Civil Integrated Management (CIM) for Departments of Transportation, Volume 1: Guidebook

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 831

Civil Integrated Management (CIM) for Departments of Transportation

Volume 1: Guidebook

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research is the most effective way to solve many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments and by committees of AASHTO. Topics of the highest merit are selected by the AASHTO Standing Committee on Research (SCOR), and each year SCOR's recommendations are proposed to the AASHTO Board of Directors and the Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

NCHRP REPORT 831, VOLUME 1

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The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

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Learn more about the Transportation Research Board at **www.TRB.org**.

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The research team wishes to thank the many people who have supported this research, not the least of which are the members of the NCHRP Project 10-96 panel. The panel provided invaluable feedback for focusing the broad topic of CIM to lead to a usable guidebook for departments of transportation. We have had assistance with data collection and useful feedback from individuals too numerous to list from DOTs, private industry, and Crossrail. This project truly reflects the wisdom and experience of the community engaged in CIM implementation.

FOREWORD

By Andrew C. Lemer
Staff Officer
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NCHRP Report 831: Civil Integrated Management (CIM) for Departments of Transportation, Volume 1: Guidebook, and *Volume 2: Research Report,* present guidance for state departments of transportation (DOTs) and other agencies for adopting and applying practices and tools entailing collection, organization, and management of information in digital formats about a highway or other transportation construction project. The business of facility production and management is moving rapidly toward all-digital practices, driven by the increasing availability, accuracy, and affordability of digital formats and advances in design technology and in-field positioning that use these formats. Much of the leadership for development and adoption of CIM practices has come from construction contractors, but DOTs and other transportation agencies stand to realize significant benefits from increased adoption of CIM. CIM can serve all project stakeholders, consistently providing appropriate, accurate, and reliable information from the asset's initial planning through its in-service maintenance. The guidance and background information presented in this two-volume report will be helpful to DOT staff and others responsible for the agency's project development and delivery activities.

The term *civil integrated management* has been adopted in recent years to encompass an assortment of practices and tools entailing collection, organization, and management of information in digital formats about highway or other transportation construction projects, that is, "horizontal construction." The term derives from similar practices used in production of building structures—vertical construction—under the umbrella term building information modeling (BIM), so called because these practices entailed generation and management of digital representations of physical and functional characteristics of places. Traditional practices for project delivery and physical asset management have relied on analog display and archiving methods—notably drawings, plans, printed specifications, and traditional survey methods—and required practitioners to mentally visualize in three and four dimensions (that is, space and time) what was represented by flat graphics. In recent years, increasingly sophisticated digital technologies enable computation to supplement or replace imagination. Formerly separated activities of facility design, construction, operation, and maintenance increasingly can be integrated to support effective life-cycle management.

Construction contractors have embraced BIM and CIM practices that help them estimate and control costs, manage job sites, and increase the quality of their products. Designers and facility managers likewise derive benefits from the increased ability to avoid conflicts among facility components and ensure that specifications are correct and met in the field. CIM can serve all project stakeholders (for example, owner, operator, constructor, designer, surveyor, planner, and operations or asset manager) by consistently providing appropriate, accurate, and reliable information throughout an asset's life cycle.

CIM practices have been successfully used in a number of notable projects, but they are not yet widely adopted in transportation projects of all scales. Neither the benefits nor the costs and management risks associated with adoption of CIM are as yet well understood. The objective of NCHRP Project 10-96, "Guide for Civil Integrated Management (CIM) in Departments of Transportation" was to develop a guide to CIM that would assist DOT managers to (a) assess their agency's use of digital information in project delivery and subsequent asset management; (b) improve project quality and more effectively control costs through increased reliance on digital project delivery and asset management; (c) identify the particular opportunities, benefits, obstacles, and costs for their agency through increased reliance on digital project delivery and asset management; and (d) identify practical strategies for increasing reliance on digital project delivery and asset management. The research was intended to draw on practices in vertical construction, case studies, and other experience of transportation agencies at various levels of reliance on digital project delivery and asset management.

The research was conducted by a team led by the University of Texas at Austin. The research team reviewed the literature and current practices in design and construction to characterize the current state of CIM practice and document the information flows typical in transportation-project delivery. Through this work and interviews with representative practitioners, the research team formulated guidance for transportation agency staff on how to consider effective mechanisms for adoption and expanding application of CIM. Useful background information from the research team's work is presented in the Research Report (Volume 2) that accompanies the Guidebook (Volume 1).

CONTENTS

SUMMARY

Civil Integrated Management (CIM) for Departments of Transportation Volume 1: Guidebook

State departments of transportation (DOTs) deliver projects in a complex environment that involves the participation of many stakeholders with different objectives. The collection and utilization of digital information for project delivery has increased with advancements in computational capabilities, design technology, and field positioning systems. Civil integrated management (CIM) is a term that encompasses all such tools and practices that facilitate the process of digital project delivery and asset management. CIM, as a life-cycle process, caters to the data requirements of various project stakeholders such as owners, designers, constructors, and operators, among others.

The holistic nature of CIM's objectives has attributed to its popularity over recent years, capturing the attention of both practitioners and researchers alike. The level of analysis required for successful implementation of the numerous CIM technologies warrants focused and coherent implementation efforts. Over the past several years, agencies have devised guidelines using one or more of the CIM technologies to support project delivery. Recently, a growing need emerged to assess the current state of practice of CIM in its entirety and document the systemic implementation efforts along with resulting benefits and challenges experienced by various agencies and other relevant stakeholders. The NCHRP Project 10-96 research team developed the CIM Guidebook to address these benefits and challenges. The Guidebook includes five chapters and two appendices. Appendix A includes a catalog of references to other useful resources categorized by specific CIM practices. Appendix B contains the Executive Briefing for the Guidebook in PowerPoint format. This appendix is not published herein, but a link to the Executive Briefing is available on the NCHRP Project 10-96 web page at www.trb.org. While this Guidebook is a stand-alone document, its companion, *NCHRP Report 831: Civil Integrated Management (CIM) for Departments of Transportation, Volume 2: Research Report*, details the survey and case study data supporting the findings and case study analyses underlying the research findings.

Drawn from a comprehensive survey of agencies and selected case studies of CIM projects, Chapter 2 briefly explains the key constituents of CIM, which include both CIM tools and functions. CIM *tools* include various technologies while CIM *functions* comprise the tasks that the tools impact. Chapter 3 illustrates the role of CIM technologies in contributing to the transition to digital project workflow. Chapter 4 presents a three-stage hierarchical framework for agencies to evaluate and implement CIM. The three stages include planning from current capabilities, assessment of future capabilities, and implementation considerations. Figure S.1 presents the basic relationship between the three stages of the implementation framework.

1. In the first stage, agencies evaluate the functional needs of their divisions (such as Design, Construction, and Maintenance). They can use the maturity model presented in Section 3.2 to facilitate the evaluation process. The model provides a basic framework and guidelines for all CIM-related divisions at an agency. The agencies can also further develop detailed

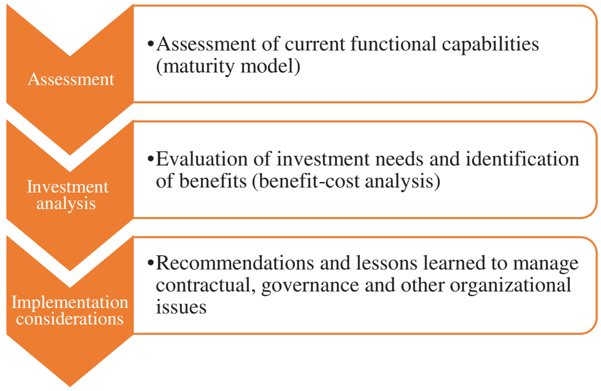


Figure S.1. CIM implementation framework.

guidelines from this model suited to their needs. After evaluating their functional needs, the agencies should consider developing a formal CIM Implementation Plan (CIP), a strategic document that integrates the divisional needs and the business constraints. The (minimum) contents of a CIP include vision, mission statements for CIM, and target short- and long-term goals for CIM implementation. This CIP should act as an information resource from which the agencies hash out future requirements.

2. Building on the CIP, the second stage involves identification of investment needs and anticipated benefits from the proposed implementation. Major costs for CIM implementation include technology-related investments such as hardware, software, and training costs. Resources also include investments for creating and adopting standards, meeting staffing needs, and dealing with temporary workflow disruptions. The benefits are two-fold and include (1) direct benefits, such as performance improvements from the CIM functions that are transformed by one or more of the CIM tools and (2) indirect benefits, such as communication and collaboration among stakeholders and others. The benefit-cost analysis may highlight more than one CIM tool. The agencies can prioritize investments in tools that have greater potential for implementation across the agency. Table S.1 summarizes the methodologies and insightful results that agencies (DOTs) obtained by conducting benefit-cost studies for some of the prominent CIM tools. At the end of this stage, the agencies should have the following documents to support implementation: standards and specifications, general information requirements, training manuals, and benefit-cost analysis results.
3. Finally, the third stage consists of implementation considerations that agencies can examine when implementing finalized tools. These considerations represent the research team's assessment based on the literature review, surveys, and case studies conducted in this research project. The third stage addresses Project Delivery Strategies, Standards and Specifications, Training and Cultural Shift, Governance and Policy Issues, and Information Management.

Chapter 4 also provides illustration and case examples to demonstrate the utility of the framework for agencies. A situation where a hypothetical agency is utilizing the proposed framework for CIM implementation connects all the illustration examples. The case examples are actual snippets of observations from literature, surveys, or case studies that support and validate the framework presented here. There is scant data on the benefits and costs of CIM implementation, but Chapter 4 details a series of case studies where agencies have made these estimates.

Finally, Chapter 5 includes implementation resources that contain key points from the case studies, literature review, and the other tasks of this research effort, while Appendix A presents a catalog of CIM resources.

Table S.1. Summary of benefit-cost studies for CIM tools.

Agency	Focal point for analysis	Brief description
MDOT	e-document management systems (ProjectWise)	MDOT performed agency-wide implementation of electronic document management systems and digital signatures. Reported monetary benefits through paper-less work process and efficiency improvements (*approx. $185,000 savings in Latson road project ($32m)*) (See: http://construction.transportation.org/Documents/Meetings/e-Construction-Farr-CT.pdf)
WisDOT	3D design (Clash detection) (Parve 2012)	WisDOT used 3-D models for clash detection processes on its SE Freeways Mitchell and Zoo Interchange projects. Reported considerable reduction in RFIs, change orders, and design issues *(7% RFI reduction in $298 million Mitchell Interchange project)* (See: http://www.efl.fhwa.dot.gov/files/technology/3d-modeling/thursday_meeting/lance-parve.pdf)
Caltrans and WSDOT	Mobile LiDAR (Yen et al. 2014)	Caltrans and WSDOT examined different strategies of deploying mobile LiDAR for agencies' asset and inventory management programs. Purchasing and operating surveying grade mobile LiDAR emerged as least cost option *($6.1 million dollars less for 6 years life cycle)* (See: http://ascelibrary.org/doi/abs/10.1061/(ASCE)IS.1943-555X.0000192)
TxDOT	3D design and ProjectWise (TxDOT 2014)	TxDOT conducted a preliminary NPV analysis for agency-wide implementation of 3D design on its projects and ProjectWise to support the 3D workflow. Reported positive return on investments *(NPV estimated to be $70-95 million dollars over 5 years.)* (See: http://ftp.dot.state.tx.us/pub/txdot/commission/2014/0918/3a-presentation.pdf)
ODOT	Information Technology Benefit-Cost Evaluation Report (Hagar 2011)	ODOT evaluated the benefits and costs of nine IT systems that included GIS infrastructure, environmental analysis tools, electronic document management systems, engineering tools, and work zone analysis tools, among others. Reported time savings (converted to labor-costs through hours saved), workflow and efficiency improvements in information management *(B/C ratio estimated to be 2.1)* (See: http://www.oregon.gov/odot/hwy/otia/docs/otiaiii_informationtechnologybenefitcostevaluation_report.pdf)

CHAPTER 1

Introduction

"Civil Integrated Management (CIM) is the technology-enabled collection, organization, managed accessibility, and the use of accurate data and information throughout the life cycle of a transportation asset" (FHWA 2012). CIM focuses on promoting successful and effective life-cycle application of modern technologies, such as information modeling, advanced surveying methods, subsurface mapping of utilities, automated machine guidance (AMG), and integration of project data with Transportation Asset Management (TAM). These tools have the potential to enable the transition to digital project delivery and enhance the role and quality of information available for project management tasks.

The research objectives were to assess the current state of CIM practices, document the observed trends across the agencies (benefits, costs, opportunities, risks), and develop a guidebook that can be used by DOTs to enhance their level of CIM utilization. *NCHRP Report 831: Civil Integrated Management (CIM) for Departments of Transportation, Volume 1: Guidebook*, is intended to assist both decision-makers and practitioners. Section 1.1 provides more detail on the organization of the chapters in this Guidebook and the intended audience.

1.1 Readers' Guide

Chapter 2 presents an overview of CIM and its associated tools and functions to inform the readers about the research scope. This concise and educational chapter is beneficial to both senior executives and project management teams in an agency because it briefly explains the key terminologies to get started with CIM.

Chapter 3 explains the anticipated changes in project delivery processes resulting from CIM implementation. Thus, this chapter would prove useful and interesting to project management representatives who are responsible for the oversight of the project work processes.

The focus of this Guidebook is the implementation framework presented in Chapter 4. It provides a general strategy to support critical decisions regarding assessment of an agency's current capabilities and determination of future investment decisions. This chapter also contains necessary information that would be of interest to an implementation team that might include working representatives from all disciplines and senior management. Various stakeholders who may find this chapter useful include agencies, contractors, suppliers, and legal authorities.

Chapter 5 consists of the optional supplemental materials that the research team gathered throughout the research effort. Although not directly supportive to CIM implementation, it contains references to important materials and research studies that are relevant for CIM both nationally and internationally.

Appendix A presents a catalog of references to CIM resources gathered from the literature review and other data collection efforts. These resources are classified by different subcategories related to CIM and can be of interest to personnel responsible for implementing CIM at an agency. Appendix B contains a PowerPoint slide deck as an executive briefing. The link to the slide deck is available on the NCHRP Project 10-96 web page at www.trb.org. The slides review the key findings from this research. They may be used, in whole or in part, as a briefing for management on the uses, benefits, and conditions for CIM implementation.

CHAPTER 2

Overview of CIM Tools and Functions

CIM, as a system, consists of both foundational processes and emerging practices in the highway construction sector. As the technology has grown, so has the taxonomy and definitions. This chapter explains CIM's scope and the associated terms.

CIM encompasses several technologies that have the potential to improve the performance and predictability of the related project work processes, including scoping, surveying, design, construction, operation, and maintenance. The primary objective is to enable a transition to digital project delivery to better align it with the modern tools and technologies that have emerged in both the office (planning and design phases) and the field environments (construction and operations and maintenance phases). To understand the benefits of CIM and develop systematic guidelines, it is helpful to classify CIM under two categories:

- *CIM tools category*, which includes the associated technologies and tools
- *CIM functions category*, which contains the functions (work areas) that one or more of the highlighted CIM tools improve or transform

As per FHWA, CIM, at its entirety, also encapsulates contractual and legal considerations (FHWA 2012). It is important to consider their significance when incorporating CIM functions on projects. Section 4.3 includes a discussion on these topics.

2.1 CIM Tools

CIM tools represent the fundamental, core technologies. They enable the possibilities of finding new and improved solutions for performing project delivery functions. Figure 2.1 enumerates the list of CIM tools and their codes under three categories (used herein for identification purposes): modeling tools, data management tools, and sensing tools.

2.1.1 Modeling Tools—Category A

Modeling tools include the technologies that provide the capabilities to create virtual/digital representations of project data (Eastman et al. 2011). Figure 2.2 describes the various subcategories.

2.1.2 Data Management Tools—Category B

Data management tools are collaborative (software) platforms to manage the information generated from various stakeholders throughout the project life cycle. Moreover, they are also essential for the process of implementing 3D design tools and supporting the model-based deliverables. Figure 2.3 briefly explains the subcategories under data management tools.

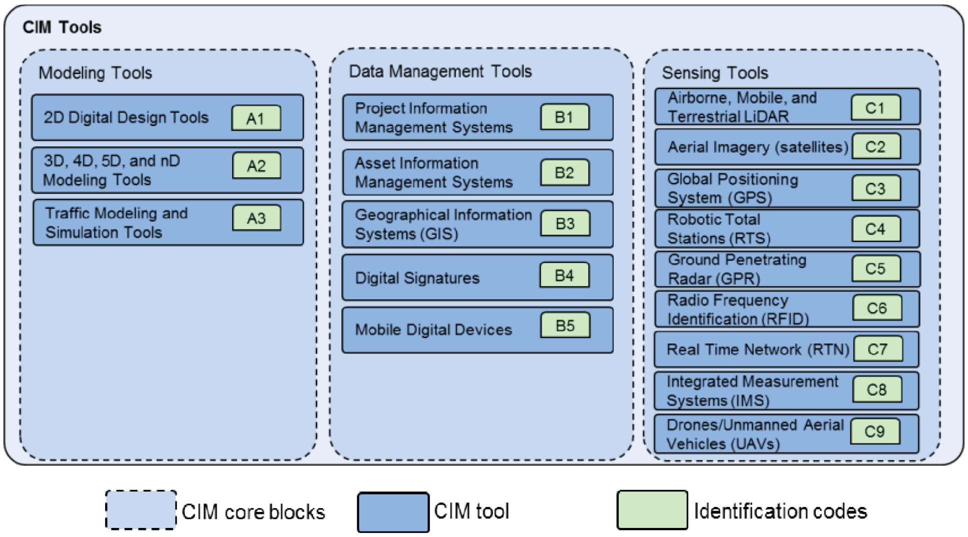
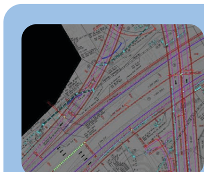
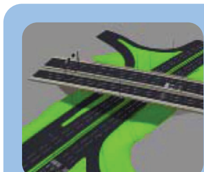


Figure 2.1. Pictorial representation of CIM tools.



2D Digital Design Tools (A1)

- Tools that agencies use for design data exchange and organization (Pardue 2008).
- Some examples include plans, specifications, and 2D CAD files.



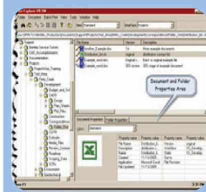
3D, 4D, 5D and nD Modeling Tools (A2)

- Tools that facilitate creation of 3D models for design and visualization of various design elements. Quite often, schedule (4D) and cost (5D) information are integrated.
- These tools provide a clear picture of the design with a 3D visualization to resolve conflicts among design entities and construction activities, and can be geo-referenced to improve quality of the information (FHWA 2013).

Traffic Modeling and Simulation Tools (A3)

- Traffic models are used to conduct studies and determine impact on traffic conditions through simulations at the microscopic (roadway) to macroscopic (city or state network) levels (Warne 2011).
- These tools are used to calculate various metrics (such as delays for the users of the road under construction). In combination with design visualization, they enhance the Public Information process (Wei and Jarboe 2010).

Figure 2.2. Modeling tools—Category A.

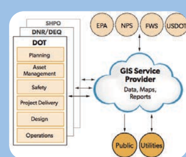


Project Information Management Systems (B1)

- Refers to the information management tools and exchange framework put in place for effective collection, storage, organization, and utilization of information required for an agency to execute its projects successfully.
- Includes document management systems—typically a class of information management systems; they use electronic applications to manage and distribute information according to established policies and procedures at agencies (Spy Pond Partners, LLC 2015; Cambridge Systematics 2013; Codling 2015; Ziering et al. 2007).

Asset Information Management Systems (B2)

- Includes tools and standards that integrate the engineering and construction data for the needs of operations and maintenance (O&M) and asset management (Gordon et al. 2011).
- Supports the information requirements for maintenance (such as inventory management, the streamlining of the archival process and updating the asset information, and integration with GIS to support various operational requirements) and also assists in new project development (Teizer et al. 2005).

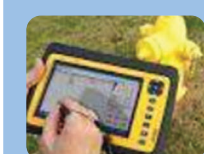


Geographical Information Systems (GIS) (B3)

- Associates databases with geospatial positioning information (coordinate systems) for organizing, managing, and analyzing data.
- Offers benefits during planning and programming stages of a project (such as environmental studies, geospatial tracking of project limits), surveying, and highway (spatial visualization and analysis of design data) and asset management (inventory and asset improvements).

