Transportation Infrastructure Asset Monitoring Through the Industrial Internet-of-Things

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Final Report

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16. Abstract
The Internet-of-Things (IoT) is a rapidly growing area of wireless communication technology that allows devices to communicate with computers and humans via the Internet. This technology goes far beyond simply connecting devices to the internet, it creates opportunities to combine data from these devices with automated systems for the purpose of analyzing, displaying, and predicting results. The research goal of this project is to explore the current status and viability of Industrial Internet-of-Things (IIoT) technology for the purpose of asset management of transportation infrastructure or the built infrastructure distributed along the highway system in the state of Missouri. Phase 1 of this project (cmr20-011) focused on preliminary research to assess the readiness of IIoT for initial implementation on the transportation highway system (such as: bridges, pavements, retaining walls, signs, etc.). This project conducted a pilot study on a limited number of assets to evaluate the IIoT technology. Through the one year of deployment of sensors on retaining walls, crash barriers and sign structures, the project realized both successes and obstacles, leading to multiple recommendations and lessons learned to benefit future deployments. Real-time data has successfully been transmitted from IIoT sensors and is viewable via the shared dashboard. Alerts have been configured to notify personnel of triggered events, including the hit-and-run impact detected at one of the monitored crash barriers. It is recommended that future IIoT deployments consider ongoing monitoring and proactive maintenance of these devices or engage third-party contractors to reduce down-time. It is the opinion of the research team that this technology is suitable for further deployment for the purpose of asset management contingent upon the consideration of lessons learned presented in this report.

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Transportation Infrastructure Asset Monitoring Through the Industrial Internet-of-Things

Phase 2 Pilot Project
Final Report

Missouri Department of Transportation

Project number: TR202110

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DRAFT

Delivering a better world

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Executive Summary

The Internet-of-Things (IoT) is a rapidly growing area of wireless communication technology that allows devices to communicate with computers and humans via the Internet. This technology goes far beyond simply connecting devices to the internet, it creates opportunities to combine data from these devices with automated systems for the purpose of analyzing, displaying, and predicting results. Allowing for near real-time transmission of data provides users remote access of useful information without having to physically visit locations of interest. Recent implementation of this technology in factories, utilities, and smart cities is often referred to as the Industrial Internet-of-things (IIoT). The research goal of this project is to explore the current status and viability of the IIoT technology for the purpose of asset management of transportation infrastructure or the actual built infrastructure distributed along the highway system in the state of Missouri. Phase 1 of this project focused on preliminary research to assess the readiness of IIoT for initial implementation on the transportation highway system (such as: bridges, pavements, retaining walls, signs, etc.). This report summarizes the implementation of a pilot project on a limited number of assets to evaluate the technology.

Coordination with the MoDOT Technical Advisory Committee consisting of key representatives from various disciplines and departments assisted to finalize assets (retaining walls, sign structures and crash barriers) to be instrumented and monitored. The project team selected asset locations based on several factors including maintenance of traffic, crash history, existing conditions, jurisdiction, traffic volume, and cell reception. Based on these factors the project team selected two retaining walls, two sign structures, and four crash barriers to be instrumented and monitored across the St. Louis Metropolitan Area.

The project team developed system design requirements to guide the project team in selecting a vendor to procure and install the IIoT system. Market research was conducted to investigate vendors within the industry and resulted in meetings with eight suppliers of both sensors and IIoT communications equipment. A set of criteria evaluated each vendor against their relevant experience, capability to provide a full installation, software requirements, capability to instrument all asset types, and ability to offer cellular communications. Bridge Diagnostics, Inc. (BDI) was selected to procure all equipment and install half of the asset locations while MoDOT staff installed the remaining sites. Additional accelerometer test units were obtained from Pi-Lit and installed on crash barriers simultaneously with the BDI equipment.

The data architecture designed for this project transmitted data from IIoT sensors to the cloud, filtered and processed data in the cloud, and shared the data with users via a Power BI dashboard. At each asset location, sensor data was transmitted from each sensor's wireless node to the site gateway. Each gateway then transmitted data at a set frequency to the BDI cloud. At this point an AECOM utilized timer triggered azure functions to retrieve data via BDI's API and stored the data in AECOM's cloud database. Data and visualizations were then shared with users in the Power BI dashboard to view both current and historical sensor data.

A main objective of this research project was to test the viability of utilizing IIoT technology for the purpose of asset management in on a transportation highway system. Through the one year of deployment, the project realized both successes and obstacles, leading to multiple recommendations and lessons learned to benefit future deployments. Real-time data has successfully been transmitted from IIoT sensors and is viewable via the shared dashboard, including historical data. As a result of this deployment, sensors deployed at crash barriers successfully detected a hit-and-run collision on May 28, 2023 at 3:13am at the WB I-64 Exit to Big Bend Boulevard. Notice of this impact was not communicated to MoDOT staff via other outlets. Crash detection technology proved to be the first method of notification and offers a promising future now that Emergency Response units are not present over weekends.

Key lessons learned from this project offer insight to benefit deployment of IIoT systems in the future. Some sensors experienced communication errors during the project, resulting in loss of data. It is recommended that future IIoT deployments consider ongoing monitoring and proactive maintenance of these devices or engage third-party contractors to reduce down-time. A variety of other lessons learned are noted in the final report related to asset selection, system design, field deployment and data management.

Overall, this project confirms the viability of deploying an IIoT system for the purpose of monitoring transportation highway system assets. It is the opinion of the research team that this technology is suitable for further deployment for the purpose of asset management contingent upon the consideration of lessons learned presented in this report.

1. Introduction

The Internet-of-Things (IoT) is a technology that has been growing since its inception in 2009. The technology is dependent on sensors that gather information from physical objects and communicate it to other devices, computers and eventually humans. Even though this technology started with consumer applications, it has entered many industrial applications in factories, utilities, and smart cities. Recently these applications are being referred as the Industrial Internet of Things (IIoT). The IIoT sensors can vary from simple thermocouples to more advanced electro-mechanical devices, such as accelerometers.

The research goal of this two-phase project is to explore the current status and viability of the IIoT technology for the purpose of asset management of transportation infrastructure or the actual built infrastructure distributed along the highway system in the state of Missouri. Phase 1 of the project focused on preliminary research to assess the readiness of IIoT for initial implementation on the transportation highway system (such as: bridges, pavements, retaining walls, signs, etc.) and the results are summarized in **Section 1.1**. Phase 1 of the project concluded on July 31, 2020. Phase 2 of the project has implemented a pilot project on a limited number of structures to physically evaluate the IIoT technology. This report summarizes the key tasks executed as a part of Phase 2.

1.1 Summary of Phase I Research Project

The Phase 1 research project reviewed the current state of the industry as it relates to deploying IIoT devices for the purpose of transportation infrastructure asset management. Elements of Phase 1 included deploying a survey to the state Departments of Transportation within the US, determining the key components of an IIoT system, and outlining the system requirements of a future pilot project to be deployed in Phase 2.

The survey administered to the state DOTs included questions related to asset management, monitoring and the use of IIoT. The response rate for the survey was about 48% and revealed that all DOT respondents conduct inventory and monitoring of bridges and pavements, while other assets being monitored vary from state to state. The survey respondents noted that some level of inventory and monitoring is performed for Transportation Management System (TMS) devices and components. Most agencies monitor bridges and pavements in a frequency interval of one to two years, while other assets are monitored in a frequency interval of one to five years. When it comes to the methods used to collect data, it was noted that the majority of data collection is completed manually by visual inspections, and about a third of the data is collected via an electronic device (data logger, wired or wireless). Regarding data storage, the survey reported that most DOTs use a centralized server to store information and more than 50% use an online GIS system. At the time of taking the survey, about half of the respondents were evaluating IIoT technology and 30% had used it to some degree on vehicles and TMS devices but not for asset management. The Phase 1 report noted that the Missouri Department of Transportation (MoDOT) aligned with national trends at the time and highlighted MoDOT’s desire to stay ahead and consider IIoT technologies for asset management and monitoring.

The key components of an IIoT system noted in Phase 1 include: sensors, gateways, platforms, and dashboards. Sensors may have built-in communications or communication with a gateway to allow them to communicate with a central server or cloud storage system. Further data processing generally takes place on the platform and dashboard that displays the raw data and results of the field measurements. In newer technologies called “edge computing” the data processing may take place at the gateway to distribute computational power. Key considerations for an IIoT deployment include power to the sensors and gateways, field hardened devices, communication, data storage/ processing capabilities, and data security. All these aspects must be evaluated in making the choice for an asset monitoring system using IIoT. The Phase 1 project created a solution matrix to illustrate the variety of assets that may be monitored, but only a select number of assets were recommended for the Phase 2 pilot project, which initially recommended bridges (3), retaining walls (2), and sign structures (2).

A full version of the Phase 1 final report is linked in **Appendix A**.

1.2 Project Goals and Objectives

The overall goal of the Phase 2 pilot project is to procure, deploy, and monitor IIoT devices to test the system's viability in being used as a technology for asset management of transportation infrastructure. As noted in the Phase 1 report, transportation infrastructure is defined as the actual built infrastructure distributed along the highway system.

The scope and objectives as well as the tasks completed as part of this project are outlined below:

Task 1 – Project Management: Coordination of tasks were led by AECOM's project manager, John Song, PhD, PE. Regular meetings were conducted with MoDOT, vendors, and AECOM internal experts.

Task 2 – Finalize Assets to be instrumented by IIoT: An initial set of assets to be equipped by IIoT devices was proposed in the Phase 1 final report. Drive-through analysis, review of existing crash data and additional review with MoDOT was conducted to narrow the original list to specific site locations, which included two retaining walls, two sign structures, and four crash barriers.

Task 3 – System Design and Procurement: A set of system requirements were determined that included the list of sensors to be deployed at each asset, type of communications and installation requirements. Market research was conducted to evaluate IIoT capabilities offered by a variety of vendors against the system requirements. A short list of vendors was compiled that met system requirements and presented to MoDOT before procuring system devices. Conversations with the selected vendor provided insight into determining the structure of the data platform where sensor data would be stored.

Task 4 – Field Deployment and Testing: The selected vendor, AECOM, and MoDOT were present for the installation of half of the asset sites. MoDOT personnel were responsible for installing the remainder of the devices.

