.p.A.)

EdiLus (ACCA Software S.p.A.)

EDMmodelServer(ifc),Ñ¢ (Jotne IT)

EDMS Global Document Management System (ENKA Systems Yazilim A.S.)

ELITECAD Architecture (XEOMETRIC GmbH)

EstiaBIM (SwissWeb Development)

ETABS (Computers and Structures, Inc. (CSi))

eveBIM (Centre Scientifique et Technique du Batiment (CSTB))

Excel2IDS (buildingSMART community project)

Fabrication (Autodesk, Inc.)

FEM-Design (StruSoft AB)

Ferrovia (CGS Labs)

Field Link (Trimble MEP (Trimble, Inc.))

File::IFC Perl library (*open source)

Flex (xbim ltd.)

FME (Safe Software Inc.)

Forge (Autodesk, Inc.)

FreeCAD (*open source (GNU LGPL2+ & CC-BY-3.0))

FusionLive (Opidis (Idox Plc))

Fuzor (Kalloc Studios, Inc.)

GALA Construction Software (GALA Software d.o.o.)

GEO5 (Fine spol. s.r.o.)

GEORAIL (GEOMEDIA)

GliderBIM (Glider Technology Ltd.)

GloBLD (GloBLD)

GRIT (Grit Virtual)

GSA (Oasys)

GstarCAD (Gstarsoft)

HiCAD (ISD Software und Systeme GmbH)

HiveDrive (SilentWave)

HOOPS Exchange (Tech Soft 3D)

HVAC for AutoCAD (Design Master Software, Inc.)

iConstruct Exporter (iConstruct (Hexagon AB))

iConstruct PRO (iConstruct (Hexagon AB))

IDA ICE (Equa Simulation AB)

IDS4Revit (DiRoots)

IES-VE (Integrated Environmental Solutions (IES) Ltd.)

IFC Builder (CYPE Ingenieros, S.A.)

IFC COBie (*open source)

IFC Editor (RDF ltd.)

IFC Engine (RDF ltd.)

IFC Exporter for AutoCAD Plant3D (Codemill Oy)

IFC File Analyzer (National Institute of Standards and Technology (NIST))

IFC Framework (apstex)

IFC Importer for AutoCAD (3D) (BIMDeX (SrinSoft Inc.))

IFC Importer for Creo (BIMDeX (SrinSoft Inc.))

IFC Importer for Inventor (BIMDeX (SrinSoft Inc.))

IFC Importer for Rhino (BIMDeX (SrinSoft Inc.))

IFC Quick Browser (GEM Team Solutions GbR)

IFC SDK (Centre Scientifique et Technique du Batiment (CSTB))

IFC SDK (Open Design Alliance)

IFC Toolbox (BIMMARS)

IFC Tree Viewer (GeometryGym)

IFC Viewer (RDF ltd.)

IFC Viewer (Sortdesk)

IFC WebGL (RDF ltd.)

IFC.js (*open source (MIT))

IFC++ (*open source (MIT))

IfcClash (IfcOpenShell Contributors)

IfcConvert (IfcOpenShell Contributors)

IfcDiff (IfcOpenShell Contributors)

IfcFM (IfcOpenShell Contributors)

IFChecker (The Hard Code GmbH)

IFChub (IFChub Ltd.)

IfcMax (Josef 'spacefrog' Wienerroither)

IfcOpenShell (*open source (GNU LGPL))

IfcSharp (*open source (MIT))

IfcTester (IfcOpenShell Contributors)

IFC-Validator (Tyréns AB)

IfcWebServer (IfcWebServer)

IGEO (VELOCITI SpA)

ILoveIFC (ILOVEIFC S.L. / SPA Planeamento SL)

Imerso (Imerso AS)

InEight (InEight)

InfoCAD (InfoGraph GmbH)

InfocadFM (Descor Srl)

Intergraph Smart Interop Publisher (Hexagon AB)

Inventor to IFC Exporter (BIMDeX (SrinSoft Inc.))

ISTRAM (BUHODRA INGENIERÍA, S.A.)

ISY Calcus (Norconsult Informasjonssystemer AS)

iTwin Platform (Bentley Systems, Inc.)

KITModelViewer (Karlsruhe Institute of Technology)

KOMPAS-3D (ASCON)

KorFin (A+S Consult GmbH)

LastBIM (LastBIM GmbH)

Lesosai (E4tech Software SA)

lexocad (cadwork informatik AG)

lexocad (cadwork informatik CI AG)

liNear (liNear GmbH)

Luciad (Hexagon AB)

MagiCAD (MagiCAD Group (Glodon Group))

MAGNET Explorer (Topcon)

MassMotion (Oasys)

Mc4Suite (Mc4Software Italia S.r.l)

Mensura CivilBTP (Geomensura)

Mensura Genius (Geomensura)

Mensura Quarry (Geomensura)

Mezzoteam (Prosys)

mh-BIM 6.0 (mh-software GmbH)

mh-BIM 7 (mh-software GmbH)

MicroStation (Bentley Systems, Inc.)

MicroStation PowerDraft (Bentley Systems, Inc.)

MIDAS CIM (MidasIT)

Modelspace FM (Gravicon Oy)

MORADA (SMB AG)

Navistool IFC Exporter (Codemill Oy)

Navistools IFC Extension (Codemill Oy)

Navisworks (Autodesk, Inc.)

