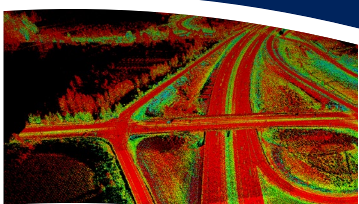
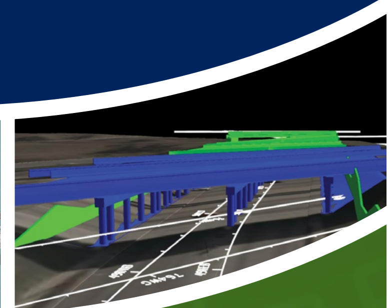
Guide for

3D Engineered Models for Bridges and Structures

Summer 2017





U.S. Department of Transportation
Federal Highway Administration

3D Engineered Models:

Schedule, Cost, and Post-Construction

*An **Every Day Counts** Innovation*

Contents

This guide provides an overview of different types of 3D engineered models for bridges and highway structures and how they can be applied across the asset lifecycle. Some specific uses explored in this guide include creating models to increase efficiency by generating more accurate plans, schedules, and estimates, and the secondary uses that emerge from repurposing those models. The guide looks at how project characteristics affect the favorability of creating and using bridge models. It also presents some critical issues for sharing bridge models, such as communicating the Level of Development and managing the horizontal distance distortions implicit to geospatial coordinates.

3D Engineered Models for Bridges and Structures

Introduction

While much of the adoption of three-dimensional (3D) modeling for highways has been driven by cost savings, efficiencies, and lower risk in construction, routine inspection and asset management requirements for bridges make cross-functional uses a primary consideration for 3D models for structures. With so many bridges across the country needing rehabilitation or replacement, creating significant impacts to motorists who use them daily,[1] visualization and construction simulation (also known as 4D or 5D modeling) helps transportation agencies engage with the public and plan work activities in narrow rights-of-way. These are priority value-added uses of 3D engineered models, but the most immediate and scalable use of 3D engineered bridge models could be to increase automation through dynamic change propagation in bridge plans production, rebar scheduling, and quantity take-off. These plans production models can be repurposed to serve both the visualization, construction simulation, and inspection uses.