Task 5 – Project Summary and Recommendations: Included in the report is a summary of findings, lessons learned and recommendations for future large-scale deployment of IIoT for the purposes of asset management.

Task 6 – Data Management: Data collected from the field and stored in the cloud database is pushed to a custom Power BI dashboard, accessible to MoDOT personnel. The dashboard is capable of showing historic data for each sensor, highlighting communications errors, and informing users of critical sensor readings.

1.3 Project Team

The Phase 2 project was led by AECOM Technical Services with additional technical consulting from Luna Consulting, LLC. Key MoDOT staff formulated the Technical Advisory Committee (TAC) and included representatives from various disciplines and departments: Traffic Management Center, Pavement Engineer, and District Geologist. The purpose of the TAC was to guide the IIoT implementation, provide technical input and documentation reviews during the Phase 2 pilot project.

2. Finalize Assets

The first major task of the Phase 2 pilot project consisted of identifying the MoDOT assets to be instrumented with IIoT devices. At the conclusion of the Phase 1 project, it was expected that three bridges, two retaining walls, and two sign structures would be monitored. During the scoping of the Phase 2 pilot project, it was determined that bridges would be excluded from the pilot project and substituted with four guardrails/safety barriers.

Initial conversations with the MoDOT TAC yielded a list of potential locations to be monitored for each asset type. These draft locations were evaluated by the project team against a variety of factors (**Table 1**) to select the final location for deployment of IIoT devices. Supplemental information including traffic volume, cellular reception, crash history, drive-by analysis and photos were reviewed to inform the selection of assets. Due to the nature of this pilot project, some factors were prioritized more than others to promote ease of installation and testing, such as accessibility and maintenance of traffic. A summary of potential locations is shown in **Table 2** with selected locations highlighted in yellow. **Figure 1** illustrates locations selected for each asset type within the St. Louis Metropolitan Area.

Table 1. Asset Location Factors

Factor	Pilot Project Priority	Future Implementation Priority
Accessibility and Maintenance of Traffic (MOT)	This pilot project required its own MOT to install IIoT equipment. Locations were selected such that complex and lengthy MOT plans were not required. Prioritizing safer installation practices allowed additional personnel to be present to observe the installation of IIoT equipment.	Installing IIoT devices on future assets should consider taking advantage of existing MOT plans, which may occur during other construction or maintenance activities. All future devices must remain accessible to maintenance personnel.
Crash History	Specific to the selection of crash barriers, high crash locations were prioritized over low crash locations.	High crash locations should continue to be prioritized over low crash locations when selecting locations to deploy crash detection systems.
Existing Condition	Assets expected to be reconstructed within the pilot project schedule were omitted from consideration due to the possibility of a reduced monitoring period.	Assets should be evaluated and discussed with the necessary MoDOT departments to determine which key assets should be prioritized from an asset management perspective.
Jurisdiction	All assets selected are under MoDOT jurisdiction.	It is likely that future assets will fall under MoDOT jurisdiction. If assets are shared by MoDOT and other agencies, special agreements may be required.
Specific Asset	Within each asset type, the project aimed at selecting locations exhibiting various characteristics. For example, one cantilever and one single span sign truss were selected for evaluation.	Not applicable. Future implementation shall rely on other factors to prioritize deployment of IIoT devices.
Traffic Volume	Low volume roadways were selected over high-volume roadways to allow for less impact during installation as a result of reducing lanes for maintenance of traffic.	Future implementation may determine that monitoring assets along high volume roadways are a higher priority.
Cell Reception	Poor cell reception would require alternative communications methods. For simplicity in system design, only locations with sufficient cell reception were considered.	In locations with poor cell reception, alternative forms of communication (fiber optic cable) will be necessary, which would require additional coordination with the MoDOT IT department.

Table 2. Asset Locations

Asset Type	Specific Asset	Proposed Location	Notes
End Treatments/Guard Rail/Safety Barrier (choose 4)	SCI Smart Cushion	I-64 EB Exit Gore to Big Bend Blvd.	Low crash history
	TRACC	I-64 WB Exit Gore to Big Bend Blvd.	High crash history
	SCI Smart Cushion	I-55 NB Exit Gore to 3200 Broadway	High crash history
	TRACC	MO 364 WB Exit Gore to Central School Rd/Kisker Rd.	No crash history
	SCI Smart Cushion	I-170 NB Exit Gore to I-270	Close second
	TRACC	I-64 EB Exit Gore to McKnight Rd.	Close second
	TRACC	Eager Rd. EB Ramp Gore at Hanley Rd.	Not a MoDOT road
	REACT	I-170 SB Ramp Gore at I-64/Eager Rd. Split	Selected to vary asset type
	QuadGuard Elite	I-170 SB Ramp Gore at I-64 EB/WB Split	Selected to vary asset type
	TRACC	I-70 EB Ramp from Veterans Memorial Pkwy. To EB 70	Low crash history
	End Treatment	WB I-70 at Lindbergh NB/SB Ramp	High crash history
	Guard Rail	WB I-70 at Lindbergh NB/SB Ramp	High crash history
Retaining Wall (choose 2)	MSE Wall	I-44 WB at Macklind Ave.	
	MSE Wall	I-270 Ramp to Route 180 (St. Charles Rock Rd., Bridgeton)	Unselected after wall would be reconstructed during middle of pilot project.
	MSE Wall	I-44 WB to Berry	Selected to replace the I-270 Ramp to Route 180
	Gabion	Rte. N at Emerling Drive	Not recommended by MoDOT
Overhead Sign (choose 2)	Sign Truss	I-270 EB approaching I-70 Exit	
	Sign Truss	MO 141 SB after Clayton Rd.	Low traffic
	Sign Truss	NB Lindbergh Blvd at I-70 EB Ramp	
	Cantilever Sign	SB Lindbergh Blvd at I-70 EB Ramp	
	Cantilever Sign	SB 141 at I-64	
	Cantilever Sign	SB 141 at MO 100	Low traffic
	Cantilever Sign	NB 141 at MO 100	

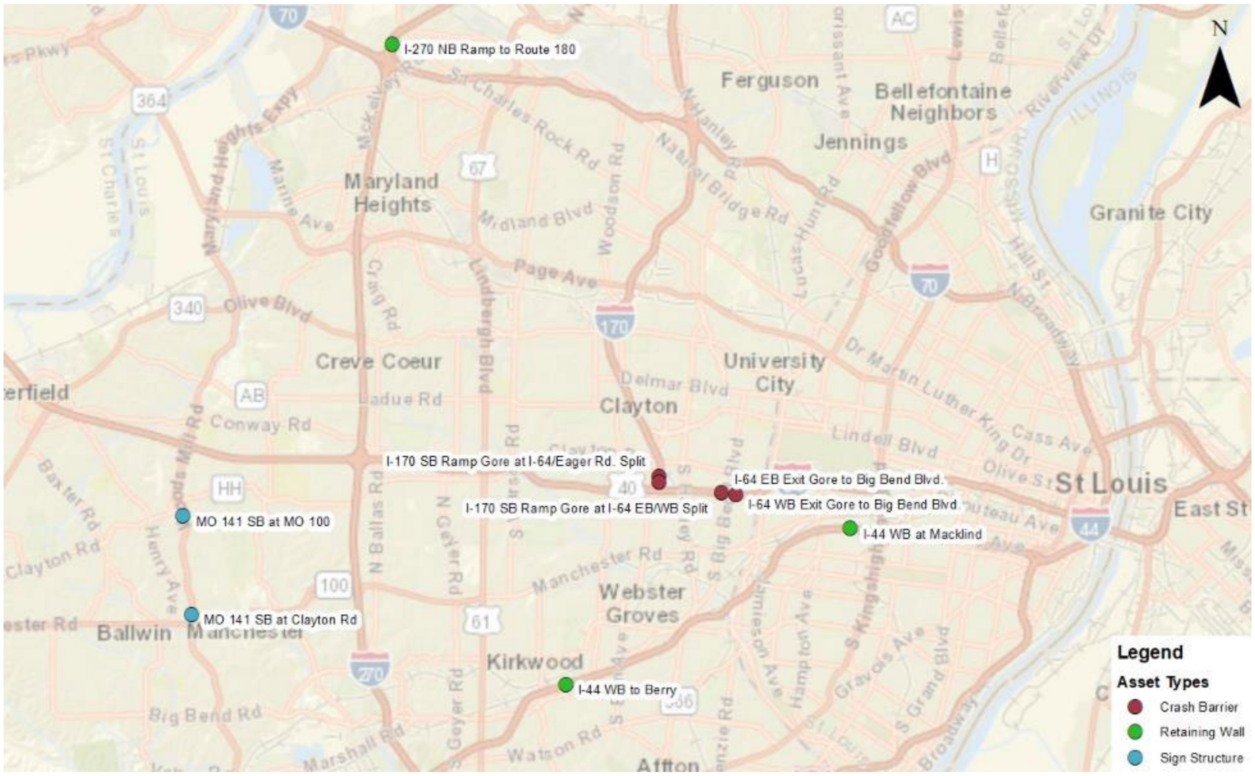

Figure 1. Asset Location Map

3. System Design and Procurement

System requirements were developed in consultation with the MoDOT TAC to include the list of sensors to be installed at each asset, data to be acquired by each sensor, communication architecture and installation requirements. Research was conducted with a variety of vendors who supply sensors, communications equipment and data platforms and have capabilities of integrating within an IIoT environment. Based on the results of several vendor meetings, the project team including AECOM and MoDOT TAC reviewed quotes from a short list of vendors before procuring system devices to be installed. The following notes summarize research efforts with multiple vendors and will highlight recommendations for future system deployments.

3.1 System Requirements

A set of high-level system requirements were developed at the beginning of Phase 2 that provided an outline for future conversations with leading vendors in the infrastructure sensing and IIoT industry. **Table 3** highlights key system requirements guiding the implementation of the project from vendor procurement through sensor installation and data management.

