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Weather-Savvy Roads: Sensors and Data for Enhancing Road Weather Management: Final Report

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16. Abstract This project is focused on enhancing road weather management during wildfires, flash floods, and other extreme weather through data collection, sharing, and public dissemination technologies. Three areas of focus include research and practical findings regarding best practices in roadway operations, a curated data catalog relevant to roadway management, and the dissemination and evaluation of sensors to aid in operational decision-making and information selection for the traveling public. Further implementation requires (1) integrating sensor data into Texas Department of Transportation IT architecture and existing software systems, (2) properly archiving and creating accessible data for analysis and validation purposes, (3) refining methods to improve sensor data coverage and reliability, (4) defining and continuing to track performance metrics, and (5) developing further processes to disseminate relevant information and data among agencies and to the public. The findings, lessons learned, sensors, and data analytic techniques were demonstrated in two workshops conducted in Abilene and Austin, TX, to familiarize practitioners on key concepts needed for conducting a successful sensor deployment and data analytics practice.					
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**THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH**

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Products

The first product developed by this project was the data catalog (5-9053-01-P1). This product is available here: <http://w-catalog.utmcc.org>

The second product is a set of PowerPoint training slides, available as a separate publication: *PowerPoint Presentations for the Training Workshop* (5-9053-01-P2).

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Chapter 1. Introduction and Executive Summary

Wildfires, flash floods, freezing events, and other types of extreme weather events have a significant impact on safety and mobility throughout Texas. The Texas Department of Transportation (TxDOT) plays a critical role in enabling effective inter-agency coordination for the evacuation of affected residents, as well as the delivery of necessary resources in emergency conditions. Operating TxDOT roadways in the safest way feasible is of paramount importance: deaths caused by frozen or flooded roadway conditions can be avoided if receptive travelers are better informed and prepared.

Project 5-9053-01, “Enhancing Road Weather Management during Wildfires and Flash Floods through New Data Collection, Sharing, and Public Dissemination Technologies” was instigated to address two objectives. First, challenges, benefits, and strategies for data collection and sharing are identified to maximize the ability for TxDOT and partnering agencies to improve responses to extreme weather events. Second, new technologies are explored to find effective ways to disseminate weather-related roadway information to the public.

To achieve these, the project covers three major areas of focus (as depicted in Figure 1.1):

- **Practices:** Identifying methods for and enhancements in roadway operations via a literature search and stakeholder input;
- **Data Catalog:** Curating multidisciplinary data sources that may be of benefit to roadway operations or post-event analysis; and
- **Sensors:** Evaluating the use of new technologies available in sensing devices for generating data that helps with roadway operations decision-making and conveying information to the public.

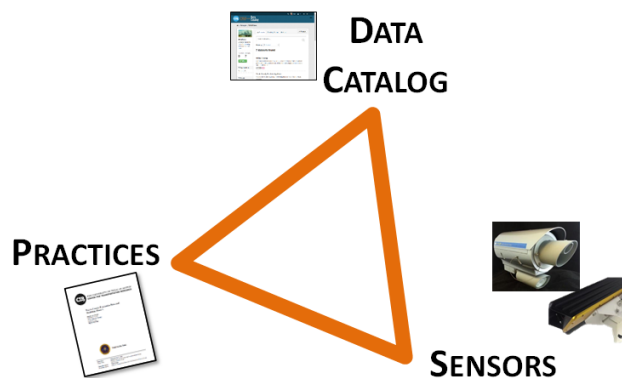


Figure 1.1 Project areas of focus

From these channels, a number of local and national best practices are identified within this project, offering recommendations in:

- sharing data from multiple sources to enhance safety during extreme weather events;
- reducing the impacts of such events on mobility; and,
- supporting evacuation operations when needed.

Among the tools available for accomplishing these, sensors, integrated mobile observation (IMO) devices, and social media are explored for enhancing data collection techniques and disseminating information in real time. Along the way, new data sources offer abilities to make better roadway operations decisions that can reduce cost and improve safety. An example of a roadway operations decision is determining where and when to apply anti-icing agent to the roadway in preparation for freezing weather. Such tools can also provide valuable information to analyze the outcomes of traffic management strategies in the aftermath of an event.

For this knowledge to be useful, it must be transferable and relevant. This project delivers these products and outcomes:

- **Training materials** are created for two workshops on sensors and data that were delivered in Abilene and Austin, TX. The workshops are created to inform participants of ingredients necessary for a successful sensor deployment, as well as strategies for effective data analysis.
- A variety of **sensing technologies**, including mobile temperature monitoring, weather recording, flood detection, ground surface ice characterization, and fire/pollution detection, are demonstrated.
- An online, interactive **data catalog** is created (<http://w-catalog.utnmc.org/>) for the purpose of facilitating conversation on how data sources may be understood and shared.
- **Stakeholders** from state and local roadway operations and emergency response agencies met in four workshops (including the Austin sensors and data workshop) to share knowledge and learn from counterparts in other agencies.
- **Best practices** in roadway weather operations and management are compiled from practices documented from other agencies across the United States, as well as local practitioners.
- **Recommendations** are made for new directions and future implementation efforts on roadway operations practices within Texas.

1.1 The Path to Implementation

Through this work, paths for achieving concrete implementation within TxDOT have become clear, motivated by needs for cost reduction, transferability, and improvement of safety:

- Sensor data and outputs from decision support systems need to be **integrated** into the TxDOT IT architecture and existing software systems (e.g., Lonestar active traffic management system). This not only allows for safe and secure operation, but it also allows for access where the data is needed the most, especially in emergencies.
- The data needs to be **archived and accessible** for analysis and validation purposes. This should be integrated with the TxDOT Information Management Division’s “data lake” efforts.
- Methods for improving the **coverage and reliability** of sensor data should be refined to detect sensor faults and failures, and to maintain a quality suitable for decision-making and forecasting.
- Well-defined **performance metrics** help in understanding the reliability and value of a sensor network, as well as to justify the expense for future expansion.
- Processes need to be developed further for more widely **disseminating** relevant information and data to the traveling public. While mobile technologies continue to emerge, much of the work lies in streamlining data pipelines and decision-making processes within TxDOT roadway operations and partnering agencies.

1.2 Report Organization

This report is organized into the following chapters:

- “Analysis of Current Data Used to Support Roadway Weather Management” (Chapter 2) surveys data sources and existing tools that are applicable to weather-related roadway operations.
- “Analysis of Mitigation Strategies for Roadway Weather Management” (Chapter 3) looks at how impacts of weather events are mitigated within agencies across the United States.
- “Recommended Enhancement of Roadway Management during Weather Events” (Chapter 4) builds upon the previous chapter to offer conclusions, best practices, and recommendations for effective mitigation strategies within TxDOT.
- “Data Analysis for Decision-Making” (Chapter 5) looks at novel analyses of multiple data sources to explore value added by data fusion.

- “Implementation Plan” (Chapter 6) documents a reusable plan for sensor deployment using the sensors that were acquired and evaluated during the course of this project.
- “Workshop Sensor and Data Demonstrations” (Chapter 7) documents all of the hands-on sensor and data demos that were conducted for the project’s training workshops.
- “Getting Started with Tableau” (Appendix A) offers a brief “quick start” introduction on analyzing data with Tableau, a software package that is used by entities within TxDOT.
- Other appendices capture cataloged data sources, stakeholder meeting survey responses, installation notes for sensors, and training workshop outlines.

Through these efforts, the intended outcomes are to make better-informed roadway operation decisions, share data among agencies and departments, and inform the traveling public in impactful ways. Ultimately, the bottom line is to improve safety, reduce costs, and increase effectiveness.

Chapter 2. Analysis of Current Data Used to Support Roadway Weather Management

2.1 Introduction

To meet project objectives, the research team devised the Data Catalog and coinciding Stakeholder Meetings. The primary motivation is to determine current use of weather, evacuation, and transportation data during weather events, and to share a preliminary list of relevant data sources. Some of these data sources are those that are used to plan evacuations. An open-source web-based framework has been leveraged in an initial attempt to catalog and curate datasets on an open basis. In cases where there is no other home for data, such as data coming from sensors that had been purchased for this project, the same environment can publicly host the data.

During the stakeholder meetings, data discussions revolved around a series key themes, including:

- Improving communication;
- Increasing the number of data sources;
- Improving coordinated pre-planning and preparedness;
- Enhancing data sharing and availability;
- Providing cross-platform, real-time reporting and display of info; and
- Facilitating online statewide volunteer sign-up

While these themes are general, they point to concepts that motivate ongoing work around the use of data in planning, modeling, and decision-making.

The work formed a foundation for later tasks in the project having to do with best practices for managing data and sensors. Later chapters describe the further literature searches, conversations with practitioners, and stakeholder input that informed new and enhanced mitigation/information dissemination strategies, and also led to roadway management strategies.

2.2 Background

This section identifies several data sources and tools used in adverse weather events, evacuations, and risk assessment. In considering the use of data, it is also important to identify viable tools that can be used, whether they be processes, web applications, or general analysis tools. It is the combination of data with such tools, along with technical experience, that allows the value of data to be fully realized.

2.2.1 Freezing

The National Weather Service (NWS) provides data, analysis, and products from a national information database to help deliver inclement weather warnings (NOAA National Weather Service, n.d.). The use of this source is helpful to government and private agencies as well as the general public. Both Dan Richardson, TxDOT Director of Operations, Abilene District, and Brian Dodge, TxDOT Emergency Management Coordinator, identified the NWS as their primary source of weather knowledge. In both cases, personnel from agencies consult with NWS staff routinely, obtaining valuable weather analysis. Consequently, roads are frequently pre-treated 2 or 3 days before an anticipated freezing event.

Freezing Challenges

As an example of the data challenges faced by a TxDOT district, Richardson reported that fully-featured weather sensors are sparse in the Abilene District. There is a sensor at the airport and in three cities west of the IH-20 corridor; these sensors collect weather data such as humidity and windspeed. More weather station coverage would greatly help in determining where to pre-treat before a freezing event, and where to respond to freezing during an event. It follows that there would be benefit in having tools to efficiently manage and visualize data from all of the sensors. In addition to having more weather stations, it is desired that sensors measure freezing on bridges; a suggestion is to embed the sensors. Activities in TxDOT Projects 0-4834 (Yildirim, Dossey, Fults, Tahmoressi, & Trevino, 2007) and 0-1778 (Medina, McCullough, & Dossey, 2004) were to embed iButton Thermochron sensors into pavements within experimental sites, but no indication had been found of these systems being maintained today. While existing sensors lie along IH 20, sensors are needed for many other major rural routes in the district, as well as urban centers. Sometimes these areas are missed when pre-treating.

Some stations that show up on the Abilene District weather map are private (e.g., located on a ranch and owned by the rancher). Stations are also located along the railroad (Union Pacific), and reported back. Even so, many sensors don't measure rainfall.

It is a frequent practice to assess icing by driving across the district, and it is challenging at night. In addition to TxDOT assessment efforts, the Sheriff's Office will make assessments and report on road conditions, both to the NWS and TxDOT. While the "data" in use today are currently these assessments, there are opportunities for collecting other types of data via sensors on vehicles.

Stakeholders have also offered that there could be opportunities to leverage data from the vehicles themselves that pertain to braking and stability. Data points that are registered with time indices and GPS coordinates can then be visualized.

The incorporation of a Road Weather Information System (RWIS), which provides automated real-time weather data, enables anti-icing to become more effective because the system allows for more informed decisions about material placement. However, some drawbacks to an RWIS

include high initial cost, insufficient sensors/stations, and high maintenance and upkeep costs (Texas Department of Transportation, 2017).

Additional Data and Resources

In general, RWIS stations and de-icing and anti-icing capabilities require more specific details than what the NWS can provide (Texas Department of Transportation, 2017). Available resources on the internet recommended by TxDOT for monitoring weather warnings include:

- <http://www.accuweather.com/wx/index.htm> – Accuweather – Forecasts, radar & satellite
- <http://www.intellicast.com/> – Intellicast – Forecasts, radar & satellite
- <http://www.wunderground.com/> – Underground Weather – Forecasts, radar, satellite
- <http://www.rap.ucar.edu/weather/radar/> – Real-Time Weather Data – Forecasts, radar, satellite
- <http://www.mesonet.ttu.edu/> – Weather forecasts and data for West Texas

Reporting information at the federal level related to snow and ice conditions involves furnishing maintenance management system reports to the Federal Emergency Management Agency (FEMA). This helps repair cost assessments in the event of storm damage. State reports are done through Highway Condition Reports (HCR), which provide unedited information to the public and to TxDOT (Texas Department of Transportation, 2017). District and local reports are completed from maintenance officials with heavy detail to truck operations.

2.2.2 Flooding

With the recent damage to Houston during the Hurricane Harvey event as well as other times of extreme rain, flooding is at the forefront of many people's minds. Opportunities exist for finding new sources of data that can help with roadway operations as well as informing the traveling public.

Most prominently, TxDOT provides the interactive travel information site DriveTexas for travel planning that shows highway conditions (TxDOT, 2017). This tool is recommended for users during winter storm situations as well as floods, wildfires, and other hazardous conditions. The information presented in DriveTexas comes from field observations made by TxDOT personnel, serving as a single dissemination point. Highway conditions are accessible on the TxDOT website and through a toll-free service number; a searchable web query tool is available as well. This tool is recommended for users during extreme weather situations, and other hazardous conditions. Possible contraflow or evacu-lanes are shown in a separate model and activated into current conditions only when in use by the network.

Floods typically occur in early spring. In the Abilene District, the maintenance supervisor is familiar with the sites susceptible to flooding. The supervisor will drive on the road and make assessments at these sites. These assessments result in DriveTexas updates, as well as the Sheriff's Office's involvement in closing roads. Sensors on vehicles along with GPS receivers can offer added benefits.

