Aurora

working to advance road weather information systems technology

Non-Invasive Sensor Deployment in Aurora Member States

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Aurora Project 2018-02

Final Report
June 2022

About Aurora

The Aurora program is a partnership of highway agencies that collaborate on research, development, and deployment of road weather information to improve the efficiency, safety, and reliability of surface transportation. The program is administered by the Center for Weather Impacts on Mobility and Safety (CWIMS), which is housed under the Institute for Transportation at Iowa State University. The mission of Aurora and its members is to seek to implement advanced road weather information systems (RWIS) that fully integrate state-of-the-art roadway and weather forecasting technologies with coordinated, multi-agency weather monitoring infrastructures.

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16. Abstract

This project pursued a large-scale effort to deploy non-invasive sensors adjacent to invasive sensors (embedded in the pavement) located at existing road weather information system (RWIS) stations and to consider agency suitability between the different sensors. While some RWIS stations may have multiple invasive sensors measuring pavement temperature at various locations (e.g., bridge deck and approach), this deployment was unique in that both the invasive and non-invasive sensors were measuring the same, proximate physical locations.

Within this effort, the project team was responsible for identifying the non-invasive sensors on the market, purchasing and distributing the compatible devices and necessary auxiliary equipment to participating Aurora member states and, once installed, assimilating agency experiences and establishing access, if possible, to the sensor data for comparison and visual presentation. The participating Aurora agencies were responsible for site selection, sensor calibration, installation, and maintenance.

In general, many participating states provided positive feedback with respect to non-invasive sensors and their reported data. Some of the challenges that were shared included identifying a suitable installation location due to sensor specifications, initial sensor operation, and integration and data retrieval.

As a result of this experience, some participating state departments of transportation (DOTs) have decided to adopt non-invasive sensors, expand their deployment of them, or even consider applications beyond those planned with this project. While this project initially targeted pavement surface temperature, one participating agency with limited non-invasive sensor experience is planning on statewide deployment for real-time friction measurements for use in agency decision making.

The project allowed participating agencies to work with new vendors, creating an opportunity to evaluate the different products, encounter potential issues, and identify possible solutions through a low-risk environment. This effort will support future research on both pavement temperatures and friction across the US based on data from the same makes and models of non-invasive equipment.

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NON-INVASIVE SENSOR DEPLOYMENT IN AURORA MEMBER STATES

Final Report
June 2022

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EXECUTIVE SUMMARY

This project pursued a large-scale effort to deploy non-invasive sensors adjacent to invasive sensors (embedded in the pavement) located at existing road weather information system (RWIS) stations and to consider agency suitability between the different sensors.

While some RWIS stations may have multiple invasive sensors measuring pavement temperature at various locations (e.g., bridge deck and approach), this deployment was unique in that both the invasive and non-invasive sensors were measuring the same, proximate physical locations.

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1 INTRODUCTION

1.1 Problem Statement/Need

Collecting, analyzing, and sharing weather information is critical for the safety, mobility, and vitality of surface transportation in the US. In terms of surface transportation, nearly 5,000 people are killed and more than 418,000 people are injured on average from weather-related crashes each year. This is according to 10-year averages from 2007 to 2016 analyzed by Booz Allen Hamilton based on National Highway Traffic Safety Administration (NHTSA) data (FHWA 2020).

In the transportation industry, both public and private agencies use road weather information system (RWIS) data to understand, analyze, and forecast weather-related impacts to traffic safety, roadway and supply chain operations, maintenance, and a variety of related decision support. Traditionally, RWIS locations relied on in-pavement sensors physically connected back to the roadside equipment for pavement temperature and other variables. Unfortunately, this style of in-pavement sensing is vulnerable to damage as road surfaces are replaced or maintained over time.

The recent market availability of non-invasive sensors has added a new element for consideration as agency personnel contemplate the use and integration of non-invasive sensing. A variety of non-invasive temperature sensors from different manufacturers exclusively built for pavement surface temperature or condition measurement are currently available. Given this, agency staff are interested in understanding how non-invasive sensing serves their needs and matches up with their legacy invasive sensing data since pavement temperature readings are critical for winter weather treatment decisions.

The lack of comparative data, as well as comparative cost, has potentially slowed technology adoption of non-invasive sensing by some state departments of transportation (DOTs). Meanwhile, some small-scale studies comparing remote and in-pavement sensors have provided promising results confirming that the pavement temperature measurements from non-invasive sensors were comparable to the data obtained from in-pavement sensors (Feng and Fu 2008, Tilley 2010).

Aurora pooled fund member agencies are continually considering innovative strategies and sensing equipment to reduce the impacts that weather has on mobility and safety. This study seeks to support agency decision-making in terms of understanding the agreement between invasive and non-invasive sensing data and the additional measurements that non-invasive sensors may report. This study provided an opportunity for many agencies to utilize and evaluate different non-invasive sensors for the first time and to evaluate them at the same locations as existing invasive sensors.

1.2 Research Plan

This project pursued a large-scale effort to deploy non-invasive sensors adjacent to invasive sensors located at existing RWIS stations and to consider agency suitability between the different sensors. While some RWIS stations may have multiple invasive sensors measuring pavement temperature at various locations (e.g., bridge deck and approach), this deployment was unique in that both the invasive and non-invasive sensors were measuring the same, proximate physical locations.

Within this effort, the project team was responsible for identifying the non-invasive sensors on the market, purchasing and distributing the compatible devices and necessary auxiliary equipment to participating Aurora member states and, once installed, assimilating agency experiences and establishing access, if possible, to the sensor data for comparison and visual presentation. The participating Aurora agencies were responsible for site selection, sensor calibration, installation, and maintenance.

1.2.1 Accounting for the Diversity of Operational Conditions Across the US

This project was planned to account for the great diversity of climate and roadway settings among Aurora member states. While installation sites were at the discretion of participating states, sensors were deployed in a way to evaluate a variety of conditions representative of the host states’ roadway and weather conditions.

1.2.2 Accounting for the Diversity of DOT Practices

At this beginning of this project, there were different approaches toward the use of non-invasive sensors among the US states as reflected in this effort. Several DOTs, including Aurora member states, were already using non-invasive sensors, so they did not choose to participate in this project and allowed other states to use the sensors allocated to their agencies. Other agencies predominantly used invasive sensors and were very interested in evaluating non-invasive sensor performance. Lastly, other agencies had considered non-invasive sensors, having deployed them in a few locations for performance evaluation, but were interested in participating in a larger study with other Aurora member states. Such participation allowed for a more comprehensive assessment of the pros and cons of non-invasive sensors and different models.

1.3 Remaining Report Overview

Chapter 2 covers equipment selection; Chapter 3 covers procurement; Chapter 4 covers deployment and includes sample data comparisons; and Chapter 5 provides a summary and conclusions, including potential next steps and future opportunities.

2 EQUIPMENT SELECTION

2.1 Input from the Member States on Overall Specifications of Equipment

To participate in the project, each state had to commit to cover the costs of non-invasive sensor installation, either by embedded DOT staff or contractors. Project funds would cover non-invasive sensor costs and selected auxiliary equipment, which are discussed later in this report.

Prior to equipment selection, participating states provided input on their expectations for the non-invasive sensors with respect to performance and overall specifications. Many state DOT staff members envision a low-maintenance RWIS network and are developing agency roadmaps with this objective in mind. Calibration and maintenance requirements were a primary concern regarding sensor deployment and performance. Even if all other aspects of performance were satisfactory, sensor maintenance and calibration were still a concern.

Another critical sensor specification was measurement distance, which could dictate where the non-invasive sensors could be installed. Because non-invasive sensors are mounted on a pole or overhead, a site's characteristics may only allow a pole to be installed at certain distances from the road surface (which can be greater than the sensor's range).

As noted previously, documentation comparing in-field non-invasive sensors and invasive pavement temperature readings is limited, even among the agencies with experience deploying them. Several Aurora states that have deployed non-invasive sensors have done so in a limited number of locations, focused primarily on the practical high points and logistics, with sensors from only one manufacturer and not generally co-located sensors. Therefore, only a few combined sites (where both sensor types are deployed) were available, producing very limited comparative data.

2.2 Market Availability

Prior to identifying specific needs and practices of Aurora member states, the project team investigated the non-invasive sensors available on the market and solicited feedback from others, such as Aurora members, Friends of Aurora, and vendors. The resulting list of non-invasive sensors, representing four manufacturers and six models, is presented in Table 1.

Table 1. Available sensors on the market deemed suitable for this project

Manufacturer	Non-Invasive Pavement Sensor Model
Vaisala	DST 111 Remote Road Temperature Sensor
Vaisala	DSC 211 Remote Surface State Sensor
High Sierra Electronics	IceSight 5433-34
Lufft	NIRS31-UMB (8710.UT01)
Lufft	StaRWIS (8711.U55)
Boschung	R-Condition

This market availability list was used as the basis for the procurement plan, which shortlisted equipment based on procurement guidelines, bid results, and selection of final equipment to meet the needs of each state. The procurement plan defined the equipment and quantities per member agency. The procurement budget also included auxiliary components/equipment for the sensors, such as wiring, poles, mounting hardware, and data loggers Not all agencies required auxiliary components.