Table 3. System Requirements

System Requirement	Description
Sensors to be installed at each asset type	Retaining Wall (in-place inclinometer, tiltmeter, piezometer, crack meter) Sign Structure (strain gauge, vibration meter) Crash Barrier (accelerometer)
Data to be collected from each sensor	In-place inclinometer: rotation (multi-axial), temperature Tiltmeter: tilt (multi-axial), temperature Piezometer: pore pressure, temperature Crack meter, displacement Strain gauge: strain Vibration meter: acceleration (multi-axial) Accelerometer: acceleration (multi-axial)
Communications architecture	Utilize a network of nodes and gateways to send sensor data to a cloud database. Each sensor (or multiple sensors) is connected to a single node which wirelessly transmits data to the gateway device at each site. The gateway device sends sensor data to a cloud storage database (vendor maintained or AECOM maintained). APIs are utilized where necessary to pull data from vendor databases to ingest into the client facing dashboard.
Installation requirement	Vendors will be required to complete the installation of sensing equipment and demonstrate to MoDOT the installation process for future replication.
Vendor software requirements	Vendor proprietary software must not be required to operate said vendor's equipment. Data must be accessible via API for AECOM to host an in-house constructed dashboard.

3.2 Vendor Market Research

A list of conventional sensor vendors and IIoT specific vendors was included in the Phase 1 final report. This list was used as a starting point to begin further research into potential vendors that could provide a full turn-key solution. Several IIoT specific vendors from the initial list were removed from consideration during preliminary research due to inexperience in working with public infrastructure agencies or not having the capabilities to offer full installation. Following initial research, eight vendors were contacted and interviewed to gain additional information on their sensor and IIoT products. An outline of common questions asked during these conversations is included in **Appendix B**.

A matrix of system requirements and vendors was compiled based on conversations held during each meeting. **Table 4** summarizes this matrix with key evaluation criteria used to simulate system requirements to determine a short list of vendors to request additional information. Within the table, green arrows (▲) symbolize a positive ranking against the criteria, black bars (▬) symbolize mediocre rankings, and red arrows (▼) symbolize negative rankings. All rankings were applied with respect to each vendor. For example, vendors capable of supplying all sensor types to be deployed were prioritized over vendors not capable of supplying all sensor types. The following list summarizes key points resulting in the “Recommended Ranking” included at the bottom of the evaluation matrix.

- **RST Instruments**: Eliminated from consideration due to not offering installation services and not providing a solution for vibration sensing and accelerometers.
- **GEOKON**: Ranked in a tie for third due to additional coordination and development that would be required for a turn-key installation and procurement of accelerometer sensors (custom sensor required).
- **Bridge Diagnostics, Inc.**: Ranked second due to additional coordination required to integrate with a cloud dashboard.
- **Resensys**: Eliminated from consideration for not offering full installation and not suppling all types of sensors.
- **Sensemetrics**: Ranked in a tie for third due to requirements to purchase their proprietary software and not offering full installation. They were not eliminated due to the option for a more extensive 2 to 3-day training on installation procedures.
- **WorldSensing**: Ranked first for meeting all system requirements. No downsides noted following initial conversations.
- **AVNET**: Eliminated based on lack of relevant experience in the public infrastructure industry.
- **Ackcio**: Eliminated based on lack of relevant experience in the United States with public infrastructure agencies as well as not meeting several other system requirements including full installation and providing all sensor types.

Quotes were requested from the top two ranking vendors, BDI and WorldSensing. Initial quotes received from both vendors came in above the allocated budget to perform full installation of all asset locations. Both vendors were requested to explore cost saving strategies and re-submit quotes. The second round of quotes included a reduction in total cost at the expense of reducing services to be performed by the vendors. Reductions were realized by removing vendor performed drilling services, removing vendor installation services, and reducing indirect costs. Individual meetings were held with each vendor to further refine their proposed quotes before MoDOT approved the final vendor proposal.

Following discussions with each vendor, the project team selected BDI to procure and install sensing and IIoT devices for the project. Due to quotes from both preferred vendors still exceeding the allotted project budget for system devices and installation, several components of the project were revised including the following:

- Drilling services for in-place inclinometers and piezometers would be performed through MoDOT’s pre-approved list of drilling contractors.
- BDI would perform the full installation for half of the asset locations. Remaining devices would be provided to MoDOT for MoDOT to install.

Table 4. Vendor Evaluation Matrix

Evaluation Category	RST Instruments	GEOKON	BDI	Resensys	Sensemetrics	Worldsensing	AVNET	Ackcio
Relevant Experience *(DOTs, Public Agencies, etc.)*	▲	▲	▲	▲	▲	▲	▼ No civil infrastructure.	▼ No examples in the United States.
Full Installation *(Sensors and Communications)*	▼ In-Person support offered.	— Not standard practice, support only (in-person or virtual).	▲	— Not standard practice, support only (in-person).	▼ 2 to 3-day training offered.	▲ Partner Engineering Service Provider	▲	▼ Installation training offered.
Software Requirements *(Visualization Platform)*	— Unknown	▲ No visualization platform required. Only for device health and configuration.	— Performs data management and will integrate with the cloud.	▲ No visualization platform required.	— Yes. Must include visualization platform.	— Visualization platform required to view device health and configure device settings.	▲ No visualization platform required.	— Visualization platform required to view device health and configure device settings.
Sensors	▼	—	▲	▼	▲	▲	▲	▼
Strain Gauge	✓	✓	✓	✓	Variety of sensors from third-party vendors are compatible.	Manufacture own tiltmeter. Variety of sensors from third-party vendors are compatible and allow for other integration as needed.	Variety of sensors from third-party vendors are compatible.	Variety of sensors from third-party vendors are compatible.
In-place Inclinometer	✓	✓	✓					
Tiltmeter	✓	✓	✓	✓				
Piezometer	✓	✓	✓					
Crack Meter	✓	✓	✓	✓				
Vibration			✓	✓				
Accelerometer		Custom	✓	✓				Not Compatible
Cellular Communications	▲	▲	▲	▲	▲	▲	▲	▲
Recommended Ranking	Eliminated	3 (tied)	2	Eliminated	3 (tied)	1	Eliminated	Eliminated

Legend

▲: Positive Ranking —: Mediocre Ranking ▼: Negative Ranking

3.3 System Design

Further coordination took place between AECOM, MoDOT and BDI in preparation of installing the system. These activities are summarized in the following two sections on Infrastructure and Data Architecture design.

3.3.1 Infrastructure Design

The infrastructure design included all physical elements of the system including sensors, nodes, gateways, cables, solar panels, junction boxes, and mounting equipment. The following sections summarize key design information for communications elements and each sensor deployed per asset location.

3.3.1.1 Communications Infrastructure

3.3.1.1.1 Gateway Device

- Gateways shall be contained within a weatherproof enclosure capable of housing the gateway device, battery, and other necessary equipment to power the equipment (solar vs. wired power).
- Sites shall determine an appropriate power source, either solar powered or wired from a local electric service. This project utilized solar power at all asset locations. Sites were reviewed for the placement of the gateway device such that the mounted solar panel could be angled to the south and be free of obstructions (buildings, foliage, etc.).
- Gateway junction box mounting may vary. Where applicable, junction boxes would be mounted to existing MoDOT infrastructure such as ITS poles or sign structure supports. When existing mounting supports were not available, it was recommended to install a 3-inch diameter round post, with a minimum height of 8 feet above ground. Site access dictated the gateway location, but it was recommended that gateway devices be mounted out of reach from the public to prevent vandalism. Additional preventative measures included locating the gateway junction box within areas accessible to only MoDOT personnel and/or installing the gateway equipment within a lockable enclosure.
- Locating the gateway junction box shall consider maintenance accessibility in the event equipment must be checked or batteries replaced. Locations should consider where maintenance personnel will park, how personnel will access the gateway site, equipment required to access the junction box (ladder, bucket truck, etc.) and traffic control required to access the site.

3.3.1.1.2 Node Device

- Nodes shall be located within the near vicinity of each sensor due to the cable running from the sensor to the node box.
- Similar to gateway device locations, node box locations should consider future maintenance accessibility when determining their location. Certain restrictions applied, such as proximity to the sensor, but boxes should not be located in difficult to access areas.
- Node boxes must communicate with the gateway device. Large obstructions such as concrete walls, bridges, and heavy foliage will result in a poor signal and may cause interruptions in continuous data feeds. For example, this project installed crack meters at the base of a retaining wall. The node for each crack meter was mounted at the top of the retaining wall in closer proximity to the gateway device.

3.3.1.2 Retaining Wall Sensors

3.3.1.2.1 In-place Inclinometer

- In-place inclinometers were selected to monitor ground movement behind each retaining wall.
- Locations of in-place inclinometers shall consider the depth of installation. In-place inclinometers can be procured such that multiple sensors are placed in a single casing where sensors will monitor segments of underground displacement at a set interval. For example, a casing 20 feet deep could have an in-place inclinometer installed that consists of two 10-foot segments. Each segment consists of a sensor that will provide rotational data in two axes for each 10-foot segment.
- In-place inclinometers require a casing to be drilled and installed prior to sensor installation.

3.3.1.2.2 Tiltmeter

- Tiltmeters were selected to monitor small movements of the face of each retaining wall.
- Locations of tiltmeters considered sections of retaining walls that have exhibited movement.

3.3.1.2.3 Piezometer

- Piezometers were selected to monitor the pore water pressure behind the retaining wall.
- Piezometers require a casing to be drilled and installed prior to sensor installation.
- It is recommended that the existing ground water levels be investigated prior to selecting locations for piezometers to ensure proper function of the sensor.

3.3.1.2.4 Crack Meter

- Crack meters were selected to monitor existing cracks and joints at existing retaining walls.

3.3.1.3 Sign Structure Sensors

BDI designed the sign structure system to operate under the following conditions. A vibration sensor would be attached to either the end of the cantilever sign structure or middle of the single span structure. When the vibration sensor detects movement that exceeds the preset threshold, a series of strain gauge readings will be recorded. Strain gauge readings will not be recorded continuously. To allow for maintenance personnel to replace the vibration sensor batteries, power is cycled to the vibration sensor from the base of the sign structure such that maintenance personnel must only access the base of the sign structure to replace batteries.

3.3.1.3.1 Strain Gauge

- Strain gauges were selected to monitor induced strain on sign structures during heavy vibration events.
- BDI initially proposed the use of spot weldable strain gauges, however, upon further discussion with the MoDOT structural department, weldable strain gauges would not be allowed. An alternative strain gauge was substituted in its place that is installed with epoxy. It should be noted that installing epoxy strain gauges required more time and is more tedious than the originally proposed spot weldable strain gauges.