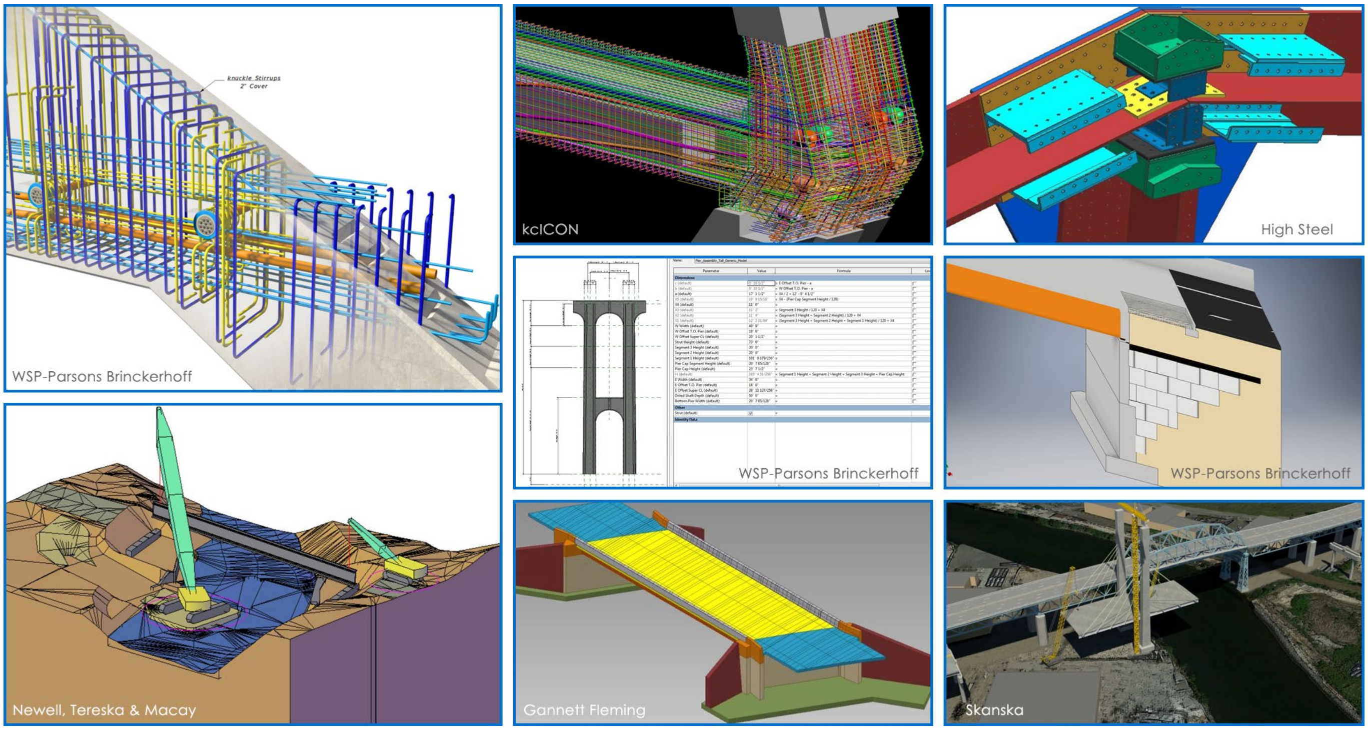


Figure 1: There is a broad range of uses of 3D models that support the development and management of bridges.

1 American Road & Transportation Builders Association. *Most Traveled U.S. Structurally Deficient Bridges, 2016.* Washington, DC: American Road & Transportation Builders Association, 2017.

Types of Models and their Applications

Not all 3D models are created equally. There are four main types of 3D models for bridges and structures that, as a result of the data structure, have different limitations. All of them have the ability to have visual textures applied to the models, providing components that can be used in visualization and simulation. More advanced uses, such as plans production, detailing, scheduling, and quantity take-off, require more advanced parametric *information models*. The parametric nature of these information models means that a State Transportation Agency (STA) may create a library of standard components (piers, abutments, beams, bearings, etc.) that can be used to create models efficiently and in a standard manner that improves quality control and makes it easier to share with future users.

Table 1: Different Types of 3D Models

Model Type	Description	Uses	File Formats
Parametric Information Models	Structured like databases. Tables of parameters and defined parametric constraints control the geometric properties of smart objects. Some objects may host other objects; for example, concrete pier may host reinforcement and revise the rebar layout when the pier geometric properties change. May have information embedded as attributes, such as material types, densities, and pay item numbers. May have visual textures applied.	▸ Plans production with dynamic sections and views ▸ Quantity take-off ▸ Automated rebar layout and scheduling ▸ Detailing and shop drawings ▸ Visualization and simulation ▸ Information attribute queries via database connections	IFC, proprietary
Visualization	Solid or mesh components that may have visual textures applied, but do not normally contain information or intelligent properties.	▸ Visualization and simulation	DXF, STEP, SAT, proprietary
Terrain	Surface models composed of triangulated irregular networks (TINs). Surface models have no depth, but visual textures may be applied. Terrain models are usually used to show existing, interim, and final terrain. Used for excavation staging and quantity take-off.	▸ 2D and 3D area quantities ▸ 3D volume quantities by surface-to-surface comparison ▸ Automated Machine Guidance ▸ Visualization and simulation	LandXML, proprietary

Most projects require using a combination of different model types. For instance, terrain models would be used to depict the existing conditions and as a basis for earthwork calculations and model abutment grading, as well as to develop the grading components of the site plan. Parametric information models would be used to create the bridge foundations, substructure, retaining walls and superstructure.