Newforma (Newforma)

NOVA BIM (NOVA BUILDING IT GmbH)

Novapoint (Trimble, Inc.)

Novorender Explorer (Novorender)

Omega 365 BIM (Omega 365 Solutions)

Omniverse (NVIDIA)

One Click LCA (Bionova Ltd.)

Onuma System (Onuma, Inc.)

Open BIM Analytical Model (CYPE Ingenieros, S.A.)

Open BIM Construction Systems (CYPE Ingenieros, S.A.)

Open BIM Layout (CYPE Ingenieros, S.A.)

Open BIM Model Checker (CYPE Ingenieros, S.A.)

Open BIM Quantities (CYPE Ingenieros, S.A.)

Open CASCADE (Capgemini)

OpenAEC (ONESTRUCTION Inc.)

OpenAEC for bSDD (ONESTRUCTION Inc.)

openBIM Checker (ZWING Innovation)

OpenBridge Designer (Bentley Systems, Inc.)

OpenBuildings Designer (Bentley Systems, Inc.)

OpenBuildings Speedikon (Bentley Systems, Inc.)

OpenBuildings Station Designer (Bentley Systems, Inc.)

OpenIFCViewer (Open Design Alliance)

openMAINT (*open source (GNU AGPL))

OpenPlant Modeler (Bentley Systems, Inc.)

OpenProject BIM (OpenProject)

OpenRail (Bentley Systems, Inc.)

OpenRoads (Bentley Systems, Inc.)

OpenStudio (*open source (GNU LGPL))

OpenText Core for BIM (OpenText (Energy & Engineering Solutions))

O-Prognose (Spacewell (Nemetschek Group))

Parabuild (CAD Systems nv)

Pathfinder (Thunderhead Engineering Consultants, Inc.)

PAVE (PMG Projektraummanagement Gmbh)

performa Asset Management System (Quartz SYS)

performa Building Monitoring System (Quartz SYS)

performa Integrity checker (Quartz SYS)

performa Manager (Quartz SYS)

performa Urbanscape (Quartz SYS)

Pillr (NTI CAD & Company)

Pilot-ICE (ASCON)

PipeDesigner 3D (Trimble MEP (Trimble, Inc.))

PiXYZ (Unity Technologies)

PLANBAR (Precast Software Engineering (Nemetschek Group))

Plancal nova (Trimble MEP (Trimble, Inc.))

Plannerly (Plannerly)

PlanRadar (PlanRadar)

Plateia (CGS Labs)

PLAXIS 3D (Bentley Systems, Inc.)

Pleiades (IZUBA énergies)

Pointscene Web (Pointscene Ltd.)

PolyTrans|CAD+DCC Translation System (Okino Computer Graphics, Inc.)

PriMus-IFC (ACCA Software S.p.A.)

ProjectSight (Trimble, Inc.)

Propeller Platform (Propeller Aerobotics Pty Ltd)

ProSheets (a plugin for Autodesk Revit) (DiRoots)

ProStructures (Bentley Systems, Inc.)

PTV Viswalk (PTV Group)

PyroSim (Thunderhead Engineering Consultants, Inc.)

Quadri (Trimble, Inc.)

Raumtool 3D IFC-Import (SOLAR-COMPUTER GmbH)

REFLECT (Tipee)

RENDERLights (RENDERLights Oy)

Renga BIM (ASCON)

Revit (Autodesk, Inc.)

Revizto (Vizerra SA)

Revu (Bluebeam (Nemetschek Group))

RFEM (Dlubal Software GmbH)

RIB iTWO (RIB Software AG)

RoadPAC (PRAGOPROJEKT, a.s.)

RSTAB (Dlubal Software GmbH)

RxHighlight (Rasterex Software AS)

SAFI GSE (SAFI Quality Software Inc.)

SAP2000 (Computers and Structures, Inc. (CSi))

ScaleCAD (Jidea Ltd.)

Scia Engineer (SCIA (Nemetschek Group))

SDS/2 (SDS/2 (Nemetschek Group))

SEAL (SEAL / Dr Heinekamp)

SEMA (SEMA GmbH)

SierraSoft Hydro (SierraSoft)

SierraSoft Infra Design Studio (SierraSoft)

SierraSoft Land (SierraSoft)

SierraSoft Land Design Studio (SierraSoft)

SierraSoft Rails (SierraSoft)

SierraSoft Rails Design Studio (SierraSoft)

SierraSoft Roads (SierraSoft)

SierraSoft Roads Design Studio (SierraSoft)

SierraSoft Survey (SierraSoft)

SIGNAX TOOLS (SIGNAX)

Simergy (Digital Alchemy)

SimLab IFC Importer for SketchUp (Simulation Lab Software L.L.C.)

simplebim (Datacubist Oy)

SiteVision (Trimble, Inc.)

SketchUp (Trimble)

SketchUp-bSDD-plugin (Digibase (VolkerWessels))

SketchUp-IFC-Manager (BIM-Tools)

Sloth (BIM 42)

SmartKalk (Holte AS)

Snaptrude (Snaptrude Inc.)

Solarius PV (ACCA Software S.p.A.)

Solibri Office (Solibri)

Solibri Office (Solibri, Inc. (Nemetschek Group))

Solid Edge (Siemens Product Life cycle Management Software Inc.)

SolidWorks Premium (DASSAULT SYSTÈMES)

SPACE GASS (ITS Pty Ltd)

Spaces (Cerulean Labs Limited)

Speckle (Speckle)

SPIRIT (STI International, Inc.)