3.3.1.3.2 Vibration Sensor

- A vibration sensor was selected to monitor excessive movement along the cantilever and single span sign trusses.

3.3.1.4 Crash Barrier Sensors

Crash barrier locations were selected such that two barriers were located within proximity of each other allowing two crash barriers to be paired with the same gateway device.

3.3.1.4.1 Accelerometer

- An accelerometer was selected to detect an impact at each selected crash barrier. When an impact is detected that exceeds the pre-set threshold, an alert is sent to designated contacts.
- Each accelerometer is fully contained within the node box. Sensors are located roughly two-thirds from the front of the crash barrier to detect minor impacts and remain intact.
- Because each accelerometer is located within a node box, each sensor must be located within line of sight of the gateway device.

3.3.2 Data Architecture Design

The data architecture designed for this project is illustrated in **Figure 2** and follows the below process.

1. Individual IIoT sensors deployed in the field send data to each assigned gateway device at pre-set intervals. Many devices in this project have been configured to send data at one-hour frequencies. Crash barrier sensors are configured to send data immediately upon detecting that the threshold has been exceeded.
2. Gateway devices deployed in the field send data to the BDI cloud database at pre-set intervals. Gateway devices in this project have been configured to send data at six-hour frequencies. Each transmittal includes data from sensors communicating with the gateway from the previous six hours. Crash barrier gateway devices are configured to send data immediately upon detecting that the accelerometer threshold has been exceeded.

3. Data is transmitted to AECOM's Azure server database via BDI's API. A timer triggered azure function fetches data at preset intervals. Both raw data and post processed data are stored in the Azure SQL Server Database.

4. Data is interfaced with an AECOM built Power BI dashboard to be viewed by users. Please refer to **Section 5** for additional information on data management and the Power BI dashboard.

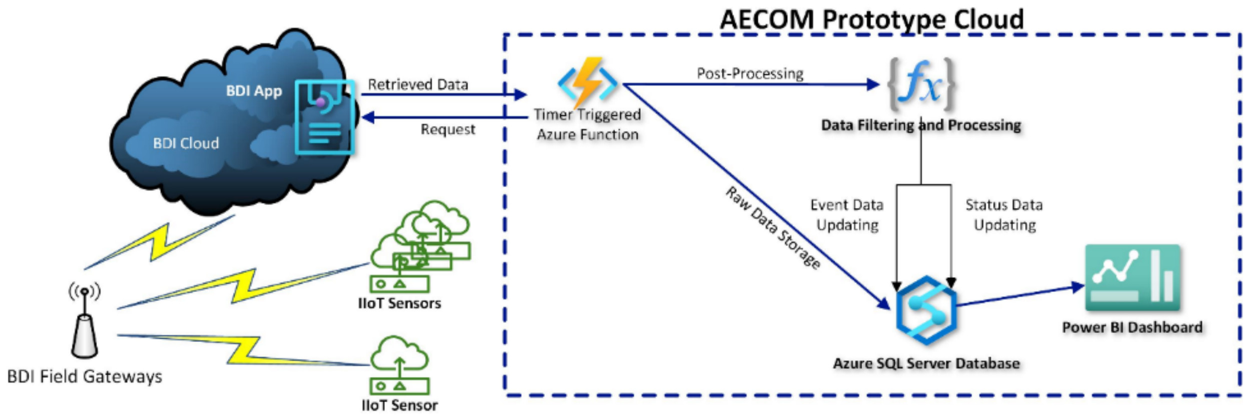

Figure 2. Example Data Architecture

4. Field Deployment and Testing

4.1 Pre-Installation

A pre-installation meeting was held in advance to prepare all parties for the week of installation. The following topics were discussed:

- BDI provided a live video feed to review all sensor and communications equipment. The equipment was set up in their facility for final acceptance testing before being packaged. BDI personnel provided brief demonstrations of how some of the sensors functioned for MoDOT and AECOM team members on the call.
- Installation procedures were reviewed, including maintenance of traffic requirements. Estimating the time to install devices was a critical input for determining the installation schedule and for coordinating with MoDOT's third-party maintenance of traffic contractors. This installation was required to follow standard MoDOT operating procedures related to lane closures. Based on volume of traffic and whether the roadway was an interstate or state highway dictated how long lane closures could be arranged for installation.
- Safety protocols for both BDI and MoDOT were reviewed to ensure all attendees arrived at the site with the appropriate personal protective equipment.
- The schedule for the week of installation was discussed.

4.2 System Installation

Installation of system devices by BDI occurred from Tuesday, October 4th, 2022 until Thursday, October 6th, 2022. All staff met at the St. Louis Traffic Management Center to review safety protocols, maintenance of traffic schedules, view communications devices up close, and review the installation schedule. The following sections document installation at three sites with the assistance of BDI personnel. Lessons learned from the week of installation are highlighted in **Section 6**.

At each site installation, it was recommended to install each gateway device prior to connecting any node devices to ensure connectivity between the node and gateway.

Pictures depicting the installation of the system are included in **Appendix C**.

4.2.1 Retaining Wall Installation

BDI performed the retaining wall installation at the I-44 and Macklind Avenue retaining wall site. Traffic control required the outside traffic lane and shoulder to be closed during the installation of sensors on the interstate facing retaining wall. Prior to the lane closure, the team was able to install the gateway device, in-place inclinometer and piezometer.

MoDOT completed the remaining retaining wall installation in June 2023 at I-44 and Berry Road. The piezometer and in-place inclinometer were not installed at this location due to space limitations.

4.2.2 Sign Structure Installation

BDI performed the cantilever sign structure installation at MO 141 SB after Clayton Road. Traffic control required the lanes under the cantilever sign to be closed during installation. The installation of this equipment took longer than expected due to on-site troubleshooting when the vibration sensor was failing to send signal to the node. It was determined that a cable splice failed. The cable was replaced on-site and all devices were in working condition after the installation.

MoDOT completed the remaining single span sign structure installation in June 2023 at SB 141 at MO 100.

4.2.3 Crash Barrier Installation

BDI performed the crash barrier accelerometer installation at I-64 WB and EB exiting to Big Bend Boulevard. Traffic control required the through lane of the WB exit ramp to be closed during the installation of the gateway and WB crash barrier accelerometer. Traffic control required the EB exit ramp to be closed during the installation of the EB crash barrier accelerometer.

To date, MoDOT has not completed the installation of accelerometers at the I-170 SB Ramp Gore, which included the crash barrier at the I-64/Eager Road split and the crash barrier at the I-64 EB/WB split.

Additional crash barrier detection devices were installed with the BDI accelerometers. AECOM received test devices from Pi-Lit to test alongside the BDI devices. The Pi-Lit devices are similar in nature and contain an accelerometer to detect the magnitude of impact. These Pi-Lit devices do not require a separate gateway device as the cellular modem is self-contained within the sensor housing.

4.3 System Testing

Multiple functions of the IIoT system were tested through this research project including data retrieval, communications, and alerts/notifications. The following section on data management elaborates on data retrieval. The following paragraphs discuss components of the alerts and notifications tested as part of this project and present a case study observed at a crash barrier site.

Two different types of alerts were tested through the native vendor management websites, sensor reading alerts and communication error alerts. Sensor reading alerts were established based on recommendations from the vendors and through conversations with the TAC. These alerts are intended to be used to notify staff of sensor readings out of range requiring attention from MoDOT staff to review. Communication error alerts were established to notify staff of a potential communications error disrupting data from being sent to the cloud database. It is intended that alerts be configured to notify key staff for review and verification before creating a work order to address the alert.

Testing the functionality of sensor reading alerts has proven successful during the one-year testing period; however, a key parameter in establishing the alert criteria has yet to be agreed upon. It is recommended that further research and study be performed to determine the recommended critical values for each sensor type. Communication error alerts established through the BDI native management website were tested and noted to work as intended, however, it is not recommended at this time to send alerts to key MoDOT staff. Communication alerts tend to be sensitive and highly dependent on the installed environment. For nodes that are installed in clear line of sight of the gateway device, the likelihood of communication errors is low, and therefore alerts may be less frequent. For nodes installed with less line of sight, for example in cases where nodes are installed on retaining walls, the team has received multiple false positive alerts. These false alerts are suspected to be sent when the node is unable to send data to the gateway for a short period of time but will eventually send the data when communications has been re-established. No loss in data has been noted at these sites.

The alert functionality was demonstrated over Memorial Day weekend on Sunday, May 28, 2023 at 3:13am when an alert was received that the WB I-64 Exit to Big Bend Boulevard crash barrier detected an impact. The alert was received by both BDI and Pi-Lit devices, however, the Pi-Lit alert provides more information to better contextualize the event. Within the notification email, a map of the sensor location and graph of the impact magnitude over the period of one second following initial detection. **Figure 3** illustrates the impact graph for the event on May 28, 2023.

Due to the project still testing events at this time, the notification was forwarded to MoDOT later that morning. MoDOT personnel later responded that the sensor alert was the only form of notification received notifying the agency of the impact. It was determined that the vehicle impacting the crash barrier left the scene, therefore no police report was filed. No longer staffing Emergency Response units on the weekends also contributed to the delay in reporting. **Figure 4** shows the impacted crash barrier. It is noticeable that the large peak in impact magnitude greater than 40 Gs resulted in a significant crash. Current developments at Pi-Lit are working to incorporate artificial intelligence to predict the severity of crashes based on impact diagnostics recorded by the sensing device.