The City of Austin provides another example, as “flooding is the most common hazard for the Austin area” (City of Austin, 2016), and flooding can occur anywhere—not just in proximity to creeks or floodplains. Austin's Office of Homeland Security and Emergency Management recommends road users stay informed on flood information and emergency road closures. Such information is provided by a site maintained by the City of Austin Flood Early Warning System team, ATXfloods (www.atxfloods.com). Along with updates to the user interface, this name is soon to be changed to CTXfloods, which better represents the fact that the tool covers the greater Central Texas region that includes and extends beyond Austin. ATXfloods is a multi-jurisdictional collaborative website, which shows green dots where low water crossings are open and red dots where closures have occurred (Porcher, 2015). It is also important to note that ATXfloods is manually updated and supported by about 200 admins; the points are not tied to a sensor. This visual interface, however, is an improvement upon previous methods of closure lists on the emergency operation center website. The website also provides alerts relevant to user location for pre-emergency notification. Through the ATXfloods website users can also link to ATX FloodPro and the LCRA Hydromet. The ATX Floodpro site is beneficial to identify floodplain locations while the LCRA (Lower Colorado River Authority) Hydromet provides near-real-time data on river and weather data throughout the lower Colorado River basin in Texas and additional gauges maintained by the City of Austin and United States Geological Survey (USGS).

Locally, data sources that are used within City of Austin departments for planning purposes include GIS layers of watersheds and floods, and also data coming from interviews with engineers and stakeholders, who help with vulnerability assessments. They can provide anecdotal data for missing data/parameters in their risk assessment work.

A notable research activity in East Texas that uses regional data is the FAS4 Flood Alert System (Bedient, Fang, Hovinga, & Holder, 2016). It employs LIDAR and other technologies to more accurately predict the flooding of Brays Bayou.

Unmanned aerial vehicle technologies (or drones) have tremendous potential for data collection (Yuan, Zhang, & Liu, 2015). These are mostly used to collect data currently in the form of surveillance videos that can later be manually or automatically analyzed, but the miniaturization of other sensing technologies such as LIDAR or infrared imaging can offer future opportunities for data collection.

In addition to the NWS offerings, the National Oceanic and Atmospheric Administration (NOAA) provides an online source of severe weather records called the Severe Weather Data Inventory

(SWDI). The database comes from multiple integrated sources and offers historic records of severe weather incidents, including data that is derived from radar data (NOAA, n.d.). The Storm Risk Assessment Project sponsored by NOAA exemplifies the capabilities of the SWDI to produce valuable climatology products. In this project, climatology information was gathered from SWDI and merged with socio-economic datasets to assess severe weather risks to safety and property (Ansari, Phillips, & Greco, 2014). This type of assessment is relevant to many users such as emergency management and municipal planning.

The USGS provides a continuous source and storage of hydraulic data valuable to emergency management through the National Weather Information System. The USGS possesses the capabilities to monitor water conditions at any U.S. location. Partnering with USGS can provide further technical assistance for relevant decision-making assessment tools (U.S. Geological Survey, 2015). The Texas Watershed Dashboard, a web mapping application of real-time water data and weather conditions, is the product of such a partnership by the USGS Texas Water Science Center. The Texas Watershed Dashboard updates information from over 750 stream gages to the mobile device-friendly site and active Twitter feeds in real time. The application was released in April 2016 and the intended audience includes emergency managers as well as the general public. The success of the innovative one-stop site is growing and has the potential to expand to the rest of the nation (U.S. Geological Survey, 2016).

Crowdsourcing and Citizen Reporting

A growing trend across the United States is data collection through crowdsourcing. Data collection through social media or mobile applications is of growing interest in the area of road weather management according to the FHWA. Crowdsourced apps like Waze have become popular resources for drivers to obtain traffic information. Waze also encourages partnered agreements with DOTs, including as of October 2017, TxDOT. Outside of these contractual agreements, the information from the crowdsourcing apps, intended for drivers, is not targeted well enough for direct use by transportation departments (FHWA, n.d.). DOTs located in Wyoming, Utah, Idaho, Iowa, and Minnesota have modified public reporting programs into citizen reports, to better suit their data collection needs and provide updated road conditions. Instead of relying on social media or GPS-based apps to track a report location, citizen reports utilize tailored location identifiers that can be pre-defined or user-defined based on a created route system. Quality control is handled through verifying information and proper training. Spot checks are implemented periodically and more so on new reporters. Citizen reporters also come from willing volunteers who are trained in each states' program collection portal (either via web, phone, or app). The departments have reported the need of more volunteers, but the data collected in these early stages has been accurate and promising. "The Wyoming Department of Transportation reports that the benefits of the increased information far exceed the costs, which are minimal to the department of transportation" (FHWA, n.d.).

CARS

Currently, ten states have implemented the use of the citizen reporting system called CARS (Condition Acquisition and Reporting System). CARS was developed initially on behalf of four state DOTs by Castle Rock, a private intelligent transportation system (ITS) agency. It is now communally owned and maintained by a consortium of states, which enables open involvement opportunities and motivates internal improvements to the system. The design of CARS allows easy integration and extensions to “ITS applications, CARS-511 travel information system, commercial vehicle operations, public information web sites, Dynamic Message Signs (DMS), Highway Advisory Radio (HAR) and Low Power FM Radio (LPFM), among other components” (Whited, n.d.). In CARS, users can manually enter roadway events or import from a third party such as Waze, NWS, or from a traffic management system. The collaborative nature of the program promotes frequent communication with others in the group to compare successes and difficulties. New groups entering the CARS program gain access to the body of knowledge shared in the group, and existing members benefit from that new funding, which can be used to improve the system (Davies & Virshbo, 2009). Members of the CARS program drive the priorities of the system developments and maintenance relative to current needs and budgets. The use of the pooled funding concept throughout the program has helped the success of the system and benefits its members by allowing the leveraging of each others’ capital investments and promoting shared knowledge.

CoCoRaHS

CoCoRaHS, which stands for the Community Collaborative Rain, Hail and Snow Network, is a citizen reporting network utilized to measure, map, and share precipitation levels. Sponsored by the NOAA and the National Science Foundation (NSF), “CoCoRaHS is now the largest provider of daily manual rainfall measurements in the United States” (Reges et al., 2016), and is dedicated and proven to provide free quality data available for weather prediction and alerts. Tests of the CoCoRaHS gauges against the NWS gauge resulted in a collection efficiency of 101–105% greater than the NWS gauge (CoCoRaHS, 2018). Over 37,000 volunteers participate in the program and provide data useful to organizations and individuals such as the NWS, emergency managers, and public users. The community organization is still growing and providing education and training to expand its data capabilities. CoCoRaHS data reports and maps are available at www.cocorahs.org.

511DFW System and Waze Partnership

The 511DFW system is a combined web and phone communication system that disseminates information to the public in real time regarding accident information and status, modal availability, travel times, conditions, transit routes, schedules and vehicle tracking, weather, and parking management (Paul, Short, Denholm, & Lee Engineering, 2016). The 511DFW system is the first of its kind in Texas while other 511 systems exist in over 30 states. This system, which is already generating further interest, has the potential, with improvement, to extend from regional to statewide. The agencies in charge of the system and their involved roles include:

- TxDOT – provides real-time data through entering information into the “Lonestar Freeway Management System” connected via web to the service, and by funneling traffic monitoring feeds linked to their dynamic integrated mobility management system called EcoTrafIX, and the data fusion engine into the 511DFW system (Paul et al., 2016). The data fusion engine is maintained by a private contractor and brings traffic speeds, weather, transit locations, and incident information together in the system.
- North Central Texas Council of Governments – maintains active involvement in operations and system evaluations, and was the primary funding source in 2016 for the operations and maintenance costs.
- DART – manages the project as the leading agency; also provides real-time data and supplements feeds that are not automatic.

The assessment of the 511DFW System provided by *511DFW Traveler Information – Independent Evaluation* in 2016 noted certain weaknesses, including the lack of road surface condition information available in the weather feature. The basic current conditions are shown in the system, but the reviewers recommended enhancing this feature by associating with the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) to obtain detailed weather-related road information for a low cost. Overall, the user aspect of the 511DFW system was determined to be too complex, and the evaluators specifically referenced DriveTexas and the TxDOT ITS websites as more intuitive traffic information sources. The suggestion from the report to partner with Waze was in fact initiated the following year in October 2017, by the City of Frisco. The changes to the system with the newly available Waze data stream are still in the early stages. The integration of Waze will provide event data related to jams, alerts, and irregularities, which will be strategically filtered before publication for quality control. The annual system costs, including suggested improvements and marketing fees evaluated in 2016, are provided in Table 2.1.

Table 2.1 511DFW System Costs

Items	Cost (USD)
Operational cost	\$1,100,000 (annual)
Agency personnel training on data entry software EcoTrafIX	\$40,000–\$50,000 (one-time training for each agency)
Enhancements of 511DFW (website, interactive voice response system, My511, and mobile app)	\$250,000–\$400,000 (one-time improvement cost)
Bilingual system (Spanish version in addition to current English version)	\$50,000–\$60,000, it could be as much as \$250,000 (one-time deployment cost)
Marketing and campaigning	\$700,000–\$1,500,000 (one-time cost)

Source: (Paul et al., 2016)

2.2.3 Wildfires

Research provided in *Best Practices for TxDOT on Handling Wildfires* (2012) outlines current practices and interviews 12 TxDOT districts regarding involvement with wildfire events. Two

important forms of collecting and reporting data found in this research include the HCRs and the National Incident Management System (NIMS). HCRs, mentioned earlier, can be accessed through the TxDOT website, and include wildfire updates affecting highway conditions that are updated every weekday morning. NIMS integrates organizations, allowing them to work together to mitigate, respond, and recover from incidents. The 12 district interviews yielded the primary finding that TxDOT plays a significant role in managing a wildfire emergency, even though the agency does not directly provide firefighting support.

Texas Forest Service (TFS) is the lead NIMS-implementing agency and is involved in Texas statewide emergency management for handling wildfires (Nash, Senadheera, Beierle, Kumfer, & Wilson, 2012). TFS provides guidelines and technology helpful for developing a successful Community Wildfire Protection Plan (CWPP). For example, they provide the tool used in Travis County's CWPP called TxWRAP, which stands for Texas Wildfire Risk Assessment Portal. This web-based application can identify community boundaries and provide information for wildland urban interface, fire occurrences, fire behavior, risk assessment, and future wildland restoration (Union of BC Municipalities, 2017). It is also a useful tool to allow agencies to work together to improve emergency response overall. TFS also provides an accessible Keetch Byram Drought Index (KBDI) map helpful for wildfire planning.

Further data collection techniques for TxDOT districts include emails and SharePoint, maintenance division database, daily activity reports, employee diaries, situation reports, and equipment and personnel logs (Nash, Senadheera, Beierle, & Kumfer, 2013).

The availability of information available on wildfire emergency information is a strong resource in local emergency planning. As an example, Section 4 of Travis County's CWPP provides detailed wildfire risk modeling with location-specific maps and areas ranked by combustion risk. Data sources and formulas used for modeling are found in Appendix B of Travis County's CWPP. The 83 boundaries or zones were determined by physical features, jurisdictional boundaries, and local area judgement. The fire behavior modeling used FlamMap, an application that simulates the occurrence and spread of a fire in a designated study area. Identification of risks for the CWPP involved the use of multiple GIS-based models and data sources including:

- City of Austin GIS ftp site
- Capital Area Council of Governments (CAPCOG) geospatial data website
- Travis County
- Travis County Tax Appraisal District
- US Department of Agriculture
- Texas Natural Resources Information System

- Austin Fire Department
- Texas Parks and Wildlife Department

2.2.4 Risk Assessment

The primary motivation for looking at risk management is to prioritize and justify the allocation of resources, both in the early drawing board stages of planning, and also in the execution of the plan during an emergency. This also extends to prioritization and allocation of resources to collect or procure data.

Best practices for assessing the vulnerability of a transportation network under extreme weather and options available for adapting and improving are available in the report, *Central Texas Extreme Weather and Climate Change Vulnerability Assessment of Regional Transportation Infrastructure* (2015) (Cambridge Systematics Inc., 2015). This report outlines transportation data, asset criticality, sensitivity thresholds, climate data, vulnerability assessment, and fundamental takeaways. The study involved the U.S. DOT Vulnerability Assessment Scoring Tool (VAST) (U.S. Department of Transportation, 2015), which breaks the assessment into three components: exposure, sensitivity, and adaptive capacity. The assets or roads analyzed were selected based on the premise that their removal from the network, due to extreme weather, would cause significant impacts.

VAST classifies exposure as whether the asset experiences the indicated stressor, such as flooding or wildfire. Examples of exposure indicators for various stressors (flooding, wildfire, winter weather, etc.) include past exposure, proximity to the 100-year floodplain, wildfire threat (defined by TxWRAP), and projected change in number of ice days.

2.3 Data Catalog

A brief introduction to hosting and representative formats is presented before the specifications of the Data Catalog created for this project. The Data Catalog includes a number of data sources identified through research and stakeholder discussions as potential resources to aid in extreme weather management or evacuation planning relevant to TxDOT. The development of the data catalog described in the Data Catalog Methodology aligns with the structure of an ideal data management plan outlined in data management best practices by the U.S. Department of Energy Office of Science (2016). The benefit to maintaining a data catalog allows relevant content to be shared and accessible between departments. Transference to a third party or just handing over the projects findings is made simple through the detailed data catalog methodology provided. A list of preliminary data sources identified in this project can also be found in Appendix A.

2.3.1 Introduction to Hosting and Representative Formats

Raw, cleaned, processed, and curated data of all forms may appear in an accessible representation online (via a public or private network) for a number of reasons. The formats for representations include the following:

- Data Lake
- Data Warehouse
- Data Mart
- Dashboard or Visualization Application
- Data Catalog

Each has a set of purposes and capabilities, and the choice of representation(s) for any one data source depends heavily upon how it is to be used. They may cross over and feed into each other. The following subsections describe each kind of representation. (Note that this is a high-level view, and definitions in reality may incur some degree of crossover and variation.)

Data Lake

This is designed to hold large amounts of raw or minimally processed data. It may require additional structure to be applied in order for the data to be useful for a particular purpose (Levy, 2016). This would be leveraged more for analytics rather than operations.

Data Warehouse

This contains data that conforms to a stronger well-defined structure than what one would expect from a Data Lake. Although multiple sources and variations of raw data may feed into the data warehouse, the data warehouse is meant to offer a trusted, clean, unified version of the information (Levy, 2016). For that reason, it is a good target for analytics, but it can also be updated live and queried for operational purposes.

Data Mart

Through the use of a well-defined application programming interface (API) or view structure, data from a Data Lake or Data Warehouse is limited and presented according to the needs of a particular application or discipline (Levy, 2016). While these are helpful for implementing well-defined analytical use cases, ongoing creation of Data Marts may not be sustainable.