2.3 State Input and Compatibility

The project team surveyed the participating Aurora states to identify the non-invasive sensor(s) of interest, relevant existing RWIS equipment, and auxiliary equipment required. Each Aurora agency was responsible for site selection and installation. Survey findings are shown in Table 2.

The existing RWIS configuration in some states dictated non-invasive equipment choice due to compatibility.

2.4 Equipment Matrix by State

Table 3 presents the final list and quantities of non-invasive sensors and auxiliary components selected by participating Aurora agencies and the potential number of sites.

Table 2. State equipment and compatibility survey findings

State agency	Non-invasive manufacturer	Non-invasive equipment model	Existing RWIS equipment	Need for a new pole	Need for extra equipment
Alaska DOT&PF	Vaisala	DST111 Remote Surface Temperature Sensor	Vaisala LX RPU	No	Yes
	Vaisala	DCS211 Remote Surface State Sensor	Vaisala LX RPU	No	Yes
California DOT	Vaisala	DST111 Remote Surface Temperature Sensor	Campbell CR1000	No	No
	Vaisala	DCS211 Remote Surface State Sensor	Campbell CR1000	No	No
	High Sierra	IceSight Non-Intrusive Road Condition	Campbell CR1000	No	No
	Boschung	R-Condition	Campbell CR1000	No	No
Colorado DOT	Vaisala	DST111 Remote Surface Temperature Sensor	Vaisala	No	No
	Vaisala	DCS211 Remote Surface State Sensor	Vaisala	No	No
Delaware DOT	Lufft	StaRWIS-UMB-Stationary Road Weather Info Sensor	N/A	Yes	N/A
	Boschung	R-Condition	N/A	No	N/A
Illinois DOT	Vaisala	DST111 Remote Surface Temperature Sensor	N/A	No	No
	Vaisala	DCS211 Remote Surface State Sensor	N/A	No	No
Iowa DOT	High Sierra	IceSight Non-Intrusive Road Condition	Vaisala LX	No	N/A
	Lufft	Non-Invasive Road Sensor NIRS31-UMB	Lufft L-COM RPU	No	N/A
	Lufft	StaRWIS-UMB-Stationary Road Weather Info Sensor	Lufft L-COM RPU	No	N/A
	Boschung	R-Condition	Likely a Lufft L-COM	No	N/A

State agency	Non-invasive manufacturer	Non-invasive equipment model	Existing RWIS equipment	Need for a new pole	Need for extra equipment
Kansas DOT	High Sierra	IceSight Non-Intrusive Road Condition	Vaisala - Linux	Yes	N/A
	Lufft	StaRWIS-UMB-Stationary Road Weather Info Sensor	Lufft	Yes	N/A
	Boschung	R-Condition	Campbell Scientific Data Logger Model No. CR1000X	Yes	N/A
Michigan DOT	High Sierra	IceSight Non-Intrusive Road Condition	RPU: Lufft LCOM	Yes	Yes
	Lufft	Non-Invasive Road Sensor NIRS31-UMB	RPU: Lufft LCOM	Yes	Yes
	Lufft	StaRWIS-UMB-Stationary Road Weather Info Sensor	RPU: Lufft LCOM	Yes	Yes
	Boschung	R-Condition	RPU: Lufft LCOM	Yes	Yes
Minnesota DOT	Vaisala	DST111 Remote Surface Temperature Sensor	Vaisala RWS200	No	Yes
	Vaisala	DCS211 Remote Surface State Sensor	Vaisala RWS200	No	Yes
	Lufft	Non-Invasive Road Sensor NIRS31-UMB	Lufft LCOM	No	Yes
Missouri DOT	Lufft	Non-Invasive Road Sensor NIRS31-UMB	N/A	No	N/A
	Lufft	StaRWIS-UMB-Stationary Road Weather Info Sensor	N/A	No	N/A
North Dakota DOT	High Sierra	IceSight Non-Intrusive Road Condition	Lufft LCOM RPU	No	Yes
	Lufft	StaRWIS-UMB-Stationary Road Weather Info Sensor	Lufft LCOM RPUs	No	Yes
	Boschung	R-Condition	GFS 3000 RPU, Arctis, sensor, BOSO II sensor	Yes	Yes

State agency	Non-invasive manufacturer	Non-invasive equipment model	Existing RWIS equipment	Need for a new pole	Need for extra equipment
Ohio DOT	Vaisala	DST111 Remote Surface Temperature Sensor	N/A	No	N/A
	Vaisala	DCS211 Remote Surface State Sensor	N/A	No	N/A
	Lufft	Non-Invasive Road Sensor NIRS31-UMB	N/A	No	N/A
Pennsylvania DOT	Vaisala	DST111 Remote Surface Temperature Sensor	Vaisala	Yes	N/A
	Vaisala	DCS211 Remote Surface State Sensor	Vaisala	Yes	N/A
Virginia DOT	Vaisala	DST111 Remote Surface Temperature Sensor	Vaisala	No	N/A
	Vaisala	DCS211 Remote Surface State Sensor	N/A	No	N/A
	High Sierra	IceSight Non-Intrusive Road Condition	N/A	No	N/A
	Lufft	Non-Invasive Road Sensor NIRS31-UMB	N/A	No	N/A
Washington State DOT	High Sierra	IceSight Non-Intrusive Road Condition	Vaisala RWS200	N/A	N/A
	Lufft	Non-Invasive Road Sensor NIRS31-UMB	Vaisala RWS200	N/A	N/A
	Lufft	StaRWIS-UMB-Stationary Road Weather Info Sensor	Vaisala RWS200	N/A	N/A
	Boschung	R-Condition	Vaisala RWS200	N/A	N/A
Wisconsin DOT	Vaisala	DST111 Remote Surface Temperature Sensor	Lufft	Yes	N/A
	Vaisala	DCS211 Remote Surface State Sensor	Lufft	Yes	N/A
	Lufft	Non-Invasive Road Sensor NIRS31-UMB	Lufft	Yes	N/A
	Lufft	StaRWIS-UMB-Stationary Road Weather Info Sensor	Lufft	Yes	N/A

N/A- Not applicable

Table 3. State equipment matrix

Manufacturer	Model	AK	CA	CO	DE	IA	IL	KS	MI	MN	MO	ND	OH	PA	VA	WA	WI	Totals
Vaisala	DST 111 Remote Road Temperature Sensor	2	1	2	–	–	2	–	–	2	–	–	1	2	1	–	1	14
	DSC 211 Remote Surface State Sensor	2	1	2	–	–	2	–	–	2	–	–	1	2	1	–	1	14
High Sierra	IceSight 5433-34	–	1	–	–	1	–	2	1	–	–	2	–	–	1	1	–	9
	High Sierra Datalogger	–	1	–	–	1	–	–	1	–	–	–	–	–	–	1	–	4
Lufft	NIRS31-UMB (8710.UT01)	–	–	–	–	1	–	–	1	1	2	–	2	–	1	1	1	10
	StaRWIS (8711.U55)	–	–	–	2	1	–	1	1	–	2	1	–	–	–	1	1	10
Boschung	R-Condition	–	1	–	2	1	–	1	1	–	–	1	–	–	–	1	–	8
Total Sensors (excluding dataloggers)		**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**5**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**65**
Potential Installation Sites*		**2**	**3**	**2**	**4**	**2**	**4**	**4**	**4**	**3**	**4**	**4**	**3**	**2**	**3**	**4**	**3**	**51**

* Vaisala sensors are deployed in pairs—one for measuring surface temperature and one for determining surface state; thus, there were two Vaisala sensors per RWIS site

In general, one non-invasive sensor would be deployed per RWIS site, with the exception of the Vaisala sensors. These sensors are deployed in pairs—one for measuring surface temperature and one for determining surface state. Thus, there were two Vaisala sensors per RWIS site.

A total of 65 non-invasive sensors, representing 51 potential sites, were purchased from four different vendors and distributed to 16 participating states.

2.5 Firmware Update

Given the existing RWIS configuration in several participating states, as well as their preference with respect to integration of the non-invasive sensors, a firmware update was also solicited. This firmware update facilitated communication with an existing system instead of requiring integration of a new datalogger. The required changes primarily involved a minor update to the configuration of the data acquisition software to connect to the remote sensors and download data.

In a few cases, where the HighSierra IceSight sensors were used, the intermediary firmware (UNICON-IceSight) converted the sensor's communication protocol into the Universal Measurement Bus (UMB) channels. UMB is a protocol developed to facilitate communication with meteorological sensors (UMB Protocol 1.0 Universal Measurement Bus Communication Protocol for Meteorological Sensors, version 1.7, OTT HydroMet).

3 PROCUREMENT

3.1 Bid Documentation

Equipment procurement involved working through Iowa State University Procurement Services in terms of the bidding process, vendor communication, and coordination with the project team.

3.2 Purchasing

The project team identified the relevant existing RWIS equipment and whether auxiliary equipment was required. Based on this information, the project team coordinated with Procurement Services to purchase the required equipment from the successful bidders, ensuring that all purchasing guidelines were met. Three types of purchases were made, as follows:

- Non-invasive sensors, as shown in the previous Table 3
- Auxiliary equipment, including poles, cables, mounting hardware, and dataloggers
- Firmware update

3.3 Equipment Delivery

As part of the purchasing process, successful bidders were provided with the appropriate contacts and shipping information (in participating states) for each component. Equipment delivery was the responsibility of the successful bidders and was not within the control of the project team or Procurement Services. Procurement Services did incrementally follow up with the bidders regarding shipping, and the project team inquired about delivery with Aurora agencies. Delivery timelines varied among bidders and began in fall 2019. Unfortunately, the delivery timing resulted in some challenges with respect to installation prior to the winter of 2019/2020.