Digital Signatures (B4)

- Refers to the class of electronic signatures embedded in electronic documents that are secured and authenticated using encryption/decryption technology.
- Eliminates need to print, sign, and scan documents and allows for continuous flow of digital documents and data.



Mobile Digital Devices (B5)

- Includes handheld electronic devices, such as tablets or smartphones, that have the ability to access and manage documents, databases, videos, and 3D models.
- Helps quickly gain access to the latest design or construction information and eliminates the need to carry the standards and plan sets required for inspection of projects.

Figure 2.3. Data management tools—Category B.

2.1.3 Sensing Tools—Category C

This category consists of advanced surveying tools that improve performance of many aspects, such as coverage, speed, cost, and data accuracy in comparison to traditional surveying methods (Singh 2008). Figure 2.4 describes the subcategories of surveying tools.

2.2 CIM Functions

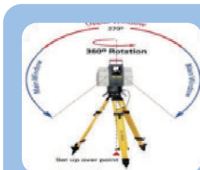
Technology implementation positively affects a project's performance through transforming the functions in the pertinent project work areas (Kang, O'Brien, and Mulva 2013; O'Connor and Yang 2004). Figure 2.5 identifies the CIM functions and clusters them under project activities. In this figure, project activities do not correspond to project phases but rather the CIM

Airborne, Mobile, and Terrestrial LiDAR (C1)
LiDAR is a technology that illuminates the target with a laser and performs distance calculations by evaluating the time taken for the light to be reflected. It is used for scanning and measurement in three different configurations—airborne, mobile, and terrestrial—and produces images and point clouds for design, quantity estimates, and 3D models. Image data can be combined with GPS data to record its location (Ellsworth 2012).

Airborne LiDAR—equipment mounted on a fixed-wing aircraft or on a rotary-wing helicopter and used in areas such as transportation planning, coastal mapping, and green field studies. Although it is least accurate, its coverage is the highest.

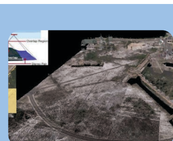
Mobile LiDAR—equipment mounted on a moving ground vehicle and used for transportation and civil infrastructure (Hannon 2007). Provides a good tradeoff between speed, coverage, and accuracy (surveying grade LiDAR can have an accuracy of order of 0.03 ft).

Used for rapid data collection to obtain point clouds of highway systems.



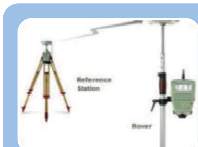
Terrestrial LiDAR—nonmoving systems mounted on tripods used for mapping, reverse engineering, structural analysis and testing, and performing as-built surveys of facilities. Agile, cost-effective, and highly accurate (of the order of 0.02 ft or lower).

Can be used cost-effectively for developing a 3D point cloud of a bridge structure.



Aerial Imagery (satellites) (C2)

- Overlaps two grayscale photos taken from an aircraft to provide 3D information of the terrain; used for mapping, cadastral work, and design and computation of terrain data through photogrammetry (Mayer 1999).
- Is used for visualizing current or future topography; complements LiDAR and acts as a control measure for the latter (Olsen 2013).



Global Positioning System (GPS) (C3)

- Includes navigation system that provides 3D spatial coordinate data all over the globe.
- Uses for highways range from mapping and surveying (using GPS rovers) to AMG (operations that generally require lesser vertical accuracy such as scrapers, dozers, excavators) (Hannon 2007).

Robotic Total Stations (RTS) (C4)

- Is an efficient variant of Total Stations that facilitates remotely controlling the surveying equipment from the intended observation point (accuracy of 0.02 ft. or lesser).
- Eliminates the need for an operator at the instrument, provides greater vertical accuracy for surveying, and contributes to the positioning and QA/QC checks for AMG (Stringless concrete paving, asphalt paving, among others).

Ground Penetrating Radar (GPR) (C5)

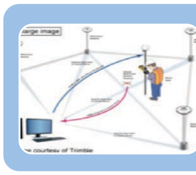
- Is technology used to create subsurface mapping; radio waves produce radargrams that are then processed to extract details in the substratum.
- Is used for locating underground utilities, groundwater, tunnels, and other objects without the use of heavy machinery to execute an excavation (Fekete et al. 2010).

Radio Frequency Identification (RFID) (C6)

- Uses tags or chips that, via radio waves, are able to send or receive information to a reader that can be either mobile or stationary.
- Is used to manage tracking of materials and fleets, identification of equipment, among other uses (Jeong et al. 2003).

Figure 2.4. Sensing tools category—Category C.

(continued on next page)



Real Time Network (RTN) (C7)

- Consists of continually operating reference stations (CORS) that cater to the real-time positioning requirements of various operations (surveying, engineering, and GIS mapping).
- Is used for machine control during construction and post-construction quality control (QC) checks.

Integrated Measurement Systems (IMS) (C8)

- Is a feedback control system used to track hot and cold mixed asphalt, using precise sensors and GPS; used for intelligent compaction (IC) (FHWA 2013).

Drones/Unmanned Aerial Vehicles (UAVs) (C9)

- Consists of small remotely controlled aircraft that collect geo-referenced aerial images with high geographical precision (accuracy: 0.1 ft and lower) and image resolution.
- Possess great potential to achieve practical accuracy required for cadastral, engineering and topographic surveys.
- Reduces time spent on surveying and keeps staff off field, which reduces risk of accidents in remote/extreme locations.

Figure 2.4. (Continued).

functions are grouped based on the task they perform. It also depicts the functions mapped to the relevant CIM tools (see Section 2.1 for CIM tool identification codes and descriptions). Each of the mapped CIM tools can transform or improve the processes associated with a function in a certain way.

This section defines the functions of these four categories: Surveying, Design, Construction, and Project Management. It also provides an overview of how the mapped CIM tools can improve these functions.

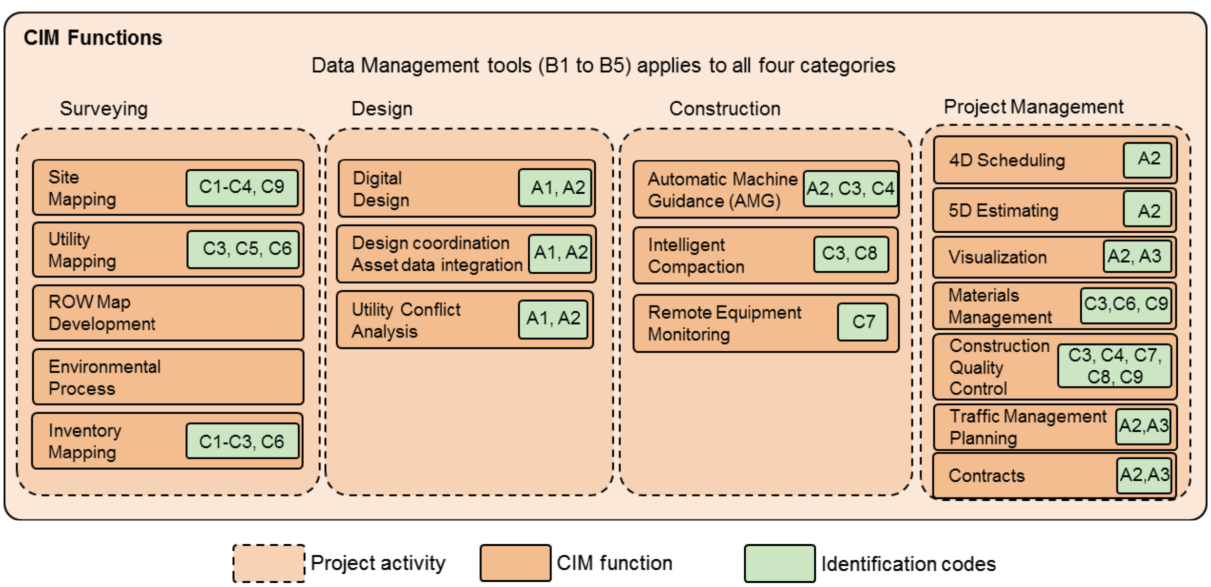


Figure 2.5. CIM functions (mapped to their corresponding CIM tools).

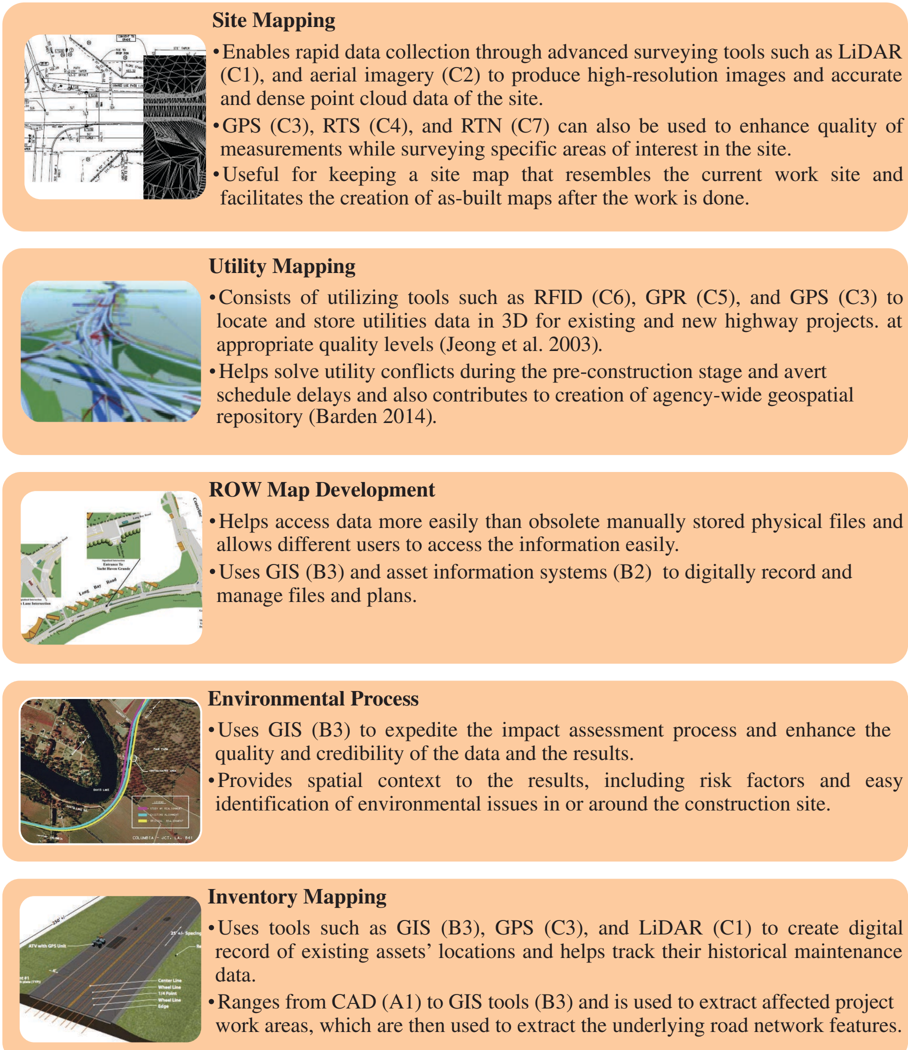


Figure 2.6. Surveying activities category.

2.2.1 Surveying

Surveying activities refer to the cluster of CIM functions that primarily relate to data collection and measurement tasks for project development and asset management purposes (Figure 2.6) (O'Brien et al. 2012; Oldenburg 2011).

2.2.2 Design

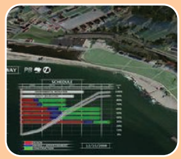
The design activities include all CIM-related functions that perform design or design-related tasks in the project delivery process (Figure 2.7).

2.2.3 Construction

This activity cluster consists of all CIM functions that directly relate to construction of the facility (or field activities) (Figure 2.8).

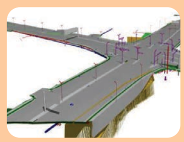
Digital Design

- Creates 3D engineering models (A1, A2) of existing and proposed surface and pavement layers to support machine-enabled construction activities.
- Produces information-rich 3D models for structures, drainage, utilities, among other design entities to support numerous project management applications (clash detection, constructability reviews).
- Enables collaborative design and modeling for hydraulics, safety assessment, and code (or standards) compliance assessment.



Design Coordination and Asset Data Integration

- Represents the broader task of coordinating design reviews among several disciplines assisted by nD modeling (A2) and appropriate information management tools (such as web-based collaboration, video-conferencing).
- Provides early identification of design and constructability issues, O&M and asset inventory needs (CAD to TAM tools help asset identification and attribution entry early during design phase by integrating with the proper TAM feature database).



Utility Conflict Analysis

- Uses 2D (A1) and nD models (A2), and clash detection software to detect conflicts among the different utilities and between utilities and project elements (such as drill shafts, embankments, and drainage).
- Helps reduce Requests for Information (RFI) and time wasted solving utility conflicts and avoids unexpected changes.

Figure 2.7. Design activities category.

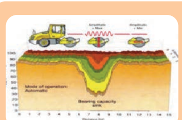
2.2.4 Project Management

This category encapsulates other critical CIM functions that assist in successfully monitoring and controlling project performance (such as costs, schedule, and quality among others) throughout surveying, design, and construction phases (Figure 2.9).

The list of CIM tools and functions presented consists of the major known elements per the literature and current state of practice. Future research efforts warrant inclusion of more tools and functions for this chapter. Thus, the agencies can consider updating this compilation to keep pace with advancements in digital practices. Chapter 3 describes the impact of CIM on project delivery based on a workflow model.

Automated Machine Guidance (AMG)

- Uses DTMs (A2) and GPS (C3) to automate construction operations in the field (dirtwork, excavation, and grading among others).
- Uses Robotic Total Stations (C4) and other suitable methods to increase vertical accuracy required for stake-less paving operations (e.g., asphalt paving, concrete slipform paving).
- Increases productivity and safety on-site and helps in QA/QC checks post-construction (FHWA 2013).



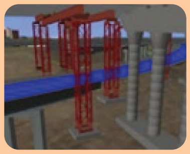
Intelligent Compaction (IC)

- Uses GPS (C3) and IMS (C8) to ensure efficient compaction of soils and pavements.
- Reduces time and money spent in the compaction operation and improves the quality of the pavement for its service life (The TransTec Group 2014).

Remote Equipment Monitoring

- Helps track fleet location and mechanical status using GPS (C3) and RTN (C7), reduces idle time and improves utilization rate (also called equipment telematics).
- Optimizes fleets, reduces fuel consumption rates, decreases labor hours, and improves utilization rate of the equipment.

Figure 2.8. Construction activities category.



4D Scheduling

- Uses nD modeling (A2) tools to support scheduling tasks (model-based scheduling where schedule activities are linked to model elements).
- Assists in constructability analysis for complicated construction (such as bridges, interchanges) and identifying temporal conflicts in staged construction (Liapi 2003).

5D Estimating

- Includes the cost data to the 4D scheduling (A2).
- Assists owners in bid price estimation (QTO) to develop and maintain model-based pre-construction and cost estimation packages.
- Helps developers visualize and validate quantities and manage and track expenses of a project at any given time (FHWA 2013).

Visualization

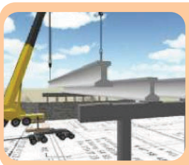
- Enhances the physical, geospatial, and/or functional details of the design model using tools such as GIS (B3) and nD modeling (A2).
- Can be integrated with interactive traffic microsimulation models (A3) to produce real-time traffic data.
- Is commonly used for communication among project team members and executives, and for Public Information purposes.

Traffic Management Planning

- Uses nD modeling tools (A2) and traffic simulation tools (A3) to aid preparation of control plans (lane closures, detours, and temporary construction among others).
- Is used to analyze the construction staging requirements (when mobility and safety of roadway conditions were to be affected by the construction process).

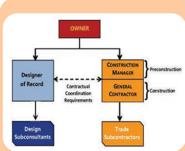
Construction Quality Control

- Uses the combination of mobile digital devices (B5), GPS rovers (C3), RTS (C4), RTN (C7) and IMS (C8) to perform QA/QC checks for pavement construction, asset inspection for TAM, and facilitate the communication between job sites and offices.
- Uses digital signatures (B4) for performing reviews and approvals.
- Can also use drones (C9) for rapid data collection and inspection.
- Overall, facilitates the making of as-built 3D models, reduces required workforce, and reduces surveying costs and effort.



Materials Management

- Helps track location of materials using either RFID (C6) or GPS (C3) technologies or a combination of both.
- Can use drones/UAVs (C9) to estimate quantities of materials used (such as earthwork and construction materials).



Contracts

- Includes information management systems (B1) that integrate documents and model-based data (A2, A3) to help the agency in contract administration and management (e.g., bid letting, RFIs, shop drawing reviews and approvals, submittals and correspondence).

Figure 2.9. Project management category.

CHAPTER 3

Impact of CIM on Project Delivery

Chapter 2 gave an overview of the CIM tools and their impact on different functions of the project delivery process. This chapter describes how these functions interact when transitioning to digital workflow. It also describes a workflow for CIM that encompasses key concepts and components of the major requirements of digital project delivery in the future. Data, rather than documents, will form the central component for projects using CIM (Jahren 2014).

3.1 Transitioning to CIM—Project Work Processes

At time of publication, no one project or agency has deployed all available CIM tools; the inclusiveness of the workflow presented here is a result of organizing inferences from multiple data sources, including the literature review, surveys, and case studies.

Driven by technological advancements and an increased participation of agencies in the digital delivery of projects, the planning and scoping processes can make use of GIS-based decision-making tools for site evaluation, alternative analyses, environmental assessments, and various other planning applications. The project development process can use most of the digitally signed and archived asset data for surveying and engineering. Advanced surveying methods such as Mobile LiDAR, UAVs, RTN, aerial imagery, digital photography and photogrammetry can augment the data on existing conditions (digital archives) by providing semantically-rich and geospatial digital information—such as point clouds, 3D mesh models, high-resolution images, and digital terrain models (DTMs).

Availability of good quality data can enable the paradigm shift where most design disciplines can perform their design digitally (in 3D). The design elements also incorporate the identification attribute related to its asset inventory database to create geospatial referencing of the asset throughout the design process. Agencies (and/or design consultants) can enhance the density of critical elements in the model (such as terrain models for surface layers and 3D breaklines), convert this digital design data into machine-readable formats, and hand over the deliverables to the contractor. The 3D models for structural entities can support various project management tasks such as constructability analysis, model-based clash detection, visualization, and public information.

In the construction phase, the contractors can use this information for AMG during earthwork operations (such as excavating and grading) and obtaining stakeout location for structural elements. Pavement operations for asphalt and concrete slipform paving generally require augmentation of vertical accuracy for machine control, and Robotic Total Stations (RTS) are commonly used for this purpose. Subsequently, field representatives can perform as-built surveys after construction using GPS-based technology such as rovers. They can also deploy drones for site inspection, progress monitoring, and estimation of quantities.

Finally, the as-built electronic data can be archived in its native form for O&M and asset management. In this workflow, agencies can continually use electronic document management systems and digital signatures to support fast and effective flow of deliverables across various phases. Agencies can then archive the digital data from as-built surveys and continue updating it until it becomes available for new project development (Singh 2008). Figure 3.1 presents a graphical representation of this workflow, along with corresponding phases and information exchange loop.

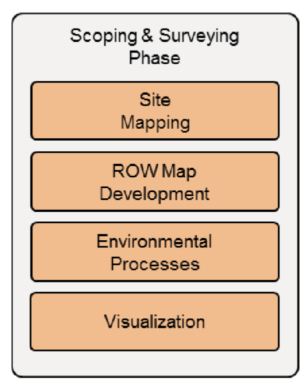
Theoretically, CIM-based project delivery incorporates the information flow for the entire life cycle of the highway facility. The quality and type of data in the information deliverables play a central role in the transition to digital project delivery and asset management. In other words, the mode of information exchange (data, document, or models) between subsequent phases (and in turn the constituting CIM functions) can be a key indicator of an agency's business efficiency—and thus, its potential for successful transition to digital project delivery. These modes of information exchange are included in the model at terminal points between phases by clustering and representing them as "DDMI," an acronym for document-, data-, and model-based information. Document-based information includes specifications, contracts, or plans; data-based information will include databases, Excel spreadsheets, Extensible Markup Language (XML) data, or electronic 2D or 3D CAD files (i.e., native files); and model-based information includes information models. Note that Figure 3.1 does not depict the information exchange between functions in a particular phase, because they can be complex and specific to an agency's particular business processes.