Dashboard or Visualization Application

This is a mechanism for presenting a static or intractable view of underlying data. It is common for a Dashboard or Visualization Application to interface to a Data Mart, although such can also

interface with a Data Warehouse by exercising finer control within the application. These often heavily rely upon graphical elements

Data Catalog

The intent of a Data Catalog is to provide a means for operations personnel and data practitioners to gain an improved understanding of data sources that are available and how new data sources can be applied to roadway operations. Ideally, this would also allow collaborations to be enhanced by an improved forum for data exchange, and better communication of data format information. The Data Catalog references other data sources without needing to re-host data.

2.3.2 Data Catalog Methodology

The data catalog created for this project has the capability of identifying relevant data sources for a public audience. In designing a catalog, the following tenets were observed:

- Apart from data sources emanating from the sensors purchased for this project, we are not trying to host or clean others' data; we are instead *curating* data.
- We want a sustainable solution for keeping the data catalog populated and current.
- For the catalog to be useful, it needs to be online, searchable, and filterable.
- The software is to be open-source.

This led to the exploration of open-source data repository server software packages that are available today, because the prospect of designing a custom catalog from scratch was not feasible given the project schedule, and arguably not in the best interest for maintainability. Several solutions exist, including the highest ranking ones, Dataverse and CKAN. OpenGov's CKAN was chosen as the software package to use because of its versatility, database back-end, and ease of setup. It is developed by an open source consortium and actively used by many government agencies throughout the world. This project's copy is currently hosted on a CTR virtual machine server that resides at the UT Austin Data Center, but can be moved to another solution hosted by another organization or cloud service as needed.

Usage

The preliminary catalog can be accessed online at <http://w-catalog.utnmc.org>. Once inside the catalog, select "Datasets" to view and filter among all of the cataloged datasets. Alternatively, go to "Organizations" and select one of the choices (see Figure 2.1). The organizations facilitate the inclusion of both datasets and data-providing organizations without confusing them together. The organizations currently in use include:

- **Datasets:** Lists specific, granular datasets and provides information on accessing the data, as well as providing hyperlinks to documentation or API access;

- **Data Organizations:** Lists data-providing organizations that may offer multiple datasets; and
- **Apps and Tools:** Provides online resources that guide the usage of data.

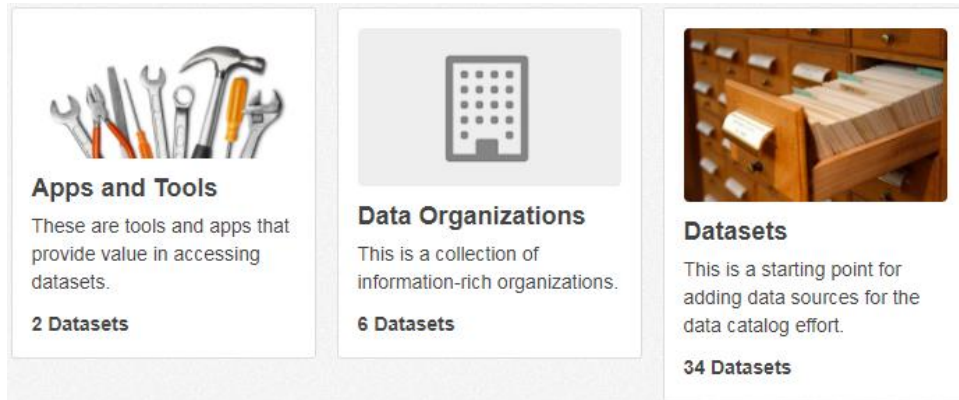


Figure 2.1 Organizations of the Data Catalog

On the left side of the view are a variety of filters that can be switched on and off for fast searching. These filters come from groups, tags, and formats that are already associated with entries within the Data Catalog. Further, there is a text search capability that finds datasets whose descriptions match the given search criteria.

One feature that is planned to be added but isn't available yet is a geographic filtering mechanism. This will be facilitated by a CKAN plug-in that allows searches to be restricted to all datasets that intersect a bounding box drawn on a map. Additional tags may also help in this effort, where datasets can be labeled as “local”, “regional”, “state”, or “national”.

The following subsections explain the different entries that currently appear in the filter list.

Groups

Groups allow datasets to be categorized according to overall purpose (see example in Figure 2.2). Each dataset may be a member of zero, one, or multiple groups. The current groups that are defined include:

- **Evacuation:** Datasets that address mostly evacuation planning or modeling
- **Wildfires:** Datasets that apply mostly to wildfires. Some of these may be useful for evacuation planning purposes even though they might not share the same group.
- **Extreme Weather:** Datasets that apply to extreme weather events, including flooding and freezing. Some of these may peripherally relate to evacuation planning.
- **Transportation:** Datasets that pertain primarily to roads, traffic, or other transportation information.

- **Other:** To facilitate clearer filtering, datasets that are not a member of any other group are a member of this “Other” category.

One challenge in creating groups is that the distinction in level of applicability can be arbitrary. The group assignment scheme can be altered in the future.

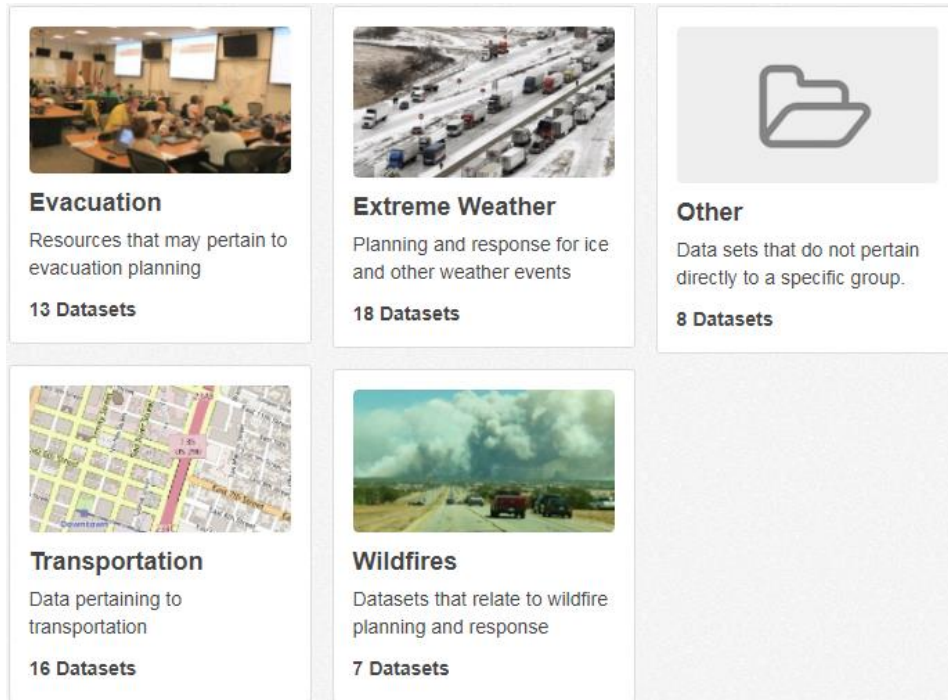


Figure 2.2 Data Catalog groups provide further levels of categorization

Tags

Tags are arbitrary keywords that are applied to each dataset, and appear in the filter list to offer quick searching capabilities. This is an area that may be expanded in the future to further categorize datasets according to content. Currently, the tags describe the layout of the data:

- **Text:** Data in the form of paragraphs and/or documents
- **Tabular:** Data (numeric or text) that are stored in spreadsheet format
- **Infographic:** Data presented through picture form
- **Geospatial:** Data that are registered to a map of a region

Formats

Each dataset may offer one or more *resources* that can be classified according to the presentation format. These may include the following:

- **Webpage:** A static or interactive online resource accessible through the Web

- **HTML:** A supporting document that is available on the Web
- **API:** A means of programmatically accessing a dataset's data that may be of interest for data mining or large-scale data analysis efforts
- **PDF:** A document in Acrobat format
- **CSV, XLS:** Data in spreadsheet format

Licenses

This describes the availability of the data, including:

- **Other (Open):** Data provided as open-source and/or public domain; and
- **Other (Not Open):** Data that requires a fee or departmental approval for access.

These may be expanded in the future to further differentiate between free datasets that require a process to obtain exclusive access, and datasets that require a fee.

Updating and Continual Maintenance

When new datasets are to be added, or corrections are needed, one or both of these approaches can be facilitated:

1. Project team members with administrative access can be notified through email, and manually make the necessary changes, or
2. A representative for TxDOT or subcontractor can be given an administrative account so he/she can make the changes.

Within CKAN, system administrators have the ability to check on the Activity Stream of any administrator, reviewing the details of the last edits or additions made by each user to the catalog with hyperlinks to the entry. CKAN also allows administrators to categorize sets to the user who uploaded them. Parties involved in maintaining the data, whether it is a singular person or small team, can also “follow” system administrators to enable notifications of their catalog actions to their own private Dashboard News Feed. This increases communication among the catalog and tracks changes being made to ensure quality, uniformity, and reliability.

2.3.3 Sustaining a Data Catalog

A demonstration of the Data Catalog was given at a stakeholder meeting, and comments were collected. Most comments focused upon new organizations and data sources that can be added, as well as the overall maintenance of the resource.

While the preliminary Data Catalog involved “one-off” populating efforts within the CKAN graphical user interface, a more sustainable approach is needed for the Data Catalog to be

maintained in the future. An idea that is currently under development involves keeping a flat table scheme that holds metadata that fully captures the Data Catalog contents. There can then be an automatic process to periodically populate and update CKAN. This flat table scheme allows for better editability and fewer inconsistencies, and also opens the door for other types of applications or reports to be produced from the same metadata.

Data Governance

Issues concerning data quality, ownership, and maintenance—data governance—are a definite concern that must be addressed to ensure proper execution of data management. Implementing a data governance framework helps to standardize data definitions across an initiative and increases the value of the data and efforts involved. The framework of a strong data governance boils down to three main categories: rules and rules of engagement, people and organizational bodies, and processes. A more detailed view of the categories includes specifying the following components (Thomas, n.d.):

Rules and Rules of Engagement

1. The projects' main objective and motivation
2. Goals and governance metrics
3. Data rules and definitions: formalize this information
4. Decision rights: appointing a project lead and decision process
5. Accountabilities: defining, distributing, and adhering to tasks
6. Controls or risk management

People and Organizational Bodies

7. Data stakeholders: such as creators, users, decision-makers, etc.
8. Data Governance Office: a team structured to continually communicate information to stakeholders and to collect, measure, and report metrics
9. Data Stewards: those entrusted with decision-making and policy authority

Processes

10. Methods used to govern the data during all aspects of the projects life

While data governance programs vary in intent, they offer many common benefits. A strong framework enables better decision-making, increases efficiency, protects the needs of the stakeholders, and ensures transparency of processes (Thomas, n.d.). Also, data governance builds uniform and repeatable techniques to approach the project and preemptively tackle data issues. For example, data issues concerning this project include:

- Whether the data resource is online at the given URL; and,

- When the last-updated date is.

If a problem is discovered, then the Data Catalog maintainer can be notified so that it can be investigated, and the metadata can be updated.

In sum, sustaining a Data Catalog requires not only a proper data management structure but continual enforcement. The outlined methodology of the Data Catalog provides decision-makers with a solid foundation that can be expanded, reorganized, or improved to align with the interests of stakeholders involved.

Chapter 3. Analysis of Mitigation Strategies for Roadway Weather Management

To meet project objectives, the research team identified current methods that agencies use to act upon and distribute information associated with weather events. These methods include inter-agency communications to support agency decision-making, as well as public dissemination to inform travelers. Many of these overlap with efforts used to construct the Data Catalog in terms of identifying existing data sources and how they are used.

The task of this chapter facilitates a key step in understanding possible improvements for roadway management procedures in extreme weather events. Understanding how current systems work is critical for these reasons:

- Successful integration of new methods within the existing system platform and architecture is facilitated, especially working with the people and processes that are currently in place. Ideally, multiple players in different organizations (e.g., research, DOT, MPO, county, city, etc.) need to communicate and provide support to ensure success in scoping out, deploying, and utilizing new sensors and sources of data. (Mechanics of this will be explored further for inclusion in training materials).
- Because of time, cost, and person-resource limitations, it makes sense to leverage existing systems as much as possible.
- Without proper understanding, efforts may be wasted on objectives that are not in the best interests of the targeted audience.
- It can be argued that the best efforts in creativity, engineering, problem-solving, and “thinking outside of the box” rely upon constraints, which require familiarity with existing systems (Belle, 2014).

This chapter summarizes key themes that have emerged from stakeholder meetings and telephone conversations, including additional literature search findings. The list of activities and communication paths that stakeholders take when preparing for or responding to extreme weather events is found in Appendix C.

Included in this appendix are the activities, proactive efforts, reactive efforts, other organizations involved, and data used by the stakeholders involved in extreme weather events. These insights guide further work in using data for roadway operations, including deploying sensors, identifying analysis methods, and proposing improved mitigation strategies.

3.1 Summary of Insights

Given the input from stakeholders through group conversations at stakeholder meetings, surveys, phone conversations, and literature search, a number of general concepts emerged that are summarized here regarding:

- Collaboration
- Data and Sensors
- Technologies
- Privacy
- Dissemination
- Performance Metrics
- Weather-Responsive Management Examples
- FHWA Relevant Initiatives

3.2 Collaboration

One of the most prevalent topics discussed among stakeholders revolve around collaboration. Virtually all practitioners rely upon collaborations with other organizations to perform their jobs successfully. While collaboration is paramount, it also presents some of the most significant challenges. Even within multi-agency emergency response centers such as TranStar at CTECC (Combined Transportation, Emergency & Communications that serves the greater Austin area), individuals expressed concern about a siloed nature of working. Participants of this project's stakeholder meetings acknowledged the value of multiple agencies and specialties coming together to not only improve awareness, but also to make new collaborative connections. There is agreement in the idea that inter-agency and interdepartmental collaboration takes discipline. Relationships must often be established and maintained during idle, non-emergency times. In other cases, organizations make the effort of providing or utilizing a single point of contact. For example, agencies consult utility companies concerning gas lines, etc. via single-point phone numbers or contacts.

Two major benefits of collaboration are apparent:

- A practitioner in one agency collaborates to delegate or initiate activities to be performed by personnel in other agencies because the other agencies have the commission, skills, resources, and availability that are better in-line with the activity. Especially during times of emergency, tasks can be accomplished efficiently and quickly with proper delegation.