SteelVis (National Institute of Standards and Technology (NIST))

STEP Tools (STEP Tools, Inc.)

STR Vision CPM (TeamSystem S.p,A.)

STRAKON (DICAD Systeme GmbH)

STRAP (ATIR Engineering Software Development Ltd)

StreamBIM (Rendra AS (JDM Technology Group))

StruBIM Suite (CYPE Ingenieros, S.A.)

Studio 3DX (Parametricos)

SUperPlan (SUper Plan Software)

SYNCHRO PRO (Synchro Software Ltd. (Bentley Systems, Inc.))

Tcp PointCloud Editor (APLITOP)

TcpGPS for Android (APLITOP)

TcpMDT Professional (APLITOP)

TcpScancyr (APLITOP)

TcpTUNNEL CAD (APLITOP)

Tekla BIMsight (Tekla (Trimble Inc.))

Tekla Civil (Tekla (Trimble Inc.))

Tekla PowerFab (Tekla (Trimble Inc.))

Tekla Structural Designer (Tekla (Trimble Inc.))

Tekla Structures (Tekla (Trimble Inc.))

TeKton3D (iMventa Ingenieros)

TerMus (ACCA Software S.p.A.)

TerMus PLUS (ACCA Software S.p.A.)

Tetra4D Converter (Tetra 4D)

THC.IFC.Reactor (The Hard Code GmbH)

Tilt-Werks (Dayton Superior)

TIM (Precast Software Engineering (Nemetschek Group))

Topocad (Adtollo)

TopSolid (TopSolid)

Tracer for IFC (Proving Ground)

TRICAD MS (Venturist IT)

Tricalc (Arktec, S.A.)

Tridify (Tridify Ltd.)

TriDyme (TriDyve)

Trimble Connect (Trimble, Inc.)

TwinUp (dataArrows)

Unreal Engine (Epic Games, Inc.)

usBIM (ACCA Software S.p.A.)

usBIM.bcf (ACCA Software S.p.A.)

usBIM.bSDD (ACCA Software S.p.A.)

usBIM.bSDDeditor (ACCA Software S.p.A.)

usBIM.checker (ACCA Software S.p.A.)

usBIM.clash (ACCA Software S.p.A.)

usBIM.compare (ACCA Software S.p.A.)

usBIM.editor (ACCA Software S.p.A.)

usBIM.geotwin (ACCA Software S.p.A.)

usBIM.IDS (ACCA Software S.p.A.)

usBIM.IDSeditor (ACCA Software S.p.A.)

usBIM.planAI (ACCA Software S.p.A.)

usBIM.platform (ACCA Software S.p.A.)

usBIM.refactor (ACCA Software S.p.A.)

usBIM.viewer+ (ACCA Software S.p.A.)

VCAD (Blogic s.r.l.)

VDC Manager (thinkproject (Reseller: IB&T Software GmbH))

VectorDraw (VectorDraw Software Corporation)

Vectorworks Architect (Vectorworks, Inc. (Nemetschek Group))

Vectorworks Architect/Landmark/Spotlight/Design (Vectorworks Inc.)

Verifi3D by Xinaps (Xinaps)

Vertex BD (Vertex Systems Oy)

ViCADo.arc (mb AEC Software GmbH)

ViCADo.ing (mb AEC Software GmbH)

Vico Office (Trimble General Contractor Solutions)

Visicon Smart BIM Tools (Visicon)

VisiLean (VisiLean)

Visoplan (Visoplan GmbH)

VisualARQ (Asuni CAD, S.A.)

Voxxlr (Geist Software Labs)

Vrex (Vixel AS)

warboard (Space Applied Technologies (Space Group))

WeStatiX (CAEmate S.r.l.)

WeStatiX SHM (CAEmate S.r.l.)

xbim Toolkit (*open source (CDDL))

xeokit BIM Viewer (Creoox AG)

xeokit SDK (Creoox AG)

xeoServices (Creoox AG)

xeoVision (Creoox AG)

YouBIM (YOUBIM)

Ziggurat Viewer (Ziggurat Systems Ltd.)

B.2. Open BIM IFC Certified

The following are software platforms that have been certified for IFC compliance by buildingSMART International (bSI), as listed on the official IFC certification registry[34]. These certifications indicate that the software has been tested against defined exchange requirements for Industry Foundation Classes (IFC) interoperability. However, this list is provided as a reference only; the CBTL project is not independently verifying the accuracy or validity of the certification claims. Identifying IFC Certified platforms is critical to ensure that the CBTL supports a broad range of tools capable of consistent and standardized data exchange, aligning with openBIM principles for transportation infrastructure projects.

Allplan

ArchiBIM Server

ArchiCAD

ARCHLine.XP

AutoCAD Architecture

Autodesk Revit

Autodesk Revit Architecture

Autodesk Revit LT

Autodesk Revit MEP

Autodesk Revit Structure

AVEVA E3D Design

Bausoft Haustech-CAD

Bexel Manager

BricsCAD

BridgeBIM

C.A.T.S.