Section 3.1.1 presents an analysis of the digital workflow from the point of view of phases in a facility's life cycle. Each of the CIM functions used in a particular phase produce a certain transformation in the latter, ultimately leading to changes in the information deliverables (quality or type) across the life cycle. Thus, the section also enumerates notable deliverables for each of the phases based on CIM functions and contains examples or references from literature and case studies to demonstrate the impact and utility of a particular CIM function.

3.1.1 Scoping and Surveying Phase

CIM for the scoping and surveying phase can enhance the quality of data collection and workflow process for various functions contributing to project development. As can be deduced from Figure 3.1, the following transitions can occur:

- **Site mapping** processes involve the assimilation of digital data through increased usage of integrated surveying methods (with LiDAR, GPS, aerial imagery, UAVs, and CORS stations). For an example, see the Portland LiDAR consortium for highways (Madin 2015).
- Increased utilization of GIS-based tools can influence the **ROW map development** process. Many agencies now use web- and cloud-based GIS applications for this purpose. For an example, see the UDOT's UPlan (UDOT 2014).
- GIS tools can also contribute to the tasks related to **environmental processes** and permitting, such as Environmental Impact Assessments. For an example, see the FDOT's Environment Screening Tool (FDOT 2015).
- In the early stages of project development, when detailed design information is scarce, CIM tools also contribute to **visualization** and communication purposes. Some GIS-enabled software applications use layers of project entities (such as roads, bridges, and ROW entities) to produce models with reasonable details necessary for early project communication. Agencies' internal GIS databases and open source data from platforms, such as the United States Geological Survey, can complete the data requirements.



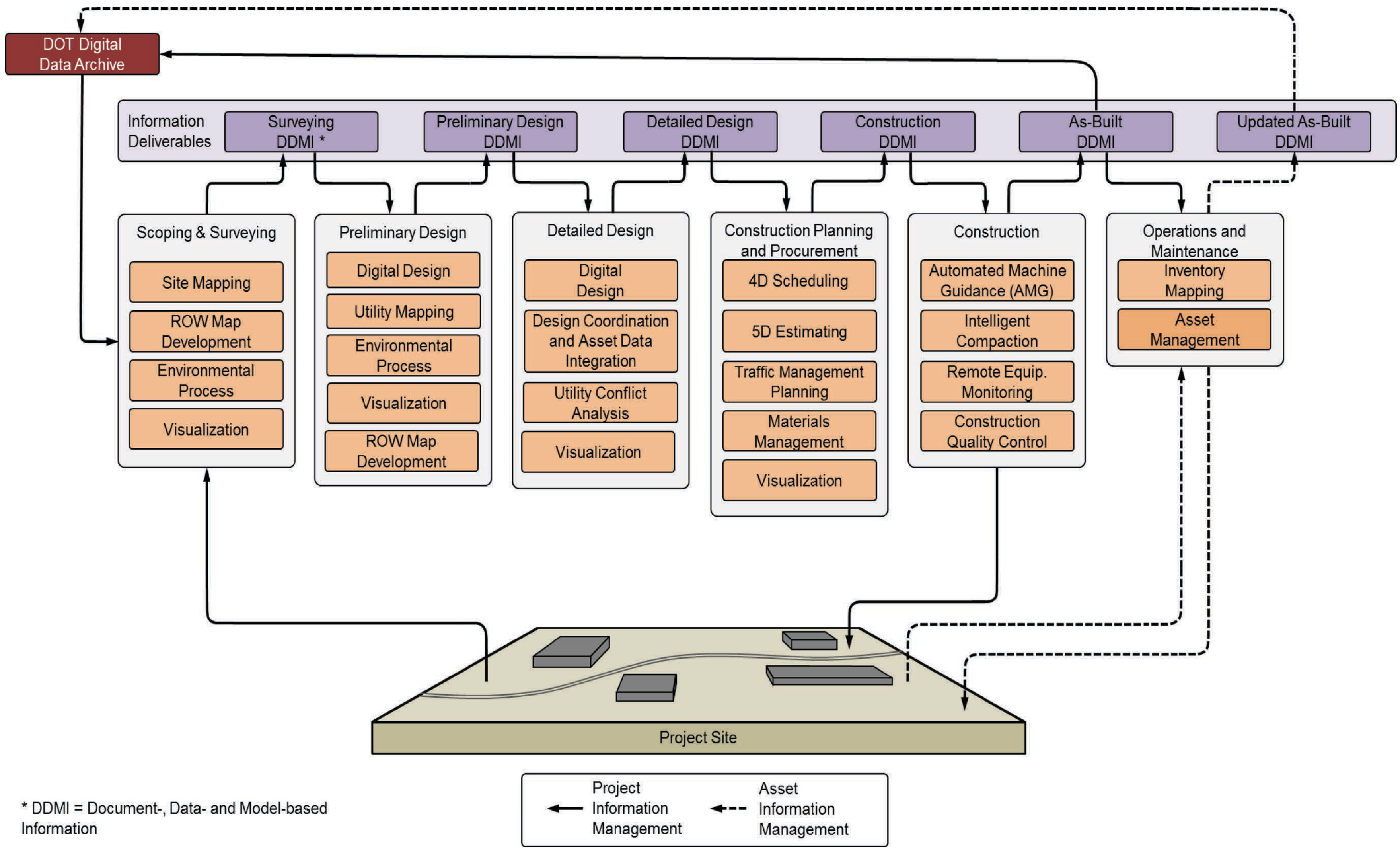
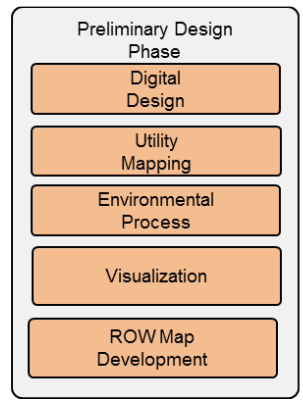


Figure 3.1. CIM workflow model—impact on project delivery.

Deliverables and Stakeholders. The various deliverables that emerge from scoping and surveying include interactive site and ROW maps, processed point cloud data of the project elements (such as DTMs of surfaces), animations and renderings of the preliminary model developed using GIS layers, and intelligent reports for environmental processes, among others. The major stakeholders that contribute to utilization of CIM will be agency personnel (e.g., surveyors and GIS analysts), consultants, and engineers for preliminary design.

3.1.2 Preliminary Design Phase

CIM functions can have a major impact on project delivery when used in a coordinated manner during the preliminary design phase, as the decisions and practices followed here will affect the entire project delivery process. Thus, agencies should plan CIM functions carefully in this phase.



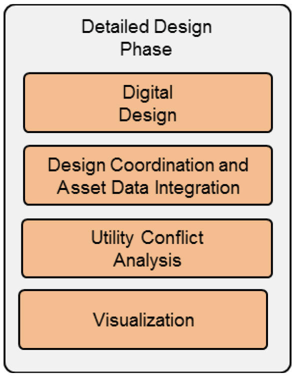
- Availability of high quality surveying information from the preceding phase can now enable the possibilities of **digital design** (3D mode) using interoperable applications and data exchange framework for various design entities, such as roadways and structures, utilities, surface, and drainage, among others. For an example, see the WisDOT case study (Oldenburg 2011).
- CIM-based design can also influence **utility mapping**. Agencies and consultants use the capabilities of subsurface utility engineering technologies and 3D design applications to model existing and proposed underground utilities in 3D. In the long term, they can also envision creation of central repositories for utilities data and integrate the 3D spatial information available from project-level implementation. For an example, see the MDOT Guide for utilities mapping (Barden 2014).
- CIM functions for **environmental process, visualization,** and **ROW map development** can continue throughout this phase.

Deliverables and Stakeholders. Information from this phase includes schematic CAD/DGN/XML design files with models for terrain, utilities, structures, and their supporting documents for detailed design (such as plans, specifications & estimates [PS&E] information and preliminary schedules). If agencies use the design-build method, they can share these deliverables with a design-builder during the RFP phase. This stage will see participation from designers of several disciplines (agencies), responsible personnel for contract letting, and design consultants for specialized work, among others.

3.1.3 Detailed Design Phase

This phase marks the timeframe when designers from agencies and other firms spend significant effort on improving and finalizing the project documents (design, estimate, schedule, and specifications, among others). Functions (tasks) utilizing CIM in this phase affect the means and methods of construction activities (such as facilitating AMG through digital design) and improve the predictability in project execution (e.g., by identifying spatial conflicts and constructability issues virtually and resolving them). Although the project information management systems play a significant role throughout the project's life cycle, their robustness and integration capabilities will be critical here, because this phase can generate the greatest amount of information.

- **Digital design** activities continue in this phase with detailed scope and finer level of detail.
- Presence of 3D data helps agencies perform **design coordination** and conflict identification among various design entities. When CIM usage becomes mature (i.e., design data becomes electronic or model-based), agencies can explore automating the review processes for design



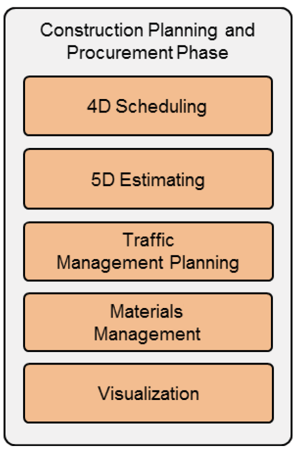
submittals. The designers can also incorporate agencies' **asset data integration** needs during design. **Utility conflict analysis** using model-based data can identify and resolve clashes and reduce change orders that result from design issues.

- 3D models also assist in **visualization** and public information dissemination when they contain appropriate levels of information for the intended audience.

Deliverables and Stakeholders. The type of CIM deliverables can be the same as that of schematic design with the addition of design coordination reports, detailing of design entities, final versions of 3D models, and supporting information for contract documents. Designers, consultants, contractors, and external stakeholders (such as utility companies) will participate in this process.

3.1.4 Construction Planning and Procurement Phase

Incorporating CIM-based workflows also improves the effectiveness of the construction planning and procurement tasks. CIM functions in this phase improve the predictability and performance of construction activities during the actual construction.



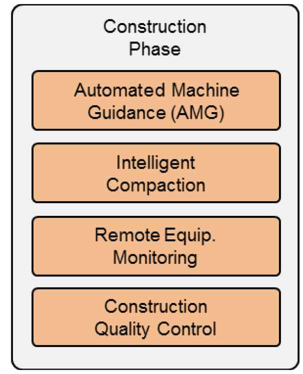
- Literature shows several advantages for **4D scheduling**. In short, model-based scheduling helps to identify and resolve spatial and temporal conflicts among project elements. It can also facilitate examining and developing schedule alternatives to suit various objectives (such as minimizing construction cost or maximizing vehicular mobility). The availability of 3D models and detailed schedules make this task feasible. Also, with high maturity in model-based delivery, there exist possibilities to create schedules simultaneously with 3D design process.
- Presence of model and estimate data also enables **5D estimating** processes. Applications include visualizing cash flow, performing quantity take-offs (QTO), and monitoring progress and payments for contractors. For an example, see the NYSDOT case study in Table 5.2.
- CIM for **traffic management planning** involves performing microsimulation to model the traffic behavior with lane closures and detours and predict user delays and congestion effects. Such traffic simulation can also be integrated with design **visualization** to enhance the quality of the Public Information process (Wei and Jarboe 2010).
- CIM for procurement can progressively affect both **materials management** on-site and tracking of the supply chain itself. Advancements in material management systems can help perform these activities in an efficient manner. For an example, see the Dallas-Fort Worth Connector project (Anderson 2012).

Deliverables and Stakeholders. The deliverables can include 4D/5D models, data and model outputs for traffic simulation, and material management reports. Stakeholders relevant for CIM in this phase include contractors (and subcontractors), suppliers, consultants, and agency personnel responsible for construction planning and traffic control.

3.1.5 Construction Phase

Digital project delivery can manifest itself in the construction phase. CIM-based workflow can lead to major changes, including the use of AMG (automation for grading, excavation, and finished surface construction, among others), Intelligent Compaction (IC), and quality control inspections using rovers and mobile digital devices. In addition, CIM functions enhance the connectivity to the site and assist in monitoring and controlling operations.

- **AMG** for construction activities is a major improvement with CIM implementation. Contractors can automate activities related to excavation, grading, compaction, and finished



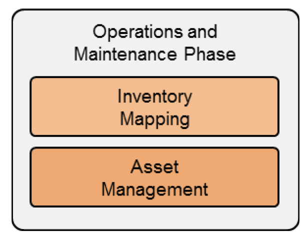
surface construction, thereby increasing productivity, and safety on-site. Availability of 3D models and sophisticated machines also automate construction of concrete barriers and retaining walls and generate stakeout points for major bridge elements in the field. For an example, see the ODOT's "Design to Paver" Workshop (ODOT 2014).

- Usage of **Intelligent Compaction** can improve the control in the compaction operations for soils and asphalts, thereby enhancing the quality of work on-site.
- With real-time connectivity to the site, agencies can use **remote equipment monitoring** to control construction machinery and equipment. They can also use the information gathered from these activities for improving operational efficiency (fleet utilization rate, emissions control, and equipment safety).
- With CIM tools, field staff can perform **construction quality control** checks frequently and accurately using rovers and mobile Transportation Asset Management (TAM) devices. They can also use mobile devices to inspect the structural elements.

Deliverables and Stakeholders. The various CIM deliverables from this phase include as-built models, quality control records, and reports concerning equipment usage on-site. The various stakeholders involved will be agency staff and contractors' field representatives.

3.1.6 Operations and Maintenance Phase

CIM-based project delivery also affects the functions of the O&M phase. It is necessary to encapsulate O&M to ensure CIM implementation across the asset life cycle.



- **Inventory mapping**, when performed with CIM tools such as LiDAR, aerial imagery, and GIS, can meet the data needs for asset O&M. Agencies with higher levels of CIM utilization under this category build up and regularly update a digital data archive that can inform decisions about managing existing facilities and developing new projects.
- Asset identification needs, considered during planning and integrated during design, improve the objectivity in the decision-making process for **asset management**. Maintenance personnel can have timely access to the accurate data they require to carry out their tasks. Additionally, asset management connects to broader objectives of facility maintenance that will fall outside the realms of project delivery. Figure 3.1 distinctly identifies information collection and management efforts related to asset management functions.

Deliverables and Stakeholders. The various deliverables from this phase can include updates to inventory data and digital data archives, among others. Agency O&M personnel and other consultants will be the major participants in this phase.

3.1.7 Information Management

Although it is unconventional to perceive information management as a separate category, this area needs special attention because it stays relevant throughout an asset's life cycle. The management of digital information is a continuous process that has the potential to yield significant benefits if the information deliverables from respective phases support the objective of utilizing this data continuously. With CIM integration, the functionality of an information management system can have the following major characteristics:

- Capabilities to produce and deal with information deliverables in document- and model-based formats
- Ability to deal with increased usage of digital signatures by different functional areas for approvals, submittals, and review purposes
- Potential to seamlessly integrate geospatial information to enhance the robustness and utility of the asset data throughout its life cycle

- Adoption of common industry standards across the agency for generating and sharing the information (examples include LandXML, TransXML, IFC classes, and common coordinate systems for surveying and GIS activities, among others)
- Information handover at the completion of respective project activities

This function deals with managing the deliverables generated across the project life cycle. The stakeholders involved will include personnel from the following:

- Information technology group staffers to manage information
- Representatives from all other divisions to identify new requirements or convey the needs of upgrades or maintenance
- Other vendors or third party groups that handle the upgrades or maintenance

3.2 Maturity Model for CIM

In practice, agencies do not use all CIM functions for project delivery. Furthermore, an assessment of the status quo reflects different levels of CIM utilization by different divisions within the same agency. Thus, agencies require a framework that can assist in evaluating the current maturity for CIM functions relevant for the divisions. Figure 3.2 presents a three-level maturity model based on the capabilities of divisions responsible for project phases from planning to O&M. Information management systems are integral requirements for all the project phases; hence, Figure 3.2 identifies them distinctly. The three levels of maturity in this model are "Initial," "Intermediate," and "Advanced." The maturity levels have their specifications defined based on the survey results (presented in Chapter 5) that included responses concerning all the major divisions of DOTs.

- The Initial level corresponds to the maturity where most of the information exchange processes remain document-centric. The functions building up the phases of a facility incorporate limited CIM-based procedures. Theoretically, any agency just beginning to implement CIM capabilities from scratch can use this level as a reference point for progressive implementation efforts.
- The Intermediate maturity level shows significant improvements in CIM integration for functions, with the workflows becoming data-centric. An agency in this category has made major strides in CIM adoption for surveying, design, and construction, demonstrating CIM's potential on one or more of its projects. However, some document-centric processes can hamper further transition, thereby making the life-cycle implementation incomplete. As per the current state of practice, most of the DOTs' divisional capabilities are at the Initial or Intermediate level.
- The Advanced level represents a coherent approach where executing projects through CIM functions becomes the norm. An agency at this maturity level uses model-centric workflow where a few processes can remain data-centric (when model-based workflow is impractical). Importantly this level represents the life-cycle adoption of CIM (including construction and O&M phases). Note that the capabilities of this level are determined by organizing elicitations from survey results and case studies; each of them reported high utilization and performance of CIM functions. Although some DOTs had executed a few projects with CIM tools and functions reflective of Advanced maturity, life-cycle (agency-wide) implementation remains a milestone that they have yet to achieve. Thus, the third level can serve as the target for any agency for at least the forthcoming decade.

Agencies can use this concise yet comprehensive tool to analyze the current maturity of CIM across their divisions. The functions described in the project phases in the model include only those relevant for CIM. Furthermore, this guideline cannot directly translate to detailed, operational specifications for an agency; rather, its objective is to serve as a basic framework that any

	Initial Level Most of the functions and deliverables are non-CIM with limited/no utilization of CIM technologies; information integration across phases is limited	**Intermediate Level** Usage of model-based tools for performing certain functions; information deliverables are matured with points of integration across phases	**Advanced Level** A matured approach for project delivery where CIM-based functions dominate the project workflow with full information integration across phases
Scoping & Surveying Phase	• GIS-based platforms with basic capabilities for project development activities (e.g., ROW map development, and environmental processes); • Use of traditional surveying methods together with static LiDAR for project-level data collection.	• GIS-based platforms with basic capabilities for project development activities; • Basic use of visualization (GIS layers); • Increased use of advanced surveying methods for project-level data collection; • 3D geospatial data for design may not be an outcome.	• Geospatial and cloud-based tools for project development activities; • Extensive use of visualization for concept design and approval (GIS layers, conceptual 3D models); • Extensive use of advanced surveying methods to produce 3D data (integrated surveying with LiDAR/GPS/RTN/Robotic Total stations).
Preliminary & Detailed Design Phase	• Terrain model design performed in 3D, but detailing is in 2D (e.g., gore areas, intersections); • All other design disciplines work in 2D environments; • PS&E documents are delivered in 2D; • Use of traditional utility location methods for project-level data collection; • Design coordination/reviews and utility conflict analysis performed in 2D.	• Terrain model design and detailing performed in 3D; • All other design disciplines work in 2D but produce representative 3D CAD models; • PS&E delivered in 2D; limited use of modern SUE technologies (e.g., GPR, EMI, RFID) for project-level data collection; A 3D geospatial model may not exist; • Design coordination and utility conflict analysis performed in both 2D and 3D.	• Collaborative design by all disciplines in 3D; structures designed to the required LOD (detailing in 2D) with O&M data IDs / needs; • PS&E delivered in 2D and 3D (wherever required); • Extensive use of modern SUE technologies to produce 3D geospatial data for project-level data collection; • Design coordination and utility conflict analysis in 3D.
Construction Planning & Procurement Phase	• Traditional (paper-based) scheduling and estimating methods; traditional materials management; • Traffic Control Plans (TCPs) developed and visualized in 2D - temporary construction, lane closures, crash barriers, variable message signs, barricades, and other traffic control devices	• Use of 4D/5D models for visualization purposes only; • Real-time tracking of materials using CIM tools (such as RFID) and web-based solutions; • TCPs developed in 2D, but visualized in 3D.	• Use of 4D/5D models for visualization, constructability analyses, progress monitoring, and cost control (i.e., model-based project controls); • Real time tracking of materials using RFID and cloud-based tools; • TCPs developed in 2D and visualized in 3D with real-time traffic data.
Construction Phase	• Use of AMG for excavation and grading operations (dirtwork); • Use of mobile digital devices for field verification (using 2D plan sheets); • Limited/No use of rovers for QA/QC checks; • No use of Intelligent Compaction Technologies; • As-built checks and record creation not very frequent	• Use of AMG extended to finished surfaces (e.g., asphalt or concrete pavements); • Use of remote site monitoring (equipment telematics); • Use of intelligent compaction; • Use of mobile digital devices for field verification (2D plans and 3D models for pavements); • Use of Rovers/RTS for QA/QC checks and as-built records are frequent.	• Extensive use of AMG (including concrete barriers, retaining walls); • Use of remote site monitoring and active control (design updates); • Use of intelligent compaction; • Use of mobile digital devices for field verification (3D models); • Use of Rovers/RTS for QA/QC checks, drones for inspection; accurate and frequent creation of as-built records
Operations & Maintenance Phase	• Document-based data and basic GIS support for various functions of O&M (Performance monitoring, infrastructure maintenance works, asset inventory, among others). • Data archives (databases) are electronic and updated periodically. • O&M operations are functionally separate from other phases.	• Electronic data with GIS platforms to support various functions of O&M. • Database systems are integrated, geo-referenced and updated simultaneously with new information (less redundancy). • O&M operations are functionally separate from other phases.	• Model-based data and advanced GIS platforms to support various functions of O&M. • Data (database systems) and model elements are intelligently connected and geo-referenced. • O&M operations are functionally integrated with other phases of project's lifecycle.
Information Management	• Most work processes and deliverables are Document-centric; although some are Data-centric, and a few are Model-centric. • Only Document-based information is digitally signed, and information is not geo-referenced. • Different disciplines develop their own DDMI, which is not shared in any collaboration platform. • Different disciplines follow different industry data standards. • Information handover occurs at completion.	• Most work processes and deliverables are Document- and Data-centric; although some are Model-centric. • Only Document-based information is digitally signed, but most of information (in all formats) is geo-referenced. • Different disciplines develop their own DDMI, which is shared in a collaboration platform. • All disciplines follow the same industry data standards. • (Most of) Information handover occurs simultaneously.	• Most deliverables are Data- and Model-centric; some deliverables are Document-centric. • All information (in all formats) is digitally signed and geo-referenced. • Different disciplines work on the same DDMI, which is stored and managed in one collaboration platform (integrated information management). • All disciplines follow the same industry data standards. • Information handover occurs simultaneously.