Visualization for public engagement needs to portray interim conditions or the surrounding context of the bridge. Visualization models can be quick to generate but may lack detail or geometric accuracy. Other uses for visualization models include models of construction equipment and temporary works, like shoring, supports, and formwork. These features usually convey the contractor's means and methods, so they are usually only used illustratively or where site conditions are very congested and specific staging is necessary.

Project Characteristics for Different Types of Model Uses

In this era of constrained funds for infrastructure and a growing maintenance backlog, a significant number of bridge maintenance and construction projects involve existing structures under active traffic. Some level of visualization may be indicated for almost any project that imposes lane closures or detours upon the motoring public, but 3D models do not always contribute efficiencies in design or plans production, bidding, or construction. New software tools make low-detailed visualization accessible for a wide range of projects, but do not result in models that can be used in other ways. When considering how 3D models may support a particular project, it's important to consider the primary use, the level of investment to support that use, and what secondary uses may become accessible. In some cases, there may only be value in creating 3D models of specific bridge elements, for instance, if there is a particularly congested or complex detail.

Table 2: Primary and Secondary Uses of 3D Bridge Models

Primary Use	Project Characteristics	Secondary Uses
Visualization and Simulation	‣ Large impacts on the public that require extensive consultation and communication. ‣ Constrained sites with critical staging, either for maintenance of traffic or for site logistics.	‣ Constructability reviews
Plans Production, Quantity Take-off, and Scheduling	‣ New bridges, new alignments, full replacements.	‣ Visualization and simulation ‣ Clash detection ‣ Constructability reviews
Detailing and Shop Drawings	‣ Prefabricated elements and systems. Concrete components with reinforcement, especially congested or complicated detailing.	‣ Visualization and simulation ‣ Microscale clash detection (e.g., checking clearances between post-tensioning and rebar) ‣ Virtual fit-up

Creating Efficiencies in Plans Production

Using parametric information models for geometric design, plans production, schedule creation, and quantity take-off has the potential to introduce efficiency to the design process. When the plan sheets, schedules, and quantity tables are created to be populated directly from the model, then changes propagate dynamically. **Design is an iterative process, especially bridge design, which must advance based on preliminary information and then adapt later in the design process as geotechnical foundation recommendations, hydraulic approvals, and roadway geometrics are finalized.**

The return on investment in these types of models may be positive on a project-by-project basis, but compounds when the parametric model content is reused. The best way to realize efficiencies from this type of model is to invest in a workspace with standard components, standard views, standard sheets, and standard schedules. Just as standardizing bridge components leads to efficiencies and less risk in construction, standardizing bridge modeling components leads to efficiencies and less risk in the production environment. With standard data, the models are more easily shared and used because the recipient already understands the data and the expectations associated with it.

- The standard library of parametric bridge elements could include abutments, foundations, piers, beams, barriers, decks, and railings.
- The parametric models of concrete elements can also include standard rules for laying out rebar in each of these different element types.
- Standard rebar schedules can be created for each element type.
- The workspace can include presets that control how elements are displayed in different sheets.
- The view presets may include rendering for visualization.
- With parametric models, the dimensions and other annotations update dynamically. Standard models can have sheets based on standard views, such as pier sections, foundation plan views, and so on, which update dynamically as the table of controlling parameters is updated.

Using a customized workspace with a standard model content library can create efficiency, increase accuracy in the schedules and quantity tables, and improve standardization in the contract documents, which aids design review and estimating. There are other value-added benefits to approaching plans production with 3D parametric models. Traditional plans can be augmented with a new suite of standard deliverables to clarify design intent:

- 3D PDFs with saved views (see call-out box)
- Renderings and visualizations
- Construction simulations

Managing Geospatial Distance Distortions

The 3D coordinate systems we design on are created by projecting the curved surface of the earth onto a plane. This projection introduces horizontal distance distortions. Surveyors define a Combined Factor, sometimes called a Combined Scale Factor, to describe the relationship between *grid* distances measured in coordinates and true *ground* distances. In reality, the Combined Factor varies across the mapped area, but for a small project, usually a single Combined Factor will be reported. For widely dispersed projects, sometimes a Combined Factor will be computed for every bridge location.