4 DEPLOYMENT

4.1 Site Selection by State

The project team provided recommendations for deployment site characteristics in line with the research plan. General guidelines for selecting the most suitable sites were provided to the state agencies, i.e., sites exemplifying the state's typical environmental and operational conditions, would be of benefit to the agency, and co-located with invasive pavement sensors.

Sensor deployment sites, installation, and integration were ultimately at the discretion of each agency per its own preferences and priorities. The primary request was that agencies co-locate the non-invasive sensors with an in-service, invasive sensor that measures pavement surface temperature.

4.2 Installation Status and Data Availability

A questionnaire was sent to the participating agencies to assess the status of sensor installation and, if installed, the location of installation, data availability (including Weather Data Environment), and feedback about the installation and operation experience.

In addition to the questionnaire, the project team regularly followed up with the participating states to inquire about the deployment sites and status of sensor installation, operation, and data availability. The installation status of the sensors, based on agency feedback at the time of this report, is shown in Table 4 for responding states. Not all current installations may be represented.

Table 4. Non-invasive sensor installation status

	No. of Sensors Received	No. of Sensors Installed
Alaska	4	4
California	4	3
Colorado	4	0
Delaware	4	0
Illinois	4	0
Iowa	4	4
Kansas	4	0
Michigan	4	3
Minnesota	5	3
Missouri	4	0
North Dakota	4	3
Ohio	4	0
Pennsylvania	4	4
Virginia	4	0
Washington	4	0
Wisconsin	4	0
Totals	65	24

Known locations and models of the installed sensors are given in Table 5.

Table 5. Locations and models of installed sensors

State	Installation date	RWIS site name and location	RWIS site coordinates (lon, lat)	Model
AK	9/12/2019	Hillside Road @ Upper Huffman Road	-149.744807, 61.107798	Vaisala DST/DSC
	11/20/2019	North Douglas Highway MP 4.4	-134.502251, 58.333031	Vaisala DST/DSC
CA	N/R	Sims Road SHA 5 R 57.87	N/R	Vaisala DST/DSC
	N/R	Dansmuir SIS 5 R 2.16	N/R	High Sierra IceSight 5433-34
IA	Summer 2020	Osceola RWIS35, US 34 EB	-93.7943, 41.0267	High Sierra IceSight 5433-34
		Grimes RWIS71, IA 415 EB road	-93.7757, 41.7396	Lufft NIRS31-UMB
		DeSoto RWIS18, I-80 EB bridge approach	-94.0112, 41.5415	Boschung R-Condition
MI	12/21/2020	MI-02 Gaylord North	-84.6885, 45.0549111	High Sierra IceSight 5433-34
	11/1/2020	MI-05 Hartford	-86.1657, 42.192917	Lufft NIRS31-UMB
	12/21/2020	MI-2 Reed City	-85.52686, 43.88729	Boschung R-Condition

State	Installation date	RWIS site name and location	RWIS site coordinates (lon, lat)	Model
MN	N/R	Ely, TH 1 EB @ MP 275.25	N/R	Vaisala DST/DSC
	N/R	Beaver Creek, I-90 EB @ MP 3.8	N/R	Lufft NIRS31-UMB
ND	5/1/2020	Gladstone ESS, I-94 RP 73	-102.55051, 46.873856	High Sierra IceSight 5433-34
	N/R	Pembina Mini RWIS, I-29 RP 217.11	-97.23939, 48.996445	High Sierra IceSight 5433-35
	5/1/2020	Mandan Mini RWIS, I-94 RP 157.79	-100.84576, 46.821938	Boschung R-Condition
PA	N/R	I-70 W/B @ Exit 156 Town Hill Fulton Co.	-78.2437, 39.885119	Vaisala DST/DSC
	N/R	US 22 W/B @ Penn View Mtn Indiana Co.	-79.156219, 40.451889	Vaisala DST/DSC

N/R- Not reported

Due to installation status, two states also temporarily provided sensors in support of the Aurora project, Roadway Friction Modeling: Improving the Use of Friction Measurements in State DOTs.

Challenges related to sensor installation are discussed later in the following sections of this report.

Regarding data availability, a number of participating states have agreements in place to make all of their RWIS data available on the Federal Highway Administration (FHWA) Weather Data Environment portal at https://wxde.fhwa.dot.gov/?org.apache.catalina.filters.CSRF_NONCE=CE9A194D4D12C00983C4710C50368FA6, as outlined in Figure 1.

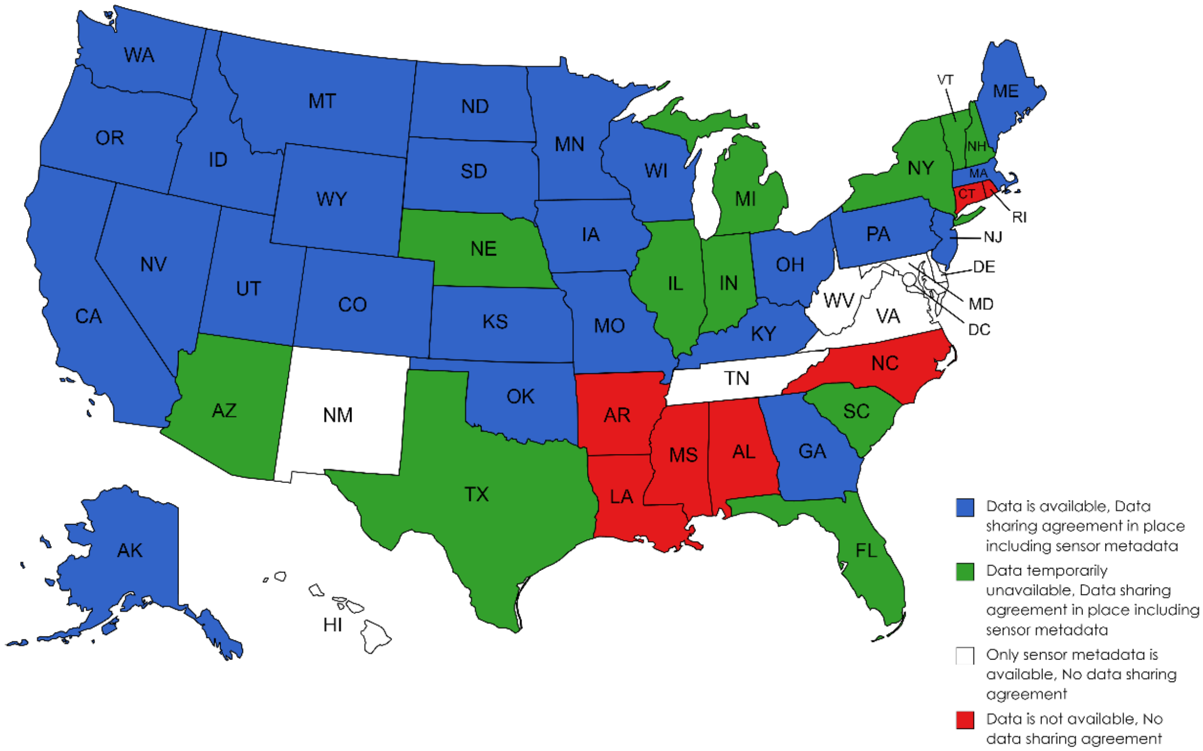

Figure created using www.mapchart.net

Figure 1. States that have an agreement in place to share all their RWIS data via the FHWA's Weather Data Environment

At this point, limited non-invasive data for the new installations were available; however, this may improve in the future. Table 6 presents data access to date.

Table 6. Data availability status of installed sensors

State	Via FHWA Weather Data Environment	Via another service	Comments
AK	–	X	Raw data are available on https://rwis3.dot.state.ak.us/rwisData/
CA	–	X	Shared with project team by DOT staff; may also be available via Caltrans Commercial Wholesale Web Portal
IA	–	X	Data can possibly be downloaded from the Iowa DOT DTN API
MI	–	X	Shared with project team by DOT staff
MN	–	X	Via Vaisala SCAN WEB at http://rwis.dot.state.mn.us/scanweb
ND	–	X	NDDOT ATMS Reports
PA	X	–	Data currently contains only one pavement temperature value

Some agencies have attempted to provide data access via other means.

4.3 External Impacts on Deployment

Unfortunately, sensor installation and deployment were impacted by multiple external factors that delayed or adversely affected several aspects of the project, particularly ongoing, more comprehensive comparisons of invasive and non-invasive sensor data.

The COVID-19 pandemic was the most critical of all external factors, significantly changing the working dynamics of many participating agencies. A notable example, reported by at least one agency, was that pandemic-induced budget cuts resulted in the termination of the maintenance contracts that encompassed RWIS equipment installations. COVID-19 also impacted staff availability and allowable activities, both in-agency and with consultants. This then shifted the timelines of other agency projects and responsibilities, ultimately leading to additional installation challenges during the winter of 2020/2021. If/when sensors were eventually installed, the time and ability to address initial data acquisition or external sharing were impacted. Of primary concern, however, was that participating agencies would be able to use the data internally, which was often the case.

