ITS AMERICA

ITS America Digital Twinning Decoded

ITS America Digital Twinning Working Group

White Paper

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Digital Twinning Decoded

Introduction

The Intelligent Transportation Society of America (ITS America) has developed this white paper, Digital Twinning Decoded, to explain the concept of digital twinning in a practical, nontechnical way for transportation practitioners and non-practitioners alike. Digital twinning represents a substantial shift in our ability to simulate the world around us, going well beyond digital modeling. The use of digital twins is well-established in manufacturing, construction, energy, and even healthcare to improve efficiency, productivity, and safety. In the manufacturing industry, for example, Siemens reports over 170,000 companies using digital twin software during the product development lifecycle.[1]

Digital twinning is an increasingly valuable tool across the transportation landscape in the United States as well, with potential applications in traffic management, bridge construction and monitoring, and automated vehicle testing, among others. Demystifying the capabilities of digital twins and increasing awareness of successful transportation use cases will help the industry realize the transformational benefits of this technology.

Readers will learn about potential applications, distinctions among adjacent modeling concepts, various challenges, and the experience of transportation agencies around the world that have pursued digital twin initiatives. The real-world use cases highlighted in this paper will help readers understand how digital twins can be used and encourage them to think about how the technology could be applied to their own work. Ultimately, this paper will better prepare readers for discussions within their organization about investing in digital twin technology.

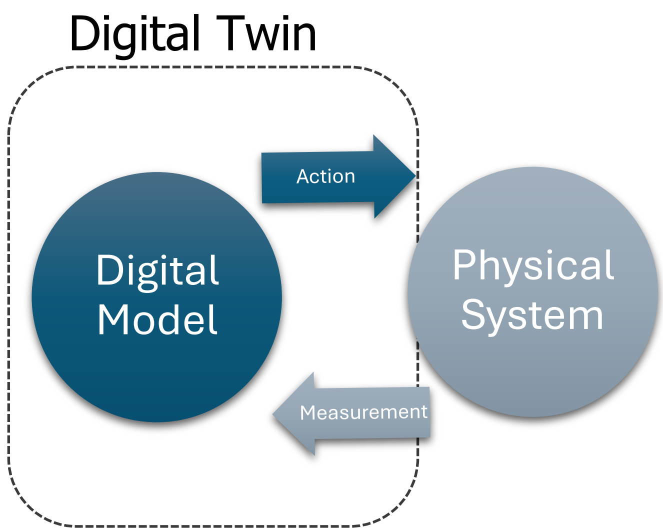
What is a Digital Twin?

What do you think of when you hear "digital twin"? Perhaps a digital replica of an existing object or system comes to mind. While true, a digital twin also makes it possible to test a hypothesis on an existing object or system and anticipate the outcome. This provides the benefit of hindsight before acting.

A digital twin is a constantly updating, dynamic virtual model of a physical system or object that can be seamlessly connected to measurement systems via digital infrastructure and continuously updated to reflect changes in the physical world, enabling monitoring, analysis, and optimization of complex systems.

Importantly, the fidelity of the digital twin and the speed and the synchronization mechanism between the physical and digital can vary based upon the use. For transportation engineers, a digital twin serves as an invaluable tool for modeling infrastructure, such as highways, bridges, rail systems, and transit networks (both urban and rural), while also accounting for users, such as bicyclists, pedestrians, and drivers. Just as a surgeon might use a digital twin of a human body to perfect a surgical procedure before performing it, a transportation engineer might use a digital twin of a roadway to add a lane and measure its effectiveness – and correct any unintended consequences – before deciding to construct it.

At its core, a digital twin integrates data – especially real-time data – from various sources including infrastructure sensors, traffic probes, and vehicles connected to the internet to create a dynamic model that reflects the current state of physical assets and anticipates the impact of various scenarios. This allows transportation engineers to predict the outcomes of future scenarios based on constantly updated data analytics. By leveraging software based on artificial intelligence (AI), machine learning (ML), or algorithmic simulation techniques, digital twins facilitate informed decision-making processes and enhance operational efficiency. Moreover, digitizing transportation data and introducing layers of connected analytics offers the capability to reduce human translation time augmented by ever-increasing computing power.



Digital twins can be used at all stages of the project life cycle, from design to build to maintenance and operations. The use cases shared in this paper (see Appendix A) include applications of digital twins for designing and building roadway assets as well as commissioning, maintaining, and operating assets throughout the transportation ecosystem.

Today, transportation digital twins are being used for:

- **Real-time Monitoring**: Continuous tracking of transportation systems, providing real-time data that helps optimize traffic flow and enhance safety.
- **Predictive Analytics**: Simulating various scenarios, allowing engineers to forecast potential issues, enabling proactive maintenance, and reducing downtime.
- **Integrated Decision-Making**: Facilitating a holistic view of transportation networks, supporting data-driven and artificial intelligence-assisted decisions for infrastructure improvements, resource allocation, and dynamic road-use policy.

Keeping Roadway Designs Current

Use of digital twins during the full life cycle of design and construction will enable TxDOT to reduce unnecessary change orders by 40%.

See Appendix A.3.

What a Digital Twin is Not

Conceived in 2002 at the University of Michigan[2] and brought into widespread use by the National Aeronautics and Space Administration (NASA) in 2010 for spacecraft development[3], the term "digital twin" has been floated as a next-generation industry term ever since. If you were not building a digital twin, according to some schools of thought, you risked falling behind your competitors. This buzzword effect notwithstanding, digital twins represent an evolution of modeling and simulation that has real value.

While the use of digital twins in transportation infrastructure is still in its infancy, the availability of comprehensive and accurate digital renderings can serve multiple purposes. An accurate view of roadway infrastructure, for instance, can enhance collaboration across multiple departments and form the foundation for integration and maintenance of relevant information across teams, agencies, and platforms. In addition, many analytics tools we work with in transportation today can connect with live data sets in a variety of formats from multiple locations. Digital twins are unique because they are purpose-built to automatically integrate data into simulations and models, utilizing digital infrastructure to be continuously updated.

Augmented Reality and Building Information Modeling

You may be familiar with immersive technologies like augmented reality (AR) and building information modeling (BIM) and wonder how these overlap with digital twins. AR and BIM are indeed useful for creating enhanced visuals depicting the physical world. Compared to AR, digital twins are used for monitoring, simulation, analysis, and action, but do not require direct interaction with the physical world. While BIM data tends to be static and disconnected from its physical counterpart, it can provide the model for a digital twin if a feedback loop is built.

Modeling and Simulation

Digital models and simulations are core components of a digital twin. What transforms a model into a digital twin, and thus worthy of a new term, is that a digital twin **incorporates real-world data, and allows the bi-directional exchange of pertinent information**.[4]

Today, much of the Geographic Information Systems, or GIS, industry is already working with a digital representation of the real world: digital maps that represent the locations and other key attributes of waterways, roads, cities, towns, and villages. This data may receive frequent updates, via crowdsourcing, or from providers like Google and Apple. These systems can form an excellent base for a digital twin even though they are not digital twins by themselves.