- Information or data that would be helpful for an agency to successfully do work or make decisions is managed, hosted, and quality-checked by another organization.

While collaborations exist and continue to be developed in these ways, government initiatives seek to facilitate improved collaboration. For example, the Pathfinder Project (a project developed under the Weather Savvy Roads initiative) includes a collaboration effort between state DOTs, NWS, and support contractors to improve road weather management through information collection and sharing. The data involved in the initial case project included traveler information, weather information, communication logs between states, and public response. The insight gained from this project is useful in future efforts to expand road weather management practices across multiple regions. Since the project's start, 14 additional states have entered into the collaboration effort (D Gopalakrishna, Ostroff, Wlodkowski, & Neuner, 2017). The best practices found by the four states involved in the initial Pathfinder Project were listed as:

- Maintaining year-long collaboration
- Expanding collaborative efforts and messaging during the warm season
- Sharing more information (traffic data, connected vehicle data, etc.)
- Improving message timing (dynamic message signs and others)
- Providing concise messages to drivers over multiple information platforms
- Holding formal after-event reviews and discussing how things went and ways to improve
- Gaining a better understanding of how various travelers receive and use weather information (i.e., truckers vs. general public)
- Expanding communication channels to adjacent States (Helsel, Boyce, Poling, & Sundararajan, 2016a).

Opening lines of communication between the weather community and roadway management requires documentation and coordination between parties. In order to maintain quality information, archival guidelines should be set to define what each partner will document as well as what records will be maintained on all ends. Example items for weather forecasting offices to maintain, which have been recommended by the Pathfinder Teams, include email exchanges, conference calls, and social media posts. The DOT can track and report alerts, traveler advisories, DMS, and other utilized roadway measures. All parties involved gain an advantage from recording best practices and lessons learned along the way as well as documenting additional resource costs, developed impact messages, identified training needs, policy changes, and noted benefits to the State, other portions of the public sector, the NWS, and the private sector (Helsel, Boyce, Poling, & Sundararajan, 2016b).

- Data that's generated, shared, and archived doesn't manage itself. For quality to be maintained, the owner or steward of the data must have resources to perform data governance activities.

Current communication between TxDOT and the weather community varies between districts. While some districts believe communication is only enacted when EOC are activated, other districts report great contact with weather services and rely on them for many events. This is the case in the Pharr District where emails are frequently used to verify information. However, several stakeholders from various agencies indicated that they would be happy to participate and contribute in a collaborative fashion within Emergency Operations Centers (EOCs) during times of emergencies. In addition to increasing the staffing needed for the EOC, it also opens unique collaboration opportunities among colleagues who do not otherwise have occasion to share knowledge or data.

When investigating TxDOT emergency response and ice prevention/removal efforts, the performing agency team identified another type of collaborative activity among TxDOT districts. When a significant response is necessary within one district because of an extreme weather event, the movement of equipment from neighboring districts is coordinated to provide resources to the affected district. This effectively reduces the necessity for each district to purchase and maintain equipment (Texas Department of Transportation, 2017). While this occurs for severe ice storms, this movement of resources also was coordinated during Hurricane Harvey.

3.3 Data and Sensors

Prevalent themes conveyed in stakeholder meetings included:

- Increasing the number of data sources to increase data quantity, quality and resiliency. This significantly helps with decision-making efforts.
- Improving data sharing and availability, which has similar effects and outcomes of increasing the number of data sources, and
- Providing cross-platform, real-time reporting and display of information, which offers rapid awareness and understanding of a situation in the field.

Access to data, and combination of multiple sources of data, is challenging because of lack of standards, as well as the inevitable uniqueness of each data set. While one may have a vision of standardizing and unifying access for all sources of data, research and practice has shown for many years that this is not feasible. Each organization may take ownership of their data to ensure their desired level of data quality and usefulness for that organization, which inherently challenges the use of standardized access or structure. Additionally, some data sources are private or restricted.

There is agreement among some practitioners that it may be feasible to try to standardize on metadata—that is, data tagged to a data set that describes the data set’s structure. This helps the efforts of analysts who need to understand a data set enough to effectively utilize it. Without metadata, the purpose and structure of fields within the data set are not readily known without the help of one within the providing organization who possesses the knowledge. However this happens, it is clear for the time being that technology-savvy expertise is often needed to integrate a data set from another organization.

A common practice is to use data repository software to store and host data. While some solutions are implemented in-house (including possible efforts of coding the software), free and commercial packages are available that can be run to host data (such as the Data Catalog powered by OpenGov CKAN). It is also common practice to use a third party to host data, which reduces the burden of hosting it in-house. The third party may be another collaborative agency that has better data hosting resources, or it may be a commercial product, including Socrata and data.world. Many of these provide capabilities for other applications to access the data, such as the Austin Open Data Portal, which uses Socrata as its back-end.

One challenge of leveraging new data sources or sensing technologies (either within an organization or from outside) is in understanding availability and capabilities. This is especially true for those who are new to data analysis. Research continues in identifying effective ways of communicating a better understanding of what is available online. Similar to the efforts of other government agencies throughout the world, this project has created a preliminary data catalog that offers tagging and searching capabilities. The intent is to curate potentially useful data sources provided by other organizations without assuming the responsibility of hosting the data.

Finally, data governance and quality continue to be important in hosting and using data. Wikipedia states: “Data governance is a defined process an organization follows to ensure that high quality data exists throughout the complete lifecycle.” Aspects of governance have to do with data quality and ownership, as well as ensuring that data is current. This includes efforts to clean data, which is especially important for using sensor data in an accurate way. An organization may preprocess raw data to weed out spurious readings and reduce noise by aggregating over time intervals. In some cases, another organization may perceive that the cleaning process oversimplifies or omits the data quantity that is deemed necessary for an analysis task. Organizations may help alleviate this by offering the cleaned data through their public portal, but offering the raw data only to trusted collaborators.

Available TxDOT sensing capabilities include speed sensors, Bluetooth readers, private sector data, and high water detection systems (HWDS). However, these are mostly focused on main roads, and many rural districts lack sufficient coverage even along these corridors. An example of this was previously mentioned in Chapter 2.2.1 for the Abilene District, which has only a handful of weather stations situated in larger population centers along the IH-20 corridor. Even along IH

20 within the Abilene urban area, portions of frontage road are susceptible to flooding, and yet lack flood detectors.

3.4 Technologies

Mature and emerging technologies play an increasing role in how data is managed and communicated. This is a summary of technology-related themes that originated in the stakeholder conversations:

- **Drones** have been used in a limited set of emergency response activities, such as Hurricane Harvey surveillance, but we are still learning how to most effectively use drones in emergency response. While their potential is great, their versatility is limited by weather conditions, limited battery power (except for scenarios where drones are tethered), and limited payload.
- **Tablets and smartphones** continue to become more commonplace for data collection efforts, especially because of their mobility and geolocation features. Many research opportunities currently exist for these. One drawback for these technologies during an emergency is the chance that the cell phone network is out of service. Apps would then ideally be resilient and allow for “offline” operation.
- **GIS and data visualization** methodologies continue to evolve, especially as computational capabilities improve and new software products (both free and commercial) emerge with innovative features. One especially prevalent area is **data fusion**, the combination of data from different sources that provide improved accuracy and resiliency.
- **Sensors** are critical for data collection within the field. New sensors such as the Sadeem precipitation/flooding sensors being tested for this project combine multiple features to provide a higher quality of data and a lower purchasing cost. For example, because of the multiple types of samples collected by the Sadeem sensor, it can provide an “atmospheric profile” that snapshots a variety of characteristics that would not be possible with an individual single-purpose sensor. Many inexpensive sensors and IoT (Internet of Things) compact computation platforms are appearing on the market, but may be more susceptible to the environmental conditions out in the field versus simpler, hardened, and more expensive “matured” sensors that have been available on the market for a number of years.

The use of technologies for data collection and sharing is limited by the need for resiliency. A common observation is that complex technology is more likely to fail; therefore, there is a resistance to rely upon cutting-edge technology. One progressive tactic used by several practitioners is to build redundancy into their workflows. For example, practitioners out in the field

who rely upon a GIS-based connected tablet app may also carry paper maps in their vehicles as backups to guard against battery failures or data network outages.

Technology is also limited by the expertise of the users and organizations. While a particular technology may offer many powerful features, it may be practically useless without the proper investment in appropriate training, services, and new hires. This also plays a role in the acquisition of technologies, as lack of expertise begets a lack of awareness and added scrutiny among decision-makers who control the purchasing. Three strategies of successful commercial providers reduce this impact:

- Products are offered that rely upon sensors and communications equipment that are owned and managed by the provider. This places the bulk of technology burden on the provider and also offers an easy solution that allows the agency to more easily reap the benefits of the final product. One example is travel time data provided by INRIX.
- Products are designed to facilitate easy installation, requiring no or little supporting infrastructure (e.g., power and data), and eliminating impact to the traveling public by offering installation options that don't require lane closures.
- Products are offered that are carefully designed to be usable with minimal training. One example is Gridsmart cameras that offer minimal installation impact and many integrated features via a usable online interface. One variation of this is in new products that are operated or interacted in ways that are similar to previous-generation counterparts. One example of this is a typical next-generation traffic signal controller that offers a user interface similar to that provided in the 1980s.

It is always advantageous to understand how other states use newer technologies and hear of their success stories. While these appear in research papers, technical reports, and guidance documents, they also are piloted at home by “champions” who are aware of the new technologies and want to try them out for themselves. For example, Fariello reported that TxDOT Austin District is working on improving lane closure information delivery by piloting the Virginia DOT LCAMS system in the Austin area.

3.5 Privacy

Much of the challenge in inter-agency sharing of data lies in the protection of sensitive information. Although there is some consensus that agencies are aware of challenges around protecting information, some agencies' level of protection exceeds other agencies. One example is data sources that are maintained by the Texas Department of Public Safety; these sources are not openly shared because of their sensitive nature. Such sensitivity also exists within emergency response centers, such as seen with 911 calls arriving at CTECC. In these kinds of cases, it is common practice among traffic management center (TMC) operators or emergency services to have on hand a list of common public messages that can be used to communicate information to the public.

These messages would have already been pre-approved by the organization and checked for quality and clarity, which helps to reinforce the reputation of the organization.

A mechanism for limiting the distribution of data lies in contractual agreements around the purchase of data or services, such as traffic data provided by INRIX. In that example, payment is made to the commercial entity in exchange for access to data covering an agreed-upon span of time (e.g., months or years). Meanwhile, it is agreed that the data is not to be distributed to others.

Data quality and cleanliness also carry some privacy implications. Raw data may contain sensitive information that must be scrambled or removed before it is shared with the public or other organizations. One example is Bluetooth travel time detectors; raw data coming from these devices contain information that allows individuals to be identified and tracked, which is not looked upon favorably by a significant portion of the public. Before such data is made available to the public, the identifying information is scrambled (or “hashed”) with a key that changes for each day, to avoid being able to positively identify individuals who drive on the same corridor every day. Even in cases where sensitive data is not present, organizations may be wary of sharing raw data that had not been validated or cleaned. There exists the risk that an organization’s reputation may be tarnished if someone outside the organization publishes analyses based upon bad or misinterpreted data.

Industrial control systems (ICSs) continuously monitor and/or control critical processes and physical functions through computer-based facilities or equipment. ICSs collect data from specified areas and process and display the information, or in some cases relay commands to equipment or operators (Transportation Sector Working Group, 2012). ICSs in transportation control items like message signs and must remain reliable to protect traveler’s safety. With any advanced sensing and communicating technology, the importance of system security or privacy in design and maintenance is critical to ensure reliability and function. Detailed plans for ICSs cybersecurity standards and practices are provided by organizations such as National Institute of Standards and Technology (NIST), U.S. Department of Homeland Security, and American Public Transportation Association (APTA).

When considering privacy, a balance must be struck between ease of access and security. If access is too easy or open, there may exist vulnerabilities or sensitive information that could be used unfavorably. On the other hand, if security is too rigid or limiting, there may be too many roadblocks for the data to be truly useful.

3.6 Dissemination Outlets

Historically, information concerning major events was disseminated to the public by government officials. Approaches for informing the public have traditionally been centered around televised or radio media, Highway Advisory Radio (HAR), or DMS signs, with the more recent addition of web portals, online apps, and social media continuing to evolve. It has also been reported that video sharing system from TxDOT to the media is quite antiquated and requires a lot of effort and

equipment in the process. This is looking to be addressed in a new system in the future. Another traditional outlet has been the Emergency Alert System that coordinates the broadcast of alerts via local media and cell phone providers (Texas Association of Broadcasters, 2012).

511 Systems and Websites

511 systems such as the 511DFW System mentioned in Chapter 2.2.2 are often merged or linked with agency websites. Websites continue to develop and evolve as means of communication to travelers and the weather community. An example of another active traffic information source like DriveTexas mentioned previously is TxDOT's ITS website¹. Through this portal, public users have access to traffic maps, estimated travel times, incidents, lane closures, traffic camera feeds, DMS information, and flood stations. Traffic management decisions are also assisted by the available data provided.

Social Media or Mobile Apps

Social media is utilized by TxDOT to provide related road weather information updates through sites such as Twitter and Facebook. While it is difficult to track the impact of social media, most DOTs receive a great deal of traffic on social media sites and it serves as another redundant and virtually free information source.

Twitter

TxDOT provides easily accessible statewide and district-specific Twitter feeds. All 25 TxDOT districts have their own Twitter accounts and a few ongoing TxDOT projects also provide feeds managed outside of TxDOT. Some districts have more active feeds than others (some with as little as 700 followers or 900 tweets) and a few existing examples are shown in Table 3.1.