3D PDFs

3D models can be more accessible to reviewers, but the sophisticated 3D modeling software often is not. 3D PDFs offer functionality to navigate 3D models in a format that is relatively universal.

A 3D PDF supports basic PDF functionality: users can view a file and insert notes, annotations, and other mark-ups. A 3D PDF also has basic 3D navigation functionality, i.e., users can pan, zoom, and section a 3D model.

The 3D PDF format has additional functionality that vastly increases its utility.

The levels that separate 3D model elements are preserved, so they can be turned on and off at will.

Saved views are also preserved; the views save the location, camera angle, the level presets, the visual texturing, and lighting. This means a 3D PDF can include sheet-like views, visualizations, and a navigable 3D model in a single file.

Comments can be embedded in the 3D PDF.

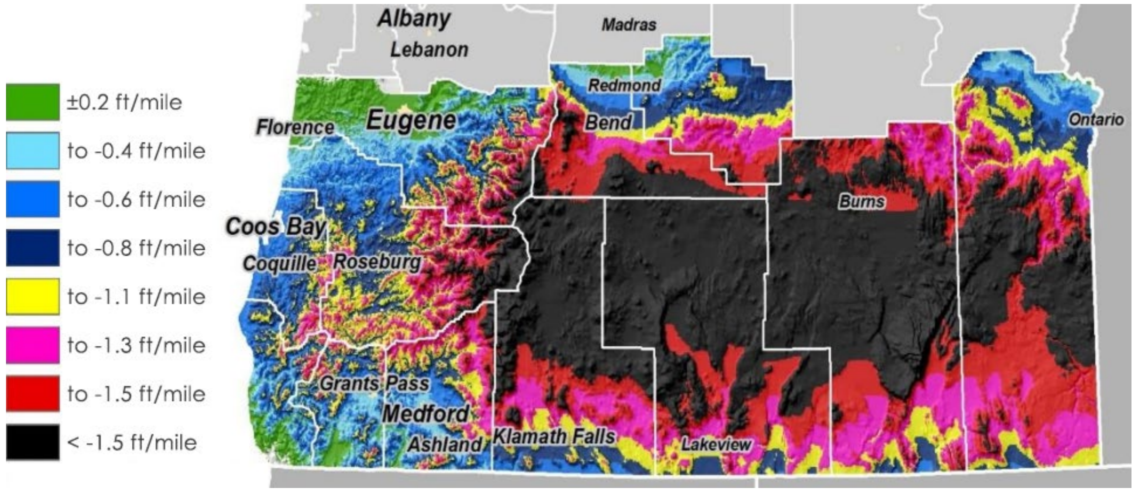


Figure 2: Horizontal Distance Distortions in the Oregon State Plane Southern Zone (See footnote 2)

When Oregon used a two-zone State Plane Coordinate System, bridge engineers had to contend with distance distortions so extreme that much of southern Oregon, shown in Figure 2, had distortions in excess of 1.5 feet per mile. Using grid scale distances in the area shown in black in Figure 2 would result in 1/8 inch of distortion every 37 feet. In other words, many dimensions on most bridges would be outside of the standard dimensional tolerance if the model were created in *grid* coordinates.

Oregon replaced the previously used State Plane Coordinate System with a low-distortion coordinate system for engineering design.[2] However, many states still use State Plane Coordinate Systems, and some have to deal with significant distance distortions on the same scale. This is not new to bridge design; normally, bridge engineers overcome the challenge by providing location information in *grid* coordinates, but all dimensional information in *ground* distances. It emerges as a significant issue for creating 3D bridge models.[3]

Bridge models need to line up with roadway and other design information that is created on *grid* coordinates (such as utilities) so that they can be used in visualization, simulation, design coordination, and constructability review. Bridge models also need to be dimensionally accurate so that they can be used for quantity take-off and fabrication. It takes advanced and sophisticated CADD (computer-aided design and drafting) management to satisfy these conditions with a single model. A safer and perhaps more scalable approach would be to have a *grid* scale model for location plans, design coordination, and visualization, and a *ground* scale model for structure plan dimensioning and detailing. This largely mimics the current workflow.