FEMA's Hurricane Evacuation Modeling

Approaching the definition of digital twin, the Federal Emergency Management Agency's (FEMA) HURREVAC toolset integrates live National Weather Service (NWS) weather forecasting to aid in evacuation route planning. Adding real-time traffic data would tip it into the realm of digital twinning.

Transportation Applications of Digital Twins

Now that we have looked at what is and what is not a digital twin, what sorts of considerations are needed to build digital twins of transportation systems? A cloud-based data repository is an essential starting point. This provides a technology platform upon which you can build a secure and flexible environment for data exchange, map creation, visualization capabilities, location services, and application development. It can then be tailored to specifically meet the requirements of user(s) and offer seamless access to data layers from a virtual menu of private industry and public sector data sources.

Prioritizing Roadway Maintenance

The Hawaii Department of Transportation, with Blyncsy, found the use of digital twins can reduce the need for manual surveys by up to 95%, saving up to 23,286 pounds of carbon emissions per vehicle from fewer work vehicles on the road.

See Appendix A.6.

When considering whether to use a digital twin, organizations should consider whether it would:

- Meet a program's digital infrastructure strategic objectives, produce operational efficiencies, as well as help automate data collection, processing, and conflation.
- Be a collaborative solution, maintain interoperability, and ensure access for all users.
- Create a location-based platform to unite tools, data, and services, while not requiring users to relinquish their own data.

The digital representation is the foundation of a digital twin and where incremental results can be achieved by building 2-dimensional (2D) or 3-dimensional (3D) models of continuously updated (and even real-time) data. Doing so puts the concept of the digital twin into practice by building out a more comprehensive database of the location of relevant assets in the real world to achieve the program's objectives.

Digital twins can help by:

- Visualizing and analyzing proprietary data (locally or remotely) with interoperability.
- Combining proprietary data with map data and other location data to solve various use cases.
- Incentivizing standards in incoming data from disparate sources (such as with Project Open Data.)[5]
- Developing effective location applications using industry and public sector geospatial data.
- Accessing the freshest map content combined with real time data feeds.
- Providing software tools for scenario-based analytics/location value evaluation.

Situational awareness is one of the most desirable capabilities for transportation agencies. Agencies require access to incremental datasets for a variety of use cases related to the road network to develop more robust and contextual applications for themselves, other users, and the public. Obtaining access to necessary data sets can be challenging, as is standardizing them to be easily and quickly integrated into services or web apps. Moreover, updates to the data must be delivered consistently.

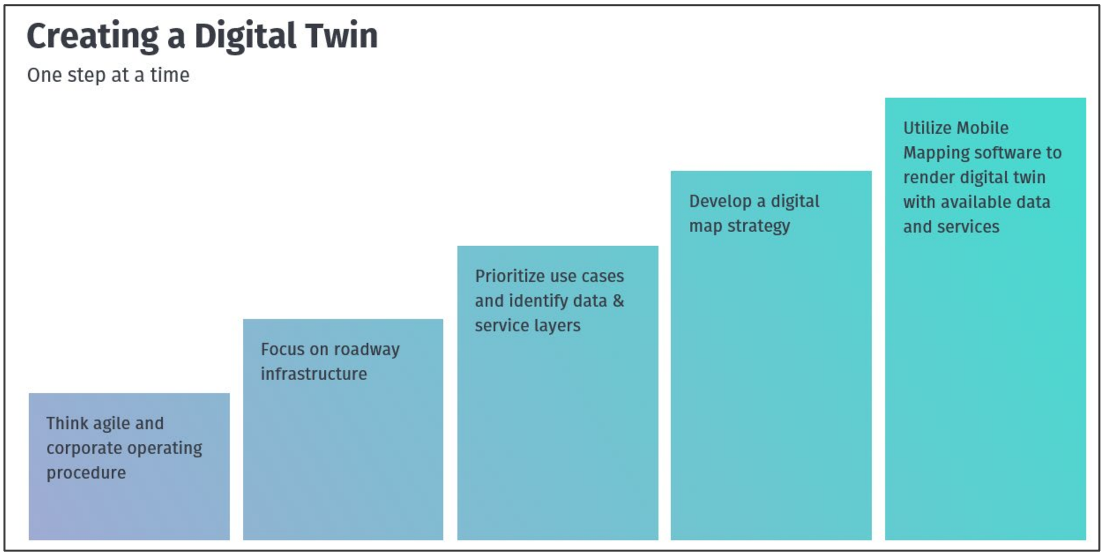


Figure 1: An unnamed DOT's method for digital twin creation.

Many agencies have begun collecting assets via mobile mapping solutions. This can be achieved through the targeted collection of data using special vehicles equipped with sensors, Light Detection and Ranging (LiDAR) and 360-degree spherical cameras. The data collected by these vehicles is stitched together to create a comprehensive view of the roadway and its associated infrastructure.

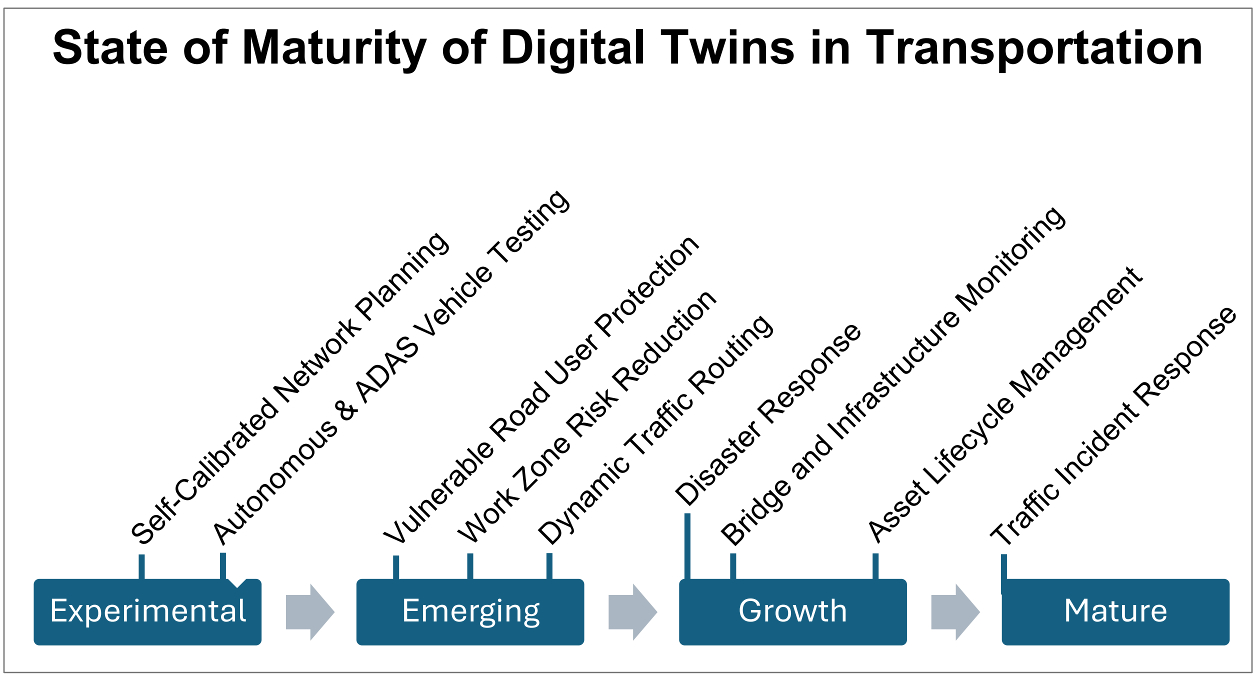
More importantly, this data can then be used to detect vital assets at scale, especially via artificial intelligence and machine learning tools to identify their precise locations. Further details, such as the categorizing of the type of asset, its condition, and other elements, can be extracted. In the future, standard passenger vehicles might be able to accomplish this task using their own powerful sensors, though that would require automotive manufacturers to share data, either commercially or via a regulatory framework.