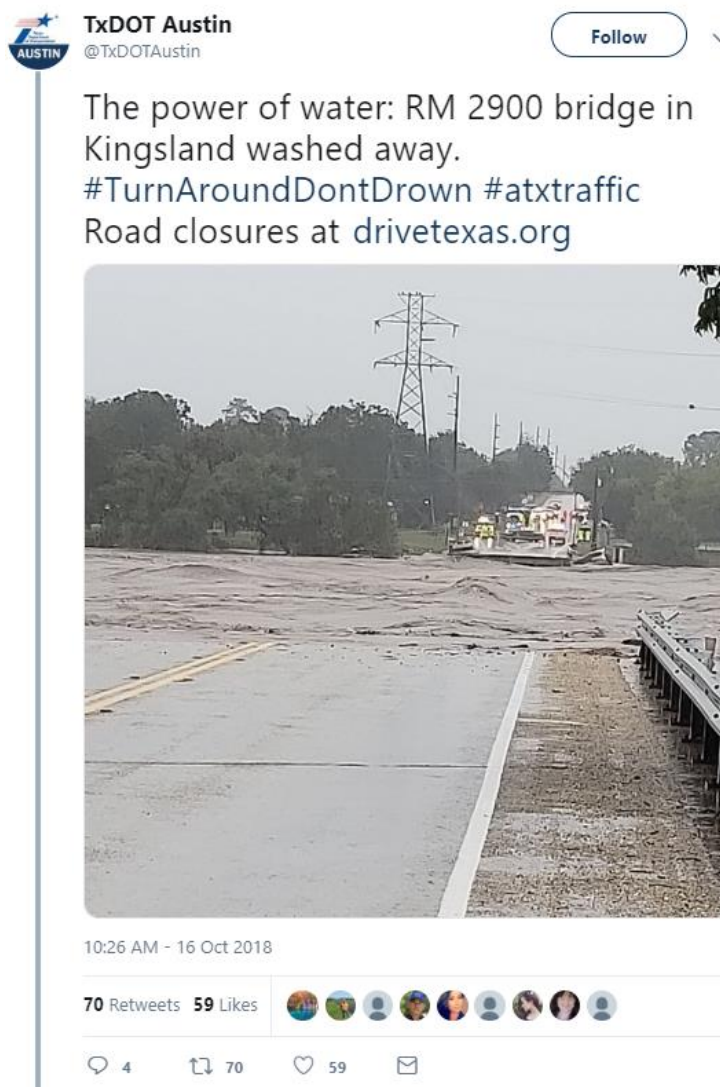
Table 3.1 Twitter Account Examples

Twitter Account Handle	Tweets	Followers	Likes
@TxDOT	14,300+	84,200+	5,200+
@TxDOTAustin	9,400+	30,500+	260+
@ImproveMopac	3,500+	4,500+	250+

While it is difficult to determine the effectiveness of social media alerts, account holders do have the ability to check to see how many times the Tweet was seen on Twitter. Travelers benefit through available information on Twitter by responding to Tweets using the “@” sign and Twitter account. Hashtags “#” can also be placed before a word or phrase without any spaces in a message to show up more easily in a Twitter search for anyone who might not follow the account (e.g., #TurnAroundDontDrown). The hashtag is connecting to all other related Tweets who have used

¹ <http://www.transguide.dot.state.tx.us/>

the same term as well. An example of a Tweet by the Austin TxDOT district is shown in Figure 3.1 and includes a quick breakdown of retweets, likes, and comments received for the one post.



Source: (Adapted from <https://twitter.com/TxDOTAustin>)

Figure 3.1 Example tweet of road weather dissemination

Mass Notification Systems

Systems called Mass Notification Systems are services provided by private entities that have the ability to send emergency notifications to many people within a given geographic area. While most notifications are achieved through robot phone dialers that corresponding people can subscribe to, notifications can also be delivered through other means such as mobile apps. Providers for this service include CodeRed and Everbridge Mass Notification System (EMNS).

- These mobile apps can be branded to create a positive association among a jurisdiction's residents, reinforce authenticity, and ease the ability for a jurisdiction's agency to change mass notification providers without creating public confusion.

CodeRED

Through the course of this project the Capital Area Council of Governments (CAPCOG), consisting of Bastrop, Blanco, Burnet, Caldwell, Fayette, Hays, Lee, Llano, Travis, and Williamson counties, switched from the regional notification system CodeRED to EMNS.

CodeRED was used to warn the public during extreme weather events such as the previous October Floods in Austin. During this event, CAPCOG issued an evacuation notice via CodeRed through cellphones, landlines, and emails (S. Brannon, personal communications, October 27, 2017). However, in order to receive personal notifications from CodeRED, residents must register their information through WarnCentralTexas.org. This site also provides links to the previously mentioned social media information outlets specific to the users' regional area. Additional public resources include calling 3-1-1 for more information or monitoring television news stations.

Everbridge Mass Notification System (EMNS)

EMNS is a tool available for organizations to send notifications through over 25 contact paths in case of emergency. The Office of Emergency Management for the City of San Antonio uses EMNS to power their emergency notification system known as AlertSA. The appeal of EMNS includes a single access point to notify contacts and manage data as well as a user-friendly GIS interface. Alerts can be sent in a flexible manner based on varying parameters such as distance from an incident or specific contact types. Users can access the information by signing up for alerts on the emergency management webpage. Other regions using Everbridge include New Orleans, Philadelphia, and multiple cities in California.

In 2015, the City of Plainview made the switch from using CodeRED to Everbridge to upgrade their communication abilities at the same cost (Benanto, 2015). The move over to the EMNS enabled the city to have more methods of communication and allowed for an easy integration of data from their 911 system. Other Texas towns and counties who have crossed over from CodeRED to the Everbridge system include Corsicana, Duncanville, Denton County, and a few others. Movement to switch from Blackboard powered notification systems to Everbridge is also notable. Blackboard currently powers Baytown's emergency system and used to power Burleson County before they reevaluated their system and switched in 2014. While Blackboard provides automatic alerts like auto-dialers, Lavaca County reported the need to change notification systems from Blackboard because it was more costly than other providers and failed to send out notification to residents after Hurricane Harvey (Aldaco, 2018).

As of September 2018, CAPCOG, like various other Texas towns and counties, made the switch and upgraded the regional notification system to EMNS. The switch from CodeRED to EMNS by

CAPCOG is very recent and still requires residents to register their information through WarnCentralTexas.org. As this is a new change to emergency management efforts, it will be interesting to monitor its future impact.

3.6.1 Road Weather Message Dissemination Guidelines

The efforts of collaboration projects such as the Pathfinder Project have enabled the FHWA to develop and publish *Guidelines for Disseminating Road Weather Messages* to identify and distribute an effective message for DMS, auditory messages, and websites (Lichty, Richard, C., 2012). A clear and uniform message enables travelers to make informed decisions during bad weather to reduce the possibility of crashes or congestion and improve safety and convenience.

Key Elements to DMS

- Provide information about the problem the driver will encounter
- Describe the location or distance to the situation
- Recommend the action the driver takes to respond to the problem

Auditory Message Content

- Provide an introduction to verify the news source
- State the problem to make travelers aware of the situation
- Motivate listeners to follow the advice of the announcer
- Include location information
- Recommend the action travelers should take

A Few Tips to Enhance Message Credibility across All Media Platforms

- Provide actual percent likelihood of the event
- Use descriptive features of likelihood such as certain, possible, or a chance
- Include details related to its driving impact such as location, and timing
- Strive for accuracy and current information, signs remaining after an event
- Avoid repetitive information over extended periods of time
- Avoid trivial information unrelated to driving needs

Additional specifics for improving road weather messages include notes on delivery, length, degrees of urgency, formatting, color selection, icon selection, map display suggestions, text display, proper linking to road weather information, tutorials for social media, and more.

A brief overview of message design follows the FHWA's four-step approach and utilizes their pre-established reference tables, including the Safety/Mobility Impact Table, the Travel Decision Table, and the Design Guidelines Look-up Table; see Table 3.2. Access to the reference tools can be found online through the mentioned report *Guidelines for Disseminating Road Weather Messages* (2012). The initial message design tool step defines the safety and mobility impacts based on the weather event. The second step identifies likely travel decisions and suitable dissemination methods. The third step involves the use of relevant design recommendations. And the final step is implementation of the recommended designs.

Table 3.2 Message Design Tool Steps

Question	Description
<i>Step 1: Identify safety/mobility impacts based on the weather event (Safety/Mobility Impact Table)</i>	
What is the weather event?	Identifies key safety/mobility impacts, and provides contextual information for message content and details about the weather event in general (e.g., timeframe, location, etc.).
What are the safety/mobility impacts of greatest concern?	Used to identify the travelers' key travel decisions, which correspond to their key information needs.
<i>Step 2: Identify likely travel decisions and suitable dissemination methods (Travel Decision Table)</i>	
What are the key trip decisions and behavior changes that travelers would likely make in response to the safety/mobility Impacts?	Travelers will seek out information based on what travel plan changes they have to make (i.e., their travel decision). This information is related to the weather message content.
What dissemination methods are most suitable given the traveler's situation?	Used to identify the dissemination methods that are most likely to be suitable/available to travelers, based on their travel situation.
What are the specific traveler information needs?	Can be used to identify information that should be included in the road weather messages to support traveler decision-making. This step is optional and only required if additional guidance is needed regarding what the message should say.
<i>Step 3: Lookup relevant design recommendations (Design Guidelines Look-up Table)</i>	
For the specified dissemination methods, which human factors design recommendations apply to the message content and presentation format?	A "look-up table" is used to identify message design guidelines that are specific to the identified dissemination methods.
<i>Step 4: Apply design recommendation information (See additional Weather Message Guidelines)</i>	
What are the specific design recommendations?	This is the key message design recommendation. This guidance provides information about how to communicate a message that is easy to read/hear and understand given the presentation constraints inherent in specific dissemination methods.

Source: (Lichty, Richard, Campbell, & Bacon, 2012)

3.7 Performance Metrics

The FHWA's Road Weather Management Program (RWMP) measures the initiative's success (to improve roadway management and performance during adverse weather) through RWMP records, state DOT survey participation responses, agency sources and literature reviews, and further

additional supplemental sources (D Gopalakrishna et al., 2017). Analyses have reported a recent increase in the number of State DOT efforts in disseminating information to the public. One measure of performance is cost savings, often expressed as a benefit-cost ratio. Along these lines, a study showed a benefit-cost ratio of 22 for a deployment of RWIS in Idaho. Another measure is travel time savings, which can also be equated to cost. For example, a weather-responsive traveler information system deployed in Michigan was shown to decrease user delay costs between 25 and 67% at times of NWS warning and advisory alerts.

In times of extreme weather events, a practical performance evaluation of data sharing and dissemination can be measured through resource usage. Looking at the regional level, Houston's TranStar, which combines information and resources from the City of Houston, Harris County, METRO and TxDOT, is a central source of real-time data available online (<http://traffic.houstontranstar.org>) and used to manage the region's transportation system and keep drivers informed. The success of TranStar is evaluated each year in their Annual Reports through benefit-cost ratios that factor in reduced traveler delays and fuel costs. What is most relevant to road weather management in these Annual Reports are the user counts of the TranStar site data, which show spikes during extreme weather events.

At this time, the most recent available hurricane assessment is from the 2005 Hurricane Rita, where TranStar was experiencing and managing their first major emergency event. Analysis of website trends for unique users—individual users regardless of how many visits—shows an increase from about 200,000 to 700,000 during the month of the hurricane (Houston TranStar, 2005). A large portion of those users were outside of the Houston area during the event, and views to speed charts increased by four times the normal amount during the hurricane month as well (Houston TranStar, 2005). Increased usage supports the overall value of TranStar and has prompted website improvements that better allow an influx of users at one time. (No mention of Houston TranStar's performance during Hurricane Harvey is made here at this time because the 2017 Annual Report is not yet available).

3.8 Weather-Responsive Management Examples

It is important to showcase what other DOTs have done to utilize road weather data through various technologies and dissemination practices. The following case studies outlined in Table 3.3 reflect the value gained by each DOT through reported safety improvements, traffic flow benefits, and communication enhancements.

Table 3.3 Summary of DOTs Utilizing Road Weather Data

DOT	Technology/Data	Dissemination	Impact
Wyoming	Speed detection, RWIS, CCTV, historical and current crash data	DMS, VSL, 511 Travel Alert System - wyoroad.info	Safety – reduced speed, fewer crashes. Communication – near real-time weather and road condition available to the public.
Florida	Embedded pavement sensors, vehicle detection sensors, crash data	Flashing beacon with VSL	Safety & traffic flow – decreased speed variance and reported crashes
Oregon	Weather sensors, crash data	VSL/DMS	Safety & traffic flow benefits - 21% reduction in crashes, reduction in severity of incidents, improved corridor reliability
Idaho	Weather sensors (primarily visibility data), vehicle detectors, crash data	DMS	Safety – reduced speed due to weather related advisories
Alabama	Weather visibility sensors, CCTV cameras	DMS	Safety – reduced average speed and minimized crash risk

Wyoming DOT

Wyoming DOT (WYDOT) implemented a variable speed limit (VSL) system to combat safety and traffic issues. In this case, the VSL system targeted an interstate corridor 52 miles long which experiences extreme and dangerous weather such as high winds, heavy snow, and ice (Deepak Gopalakrishna, Cluett, Kitchener, & Balke, 2011). WYDOT's system includes multiple DMS, speed detection devices, Road Weather Information Systems (RWIS), CCTV cameras, and many VSL signs controlled by traffic managers. Additionally, WYDOT uses a 511 travel alert system to allow the public to see all the changes which can be updated in near real time (www.wyoroad.info). Information available to the public includes condition information and maps detailing weather and road conditions as well as closures, advisories, and construction information.

Results from the varying speed levels revealed that for every 10 mph in posted speed reduction, there is about 6–8 mph of actual speed reduction on the roadway. The feed of the RWIS data was appended to the base data of the speed sensor records to capture and report speed reduction. This simple performance metric conducted resembles that of initial weather-responsive traffic calculations performed in this project on existing data and presented in Chapter 5. Additionally, in the first year of evaluation from 2009 to 2010, crash data along the VSL segments were lower than historical trends of the past ten years (Deepak Gopalakrishna et al., 2011).

Florida DOT

In order to mitigate wet weather crashes at interchanges, Florida DOT installed pavement sensors embedded in the road surface to remotely monitor and address roadway conditions. The pavement condition data combined with vehicle detection sensors are used to emphasize the posted speed limit by activating a flashing beacon when warranted (Deepak Gopalakrishna et al., 2011). During the nine-week evaluation period, speed variance as well as reported crashes decreased.

Oregon DOT

In an attempt to reduce accidents and improve traffic flow, the Oregon Department of Transportation (ODOT) evaluated and implemented variable speed limit systems in response to extreme weather conditions (Al-Kaisy, Ewan, & Veneziano, 2012). To achieve this, ODOT installed weather sensors in safety problem areas such as those near highway ramps, which tend to cause rear-end crashes near interchanges or pose additional threat during wet or icy conditions. Additionally, dynamic message signs (DMS) were installed in the designated problem areas to warn drivers of existing conditions and vary speeds. The DMS are activated in response to monitored pavement conditions through the weather sensors based on a predetermined algorithm.