The one important consideration for parametric model-based plan production is to review the standard plans to ensure that *grid* and *ground* information is not conflated, as that can be confusing to contractors. All geospatial coordinates and station-offset data is *grid* scale. The authoritative source of information for these sheets would be the *grid* scale model. All sheets with local dimensions would be derived from the *ground* scale model.

2 Armstrong, Mark L., et al. *Oregon Coordinate Reference System Handbook and Map Set.* Salem, OR: Oregon Department of Transportation, 2017.

3 See also: *The Oregon Coordinate Reference System: A Surveying Approach for Supporting Geospatial-Based technologies in Transportation Applications* (https://www.fhwa.dot.gov/construction/3d/hif16023.pdf)

Defining 3D Model Requirements

Given the nuances with different types of models and different ways in which the models can be used, bridge engineers are challenged with how to clearly articulate the specifications for the model. While many bridge engineers have selectively used 3D models for their own purposes, few have shared those models with others because of the challenge of describing all the assumptions behind the model and the limitations in how it may be used. If a STA wants to institutionalize the use of 3D models for bridges and structures, they need a framework to clearly articulate the requirements for the models so that bridge engineers can create models that fit the intended purpose and can share them with confidence.

Model Contents

The first important piece of information is what to include. It may seem obvious at first, but there can be subtle differences regarding which existing, interim, and contextual features to include.

Table 3: Different Types of Features in a 3D Model of a Bridge

Feature Type	Example Features	Notes
Proposed	‣ Major systems (substructure, foundations, superstructure) ‣ Major elements (abutments, piers, footings, bearings, girders, decks, railings, etc.) ‣ Other elements (reinforcement, post-tensioning, joints, diaphragms, cross-frames, etc.) ‣ Site plan features (grading, barriers, walls, scour protection, etc.) ‣ Roadway features	The primary use of the bridge model will determine the requirements for the amount of detail and disaggregation in the model. For example, visualization uses can be supported with a macro-scale model (exterior finishes of major systems), while structure plans and details need a microscale model (interior elements, joints, etc.).
Existing	‣ Existing terrain ‣ Existing bridge elements that will be modified ‣ Existing bridge elements that will be demolished	The value of using model-based plans production to support rehabilitation or demolition plans is not assured. Existing bridge models may be most valuable for visualization and simulation models where they can be generated at a low LOD.
Interim	‣ Interim earthwork states (substructure excavation, stockpiles, etc.) ‣ Temporary works (shoring, falsework, etc.) ‣ Detours and shoofly structures	These features often convey the contractor's means and methods and are only valuable when site constraints mean that staging must be predetermined and communicated to the public or prospective bidders.
Contextual	‣ These are landmarks and other features outside of the project limits that are included to provide orientation.	Generally, contextual features are only included in models intended for the general public or non-technical stakeholders, such as emergency responders.

Level of Development (LOD)

Since 3D models are inherently visual, there is a danger that models may be inadvertently used in ways for which they are unsuitable. It is important to communicate the level of development (LOD) behind the 3D model so that engineering professionals understand the limitations on how the models may be applied. Figure 3 illustrates the LOD concept. The model on the left is a macroscale model showing only the exterior finishes. The middle model has sufficient detail to support structure plan development, rebar scheduling, and quantity take-off. The model on the right is further developed to support fabrication.

Figure 3: A Prestressed Beam Shown at Three Different LODs[4]

LOD is a measure of how reliable the information is. Is it geometrically accurate? What's the dimensional tolerance? Is it based on robust analysis? The American Institute of Architects (AIA) and Associated General Contractors of America (AGC) collaborate through the BIMForum to produce standard element-level LOD definitions that primarily serve building information models (BIM). The fundamental LOD definitions are too abstract to relate directly to bridge systems and elements. Until the industry standardizes on standard element-level LOD tables for bridge elements, it would be prudent to clearly articulate the following characteristics for each model:

- The dimensional tolerance; this defines the geometric accuracy.
- The basis for the 3D coordinate system; is it a *grid* scale model or a *ground* scale model? If it is a *grid* scale model, the geospatial metadata must be clearly defined and conveyed with the model. If it is a *ground* scale model, the reference points and lines that connect it to the site plan must be included.
- The intended or authorized uses for the model. It is important to identify if the model does not show the full detail required for construction. There are many beneficial uses of 3D bridge models that are not fully developed to support construction uses.