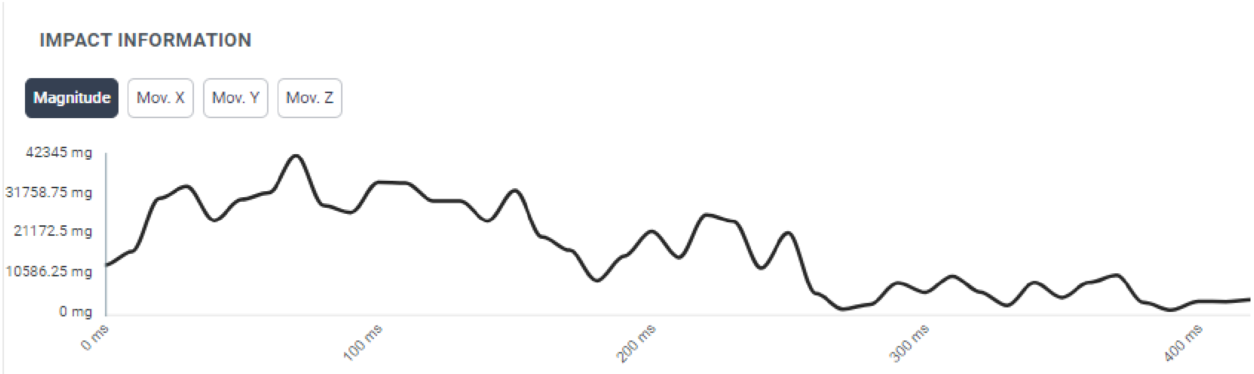

Figure 3. Pi-Lit Impact Information Graph

Figure 4. WB I-64 Exit to Big Bend Boulevard Crash Barrier Impact

5. Data Management and Dashboard

This section discusses key components and processes involved in managing and visualizing data obtained from IIoT devices using third-party APIs, Azure services, and Power BI. The project's primary goal was to provide MoDOT with a comprehensive dashboard for monitoring various sensors, including piezometers, accelerometers, tiltmeters, crack meters, in-place inclinometers, and vibration sensors.

5.1 Data Sources

5.1.1 BDI API Integration

AECOM integrated data from the BDI API, which provided critical information related to the sensors. The following steps were involved:

- Setting up connectivity to the BDI API.
- Implementing Azure Timer Functions to automate data retrieval from the BDI API at regular intervals.
- Storing the obtained data in an Azure SQL database for further analysis and visualization.

5.1.2 Pi-Lit API Integration

AECOM also integrated data from the Pi-Lit API, which supplied information from four accelerometer sensors, two of which were active during the pilot project. The following steps were taken:

- Establishing connectivity to the Pi-Lit API.
- Employing Azure Timer Functions to periodically fetch data from the Pi-Lit API.
- Storing the acquired data in the Azure SQL database alongside the BDI data.

5.2 Data Management

Data from both BDI and Pi-Lit APIs were consolidated and stored in an Azure SQL database. This central repository served as the foundation for data management and analysis. Key aspects of database management included:

- Designing an appropriate database schema to accommodate various sensor data types.
- Implementing data validation and cleaning processes to ensure data quality.
- Developing views to integrate with the dashboard.

5.3 Dashboard Creation

The dashboard was created on January 27, 2023, with the primary aim to provide an intuitive and comprehensive visualization of the data collected from the IIoT devices. This tool was the primary deliverable and enables MoDOT to monitor and analyze data from various sensors in one location.

5.3.1 Purpose of Creation

The dashboard was specifically designed to:

- Facilitate real-time monitoring and alerting for various parameters such as degrees of tilt, displacement, temperature, pre pressure, strain, and vibration.
- Provide an easy-to-understand visualization of complex data sets to assist in monitoring and making informed decisions.

- Enable historical data analysis for trend identification and predictive maintenance.

5.3.2 Data Flow and Integration

The data for the dashboard was sourced from an Azure SQL database, which served as a central repository for data collected from the Device API's. The data integration process involved the following steps:

- **Azure Timer Trigger Functions:** These functions were set up to automatically retrieve data at regular intervals from the IIoT sensors with API's. This ensured that the dashboard displayed the most recent data without manual intervention.
- **API Integration:** The Azure Timer Functions interacted with APIs provided by the sensor vendors (such as BDI and Pi-Lit) to fetch the latest sensor readings.
- **Data Processing:** Once retrieved, the data was processed and formatted to align with the dashboard's visualization requirements. This step included data cleaning, validation, and transformation to ensure accuracy and usability.

5.3.3 Dashboard Features

The Power BI dashboard offered several key features:

- **Real-Time Monitoring:** Live data feeds from sensors enabled immediate visualization of current conditions at various asset locations. Data feeds included sensor readings applicable to each sensor type, temperature readings, and battery status for each connected node.
- **Historical Data Analysis:** The dashboard allowed users to view historical data trends, including deviation data that will aid in the identification of long-term patterns and potential issues. See **Figure 5** for an example of the crack meter data for the I-44 WB at Macklind Avenue installed at the top of the retaining wall.
- **Customizable Alerts:** Thresholds for sensor readings could be set, triggering alerts when specific conditions were met, thus enabling proactive maintenance strategies.
- **User-Friendly Interface:** Designed with non-technical users in mind, the dashboard provided a simple and intuitive interface for easy navigation and interpretation of data.

The incorporation of these features into the dashboard aimed to enhance the effectiveness of MoDOT’s monitoring capabilities, thereby contributing to the improved management and maintenance of their transportation infrastructure assets.

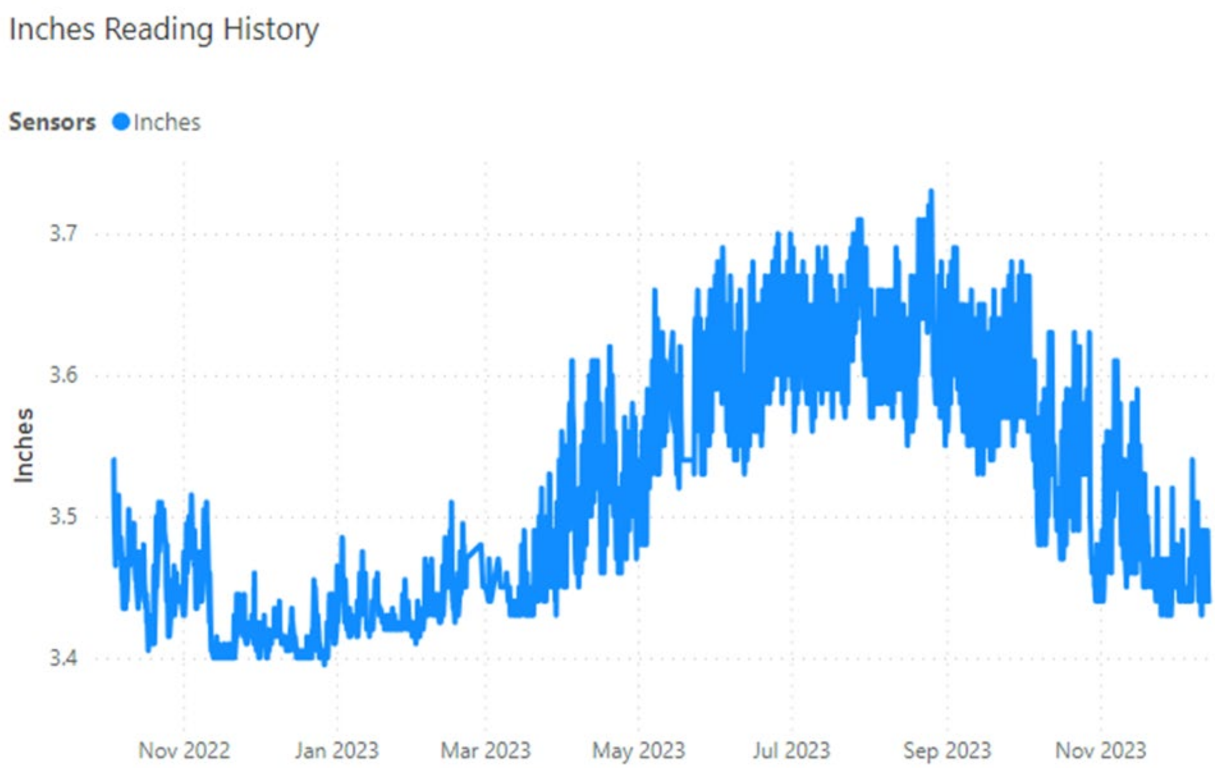

Figure 5. I-44 WB at Macklind Avenue - Crack Meter (Top)

5.4 User Experience

The Power BI dashboard was designed with a user-centric approach, ensuring that MoDOT can easily access and interpret the data. User feedback and iterative design were critical in achieving this goal. The following text and **Figure 6** to **Figure 10** illustrate various pages within the dashboard accessible to users. All charts included in the dashboard include filtering capabilities by date range, x-axis, and y-axis.

- **Latest Device Info:** High level overview of all devices, viewable in both a map and table view. Hovering over sensors in the map view will display current sensor readings and show an image of the sensor installation. Highlighted columns in the table view will report on current status related to sensor communications, sensor readings, and battery life. Red highlights alert users of potential issues that may need to be further investigated.
- **Historical Device Info:** This page shows the historical record of critical readings for the last 3 months. A full export of all sensor readings for a device may be downloaded in excel format by following the directions noted in the top right corner of the page.
- **Deviation from Install:** To better understand the trends and changes in sensor data over time, this page includes graphs that depict the change in sensor readings since the install date.
- **Reading History by Sensor value Definition:** This page shows in-depth charts for all data reported by each sensor, including temperature if available. Depending on the type of sensor, data may not be reported in all charts. Crack meter data is report in the “Inches” reading history while tiltmeter and in-place inclinometer data is reported in the “Tilt Degree” reading history.
- **PiLit Sensor Data:** Pi-Lit summary data is reported on this page. This page is best utilized as an overview of installed sensors. For more interactive features of Pi-Lit devices, it is recommended that users utilize the vendor management webpage.