Linking these identified assets to existing two-dimensional map data results in a 2D/3D hybrid model of the real world that can be implemented across organizations and enable multiple use cases. Beyond the 2D/3D hybrid data model concept, increasingly available real-time information can be overlaid on top of the model that can drive toward other safety and emergency management solutions.

Real World Adoption

Not surprisingly, the adoption of digital twinning for transportation use cases varies widely by application. Some uses, like incident management and roadway operations and maintenance, have had success because they are approaching maturity or are already established. Others, such as traffic modeling and automated vehicle testing, are still firmly in the research realm, though steadily advancing. While overall digital twin use for transportation is in its infancy, it is helpful to look at the relative maturity levels of various applications and use cases, especially as you work within your organization to consider implementation or developing new market opportunities. We can broadly categorize uses[6] into the following typical stages:

1. **Experimental:** These are use cases where the applications and technologies are in their infancy – they may be simply theoretical (i.e., exploratory research) or tested within simulated or controlled environments rather than in the real world.
2. **Emerging:** These are applications and technologies that have been introduced into real-world environments through small-scale pilot projects where little is known about impacts and benefits.
3. **Growth:** These are applications or technologies where pilots have successfully demonstrated positive impact, and the technology is being actively used and scaled up in uncontrolled environments.
4. **Mature:** These are applications and technologies that are well-proven, with benefits that are well-documented, and have been adopted at-scale by multiple organizations.



Infrastructure Owner-Operator Maturity Survey

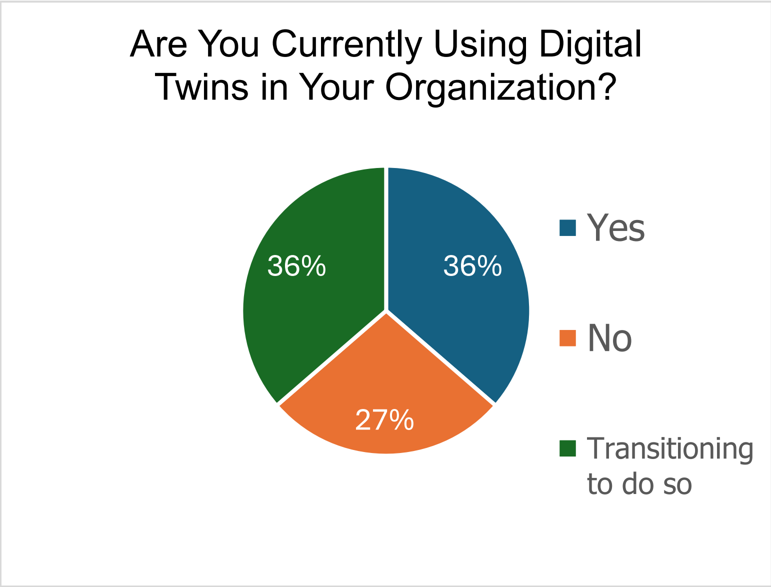


Figure 2: Adoption of digital twins by IOOs. ITS America survey 2024.

ITS America surveyed Infrastructure Owner Operators (IOOs) in July 2024 on the state of maturity of digital twinning concepts within their organizations. The survey collected responses from stakeholders regarding the adoption, challenges, and applications of digital twinning in their organizations. We found that two thirds of respondents are currently using or implementing digital twins in some parts of their organization.

Top use cases included asset management, as well as design/build/operate/maintain activities. The summary below highlights the state of digital twinning maturity across diverse organizations, emphasizing both the potential of the technology, and the challenges of using it effectively.

Challenges Identified

- Lack of data governance and standardization
- Requires stakeholder buy-in
- Relies on third-party developers
- Demands high investment of time and effort to create accurate digital twins
- Limited understanding of the concept
- Must ensure accurate representation of below-ground infrastructure
- Need to address data interoperability and privacy concerns

Use Cases and Applications

- Bridge and infrastructure monitoring
- Traffic management, precision engineering, and preventative maintenance
- Safety analytics and asset management
- Lifecycle management of assets, predictive maintenance, and tunnel management
- Network design and optimization

Data Standards

- GIS-based geospatial standards
- Data protection and acceptable use agreements
- Open application programming interface (API) compatibility and formats excluding personally identifiable information (PII)

Leadership and Integration

- A minority of survey respondents have a group dedicated to digital twin advancement
- GIS departments often lead efforts in integration
- Pilot projects and smaller proofs of concept used to engage stakeholders and demonstrate value

From this survey, the ITS America Digital Twin working group has made the following observations and recommendations:

- **Emerging Nature:** Digital twins are still evolving, with varied definitions and use cases. Consult standards organizations for guidance.
- **Integration Challenges:** The success of digital twins depends on their integration into existing workflows and alignment with organizational goals.
- **Cross-Sector Collaboration:** Universities and private organizations are key partners in advancing this technology.

Mitigating Flooding in Roadway Tunnels

Parsons connected data from various enterprise systems, including geospatial, maintenance, asset management, traffic management, Supervisory Control and Data Acquisition (SCADA), and financial, to create the first instance of a digital twin solution for flood mitigation in roadway tunnels.

See Appendix A.2.

Benefits

The potential benefits of digital twin uses are fundamental to transportation: increased safety, efficiency, and accessibility for our society. Key among digital twin use is the ability to see these improvements in tandem with reduced cost of implementation. If a bridge's cable performance can be extended by several years due to real-time sensors informing a digital twin, the replacement lifecycle savings may far exceed digital twin implementation costs.[7] Thinking far out into the future, if a traffic model can utilize real-time connected vehicle data, the road network could improve throughput while also removing the need for traditional monitoring infrastructure like cameras, ground loops, etc.

Monitoring a Bridge's State of Health

The University of Washington and Washington State Department of Transportation are employing a digital twin to extend the life of a floating bridge on Interstate 90, with a potential ROI of up to 2000%.

See Appendix A.5.