Visualization Quality

Plans production models in particular can be repurposed in many ways. While visualization uses require an investment in texturing the models so that they look realistic, engineering-type uses do not. It is important to articulate at the beginning what the expectations are regarding the visual quality of the model outputs. In Figure 4, the model on the left has textures, but the model on the right does not. Both are shaded views. Textures are often not necessary to support the intended uses.

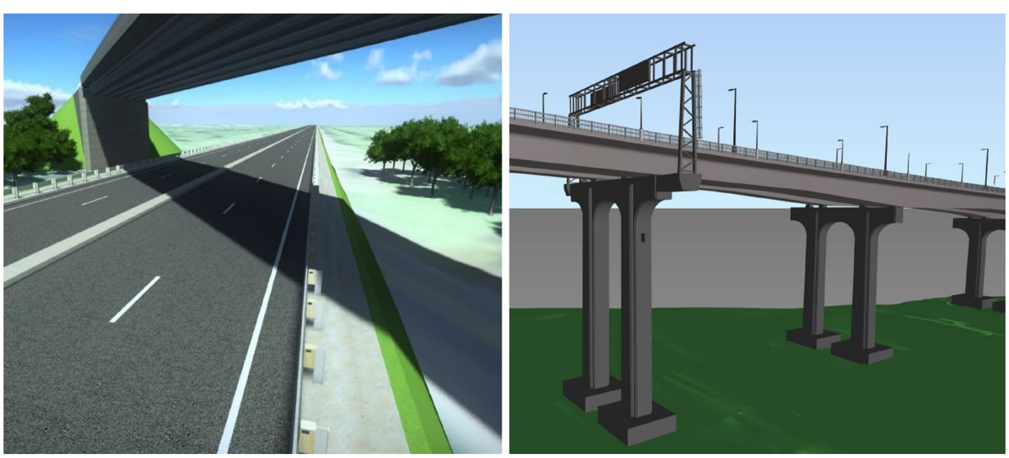


Figure 4: Comparison of Textured and Untextured Models

4 BIMForum. *Level of Development Specification*. s.l.: BIMForum, 2016.

The intended audience for 3D models should be clearly stated. Incorrect assumptions regarding the need for visualization (textures, camera locations, lighting, and rendering) can have a large impact on the time and cost to produce the required outputs. There is no standard scale for visualization quality. Instead, clearly define the expectations regarding the intended audience and purpose of any visualization and simulation outputs.

Model Outputs

The standard outputs would be plans, specifications, and estimated quantities. However, using model-based plans production, or creating models for visualization and simulation, creates an opportunity to provide value-added outputs. These fall into four primary categories: 3D models, images, videos, and simulations. These value-added outputs can take time (and cost) to produce. It is important to set clear expectations on the number and type of image and video or simulation outputs. For simulations, refer to the ***Guide for Creating and Maintaining 4D Models*** and the ***Guide for Selecting Projects Suitable for 4D Modeling***.

