As advances in 3-D modeling technology make images like this one possible and traditional paper plans grow obsolete, how do we identify, organize, and track all of the data needed for each asset shown? Digital twins—virtual models of a physical object or system—may help agencies close the project development information gap and better organize data.

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Many state transportation organizations are searching for new technologies to provide quick and accurate collection, verification, and analysis of data to fill the void caused by reductions in staff and increases in work load” (1, p. 24). This sentence introduces an article, Laser Videodisc Technology Meets Changing Operational Demands, in TR News 176, a special theme issue on automation and robotics in highway design, construction, and maintenance. Unfortunately, many agencies still find themselves in this position today, a sobering 27 years after this issue’s publication.

The TR News article describes how the Connecticut Department of Transportation (DOT) implemented a program to scan the highway system with multiple sensors and store the resulting data set on laser videodisc, which was current technology in the mid-1990s. It describes how users across the department eliminated the need for 80 percent of their data collection field trips, saving an estimated $1 million in labor and travel costs and 200,000 miles of vehicle travel. The cost savings estimated from using the system to inventory the state’s signs alone were remarkable—from a cost of $1.3 million using manual methods to $0.5 million using the photolog.

The photolog vans collected images of the pavement and roadside, as well as geometric data, at a density of 100 data points per mile. The vans captured route numbers, direction of travel, roadway cross-slope, compass bearing, date, time, horizontal and vertical curvature, pavement roughness, grade, side friction, and vehicle speed. The information was stored digitally, and it was accessible. Agency staff could find the information for the road segment of interest easily. In 1994, Connecticut DOT produced a digital model, which was the first step toward creating a digital twin.

What Is a Digital Twin?
A digital twin is a virtual model of a physical object or system, and the bidirectional relationship between the
Using validated predictive analytics, a digital twin triggers timely intervention and maximizes agency operations and safety benefits. For example, if a driver crashes into a sign, the incident responder scans a barcode on the damaged sign, which changes its status. The change in status triggers a workflow to add the sign’s repair to the maintenance schedule. Speed sensors pick up the traffic slowdown, which creates an alert in the traffic operations center. Someone in the traffic operations center accesses a nearby camera feed, verifies the situation, and revises the variable speed limits in the corridor. Traffic continues moving at a safe speed until the incident is cleared.

It is harder to conceive of a digital twin application beyond safety and operations. The pace of change for highway assets is glacial compared to the industries where digital twins currently bring value. Highway assets undergo changes due to time, weather, incidents, and renewal activities that manifest as maintenance or construction projects. The largest changes occur during construction, but these are also the most controlled.

Digital twins analyze how the assets work together to provide insights on how to intervene to improve outcomes. Today, digital twins appear in places like manufacturing production lines. Sensors stream data to analytical models that monitor productivity and quality. The digital twins identify interventions in real-time to correct issues as they arise. Figure 1 shows how digital twins could be used for highway assets: Analytical models would use observation and sensor data from the physical asset, and they would produce visualizations and insights to support decision making. These decisions lead to interventions on the physical asset that result in the predicted or planned outcomes.

Digital twins would enable agencies to implement human-in-the-loop automation, a partially automated process that requires human input for higher order decisions. Sensors would automate repetitive tasks—like making and recording routine observations. Analytical models would conduct routine analyses of the sensor data, update dashboards, and trigger alerts when a decision needs to be made. Well-designed human-in-the-loop automation systems increase efficiency and safety. Currently, traffic operations centers are the closest to a digital twin implementation in the highway domain.

### Assessing the Need for Digital Twins

In How to Tell the Difference Between a Model and a Digital Twin, the authors argue that obfuscation and conflation of models with digital twins lead people to dismiss the entire concept as hype (2). Using validated predictive analytics, a digital twin triggers timely intervention and maximizes agency operations and safety benefits. For example, if a driver crashes into a sign, the incident responder scans a barcode on the damaged sign, which changes its status. The change in status triggers a workflow to add the sign’s repair to the maintenance schedule. Speed sensors pick up the traffic slowdown, which creates an alert in the traffic operations center. Someone in the traffic operations center accesses a nearby camera feed, verifies the situation, and revises the variable speed limits in the corridor. Traffic continues moving at a safe speed until the incident is cleared.

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Asset stewards could use digital twins to forecast conditions under cross-asset allocation scenarios to inform how to program maintenance and renewal actions. It is not clear, however, that a more sophisticated approach to programming maintenance and renewal activities using digital twins would bring more than marginal benefits; time scales and analytics are simply not that precise.