Risks, Challenges, & Barriers

The use of digital twins in transportation is relatively new, making the risks and barriers still quite formidable. The most critical risk is the question of return on investment (ROI). Wache and Dinter's literature published on digital twins (broadly) has focused on technology barriers and lacks discussion about organizational and business value.[8]

There are other challenges as well. Data collection can be expensive, and the operational requirements will depend on what organization is leading the planning. It should also be recognized that the availability of a comprehensive, accurate, and reliable database of roadway infrastructure could serve multiple purposes beyond those identified within this document.

Managing Traffic Incidents

Working with a state DOT, Rekor utilized a digital twin to better manage traffic incidents. This resulted in an increase in incident detection of 159%, leading to a 29% reduction in secondary crashes.

See Appendix A.4.

Industry Standards

Digital twins have been used in advanced manufacturing for some time, and there are several international standards available from organizations such as the National Institute of Standards and Technology (NIST), the International Organization for Standardization (ISO), the Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), and the International Telecommunication Union (ITU). For example, in 2021 ISO released ISO 23247 – Digital Twin Framework for Manufacturing, which is perhaps the most comprehensive global standard on digital twins.[9] In Intelligent Transportation Systems (ITS) specifically, and even in transportation more broadly, no such standards yet exist. However, in 2023 ISO and the IEC released ISO/IEC 30173 – Digital twin — Concepts and Terminology, which "establishes terminology for digital twin (DTw) and describes concepts in the field of digital twin, including the terms and definitions of digital twin, concepts of digital twin (e.g., digital twin system context, life cycle process for digital twin, types of digital twin), functional view of digital twin, and digital twin stakeholders."[10]

ISO/IEC 30173 defines a digital twin as a "digital representation of a target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization." The ITS America Digital Twin Working Group has aligned with this definition, which makes clear that the exchange of data between the physical and digital does not need to be "real-time", but appropriate for the use case.

> ***Reducing Construction and Operations Costs***
>
> *Parsons's Paradim® digital twin tool simplifies access to all project information via an interactive and bi-directional 3D model interface.*
>
> *See Appendix A.1.*

Numerous industry groups are working on digital twining solutions. For example, the Digital Twin Consortium, based in Boston, Massachusetts, is an industry-membership based organization active across more than a dozen industry sectors. The consortium's Mobility and Transportation working group is identifying use cases, working on pilot deployments, and implementing some shared functionality via collaboration.[11]

Digital Twinning Use Cases

It is important to note that this document is not solely focused on use cases that have been identified and talked about over the years, such as traffic simulation (for planning). This is an opportunity to focus also on the less discussed but no less critical use cases for digital twins. Identifying these use cases and discussing their value may help to accelerate future applications, adoption, and lifesaving uses of digital twins.

It often is hard to envision exactly how a digital twin might assist a particular group. Consider a traffic operations center (TOC), managing traffic in real time. Aren't digital twins supposed to help identify future problems with the static infrastructure based on relatively real-time data? What if there was an opportunity for a TOC to have a digital twin of their road network monitoring all incoming data from cameras, roadway sensors, weather sensors, connected vehicles and more? What would the possibilities mean for identifying an incident in "real-time" based on hard breaking data from connected vehicles?

That digital twin could run several scenarios (operational plans and considerations – often already prepared by an agency) to determine the impact of an incident immediately after occurrence, using historical traffic data, current traffic data, weather data, and existing road work. The output could save emergency responders time arriving at the scene, bypassing traffic backups, and taking routes not previously considered. The TOC could alert drivers to exit the roadway or seek alternate routes to avoid backups. Options would be provided automatically, within minutes or even seconds, versus the number of people and hours it would take to make those determinations manually. This frees up those individuals to help manage the incident at a higher level.

Additionally, the digital twin could provide a mirror image of the physical roadway features and dimensions – an as-built layout upon which proposed improvements could be overlayed. Further, the digital twin as-built could be updated in real-time with live inputs from vehicle probe sensors. For example, a vehicle sees a damaged guard rail, a pothole, or a knocked down sign. That information could immediately inform the digital twin for action to be taken by system operators. Taking this concept further, the digital twin could be used for assessing before and after safety countermeasure roadway improvements using snapshots. AI techniques could also be introduced using the digital twin's data to imagine even more solutions. Once the data is digitized, the possibilities are endless.

The following table categorizes key digital twinning use cases in transportation into five distinct areas: Incident Management/Emergency Response, Construction/Work Zone, Traffic Management, Operations and Maintenance, and Planning & Design. Each entry highlights the use case category, intended user(s), the problem being addressed, the digital twin application, and the associated benefits. While this table provides a comprehensive overview, it is not exhaustive; additional detailed use cases can be found in Appendix A, offering further insights into the transformative potential of this technology.

Use Case Category	User(s)	Problem Statement	Digital Twin Application	Benefits
Incident Management / Emergency Response	Traffic Operators	Difficulty in detecting and verifying incidents particularly in areas with no cameras, sensors, detection equipment.	Real-time incident detection and verification using connected vehicle data to roadway infrastructure data exchange, removing the need for cameras.	Near real-time incident detection and verification with ground truth connected vehicle data communicating 24/7 even in rural areas where cameras and detection may not be available
	Drivers	Unexpected traffic delay due to the incident and secondary crashes	Automated near real-time incident alert enabling dynamic alternative routing and avoiding incident congestion and traffic delay	Reduced risk of being involved in a secondary incident and potential delays due to traffic congestion and other secondary crashes
	First Responders	Delayed incident response time due to accumulative traffic around the incident	Proactive driver rerouting reducing traffic accumulation paired with dynamic optimized route recommendations enabling swift incident response	Improved emergency response times and incident clearance to get traffic back to normal
	Public Safety Officers	Inefficient traffic routing during incident clearance	Dynamic traffic signal adjustment for effective traffic management	Minimized risk of secondary crashes
	Cross-agency Operators	Inconsistent information sharing across agencies	Coordinated multi-agency response	Improved coordination among agencies

Use Case Category	User(s)	Problem Statement	Digital Twin Application	Benefits
Construction / Work Zone	Drivers	Unaware of active work zone hazards (lane closures, workers present, detours, etc.)	Work zone-to-vehicle communication automating speed reduction, lane closure, detours, etc.	Improved traffic flow through the work zones, reduced risk of accidents and traffic congestion headed into the work zone
	Construction Workers	High-risk work zone conditions with high-speed traffic	Work zone-to-vehicle communication and automation reducing safety risks in work zones	Improved worker safety
	Traffic Operators & Owners	Insufficient work zone traffic monitoring and incident management	Near real-time work zone conditions monitoring and incident detection	Improved incident response and clearance time, reducing traffic congestion and secondary crash risks
Traffic Management	Traffic Operators	Inefficient traffic flow during peak times, planned events, and incidents	Dynamic traffic signal adjustments and traveler information. Connected vehicles-to-infrastructure communication can assist in regulating traffic automatically by optimizing signal timing and traffic rerouting	Dynamic traffic demand management for improved traffic throughput, better messaging from traffic operators to users
	Road Users	Delayed travel times due to inefficient transportation	Dynamic transportation mode recommendations	Enabling users to reach their destinations quickly