CADMATIC Building

CADMATIC Electrical and HVAC

cadwork 3D

CerTus-HSBIM

CerTus-IFC

CerTus-PN

DATAflor BIM-MANAGER

DDS-CAD

DDS-CAD MEP

Edificius

Edificus MEP

EdiLus

FORNAX

FulcrumHQ

Glodon Takeoff for Architecture and Structure

Lexocad

LynxEye - version 25.1.3

MagiCad

ManTus-IFC

Mc4Suite

midas CIM

NaviTouch

NOVA AVA BIM

NX

OpenBuildingsDesigner

Plancal nova

Platform access

PriMus-IFC

RFEM/RSTAB

RIB iTWO

S&C bocad

Scia Engineer

SDS/2

Solarius-PV

Solibri

Solibri Model Checker

STR Vision CPM

STRAKON

Tekla Structures

TerMus

TopSolid

TRICAD MS

usBIM.clash

usBIM.code

usBIM.editor

usBIM.gantt

usBIM.platform

usBIM.viewer+

Vectorworks

ViCADo

[34] https://technical.buildingsmart.org/services/certification/ifc-certification-participants/

B.3. Open Source

The following list of open-source software was provided by Open-Source Architecture (OSArch)[35], a community-driven initiative dedicated to promoting the use of open-source software and open data standards in the architecture, engineering, and construction (AEC) industry. Open-source solutions align closely with the CBTL's goals of fostering transparency, collaboration, and interoperability. By leveraging open-source tools for BIM data creation, analysis, simulation, and collaboration, the CBTL can reduce reliance on proprietary systems, support customizable workflows, and ensure that data remains accessible and adaptable to evolving industry standards. The following list highlights relevant BIM-related open-source software categorized by functionality:

1. Geometry Scanning and Processing:

- Blender Photogrammetry Importer
- CloudCompare
- COLMAP
- GeoEasy
- MeshLab
- MeshRoom
- OpenDroneMap
- Point Cloud Visualizer
- Potree
- Regard3D
- gradslam
- Torch Points3D
- Total Open Station

2. CAD/BIM Design and Development:

- Archipack
- BHoM
- Blender2Godot
- BlenderBIM Add-on
- BlenderGIS add-on
- CAD Sketcher
- CAD Transform
- GroupPro
- Home Builder
- Import3dm
- MeasureIt-ARCH
- Point Cloud Visualizer
- Sorcar
- Sverchok
- Tissue
- Ubisoft Mixer

3. Analysis and Simulation:

- Energy2D
- EnergyPlus
- Ladybug Tools
- OpenFOAM
- VI-Suite

4. Project Management and Collaboration:

- OpenProject
- Speckle
- BlenderBIM Add-on/BlenderBIM Add-on FAQ

[3535] https://wiki.osarch.org/

B.4. Common Data Environments (CDE)

Common Data Environments (CDE) are centralized digital platforms designed to manage, share, and collaborate on project data across all stakeholders in a structured and secure environment. In the context of the Central BIM Transportation Library (CBTL), CDEs play a critical role in ensuring consistent access to up-to-date BIM artifacts, documents, and project information. By integrating with CDE platforms, the CBTL can facilitate seamless data exchange, version control, and collaborative workflows among state DOTs, software vendors, and industry partners, supporting the broader objectives of openBIM and digital project delivery.

- **Aconex**: An online platform by Oracle for project-wide collaboration, which includes document management, workflow automation, and project communication features.
- **Autodesk BIM 360**: A cloud-based platform that provides tools for project management, document management, and collaboration, ensuring that all stakeholders have access to up-to-date project information.
- **Asite**: A cloud-based platform that enables project teams to manage and share project data, documents, and workflows efficiently **Trimble Connect**: A collaboration platform that allows project teams to share, review, and coordinate building information models and other project data in real-time.
- **Bentley ProjectWise**: A CDE designed to support engineering project collaboration, providing secure data management, project workflows, and team collaboration tools.
- **Bluebeam Studio Projects**: Part of Bluebeam Revu, it allows teams to manage documents, drawings, and markups in a centralized cloud environment.
- **Catenda Hub**: A BIM-based Common Data Environment (CDE) built on open standards like IFC and BFC, it supports collaboration through API and integrations connect in real-time to existing tools. Intuitive design and unlimited users ensure adoption across the project life cycle.
- **Dalux Box**: A CDE platform for document management and BIM collaboration, providing mobile-friendly access to project data with strong focus on field applications.
- **iTWOcx (formerly Aconex Field by RIB Software)**: A project collaboration platform that integrates document control, workflows, and project communication with field management capabilities.
- **Newforma Project Center**: A software solution that integrates project information management, providing a centralized repository for project data, emails, and documents.
- **Procore**: A comprehensive construction management platform that includes tools for project management, document control, and collaboration, ensuring that project teams have access to the latest information.
- **Revizto**: A cloud-based Integrated Collaboration Platform (ICP) that acts as a CDE for BIM and project data, streamlining communication between project teams.
- **Thinkproject CDE**: A robust CDE platform that facilitates information and process management across large construction projects, ensuring compliance and data security.

- **Viewpoint for Projects**: A collaborative project management solution that offers document control, project communication, and information sharing capabilities.

B.5. Development and Operations (DevOps)

Development and Operations (DevOps) refers to a set of practices, cultural philosophies, and tools that integrate and automate the work of software development, frontend engineering, and IT operations teams to support the continuous development, deployment, and maintenance of the CBTL platform. Within the CBTL context, DevOps ensures that updates to user interfaces (UI), data models, and APIs are delivered efficiently and reliably through streamlined workflows. By adopting Continuous Integration and Continuous Delivery (CI/CD) pipelines, the CBTL can rapidly evolve its frontend and backend systems to meet emerging standards, enhance interoperability with external repositories, and maintain the high quality, performance, and security of its services for state DOTs and other transportation stakeholders.