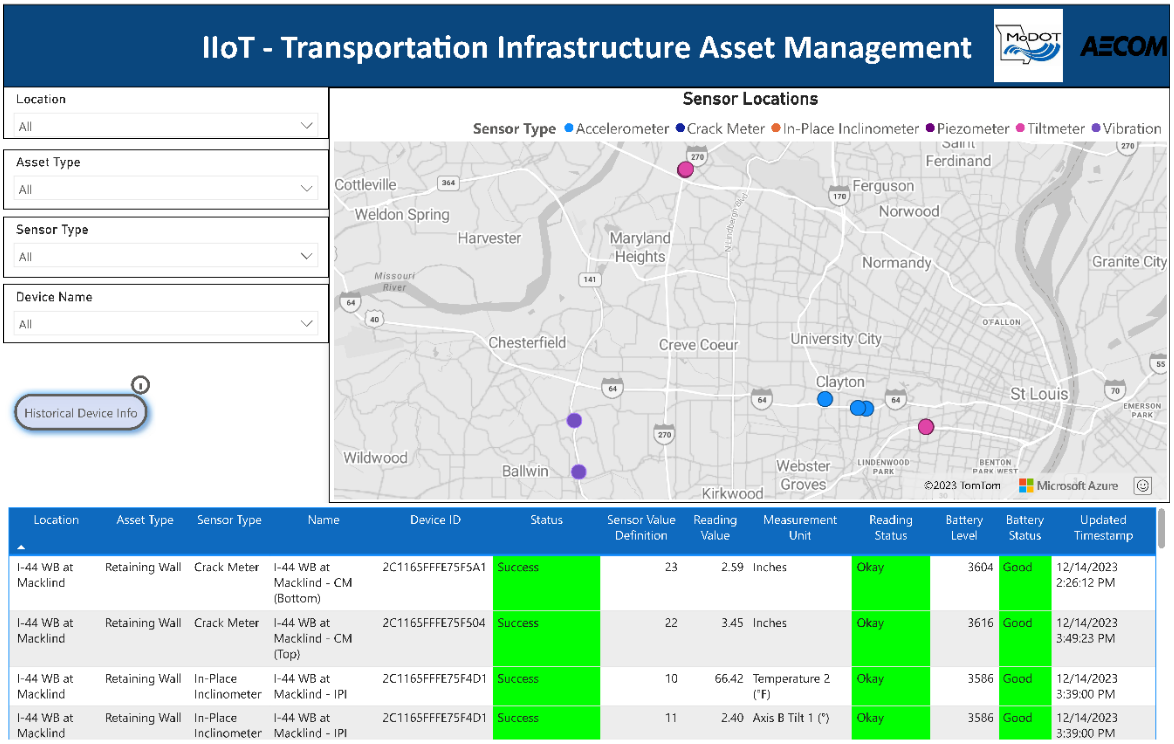

Figure 6. Latest Device Info Dashboard Page

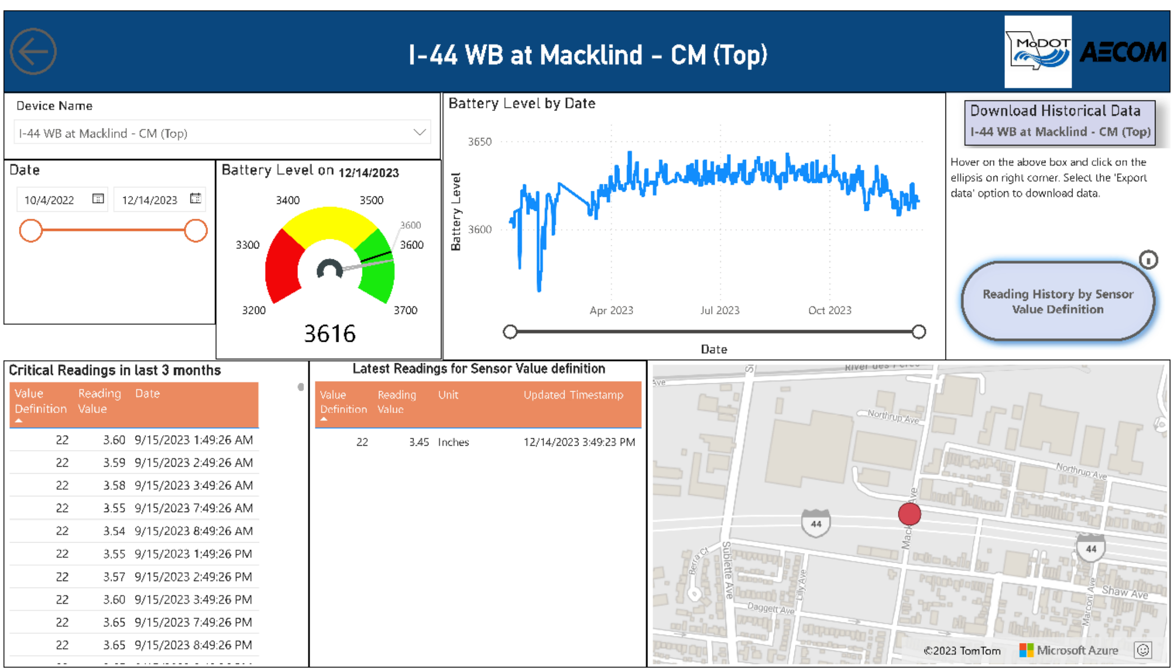

Figure 7. Historical Device Info Dashboard Page

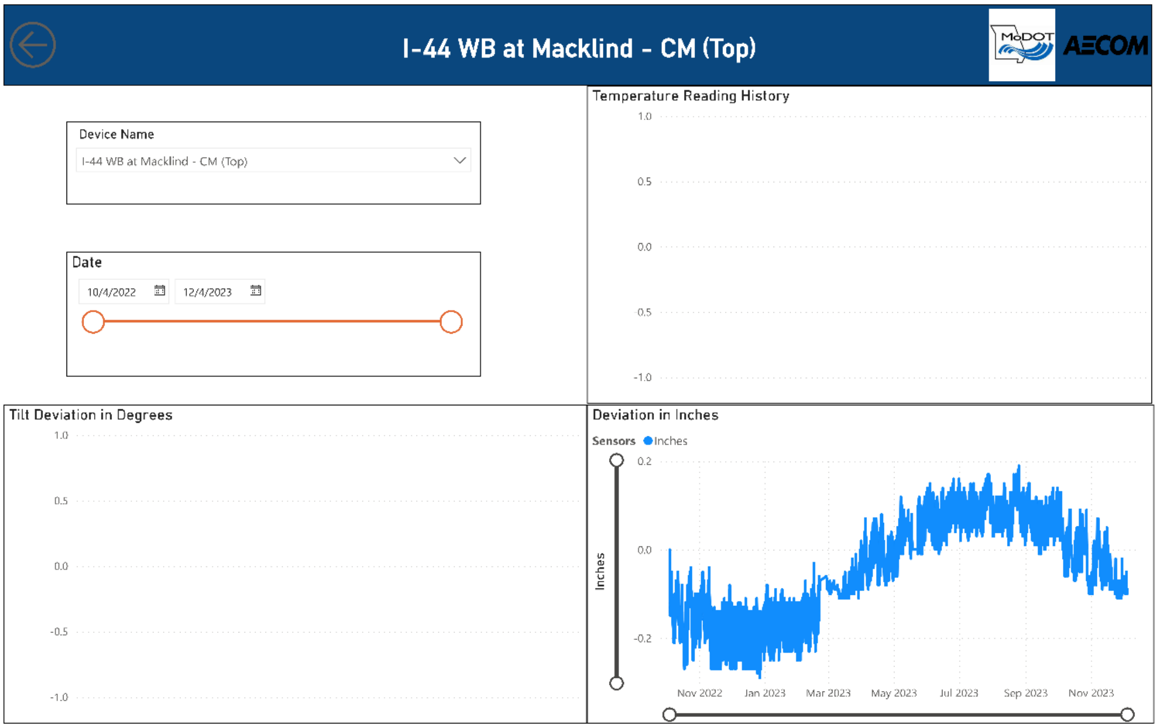

Figure 8. Deviation from Install Dashboard Page

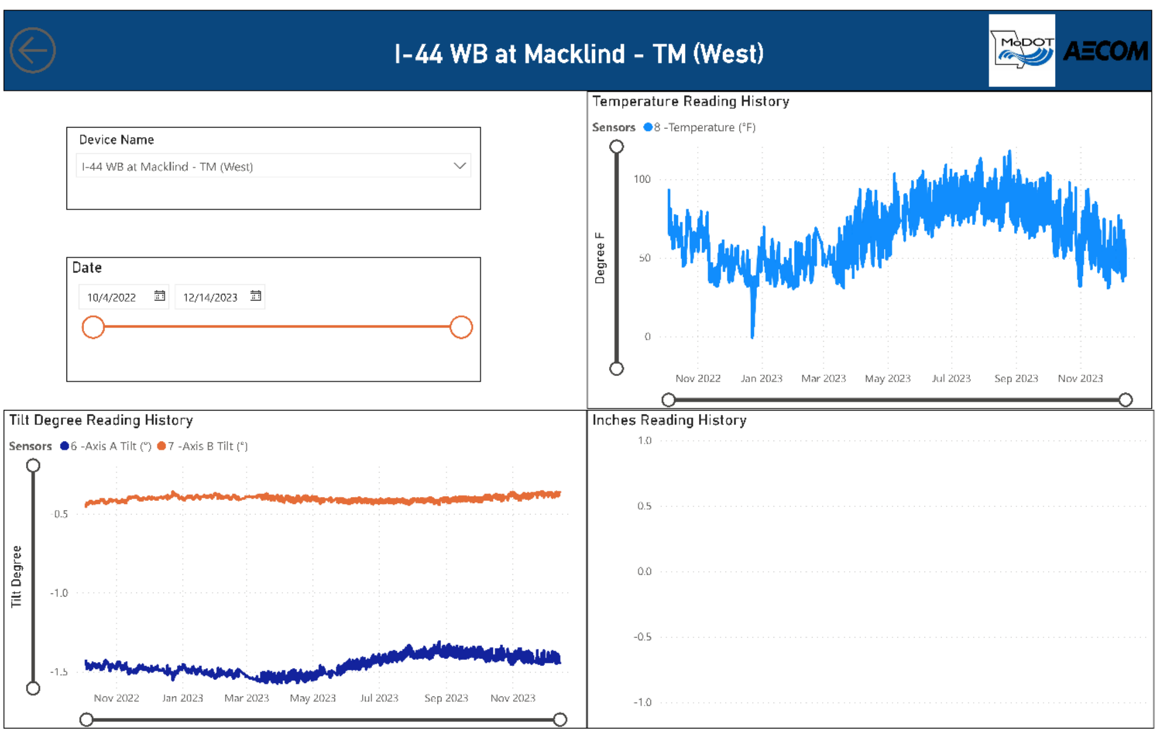

Figure 9. Reading History by Sensor value Definition Dashboard Page

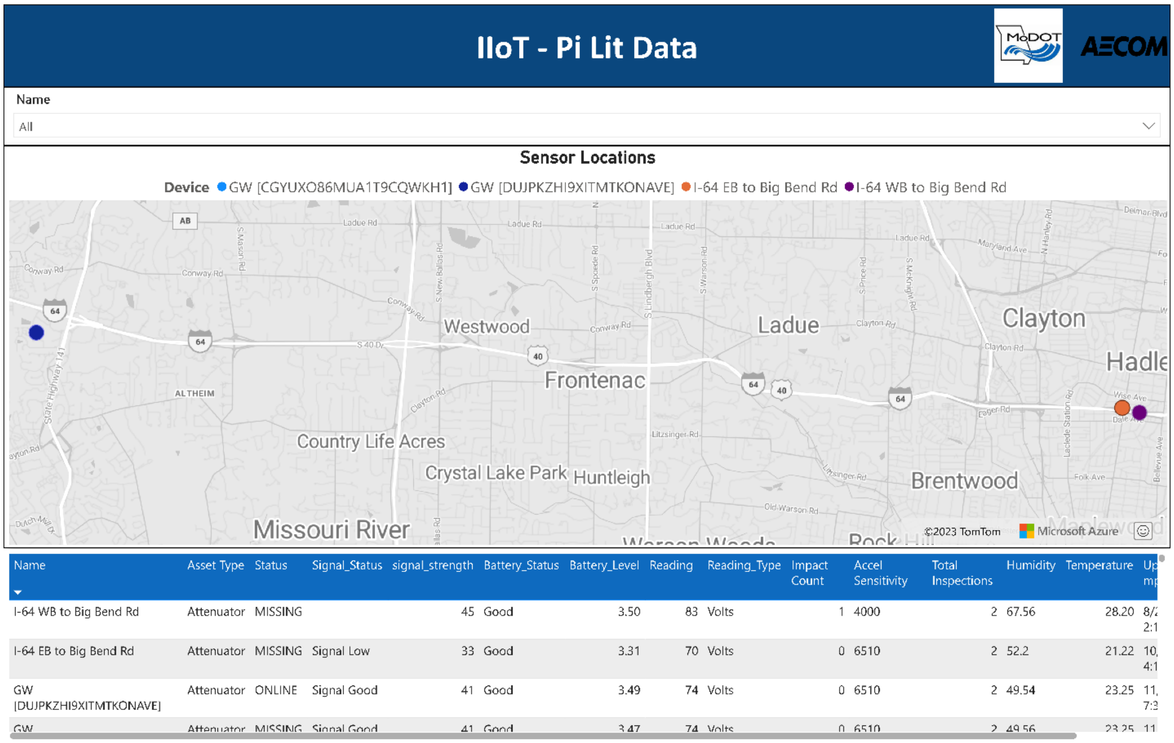

Figure 10. Pi-Lit Sensor Data Dashboard Page

5.5 Future Enhancements

It is recommended that future enhancements be considered should MoDOT continue monitoring IIoT devices, such as:

- Implementing predictive analytics to forecast potential issues.
- Incorporating additional sensors or data sources.
- Expanding the dashboard's capabilities to support more advanced analytics.

6. Lessons Learned

Deploying small scale pilot projects to test the viability of a technology provides the project team with valuable insight into all stages of the project. Decisions made early on in a project may cause unintended results later in the project. Evaluating processes and outcomes can provide actionable steps to be taken when planning and implementing future larger deployments. The below sections outline lessons learned and recommendations to be taken when deploying future IIoT systems.

6.1 Finalize Assets

Later stages of the project have provided insights that can better inform decision makers when selecting assets to include in an IIoT system deployment as noted in the following lessons learned.

- Instrumenting overhead sign structures caused additional delay to the project when concerns were raised with the attachment method of strain gauges. Industry standard attachment methods for strain gauges would utilize a spot bonder to attach weldable foil strain gauges. It was determined that spot bonding was an unacceptable form of attachment, and the alternative method would utilize epoxy attached strain gauges. The epoxy strain gauges require more time and expertise to attach to the sign structures. It is recommended that future deployments reconsider the use of spot bonding. Doing so would allow for more efficient installations and require less technical training for personnel performing the installation.
- If spot bonding is not allowed in future deployments, inclusion of strain gauge monitoring should be revisited. The skills required to perform the attachment of epoxy strain gauges may not be readily available within MoDOT. An alternative would be to out-source all installation to a third-party provider.
- It is recommended that key personnel overseeing asset types (bridges, sign structures, etc.) should be involved early in the project to decrease the likelihood of future delays, as experienced with the sign structure assets with this project.

6.2 System Design and Procurement

The following notes highlight lessons learned related to system design and procurement.

- It is recommended that additional information be obtained at sites where in-place inclinometers and piezometers are installed prior to determining if these sensors are appropriate for the site.
  - During site-preparation, several boring holes reached bedrock and did not allow for the full length of the sensor installation. Site limitations required alternative boring methods be used that limited boring depth. It is recommended that sites be thoroughly evaluated for the appropriate boring techniques based on the desired use of sensors.
  - It was discovered during the installation of the piezometer at the I-44 and Macklind Avenue retaining wall site that the water table did not extend up to the bottom of the bore hole. Water was added during the installation of the sensor but was expected to drain over time. Once the bore hole dried up, the sensor reading was lost. It is recommended that the water table elevation be investigated and assist in determining if a piezometer is an effective sensor to monitor pore water pressure.
- Additional measures should be taken to secure gateway devices at each site. The junction boxes deployed with this pilot project are not capable of being locked. Future projects should consider utilizing NEMA enclosures with either a built-in locking mechanism or have the capability to be secured with a padlock.
- During installation of the sign structure sensors, a failed splice was discovered between a connector and the cable. It is recommended that systems limit the number of splices between cables and connections. If possible, it is recommended to utilize factory terminated cables to reduce the likelihood of splice failures. It is understood that it may not be possible to procure cables at custom lengths and this recommendation may not always be feasible in practice.

- As noted previously, two crash impact sensors were deployed for testing, one from BDI and one from Pi-Lit. The following text documents lessons learned from utilizing each vendor to better inform procurement of crash detection sensors in the future.