Use Case Category	User(s)	Problem Statement	Digital Twin Application	Benefits
		modes and poor traffic conditions	based on traffic conditions	improves economic prosperity, safety
	City Planners & Traffic Engineers	Inadequate traffic demand insights for city planning optimization	Rich ground truth data insights enabling scenario-based planning and optimization	Informed infrastructure investment and sustainable long-term transportation planning
Operations & Maintenance	Maintenance Operators	Difficulty in identifying infrastructure issues like cracks, wear, or malfunctioning equipment early on	Integrated sensor data from bridges, roads, signs, traffic lights, and other assets allows for continuous synchronization of data for monitoring the health and performance of those physical objects	Real-time monitoring based on live data enables proactive maintenance to reduce operational down time, reduce worker exposure
	Maintenance Managers	Difficulty in retrieving maintenance records to support future inspections	Centralizes maintenance reports, photos, and history logs for easy inspection support	Easy and organized access to all necessary asset records for smooth inspection process
	Maintenance Managers	Difficulty in deciding assets' maintenance schedule effectively with lack of asset deterioration rate	Simulate various scenarios and predict asset performance degradation rate for maintenance prioritization	Enables predictive maintenance, preventing asset failures before they occur. Ensures that all assets are performing as

Use Case Category	User(s)	Problem Statement	Digital Twin Application	Benefits
				expected, reducing downtime. Also helps effective resource allocation, inventory management, and cost reduction
Planning & Design	Emergency Prevention Officers	Difficulty in assessing the resiliency of transportation systems to develop contingency plans and emergency response procedures	Scenario simulation of natural disasters, cyber-attacks, and other threats, allowing effective assessment of mitigation strategies and contingency plans creation	Enables risk mitigation by simulating various disaster scenarios to develop preventative measures avoiding potentially costly and catastrophic outcomes
	City Planners & Traffic Engineers	Complex and time consuming when designing an effective transportation system factoring in population growth and travel demand estimations	Transportation needs estimation by modeling population growth, travel demand patterns, identifying infrastructure gaps and bottlenecks	Faster and more accurate simulation and scenarios addressing effective capacity planning
	Agency leaders	Difficult and time consuming in analyzing cost and benefits across multiple investment	Seamless integration of all data sources to quickly evaluate cost and benefits across multiple investment	Adapt and adjust dynamically based on available data sources - such as cost, time savings, reduced congestion, safety measurements

Use Case Category	User(s)	Problem Statement	Digital Twin Application	Benefits
		projects decision-making and prioritization	projects simultaneously, accelerating decision-making and prioritization	- to easily update the cost-benefits models across multiple projects accurately and efficiently avoiding human errors
	System Designers	Complex and time consuming to validate and minimize system design errors - such as material performance in the real world, overlaps between structural, mechanical, and plumbing infrastructures, etc.	Simulate various scenarios and predict material performance in the real world, and/or see and adjust any overlaps between structural, mechanical, and plumbing infrastructures to avoid design errors	Better prediction of material performance in the real world, and/or see system designs virtually before implementation to avoid costly design errors
	Environmental Urban Planner	Difficulty assessing environmental impact on an urban project with siloed data sources	Centralize necessary data sources to effectively assess the environmental impact of a given urban project	Easy and seamless data analysis can be performed within the digital twins enabling effective environmental impact analysis
Connected / Automated Vehicle Verification	Researchers & Engineers	Risk of testing automated behaviors during safety critical events	Create virtual vehicles, people to blend with physical test facility	Accelerate testing, validate pure simulation tests with real vehicle; reduce risk to engineers and

Use Case Category	User(s)	Problem Statement	Digital Twin Application	Benefits
				improve safety behavior of vehicles
	City Planners & Traffic Engineers	Unknown impact on area roadways when automated vehicles are scaled	Use actual behavior of automated system, behavior of human drivers in the real road network to create a self-calibrated model	High-quality forecast of traffic impacts of automated systems prior to deployment, giving IOOs time to prepare or suggest solutions

Next Steps for Stakeholders

Now that you have a good understanding of digital twinning, and areas of transportation where the concept is being developed and used today, you may be thinking about how a digital twin might benefit your organization. Here are some recommendations on how to get started.

Infrastructure Owner-Operators

Begin with information gathering: Is there an existing champion for digital twinning within your organization? Has anyone successfully implemented a digital twin within your organization? What were the results? Did they measure the return on investment? What is your organization's appetite for risk? Is it an early adopter of new concepts and technologies, or an implementer of "tried and true" solutions using extensive data published by another organization? If your organization is looking for common definitions of a digital twin for planning or strategic needs, ISO/IEC 30173 is a great starting place.

Next, find an existing model or process you work with that would be a viable candidate for digital twinning. Reference the state of maturity chart we have previously discussed. What data sources do you have access to that can connect your model to its real-world counterpart? What expertise is missing?

Finally, share your experience! Use organizations such as ITS America and meet with your peers as you go. ITS America runs a working group dedicated to digital twins and an Emerging

Technology committee where you can share information, learn best practices, and contribute to documents like this one. You will find others who can share stories about mistakes they made along the way and use this knowledge to guide your implementation decisions.

Industry

University of Michigan Assistant Professor of Information Ben Green wrote, "Contrary to the fables told by smart city proponents, technology creates little value on its own—it must be thoughtfully embedded within municipal governance structures."[12] If you are implementing a new digital twin solution for the market, here are some things to consider first:

- Is your solution solving a real problem? Can you articulate the value of that solution?
- Will it reduce costs for your customers, for example, allowing them to install and maintain less physical infrastructure?
- Will your solution allow customers to use their existing resources more efficiently (roads, ITS, fleets)?
- For potential public sector customers, will an open-source digital twin be compatible with your business model to encourage adoption and interoperability?
- How might your solution help your customers demonstrate benefits to their own constituents? For example, if you create a digital twin solution to improve traffic signal timing with real-time vehicle data, can your solution also measure and demonstrate actual improvements at intersections?

Last, you must continue developing innovative digital twin concepts into reality, working in collaboration with others in the transportation industry to prove the validity of those ideas, and with those in the public sector to ensure they are brought to market in the most broadly beneficial way possible.

> ***Joint Control of Automated Vehicles and Traffic Signals***
>
> *In partnership with the National Science Foundation, Mcity, at the University of Michigan, has released their digital twin as an open-source tool, free for commercial and academic use.*
>
> *See Appendix A.7.*

Academia

A willingness to experiment with modern technologies to maximize their societal impact is extremely important to the technology's success and overall value. Referencing the state of maturity chart included in this white paper, consider what opportunities exist for digital twin use that have not yet been explored. What techniques for data privacy and security should be adopted? What recent technologies are experiencing rapid adoption (e.g., 5G, AI) that could be utilized for broad digital twin creation in five to 10 years? Much like the explosion of the mobile internet a decade and a half ago, digital twin technologies will drive the creation of tremendous new possibilities and, eventually, business. Your entrepreneurial spirit is needed!

The Entire Transportation Community

Most of all, the power of digital twins to accurately model and test complex systems in a digital realm will enable us to improve the safety and efficiency of our transportation networks. But only if we get to work, are unafraid to make mistakes, and learn from the mistakes can we make a better, safer, more interconnected world.