Figure 3.2. CIM capabilities maturity model.

agency can use for planning and developing its own evaluation tool. Assessment of an agency's capabilities will require detailed analyses and studies of its current business practices pertaining to the CIM functions. In this Guidebook, the maturity model serves as the foundation for determining future implementation efforts.

It will be challenging to quantify the efforts required for progressing across levels and hash out the directions specific to any particular agency. However, a totalistic assessment of the maturity levels can delineate some general guidelines for the transition.

Moving from the Initial to the Intermediate level requires the following:

- Envisioning (specific) strategic vision and mission statement for CIM implementation
- Overcoming learning curves for all related CIM functions
- A committed leadership for investment and implementation requirements
- A participatory approach from all major stakeholders with willingness to overcome individual barriers for achieving project goals

Transitioning to the Advanced level necessitates these additional requirements:

- Using CIM functions across multiple projects (agency-wide)
- Standardization of business workflows (wherever possible)
- Sustaining innovative efforts to find solutions to overcome barriers (technical, financial, human, and process-related)
- Rapid and effective dissemination of information to all stakeholders (lessons learned, best practices, and updates to standards or specifications)

Because this Guidebook focuses on implementation at agencies, the maturity evaluation process focuses on the divisions (such as surveying and design) and not on a particular project's phases. For this purpose, an agency can consider identifying its divisions' characteristics in the context of a "typical" project it performs as part of its program. Ascertaining these characteristics can be challenging, because the interpretation of "typical" is subjective. One approach is to synthesize an agency's available data and identify the characteristics of its own "Xth percentile" project, where Xth percentile represents the range acceptable to all the divisions. It can calculate this value based on consensus of domain experts. This process can involve experienced personnel from agencies and third-party subject matter experts. In the future, agencies can explore and potentially implement mergers of their divisions to adopt an integrated approach for project delivery. The model's utility remains valid because the project phases (not the nomenclatures of divisions) define the specifications. The evaluation process involves the (changed) divisions responsible for executing the project phases.

Illustration Example 1 explains the utilization of the CIM maturity model to assess CIM capabilities of an agency's divisions.

Illustration Example 1: Capabilities Assessment Using the CIM Maturity Model.

Agency "A" convenes a Task Committee to understand how effective its Divisions are in terms of adopting CIM functions on its projects. The Committee appoints a task leader who will oversee this investigation process, conduct appropriate studies, and submit a detailed report to the Committee. The task leader comes across the CIM maturity model and decides to use it for conducting the analysis.

The task leader observes that his/her agency executes projects with a variety of characteristics: roads and bridges, new construction and maintenance, budgets ranging from $5 million to $1 billion. To determine the maturity levels, he/she creates a Panel with experienced personnel from all the Divisions relevant for CIM. After several meetings and analyzing the information available at the divisions, the Panel arrives at the conclusion that it is reasonable to evaluate the Divisions' maturity for the 90th percentile project that the agency executes.

The Panel then uses the CIM maturity model, where the experts rate the capabilities of their respective Divisions into the three prescribed levels. They arrive at results shown in Figure 3.3.

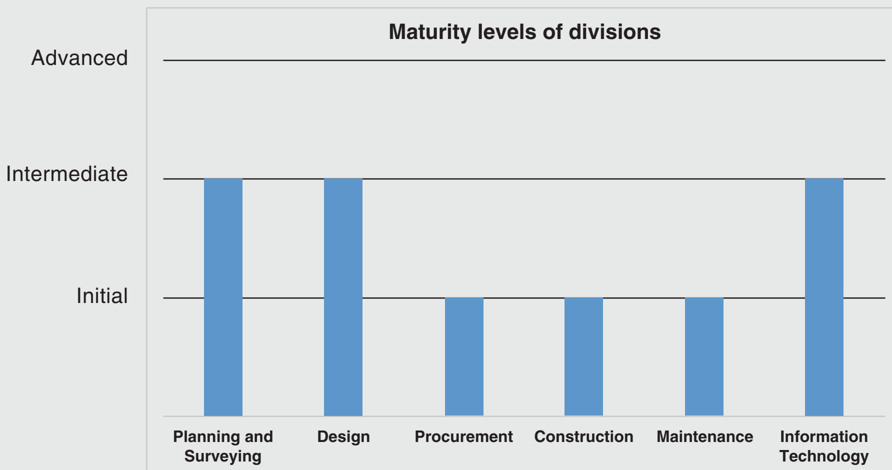


Figure 3.3. Graphical representation of the maturity levels of the divisions.

Along with the maturity results, the Panel makes the following observations (as shown in Table 3.1) for each division and submits them to the Task Committee.

Table 3.1. Recommendations for divisions at Agency A.

Division	Observations
Planning and Surveying	Consider widespread adoption of integrated surveying methods, especially mobile LiDAR and drones.
Design	Consider performing design of structures such as bridges in 3D to a reasonable level of detail. Try integrating models on projects.
Procurement	Consider advancing materials management capabilities on larger projects.
Construction	Consider improving quality control checks on projects. Attempt AMG for finished surface construction on a few projects.
Maintenance	Consider improving capabilities of GIS platforms for operations.
Information Technology	Collaborate with design, construction, and maintenance to identify their needs for progress—consider upgrading software to handle model data.

CHAPTER 4

Implementation Framework for CIM

The assessment of the CIM maturity levels lays the foundation for understanding an agency's current state of CIM practice and making investment and implementation decisions. Building from the maturity model, this chapter proposes a hierarchical framework to represent these issues in a systematic manner and guides the agencies in developing their own operational-level implementation plans. Figure 4.1 presents the graphical depiction of the implementation framework. It is a three-stage process cycle involving planning from current capabilities, identifying investment requirements, and considering major implementation lessons.

The first stage involves gauging the divisions' current maturity levels (reflective of the functional needs) and preparing an implementation plan balancing the functional needs and business requirements.

The second stage involves evaluating the agency's future capabilities by examining the investment needs based on the implementation plan and determining the benefits that arise through process improvements from the corresponding CIM functions.

The next stage provides a synthesis of implementation considerations for CIM that can act as ingredients for success. Agencies can consider incorporating them in the implementation decisions. Recommendations from subject matter experts and lessons learned from the current research effort are the main sources for this compilation.

The last requirement in the process cycle is documenting the lessons learned based on the actual implementation efforts and devising appropriate strategies to disseminate it to concerned stakeholders throughout the agency. This is vital to ensure that the feedback is completed and decision-makers of the future have adequate information to guide the implementation efforts at the agency.

4.1 Planning from Current Capabilities—Stage I

The first stage in the process cycle consists of translating the functional needs arising out of the maturity model into a pragmatic agency CIP. In this process, the first step involves analysis and determination of functional needs from maturity levels across all divisions. The second step involves integrating these needs into an organizational planning document that takes into account the agency's business constraints and other requirements. Section 4.1 explains the two steps in detail.

4.1.1 Action Steps for Functional Needs

In general, the CIM maturity model can reasonably capture the level of CIM usage across the divisions. However, it cannot cover all agency-specific business or workflow constraints. Thus, the

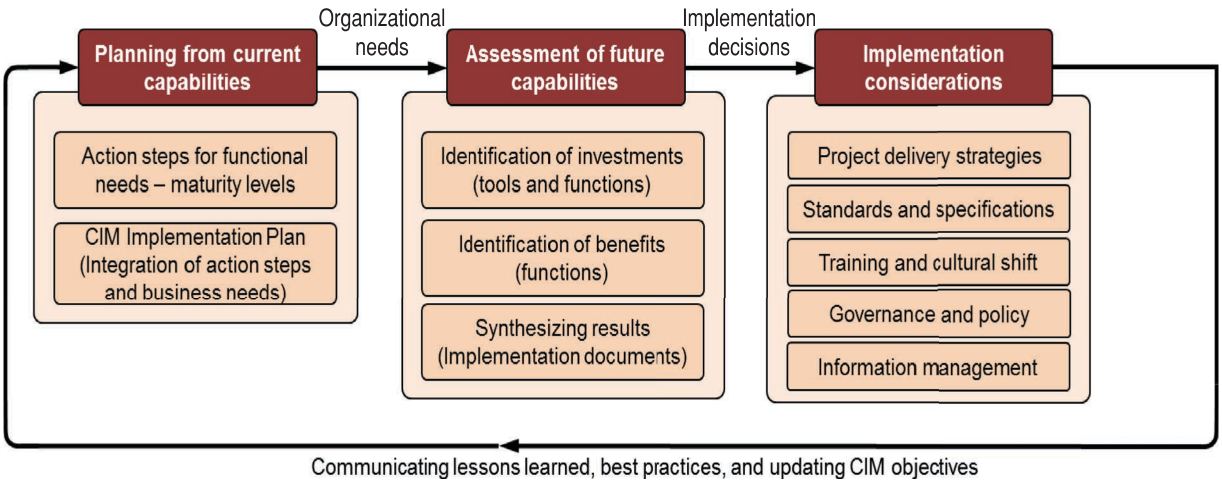


Figure 4.1. Process cycle for CIM implementation.

research team suggests that the agency articulate its constraints for the identified maturity improvements across divisions. Then, it can finalize the appropriate action steps taking into consideration both the technical requirements (from the maturity model) and the business considerations for CIM. A few instances of organizational constraints and plausible solutions are described below.

The constraints can be either resolvable or challenging. If the constraints turn out to be resolvable, an agency can determine the appropriate corrective measures. Otherwise, sustained efforts will be necessary to strengthen its CIM foundation and to obtain its objectives for higher maturity. Consider a situation where an agency may be at the Advanced level in terms of using integrated surveying methods and model-based design. However, it may not have used the deliverables effectively to leverage CIM potential during construction operations and other downstream activities. This scenario can arise as a result of legitimate constraints in the Construction Division that are challenging to deal with (lack of technical expertise, skilled and trained labor shortage, financial issues, or restrictions on contracting abilities). These issues are largely beyond the scope of technical implementation. In this case, the agency can try outsourcing, innovative financing, training and motivation sessions, reallocation of skilled resources, and negotiation with appropriate stakeholders to upgrade information systems to support deliverables for construction. The other reason can be that the Construction Division has the potential to embrace new CIM functions but has not yet upgraded because of several resolvable issues (such as lack of consensus among decision-makers, lack of awareness, and trust deficit with new technologies).

Besides the constraints, the current CIM maturity also plays an important role in determining the action steps. Divisions with low CIM maturity can identify easy targets to help them with initial breakthroughs; also, there have to be sustained efforts to innovate and solve the constraints. Divisions with high CIM maturity (Intermediate or Advanced) can continuously keep assessing and updating processes for potential efficiency improvements. They can also consider cross-allocating resources to other areas requiring improvement.

Illustration Example 2 provides the steps involved in the analysis process and a determination of the action steps for the divisions at an agency.

4.1.2 CIM Implementation Plan

While maturity models indicate the areas needing technical improvements, an agency can integrate its business needs and develop a formal CIP. In other words, an agency's selection

Illustration Example 2: Action Steps for Construction Division at the Agency "A" *(Continued from Illustration Example 1).*

Once the Task Committee receives the Panel's observations, it deems it necessary to forward the Panel's suggestions to the concerned divisions' heads and request their comments on potential implementation steps at their respective divisions to enhance their CIM maturity.

The Construction Division Head receives the report and asks an experienced colleague (investigator) at the agency to conduct an assessment study and apprise him/her of the options. On noticing the Initial maturity level of the Construction Division's CIM capabilities, the investigator first evaluates the functional needs and comes to the following conclusions:

- Absence of rovers and RTN stations for rapid QA/QC checks on most of their projects.
- Absence of specifications for widespread adoption of AMG.
- Agency has little experience in implementing IC technologies for soils and asphalt.

Second, the investigator determines the business factors and other issues limiting the division's capabilities. The investigator finds budget deficits and staff availability constraints to be the major factors involved. Because these issues are very challenging to deal with and take time to resolve, the investigator comes up with the following "action steps" and recommends them to the Division Head:

- Ensure deliverables for AMG are available from the Design Division; if not, contact the Design Division to learn what is needed.
- Conduct pilot projects for AMG (finished surface) and IC technologies; ensure skilled laborers' availability for them (cross-allocate from other districts or county, if possible).
- Collaborate with sophisticated contractors to provide rovers on-site; try conducting training sessions for available staff.
- Negotiate contract and training deals with vendor companies, beginning with small-scale implementation of hardware and software tools.

process for CIM implementation should balance both its technical ambitions and its pragmatic business requirements. An efficient way to meet this objective is to develop a CIP to centralize considerations. The principal elements of a CIP include the following:

- Vision and mission statements for CIM
- CIM functions to be promoted at the agency's divisions (based on action steps)
- Short-term and long-term mission requirements for promotion (investment/funding requirements)
- Critical organizational workflows being impacted or having impacts
- Allocation of lead responsibilities, resources, and ways for executive management buy-in
- Definition and measurement strategies for performance objectives
- Strategies for involving all stakeholders (contractors, vendors, and utility companies)
- Tracking and reporting requirements

It is important to prepare, organize, and continually track an agency's progress with respect to its baseline CIP. The aforementioned list may not include the entire set of requirements but will help determine the important elements. The CIP shall also encapsulate any other organizational processes regarding CIM that the agency deems necessary.

Although no agency has produced a comprehensive document, using the approach suggested here, Case Examples 1 and 2 can serve as references for agencies to develop a CIP. The primary difference is that, in these references, the requirements of divisions have been identified using past experiences, lessons learned, and taking stock of current practices (unlike a formal maturity-model-based assessment). These case examples integrate the functional needs, business requirements, and organizational vision.

Case Example 1: WisDOT's 3D Technologies Implementation Plan.

This plan is an example of planning at an organizational level for CIM. It contains the following main ingredients of an effective planning initiative:

- Vision statement: "Adoption of three-dimensional (3D) methods and seamless data flows throughout initial survey, design, contracting, construction, as-built survey, and other applications included within the infrastructure lifecycle."
- Eight statewide initiatives that relate directly to the CIM technology-based methods. Each of the eight initiatives is further elaborated with associated background information, current and future issues, and short-term (1–2 years) and long-term (2–5 years) goals to address the ascertained issues.
- Identification of other stakeholders who have shown the intent to participate.
- Strategic management plans that identify the agency representatives who will lead the effort(s) and manage and update the planning documents.

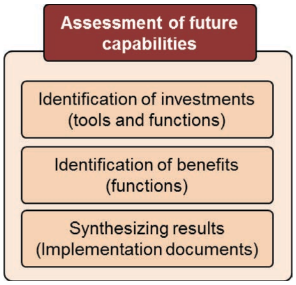
Source: Vonderohe (2013).

Case Example 2: ODOT's Engineering Automation Plan.

This plan includes a long-term 25-year plan that identifies major technological adoptions planned at the agency and connectivity of these objectives as a system. It also serves as a baseline for other short-term documents that could be developed. It considers lessons learned and designates specific functional roles and responsibilities and stakeholder partnerships required for successful implementation.

Another significant feature of this document is its strong case for utilizing digital data for project delivery. It provides a conceptual framework for managing infrastructure life-cycle data from a digital archive of the agency. It also identifies and defines the role of the key technologies and process paradigms that will help achieve this transition.

Source: Singh (2008); ODOT (2014).



4.2 Assessment of Future Capabilities—Stage II

The CIP identifies the functions and consequently the tools that an agency can implement at its divisions. It also provides the basic information on the resource requirements and the personnel responsible for executing these tasks. The agencies can now perform detailed analysis of investments and benefits, focusing on the identified implementation tasks. These analyses provide the necessary information for practitioners to make implementation decisions. This section describes this benefit-cost analysis process in detail.

4.2.1 Identification of Investments

Agencies beginning to deploy a new technology often do a pilot project and then make a decision on agency-wide adoption. This is because investments at a project level can be acceptable to an agency trying out new CIM tools. An agency can adapt to the disruptions in workflows for the specific project/processes and document lessons learned and best practices to disseminate them to other stakeholders for their consideration. Engaging senior management and procuring funding for such projects can be challenging; however, the investment will be worthwhile considering the potential work process improvements and the ability to support critical decisions based on this pilot experiment. CIM tools constitute most of the monetary investments and this section provides guidelines to assist this process.

The process of quantifying investments can be challenging for an agency-wide CIM implementation, because CIM consists of an assortment of tools. Agencies need to understand these challenges—described below—when reaching out to obtain reliable and accurate cost data.

- The investment details for specific CIM tools can vary depending on in-house technical expertise, the contract between vendor organizations and DOTs (duration, type of ownership, and type of subscription, among others), and an agency's financial capabilities.
- The agencies can find it challenging to quantify some of the external factors (such as contractual and legal issues) for benefit-cost analysis. For example, there are no definitive findings on how to incorporate the impact of project delivery methods (design-build vs. design-bid-build) while quantifying the benefits over investments. Similarly, federal or state regulations or time-tested contract clauses can impose restrictions on some project delivery processes. They are subjective issues that evolve over time based on consensus and are outside the realms of the research scope; incorporating them in a benefit-cost analysis can produce unrealistic results and inferences. However, agencies have to factor them in while making decisions. Section 4.3 describes these issues.
- The prices for CIM tools can keep changing due to efficiency improvements in existing tools and market adoption of new tools. Some of these estimates can be vendor specific.

Looking beyond these challenges, there is also a need to identify general categories of investments that can assist decision-makers and senior executives at DOTs in evaluating investments on CIM tools. This section explains the costs from an agency perspective and does not focus on implementation challenges related to specific projects. This objective also aligns with the overall scope of this Guidebook, which aims at agency-level implementation.

Typically, agencies have to deal with initial costs for deployment of CIM tools and annual costs for maintenance and upgradation. Although the monetary costs are primarily associated with CIM tools, the agencies should give priority to identifying the requirements of specific CIM functions identified in the CIP while making investment decisions. Thereafter, they have to determine the relevant CIM tools. The following points summarize various steps involved in determining major investments:

1. Identify the functional areas of potential improvements from CIP, select the appropriate CIM tools, and check for the data requirements to implement these tools.
2. Determine the training needed for staff to use the new technology.
3. Determine the labor allocation requirements for managing the implementation process.
4. For the functional areas, create standards and specifications to reflect new workflow.
5. Factor in workflow disruptions and non-CIM factors to ascertain the final investment needs.