The feedback from this project was extremely positive, including a 21% reduction in crashes as well as a reduction in severity of incidents. Corridor reliability also improved with an average decrease in varying travel times. Overall the system made a significant impact on safety and traffic.

Idaho DOT

With safety as the primary concern, Idaho DOT uses combined weather sensors and vehicle detectors to monitor visibility and driving conditions. Recorded observations include pavement conditions, wind speed and direction, precipitation type and rate, air temperature, and relative humidity. Once these measures fall below a specific threshold, traffic managers are alerted and then able to enter appropriate advisories and warnings on DMS. The evaluation of the system from 1993 to 2000 revealed a significant reduction in speed due to advisories, as shown in Table 3.4.

Table 3.4 Idaho Safety Impacts

Road Weather Condition	Speed without Advisories	Speed with Advisories	Speed Reduction due to Advisories
High Winds (over 20 mph)	54.8 mph	42.3 mph	23%
High Winds and Precipitation	47.0 mph	41.2 mph	12%
High Winds and Snow-Covered Pavement	54.7 mph	35.4 mph	35%

Source: (Paul Pisano & Goodwin, 2004)

Alabama DOT

Following a safety incident, Alabama DOT implemented a fog warning system in 2000 (Pisano & Goodwin, 2004). Combined CCTV cameras and data from visibility sensors are used to observe

conditions and then to post warnings on DMS. Advisories and strategies used are based on available visibility distance and include speed reductions, lane use restrictions (such as trucks must keep right), and lane closures. This system has improved safety through average speed reduction and by minimizing crash risk.

3.9 Relevant FHWA Initiatives

The summary of insights discussed so far align well with current FHWA practices and goals. A major FHWA initiative of significance and support to this project includes the Road Weather Management Program (RWMP). The RWMP is an initiative to improve roadway management and performance during adverse weather. The program's goals are organized into four areas:

- Stakeholder Coordination (Bringing a multi-disciplinary approach to road weather challenges)

Road Weather Research and Development (Improving observing networks, modeling, road weather information dissemination, and integrating road weather technologies)

- Technology Transfer, Training and Education (Raising awareness of road weather capabilities through outreach)
- Performance Management and Evaluation (Defining and tracking performance measures)

3.9.1 Stakeholder Coordination & Road Weather R&D

FHWA also sponsors the Every Day Counts (EDC) program, which identifies and accelerates the deployment of innovative solutions for state transportation programs, such as Weather-Savvy Roads. The solutions provided in Weather-Savvy Roads include the Pathfinder Program (discussed previously) and integrated mobile observations (IMO). Developments from the highly collaborative Pathfinder Program, which improves road weather management through the dissemination of consistent and effective weather information to the public, include a multi-step process on not only *what* information to share, but *how* and *when* to share the information. The IMO solution supported by Weather-Savvy Roads involves enhancing access to real-time weather data to support decision-making through the addition of sensors to existing government fleet vehicles.

Integrating Mobile Observations (IMO)

IMO implementations enhance access to real-time weather data at a relatively low cost to support decision-making. The sensors measure things like air temperature, relative humidity, surface temperature, and wiper/brake status to provide a detailed view of the weather and road conditions. The information collected supports maintenance, traffic, and performance management strategies to maintain a high level of performance. IMO data can also be integrated with existing environmental sensor stations (ESS). The information collected supports

maintenance, traffic, and performance management strategies to maintain a high level of performance. IMO data can also be integrated with existing environmental sensor stations (ESS).

IMO Case Study

Michigan, for instance, utilized an automatic vehicle location (AVL) GPS-based phone application called DataProbe for three days without any error, pinpointing weather events within a 400-foot area (Belzowski & Cook, 2016). Their system framework involved 15 IMO MDOT vehicles and about 300 snow plow trucks equipped with DSRC, cellular, and WiFi. The vehicles, combined with existing RWIS and other stationary weather trackers, communicate back to various servers. The information collected is used to communicate to publicly accessible websites and apps, traffic managing centers, and dynamic traffic messages. The hardware costs totaled \$3,000 per vehicle and included GPS, connections, Controller Area Network (CAN) bus, and sensors. The maintenance decision support software (MDSS) forecasting costs totaled \$240,000 for the winter season. Since deployment of both IMO and MDSS, MDOT estimates a 25% reduction in salt usage, which totals to about \$2.1 million in annual savings (FHWA, 2018). Time saved from staff by automatic system reporting was estimated as \$680,000. Additional costs to consider when implementing an IMO system are monthly cellular or communications charges, MDSS usage, server space, data management costs, and of course operations and maintenance costs.

IMO utilizes existing government vehicles to optimize road weather operations and promotes information among staff and the public to improve safety, mobility, and productivity. Additional financial benefits include material savings, agency efficiencies, and possible future reduction in equipment usage. Costs associated with IMO systems include those mentioned in the Michigan study such as AVL equipment and weather sensors, decision support software development and integration, roadside equipment, staff training and coordination, operations and maintenance, and communications (monthly). While each states IMO framework varies operation and design the benefits have outweighed the cost of the project's feasibility for the current participating states.

Reported benefits of implementing AVL systems and GPS from other State DOTs include a \$6.40 benefit for every \$1.00 of cost by Iowa DOT. Minnesota DOT found that utilizing this type of system decreased salt usage by more than 50% compared to the areas outside their scope of AVL and MDSS. And Michigan DOT is continuing its success with IMO participation as their reported Return on Invested Capital (ROIC) is 2.0 in year two for both light/medium fleets as well as winter maintenance truck fleets (Chaput, Cook, Geib, Kirschenbauer, & Ranck, 2013).

Pikalert 5.0

Transitioning from streams of mobile vehicle data to road weather applications requires extensive data processing to make use of the observations. The Pikalert System is a free, open-source system that ingests, processes, and distributes current and future weather and road conditions for up to 72 hours in near real time (Boyce, Weiner, & Anderson, A Linden, 2017). The system displays information collected from RWIS, radars, weather model analysis fields, and connected vehicles.

Pikalert focuses on precipitation, road surface, and visibility conditions and is primarily geared towards utilizing connected vehicle observations. Displays available through the system include web based (geared towards maintenance), mobile web (geared toward the public), and mobile application (also public oriented). The Pikalert 5.0 software is available to download online (<http://www.itsforge.net>) and supported by the Weather-Savvy Roads initiative. Case studies provided by Michigan, Nevada, and Minnesota furthered the enhancement of the features available by implementing the system and other states have initiated new projects using the system. However, Pikalert is open-source; therefore, the potential exists for upgrades and improvements such as mobile app display enhancements, weather alert notification capabilities, and travel time impacts from weather (Boyce et al., 2017).

- Considerations should be made for State participation with the Pathfinder Project and IMO, as they are geared for improving roadway operations and offer opportunities for information sharing and collaboration.

Pooled Fund Programs

Additional collaboration efforts stem from FHWA pooled fund programs such as Clear Roads and the Aura Program. Both programs have goals similar to the RWMP in that they wish to advance road weather coordination and initiatives. Clear Roads drives innovations in the field of winter maintenance, and the Aura Program works to advance RWIS technology. The agenda of programs under the pooled funds category is set by the agencies involved and carried out by selected members. The results and benefits of studies and pilot programs are then shared to all members. Annual membership fees for each program costs about \$25,000 and promotes collaboration among DOTs as well as interagency collaboration.

Meteorological Assimilation Data Ingest System (MADIS)

The agenda of the Clarus Initiative, beginning in 2004, was to integrate transportation data and weather data into a source of viable and accessible metadata (PA Pisano, Pol, Goodwin, & Stern, 2005). The initiative and its resulting system transitioned into the NOAA observational database and delivery system, MADIS (Meteorological Assimilation Data Ingest System). MADIS launched publicly in 2001 and contains archived and real-time observational datasets. The interface of MADIS shows an interactive real-time surface analysis which combines all datasets. The Clarus Road Weather data now integrated into the MADIS system supports transportation operations and provides road weather conditions to the public. Data in MADIS comes from NOAA, and various non-NOAA organizations including MADIS program participants. Participation in the MADIS program is seen as a notable road weather performance measure by FHWA. As of 2017, Texas was not listed among the 21 State DOTs participating in the MADIS data sharing program (D Gopalakrishna et al., 2017).

User Resources

Access to the stored metadata is available through the MADIS Data Application online (https://madis.ncep.noaa.gov/data_application.shtml). The short application process enables free distribution of real-time data and access to the online archive through LDM, FTP, or in some cases Text/XML. Users must specify type of organization (private, government agency, research institute, educational group) and they are not able to redistribute or display the data without notifying NOAA. If a dataset is classified as restricted, a user can request additional permission to access the information and will be evaluated by case. Datasets come from sounding systems, satellites, radars, aircrafts, surface observations, and radiosonde. The sources and sensors come from a variety of providers such as NWS, NOAA, public and private agencies, crowd-sourced organizations, and many others.

Provider Resources

MADIS partners with public and private agencies, universities, and volunteer networks to help improve NWS Numerical Weather Prediction and forecasting services. Advantages provided to those who partner with MADIS as a provider include quality control, quality control statistics, standardized access to the global database, and notification if the network or sensor is not reporting. There are about 100 different listed partners providing data to MADIS, which includes various weather agencies, DOTs (19 total), crowd-sourced weather networks, and more. According to MADIS's Federal and State DOT liaison, current DOTs use the observations for operational and planning purposes such as:

- Determining when to begin treatments
- Knowing when additional staff or equipment is needed
- Performing summer or seasonal maintenance such as striping or weed control
- Accessing observations across state lines to plan maintenance actions based on the direction of the storm in another state
- Using the observations for traveler information on message boards, 511 systems, etc.

By providing observations to MADIS and to the Weather Data Environment (WxDE), DOTs have two places to direct researchers, meteorologists, and developers without having to provide a direct feed from TxDOT. Those users have the ability to report any gaps in sensor feeds to MADIS which shows what data has consistent value to that agency or user. To become a provider, you must contact MADIS Support directly. Providers retain access to the free unrestricted datasets, and again request for additional restricted datasets is required in some cases. Collaboration with MADIS provides access to vast amounts of information with no costs associated to becoming a provider or a user.

3.9.2 Technology Transfer, Training, and Evaluation

Web-based training courses provided by FHWA and the Consortium for ITS Training and Education (CITE) are available the RWMP to help understand and develop tools and strategies for road weather problems. Courses available include Principles and Tools of Road Weather Management, RWIS Equipment and Operations, and Weather Responsive Traffic Management. Each course costs about \$400; however, they are offered free to transportation agencies.

Training and technology transfer opportunities also include workshops and open discussions among DOT districts and states. For instance, multiple Pathfinder Program workshops and webinars have taken place and continue to occur because the demand for this type of training persists. Among these discussions have also been requests for more information on new technologies available and discussing any gaps existing in the current data.

3.9.3 Performance Management and Evaluation

Defining and tracking performance measures for safety, mobility, and efficiency for a RWMP solution is important for the evaluation of current and future benefits. RWMP has helped DOTs to understand the benefits of incorporating or enhancing the integration of weather management into roadway management through online dashboards, calculating a winter severity index, publishing winter maintenance reports, and evaluating return on investment for RWM strategies (D Gopalakrishna et al., 2017). A big push within the Weather-Savvy Roads IMO solution is to integrate a share the collected data into the online dashboard known as the Weather Data Environment (WxDE). The creation of the online real-time WxDE allows roadway weather observations to be stored in one location and demonstrate the value of sharing the transportation-related weather data. The site is a part of a research project and is therefore limited to run within the constraints of the project. However, sharing IMO data through such a medium provides data quality checks, fills in temporal and spatial gaps in road weather data, combines data into one location, improves the viewing and understanding of the data collected, and enhances the road weather database (Guevara, 2018). The implementation of the WxDE for the sensors used in this project is discussed in later chapters. The program also promotes the use of innovative tools and technology such as MADIS participation, NWS products, private weather agency usage, social media involvement, and other supportive products or services.

Chapter 4. Recommended Enhancement of Roadway Management during Weather Events

4.1 Introduction

This chapter presents recommended enhancements to roadway operations management. To support this, further literature searches and stakeholder interviews were conducted and are summarized in this chapter. These include practices in data sharing and use of data during wildfires, flash-flooding, and cold weather events. Enhancements, then, pertain to data collection, analysis, usage, and testing and deployment of sensor equipment. Attention is also given to data-sharing collaborations with other agencies and private data providers.

Because data, sensors, and technologically advanced roadway operations are emerging (both in terms of information that is becoming available online, and in terms of practitioner expertise), the contents of this chapter are evolving. Much can continue to be learned and reported on from sensor deployment activities and continued conversations with stakeholders.

- Each of the following sections provides background information to support the recommended enhancements. Key guidance drawn from the support (in this and prior chapters) is boxed as seen here.

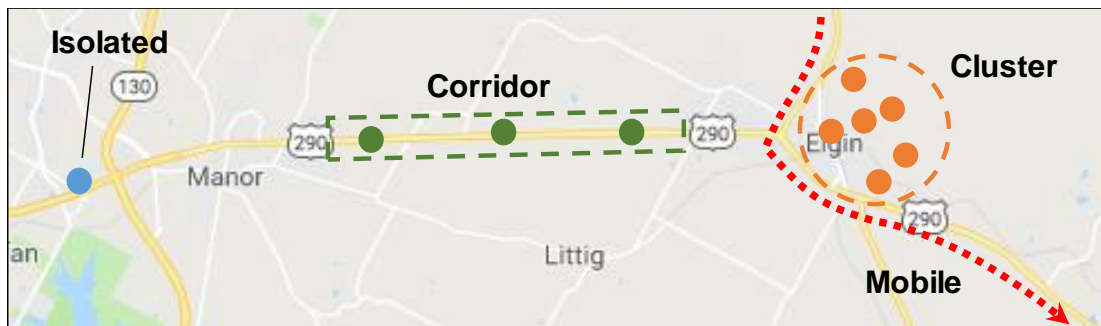
4.2 Sensors

Devices deployed in the field that perform constant or periodic measurements are powerful tools for generating new data. Sensors provide these capabilities:

- One can understand a characteristic of a location, such as water level or surface temperature. An advantage is that one need not be in the same location as the sensor. Some sensors measure multiple characteristics and combine data together to provide a more refined set of data.
- A sensor may offer more frequent or more accurate measurements than what is possible by physically visiting a given location.
- Data from a sensor is provided that can be corroborated against data originating from another source. For example, NWS data can be validated by road surface temperature readings from a deployed sensor, or vice-versa.
- Sensor data can be archived for historic analyses.