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Appendix A – Case Studies

A.1. Reducing Construction and Operations Costs

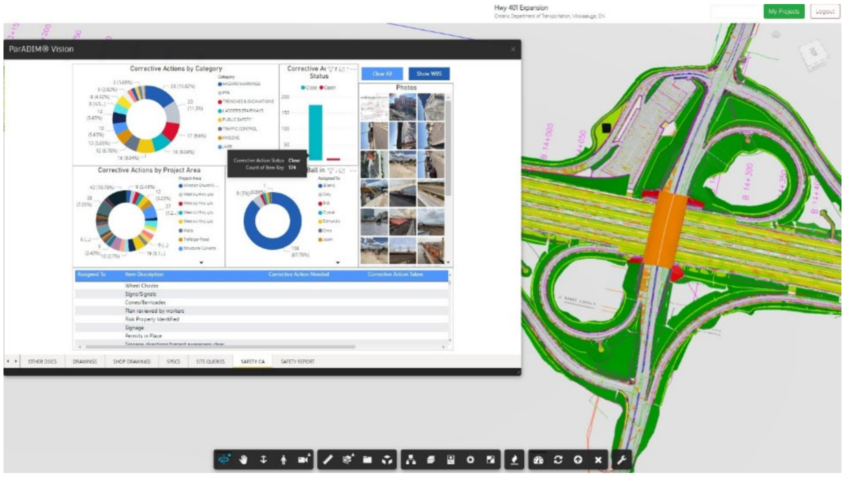
Parsons

Challenge

Construction faces significant data management challenges, including a reliance on manual processes, data waste, and paper-based documentation. The lack of centralized data storage and disparate data sources complicates data integration. Poor communication, collaboration, and reporting hinder project delivery, especially in large joint ventures lacking a unified digital platform. The biggest issue is the lack of interoperability and integration among various applications, leading to inefficient communication and data exchange. Doing nothing exacerbates these problems, resulting in inefficiencies, increased costs, and project delays.

Approach

- To address potential challenges, a digital twin was implemented to provide users with specific tools for site interaction and reporting, advanced custom automation, flexible applications, and integration across a collaborative ecosystem. The digital twin can extract and sync data from various application sources, making it accessible to relevant parties.



- Digital twin technology is the right choice because it offers a comprehensive representation of an asset's physical and functional characteristics. This approach automates information collection, integration, and management throughout the asset's life cycle, leveraging Building Information Modeling (BIM) as its digital hub. Developing a digital twin enhances the ability to monitor, analyze, and optimize asset performance in real-time.

- The solution is designed for a wide range of users, including traffic management operators, the driving public, first responders, city planners, and traffic engineers. It has been utilized by various project participants, ensuring that all stakeholders can effectively collaborate and access the information they need.

Results & Benefits

- **Single Pane of Glass Solution:** The digital twin consolidates critical asset information, including safety, quality, cost, schedule, and project documents such as requests for information (RFIs), submittals, and drawings. This integration enables users to efficiently analyze massive amounts of data, leading to higher levels of transparency and collaboration through real-time, actionable information.

- **Intuitive User-Interface:** Designed for non-BIM users, Paradim® from Parsons simplifies access to all project information via an interactive and bi-directional 3D model interface. There is a module that facilitates schedule sequencing and coordination through 4D model visualizations on the web.

- **Life Cycle Asset Management:** Upon handover, facility managers can readily access as-built data, representing the asset's physical and functional characteristics. This capability enables effective asset performance monitoring in the context of the actual built environment data.

A.2. Flood Mitigation and Operational Efficiencies a Large Public Works Authority and Parsons Corporation

PARSONS

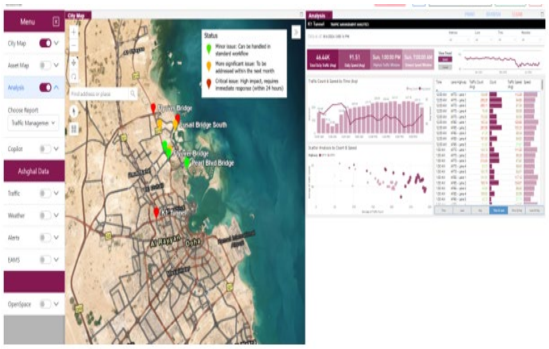
Challenge

The most pressing challenge for this Parsons' client was the flooding of tunnel assets. A significant incident recently occurred where the pumping system failed within the tunnel's drainage system, causing flooding and traffic issues. Many systems' disconnected nature was highlighted as a significant contributing factor to the incident, leading to a slow remediation process. The incident might have been avoided if the issue had been quickly diagnosed, and failovers had been engaged.

In addition to the flooding issue, other tertiary challenges were identified: **Defect Detection** like potholes and wall damage; **Maintenance Issues** like burnt-out lights and pumps operating out of range; **Traffic Alerts** for situations involving stopped vehicles or material on the road; **Environmental Alerts** for conditions such as severe temperature or wind; **Asset Lifecycle Management** for tunnel assets.

Approach

- To address these challenges, Parsons worked with the public works authority to implement a digital twin solution. An appropriate tunnel was selected for the initial deployment, and an existing BIM model was enhanced with the locations of important assets such as sensors and CCTV cameras.
- Data was collected from various enterprise systems, including geospatial, maintenance, asset management, traffic management, SCADA, and financial systems, to create the first instance of a digital twin solution. This data was connected to the digital twin and optimized for the initial slate of use cases, which are being updated routinely. Using an integration platform, we were able to connect each of these systems to the digital twin for real-time analysis.
- A digital twin system was selected for this use case due to its inherent ability to integrate and analyze real-time data streamed from sensors and enterprise systems. It provides a centralized platform for multiple users to access information and improves interdepartmental information exchange.



Results & Benefits

- **Improved Information Access:** A digital twin can integrate multiple data sources into one application, making accessing essential data much easier. Instead of having to navigate multiple applications to gather relevant information, the digital twin allows users to make informed decisions quickly and efficiently.
- **Ability to Perform Ad-Hoc Analysis:** The ability to let users view various types of information side-by-side in an easy-to-use interface, including geospatial maps, assets, work orders, and environmental data, empowers them to perform ad-hoc analyses that would not be possible if the data were viewed in isolation.

A.3. Keeping Roadway Designs Current
Texas Department of Transportation

Challenge

The Texas Department of Transportation's (TxDOT) design activities may sit on the shelf prior to bidding activities for up to a year or more. During this time, the landscape of the proposed construction area may be a site of great consumer growth. Changes to the project area result in elements that could be of concern to design plans. Utility work, terrain shifts, and traffic volume variations, for example, could impact the original design.

TxDOT faced a recurring issue with deferred change orders and design revisions for several key highway projects. Due to budget constraints and scheduling conflicts, these plans often sat idle for months. During that time, environmental factors and usage patterns frequently caused unexpected physical changes to the roadway, such as new wear patterns, unplanned utility work, and shifting traffic volumes. By the time the design finally received approval, it was often misaligned with the current conditions on the ground. This resulted in costly rework, delayed timelines, and inefficient use of resources. Without a more dynamic solution, TxDOT risked further project delays and budget overruns.