Frontend Frameworks & Libraries

Modern JavaScript libraries and frameworks that power dynamic, responsive, and scalable web user interfaces for CBTL and related platforms.

1. **React:** A popular JavaScript library for building user interfaces, developed by Facebook. Often used in single-page applications (SPA).
2. **Vue.js:** A progressive JavaScript framework known for its simplicity and flexibility in building UIs and SPAs.
3. **Angular:** A full-fledged frontend framework maintained by Google, suitable for large-scale enterprise applications.
4. **Svelte:** A modern framework that compiles components at build time, offering excellent runtime performance.

Frontend Build & Package Managers

Tools that handle frontend code compilation, dependency management, and asset optimization, streamlining development and deployment workflows.

1. **Vite:** A fast build tool and development server that leverages native ES modules for lightning-fast HMR (Hot Module Replacement).
2. **Next.js**: A React framework for hybrid static & server-rendered apps, enabling automatic routing, code splitting, and SSR/ISR capabilities.
3. **Webpack:** A powerful module bundler used for compiling JavaScript modules along with assets like HTML, CSS, and images.
4. **TypeScript**: A superset of JavaScript that adds static typing, improving developer productivity and code quality.
5. **Parcel:** A zero-config bundler that automatically configures builds and optimizes assets.
6. **npm / Yarn / pnpm:** Package managers for managing JavaScript libraries and dependencies.

Frontend CI/CD Tools

Platforms tailored for building, testing, and deploying frontend applications rapidly and reliably, often integrating serverless functions and global content delivery networks (CDN) for rapid, scalable deployments.

1. **Netlify:** A platform for automating builds, deployments, and hosting for static websites and frontend apps, with serverless function support.
2. **Vercel:** Optimized for frontend frameworks like Next.js, Vercel automates deployment and serverless backend functions for full-stack applications.
3. **Cloudflare Pages:** A JAMstack platform for frontend deployments with edge computing integration.

Frontend Testing & Quality Assurance

Testing frameworks and automation tools that ensure the reliability, accessibility, and performance of frontend interfaces across devices and browsers.

1. **Jest**: A JavaScript testing framework for unit and integration testing, often paired with React.
2. **Cypress:** End-to-end testing framework for frontend applications with a focus on speed and real-time feedback.
3. **Playwright:** Modern cross-browser automation tool for end-to-end testing from Microsoft.
4. **Lighthouse:** Google's open-source tool for auditing performance, accessibility, SEO, and best practices in web apps.
5. **Percy:** A visual testing and review platform that automates UI regression testing.

Frontend Monitoring & Performance Analytics

Real-time tools that track frontend behavior, errors, and performance metrics to ensure smooth user experiences and identify issues early.

1. **Sentry:** An open-source error tracking tool for monitoring and fixing crashes in real-time in frontend and backend applications.
2. **Datadog RUM (Real User Monitoring):** Captures user interactions to provide insights into frontend performance and user experience.
3. **New Relic Browser:** Part of New Relic's APM suite, it monitors frontend performance, JavaScript errors, and page load metrics.
4. **Google Analytics / GA4:** Tracks user interactions, engagement metrics, and behavioral data on web applications.

Collaborative Design & Prototyping (UX/UI Alignment)

Design collaboration platforms that bridge the gap between designers and developers by enabling shared prototyping, asset handoff, and alignment on UI/UX goals.

1. **Figma:** A browser-based design and prototyping tool that facilitates real-time collaboration between designers and developers.
2. **Adobe XD:** A UI/UX design tool for wireframing, prototyping, and collaborative design workflows.
3. **Zeplin:** A handoff tool that bridges design and development by providing style guides, specs, and assets.

Continuous Integration and Continuous Delivery (CI/CD)

DevOps automation tools that enable continuous testing, integration, and delivery of new code to accelerate development cycles and reduce deployment risks.

1. **Jenkins:** An open-source automation server that supports CI/CD pipelines, enabling extensive workflow customization through plugins.
2. **GitLab CI/CD:** An integrated DevOps platform providing source control, CI/CD, security, and monitoring in a single application.
3. **GitHub Actions:** A CI/CD tool built into GitHub, enabling automated workflows for building, testing, and deploying code directly from repositories.
4. **CircleCI:** A cloud-native CI/CD platform known for its speed and flexibility in automating software builds and deployments.
5. **Travis CI:** A lightweight CI/CD solution that integrates tightly with GitHub repositories for continuous integration workflows.
6. **Azure Pipelines (Azure DevOps):** Microsoft's CI/CD platform supporting multi-cloud, multi-language deployments with integration to Azure services.
7. **Bamboo:** Atlassian's CI/CD server that integrates with Jira and Bitbucket to automate builds, tests, and releases.

Container Management and Orchestration

Platforms that manage application containers and coordinate their deployment, scaling, and networking, providing consistent environments across infrastructure.

1. **Docker:** A platform for developing, shipping, and running applications in lightweight, portable containers, ensuring consistency across environments.
2. **Kubernetes:** An open-source system for automating deployment, scaling, and management of containerized applications.
3. **Podman**: A daemonless container engine that provides Docker-compatible commands and improves security by running in rootless mode.
4. **OpenShift:** Red Hat's enterprise Kubernetes platform that adds developer-friendly and operational tools for Kubernetes clusters.