For now, we cannot build a business case for digital twins based on timely intervention. There are, however, many benefits to gain by pursuing a digital twin–ready model of the transportation system. Such a digital model would consolidate cross-functional asset information, resolving issues with interdisciplinary coordination.

### Cross-Functional Digital Models

Many agencies use contemporary sensors, like mobile lidar and GPSs, to consolidate asset data collection. This routine collection...
of asset inventory information provides a snapshot of the visible assets in the transportation system. In addition to inventory information, users need to know the condition of the assets, which often cannot be determined using automation. Condition information can be captured during inspections, or it can be inferred from asset history.

Every department that interacts with an asset documents part of its history. This leads to fragmented asset information that is time-consuming to collect, verify, and analyze when users need it. In the 27 years since the publication of TR News 176, little progress has been made toward consolidating asset histories and making data easily accessible to users.

Digital project delivery has created a new impetus to close the project development information gap in asset histories by creating, storing, and sharing digital asset information collected during construction. The pursuit of digital twins could benefit agencies because of how the information is organized: by asset. There is a one-to-one correspondence between the assets that are constructed, paid for, and delivered to asset stewards who maintain and operate them. By organizing agency data around the asset, agencies can consolidate asset histories and provide quick access to complete information that has been verified by the asset’s data steward.

**Digital Project Delivery Information**

Over the past decade, designers and contractors have started making extensive use of 3-D engineered models of pavement and bridge assets. Designers have deprecated their 3-D models onto 2-D plan sheets that contractors use to create their own 3-D models. Skipping the step of deprecating 3-D models to 2-D plan sheets would create efficiencies for both designers and contractors, but a lack of interoperability of 3-D models has been a barrier to implementation. By extending the open data standard for construction information exchange (ISO 16739: Industry Foundation Classes) to infrastructure assets, the industry is rapidly making strides to overcome this challenge.²

There is a focus on replacing 2-D plan sheets with 3-D models as the medium for contract documents. This means as-built records need to be in a digital, or 3-D model-based, format. Many state transportation agencies have begun to pilot a plans-free, 3-D model-based method to deliver roadway and bridge information for construction projects.

Liberated from the need to create plan sheets, designers would have time to embed asset information as attributes in the design model. In addition to 3-D models, contractors would benefit from digital information that is searchable and includes tabular data, such as reinforcement schedules that are structured as spreadsheets. Some agencies are starting to update their design processes to create asset information and extract the as-designed information in a format compatible with the asset inventory.

So far, sharing 3-D models for construction has worked well because designers and contractors have access to the modeling software, the skill sets relate to their core job functions, and their involvement is limited to the construction project life cycle. Inspectors have a foot in both worlds—performing project-related functions and capturing asset histories needed over the life cycle of the asset. However, modeling skill sets do not relate directly to construction management and inspection, making it challenging to develop and sustain these skill sets. As

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plan sets entirely give way to 3-D models, there is a scramble to find a solution that works well for inspectors.

Closing the Project Delivery Information Gap

Despite two decades of sounding the alarm about workforce challenges, inspectors continue to be asked to do more things with increasingly complicated data and technology. The problem is not digital technology per se. Construction management and inspection workflows, such as those created with AASHTOWare Project Suite, have been digitized for a while. The issue is an unmet need to deliver the contract document information in a way that is compatible with digital inspection and construction management workflows, tools, and skill sets.

As early as 2003, a National Cooperative Highway Research Program (NCHRP) synthesis report documented issues with maintaining the construction workforce within state transportation agencies (3). The challenges associated with keeping a workforce with the necessary skills and institutional knowledge to get the job done safely and effectively are worse now. In this battle, technology often has been less of a blessing and more of a curse.

There are some notable exceptions, including mobile devices, PDF documents, and electronic tickets that track batching and delivery of construction materials. It is faster, easier, and cheaper to collaborate with electronic documents. Electronic document management works well for inspection and contract administration functions because it does not disrupt the processes and procedures from the “paper age.” Agencies need more digital project delivery solutions that make it easier to recruit and maintain a skilled inspection workforce.

Preparing for digital twins creates an opportunity to design a solution that centers on the needs of construction managers and inspectors. Providing project information that is organized by asset makes it easier to document construction outcomes in a way that supports harvesting the important asset histories—like materials testing results—and delivering them to the asset data stewards. Switching to asset-focused information delivery helps by enabling better knowledge management.