4.2.1.1 Technology-Related Investments

CIM requires investment in information technology hardware and software. The hardware requirements are common and are generally applicable to most CIM functions. These can include high-performance computers and mobile digital devices (such as laptops, smartphones, and tablets, among others). Software applications required to perform the necessary functions in the office and in the field represent another important investment. These can include database management systems, surveying and design software, and mobile applications for smartphones and tablets. Furthermore, there can be additional costs for specialized equipment, depending on performance specifications, for surveying and construction activities. Table 4.1 enumerates the main software and equipment requirements for most CIM functions.

The most efficient strategy to obtain accurate price estimates on these tools will be to check with the peer agencies and organizations that are leading the initiatives in the implementation efforts. The DOTs can also contact vendors to negotiate prices, suitable procurement, and subscription schemes.

4.2.1.2 Training Investments

Training for CIM falls primarily into two categories: (1) technology-related training programs and (2) process-related training programs. Technology-related training investments are relatively straightforward to identify. These involve training the agency staff in the pertinent functional areas to deal with the data, hardware, software, and deliverables for the new CIM tool. The duration will be definitive, but can range from one-time events to months of instruction. Examples include workshops, vendor-training programs at agencies, and in-house training resources (tutorials, videos, and hands-on training, among others). The training programs should also consider the possibilities of changing the roles of the existing labor disciplines while implementing CIM. For example, implementation of GPS-based automated inspection technology (such as rovers) can necessitate training field staff and surveyors as quality control specialists. Similarly, design engineers producing digital deliverables should be trained to integrate the modeling needs of the construction contractors in the field. These needs typically include additional information or increased granularity of the models for field control. Examples include densification of DTMs, adding 3D breaklines, and generating machine-readable files for AMG.

Process-related training programs are necessary to incentivize and enable the cultural shift required to deal with new systems at the organization. The characteristics of the programs under this category can be unique to each organization. Qualitative knowledge about the workforce availability, expertise, and readiness to take up new tasks can be a good indicator. The training can be formal or informal. Examples of training in this category include motivational workshops, information sessions, and partnering sessions among stakeholders.

4.2.1.3 Labor Investments

Labor investments involve expenditures incurred when adding new resources (for using the new software and maintaining database systems). Generally, the agencies train the existing workforce to use the new tools. There are also situations where additional labor resources are required to

Table 4.1. Technology-related investment specifications.

CIM Tools	Category	Investment Specifications
Modeling Technologies		
2D digital design (A1)	Software	Generally, none; additional investment can be put toward producing digital deliverables (for integrating geospatial information).
nD modeling tools (A2)	Software	Discipline-specific needs for digital design (structures, utilities, roadway, drainage, and others) in 3D. Procuring software tools that enable geospatial integration of design can be an added advantage.
Traffic simulation tools (A3)	Software	Tools that enable microsimulation and macroscopic capabilities to perform traffic analysis at required granularity.
Data Management Technologies		
Information management systems (B1 and B2)	Software	Information management systems (documents, CAD files, databases, models, geospatial data). Efforts to integrate agency's Enterprise Resource Planning system with project information systems.
GIS (B3)	Software	GIS-enabled software platforms to serve across all CIM functions. Capabilities of such applications include performing spatial querying and analyses, integrating geospatial data, and providing geo-referenced base maps for several other functions.
Digital signatures (B4)	Software	Digital identification (encryption technology) from Certified Authorities for the agency personnel requiring them. Investments for ensuring compatibility with information management systems in place.
Surveying Technologies		
Airborne, mobile, and terrestrial LiDAR (C1)	Software	Software platforms to process, analyze, visualize, and use the resulting point clouds and the imagery. Innovative applications to extract 3D models.
	Equipment	Laser scanner (total station)—terrestrial LiDAR. Sensors (need-based), GPS equipment (supporting data), inertial measurement units, external wheel encoders, data loggers (mobile and airborne).
Aerial Imagery (C2)	Software	Software platforms that support viewing and processing high-resolution images for visualization and estimation of quantities (photogrammetry).
GPS (C3)	Equipment	GPS tool for installation on a variety of equipment as required for surveying, design, construction automation, and as-built verification using rovers. Augmentation with total stations to improve vertical accuracy.
Robotic Total Stations (RTS) (C4)	Equipment	Total station equipment and associated software platform (if any).
GPR (C5)	Software	Software tools to process the collected data (radargram) and extract the utility information, construct 3D images, and integrate them with other design entities.
	Equipment	GPR equipment (optional integration with GPS and electromagnetic induction technology to improve efficiency).
RFID (C6)	Equipment	RFID markers, with tags and readers, preloaded with necessary geospatial and project-based information.
	Software	Software platforms (GIS and Excel spreadsheets, among others) to load information.
RTN (C7)	Software	Software to work on field computers and connectivity to internet.
	Equipment	Installation of CORS hardware (concrete pillars, antenna masts, cabinets, cabling and power supply). Equipping surveying/construction machinery with GPS receiver, field computer, communication device with CORS network; GPS pole and brackets.
IMS (C8)	Equipment	Specialized tools to support IC function. Onboard computer reporting system, accelerometers, GPS-based mapping, temperature sensors, and optional feedback control.
Drones/UAVs (C9)	Software	Software tools to control flights, process flight log and image information, and generate 3D point clouds and quality reports.
	Equipment	Survey-grade drones, GPS receivers.

meet the increased/modified demand because of the new technology. For example, literature suggests that when beginning to use 3D digital design, there is an increase in costs for modeling and a decrease in productivity that results from learning new technologies and processes. Agencies should consider this increase in expenditures when determining labor investments. They should also factor in opportunities to reallocate resources that result from efficiency improvements from a particular CIM function. For example, they can reinvest labor savings from stakeless grading with AMG and RTN surveying (see Case Example 5, for expected labor savings from RTN/CORS investments).

4.2.1.4 Standards and Specifications

Standards and specifications are inherent requirements to ensure widespread adoption of any CIM tools at an agency level. Developing standards involves participation from multiple stakeholders including agencies, contractors, subject matter experts, governmental authorities, and third parties (such as research institutions). To attain a higher level of CIM maturity, agencies should invest in creating standards for data exchange and deliverable formats. They can primarily invest in CIM functions that have influences over multiple project areas. Visualization contributes to many phases: surveying, design, construction planning, and actual construction. Agencies can consider developing standards for digital design because it can transform downstream construction methods.

Additionally, the agencies have to examine possibilities of cross-functional impacts. Deployment of new tools may also require changes in specifications of other connected functions in project delivery.

4.2.1.5 Workflow Disruptions

Workflow disruptions can be the most challenging investment to monetize in practice. They can be related to a particular CIM function or be cross-functional.

It is known that technology adoption can disrupt established workflows and temporarily negatively influence productivity. CIM adoptions can expect challenges. A leading cause of delays is the learning curve associated with adopting new technologies. Costs can be difficult to model directly in such cases, but modeling disruptions to productivity using learning curves can reveal the likely impacts. Agencies can quantify the time it would take to regain the old productivity and associated outputs with the new CIM tool. This portion represents the additional costs due to workflow disruption (for an example, see Case Example 9).

The cross-functional considerations are more complex to identify, yet they have implications as well. Adoption of a new CIM tool by a particular functional area can cause ramifications in other related functions for project delivery. For example, investments in 3D modeling tools for the design function can trigger further investments in the surveying function to meet the data requirements of the former.

4.2.2 Identification of Benefits

Agencies can identify benefits by tracking improvements realized through CIM functions. Functions are the basic building blocks for effective project processes. Costs are generally associated with specific technologies, but these technologies only produce benefits if they have a positive influence on functions. Thus, agencies looking to adopt specific technologies must do a careful mapping of affected functions and associated benefits and, of course, implementation challenges. Figure 4.2 provides a mapping between CIM Functions and supporting CIM Tools. It can shows agencies the functional areas affected by technologies.

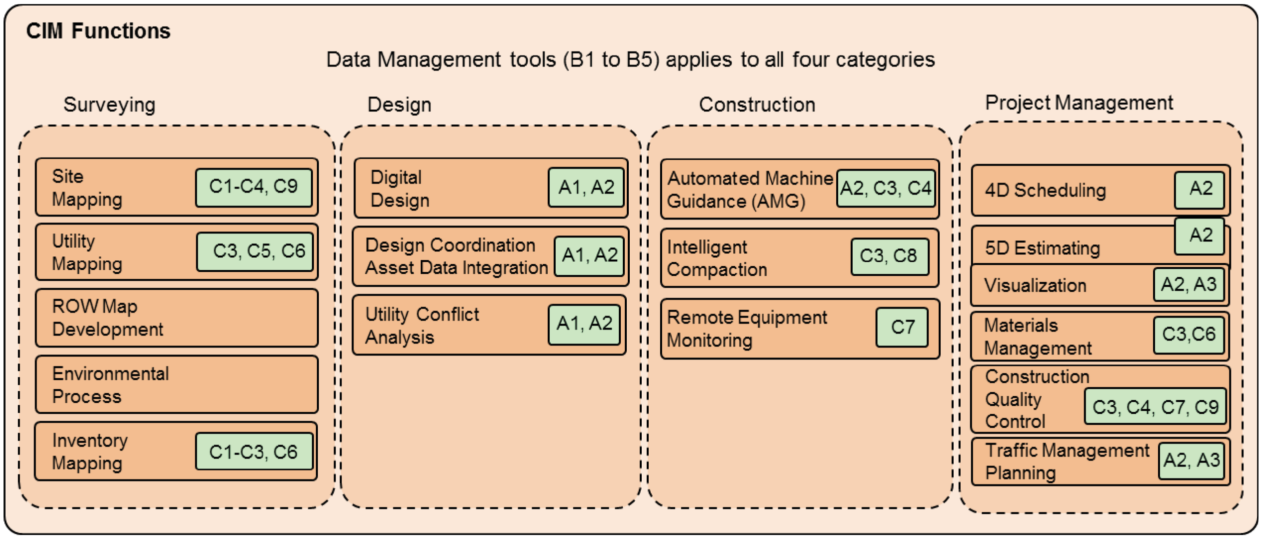


Figure 4.2. CIM functions.

Quantifying system-wide benefits of CIM is a challenging task. The benefits can be direct—translatable to performance improvements that the agencies can measure by any of the commonly accepted metrics for cost, schedule, quality, safety, and productivity, among others. Alternatively, they can be indirect—qualitative process improvements that lead to program effectiveness in the short or long term. Examples can include enhanced communication processes and improved data management processes, among others.

4.2.2.1 Direct Benefits

Direct benefits include actual monetary savings or perceived values in time reduction, safety, and quality improvements. They can be easy to identify but difficult to quantify at times. The best way to understand direct benefits is to compare a baseline situation with an existing function and a modified situation with the corresponding CIM function in place. The perceived benefits can be approximated in terms of the differences between the two situations. Table 4.2 lists the most significant benefits for each of the CIM functions.

4.2.2.2 Indirect Benefits

Not all of the benefits from CIM are easily perceived or quantified. There are some instances where there can be improvements in the overall efficiency of the agency's business practices in the future. Some of these situations are described further.

The benefits obtained from implementing CIM on a few projects may create new business opportunities. It may also increase the resource availability (budget, skilled laborers, etc.), which the agency could then use on other projects in its program. Investments in information management systems can produce life-cycle benefits despite potential higher investment costs. Because CIM improves data management processes across the asset life cycle, the benefits may be indirect and may not be apparent for any particular CIM function. The benefits of CIM may also extend beyond project delivery; it can improve the overall program delivery through increased coordination and trust among various stakeholders, given the transparency and predictability of the information involved.

Researchers have conducted benefit-cost assessments for individual CIM functions. Case Examples 3 through 6 summarize the objectives, methodologies, and conclusions of these studies.

Table 4.2. Benefits of CIM functions.

CIM Functions	Benefits
Surveying Activities	
Site mapping	Data **quality** improvements due to availability of comprehensive, accurate, reliable 3D information, geospatial integration Potential **time** and **productivity** savings due to rapid data collection **Safety** improvements due to reduction in risk of injuries to labor (GIS) Direct **cost** reduction and translatable **cost** savings from all of the above
Utility mapping	**Time** and **cost** savings due to improved certainty in locating utilities Improvement in data **quality** because of accurate position information
ROW map development, environmental processes	**Cost** and **time** savings for supporting complex decisions in project planning and development Improved data **quality** through spatial integration and opportunities for agency-wide benefits
Inventory mapping	Availability of good **quality** information for asset management **Time** and **cost** savings from supporting data collection for new projects
Design Activities	
Digital design	Improvement in **quality** of design efforts and design deliverables (3D information) **Time** or **quality** improvements for Public Information (visualization) **Cost** savings if deliverables are also provided digitally (Example: reduction in number of cross section sheets for plan sets for roadways)
Design coordination and asset data integration	**Time** or **cost** savings for design reviews and constructability studies **Time savings** for O&M personnel and asset owners due to improved accessibility to **quality** data Enhanced **quality** of the processes (Focus is now on analyzing the information rather than understanding it.) **Time** or **cost** savings due to potential reduction of RFIs, construction change orders (CCOs) during construction (processing time)
Utility conflict analysis	**Time** or **cost** savings for averting schedule delays and cost overruns by resolving conflicts **Time** or **cost** savings due to potential reduction of RFIs, CCOs during construction (processing time) Availability of good **quality** data for utility database for the agency
Construction Activities	
Automated Machine Guidance (AMG)	**Time** or **cost** savings from reduced construction costs, schedules, and fuel spent in the machines Increased **quality** of work and **safety** of construction on-site
Intelligent Compaction (IC)	**Time** and **cost** savings from optimized labor deployment during construction Improved pavement **quality** and **cost** savings across the life cycle
Remote equipment monitoring	**Time** or **cost** savings through remote monitoring and control of equipment on-site (equipment telematics) Improved **productivity** of machines, **cost** savings in fuel spent
Project Management Activities	
4D scheduling	**Time** savings during project execution by resolving temporal conflicts between construction trades, performing construction sequencing Improving **quality** of visualization and communication process by simulating construction processes virtually
5D estimating	Improving **quality** of visualization by adding cash flow to it (suitable for the initial stage of the project) Support for monitoring progress and payment to contractors (earthwork and quantity calculations)
Visualization	Support for ROW acquisition planning **Time** or **cost** savings for approvals, stakeholders' communication, and overall project management
Materials management	**Time** or **cost** savings in tracking and sharing material information in real time and managing material and associated equipment on-site **Time** or **cost** savings from minimizing trucking operations and operator charges

(continued on next page)

Table 4.2. (Continued).

CIM Functions	Benefits
Construction quality control	**Time** savings due to rapid data collection **Quality** improvements in progress monitoring and estimation of quantities due to rapid, accurate data collection using rovers, drones (UAVs)
Traffic management planning	Availability of good **quality** data for performing various analyses and creating traffic control plans Improved **quality** of information used for visualization

Case Example 3: WisDOT's Return on Investment (ROI) Analysis for CIM with 3D Design and Clash Detection (South East Freeways program).

The major costs for CIM are related to procuring and operationalizing 3D design software for roadways, sanitary storm analysis, and structures such as bridges. Purchasing such software means an expenditure of $200,000 to $250,000 per year, in 2015 dollars. The design cost for models is about 10% of the total design cost (i.e., 1% of the total project costs). On a typical $2 billion project, this cost amounts to $2 million. Additional costs would involve training and initial disruption in the workflows (apart from hardware and office space). All these costs are made up for by reductions in contract change orders and a subsequent increase in capital expenditures. ROI is evaluated against potential construction change orders (CCOs). A $1-billion project may have 8 to 10% expenditures on CCOs ($100 million). The agency estimated that a considerable portion of this expenditure could have been reduced through 3D model and clash detection. CCOs are broken down by discipline—structures, earthworks, drainage, utilities—and conflict occurrences are identified against which ROIs are evaluated. *The changes that can be controlled or addressed with CIM include design issues, clash resolution incentives, and RFIs (plan omissions, conflicts), adding up to $9 million.* Therefore, the agency's software investment for CIM can be justified. Moreover, CIM investment also has the potential to reduce future overall program costs.

However, it should be noted that 3D models would not solve all the uncertain issues in the field (e.g., unforeseen site/soil conditions). The ROI analysis should incorporate only the types of issues that can be solved by using CIM technologies. The quantifiable benefit of CIM is higher for roadway and drainage disciplines than for that of the commonly reported earthwork application (AMG).

In an FHWA Tech brief (FHWA-HIF-13-050), the WisDOT described the benefits gained by using 3D modeling on the Zoo Interchange Project, located on the west side of Milwaukee. The DOT estimated the percent cost reduction that could have been experienced if 3D modeling had been used on the Mitchell Interchange Project, which cost $256 million, and was similar in scope to that of the Zoo Interchange. *WisDOT estimated that 3D modeling could have saved the agency approximately $9.5 million (or 3.7% of the project's cost) on the Mitchell Interchange if 3D modeling had been used during the project's planning phase, with greatest estimated savings to have potentially occurred in aspects related to structures, drainage, and utilities.*

Source: *This data is based on a WisDOT case study (Mitchell Interchange and Zoo Interchange projects under SE Freeways program)* and the related FHWA Tech brief.

Case Example 4: ODOT's IT Benefit-Cost Evaluation Report.

ODOT evaluated the benefits and costs of nine IT systems put in place by the agency and the Oregon Bridge Delivery Partners (OBDP) in support of Oregon Transportation Investment Act III State Bridge Program. The systems include GIS infrastructure, environmental analysis tools, electronic document management systems (EDMS), engineering tools, and work zone analysis tools, among others.

The initial investments included the costs for hardware, software, software licenses, and internal development by ODOT and OBDP staff. The annual O&M costs comprise expenditures on software license subscriptions, staff time, data storage, and backup. The direct benefits were time savings that translated into equivalent savings in labor costs for OBDP and ODOT staff; indirect benefits included workflow and efficiency improvements in management.

The nine IT tools had a combined benefit-cost ratio of 2.1. A cash flow analysis was carried out, taking into consideration economic factors such as discount rate. The benefit-cost ratio was then calculated by taking the ratio of present values of benefits and costs. Risk and uncertainty were also incorporated in the evaluation process using the Pallisade @Risk Simulation tool in MS Excel.

"The $7.3 million of benefits are compared to investment costs of $3.5 million for a B/C ratio of 2.1. The overall net present value (NPV) is estimated at $3.8 million and the internal rate of return, 23%."

Source: Hagar (2011).

Case Example 5: Benefit-Cost Analysis for GPS/CORS Networks—MassDOT.

MassDOT conducted benefit-cost analysis for constructing and operating a network of CORS. Following are the two main cost categories considered:

- Network construction and operation costs ($300,000) that included the physical infrastructure (concrete pillars, antenna masts, cabinets, cabling, and power supply)
- Operation costs ($560,000 for a 6-year lease) that included contractor use of the GPS and CORS facility (surveying/construction machinery with GPS receiver, field computer, communication device with CORS network; GPS pole and brackets)

Direct savings came from reduction in labor (surveying crew) and equipment necessary to establish the geodetic control (which normally requires four staff members and four receivers) and surveying (that normally requires two staff members and two receivers). Using CORS, the overall process required one GPS user and one receiver. The study also identified other potential users of the facility such as town and county governments.

Source: MassDOT (2013).

Case Example 6: Benefit-Cost Analysis of Mobile LiDAR—Caltrans and WSDOT.

Digital point cloud information can be used for numerous tasks in mapping, asset, and inventory management. Caltrans and WSDOT have performed a benefit-cost analysis that examined different strategies of deploying a mobile LiDAR for rapid data collection.

Three principal application areas were examined in this study for data collection and costs. It included Roadway Feature Inventory Program (RFIP), bridge clearance measurements, and American Disability Act (ADA) feature inventory. Other application groups were not considered due to non-availability of program expenditure data from DOTs. The cost categories for these three areas included equipment, personnel, vehicle, and data collection and processing. Annual operation and maintenance costs for equipment and software also were considered. The tangible benefits from the technology were larger direct cost and productivity savings over current data collection methods, reduction in personnel cost, and fewer emissions because of the reduced size of the fleet. The intangible benefits included enhanced safety conditions, higher accuracy data, and availability of geospatial point cloud information for use by other DOT processes.

The operational strategies considered for deployment include mode of ownership (contract, rent and operate, purchase and operate) and accuracy (survey or mapping grade). The benefits and costs were calculated for all three identified program areas and for all three operational strategies. The labor requirements were also listed.