Configuration Management and Infrastructure as Code (IaC)

Tools that automate provisioning, configuration, and management of infrastructure using declarative code, ensuring repeatability and version control.

1. **Ansible**: An agentless automation tool for configuration management, application deployment, and task automation.
2. **Terraform:** An open-source tool for defining and provisioning infrastructure across multiple cloud providers using declarative configuration files.
3. **AWS CloudFormation:** A service for modeling and setting up AWS resources using templates to automate infrastructure as code.
4. **Chef:** A configuration management tool for automating infrastructure setup through code-driven definitions.
5. **Puppet:** An infrastructure automation tool that ensures system configurations are consistently applied across environments.

Monitoring and Logging

Systems that collect, store, and visualize logs and metrics from infrastructure and applications to support observability, troubleshooting, and optimization.

1. **Prometheus:** An open-source monitoring system with a multidimensional data model, ideal for cloud-native and microservices architectures.
2. **Grafana**: A visualization and analytics platform that integrates with Prometheus and other data sources to create interactive dashboards.
3. **Nagios**: A veteran monitoring system providing infrastructure monitoring, alerting, and integration with IT operations.
4. **ELK Stack** (Elasticsearch, Logstash, Kibana): A popular stack for centralized logging, searching, and visualizing structured and unstructured data.
5. **Datadog:** A cloud-native observability platform providing infrastructure monitoring, application performance monitoring (APM), and log management.
6. **New Relic:** An APM and observability tool that helps monitor applications, infrastructure, and digital customer experiences.

Deployment Automation

Solutions that simplify and automate application releases, reducing manual intervention and ensuring consistent delivery across environments.

1. **Octopus Deploy:** A deployment automation server that simplifies complex deployment processes across multiple environments and platforms.
2. **Spinnaker:** An open-source continuous delivery platform designed for multi-cloud deployments and release management.

Source Control Management

Platforms for managing source code, version control, and team collaboration, often integrated into CI/CD pipelines and workflow automation.

1. **GitHub:** A widely used platform for distributed version control and collaboration, enhanced by integrated CI/CD through GitHub Actions.
2. **GitLab:** A complete DevOps platform with built-in SCM, CI/CD pipelines, security scanning, and monitoring.
3. **Bitbucket:** Atlassian's Git-based source control platform that integrates with Jira and Bamboo for DevOps workflows.
4. **Azure Repos:** Git repositories hosted on Azure DevOps, providing source control integration across the Azure ecosystem.

Testing Automation

Automated testing tools that validate application behavior through unit, integration, and end-to-end tests to maintain quality and reliability.

1. **Selenium:** An open-source framework for automating web browser interactions across multiple browsers and languages.
2. **Cypress:** A modern end-to-end testing framework focused on fast, reliable testing for web applications.
3. **Postman:** A collaboration platform for API development and testing, enabling automated API testing and monitoring.
4. **JUnit:** A popular unit testing framework for Java applications.
5. **TestNG:** A testing framework inspired by JUnit, offering more powerful test configurations for Java.

Collaborative Platforms and Project Management

Collaboration and planning tools that facilitate team communication, agile development, and coordination across complex DevOps projects.

1. **Jira:** A leading agile project management tool used to plan, track, and manage software development projects.
2. **Confluence:** Atlassian's collaboration tool for documentation, knowledge sharing, and project collaboration.
3. **Open DevOps by Atlassian:** A flexible open toolchain strategy that connects Jira with CI/CD, monitoring, and SCM tools.
4. **Slack:** A real-time messaging platform widely used for team collaboration in DevOps workflows.
5. **Microsoft Teams:** A collaboration platform combining chat, video meetings, file storage, and application integration for DevOps teams.

Database Management and Backend-as-a-Service (BaaS)

Tools and platforms that manage databases, migrations, and real-time backend services, enabling developers to integrate data workflows into CI/CD pipelines.

1. **Supabase:** An open-source alternative to Firebase providing a hosted PostgreSQL database, real-time APIs, authentication, and storage. Supabase simplifies backend provisioning and integrates smoothly into CI/CD pipelines for database deployments and migrations.
2. **Atlas (by Ariga):** An open-source tool for managing database schema migrations declaratively. Atlas brings Infrastructure as Code (IaC) and GitOps principles to database management, enabling automated, version-controlled schema changes in CI/CD workflows.
3. **Liquibase:** A database schema change management tool that tracks, versions, and deploys changes across environments, integrating well with DevOps pipelines.
4. **Flyway:** A simple, lightweight database migration tool that uses SQL-based versioned scripts, suitable for automating database deployments.
5. **Hasura:** A real-time GraphQL engine that instantly provides GraphQL APIs over PostgreSQL databases, streamlining backend development workflows.
6. **Firebase:** Google's Backend-as-a-Service (BaaS) offering NoSQL databases, authentication, and serverless functions.
7. **PlanetScale:** A serverless MySQL-compatible DBaaS built for scalability, enabling GitOps-based schema management for large-scale applications.
8. **MongoDB Atlas**: A fully managed cloud version of MongoDB offering automated scaling, global clusters, and robust DevOps integrations.

Security (DevSecOps) Tools

Security-first tools embedded into DevOps workflows to detect, remediate, and prevent vulnerabilities in source code, containers, and APIs.