  - The Pi-Lit device consisted of a self-contained cellular modem for communications. As of October 2022, BDI noted that developments had occurred since the initial procurement that allowed their crash monitoring device to contain a cell modem in a singular enclosure with no external gateway device required. Since this project began in 2020, standard crash detection devices contain built-in cell modems, which should be the preference for crash detection sensors in the future.
  - BDI sensors tended to be more sensitive than the Pi-Lit sensors resulting in false positive data points.
  - Pi-Lit sensors record the magnitude of impact in milli-G's for one second following the initial impact. This impact graph allows users to visualize the severity of impact. Future Pi-Lit improvements are expected to use predictive analytics to recommend severity in the alert message. The BDI system does not offer any of these features and does not record the measured impact magnitude when alerted the impact threshold has been exceeded.
  - Some issues with connectivity were experienced when attempting to connect Pi-Lit sensors to a cell network. The I-64 EB Exit to Big Bend sensor never connected to the cell network. The vendor has since noted that connectivity issues have been reduced following recent firmware updates.
- It is recommended that future deployments limit the variety of vendors used in deploying IIoT systems. A singular dashboard is capable of ingesting sensor data given the vendor supplies an API for integration purposes, however, configuration management, alerts, and thresholds are best adjusted in each vendor's native site. This lesson was evident when incorporating both Pi-Lit and BDI APIs into the singular dashboard.

6.3 Field Deployment

The following items provide insight into lessons learned surrounding the installation of the IIoT System.

- Future IIoT system deployments should consider utilizing a third-party contractor or vendor to deploy and maintain the system in accordance with established system requirements outlined in the future system design. Several elements of this pilot project substantiates this recommendation. An alternative to the outsourced approach would look to invest resources to develop in-house staff to perform installation and maintenance on a more regular basis.
  - Half of the IIoT pilot project system assets were equipped with monitoring devices in October 2022 by BDI personnel. The remaining sites were instrumented with devices in early June 2023 by MoDOT personnel. The gap in installation was partly due to BDI re-testing some devices, which were delivered to MoDOT in late February 2023. It is recommended that MoDOT consider outsourcing all installations of future IIoT systems.
  - Several devices reported communications and sensing errors throughout the pilot project period. AECOM communicated with BDI support and the MoDOT project team to troubleshoot these errors. BDI support recommended MoDOT maintenance staff visit each site. Scheduling site visits and resolving existing errors was difficult to coordinate. It is recommended that MoDOT consider outsourcing IIoT device maintenance or investing resources in an expanded training program should the IIoT program be expanded to additional sites in the future.
- Pictures and videos were taken during the installation of all IIoT devices including sensors, nodes, and gateways. Reviewing incoming data and development of the dashboard provided insights into the extent of information that should be collected during installation.
  - Crack meters: It is critical to measure the size of the existing crack being monitored. The measurement reading from crack meters does not directly correlate with the size of the crack and requires a baseline reading. During this pilot project, the team was able to determine the baseline reading from the date of installation and show the change in the crack size from the date of installation, however, it would be beneficial to reference the actual crack size.

- In-place inclinometers: It is recommended to record the orientation of the in-place inclinometer (x-axis, y-axis) when inserting the sensor into the bore hole. This information is useful when associating data readings with the real-world configuration.
- Communication nodes: It is recommended to document the Device ID (BDI specific nomenclature) or other unique identifying information along with supplemental information such as sensors connected to the node, sensor location and pictures of the installation. Especially in the case when multiple sensors of the same type are installed at the same location, recording unique identifying information will allow data management engineers to correctly associate each sensor with the correct data received from the field.

6.4 Data Management and Dashboard

The following items document lessons learned from the data management and dashboard task.