Approach

- Digital twins of the entire project site assist in this challenge. Using real-time data from traffic sensors, aerial imaging, and regular site inspections, the digital twin continuously updates to reflect changes in roadway conditions, traffic flow, and environmental impact. The digital twin allows engineers and project managers to visualize in-progress changes and adjust designs proactively rather than relying on outdated site information.
- Digital twins were the selected solution due to their real-time update capabilities, which allows the design team to keep pace with evolving site conditions and avoid redundant revisions. Target users included TxDOT project managers, design engineers, and contractors, who now have immediate insight into real-time changes, helping them anticipate necessary adjustments before designs were finalized and sent for construction.

Results & Benefits

The digital twin will enable TxDOT to reduce unnecessary change orders by 40%, saving time and resources. When site conditions evolved, engineers could make real-time design adjustments, reducing rework and ensuring that final designs aligned with the current state of the roadway.

This approach also enhanced collaboration among the project team, as they could review the digital twin collectively and address potential issues before they became costly problems. Unexpected benefits could include greater accuracy in project cost forecasts and improved communication between TxDOT and contractors, fostering a more responsive and efficient workflow.

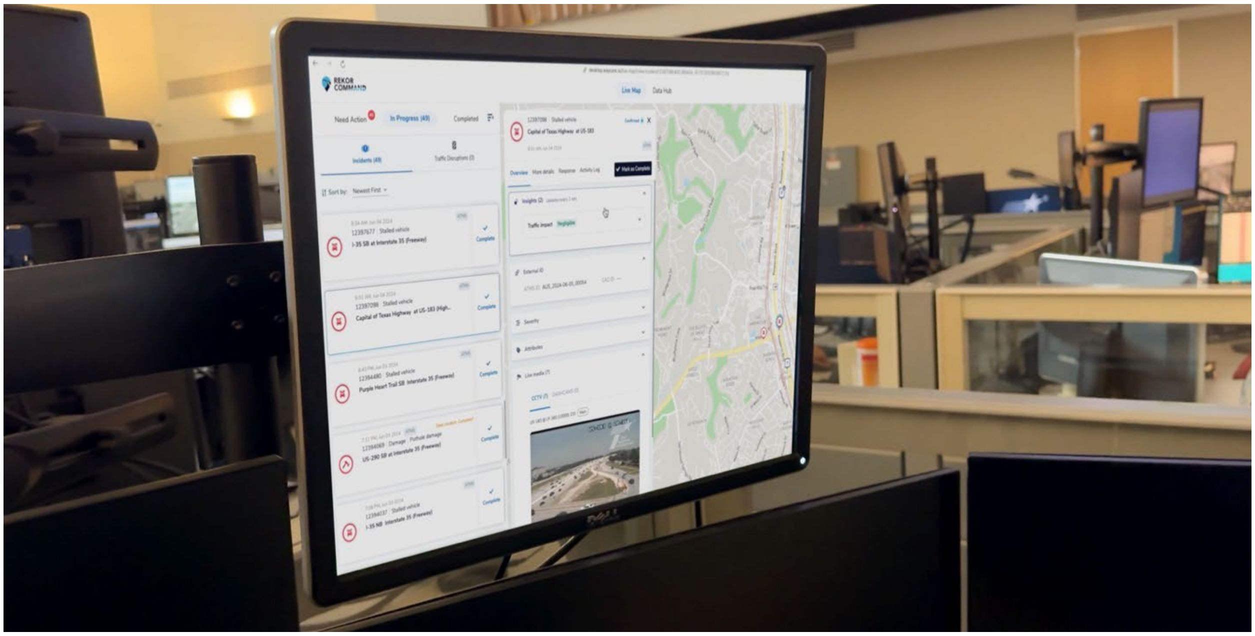
A.4. Managing Traffic Incidents
A State Department of Transportation & Rekor

REKOR

Challenge

In a rapidly growing state with historic transportation investments planned, managing traffic incidents has become increasingly important and more complicated. Delayed detection results in extended congestion, higher risks of secondary accidents, and frustrated travelers.

Traditional methods, such as manual incident reporting, and limited coverage from conventional ITS systems cannot keep pace with the situation's complexity. A more effective traffic incident management system is needed that can leverage data and AI to alleviate congestion, enhance safety, and improve mobility for both local and through traffic.



Approach

- The State Department of Transportation (DOT) selected Rekor Command, a digital twin solution specifically designed for real-time traffic incident management. This platform creates a live digital representation of the roadway by integrating data from connected vehicles, ITS devices, and traffic cameras.

- By continuously updating with real-time information, Rekor Command enables traffic operators to quickly identify incidents like crashes or stalled vehicles. Utilizing advanced AI and machine learning, it detects incidents faster, predicts risks, and facilitates timely resource dispatch, reducing the likelihood of secondary crashes. Benefits extend to traffic operators, incident response teams, and the public by improving decision-making, enhancing response coordination, and decreasing congestion while increasing safety.

Results & Benefits

- Rekor Command's digital twin technology revolutionized traffic incident management, yielding impressive results. Incident detection increased by 159%, with median detection times improving by over eight minutes and clearance times reduced by 45 minutes. This efficiency led to a 29% reduction in secondary crashes, resulting in $766,000 in savings and $1.7 million in productivity gains from improved traffic flow.
- Beyond statistics, the technology's most significant impact has been its ability to save lives. In one instance, the system identified a stranded senior citizen who might have otherwise gone unnoticed, facilitating a swift response. Providing quicker, more precise assistance to vulnerable road users exemplifies how digital twin technology is transforming traffic incident management and enhancing public safety.

A.5. Monitoring a Bridge's State of Health University of Washington & Washington State Department of Transportation

MOBILITY INNOVATION CENTER at the UNIVERSITY of WASHINGTON

Image: Sound Transit

Challenge

Transportation agencies that own, operate, and maintain infrastructure need validated, science-based tools to inform critical decisions regarding maintenance, repair, and operation of their assets. Typically, the current condition of assets (and the identification of any issues) is assessed through visual inspection and thus depends on the experience and judgment of the inspector. Maintenance and repair decisions follow these inspections and are based on the observed conditions. Given the large uncertainty and limits of the data available, this procedure has the potential either to be unduly conservative, and therefore waste precious resources through premature maintenance actions, or to miss anomalous behavior, which might lead to emergency work when the issue becomes problematic.

Approach

- This project will deploy IoT sensors on the Interstate 90 Homer Hadley floating bridge across Lake Washington between Seattle and Mercer Island. Additional attention is warranted because of the new demands imposed on the structure by trains operating on the East Link light rail extension in the coming years.
- Performance of the floating bridges is sensitive to many more inputs, and depends on many more response quantities, than a more conventional bridge. This makes them ideal candidates for applying digital twin technology, particularly because the interplay between different measured quantities, such as anchor cable forces and lateral bridge movement, cannot be examined using present methods.
- The objective of this proof-of-technology project is to evaluate the benefits, limitations, and tradeoffs that an agency or agencies could expect when using IoT digital twin technologies for asset management, maintenance, and operations.