Sensors deployed in the field can be considered part of a sensor network. Depending upon the sensor's type and purpose, the network may take one of the following form factors, as observed in Figure 4.1:

- **Isolated:** The sensor is to measure a distinct geographic point independent of other points within the vicinity. Example use case: a flood sensor mounted to a highway bridge.
- **Corridor:** A string of sensors facilitate an understanding of an entire length of roadway. Example use case: temperature and traffic detectors mounted along a highway.
- **Cluster:** A scattering of sensors, within a town, or tens of miles apart, facilitate an understanding of a geographic region. Example use case: temperature sensors covering a county or district.
- **Mobile:** A string of measurements are taken from a sensor mounted on a vehicle, each tagged with geographic coordinates, timestamp, and/or dead-reckoning distance. Measurements depend upon when the vehicle departs and how quickly it travels. Example use case: road surface temperature readings along a prearranged route through a district.



Source: (Map imagery: Google Maps)

Figure 4.1 Form factor examples for sensor networks

This section addresses sensor cost justification, testing, and performance analysis, while covering deployment, operations, and maintenance.

4.2.1 Selection and Cost Justification

Sensor equipment is useful to monitor the physical world; however, the cost-benefit ratio of such equipment depends heavily on the capabilities of the sensors, their upfront cost, and their lifetime and maintenance needs. Also relevant to the cost-benefit ratio is how much money can be saved through the use of the sensors.

Prior experience and performance metrics can be helpful in informing future purchases. (See the section “Performance Analysis” below). For this reason, especially when starting to enter the sensor market, it is important to consider dedicating necessary resources for undertaking performance analyses.

The expected lifetime of a sensor network is around 5–10 years. Over this lifetime, additional costs may be incurred (for example, sensor maintenance and battery changes), which have to be added to the upfront cost. In some applications, the odds of having a catastrophic event that requires

monitoring is very small; for example, in areas where floods are extremely improbable (and where even a 100-year flood would not cause much damage), it may not make economic sense to deploy sensors. In other locations, the same sensors may have a favorable cost-benefit ratio.

Urban and rural deployments each carry their unique requirements. It has been noted that sensor density within rural districts and environments is significantly less than that of urban environments—on the order of a hundred miles apart between sensors, if equipped at all—and yet the consequences of freezing and flooding can be as significant. The prospect of understanding weather conditions in far reaches of a rural district can be challenging.

- To help with future sensor purchases, undertake performance analyses on any current sensor systems that are deployed.
- The unique needs of rural districts should be considered along with unique needs of urban districts.
- Rural districts can benefit from greater sensor density.

4.2.2 Communications Technologies

One critical consideration for sensors is the communication technology that is chosen to allow communications with the sensor. They may include accessing the sensor to retrieve status, and sending data out of the sensor. These needs must be determined upfront when specifying sensors for a given location. The following are some of the communications technologies and methodologies that are commonly used; others also exist, and new technologies continue to emerge.

ISM Band Dedicated Communications: Radios operate on one or more of a set of frequencies that are allowed to be operated without licensing (Wikipedia, n.d.). Several bands are shared with the same frequencies that are used with WiFi and other household wireless technologies, and technologies that use ISM vary greatly in terms of data rate and range, from a few feet to tens of miles. One example of a wireless technology that uses ISM is LoRa (Semtech, n.d.). LoRa's distinguishing characteristic is that it facilitates long-distance communications by exercising low data rates (e.g., 30 to 700 bytes per second) over low-frequency bands. One would typically expect to achieve maximum line-of-sight communications on the order of 10 miles. A major advantage of ISM is that once radios are deployed, one does not need to pay for any kind of data plan. Another advantage is that one does not need to depend upon the cell phone network, which may be out of service during times of disasters.

3G and 4G Cellular Network: This is a popular, versatile option facilitated through cell modems that offer a long range and potentially high data rate. Coverage depends upon the provider chosen, and must be maintained through the annual purchase of data plans at costs ranging from \$120 to \$600 per year. All plans impose a monthly data limit that is somewhat proportionate to the price.

It has been found that in cases where sensor data rate requirements are low, 3G can be used at a cost that is less than 4G. One caveat of cell network communications is that the power requirements are generally greater than that of ISM.

Satellite: These technologies are viable for very remote sensors, but the equipment and data plan costs are significantly more than that of the cell network.

Wired: Whether Ethernet or fiber, these are expensive to install and are not considered within this project. Even so, some municipalities invest heavily in installing wired city-wide networks to improve traffic operations capabilities.

Locally Stored: Depending upon the purpose of the sensor, it may be viable in some cases to have a sensor record all readings to a datalogger or some kind of data storage medium that must be physically retrieved. Another approach that may see more traction in the future is for a fixed device to wirelessly transmit data when a utility vehicle drives nearby. While this is not viable for seeing live readings or querying sensor status from within a traffic operations center, it may be viable for some applications where a sensor is operated while mounted on a vehicle (for example, with the Mobile IceSight sensor (Innovative Dynamics Inc., n.d.)). This may involve logging to an onboard laptop, in which case the use of a ruggedized laptop would be most ideal.

- Determine communication needs (range and desired data rate) and related infrastructure very early in the selection process.
- If 3G or 4G cell phone network communications technologies are chosen, verify that service is available in a given location. Availability may vary according to provider.
- Many commercial providers of sensors also offer communications integration services, including prepaid data plans and renewals. Some sensors offer built-in communications technologies, which ease the selection and deployment process.

4.2.3 Testing

Sensor networks are a collection of sensor nodes that are deployed over a certain area to monitor a physical phenomenon. In general, a sensor node consists of a sensing device, a processing board, a transmitter/data connection and a power input device. A wide variety of sensing devices, processing boards, transmitter and power input devices can exist, and each of them will lead to different testing scenarios.

In general, these four components of the system are interconnected and placed in an enclosure that is sealed by the manufacturer. Opening the enclosure to perform unit tests of each subsystem is not recommended and can lead to a loss of warranty, depending on the manufacturer's terms of use. In addition, since the protocol for transmitting data between each component of the sensor

node is not known, it would be difficult to perform such unit tests, as they would require one to reverse-engineer the system.

Nevertheless, some aspects of the sensor nodes should be tested before deploying. These tests include:

- **Power system tests:**

- Connecting the power input device (AC-DC power or solar panel), and switching the node on: visually check that the node is powered on (e.g., via light-up status indicators).
- Check the power consumption of the node with an ammeter, and validate the average power consumption with respect to the datasheet. This test requires an average measurement of the input power over a large time interval if the sensor is equipped with a rechargeable battery, since the charge/discharge of the battery have to be averaged out to obtain a reliable average power consumption measurement.
- If a solar panel is used to power the device, it can be independently tested to ensure that it provides power. When lit in direct sunlight, the open circuit voltage (V_{oc}) and the short circuit current (I_{sc}) should match the specifications of the solar panel manufacturer. The V_{oc} is measured by connecting a voltmeter directly to the solar panel output, while the I_{sc} is measured by connecting an ammeter to the solar panel output.

- **Communication tests:**

- For wired systems: connect the sensor device with a microcontroller, oscilloscope, or data acquisition board (depending on the protocol used), and check that the sensor sends an actual signal. The measurement device depends on the protocol used by the sensor:
 - For sensors with an analog output, a oscilloscope, or a voltmeter (for slowly evolving signals) can be used to check that the sensor sends a measurement
 - For sensors with a digital output, the communication test is a function of the type of digital output (for example Pulse Width Modulation (PWM), serial). A data acquisition board, or a digital oscilloscope, are required to check the presence of an output signal
- For wireless systems: the data generated by the sensors can be sensed using a wireless packet sniffer (for example a USB packet sniffer) that receives radio frequencies in the band used by the transceiver. Several models of USB packet sniffers are available for different radio protocols (WiFi, Bluetooth, ISM band).

- If the sensor is accompanied with software, the software package may offer sufficient features to verify that communications are functioning properly.
 - **Sensor tests** are another category of tests that can be performed in calibrated (controlled) environments to make sure that the sensors are functioning correctly. These tests are a function of the type of sensor used, and consists in unit tests validating that the outputs of the sensor are correct, on a set of standardized tests. For example in the case of remote temperature sensors, these tests would involve placing the sensor above a surface of known temperature, and making sure that the measurement it generates is correct.
- It is prudent to perform power and communications tests on sensors, and to ensure they are calibrated before they are deployed.

4.3 Deployment, Operation, and Maintenance

This section looks at potential issues around the deployment and operation of sensor equipment, as well as ongoing maintenance.

4.3.1 Deployment

One of the critical issues associated with sensor networks is their deployment. The deployment of a set of sensor nodes in a geographical area needs several aspects to be taken into consideration:

- **Accessibility**, in case of node failure or maintenance
- **View of the sun**, for solar-powered nodes
- **Communications** issues, as identified in the earlier section, including data plan, and distance with respect to the network gateway, for single-hop radio systems.
- **Power** considerations, including AC power, replaceable batteries, or solar panels with batteries. It is advised that the vendor be consulted about solar panel requirements and suggested integrations.
- **Physical** deployment costs (including constructing a pole, fabricating mounting hardware, etc.)

The cost of a sensor node is only a fraction of the total cost of the system. Depending on the sensor type (solar-powered or not, wireless or not), each sensor node may require cabling for power or data. Solar-powered and wireless sensor nodes do not incur these additional costs, though they still need to be installed, which requires mounts, personnel for the installation, road closure in some cases, and possibly heavy equipment (man-lift) depending on the sensor deployment location (Dehwah, Mousa, & Claudel, 2015).

4.3.2 Accessibility

Ideally, a node should be accessible to be easily repaired in case of failure, or easily serviced (for example for changing a battery). However, a node that is easily accessible is prone to vandalism. The node should be installed away from the general public, but relatively close to a TxDOT location to facilitate maintenance. Sensor networks have been operated in remote locations (for example in the Alps, or in rainforests), though this makes the maintenance of the network more difficult.

4.3.3 Location

Solar-powered sensor nodes have the same constraints as other solar-powered road equipment (for example solar-powered road signs). They need to be deployed in areas where they can have consistent solar power, for all seasons. They should have a tilt angle close to the local latitude to maximize power, and generally oriented towards the south (in the northern hemisphere). To maintain a consistent input, the location should be known to have consistent solar power across all seasons, as shadow patterns evolve over time.

In regions with little or no rain, the solar panels should be deployed in a near vertical orientation. While this orientation does not maximize the input power, it greatly reduces the dust accumulation on the panel, which can become problematic after as little as 1 month. The daily cycles of dew/dust deposition can create a thick layer of sand deposits that is very hard to remove (Dehwah et al., 2015).

4.3.4 Operation and Maintenance

Modern sensors are built to be maintenance free (except possibly air particulate pollution sensor), though they are not failure free. However, the subsystems associated with sensors (power circuit, printed circuit boards, solar panels) can fail for a variety of reasons. Some failures can be temporary (for example failures caused by software bugs), some may be reversible (such as sand deposits on solar panels), while others may be irreversible and may require a component to be serviced or changed (for example, an overheated battery). Possible failures include the following:

- **Software failures:** These failures are caused by programming errors, which may take a long time to happen (for example in overflow errors, or memory leak errors). These programming errors can happen particularly since the sensor nodes are usually assembled from discrete hardware components (printed circuit boards, controllers, peripherals and sensors) which have their own software libraries that can be faulty in some cases. These errors can cause the sensor node to send wrong data (usually a sequence of characters that do not make sense), or can cause the sensor node to hang. Resetting the node (cycling on-off) solves these software bugs.
- **Hardware failures:** Hardware failures are related to a failure of a subsystem of the sensor node. The most vulnerable subsystems are batteries.

Rechargeable batteries have a limited number of charge-discharge cycles, and ultimately a limited lifetime, even if not used. The lifetime and number of charge discharge cycles depend heavily on the type of battery technology. In general, the environmental conditions (temperature) play an important role in the lifetime of the battery, and batteries generally degrade faster at extremely high temperatures. They can also be affected by very low temperatures, and usually have a lower capacity in these conditions.

The batteries that are most commonly used are lead-acid (for inexpensive applications where high currents are required), or Lithium based technologies (Lithium ion, Lithium Polymer or Lithium Iron Phosphate). Lead acid batteries are relatively inexpensive, but also have a short lifetime, a few years at most. Given the associated maintenance costs, manufacturers increasingly use Lithium based technologies that are more reliable, in particular Lithium Iron Phosphate (LiFePO₄) batteries that have a very long lifetime, and very high theoretical number of charge and discharge cycles. The LiFePO₄ batteries also have a high tolerance to low and high temperatures, though their energy and power density (ability to store energy in a low mass battery) is less than their Li Ion counterparts.

Batteries that have been affected by heat usually suffer from battery bloat (Figure 4.2). These damaged batteries can be very dangerous to use and initiate a fire. The temperatures in the area of deployment should be checked before deployment, and be consistent with the maximum operating temperatures of the chosen battery technology (the temperature of the battery is usually higher than the outdoor temperature since the sensor and printed circuit boards generate heat).



Figure 4.2 Example of battery bloat for an outdoor sensor network after 6 months (the battery is a 2.3Ah single cell Li Ion, and the average operating temperature is 118 °F).

Printed circuit boards are relatively reliable provided that they are away from dust and condensation (this requires the sensor box to be properly dehumidified and sealed). The printed circuit boards are rated to a maximum temperature between 160-175 °F, which is the maximum theoretical temperature of a blackbody on Earth, with maximum solar power input and no wind. This temperature can however be exceeded inside a sensor box, since the electronics dissipate

some power. Operating around this maximum temperature is not recommended, and will affect the life of the PCB (higher temperatures reduce the expected PCB lifetime).

- The cost of a sensor is only a fraction of the total cost of the system. Plan accordingly, and seek advice from the vendor.
- Consider maintenance accessibility and solar characteristics (if applicable) when planning a sensor deployment.

4.4 Sensor Performance Analysis

The analysis of sensor performance is needed for two primary purposes:

- Establishing the reliability of the sensor(s), and
- Justifying further investment in the sensor(s), including maintenance of current infrastructure and future purchases.