1. **SonarQube:** A static code analysis tool that identifies bugs, vulnerabilities, and code quality issues during development.
2. **Snyk**: A developer-friendly platform for scanning open-source dependencies and container images for security vulnerabilities.
3. **Checkmarx:** A Static Application Security Testing (SAST) solution that integrates into DevOps workflows to detect code vulnerabilities.
4. **OWASP ZAP:** An open-source web application security scanner for dynamic application security testing (DAST).
5. **Aqua Security / Prisma Cloud:** Solutions for securing containers, serverless applications, and cloud-native infrastructures.

Release Management & Feature Flags

Platforms that enable granular control over software features and rollouts, allowing teams to test, stage, and deploy functionality progressively.

1. **LaunchDarkly:** A feature management platform enabling feature flagging, progressive delivery, and controlled rollouts.
2. **Flagsmith:** An open-source feature flag and remote configuration service.
3. **Harness:** A Continuous Delivery platform that includes feature flag management and A/B testing capabilities.

Service Mesh & API Gateways

Technologies that manage service-to-service communication, security, and routing in distributed systems and microservices architectures**.**

1. **Istio:** An open-source service mesh that provides traffic management, security, and observability for microservices architectures
2. **Linkerd:** A lightweight service mesh focused on simplicity and performance.
3. **Kong:** An open-source API gateway for managing, securing, and extending APIs.
4. **Ambassador API Gateway:** A Kubernetes-native API gateway built for microservices environments.

Documentation as Code & Knowledge Management

Tools that treat documentation like code, allowing versioned, automated publishing of project and API documentation aligned with DevOps practices.

1. **MkDocs:** A static site generator for project documentation using Markdown files.
2. **Docusaurus:** A documentation site generator optimized for React projects and developer portals.
3. **ReadTheDocs:** A platform that builds, version-controls, and hosts documentation automatically from repositories.
4. **Swagger / OpenAPI:** Tools for designing, documenting, and testing APIs through a standardized API specification.
5. **Stoplight:** A collaborative API design platform offering visual editing, documentation, and testing.

Observability Pipelines & Chaos Engineering

Advanced tools that measure, visualize, and stress-test system behavior under real-world or simulated failure conditions to build resilient infrastructure.

1. **OpenTelemetry:** An open-source observability framework for collecting metrics, logs, and traces across distributed systems.
2. **Gremlin:** A Chaos Engineering platform that enables safe failure injection to test system resilience and identify weaknesses.

3. **Chaos Mesh:** A cloud-native Chaos Engineering platform that allows fault injection directly in Kubernetes environments to validate system robustness.

Edge Computing Platforms

Frameworks that allow functions or applications to run at geographically distributed locations near end users for low-latency performance and rapid scaling.

1. **Cloudflare Workers**: A serverless platform that allows you to deploy lightweight functions at Cloudflare's edge locations for ultra-low latency.
2. **Fastly Compute@Edge:** A high-performance edge compute platform enabling custom code execution closer to users for improved speed and reliability.

B.6. Pertinent Repositories

The development of the Centralized BIM Transportation Library (CBTL) relies on a robust ecosystem of digital repositories, data inventories, and engineering tools that provide structured access to transportation infrastructure information. These repositories ensure consistency, interoperability, and accessibility of BIM artifacts, datasets, and supporting documentation across bridges, pavements, materials, and asset management workflows. The following categorized repositories represent critical resources that align with CBTL's goals for standardized data exchange, life cycle documentation, and process modeling.

Digital Libraries and Repositories

Digital libraries provide foundational access to research publications, technical reports, and open science resources essential for CBTL reference models and standards alignment.

1. **National Transportation Library (NTL):** A comprehensive repository of transportation research reports, policy documents, and data resources maintained by the Bureau of Transportation Statistics.
2. **ROSA P (Repository & Open Science Access Portal):** FHWA's open-access digital repository hosting technical reports, datasets, and publications from federally funded transportation research.
3. **FHWA Research Library:** A curated digital collection of FHWA-sponsored research outputs, technical memos, and historical publications supporting infrastructure innovation.
4. **State DOT Repositories:** Individual state-level digital libraries containing design guides, specifications, and project research specific to local DOT initiatives.
5. **National Institute of Building Sciences (NIBS) Whole Building Design Guide (WBDG):** An authoritative online library of best practices, standards, and reference models for building and infrastructure design.
6. **Institutional Repositories conformant with USDOT Public Access Plan:** Platforms like Dryad, Zenodo, Harvard Dataverse, and Figshare providing DOI-enabled data sharing for transportation research outputs.

Data Inventories and Geographic Databases

Data inventories ensure the standardized classification and geospatial referencing of transportation infrastructure assets relevant to CBTL's data templates and object libraries.

1. **Bureau of Transportation Statistics (BTS) Data Inventory:** A centralized index of transportation-related datasets across modal domains, facilitating data discovery and access.
2. **National Bridge Inventory (NBI):** A nationwide database of public road bridges, capturing inventory, condition ratings, and structural attributes.
3. **National Bridge Elements (NBE):** Detailed component-level condition assessments for bridges, enhancing granularity in asset performance tracking.
4. **National Transportation Atlas Database (NTAD):** A comprehensive spatial database of transportation facilities, networks, and geographic layers.
5. **OGC InfraGML:** An open standard for encoding infrastructure alignment and linear referencing data in geospatial formats.
6. **OGC CityGML:** A standard for representing and exchanging 3D city and infrastructure models, supporting BIM-GIS integration.
7. **FHWA InfoHighway:** A portal that integrates data across FHWA's Info platforms, providing network-level visualizations and dashboard analytics.
8. **FHWA LTBP InfoBridge:** A centralized repository for bridge performance data, integrating NBI, NBE, climate variables, and LTBP research outputs.
9. **FHWA LTPP InfoPave:** The primary access point for long-term pavement performance data, including structural sections, material tests, and performance trends.