Other noteworthy factors impacting deployment included staffing changes in the participating agencies, agency priorities, contractor availability, funding equipment procurement delays, equipment delivery delays, and suitable locations. Staff changes in several participating agencies, including Aurora representatives, impacted installation and general operational activities within several DOTs.

For example, when Aurora board representatives changed, their replacements inherited the project and the equipment—possibly with limited background—as well as other non-Aurora related agency responsibilities. The project team tried to regularly engage new members and provide project objectives.

4.4 Data Visualization Tools and Comparison Methodology

While the project team had limited access to data, either due to installation status or data sharing issues, comparisons were conducted on the available data. The objective of the comparisons was not to assess the absolute accuracy of either the non-invasive sensor (or type of sensor) or invasive sensor. The simple relative comparison per site was intended to support agency assessment of non-invasive sensor operation, performance, and possible impacts, if any, on decision making in consideration of legacy data.

A straightforward point-to-point comparison method was used to present the measurements obtained from the two sensor types. The measurements obtained from each non-invasive sensor were plotted against the adjacent invasive sensor, or sensors, and assessed by linear regression for convergence.

Pavement surface temperature (in °F) was the measure of interest in the comparisons, because it was the common data item of all sensors at all locations.

The results were plotted in the Tableau environment and combined in a Tableau dashboard to enable a side-by-side comparison of different sensors and locations. Because the project team was not responsible for sensor installation, calibration, and monitoring, specific sites and sensors are not referred to in the following section.

4.5 Sample Data Comparison

Data were available and compared for six sites—four in three midwestern states and two in a western state. For each site, data were compared over multiple months, representing a variety of seasonal conditions and a wide range of surface temperatures.

Figure 2 presents a comparison of non-invasive and invasive sensor pavement temperature readings from February 25 to August 26, 2021 (161 days) at Site 1.

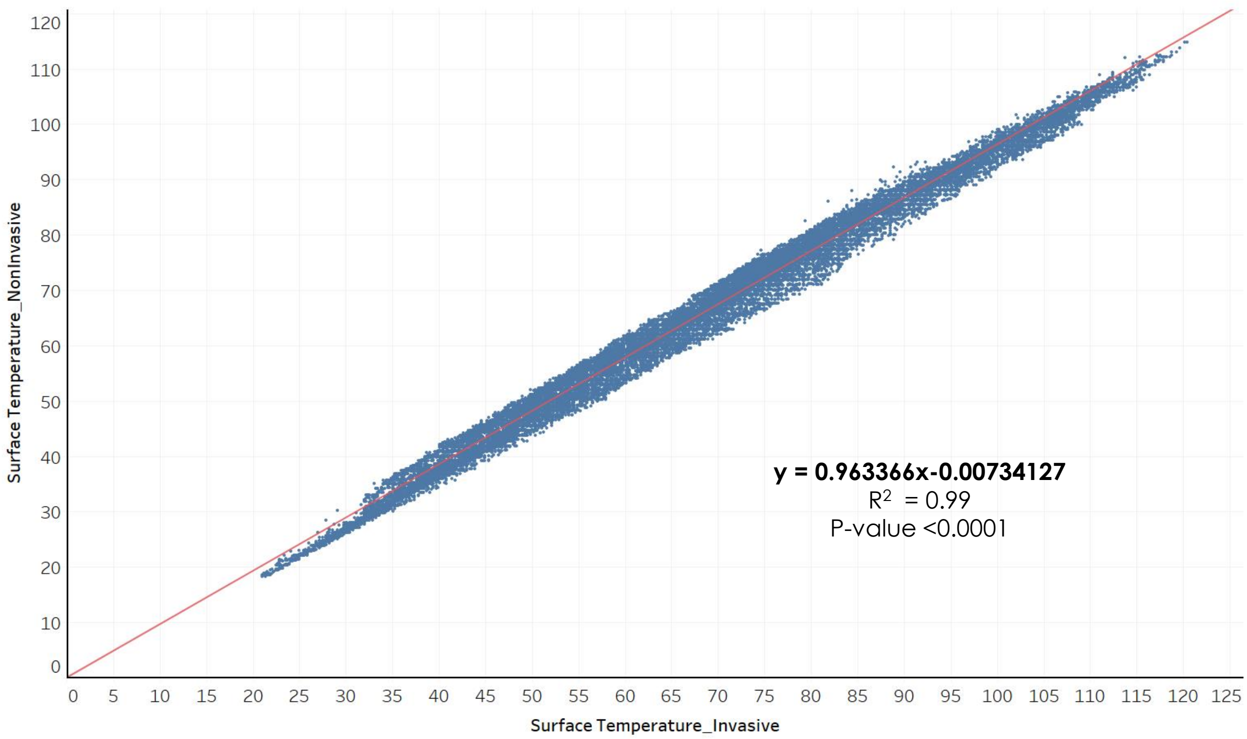

Figure 2. Non-invasive vs. invasive surface temperature readings for Site 1 in all surface conditions

The readings on two of the days were discarded during data cleaning, bringing the total length of comparison to 159 days. The readings from the two sensor types indicated a very close agreement ($R^2 = 0.99$, P-value < 0.0001) as shown in Figure 2, Figure 3, and Figure 4, which include all surface conditions, dry conditions, and wet conditions, respectively.

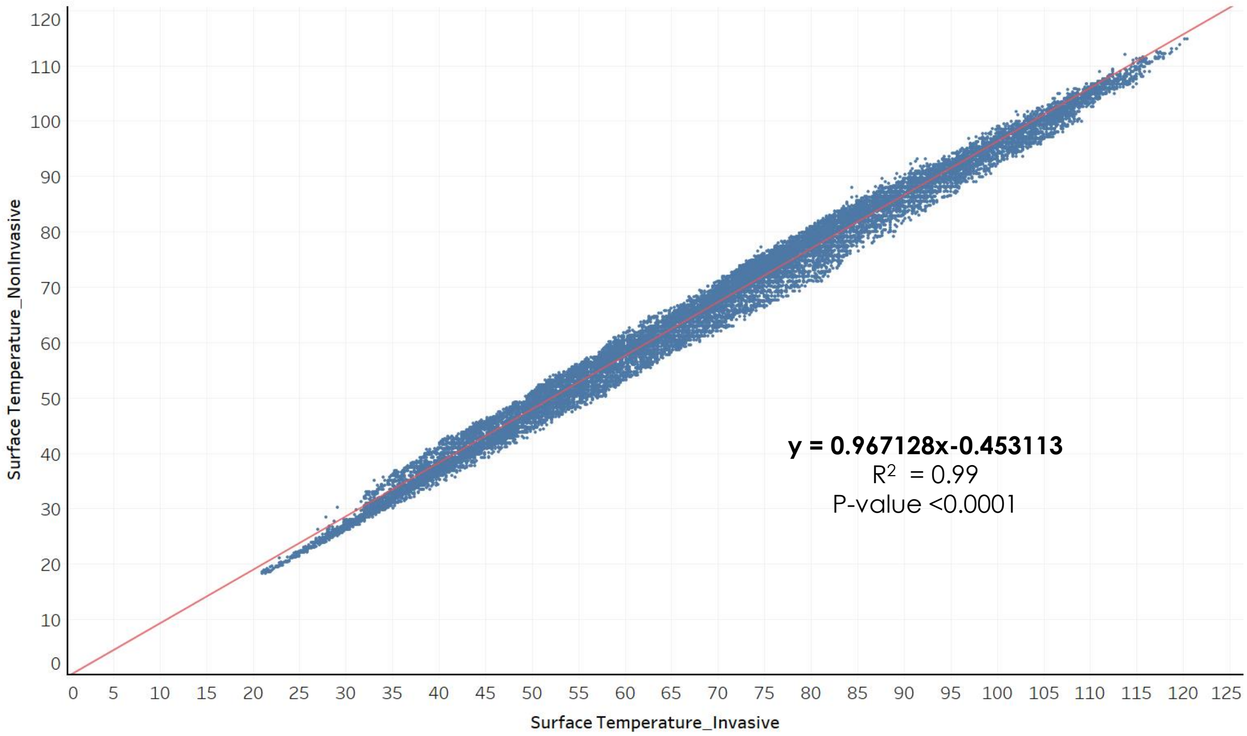

Figure 3. Non-invasive vs. invasive surface temperature readings for Site 1 in dry surface conditions