Table 4: Different Types of 3D Bridge Model Outputs

Output Type	Example	Notes
3D Model	High LOD, ground scale model of bridge elements and systems in isolation	Could be used for formwork planning, lift planning, Finite Element Method (FEM) analysis, and further developed for shop drawing production, among many other secondary uses.
3D Model	Low LOD, grid scale model that aligns to roadway and other components.	There may be a need to communicate with the public during construction, or the contractor may use the models to plan means and methods or site logistics, such as large equipment movements or lift planning.
3D Model	Interim surface models, e.g., detour roads, excavation surfaces, stockpile surfaces.	If these surfaces are generated to estimate quantities, providing them to bidders increases transparency and would be useful in developing means and methods.
3D Model	3D PDF with saved views	These add value to the production of final as-built records, especially for those agencies already using PDF editing tools. There is also easier collaboration for review and coordination.
Images	Staging graphics	A sequence of images that illustrate the assumed staging. Could communicate traffic staging, substructure construction staging, or general staging plans. These may be incorporated onto plan sheets, into presentations, or be stand-alone deliverables.
Images	Design intent clarifica-tion	A series of images from various angles that illustrate the design intent of complicated elements. May be used to visualize complex or congested details. Could be used to convey the design intent to the public.
Videos	Fly-through video	These show the overall project from a moving perspective. It could be a drive-through from the perspective of the driver, a high-level overview of the project, or a range of perspectives.
Videos	Progression video	A series of staging images can be combined into a video to convey the progression in a single file.
Simulations	4D model or 5D model[5]	A 4D model results from connecting 3D model elements to schedule tasks for the purposes of simulating the progression of construction. A 5D model has costs associated with the schedule tasks. These 4D or 5D models may be bundled and delivered, either in read-only format or in an editable format, where the schedule or model can be manipulated to test alternative scenarios. Alternately, videos can be produced from a 4D or 5D model.

5 See also: *4D and 5D Modeling: NYSDOT's Approach to Optimizing Resources* (https://www.fhwa.dot.gov/construction/3d/hif16024.pdf)

Supporting Cross-functional Use

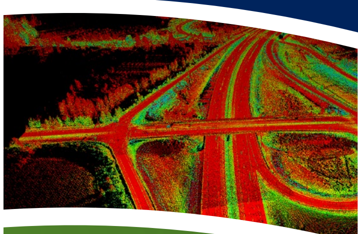
Creating 3D models of bridges and highway structures represents a significant investment in information about that asset. While the intent is that the investment should result in efficiencies or added value with its immediate use, there is an opportunity for additional value through cross-functional uses. Contractors may be able to identify cost savings and efficiencies from using the models in bidding. The public may be more informed of construction activities and planned detours by viewing images or videos made possible by sharing the model with the contractor. There may be additional benefits from using the model to manage and operate the bridge, using the model to collect element-level information during routine inspections, or having an element-level record of the structure during future maintenance or rehabilitation activities.

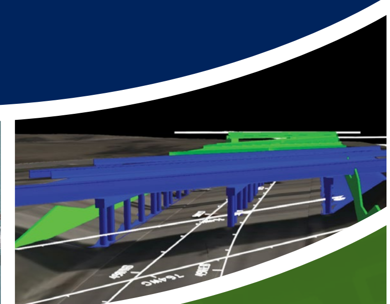
The most important consideration for achieving these cross-functional uses is to ensure that the model is in an accessible, open file format. The American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Bridges and Structures Technical Committee (T-19) is working towards a standard format for 3D bridge models. Some work has been completed evaluating Industry Foundation Class (IFC) as a standard for bridges. Another consideration is to engage with contractor partners and field staff to understand how they consume information.

Conclusion

The selective use of 3D engineered models to support bridge and highway structure project development can create efficiencies in plans production and create an opportunity to add valuable additional outputs. By focusing on immediate, primary uses, and clearly articulating the model requirements, agencies can successfully utilize 3D engineered models on a project-by-project basis. To scale these benefits across the bridge design and construction program, STAs should build a library of standard components and create a software workspace that automates repetitive tasks (like content display presets for common sheet types). Ideally, a single model can service a wide range of uses, but the need to manage the geospatial distance distortions in State Plane Coordinate Systems means that there may be a need to create separate models for different purposes. It is important to clearly articulate the dimensional tolerances and 3D coordinate basis with any 3D bridge models.

***Every Day Counts**, a state-based initiative of the Federal Highway Administration's Center for Accelerating Innovation, works with state, local and private sector partners to encourage the adoption of proven technologies and innovations to shorten and enhance project delivery.*



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