Cost savings were observed in all three applications at both DOTs for the period of analysis—6-year life cycle (or three data collection cycles). *The researchers found that purchasing and operating a survey-grade mobile LiDAR "produced the highest saving of $6.1 million" despite its higher initial costs.* Moreover, data collection and processing costs can be higher at first cycle and then lower in subsequent cycles. Another interesting finding is that the intangible benefits can be as equally significant as the quantifiable savings, or even more so.

NCHRP Report 748 has also provided guidelines on procurement considerations and implementation plans.

Source: Yen et al. (2014) and Williams et al. (2013).

4.2.3 Synthesizing Results—Prioritizing Decisions on Investments

The last step in a ROI analysis for CIM is to combine all the information and to arrive at a strategy for prioritizing the investment decisions for CIM functions. Intuitively, an agency can benefit from CIM implementation if it considers investments sequentially across an asset's life cycle. Availability of quality surveying information (and deliverables) is necessary to enable a model-based design process for all project elements. The quality of the model-based design directly affects the ability to use the data for downstream construction activities such as AMG. After construction, the quality of as-built information available post-construction affects the digital archival and asset management capabilities. Thus, an agency beginning to implement CIM for all functions can benefit more if it begins to invest in surveying that helps build the data capabilities, followed by design investments, and then construction. Besides these general guidelines, an agency can consider the following key points for prioritizing CIM investments:

Agency Utilization Rate. This is a relative measure of the probability that the agency will use the new capabilities of the functions on a typical project. Given two probable CIM functions, the agencies can invest in the one that it can use more often. Moreover, the agencies can also give preference to the functions that have applications across multiple phases, because this strategy can increase the utility.

Relative Impact. This is a relative measure of the actual/perceived ROIs of specific CIM functions (inferences from benefit-cost analysis). When deciding to invest, it would be ideal for an agency to pick up the functional capabilities that provide greater efficiency improvements.

After ascertaining these two indicators for all the considered CIM functions, the agency can use the Investment Prioritization Matrix (IPM) shown in Table 4.3 to select the most favorable investments.

Quadrant 1 can provide the agencies the list of CIM functions that it can consider primarily for investments. Subsequently, functions in Quadrant 2 can get greater priority over Quadrant 3. The objective of this Guidebook is improving agency-level implementation and the relative impact can become greater if the agencies consider using these functions on many projects. Finally, Quadrant 4 provides the functions that agencies should not consider investing in now, given analysis results. This matrix provides the foundational framework that agencies can use to develop specific guidelines. There are professional vendor applications to assist in preparing a more sophisticated decision framework. Agencies can also deploy mathematical tools to conduct detailed studies (such as the Multiple Criteria Decision Making methods, among others).

After prioritizing the investment needs, the agencies can then prepare detailed resources for aiding implementation efforts. With availability of data from benefit-cost analysis and the objectives from CIP, the scope of implementation can now become more refined and specific for particular CIM functions. This will lead the way to preparing several guidelines for all considered CIM functions detailing how the agencies can promote them, collectively referred

Table 4.3. Investment Prioritization Matrix (IPM).

Prioritization of Investment Decisions		Relative Impact (Benefit-Cost)	
		Low	**High**
Agency Utilization Rate	**Low**	Do not consider investing in the functions falling under this category given the current analysis results. (4)	Consider doing pilot projects to understand the best practices of the functions under this category. Determine the conditions that will promote agency-wide acceptance. (3)
	High	Consider these CIM functions as secondary investments. Simultaneously, explore all the opportunities to improve benefits-costs ratio. (2)	This is the most favorable investment region. Consider investing in all the CIM functions in this category. (1)

Note: The numbers in circles represent quadrant numbers.

Illustration Example 3: AMG Implementation in Construction Division for Finished Surface *(Continued from Illustration Example 2)***.**

The Construction Division Head receives the action steps for improving CIM capabilities in the division. Noting that recommendations would require further understanding and information in terms of benefits and costs requirements and specific planning documents, the Division Head appoints a Group to further develop the recommendations and gather all the necessary information for implementation efforts.

The Group conducts its research using the IPM and determines the CIM functions to be considered. From the list of recommendations, AMG for finished surface is selected as the most favorable task (*per the IPM matrix of Table 4.3, this belongs to Quadrant 1*). The Group then prepares the necessary supporting documents required for implementing AMG for finished surface construction. The following documents are submitted to the Construction Division Head for final decisions.

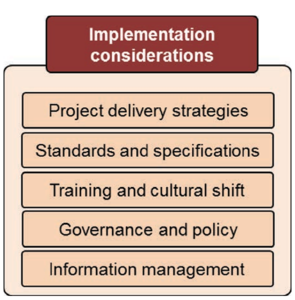
Document 1: Preparation of agency specifications for finished surface
Document 2: Workforce training programs and training resources
Document 3: ROI analysis and performance objectives for AMG considering all the constraints

to as "CIM Function Implementation Documents." This collection of documents includes the following:

- General information requirements for the CIM function
- Specifications, standards, and guidelines for the CIM technologies and their associated deliverables on projects
- Workforce training programs and resource manuals
- Project-specific performance measures for CIM (This may include documentation of anticipated benefits and costs along with necessary measurement metrics. These benefits and costs may have qualitative as well as quantitative components.)

Practical cases where a connection existed between a strategic level CIP and the focused CIM Function Implementation Documents are limited. While this workflow seems familiar, agencies have not directly followed this approach for CIM implementation. Thus, this step is demonstrated further using Illustration Example 3.

4.3 Implementation Considerations—Stage III



Integration of CIM into work processes is not only about planning and analyzing ROI but also about proactively accounting for other implementation factors. The decision-makers cannot view all the issues related to project delivery from the point of view of performance and effectiveness improvements. Some implementation issues play an integral part when deploying CIM at the agency level. This section describes all such considerations with case examples given wherever applicable. Issues are thematically arranged into five different categories: project delivery strategies; standards and specifications; training and cultural shift; governance and policy; and information management. It takes time, sustained efforts, and coordination among all stakeholders to bring about changes among all these categories.

This synthesis is neither an exhaustive compilation nor a substitute for any specific guidance that an agency has in this area. Rather, it can serve as a checklist of key issues that an agency can consider.

4.3.1 Project Delivery Strategies

1. Alternative contracting methods are an inherent constituent of CIM. The relationship between alternative contracting methods (such as D-B) and CIM practices is complex to understand. There is evidence to show that alternative contracting methods foster a collaborative environment among the major stakeholders and allow contractors to innovate with specific means and methods for construction. However, the essential benefits of CIM tools can apply to any project delivery method because CIM functions, as a system, cater to the entire life cycle of a facility, including the long-spanning O&M and asset management functions. Legally, some of the agencies cannot execute projects through alternative methods. These agencies have to find strategies to use traditional D-B-B, yet promote collaborative processes (see Case Example 7).
2. Another important issue to consider is the amount of design done in-house versus consulting on an agency's typical project. For example, an agency that performs most of the work through outsourcing has to be more collaborative in implementing CIM initiatives for 3D design than the agency that does most of its work in-house. In addition, the amount of subcontracting done by the consultants themselves can also be an important factor that affects the acceptance of CIM at the agency level.
3. The agencies can also encourage the use of Alternative Technical Concepts (ATCs) to promote innovative CIM applications on projects, especially when stakeholders are using CIM functions for the first time. The use of ATCs has been common among many DOTs, with most of them harnessing considerable benefits in the form of improved efficiencies in construction means and methodologies, reduction of risks, and savings in project cost and time. While ATCs have so far been used to enhance base design requirements or to accelerate the construction processes to alleviate the project impact on travelers and neighborhoods, few instances exist in practice where ATCs have been used for CIM tools or functions. Nonetheless, agencies embracing new CIM practices (e.g., 3D design for structures) can try utilizing ATCs to leverage the expertise of contractors to come up with cost-effective, innovative solutions. By doing so, they can not only improve the chances of successfully piloting new technologies but also learn the best strategies and practices of using them in the future.
4. The agencies can also consider using work packaging techniques and practices for scheduling, monitoring, and controlling engineering and construction work processes. Work packaging techniques refer to detailed field planning for construction as well as planning and scheduling design and procurement activities to support the planned construction sequence. Effective work packaging is typically accomplished during project planning to setup the appropriate control structures and project execution plan. Effective implementation of work packaging techniques on capital projects has demonstrated significant improvements in cost, scheduling, safety, and quality (Construction Industry Institute IR 272 [2013]; Construction Industry Institute IR 319 [2015]). Work packaging refers to process improvements independent of technology. However, for large projects, work package processes are supported by 3D modeling and related database technologies. Work packaging is an example of synergistic development of new processes supported by technologies and is illustrative of the type of applications and improvements supported by CIM technologies.
5. The agencies can consider pre-qualification for contractors and other suppliers of CIM capabilities. This approach can be an efficient strategy to control the stakeholders in the supply chain. They can ensure that the prime contractors are capable of supporting the needs of subcontractors who may not be CIM-ready.

Case Example 7: WisDOT Case Study—Hybrid Design-Bid-Build Approach for Project Delivery.

This approach is a part of the agency's innovative construction initiatives and has been tested on its SE Freeway projects. During the "design" stage, the owner and designers/consultants are the major collaborators. It is ensured that the 3D specifications are incorporated in the contract. The designer uses the owner's IT infrastructure (software, workstation, and plotting) to perform its work. Even if the designer's organization has a "building" division, it is legally/contractually prohibited from sharing the design data to prevent an unfair competitive advantage. Construction expertise is obtained from a "lessons learned" construction manual and from the involvement of in-house construction staff throughout the design and bidding processes. Thus, this approach facilitates a data-sharing and collaborative environment. The winning bidder (the general contractor) collaborates with the agency's construction staff and uses its infrastructure (along with its field/office tablet PCs).

In the "construction" phase, the contractors are leading the efforts and are adopting a Bring Your Own Device (BYOD) approach (for smartphones, tablets, and other major equipment). The only expectation is that agencies share their data on cloud-based tools to facilitate easy data accessibility and control. The challenge is on the "design" side, where getting all the disciplines to follow the data-centric CIM approach is difficult.

DOTs with funding restrictions can look toward utilizing cloud tools for data sharing and collaboration. However, future efforts should move toward a collaborative data-centric design that involves owners and designers working on a central IT infrastructure so that the maximum benefits can be attained. Cloud-based tools facilitate sharing of updated information, real-time, among all stakeholders. Collaborative IT systems have the potential (designers, consultants, and agency staff among others) to leverage the capabilities of the integrated tools and processes that allow stakeholders to work in a unified platform (as done by WisDOT in this case study). Although these practices require higher initial investments, there are considerable short-term and long-term performance benefits that can be derived from efficient information management.

6. Providing 3D (roadway surface) models to the contractors pre-bid can increase chances for contractor innovation and help reduce construction costs (FHWA 2013). Agencies can also consider providing digital information of their state highway system (such as point clouds). WSDOT, ODOT, Caltrans, and TxDOT have invested in collecting this information. Recently, some agencies have also been deploying drones for this task.
7. Technologies and functions change over time because of advancements and efficiency improvements in CIM tools. It is important for an organization to keep abreast of these changes. Furthermore, different contractors follow different means and methods to accomplish the same task. Thus, agencies can consider using performance-based specifications that use the same quality of data for digital delivery but do not explicitly specify which method to follow—over method-based specifications. For example, an agency specifying use of digital information for construction automation can include clauses regarding quality of as-builts

and associated deliverables; it can leave it up to the contractor to determine which CIM tools or functions to adopt. Another example can be engaging a consultant to collect point cloud data on the highway system. DOTs can specify the boundary, accuracy, and the density of the collected data; they can leave the choice of technologies to use up to the consultant (such as Mobile LiDAR, UAVs, digital photography, laser scanner).

4.3.2 Standards and Specifications

1. Specifications in contracts can play an important role in transforming objectives into actionable requirements. The agencies can incorporate all the consultant requirements through general contract conditions (such as 3D modeling, LiDAR data collection, and project visualization) and provide the construction requirements through specifications for contractors (such as AMG specifications, compaction quality, and QC specifications).
2. Requesting as-built information from contracts is important in order to build up an effective data archive for asset management (especially for proposed utilities). Agencies can also engage separate professional services to oversee this task.
3. Design forms the central component of CIM implementation in project delivery. The agencies can consider standardizing workflows of design for all the disciplines and their deliverables. Agencies and consultants can create software templates to be used by design personnel. The agencies can develop and adopt Electronic Engineered Data (EED) specifications supporting 3D design on projects. In general, they should cover details for existing ground, proposed ground, master design files for proposed structures, and coordinate geometry files (alignments, datum/control points).
4. The agencies can generate their plan sets automatically from 3D (surface) models and include additional details on them. They should compare 3D models and 2D plan sets for QA/QC, in addition to updating the models.
5. Another primary issue to consider is priorities of data formats. Most agencies use 2D plan sets as the governing contract documents. Some agencies have carried out pilot projects wherein they used specifications that gave 3D surface models priority over 2D plans. However, widespread implementation of this practice will require extensive collaboration of all the design disciplines (roadways, bridges, utilities, ITS, lighting, signs, etc.) to perform their designs and detailing works in 3D. In addition, legal guidelines have to evolve for this step to become reality.
6. Although agencies provide electronic data in both native and converted file formats for AMG, the models are usually "supplemental" or provided for "information only." The risk, accuracy, and liability issues arising from using them for downstream construction applications are transferred to the contractor. The agencies can consider developing better risk-sharing mechanisms or contract clauses to encourage widespread applications.
7. Establishing the level of detail (LOD) requirements for the elements in the 3D model (such as structural, traffic, surface, etc.) is critical for successful CIM integration. LOD specifications can help project teams clearly articulate and communicate the elements to be included in the CIM deliverables, as well as assist in communicating the design intent among the project team to ensure all members know the CIM requirements. Incorporating detailed specifications on LOD into contracts can also help standardize the modeling and reporting practices among all the stakeholders on projects. Many public organizations have incorporated contract specifications for LOD and have developed their own customized ways to monitor and report LOD during project development (USACE 2014; BIMForum 2014). Transportation agencies can consider developing similar guidelines to ensure clarity and consistency of the information exchange between all the project stakeholders to avoid any potential conflicts. Case Example 8 highlights a situation where a DOT has prepared a strategy to document and report LOD of its highway projects.

Case Example 8: Project Modeling Matrix for 3D Design—WisDOT.

Learning from its experiences on the SE Freeway projects, WisDOT used a Project Modeling Matrix to guide the LOD documentation process to record modeling details of various project elements—roadways, surface (existing and proposed), bridges, retaining walls, utilities, piling, embankments, and drainage, among others. Major elements of the matrix include project elements, data format (DGN/XML/CAD), level of accuracy, LOD, and work area responsible for maintaining LOD.

For all the projects, during the bidding stage, 3D design deliverables are provided. However, the LOD of the provided data varies depending on project characteristics (projects more than $100 million with greater uncertainties/risks will have structures and utilities provided in 3D).

Source: Parve (2014).

4.3.3 Training and Cultural Shift

1. People and processes are as equally important for CIM adoption as technology-based products. Workforce training programs for CIM are significant and should take the form of a continuous process, especially for design and construction areas. While construction training can equip the field staff with necessary expertise and infrastructure to handle CIM operations (e.g., GPS, rovers for QA/QC, and as-builts), design training can train the disciplines on handling the 3D surveying data and performing collaborative 3D design. Considerable effort would be required for the design-related training. Approaches such as "Bring Your Own Device (BYOD)" (as implemented by NYSDOT through its 625 specs for Contract Control Plans and endorsed by the FHWA) can facilitate rapid adaptation to CIM on the construction side. The inspection staff has the option of using the contractor's surveying equipment for inspection and QA/QC purposes.
2. The agencies can consider hiring and recruiting processes that screen for CIM-friendly employees from places of employment, such as universities. It can be worthwhile to develop detailed guidelines around this aspect.
3. Agencies can consider training as a process rather than as a one-time event. While information sessions and one-day workshops can help acquaint personnel with the concepts, continuous training efforts (through vendor participation, manuals, videos, and others) play a major role in the skill development process. Also, consider using just-in-time training, where the timing of the training sessions coincides with implementation efforts. At a minimum, the workforce should get hands-on training while learning new functions. These strategies assure maximum utilization of the resources spent on training.
4. Agencies can consider cross-discipline training to understand the various processes and uses of digital information. Cross-allocation of resources across divisions can become necessary while implementing CIM.
5. It is important to recognize the transition period for all parties to get up to speed and efficiency while adopting CIM. Perhaps there is a learning curve in all the technology adoption processes. An approach for quantifying the learning curve is presented in Case Example 9.
6. The agencies can use existing DOT-related resources and guidelines to prepare the training materials. All these resources are included in Appendix A of the Guidebook. The agencies can use them as reference materials.

Case Example 9: An Approach for Quantifying the Learning Curve (Autodesk, Inc.).

From an organizational perspective, design productivity initially goes down as users become accustomed to the new system. With time, productivity returns and continues to grow until it saturates at a higher point as the technology takes hold. This process is represented in Figure 4.3.

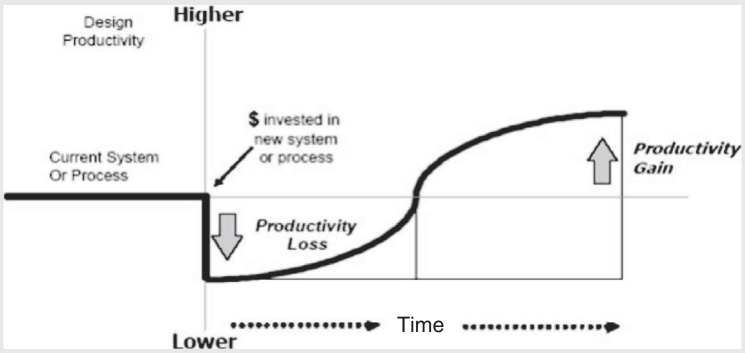


Figure 4.3. Design productivity during BIM implementation. (Adapted from Autodesk, Inc., 2007.)

A standard formula often used for measuring first year ROI is shown in the following equation:

$$\textit{First Year ROI} = \frac{\left(B - \dfrac{B}{1+E}\right) \times (12 - C)}{A + (B \times C \times D)}$$

Where A is the cost of hardware and software (dollars); B corresponds to the monthly labor cost (dollars); C is the training time (months); D is a measure of productivity loss during training (percentage), and E corresponds to the productivity gain after training (percentage). This equation uses a few key system variables related to system cost, training, and overall productivity cost savings. In short, the numerator represents the "earnings" realized as a result of implementing information modeling and the denominator represents the corresponding "cost" incurred.

Source: Autodesk, Inc. (2007).

7. They can consider outlining detailed workflow processes for the required CIM functions. Use this workflow to develop training procedures. Agencies must ensure that training is tailored to managers, supervisors, technical staff, and field personnel. They can link the training to manuals and standards, hardware and software, and customer needs.
8. A sustained and committed supply chain participation in training programs can also have scalable impacts on motivating and increasing workforce capabilities. Case Example 10 examines a good training strategy.
9. Agencies need to promote "a culture of innovation" where leadership buy-in and freedom to innovate are important. It requires a paradigm shift in the organization to provide the ability to think digitally to implement digital processes. CIM can be integrative across functions. It is essential to build the culture of information sharing.

Case Example 10: Integrated Training Approach—Crossrail Case Study.

Crossrail (CRL) and Bentley Systems launched a dedicated "Information Academy" to give hands-on training to the CRL supply chain on contemporary technology and software and to identify, formalize, and share best practices. With full cooperation in all aspects of setting up and organizing the Academy, CRL contributes empirical information through project expertise and Bentley coordinates the physical learning environment.

Building information modeling (BIM) training in CRL takes place at three different levels: (a) on the owner side for the supply chain, (b) on the contractor side for their own staff, and (c) with external institutions for the current and future workforce. Through the BIM Academy, CRL has developed a curriculum particular to CRL, which includes four major training modules: (1) CRL Vision and Strategy, (2) Document Control and Information Management, (3) Management and Control of Design Information, and (4) Asset Information Provision. These sessions are for general contractors or the subcontracting community. BIM managers, however, are considered BIM "super-users" and thus they receive sessions that are more specialized. In sum, the Academy explains CRL standards, and teaches the necessary skills to achieve them.