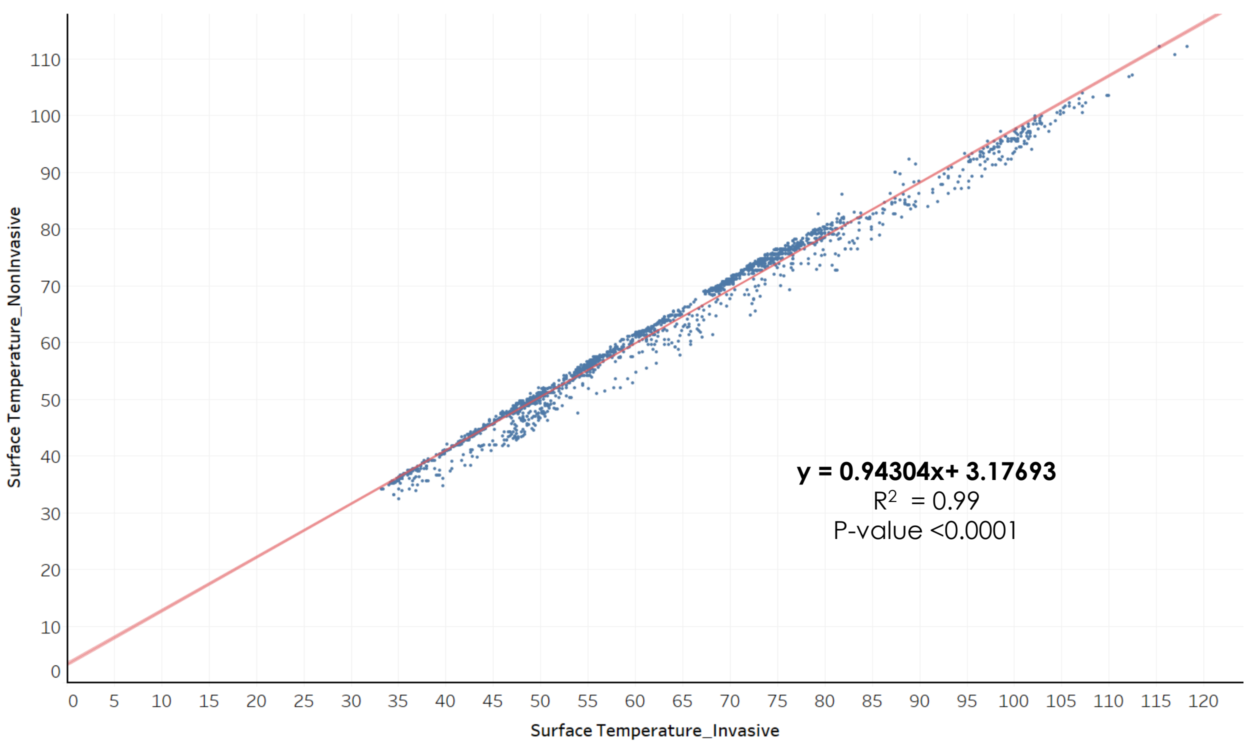

Figure 4. Non-invasive vs. invasive surface temperature readings for Site 1 in wet surface conditions

At Site 2, data from both sensors were available for all days since January 2021. For Site 3, data were available from one non-invasive sensor and two invasive sensors during the same timeframe as Site 2. One of the invasive sensors at this site was on the bridge deck, and the other one was located on the approach. The invasive sensor on the approach was more spatially proximate to the non-invasive sensor. The readings were acquired for three periods: February 25, 2021 to March 27, 2021; July 31, 2021 to August 7, 2021; and May 31, 2022 to June 4, 2022. Surface temperature comparisons are presented in Figure 5 through Figure 7.

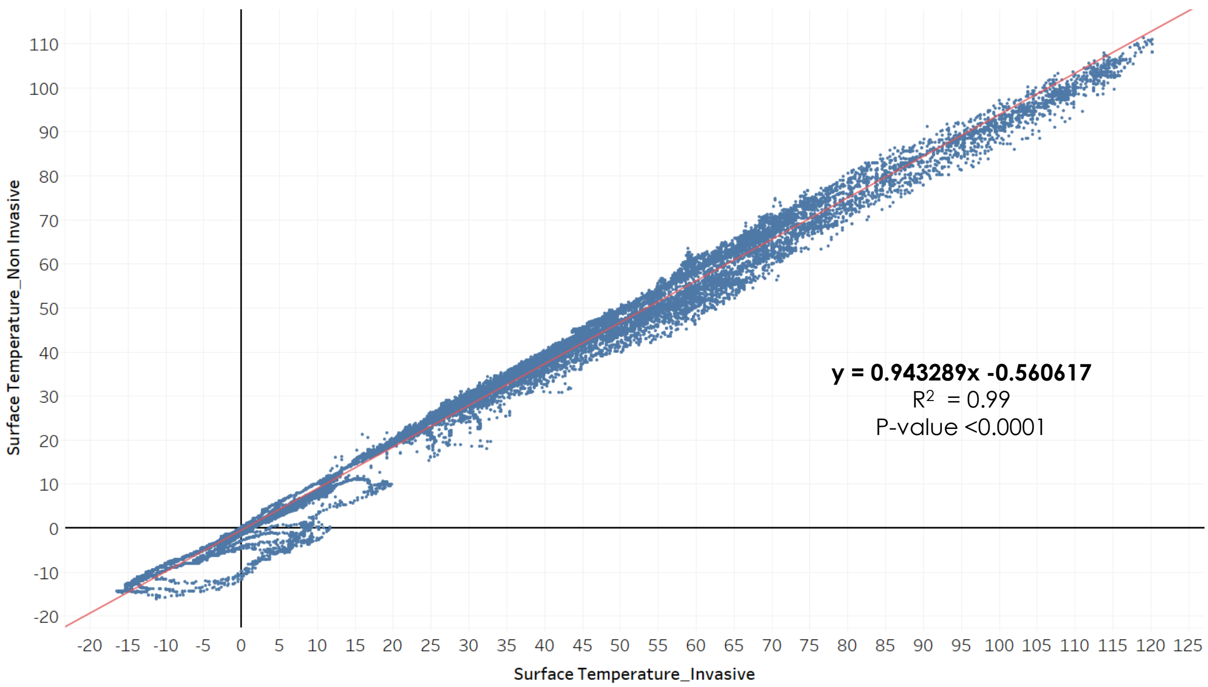

Figure 5. Non-invasive vs. invasive surface temperature readings for Site 2

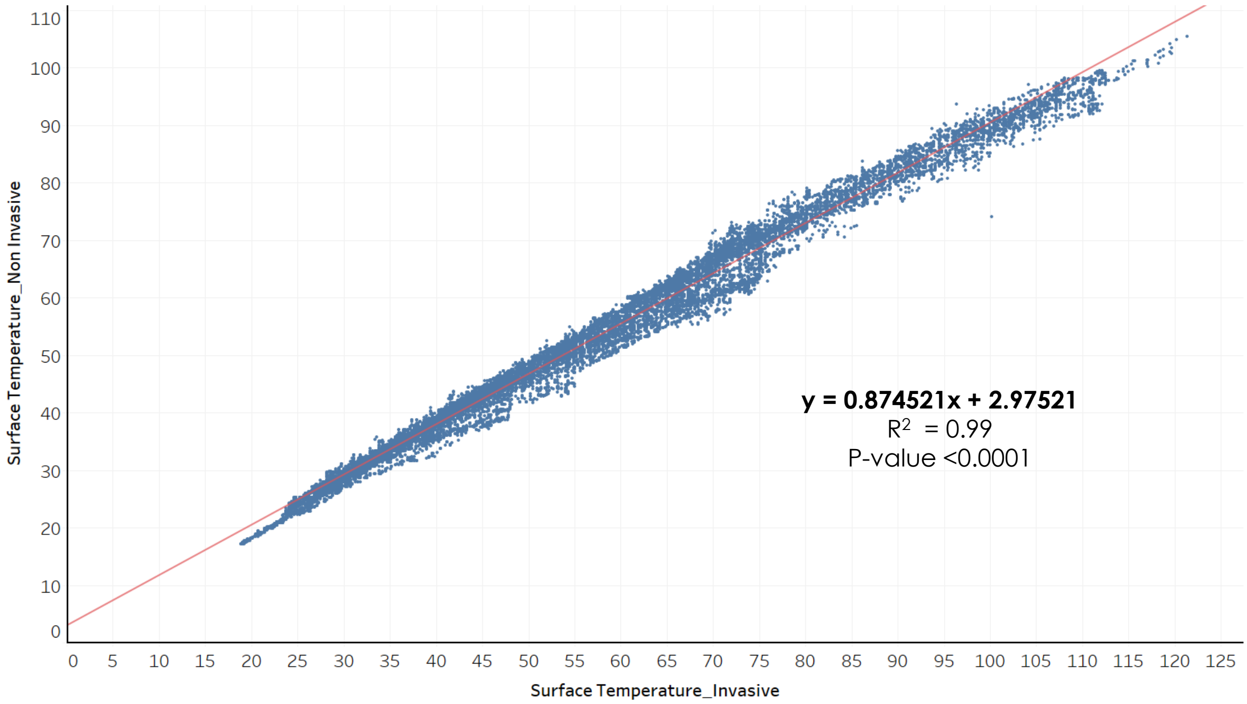

Figure 6. Non-invasive vs. invasive surface temperature readings for Site 3 with the invasive sensor on the bridge approach