- Utilizing Power BI as the dashboard platform presented limitations.
  - It is desirable to include pictures of each sensor for dashboard users to visually identify where sensors are located at each asset. Based on the structure of the current dashboard, access privileges must be shared with end users via SharePoint to view pictures in the dashboard. It is recommended that under the current architecture, picture links must be monitored to ensure links remain active and accessible to end users.
  - Multiple sensors, for example in-place inclinometers and tiltmeters, report orientation data in the form of x-axis and y-axis. It has been recommended that images of each sensor and their respective orientations be labeled to assist dashboard users understand the context of the data readings. Multiple forms of these images may need to be customized depending on the installation location and sensor orientation.
  - Integrating the Pi-Lit API with Power BI proved somewhat limiting and resulted in not capturing all Pi-Lit information reported on the vendor’s native dashboard. It is recommended to visit the Pi-Lit native dashboard to manage sensors and view event data.
- It is recommended that sensor thresholds continue to be evaluated. Baseline thresholds have been established universally by sensor type and represented in the dashboard; however, additional consideration is advised as to how thresholds are applied. The following bullets present a variety of scenarios that will vary from one sensor type to the next and depend on the asset location, priority of asset and baseline data point.
  - Crash detection sensors were pre-set with a threshold of 2500 milli-G’s but based on the location of each sensor and desired sensitivity, may be adjusted. For example, if deployed along cable barrier systems, lower thresholds may be capable of detecting impacts further from the sensor but may also be susceptible to an increased number of false positives.
  - Crack meter thresholds may vary based on use case. For example, sensors monitoring retaining wall construction joints may warrant a different threshold than surface cracks. Likewise, it may be desired to set the threshold as a discrete distance (send an alert when the crack/joint is 0.5 inches) or differential (send an alert when the crack/joint has grown 0.2 inches from the baseline).
  - Tiltmeter and in-place inclinometer data is reported in degrees of tilt and rotation respectively. Translating this data into actionable alerts may depend on the site location and priority of the asset being monitored. For example, a tiltmeter threshold may be stricter if installed on an existing retaining wall exhibiting tilting movement than if it were installed on a new retaining wall. It is recommended that alternative alerts be evaluated, such as excessive movement in a set period.

7. Conclusions

The research project followed up the Phase 1 findings that investigated the current state of the industry as it relates to deployment of IIoT devices for the purpose of asset management in the highway infrastructure system. Phase 1 concluded that the technology was mature enough to implement in a pilot project for the highway system, which resulted in this Phase 2 project selecting assets to deploy an IIoT system, developing system requirements, procuring, and installing the IIoT system, and developing a data management system with dashboard to display the collected data.

Through the system design process and yearlong deployment of the IIoT system, several lessons learned have been documented to provide recommendations for future deployments of this technology on the MoDOT highway system. Overall, this project has confirmed the viability of deploying an IIoT system for the purpose of monitoring transportation highway system assets, but the following key lessons learned shall be considered in future deployments to increase the utility of the system.

Detection of impacts utilizing crash detection sensors has shown how this technology can aid in filling resource gaps in the current incident response system. During the pilot project, the team received notification over the Memorial Day weekend on May 28, 2023 at 3:13am of an impact exceeding 40Gs at one of the monitored crash barriers. Due to zero emergency response units patrolling on weekends, the crash detection sensor was the only source of notification for this hit-and-run incident. Having the capability to detect events in real-time can allow for more efficient and effective emergency response.

Key lessons learned over the course of the pilot project span across asset selection, system design, field deployment and data management.

- **Finalize Assets:** It is recommended that key personnel overseeing asset types (bridges, sign structures, etc.) be involved throughout the project to avoid delays such as those caused by modifying the strain gauge attachment method at this project's sign structures. Future projects should re-evaluate the use of spot bonding vs. epoxy bonded strain gauges.
- **System Design and Procurement:** It is recommended that additional site condition information be obtained and utilized in determining the best use for in-place inclinometers and piezometers. Additional measures should be taken to secure gateway devices at each site. Future deployments should limit the variability in communications equipment manufacturers to reduce vendor configuration management efforts and ease of ingesting data into the database.
- **Field Deployment:** Future deployments should consider utilizing a third-party contractor or vendor to deploy and maintain the system in accordance with established system requirements outlined in the future system design. During installation, pictures, videos, and measurements should be used to document the precise location and ID of each sensor, node and gateway installed at each site.
- **Data Management:** Due to the small pilot project sample size, it is recommended that sensor thresholds continue to be evaluated with respect to sensor type, asset type, and monitoring purpose. For expanded future deployments, the data architecture and dashboard should be re-evaluated in consideration with current MoDOT IT operating procedures to ensure any MoDOT hosted data is accessible and secure.

Overall, this project confirms the viability of deploying an IIoT system for the purpose of monitoring transportation highway system assets. It is the opinion of the research team that this technology is suitable for further deployment for the purpose of asset management contingent upon the consideration of lessons learned presented in this report.

Appendix A Phase 1 Final Report

The Phase 1 Final Report can be located on MoDOT’s research report repository, report number cmr20-011.

Appendix B Vendor Question Template

Transportation Infrastructure Asset Monitoring through the Industrial Internet-of-Things

- Sensor/Data Logger Equipment
  - What is the battery life for remote devices/data loggers?
  - If solar power is recommended of your device, what is the average power consumption for a turn key system?
  - Are there limitations to communication between remote nodes and the gateway device (range, line of sight, etc.)?
  - In addition to sensor data, what other data is provided? i.e. uptime, downtime, low battery, humidity, temperature
  - Does it push data on a routine basis, trigger event or only when polled?
- Communications Equipment
  - Available power source (solar/battery/wired)?
  - Does your device include a built-in cellular modem? If so, what type of connectivity is provided (3G, 4G, LTE, etc.)?
  - What is the required bandwidth (3G, 4G, LTE, etc.)?
  - Is the device cell carrier agnostic?
- Software
  - What software is used? Does the vendor require use of their own software to access data and device health (battery, connectivity, etc.)?
  - Is the software open source?
  - What format is data provided in?
  - Does it come with Software Development Kit (SDK)? If so, in what programing language? Visual C, C#, Java, Python?
- Other
  - How secure are device installations? Are they susceptible to tampering?
  - Does the vendor offer test/demo products?
  - What is the timeline for testing and installation?
  - What information is required to obtain a quote?
  - Have these devices been used by other public agencies?
  - What type of field installation support is provided? If any.
  - Are these devices IP66 or IP67 rated? In other words, can they operate in the open environment exposed to the elements?
  - What is the expected maintenance for these devices? Does it occasionally require fine tuning or calibration?

Appendix C Installation Pictures

C.1 I-44 and Macklind Avenue Retaining Wall

Figure 11. I-44 and Macklind Avenue – Gateway Installation

Figure 12. I-44 and Macklind Avenue – Tiltmeter and Crack meter Installation

Figure 13. I-44 and Macklind Avenue – In-place Inclinometer and Piezometer Installation

Figure 14. I-44 and Macklind Avenue – Installing In-place Inclinometer

C.2 I-44 WB to Berry Road Retaining Wall

Figure 15. I-44 WB to Berry Road – Gateway Installation

Figure 16. I-44 WB to Berry Road – Tiltmeter Installation

Figure 17. I-44 WB to Berry Road – Sensors Installed on Retaining Wall

C.3 SB 141 at MO 100 Cantilever Sign Structure

Figure 18. SB 141 at MO 100 – Gateway Installation

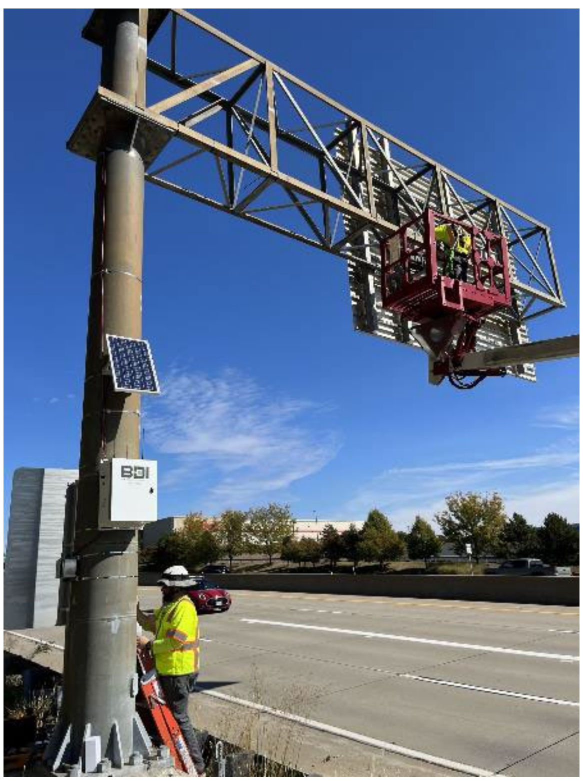

Figure 19. SB 141 at MO 100 – Accelerometer Installation on Cantilever

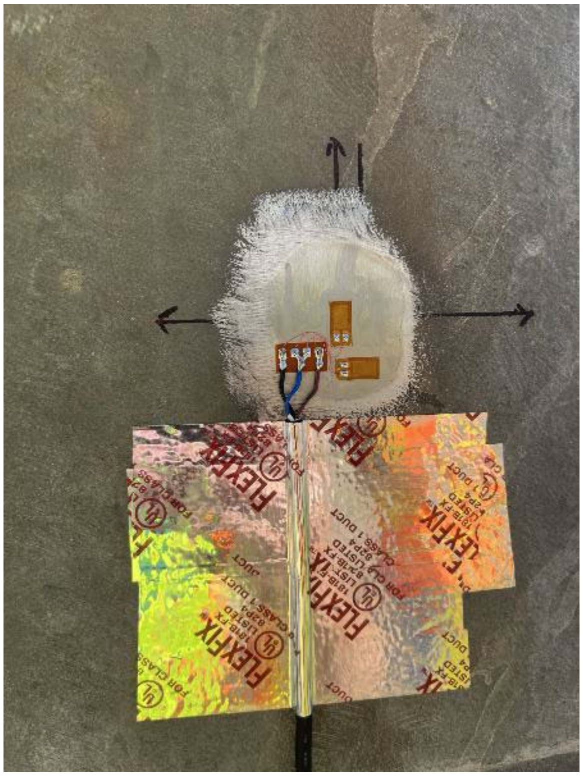

Figure 20. SB 141 at MO 100 – Strain Gauge Installation

Figure 21. SB 141 at MO 100 – Strain Gauge and Node Installation

C.4 I-64 WB/EB Exit Gore to Big Bend Boulevard Crash Barriers

Figure 22. I-64 WB/EB Exit Gore to Big Bend Boulevard – Gateway Installation

Figure 23. I-64 EB Exit Gore to Big Bend Boulevard – Accelerometer Installation

Figure 24. I-64 WB Exit Gore to Big Bend Boulevard – Accelerometer Installation

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