Results & Benefits

- This proof of technology project will provide:
    - near real-time, integrated data on the conditions of the Homer Hadley Memorial Bridge, which can be used to inform operational decisions about bridge closures.
    - alerts sent to operations and maintenance personnel when anomalies and issues are identified by the sensors (e.g., threshold water level in pontoon).
    - digital alignment guidance for seasonal anchor cable adjustments to correspond with lake level changes.
    - a historical record of cable stresses, correlated to bridge position, on which to base future seasonal adjustments to anchor cable tensions.
- Better information about ongoing cable performance could result in more informed choices about replacement. In 2022, 38 cables were replaced on the I-90 bridges for about $9 million. This represents approximately 90 times the cost of the proposed study. If the improved service-life information can show that the average cable life can be extended by five years beyond the present approximately 25 years, the potential ROI is approximately 2000%.
- If successful, this project would provide a blueprint for implementing this technology at-scale to provide real-time monitoring data for critical bridge assets.

Read more: https://mic.comotion.uw.edu/projects/digital-twin-proof-of-technology-evaluation-on-the-i-90-homer-hadley-floating-bridge/

A.6. Prioritizing Roadway Maintenance
Hawaii Department of Transportation & Blyncsy

Challenge

Road maintenance in Hawaii is a critical issue that requires continuous attention and investment from the Hawaii Department of Transportation (HDOT). Hawaii has unfortunately seen a high number of roadway fatalities in recent years.

According to data from the National Highway Traffic Safety Administration (NHTSA), there were 117 traffic-related fatalities in Hawaii in 2022, a significant increase from the 94 fatalities recorded in 2021.

HDOT also faces unique challenges when it comes to road maintenance, including the state's aging infrastructure. Many of Hawaii's roads were built decades ago and now need significant repair and replacement. Additionally, Hawaii's location in the Pacific Ocean makes it vulnerable to extreme weather events, such as hurricanes and flooding, which can damage roadways and make them unsafe for travel, and the separate geography of the four main islands can cause issues as well.

Approach

- Traditionally, organizations in charge of roadway maintenance have relied on a series of manual processes to ensure road conditions meet the expectations of road users. A general summary:
    - Problem identification: Understand the state of the roadway

- Road surveys: Determine the specifics of any issues, and enable a plan for remediation
- Road maintenance: Fix the issues

- Utilizing machine vision for roadway maintenance allows organizations to partially or wholly replace the first two steps listed above with automated processes, reducing the cost, manual work, and environmental impact. Due to the ease of adoption and low marginal cost, organizations can also expand the scope of the first two steps to better determine the extent of the problems they have, and the best place to allocate resources for road maintenance.
- Blyncsy is a complete solution to implement machine vision for any roadway nearly instantly. Blyncsy sources dashcam imagery for any road in the United States, stores and archives the images for quick access, and uses innovative machine learning algorithms to analyze imagery for any number of common or uncommon issues. All of this is then easily accessible via web interface, or open-geospatial (OGC) compliant Web Map Service (WMS) and Web Feature Service (WFS).

Results & Benefits

- Throughout this project, HDOT has gained significant insights into Hawaii's roadway system. These insights have been used to remediate critical issues that otherwise may not have even been reported, let alone fixed. Also, HDOT has been able to verify fixes that were made in the correct locations. In the past, contractors had sometimes failed to correctly address issues or fixed them in the wrong place.
- This pilot project has already resulted in cost savings compared to traditional methods. According to the Hawaii Statewide Transportation Asset Management Plan, roadway preservation tactics cost in the range of $30,000 to $500,000 per lane-mile compared to reconstruction, which costs $1.1 million to $2.3 million per lane-mile. By proactively identifying issues and resolving them, HDOT will potentially realize 97% in savings.
- While Blyncsy will never fully remove the need to manually survey, it can reduce the need for surveys by up to 95%. Utilizing dashcam images from drivers already out on the roads to gain real-time and accurate insights, Blyncsy reduces the need to manually survey and saves agencies up to 23,000 pounds (about the weight of a school bus) of carbon emissions per work vehicle per year.

A.7. Remote Testing of Joint Control of Automated Vehicles and Traffic Signals - University of Washington & University of Michigan

Challenge

The intelligent Urban Transportation Systems (iUTS) Lab, led by Jeff Ban, professor of Civil and Environmental Engineering at the University of Washington, has been working on an algorithm to control traffic signals more intelligently based on data from connected vehicles. This scenario is difficult (if not dangerous) to test in the real world. Ban needed a safe way to experiment with it. This made an excellent use case for Mcity 2.0, a National Science Foundation (NSF) project at Mcity, a public-private mobility research center at the University of Michigan.

Approach

- The iUTS wanted to test the performance of their signal controlling framework, the "SVCC" Multiscale Signal-Vehicle Coupled Control, in real-world and mixed traffic environments. They also wanted to explore how they might extend this platform to a large urban environment at different penetration levels for connected and automated vehicles (CAVs).

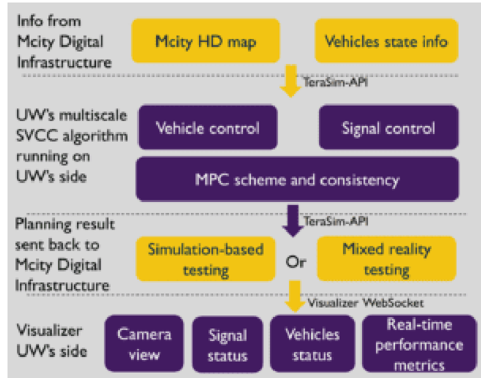


Figure 33. Flow diagram of the iUTS use of Mcity's digital twin.

- The iUTS lacked access to a physical test facility and to advanced traffic control infrastructure. Testing on public roads with background vehicles was deemed too complicated due to the safety and coordination requirements. Fortunately, these encumbrances were easily overcome as Mcity had implemented remote access to these capabilities through Mcity 2.0.
- The iUTS was also able to test their planned scenarios of 25%, 50%, 75%, and 100% CAV penetration, and hone their algorithm while proving that the algorithm indeed performs well under almost any penetration level. The performance metrics tested were fuel consumption, waiting time, time loss, queue length, and number of vehicles (through the intersection).
- Leveraging the digital twin of the Mcity Test Facility, the UW team was able to participate remotely in real-time by viewing various feeds made accessible by the Mcity 2.0 platform. They were also able to control how many background vehicles were "connected" and therefore visible to their algorithm, thus simulating various levels of penetration.

Results & Benefits

- The iUTS team was able to develop and test their algorithm using Mcity's digital twin, and eventually a mixed-reality combination of the digital twin and the physical test facility, all done remotely from the University of Washington campus more than 2,000 miles away!
- This project was so successful that Mcity has released the digital twin of its test facility as an open-source tool, free for commercial and academic use. In addition, the NSF will support the use of the digital twin by academic and industry teams across the country.