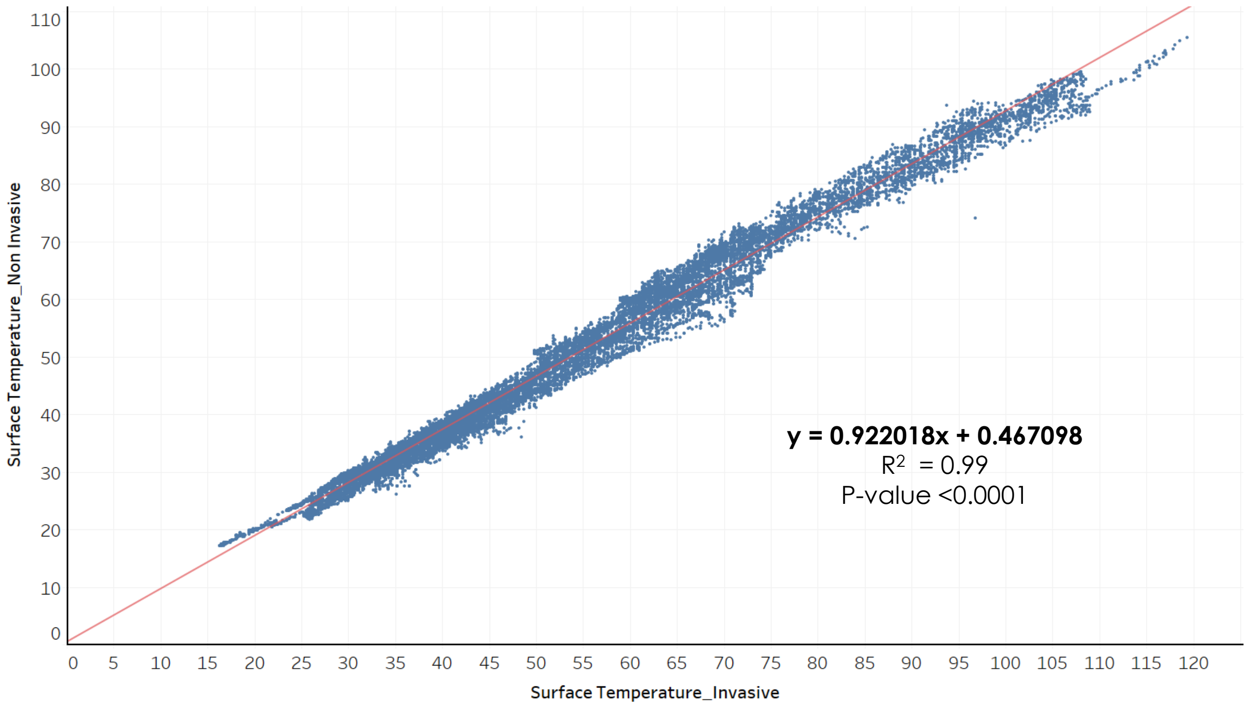

Figure 7. Non-invasive vs. invasive surface temperature readings for Site 3 with the invasive sensor on the bridge deck

Initial investigation indicated that the data appeared to not differ based on surface conditions, so the visualizations include all surface conditions. As with Site 1, the readings were highly correlated (R^2 = 0.99, P-value < 0.0001).

Data were available for Site 4 from September 1, 2021 to June 20, 2022. Potential anomalies were observed in the non-invasive readings during several days in April, May, and June 2022. On each of these days, the non-invasive sensor reported a fixed value repeated over a several hour timespan. The irregularities typically began in early afternoon and continued until approximately 12:00 p.m. the following day. An example of this is presented in Figure 8.

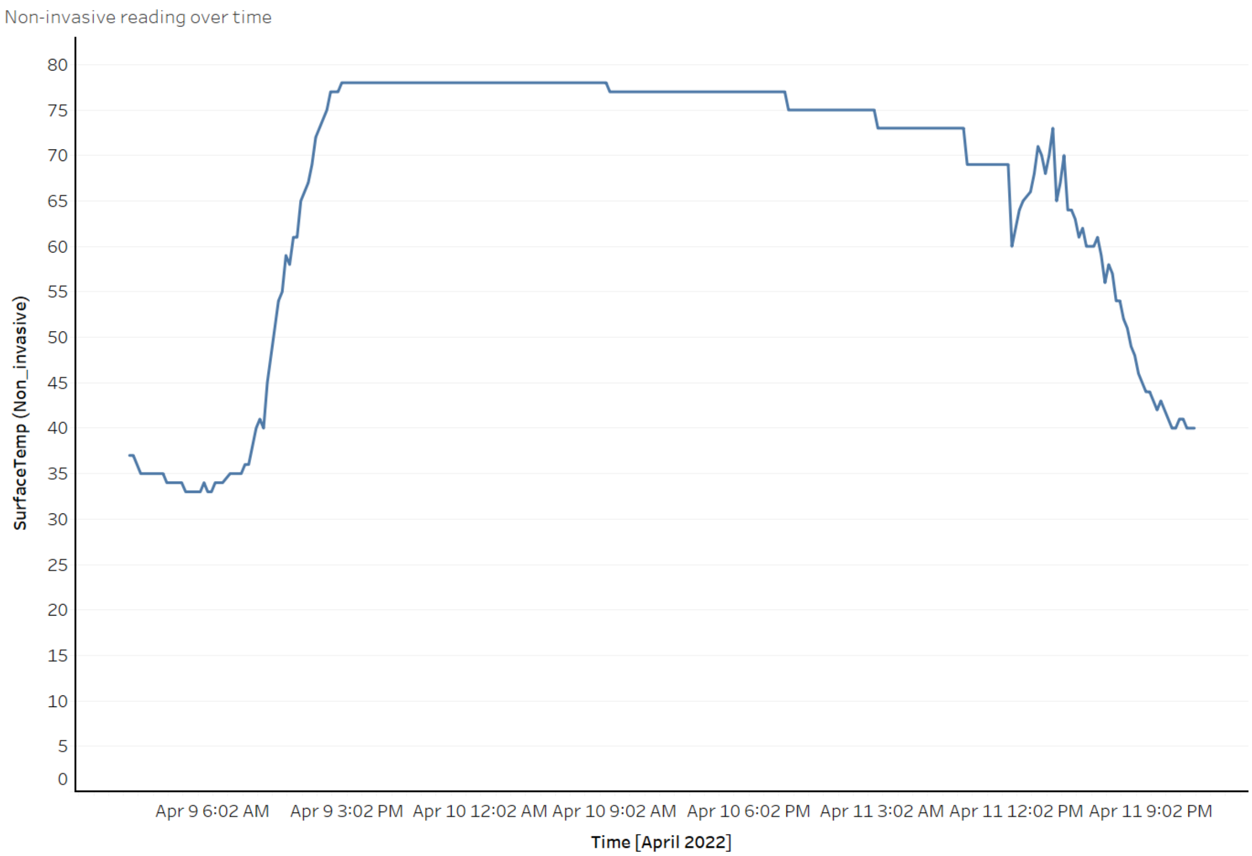

Figure 8. Site 4 non-invasive sensor irregularities

Causes of the potential irregularities were not investigated and not within the scope of this project but represented about 11 percent of the data acquired.

Figure 10 presents the surface temperature comparison for Site 4 under all surface conditions with no irregularities removed. The correlation was still relatively high (R^2 = 0.92, P-value < 0.0001).

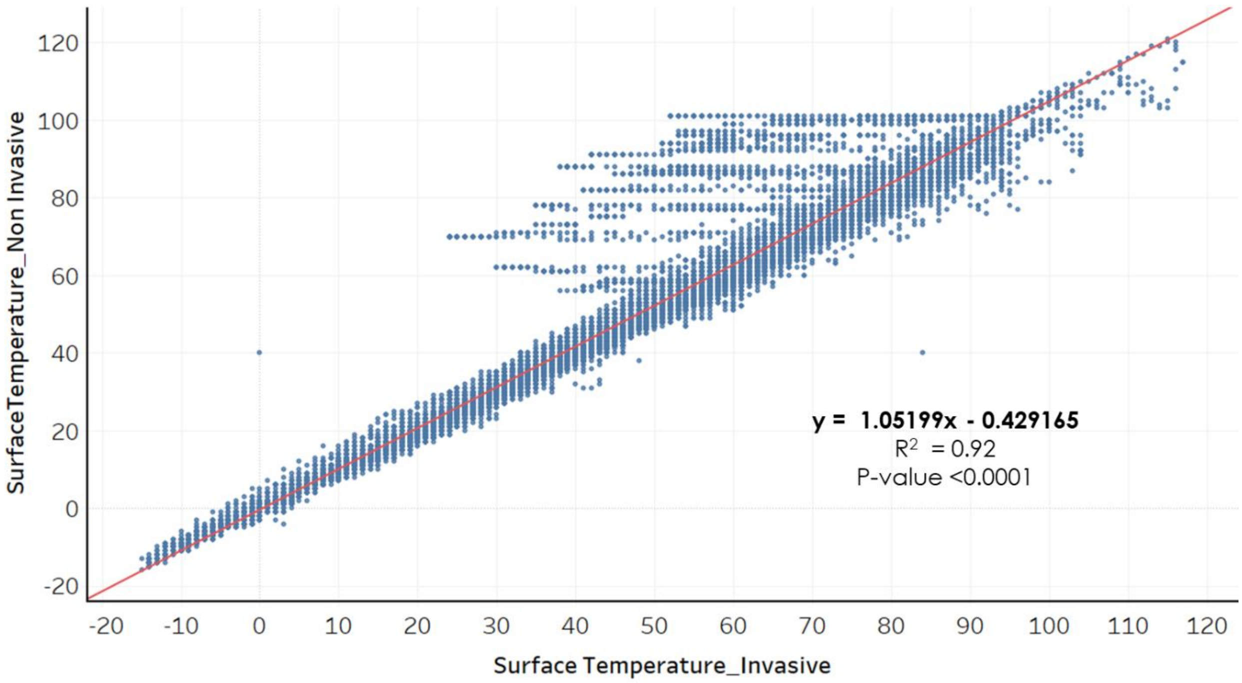

Figure 9. Non-invasive vs. invasive surface temperature readings at Site 4 (all data)

Figure 10 presents the surface temperature comparison for Site 4 under all conditions, with the potential irregularities removed, improving the correlation ($R^2 = 0.99$, P-value < 0.0001).