While contractors acknowledge the value provided by the Academy, they consider training at the in-house level is also fundamental. Their common approach is to appoint one person from each project team as the "BIM Champion." BIM managers then train the BIM Champions. The latter are then responsible for passing the knowledge and skills on to the rest of their team. BIM Champions are also asked to use their experience to provide suggestions on how to maximize the use of BIM, and to report the challenges they encounter. The combined result of CRL's and each contractor's training program results in a waterfall model for knowledge and skill transfer similar to that depicted in Figure 4.4, where training is passed from CRL to the contractor and its specific teams, and then again back to CRL.

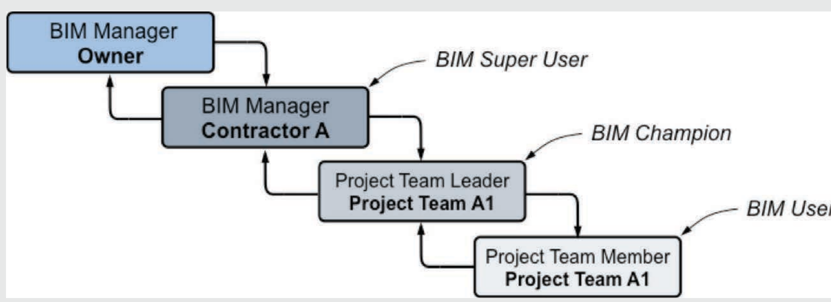


Figure 4.4. Waterfall model for BIM training in CRL.

The last pillar of BIM training in CRL is collaboration between CRL and higher education institutions. While this strategy has not been fully exploited in CRL, it is becoming one of the major focus points in future projects such as High Speed Two (HS2) Ltd.

CRL is also envisioning training document controllers to automate workflows in its EDMS. In CRL, only 18% of the information is stored in the ECMS (3D CAD data), as opposed to 75% that resides in the EDMS (non-graphical data and documentation). Thus, they believe training the controllers for automating the workflow process in EDMS can save time and money. Currently, there are some process- and skill-oriented challenges that need to be overcome to enable this profitable feature.

4.3.4 Governance and Policy Issues

1. With the advent of CIM in project delivery, a common misconception can arise regarding the risk of errors. It has to be understood that the digital or electronic mode of executing projects can provide several benefits and efficiency improvements. However, the risk and liability of errors involved in the processes do not necessarily shift with digital data. Policywise, agencies should give due importance to technical specifications, disclaimer and liability clauses, and risk-sharing mechanisms for digital data, among others. They have to consider adding language in contracts to resolve such issues.
2. Lack of clarity and consensus on the legal clauses (statutory laws and agency rules) for the use of digital signatures and digital deliverables is another critical policy issue. Some specific issues under this category include the following:
   - Legislation governing these activities (e.g., states' engineering practice acts) preceded development of model-based drawings and specifications for projects and lack effective provisions addressing such documents. For example, while there are clear guidelines for signing and sealing documents related to plans, specifications, drawings, and reviews, many states have not treated models as a "signable" piece of information or as a formal contract element. While it might take time to change this situation, the agencies can consider contacting states (such as Kentucky) that have conducted pilot projects with models as contract documents.
   - Existing guidelines for encryption tools to protect signatures vary considerably from one state to the other—with some states not mentioning the necessary security measures and others providing detailed guidelines for their use. For example, State A allows its engineers to electronically copy the original hard copy of their work (seal, signature, and date) in lieu of electronic signature, while in State B, this procedure for generating electronic signatures is prohibited. In addition, State B has laid down detailed guidelines regarding the nature of encryption for securing the signatures.
   - Lastly, the agencies have to develop specific guidelines for using digital signatures for various CIM functions that currently do not have them. For example, consider using CIM for design coordination and clash detection. There are liability issues that agencies have to consider when combining information models from disparate sources to perform this task. The entire model cannot be treated and signed as one engineering work product because the modeler (say Design-Builder) may not have the expertise to validate very fine details of some specialty trades. In such cases, the agencies have to devise suitable rules for sharing/transferring the risks, and explicitly outline responsibilities should discrepancies arise. With the possibilities of embedding digital signatures on models becoming more conceivable, there have to be guidelines for the responsible personnel about signing and maintaining the data.
3. Governance and policy issues take time, resources, and commitment from various stakeholders to be resolved. Thus, the agencies can try adopting managerial strategies that build a cooperative and trustful environment when established guidelines do not yet exist. Partnering can be an important strategy to engage stakeholders especially when agencies are considering new processes. At the project level, project team building and information sessions can be conducted to ensure alignment and coordination of team members. Case Example 11 enumerates a checklist of measures that agencies can consider when dealing with legal issues for CIM functions.

4.3.5 Information Management

1. Data is the primary requirement for successful CIM implementation. Most of the advanced CIM functions that are enabled by the relevant CIM tool must be supported by data. Agencies shall consider developing enterprise-level repositories that can meet all the CIM data requirements of

Case Example 11: A Checklist for Using Digital Intellectual Property on Transportation Projects.

- Defining software usage to avoid interoperability issues and information loss
- Ascertaining pertinent federal and state agency laws affecting usage of digital intellectual property on projects
- Apportioning responsibilities for maintaining and updating models
- Specifying ownership and copyright issues of 3D models
- Protecting collaborators on models, such as through "read-only" files, access control, and disclaimer clauses
- Establishing conflict and dispute resolution mechanisms (e.g., if discrepancies arise between 3D model and plan sets, priority should be given to plan sets)
- Utilizing partnering and team building exercises on projects to avoid potential disputes
- Defining Public Information and disclosure issues
- Devising plans to deal with trade secrecy (e.g., contractor resistance to providing digital data to owner to avoid "loss of future business;" potential liability associated with faulty data)
- Understanding digital signatures and their utility on projects
- Using strategic decisions by the government and regulatory authorities to accelerate the implementation of digital technologies. They pave the way for uniform implementation of technologies across organizations and their projects.

Sources: Adapted and extended from *NCHRP Legal Research Digest 58* (Thomas 2013) and case studies.

a facility's life cycle—from surveying through O&M. Existing asset management databases can be improved to achieve this objective. This process also requires strong management backup and collaboration between all the divisions and IT Support Groups at the agency. This process can be initiated by meeting the individual functional needs and then integrating them across the organization. Case Example 12 explains the pilot effort of an agency collecting data and creating a central repository for utilities. Case Example 13 discusses UPlan, a popular GIS-based information system used for asset management and project development.

2. Ensuring the timely accessibility of the intended version of data to all stakeholders remains an industry-wide challenge. The benefits of CIM can be maximized when this objective is achieved. It would require sustained efforts and coordinated planning and execution from agencies to make this process a reality.
3. Agencies need to develop strategies for archiving digital data (model-based information). Currently, archival processes are limited to document-based electronic data from projects such as plans sets along with the native CAD files (see Case Example 14). Such archiving practices may be insufficient to meet the life-cycle needs at the agency level. With CIM implementation, it is now possible to envision geospatial model-based archives of an agency's highway systems. CIM tools for rapid data collection (such as mobile LiDAR and UAVs, among others) and processes to update as-built information digitally can make this task possible in the future.
4. The most important issue that an agency has to consider is heterogeneity in the as-built information. Information from construction sites or as-built data collection efforts comes in a variety of formats—2D as-builts, 3D electronic, and 3D point clouds, among others. Agencies can consider developing processes to mine this information to meet the needs of asset management and future project development.

Case Example 12: Pilot Effort for Agency-Wide Utility Data Collection and Management—MUCC GUIDE, MDOT.

The overall objective of the Michigan Utility Coordination Committee's (MUCC) Geospatial Utility Infrastructure Data Exchange (GUIDE) is to improve the spatial quality of the location information of underground utilities by accurate tracking at the time of installation and creating a central repository for storing it. In 2014, the Committee laid out plans to achieve these objectives in seven pilot projects with cooperation from major stakeholders, including all the relevant utility companies. It is expected that this effort will form the foundation for improving the predictability and certainty in project management processes.

The concept was validated, and lessons learned and best practices were recorded from this pilot initiative. Key issues were identified in the data collection and storage process (such as data format, attribute information, QA/QC review, final revision, and upload to the repository), IT infrastructure (meeting resource requirements for long-term maintenance), training process, and coordination efforts between surveying staff and contractor's crew. Lack of information to quantify delay in construction specific to utilities was also acknowledged. A cost estimate of preparing and maintaining the GUIDE, as observed from the utility companies participating in the pilot projects, was also recorded.

Source: Barden (2014).

5. Consider engaging personnel from O&M for review during detailed design. Some of the data needs for the life cycle from O&M and asset management can be incorporated into the early stages of a project. For example, agencies can consider tagging an asset with an identification number (ID) as they design them. Designers should ensure availability of this information by requesting the ID from asset owner (agency). This ID can then hold references to important document- and data-based information (such as traffic) specific to that particular asset. It also enables the entry of the asset in the TAM database during the design stage. As a result, maintenance personnel can benefit from this pro-active design strategy because they will then have access to the pertinent data as needed.
6. Ensure clarity around handover requirements (in contracts/specifications) and details regarding what information is to be delivered to stakeholders and obtained from them (especially contractors). This is essential for devising strategies for archiving digital data and asset management. When there are both digital- and document-based deliverables, it has to be ensured that they convey similar information, although with varying levels of detail.
7. Reverse engineering the models from document-based data is not always advantageous. Some contractors might use this practice for creating surface models for AMG operations, but it is essential that agencies recognize the related issues. This procedure increases the probability of errors because the original design intent may be lost. It can also create redundancies since the same information is created twice. Thus, agencies can consider taking necessary steps to preserve data integrity and provenance, assuring that the data is the same as the design intent in subsequent uses. In this case, the agency can include clauses in contracts explicitly mentioning the activities of roadway construction that would require model-based AMG operations. They can also examine providing contractual priority to 3D models to streamline the process of using the electronic data directly for AMG.

Case Example 13: GIS-Based Asset Information Management Systems—UPlan.

UDOT implemented two GIS-based tools that provide a powerful platform for asset management and project development processes—UPlan and UGate.

UPlan is a powerful, easy-to-use GIS and cloud-based information tool that supports decision-making processes during the complex planning and project development tasks through efficient data sharing among diverse state units in a state DOT. It is now promoted as "UPlan Phase II" through the AASHTO Innovation Initiative Program. The portal can provide access to the following information: safety projects and crash analysis tool, UDOT Culverts Map, UDOT Maintenance Station Gallery, UDOT Pavement Management Map, the 2012 AADT map, UDOT Projects Map, UDOT Asset Management Map Gallery, Unified Transportation Plan Map (2011–40), and Access Inventory Map. UGate facilitates access to the data behind the dynamic maps and analytical tools found in UPlan, enabling sharing of the information with businesses, UDOT partners, the public, and other interested stakeholders. It provides information data in KML and other open formats that are compatible with open, public services such as Google Maps.

Some of the stated benefits of the system include cost-effective solutions (since the process is cloud-based), better communication with governmental agencies and other stakeholders, elimination of duplicate or redundant data, improved data quality through spatial integration, better access to data for all stakeholders, ease in integration of environmental and economic issues in the planning process, and effective public participation. Although there is no set procedure for estimating the ROI for the system, "an extensive independent study estimates that UDOT's long range planning efforts will result in a net benefit to the state of Utah of $1.8 billion." Reported benefits also included a savings of $300,000 in FY2012 through improved workflow and data management, savings due to LiDAR-based asset management process ($250,000/year), and an increase in benefits to partners in local government and private sector (around $2 million per year).

Source: UDOT (2014) and NASCIO (2013).

Case Example 14: Document Management System for As-Builts: PEDDS—FDOT.

Professional Electronic Data Delivery System (PEDDS) is a project-centric application developed by FDOT to archive electronically produced plan sets and other project documents that can be used for construction and storing as-builts. The application stores the agency-wide information on various projects in a database called PEDDS Database (PEDDS DB). It has features for creating, managing, authenticating, and synchronizing several project instances. It can also create and control the accessibility of different signatories who will be utilizing the database through the course of the project. Recent advancements in the PEDDS system can support digital archives using LandXML formats.

Source: FDOT (2008).

CHAPTER 5

Supplemental Resources

The research team employed a variety of strategies to collect the required information for this research—an extensive literature review, two nationwide surveys, and case studies. This section presents key findings from the data collection efforts that could act as supplemental resources for CIM implementation.

5.1 Literature Review—Summary

The adoption of information modeling has had a significant increase worldwide in the areas of building, infrastructure, and construction management. Much of the literature refers to BIM (building information modeling), which has been widely deployed on construction projects of all types. This report differentiates CIM as referring specifically to technologies and processes for infrastructure. In other reports, the terms BIM and CIM have been used interchangeably. Sometimes the term "BIM for infrastructure" is used. The literature review below refers to BIM when reporting broad findings, and CIM or BIM for infrastructure when reporting on applications specific to the infrastructure sector.

The percentage of companies using BIM jumped from 17% in 2007 to 71% in 2012 in North America. Some of the interesting findings from the Dodge Data & Analytics' 2012 report on the "business value of BIM for infrastructure" are presented below. (This survey involved 466 respondents across various infrastructure sectors in the United States.)

- Of all users, 67% reported a positive ROI for BIM use on infrastructure projects. Respondents were asked to estimate ROI in seven broad categories: negative, break-even, less than 10%, 10 to 25%, 26 to 50%, 51 to 100%, and over 100%.
- Of current users, 79% expected to be using BIM on more than 25% of their infrastructure projects by 2013.
- Top benefits included reduced conflicts and changes (58%), improved project quality (48%), and lower project risk and better predictability of project outcomes (60%).

The areas reported to require assistance in implementation include software interoperability, workforce education/training, and legal and contractual issues. The road transportation sector has seen a significant increase in CIM adoption from 2009 to 2012. The acceptance of the model-driven approach for design and construction reiterates the need for all stakeholders to devise a tailored approach and establish guidelines in their respective agencies to facilitate seamless transition to digital project delivery and asset management (Dodge Data & Analytics 2012). "BIM, which began primarily as a design tool then evolved to a must-have for leading contractors, is now rapidly gaining traction with owners around the world" (Dodge Data & Analytics 2014).

With specific reference to the transportation projects executed by state agencies (DOTs), a recent literature review revealed the following statistics on CIM usage levels (FHWA 2013).

- States reported varying levels of 3D model usage (some are advanced while some model the basic roadway prism).
- Twenty-three agencies reportedly have already transitioned to 3D modeling.
- Seven agencies were using only traditional 2D plans and profile sections.
- Fifteen agencies stated that they were transitioning to 3D modeling.
- Agencies reported using n-D modeling software from several vendors.
- Slightly more than one-half of the agencies reported using some type of LiDAR technology (aerial, static, or mobile).

The research process also considered other references such as academic journals, relevant BIM standards, research reports, and open articles, among others. The data collection efforts were also expanded outside the highway infrastructure area to capture some of the recent developments in other sectors and in other countries. Following are some important observations.

- In the United States, the U.S. Army Corps of Engineers and the General Services Administration have been implementing BIM and other modern technologies on public infrastructure projects. They have also been actively involved in devising a suite of BIM guidelines and standards (Dodge Data & Analytics 2012). The U.S. Department of Veterans Affairs (VA) developed an implementation guide, and began implementing BIM on all projects that exceed a $10 million starting design beginning in 2009. The specifications are vendor-neutral and apply to design and construction by the architects, engineers, other consultants, and contractors hired for those projects by the VA (U.S. Department of Veterans Affairs 2010).
- In the United Kingdom (UK), implementation of BIM in the multi-billion-dollar Crossrail project has proven quite beneficial in several ways. It offers valuable insights about deploying digital project delivery and asset management on a large-scale transportation project. The project presents significant opportunities to understand BIM implementation at both the agency and project levels (Munsi 2012).
- Another major initiative from the UK is the government's decision to make BIM compulsory on all public projects by 2016. The regulation mandates a shift to Level 2 utilization mark for BIM. Special interest groups such as OPEN BIM and BIM for Infrastructure (UK) have been instituted to study the benefits, challenges, and risks associated with promoting digital project delivery for infrastructure projects (Government Construction Client Group 2011).
- In Singapore, the Building Construction Authority has made BIM-based electronic submission mandatory on projects for regulatory approval. While this requirement is being implemented in phases (depending on the size of the project), the system had been tested on many projects and it has proven successful (Seng 2012).
- France has also taken a significant initiative through a large 10-year, multi-billion-euro project involving the National Institute of Geographic and Forestry Information and major utility companies to map its entire underground utility infrastructure in 3D to an accuracy of 16 in. (Zeiss 2014).

Performance indicators for measuring BIM benefits can be subjective. Nevertheless, researchers and practitioners have proposed several performance metrics that agencies can consider using for quantifying CIM benefits. The various metrics that fall under the investment category include the following:

- *Architecture and engineering costs:* The ratio of BIM engineering costs to the cost of total scope awarded in engineering.
- *3D background model creator costs:* The ratio of the BIM cost of 3D background model creation to the total design cost.
- *Contractor costs:* The ratio of BIM contractor costs to the cost of construction.

These ratios isolate the percentage of work accomplished using BIM. Other suggested metrics include reduction in the number of RFIs, change orders, and schedule savings (Barlish and Sullivan 2012).

Stanford University's Center for Integrated Facility Engineering published a technical report that formulates and validates a scorecard for Virtual Design and Construction (VDC) for construction projects. It ascertains the maturity level of VDC implementation of a project across 4 areas, 10 divisions, and 56 measures. Developed with an adaptive scoring system based on evolving industry norms, it meets the goal of making the scorecard quantifiable, evolving, holistic, and practical. The research team collected data from two countries in North America, five in Europe, four in Asia, and one in Oceania. It covers a total of 108 projects from 11 facility types (Kam et al. 2013).

5.2 Current State of Practice—Survey Results (Key Points)

The literature review revealed that no project or agency has systematically implemented CIM in its entirety. Moreover, agencies have different levels of expertise in dealing with several CIM technologies. A nationwide survey of DOT practices was conducted to comprehend the variety of tools actually being deployed on their projects. Moreover, these surveys were designed to understand the drivers and the constraints pertinent to the advancement of these technologies for projects. Two questionnaires were prepared to address this objective—an agency survey and a project survey. The key inferences from the survey results are described below.

- The main issue for integrating CIM is in recognizing the convergence of analog to digital to analog data across phases/interface points. Agencies need to work on eliminating barriers to digital transfer of information across interfaces.
- Of the respondents surveyed, 76% reported using electronic information management systems for document management and controls on their projects.
- Although contract provisions are not instituted by all the agencies, 71% of respondents believe that adding clear contract provisions on technology implementation and associated attributes would help channelize the efforts toward effective CIM deployment.
- Many agencies have incorporated 3D modeling at varying levels based on the project characteristics; 41% of the agencies reported using 3D tools for visualization. However, in all the agencies surveyed, 2D plan sets continue to dominate in contract documents over 3D models.
- Modeling in 4D and 5D has been used predominantly on those projects with complex construction sequencing (such as major detours for bridges) to facilitate visualization and communication among stakeholders. Of the 38 responses for this area, 12% and 6% reported to be utilizing 4D and 5D respectively, showing that they remain emerging tools.
- Many transportation agencies have invested in collecting LiDAR information on the facilities being built and have been employing it for facility management (such as recording bridge clearances and inventory of assets).
- Participants agreed that AMG using 3D design and IC has proven benefits. However, nonstandardization of the associated design processes and initial investment costs of these technologies has been cited as a major reason for their lower utilization level. Sixty-eight percent of the respondents reported deploying AMG technology (albeit not including finished surface stringless concrete/asphalt construction) and around 45% of the agencies reported investing in IC.
- Respondents also have varied perceptions on ROIs for these technologies. They cited the nonavailability of a uniform methodology to guide the investment decisions as the primary concern. However, there was also consensus on the point that such tools can be subjective and specific to a particular agency's business or its project environment.

- Training programs are important and have to be considered as a process, rather than one-time events. While some of the respondents understood CIM as process oriented, some still considered CIM as a finite set of technologies. The importance of standardizing electronic deliverables and specifications to streamline the information exchange process was also highlighted.
- At the project level, respondents had varied perceptions of improvements in specific performance areas. While some believed that the CIM technologies benefitted projects in terms of better cost (especially avoidance costs through clash detection) and schedule performance, others perceived maximum advantages in the areas of safety and a reduction in the number of RFIs and construction inspections (QA/QC checks).
- Interestingly, 70% of the projects surveyed had not performed an internal ROI analysis for the technologies used on projects. However, many agencies have undertaken initiatives to study the requirements of training, hardware, and software that they use on projects and document the investments being made to improve the processes.