Inspectors have to cross-reference a variety of data sources in the field. The plans indicate what to expect and where to expect it. The specifications provide the construction tolerances and acceptance factors. The payment system has the schedule of pay items and estimated quantities. Although the specifications and pay items usually match, their relationship to the plans can be complex and unrelated to how the work is constructed (Figure 2).

Using an asset-aligned, digital twin–ready approach to construction information management could be transformational for construction inspection workflows. Such a digital model would give inspectors a single access point to all the information they need. Inspectors would need less training on how to access and store information. Having a single point of entry to the digital record for each asset makes it easier to track items as they are accepted, avoiding duplicate inspections and even duplicate payments. Workflow automation could flag out-of-tolerance items as the inspection record is entered, or submit information to the asset data steward when work is accepted for payment.

A digital twin–ready model would connect a geospatial model of each individual asset to contextual information grouped into property sets. The geometric model of the asset would be geospatially located within the complete system. Designers and contractors need a detailed, 3-D geometric model that they would access via computer-aided design software. An inspector is primarily interested in the attributes and may only need a single coordinate point to locate the asset on a map interface. The interface could provide contextual menus and data tables for the type of asset and the current task. A “help button” could load a tutorial or walk the inspector through a task.

Outstanding Issues

Currently, the as-built recording responsibilities extend only to documenting deviations from the plans. From an asset-focused view, every asset undergoes changes during construction, resulting in assets that are retired, renewed, or commissioned. The actions performed on all assets during construction provide critical information—and context—for managing the assets. There is a need for someone to isolate the relevant information and deliver it to the asset data stewards. There also is a need to evaluate the business processes and identify where to build in automation to extract and deliver asset information. Proceeding without automation would create an enormous burden on those who accept and commission or decommission those

![FIGURE 2 Excavation payments can be based on volumetric quantities that are unrelated to the actual work performed.](image-url)
Assets—they would need to document the changes accurately. Most construction is executed according to plans and specifications; the acceptance workflow could automate the transmittal of as-designed information to the asset data steward.

Nationwide, there is a need to coordinate data models for high-priority secondary assets like signs, barriers, pavement markings, walls, culverts, intelligent transportation system assets, and active transportation facilities. Agencies take many different approaches to track these assets, including maintenance management systems, asset management systems, and asset tracking spreadsheets. The processes and responsibilities for documenting the complete history of these assets still need to be defined. So, too, do the governance and stewardship responsibilities for the asset data. NCHRP Synthesis Project 20-05/Topic 54-06, “Ancillary Asset Data Stewardship and Data Models,” will capture a snapshot of current practices.

Each asset life cycle needs to be mapped as a series of processes and actions that cause changes, and each change would have an associated set of properties. Some of these properties would

- Identify the asset,
- Describe its physical geometry,
- Describe its condition, and
- Contain parameters used to analyze the asset’s performance.

Each property set would need a data steward, as well as processes and tools for capturing the information.

Users should only see the information that is relevant to their context, and they should use an interface with ergonomics that are appropriate for their work environment. There are many ergonomic challenges to accessing and capturing digital information on a construction site. These ergonomic requirements need to be defined carefully to accelerate the development of suitable tools for use at construction sites.

What’s Needed Next?

Building a comprehensive business architecture that captures the complete histories of all assets is an enormous task. The first step is prioritization: Which assets—and which actions—are most important? The next step is defining the information requirements for documenting those actions. What data fields are needed? What are the acceptance tolerances? How precise does the asset’s location need to be? What construction acceptance information is relevant for its management and operation?

Defining the business and information architecture is a necessary next step in solving the bigger workforce challenges. Once the essential data model is documented, the workflows and governance structures to maintain quality need to be developed, and data need to be made accessible after they are collected. If the data architecture is published as a consensus standard, then vendors can bring products to market.

Published by the International Organization for Standardization, ISO 19650 is a global standard for the organization and digitization of information about buildings and civil engineering projects. ISO 19650 describes how to establish two information models: one for projects and another for assets. Preparing for digital twins demands a fundamental shift away from only using project-focused organization for project development information. ISO 19650 provides a rigorous approach to isolating the asset information that has value over an asset’s life cycle so that it can be extracted, ideally using automation.

Last, but not least, the industry will need to embrace the use of rigorous, standardized metadata (data that describe other data) on all project data. Metadata can be used to aggregate information from many sources over the asset life cycle, including future data sets not yet imagined.

There may not be clear beneficial uses of digital twins for highways and bridges yet, but there will be, and it is important to start preparing now. Having a complete digital model of assets and their histories will bring vast benefits through better knowledge management.

REFERENCES