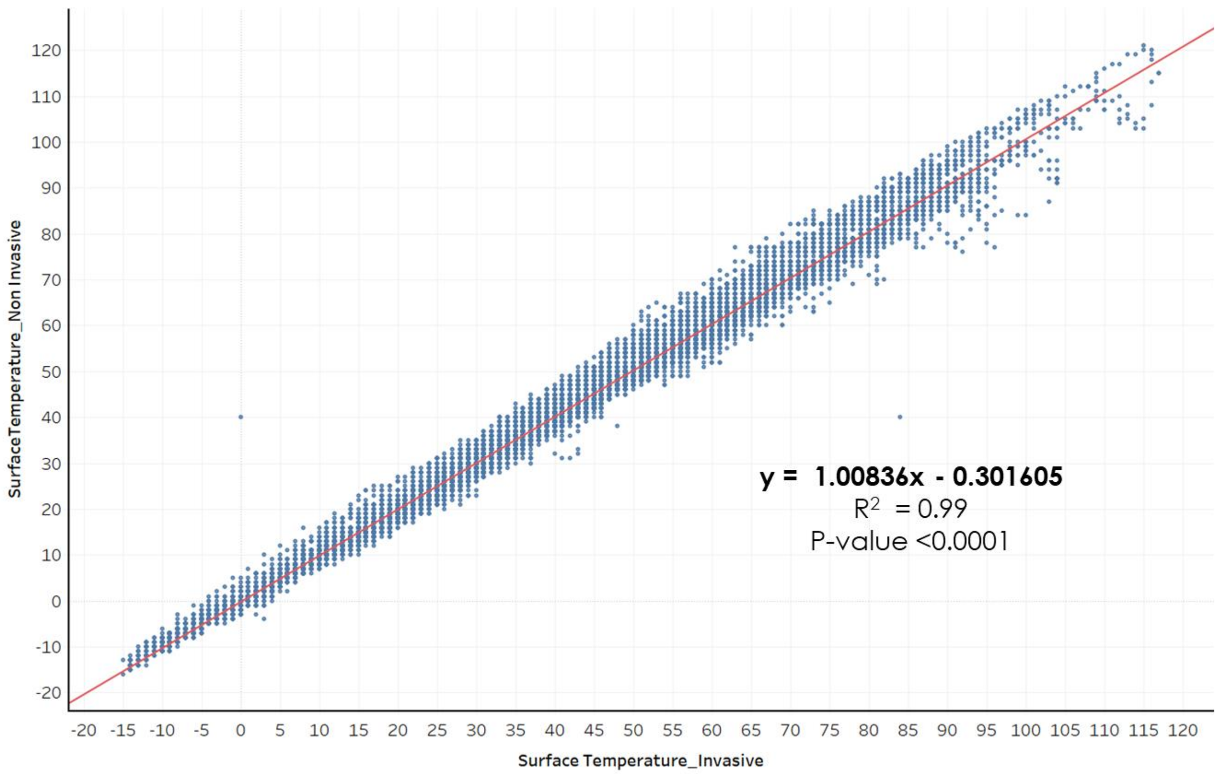

Figure 10. Non-invasive vs. invasive surface temperature readings at Site 4 (irregularities removed)

As with the other sites, the readings appear fairly consistent with some exceptions.

Data for both Sites 5 and 6 were provided for August 31, 2021 through June 22, 2022. Irregularities, similar to Site 4, were also observed at Site 5, representing an estimated 40 percent of the readings. In contrast to Site 4, the irregularities were more prevalent and distributed over a much greater time period. The possible cause of the irregularities was not investigated and not within the scope of the project. Figure 11 presents the surface temperature comparison for Site 5.

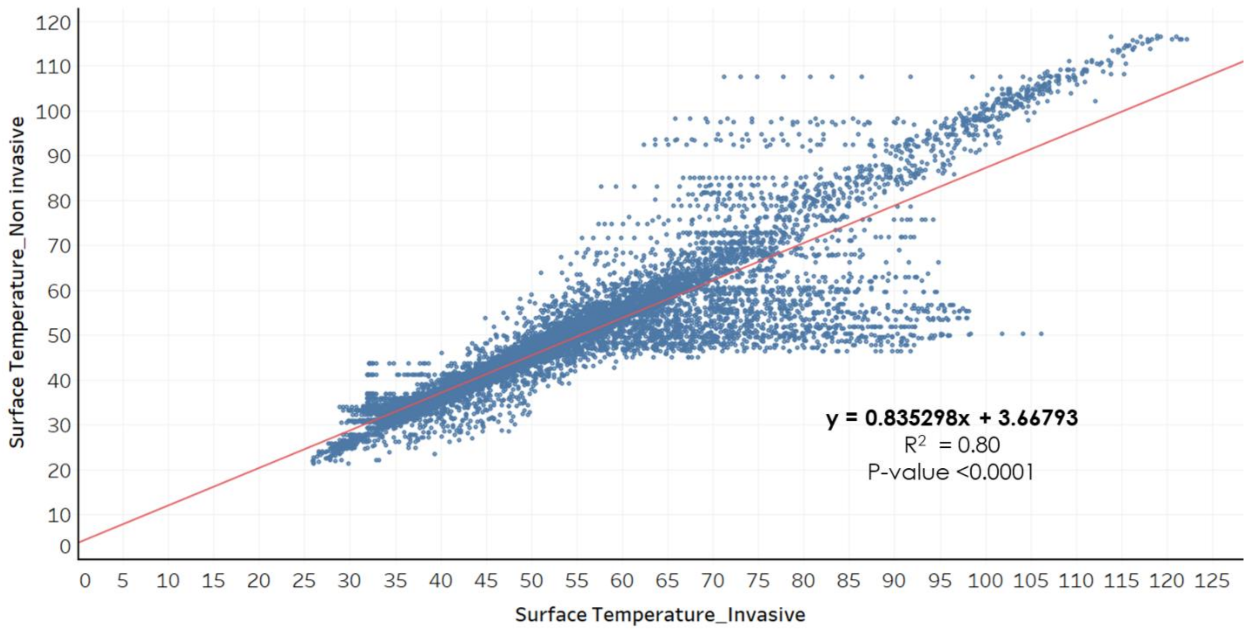

Figure 11. Non-invasive vs. invasive surface temperature readings at Site 5

The irregularities notably impacted the correlation ($R^2 = 0.80$, P-value < 0.0001). Removing a large portion of the apparent irregularities yielded a much-improved correlation ($R^2 = 0.93$, P-value < 0.0001), as shown in Figure 12.

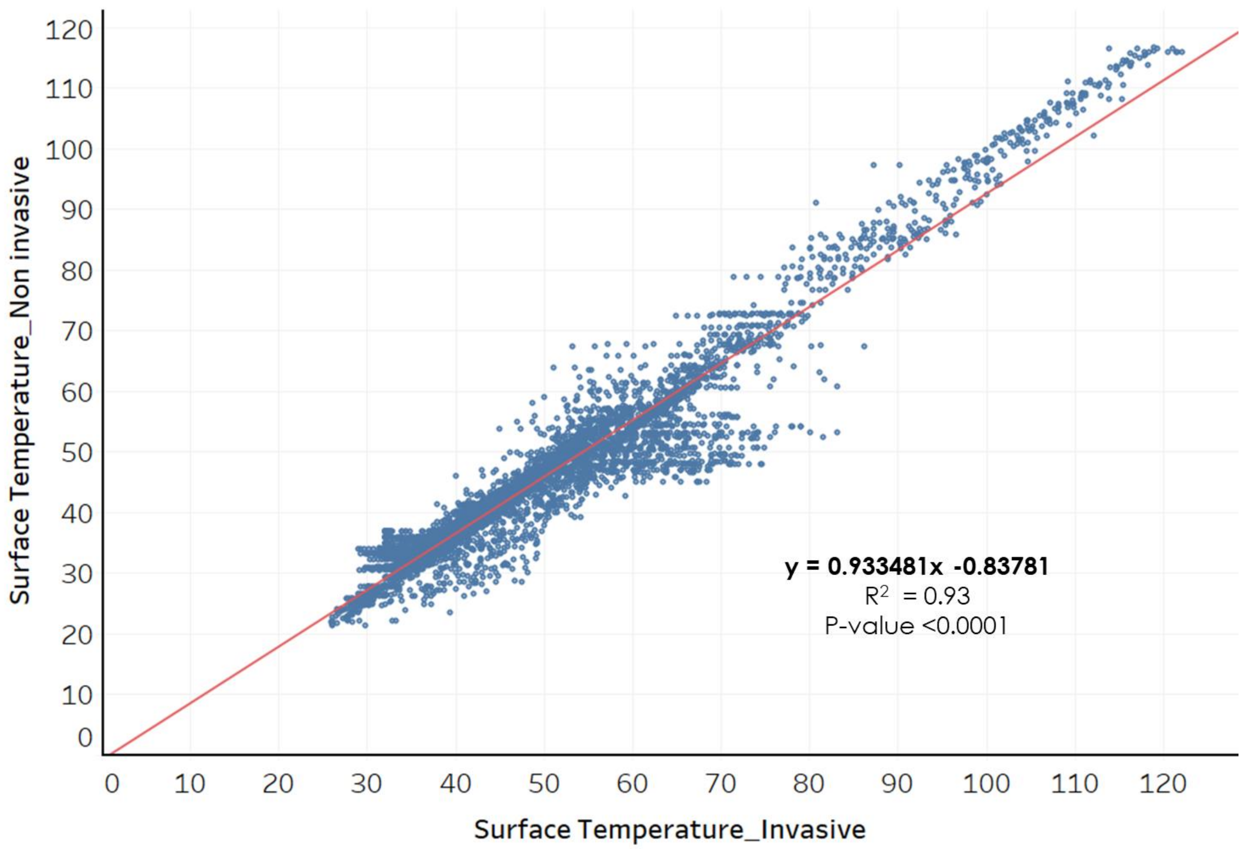

Figure 12. Non-invasive vs. invasive surface temperature readings at Site 5 (irregularities removed)