Materials Research and Performance Repositories

Materials repositories provide essential test results and performance data that can be incorporated into the CBTL.

1. **FHWA InfoMaterials:** A centralized repository of infrastructure materials testing data, including asphalt, concrete, and geotechnical evaluations.
2. **AASHTO National Transportation Product Evaluation Program (NTPEP):** A repository of standardized evaluation reports for transportation materials and products.

Safety and EMS Data Systems

Safety data systems offer critical datasets for modeling and simulating infrastructure resilience and safety workflows within CBTL.

1. **National Emergency Medical Services Information System (NEMSIS):** A nationwide database of EMS response data, enabling correlation of infrastructure incidents with safety outcomes.
2. **Roadway Safety Data Program:** FHWA's repository of roadway safety performance data, supporting proactive safety planning and risk assessment.

Transportation Management and Engineering Tools

Management systems and engineering inventories provide asset classification schemas and performance monitoring tools.

1. **All Roads Network of Linearly Referenced Roads (ARNOLD):** A comprehensive geospatial database of all public roads, supporting linear referencing methodologies.
2. **Highway Performance Monitoring System (HPMS):** A national-level inventory of roadway extent, condition, usage, and performance metrics.
3. **Model Inventory of Roadway Elements (MIRE):** A standardized framework for collecting roadway inventory and traffic control device data.
4. **AASHTO Transportation Management Hub:** A collaborative platform for managing transportation asset information and performance metrics.
5. **AASHTOWare Suite:** A suite of software tools supporting project delivery, asset management, and transportation system performance evaluation.
6. **FHWA InfoTechnology:** A portal providing best practices and selection guidance for nondestructive evaluation (NDE) methods and technologies.
7. **FHWA InfoPTF™:** A repository of full-scale accelerated pavement testing data, documenting experimental configurations and performance outcomes.

BIM Metadata and Data Repositories

BIM-specific repositories provide standardized classification systems, use cases, and data models.

1. **buildingSMART Data Dictionary (bSDD):** An international classification system supporting semantic consistency across BIM applications.
2. **bSI Use Case Management (UCM):** A structured repository of BIM use cases, facilitating process modeling and information delivery mapping.

Appendix C. Example API Calls

The following section provides example API calls from the example in section 5.6. Example – BIM Inspection Update. A general authentication call when a user logs in might look like (Step 1):

```
POST /api/v1/auth/login HTTP/1.1

Host: cbtl.gov
Content-Type: application/json

{
  "username": "john.doe",
  "password": "My$ecretP@ssw0rd1"
}
```

Successful response:

```
HTTP/1.1 200 OK
Content-Type: application/json
{
  "access_token":
"eyHJbGciOiJIUzI1NiIsInR5cCI6IkpXVCJ9.eyJzdWIiOiJKb2huRG9lIiwicm9sZXMiOiJBZG1
pbiIsImlhdCI6MTYzNzY5NTY0MiwiZXhwIjoxNjM3Njk3NDQyfQ.6uivKchh-
jmdHriOJmKJS4unNQEtTx7Zl4Cl2jTXc64",
  "token_type": "Bearer",
  "expires_in": 3600,
  "refresh_token": "d1c9a735-3e6a-4f9b-8aa7-abc123f..."
}
```

Failed Response:

```
HTTP/1.1 401 Unauthorized
Content-Type: application/json
{
  "error": "invalid_credentials",
  "error_description": "Username or password is incorrect."
}
```

Below is an example of a typical request that the CBTL might make internally to the Asset Management System (AMS) to retrieve a list of projects (Step 2). In a typical setup, the inspector or user never calls the AMS directly. Instead, the user calls the CBTL, and the CBTL (after validation) makes a separate, internal call to the AMS:

```
GET /projects HTTP/1.1
Host: ams.myagency.gov
Authorization: Bearer <access_token>
Accept: application/json
```

Successful response:

```
HTTP/1.1 200 OK
Content-Type: application/json
[
  {
    "project_id": "12345",
```

```
    "name": "I-95 Bridge Rehabilitation",
    "status": "In Progress",
    "last_updated": "2025-08-01T12:00:00Z"
  },
  {
    "project_id": "67890",
    "name": "Main St. Overpass",
    "status": "Planning",
    "last_updated": "2025-08-02T10:15:00Z"
  }
]
```

Error Example (500 Internal Server Error):

```
HTTP/1.1 500 Internal Server Error
Content-Type: application/json

{
  "error": "internal_error",
  "message": "Could not retrieve project data."

}
```

Finally, a typical API interaction for updating a bridge record (step 6) might look like the following:

```
PUT /api/v1/bridges/6789
Host: ams.myagency.gov
Authorization: Bearer <access_token>
Content-Type: application/json

{
   "bridge_id": "6789",
   "condition": "Poor",
   "last_inspected": "2025-01-15",
   "condition_rating": 2,
   "defects": [
      {
         "location": "Beam #2",
         "type": "Crack",
         "severity": "Moderate",
         "image_url": "https://cbtl.gov/images/beam2-crack.jpg"
      }
   ]
}
```