INFERENCES FOR CIM TOOL CATEGORIES

Cumulative Usage Level of CIM Technologies

- Applications under 2D category are dominant in all the phases (in line with traditional practice, contractual issues)
- Design and construction phases recorded maximum usage of CIM (transition due to innovation/better tools for processes involved)
- O&M phase reported lowest overall usage of CIM technologies (especially 3D/nD)—area for future improvement

Usage of 2D and 3D/nD Technologies

- 4D and 5D modeling appear to be in emerging areas of application (likely to increase in future)
- CIM for visualization is gaining significance, more agencies in favor of it
- 3D CADD (implementation of CAD/DGN electronic data) had the highest usage

Usage of Surveying Technologies

- CIM for utility coordination and IC recorded low usage levels (likely to increase in future)
- GIS and GPS recorded highest usage levels (as per expectations since they have numerous applications)
- LiDAR recorded significant usage levels (need to investigate application areas)
- AMG shows encouraging trend (necessary to study AMG application for individual activities)

Usage of Data Management Technologies

- Data connectivity (other than cellular towers) recorded the lowest usage (need to study further as RTN/CORS GPS networks are more common)
- Material management systems and digital signatures seem to be emerging applications
- Electronic updating and archiving of plans recorded the highest usage (may relate to actual base/master files or 2D plans sheets)

5.3 Case Studies—Lessons Learned

The research team decided to balance the data sources taken from the case study projects (those for which the pertinent agencies responded to the project survey) and interviews with CIM subject matter experts. The chosen candidates are listed below:

Projects

1. Rotary upgrade to modern roundabout (CTDOT)
2. Relocation of KY7 in Elliott County (KYTC)
3. Fore River bridge replacement project (MassDOT)
4. Kiewit case study on I-70 project (CDOT)
5. Parksville Bypass bridge project (NYSDOT)
6. I-96 Livonia construction project (MDOT)
7. Crossrail Ltd. (UK)

Subject Matter Experts

1. Lance Parve (CIM Design-Construction Engineer, SE Freeways, WisDOT)
2. Ron Singh (Chief of Surveys/Geometronics Manager, ODOT)

Some of the case studies identified through the secondary resources are as follows: WisDOT's SE Freeway project, TxDOT's Dallas-Fort Worth Connector Project, AASHTO's UPlan, and Michigan DOT's "e-construction" initiative. Although these present significant learning opportunities for CIM, separate case studies were not conducted because they overlap in scope with other ongoing TRB and NCHRP research efforts on CIM, identified in Appendix A (in particular NCHRP Project 20-68A, Scan 13-02: "Advances in Civil Integrated Management").

The salient characteristics of the projects are enumerated in Table 5.1.

CIM implementation was analyzed in-depth for each of the case studies. Several recommendations were elucidated from the projects. Table 5.2 presents the key inferences.

Table 5.1. Characteristics of the case study projects.

No.	Project	Agency	Project Delivery Method	Approx. Project Cost ($M)	Actual/ estimated completion dates*
1	Rotary upgrade to modern roundabout	CTDOT	D-B-B	1.45	Apr. 2016
2	Kiewit case study on I-70 project	CDOT	D-B-B	18	Sep. 2013
3	Relocation of KY7 in Elliott County	KYTC	D-B-B	26.5	June 2016
4	Kosciuszko Bridge Project	NYSDOT	D-B	555	Nov. 2017
5	I-96 Livonia construction project	MDOT	D-B-B	124.1	Jan. 2015
6	Fore River bridge replacement project	MassDOT	D-B	300	Sep. 2016
7	Crossrail Ltd. (UK)	Crossrail	Various	20,000	2019

Note: D-B-B refers to the design-bid-build method and D-B denotes the design-build method.
* The estimated completion dates were obtained at the time of the case study and may have changed.

Table 5.2. Summary of lessons learned from case studies.

Agency/relevant CIM practices examined	Lessons learned
CTDOT case study/ 3D design for roadway elements, electronic engineered data (EED) for deliverables	Standardizing EED deliverables for 3D design is a significant step in ensuring seamless transfer of project information across all stakeholders. 3D design can be performed in a cost-effective manner for smaller projects (project characteristics and availability of good quality survey data are the driving factors).
KYTC case study/ 3D design pilot project, AMG, unique "special note" for priority to 3D model	It is beneficial to use continuous breaklines and close attention should be paid to design, detailing, and modeling complex elements of roadways (such as intersection, gore areas, lane additions/drops, and widening for guardrail). For AMG, it is important to specify explicitly in contracts the specific construction processes using AMG (such as grading). Leadership buy-in and expert guidance are major factors.
MassDOT case study/ CIM for steel bridge, 3D modeling for structures	3D modeling can be very useful for tasks such as Environmental Impact Assessment, alternative analysis during preliminary design, and clash detection and clearance analysis, among others. Effective change management (especially during schematic-detailed design) is critical for the successful integration of model-based design with project development processes.
CDOT case study/3D CAD modeling and visualization	Performing pilot projects, workforce-training programs, collaboration with other agencies, and contractor innovation/participation can help promote successful application of CIM technologies.
NYSDOT case study/ Surveying specs, 4D/5D modeling, project controls	Updating survey specifications to suit "automated stakeout" and allowing contractor to provide equipment for QA/QC can facilitate agency-wide AMG adoption (625 specs). 5D modeling can be used to actively monitor progress, calculate quantities (earthwork), and control payment to contractors.
MDOT I-96 case study/ e-construction initiative, traffic simulation, a guide for data exchange for managing utilities	The agency now has implemented tools to support electronic document management with digital signatures for approvals, reviews, archiving, and change management. Visualization tools (3D and traffic simulation tools) proved effective for Public Information. Key points for the agencies include the following: Core competencies that a DOT needs to retain, staff, how many personnel, and their qualification and experience backgrounds. Sight set on future and the tools to use; aim for enterprise-wide data management. Solid foundations for geospatially identified data.
Crossrail case study	Contracts, execution plans, and standards are the three main documents that can operationalize the widespread deployment of several CIM processes. Life-cycle integration of CIM involves considering issues from the project conception to completion and handover. Besides training and investments in IT infrastructure, CIM implementation requires a cultural shift in the organization's business functions. Government legislation can also help accelerate and motivate the deployment of CIM by all project stakeholders.

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Acronyms

AMG	Automated Machine Guidance
ATC	Alternative Technical Concepts
BIM	Building Information Modeling
BYOD	Bring Your Own Device
CAD	Computer Aided Design
Caltrans	California Department of Transportation
CCO	Construction Change Order
CDOT	Colorado Department of Transportation
CII	Construction Industry Institute
CIM	Civil Integrated Management
CIP	CIM Implementation Plan
CM/GC	Construction Manager/General Contractor
CORS	Continually Operating Reference Stations
CRL	Crossrail
CTDOT	Connecticut Department of Transportation
D-B	Design-Build
D-B-B	Design-Bid-Build
DDMI	Document-, Data-, and Model-Based Information
DOT	Department of Transportation
DTM	Digital Terrain Model
ECMS	Electronic CAD Management System
EDMS	Electronic Document Management System
EED	Electronic Engineered Data
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GIS	Geographic Information Systems
GPR	Ground Penetration Radar
GPS	Global Positioning System
IC	Intelligent Compaction
IFC	Industry Foundation Classes
IMP	Investment Prioritization Matrix
IMS	Integrated Measurement System
INDOT	Indiana Department of Transportation
ITS	Intelligent Transportation System
KYTC	Kentucky Transportation Cabinet
LiDAR	Light Detection And Ranging
LOD	Level of Detail
MassDOT	Massachusetts Department of Transportation

MDOT	Michigan Department of Transportation
MnDOT	Minnesota Department of Transportation
MoDOT	Missouri Department of Transportation
nD	n-Dimensional
NPV	Net Present Value
NYSDOT	New York State Department of Transportation
O&M	Operations and Maintenance
ODOT	Oregon Department of Transportation
PEDDS	Professional Electronic Data Delivery System
PS&E	Plans, Specifications & Estimates
QA/QC	Quality Assurance/Quality Control
QTO	Quantity Take-Offs
RFI	Request for Information
RFID	Radio Frequency Identification
ROI	Return on Investment
ROW	Right of Way
RTN	Real Time Network
RTS	Robotic Total Stations
TAM	Transportation Asset Management
TCP	Traffic Control Plan
TS	Total Stations
TxDOT	Texas Department of Transportation
UAV	Unmanned Aerial Vehicle
UCM	Utility Conflict Matrix
UDOT	Utah Department of Transportation
VDC	Virtual Design and Construction
WisDOT	Wisconsin Department of Transportation
WSDOT	Washington Department of Transportation
XML	Extensible Markup Language

APPENDIX A

Catalog of CIM Resources

Table A.1 presents the resource list of important CIM tools and functions as obtained from the FHWA, DOTs, and other data sources. A brief description of each resource is also provided. It has to be noted that this list can become outdated. The research team suggests that agencies consider revising this table (or a similar catalog for CIM resources) periodically.

Table A.1. Resources catalog for CIM functions.

Document/Resource No.	Category	Title/Description
General Technology Synthesis and Data Management for CIM		
FHWA EDC resources	Website	FHWA resources for 3D Engineered models for construction (http://www.fhwa.dot.gov/construction/3d/webinars.cfm)
UDOT's 3D Implementation Plan	Report	A strategic agency-level document that identifies vision, short-term and long-term plans for implementation of CIM (http://www.udot.utah.gov/main/f?p=100:pg:0:::1:T,V:4450)
FHWA-HIF-12-014	Report	Identifying existing and emerging technologies in the area of intelligent construction of highways—systems, components, processes, and software.
NCHRP Synthesis 446	Report	*Use of Advanced Geospatial Data, Tools, Technologies, and Information in Department of Transportation Projects*
FHWA-IF-05-025	Report	*Innovation in Vertical and Horizontal Construction: Lessons for the Transportation Industry*
NCHRP Synthesis 372	Report	*Emerging Technologies for Construction Delivery*—usage of GPS, handheld computers, automated temperature tracking, 4D CAD modeling, and remote project monitoring with web-based video cameras.
Autodesk infrastructure case studies	Reports	A portal consisting of Autodesk's customer infrastructure projects across the globe. http://www.eni-projects.com/infrastructure/customer-showcase/article-list.html
Bentley user stories	Reports	A portal consisting of Bentley's customer infrastructure projects across the globe. (http://www.bentley.com/en-US/Engineering+Architecture+Construction+Software+Resources/User+Stories/)
WisDOT webcast series	Webcast	Series of presentations that shows how CIM is transforming the planning, design, and construction of highway projects. (http://usa.autodesk.com/adsk/servlet/pc/index?id=19561066&siteID=123112)
NCHRP 20-68A, Scan 13-02 (Active)	Report	*Advances in Civil Integrated Management*—A U.S. domestic scan program to identify advances in CIM.
Engineering automation	Report	An ODOT document illustrating the key concepts that should be included in the agency's future automation plans for digital project delivery and asset management. (http://www.oregon.gov/ODOT/HWY/GEOMETRONICS/docs/dozer/engineering_automation-key_concepts-8mar2009.pdf)

Table A.1. (Continued).

Document/Resource No.	Category	Title/Description
VDC scorecard	Report	Developed by the Center for Integrated Facility Engineering, the VDC Scorecard provides an assessment methodology that is adaptive, quantifiable, holistic, and practical to measure levels of VDC implementation. (https://vdcscorecard.stanford.edu/content/vdc-scorecard)
FDOT CIM Workshop 2012	Workshop	A workshop conducted at FDOT to train DOT personnel in several key areas related to CIM. (http://www.dot.state.fl.us/structures/DesignExpo2012/CIM2012.shtm)
ODOT Design to Paver 2014	Workshop	An “Every Day Counts” activity supported by the FHWA that gave audiences hands-on training of several intelligent construction systems and technologies. (http://designtopaver.org/)
Advanced Surveying Methods		
NCHRP Report 748	Report	*Guidelines for the Use of Mobile LiDAR in Transportation Applications*—management and decision-making and technical considerations.
LiDAR technology evaluation report	Report	An analysis of the current state of laser-based technology and its applicability, potential accuracies, and information content with respect to MoDOT applications.
Synthesis of Transportation Applications of Mobile LiDAR	Journal article	A thorough review of available literature about advancements in mobile LiDAR technology, techniques, and current and emerging applications in transportation.
LiDAR Applications for Transportation Agencies	Report	A WisDOT report focused on principles, types, and technical issues of LiDAR technology. (http://wisdotresearch.wi.gov/wp-content/uploads/tsrlidarapplications1.pdf)
Leveraging LiDAR for Asset Management Leap	Concept article	A UDOT article focused on applying LiDAR technology for improving asset management. (https://www.udot.utah.gov/public/ucon/uconowner.gf?n=8336606666333974)
NCHRP Report 506	Report	*Quality and Accuracy of Positional Data in Transportation*—a guidance report for practitioners on the use of positional or spatial data in GIS for transportation applications.
ASPRS Guidelines	Reports	A series of reports on guidelines and specifications for all types of LiDAR and its various aspects. (http://www.asprs.org/Divisions/Lidar-Division.html)
http://mobilelidar.blogspot.com/, www.lidarnews.com	Websites	Often-cited websites consisting of articles by service providers and vendors of projects as well as experiences with LiDAR.
Point cloud library	Library	An open-source library of algorithms for point cloud processing tasks and 3D geometry processing. (http://pointclouds.org/)
3D-4D CAD Modeling		
3D Engineered Models for Highway Construction: The Iowa Experience	Report	An implementation manual that describes the usage of advanced surveying tools for 3D data collection, 3D design of engineered models, and application of 3D models for construction. (http://publications.iowa.gov/20318/1/IADOT_InTrans_RB33_014_Reeder_Implementation_Manual_3D_Engineered_Models_Highway_Const_2015_Final.pdf)
4D CAD for highway construction projects	Report	A case-study-based analysis of various aspects of implementing 4D CAD on construction projects. (https://www.engr.psu.edu/ae/cic/publications/TechReports/TR_054_Platt_2007_4D_for_Highway.pdf)
3D Roadway design manual(s)	Design Manual	ODOT’s and Iowa DOT’s highway design manuals for providing guidance for delivery of roadway digital design elements (including 3D design) for use by contractors and the agency’s construction administration staff on state highway projects. (ftp://ftp.odot.state.or.us/techserv/roadway/web_drawings/HDM/2011%20HDM%20Rewrite/2012%20Chapter%2016%203D%20Roadway%20Design.pdf) (http://www.iowadot.gov/design/dmanual/manual.html?reload)

(continued on next page)

Table A.1. (Continued).

Document/Resource No.	Category	Title/Description
FHWA Webinar series	Webinars	Info for local, state, and federal highway agencies, as well as consultants, surveyors, equipment manufacturers, software developers, and contractors who are involved in designing and constructing transportation facilities. (https://www.fhwa.dot.gov/construction/3d/webinars.cfm)
Advanced Modeling Techniques for Enhanced Constructability Review	Report	A survey of state practice and related research in state DOTs who are employing 3D modeling and other types of advanced modeling techniques for developing highway infrastructure improvements. (http://www.efl.fhwa.dot.gov/files/technology/Caltrans-Enhanced-Constructability-Review.pdf)
Intelligent Compaction		
NCHRP Report 676	Report	*Intelligent Soil Compaction Systems*—an investigation of IC systems and the development of generic specifications for the application of IC in QA of soil and aggregate base material compaction.
Intelligent compaction data guidelines	Report	A MnDOT research report provides guidelines for IC data viewing and exporting in order to make use of a third-party, independent IC data management tool, Veda. (http://www.intelligentcompaction.com/downloads/software/IC_Data_Guidelines-3.0.pdf)
FHWA-IF-12-002	Report	*Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials* (http://www.fhwa.dot.gov/pavement/ic/pubs/hif12002.pdf)
FHWA IC case studies	Tech brief	http://www.fhwa.dot.gov/construction/ictssc/pubs/hif13053.pdf http://www.fhwa.dot.gov/construction/ictssc/pubs/hif13052.pdf
Evaluation of intelligent compaction technology	Report	A WisDOT research report that illustrates IC's advantages and limitations, necessary conditions, and recommendations for WisDOT. (http://wisdotresearch.wi.gov/wp-content/uploads/08-07icforsubgrades-f.pdf)
Intelligent Compaction	Website	A compilation of IC documents and resources ranging from articles and reports to a glossary of terminology. (http://www.intelligentcompaction.com/learn/resources/)
Automated Machine Guidance (AMG)		
WisDOT HMA base specifications (AMG)	Report	Implementation of 3D Technology and Development of AMG Specifications for Placement of HMA Base Course Material (http://tinyurl.com/AMG-HMA-base-WisDOT)
NCHRP Project 10-77 (Active)	Report	Report developing guidelines for use of AMG technology for state transportation agency construction projects.
Quick reference guide for implementing AMG	Report	An AASHTO Subcommittee of Construction document that addresses stages of implementing AMG. (http://construction.transportation.org/Documents/Technology%20and%20Computers/QRG%20AMG-Final.pdf)
Best practices – MnDOT	Report	A two-phase project that focused on identifying issues limiting the increased use of the technology and formulating recommendations to meet the agency's goal of increasing the use of machine control technology. (http://aii.transportation.org/Documents/BestPractices-MachineControlEvaluation_FinalReport(MnDOT).pdf)
Machine Control Online	Website	A website that contains articles on current issues related to implementing AMG. (http://www.machinecontrolonline.com/)
Construction machine automation plan	Report	A six-year plan developed by ODOT for implementing full-scale machine automation. (http://www.oregon.gov/ODOT/HWY/3DRDM/REFERENCES/6-yearConstructionMachineAutomationPlan.pdf)

Table A.1. (Continued).

Document/Resource No.	Category	Title/Description
Utility Engineering		
NCHRP Synthesis 405	Report	*Utility Location and Highway Design*—current practices in use by transportation agencies for considering utilities during the project development process—policies, guidelines, regulations, and manuals.
SHRP 2 Report S2-R15-RW	Report	Integrating the priorities of transportation agencies and utility companies so as to achieve coordination and respective goals.
SHRP 2 Report S2-R15B-RW-1	Report	*Identification of Utility Conflicts and Solutions*—reviewing trends across the country and identifying best practices, standardizing UCM, and developing training materials and implementation guidelines.
Imaging and Locating Buried Utilities	Report	An INDOT research document that identified state-of-the-art practice in locating underground utilities and development of a decision-support tool to assist practitioners. (http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1585&context=jtrp)
Utility Investigation Best Practices	Report	A TxDOT research report that compiles best practices and the effects on TxDOT highway projects. (http://d2dtl5nnlpfr0r.cloudfront.net/tti.tamu.edu/documents/0-6631-1.pdf)
Alternative Contracting Methods and Legal Issues		
NCHRP Synthesis 379	Report	*Selection and Evaluation of Alternative Contracting Methods to Accelerate Project Completion*—a synthesis report on the state of practice in the process of selecting alternative contracting methods to potentially accelerate project completion. The report considered D-B, incentive-disincentive, cost-plus-time bidding, interim completion dates, and no-excuse incentives.
NCHRP Synthesis 455	Report	*Alternative Technical Concepts for Contract Delivery Methods*—identifying various methods by which transportation agencies have successfully implemented the ATC highway contracting process.
NCHRP Project 20-68A, Scan 07-01	Report	Best practices in project delivery management.
NCHRP Legal Research Digest 58	Report	*Legal Issues Surrounding the Use of Digital Intellectual Property on Design and Construction Projects*—developing an understanding of the use of digital intellectual property in design and construction projects.
Project and procurement selection matrices	Research document	A set of documents providing a formal approach for selecting project delivery methods and procurement procedures. (http://www.colorado.edu/ceae/TCM/acm.html)
NCHRP Project 10-85	Report	A guidebook for initiating and implementing a Construction Manager-at-Risk (CMR) project delivery system for highway projects.
Digital signatures in engineering documents	Report	An ODOT document outlining issues relating to the utilization of digital signatures on engineering-related documents. (http://www.oregon.gov/osbeels/docs/Resources/digitalsignatures.rev.september_2008.pdf)

APPENDIX B

Executive Briefing

This Executive Briefing is a PowerPoint slide deck for managers and others who need an overview of the definitions, benefits, and implementation considerations of CIM. The slide deck may be used in whole or in part. The Executive Briefing may be used apart from this Guidebook, however its primary intent is as a support for CIM champions using this Guidebook and, as such, those presenting the slides should be familiar with the contents of the Guidebook. The link to the PowerPoint slide deck is available on the NCHRP Project 10-96 web page at www.trb.org.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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