As presented in Figure 13, the non-invasive and invasive sensor readings for Site 6 were much more consistent during the analysis period and highly correlated (R^2 = 0.97, P-value < 0.0001).

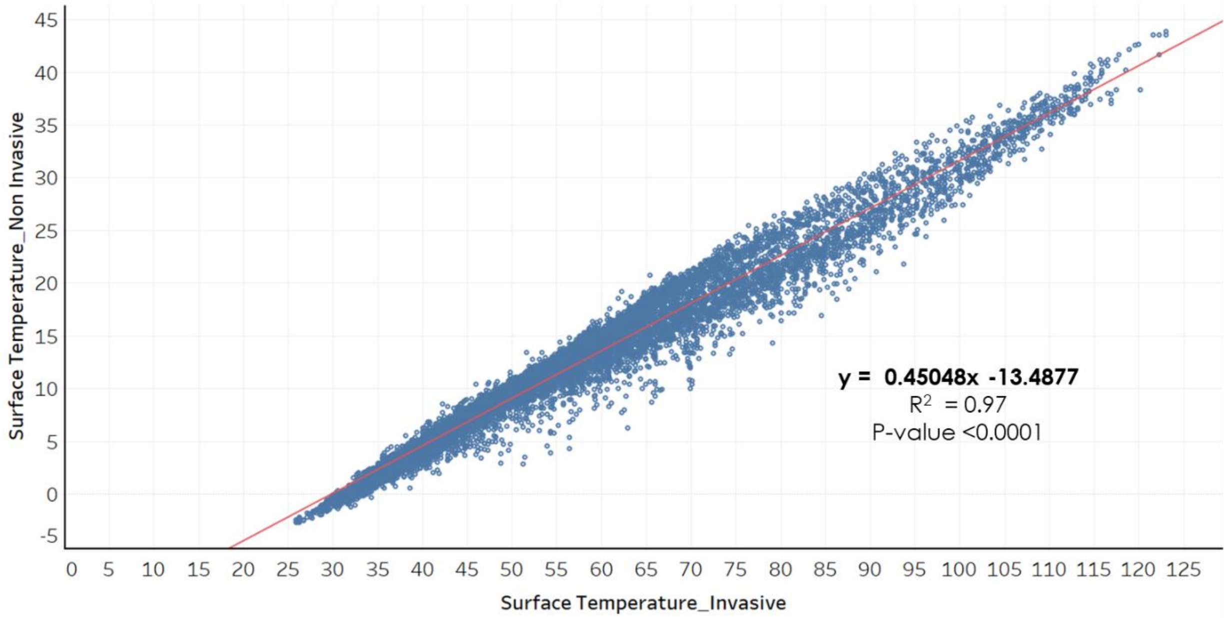

Figure 13. Non-invasive vs. invasive surface temperature readings at Site 6

Given the nature of the project, development and implementation of agency protocols for monitoring and assessing sensor performance varied. This may have impacted the ability to identify possible data anomalies, such as those observed at Site 4 and Site 5, on a real time basis. Such anomalies can become more apparent when presenting several months of historic data in comparative figures.

In addition to the data from co-located sites, some anecdotal assessments were provided by participating agencies. For example, a participating state with limited or no prior experience with non-invasive sensors regularly observed surface temperature readings at installation sites and felt that non-invasive sensors measured pavement temperatures slightly lower than the invasive sensors. Depending on the temperature, they felt that this could potentially lead to overtreatment of the roadway.

As seen in the figures, the date comparison from combined sites showed a slightly downward trend from invasive to non-invasive readings, but whether this was significant enough to impact treatment decisions is unknown and not assessed. Additional data from more sites and different sensors would be required to perform a rigorous statistical analysis.

In general, many participating states provided positive feedback with respect to non-invasive sensors and their reported data. Some of the challenges that were shared included identifying a suitable installation location due to sensor specifications, initial sensor operation, and integration and data retrieval.

Secondary objectives of the project were to provide agencies having limited or no non-invasive sensor experience with the opportunity to utilize them, while other agencies had an opportunity to work with sensors from different manufacturers.

The deployment of non-invasive sensors introduced new data, such as friction measurements, to several participating agencies. One agency began to use these data to trigger messaging and anticipated a future, larger deployment, given the real-time friction measurement capability, which may be used for speed management and truck restrictions.

5 SUMMARY

5.1 Final Status

Ten of the 16 states had deployed and were operating at least some of the non-invasive sensors. As of the time of this report, the status of the states with respect to non-invasive sensor deployment can be broadly categorized as one of the following.

- Deployed all of the non-invasive sensors at co-located sites, i.e., RWIS with an invasive sensor
- Deployed some of the delivered non-invasive sensors at co-located sites
- Deployed non-invasive sensors at independent site(s), i.e., RWIS with no invasive sensor
- Not deployed the non-invasive sensors but plan to do so
- Not deployed the non-invasive sensors, and deployment status undetermined or not anticipated

Of the agencies that had deployed non-invasive sensors, some have provided data (or access to the data) for comparison. Other agencies had provided data (or access), but an element was currently missing for comparison, or data access was planned, pending, or yet to be determined.

5.2 Challenges

A significant challenge to the project was the COVID-19 pandemic, which impacted the project's flow and progress. Under pandemic conditions, the normal day-to-day routine of all involved institutions and supporting agencies was disrupted. Priorities also shifted and changed. In some cases, agency turn-over in personnel and their experience significantly impacted the ability to get the equipment installed prior to the project end date. Lastly, accessing the data from both sensor types, i.e., non-invasive and invasive, was a challenge that limited the project team's ability to compare data sets within permissible time constraints.

5.3 Potential Next Steps

A potential next step is to continue communication with the participating agencies to track non-invasive sensor installations and to obtain additional data for comparison. As mentioned above, some available data sets simply were missing pieces of information, in which case, the problem may potentially be solved with minimal correspondence.

In the future, data could also be acquired from the remaining sites and expand the current Tableau dashboard into a comprehensive comparative presentation for the combined sites. Lastly, final confirmation of installation status and participating agency plans would be beneficial.

5.4 Future Opportunities

The sensors at the co-located sites are anticipated to continue collecting data, which may supply a huge data set to investigate how the two sensor types, i.e., invasive and non-invasive, and the equipment from different manufacturers compare. Many sites with different service conditions and installation practices share the same non-invasive equipment, providing data to assess these sensors' performance—relative to invasive sensors—in different settings.

This project involved a wide variety of agency practices, service conditions, and equipment models, giving promise to the possibility of using the experiences and results to develop a guideline for non-invasive sensor deployment. The feedback from the states regarding the long-term application of non-invasive sensors may be a valuable source for this endeavor.

If the future shows that this project has verifiably contributed to an upward trend in non-invasive sensor technology adoption by state DOTs, this framework can be modeled to promote the adoption of other useful technologies.

5.5 Conclusion

This project provides a national scale implementation of non-invasive sensors at existing RWIS locations. Sixteen state transportation agencies participated and were provided with the means and support to deploy non-invasive sensors on co-located sites where invasive sensors were in service, enabling comparison between the measurements of the two sensor types. The selected sensors were of different makes and models and based on market availability at the time the project was initiated, along with agency preferences.

Despite the considerable challenges caused by the COVID-19 pandemic and other external factors, the project enjoyed a good degree of cooperation from the state agencies and will continue to see the remaining installations completed as agencies add staff and work through their backlogs of critical projects. Although not all of the sensors were installed, many lessons were learned, and a considerable amount of data was collected by the agencies for internal use and on-going assessment.

As a result of this experience, some participating DOTs have decided to adopt non-invasive sensors, expand their deployment, or even consider applications beyond those planned in this project. While this project initially targeted pavement surface temperature, one participating agency with limited non-invasive sensor experience is planning on statewide deployment for real-time friction measurements for use in agency decision making.

The project allowed participating agencies to work with new vendors, creating an opportunity to evaluate the different products, encounter potential issues, and identify possible solutions through a low-risk environment. This effort will support future research on both pavement temperatures and friction across the US and based on data from the same make and model of non-invasive equipment.

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