Unless a clear desire and justification already exists for sensors, the benefits of sensors may be difficult to quantify. There may be human benefits (for example, reducing casualties), and there may be economic benefits. It may be helpful to ask: under what circumstances can losses be avoided, given the warning time of the sensors? For example, flood sensors may indicate immediately about a dangerous situation in a given area, but it may be that one does not have time to launch rescue operations or perform actions that would reduce economic losses.

For analysis to be conducted, performance metrics need to be chosen and measured on the sensors and as a result of the sensors' operation. Possible performance metrics include:

- Uptime (fraction of the time where sensors are operational and providing non-faulty data)
- Rates of false positives and false negatives
- If possible, human or environmental factors such as casualty reduction, saved travel time, or saved emissions.

For evaluating uptime, it is necessary to have a sense of what data is reliable and what data is faulty. One strategy is to validate data with independent sources (personal observations, news reports, other sensors known to be reliably functioning) and treat that as "ground truth". In all cases, human intervention is needed to identify the "ground truth" so that analysis and comparisons with new sensor data can be made.

Human factors follow a similar suit, where it is necessary to have an estimate (due to past roadway performance or simulation results) that attempt to quantify the metric in the absence of the sensor versus the metric derived from data that had been recorded while the sensor was deployed. These

can often be equated to an economic, quantifiable dollar amount (employing cost of travel time (TxDOT, n.d.), casualty cost, and environmental cost).

- Determine performance metrics that can be used to evaluate sensor operation.
- Establish alternative sources of data that can be used as “ground truth” to compare against the sensors being evaluated.

4.5 Sensor Case Studies

This section contains a couple of efforts that exemplify sensor deployments. (It is worth noting that sensors being considered for this project cost significantly less than these examples.)

4.5.1 High Water Detection Systems (HWDS)

Highlighted in FHWA’s *Best Practices for Road Weather Management, Version 3.0* (2012) is TxDOT’s High Water Detection Systems (HWDS). HWDS cost about \$75,000 a unit and are installed in flood prone/potential areas. The current HWDS in San Antonio allow emergency responders and the public to monitor ongoing rain conditions from afar. The information gathered from the systems is funneled into existing data disseminating portals such as TxDOT’s ITS website. HWDS is also equipped with advanced warning signs which notify drivers when a road is flooded ahead (Murphy, Swick, Hamilton, & Guevara, 2012). Placement location and establishing communication between cities are the most difficult issues related to HWDS. TxDOT has a number of HWDS, some are outside of the city some are managed by cities. It has been discussed that merging the data into one site or access point might be beneficial.

4.5.2 Pump Monitoring Systems

Pump Monitoring Systems installed in San Antonio are noted as another best practice related to managing flood incidents. The Monitoring Systems analyze the storm water pump stations to provide an approximate time till the location floods (Murphy et al., 2012). This reduces on-site involvement and costs about \$15,000 per monitoring system. Data gathered by the systems is used not only internally to manage flooding, but also to notify the public of current conditions through DMS or the media. A significant challenge related to the monitoring systems is the integration of equipment from several different manufacturers.

- These examples include proven sensing technologies that are tied to analysis and dissemination. For a sensor system to be considered exemplary, these aspects need to be considered as part of the complete system.

4.6 Sensor Network Data

Sensor networks usually generate discrete time synchronous data, i.e., measurement data points at regular time intervals. While the real-time measurements are most useful for monitoring

applications, the data are usually stored for extended periods of time. Storage is useful for several reasons:

1. Stored data can be used for a posteriori analysis of events
2. Stored data can be used to assess the maintenance needs of sensors (for example to detect conditions such as stuck sensors or anomalous sensor measurement patterns), and to detect sensor faults
3. Stored data can be used to obtain the model parameters of the underlying dynamical model (for calibration purposes) of the phenomenon to monitor.

The objectives 2) and 3) require processing of the data, which is outlined in the next section. Objective 1 is very important to investigate specific events, and is also a prerequisite for objectives 2) and 3).

Whether live data communications are to be made from a sensor or not, some simpler sensors require a datalogger, a buffer collocated at the sensor that stores the raw output. When live communications occur, the datalogger may be needed to briefly retain data between times the connection is active (especially in cases where an update of data over a cell phone network is made periodically, such as every 15 minutes). When there are no live communications by design or because of intermittent failure, the datalogger will prevent data from becoming lost until the next opportunity arises to send out data. In either case, dataloggers can be set to purge old data after a given amount of time.

Effective delivery, storage, and analysis of data requires a database, commonly located in a centralized or satellite office or data facility. It is possible to use raw output files directly, but the overall process would likely be inefficient. Different database architectures are possible, depending mainly on the sampling rate of the sensors, the quantity of information in each sample (set of values, image, video snippet, etc.), the number of sensors, and the total duration the sensor network has been operating.

Databases are most often based on the SQL language. Each database consists of multiple tables, where each contain specific data. The tables can commonly be organized as follows:

1. Properties table
2. Raw data tables
3. Filtered data tables/output tables

1. Properties table. The properties table is a table that contains the specific properties of each sensor used in the sensor network, including information such as:

- Sensor type

- Sensor ID
- Sensor location
- Date of installation
- Other historic data

The properties table may be the first table queried by a visualizer to display data, since it allows the visualizer to properly display the location and types of each sensor in the sensor network. Each entry in the data table pertains to a different sensor of the sensor network, and the properties associated with this sensor.

2. Raw data tables. The raw data tables are tables that are used to store the raw data generated by the sensors. They are directly connected to the gateway (or concentrator) of the wireless sensor network, which writes each new measurement data into these tables. Each new measurement data is a new entry of the table, and thus, the size of the table will grow over time. It is important to properly dimension the host machine (hard drives, memory) to account for this growth and the expected maximum size over the lifetime of the sensor network.

The machine hosting the raw data tables also should have some degree of redundancy (through RAID storage, power inverters, battery-based power interruption protection) to ensure that they function correctly, as a failing machine would lead to data loss, until the machine is repaired. The duration of time to archive raw data until purging is dependent upon storage capacity and predetermined need.

Two types of raw data are generated by the sensor: actual data (measurements), and operating data (data regarding the status of the sensors themselves). Actual data pertain to all the measurements that the sensor was designed for (for example water level measurement for a water level sensor), while operating data consists of data related to the health of the sensor or of the network (including for example battery voltage, solar power input voltage and current, sensor fault codes, network RSSI, packet drop percentage, etc.)

3. Filtered data tables/output tables. The filtered data tables are used to store the processed measurement data, generated by algorithms that take raw data and output processed data. Processed data can for example consist of traffic state estimates for a traffic sensor network (the estimates are computed for every location of the road network, not just the locations where sensors are present).

The visualizer is usually taking data from the filtered data tables, when they exist. In simple sensor network applications it may not be necessary to filter the data, especially if the sensor measurements are accurate and if the sensors are highly reliable

4.7 IT Architecture Considerations

The TxDOT Information Management Division (IMD) creates security guidelines to protect the safety, security, and reputation of IT architecture. This includes sensor equipment that sends data to TxDOT, and has implications on the access of external equipment from within TxDOT. As a result, any significant sensor deployment that surpasses an experimental or evaluation stage must fully take this security into consideration. With the idea that further investigation is needed, the points presented in this section identify architectural choices that have the greatest potential for coexisting well with existing IT security policies and implementations.

The main consideration is that challenges immediately arise when one proposes running a system or server that directly receives sensor data from the field (see Figure 4.3). The challenges include:

- Adjusting computing network policies and firewalls to allow data into the TxDOT network from a field device;
- Finding a sustainable solution within TxDOT for hosting the server that receives data; and
- Providing security along the data path from the device to TxDOT that safeguards against security vulnerabilities, including data tampering or spoofing.

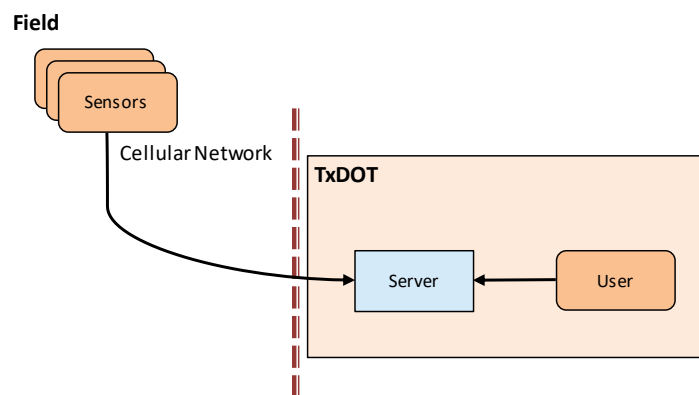


Figure 4.3 A problematic data path from field devices into the TxDOT IT architecture

A better, immediate solution involves connecting from within TxDOT to resources that are hosted outside (see Figure 4.4). This has the following characteristics:

- Any data that appears within TxDOT is through secure, approved means facilitated by web browsers and network configuration where the user within TxDOT initiates the access; and
- Security and administration of the sensor data path and web app lies with the vendor.

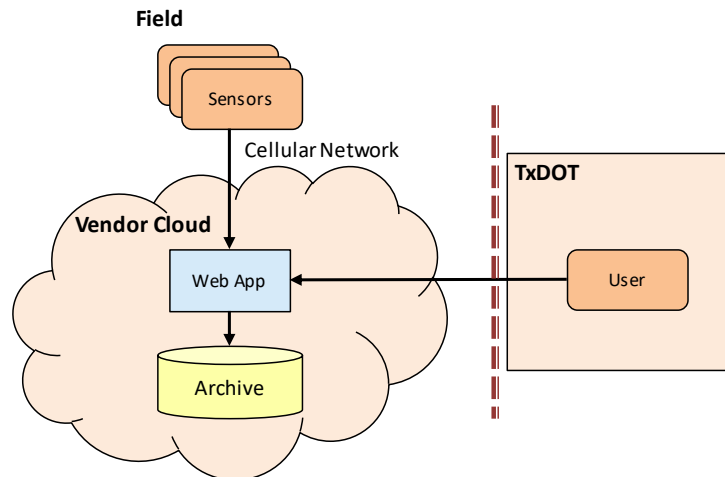


Figure 4.4 A data path where accesses originate from within TxDOT to a trusted cloud service

Even then, this is not a sustainable, long-term solution. Reasons why include:

- Users must explicitly connect to external resources. This may not be feasible within a traffic operations workflow, especially in times of emergencies;
- TxDOT does not have full control of the archived data, nor does the data reach resources provided within TxDOT for archiving data; and,
- Concern has been expressed about lack of knowledge and understanding on how much the original data is altered within the Vendor Cloud or other external service. Reliability of service is also a concern. These become more relevant as the importance of the data truly rises to the critical expectation of directly saving travelers' lives.

The answer may lie in finding ways to integrate sensor data into TxDOT's existing systems and workflows. Figure 4.5 shows an architecture where data arrives to the Lonestar ATMS via a C2C interface. Other approaches for integrating sensor outputs into Lonestar or other systems include custom-written drivers that understand particular sensor types (which is appropriate if TxDOT engages in a widespread deployment of a sensor network), and the General Purpose Input Output (GPIO) interface which is a means of inputting simple signals, such as those generated by on/off contact closures. There may also be opportunities within the field for sensor devices to be "smart" enough to bypass the need for further intervention by a service provider.

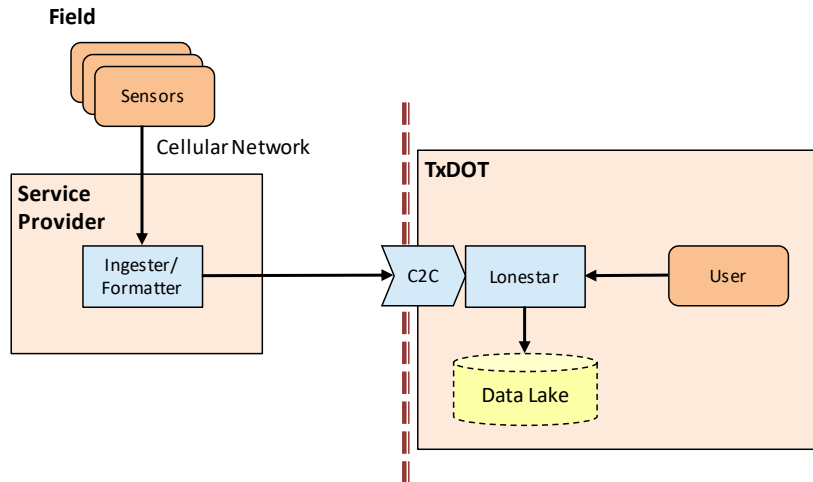


Figure 4.5 Example of a sensor system integration into Lonestar

As architectural ideas are explored for their feasibility, another consideration that can ease integration is for TxDOT to define a specification for sensor system manufacturers that encourages data quality, and security. A common driver for Lonestar and other potential systems could then readily accommodate protocols that are defined within that specification.

- To best work with IT architecture on an experimental or evaluation scale, consider sensor system solutions that allow for access from within TxDOT to a vendor-provided web app or data access portal.
- If the size of the sensor deployment is to increase or be considered permanent, a sustainable choice would be to work toward integration with the IT architecture and current policies and practices of the organization.

4.8 Overview of Sensor Planning

Sensors were purchased and deployed for the purpose of evaluating performance and impact to roadway operations. This section summarizes key guidance on the sensor selection criteria and data planning for this project.

4.8.1 Sensors

The emphases for the project are freezing, flooding, and wildfire extreme weather/environmental events. Therefore, a sampling of sensors that each address one or more of these need to be chosen. These are further rationales that guide deployment and enable knowledge-building:

- Sensor density and representation in rural environments is low, while the consequences of extreme weather events are significant. In TxDOT ITS and STIC meetings, the strongest interest for improving sensing technologies came from personnel reporting from rural districts.

- Sensor deployments especially in rural environments offer the added challenge of power and data connectivity. Therefore, solar and wireless communications technologies need to be evaluated and documented. (These would also appear in training material). ISM band radio and 3G/4G cellular network technologies will be used.
- The value of sensing technology may be more effective with lower-cost sensors that contain newer technology and multiple sensing capabilities than compared with traditional sensors as seen in the case studies at the end of Chapter 3. Value increases if these capabilities are pertinent to multiple seasons throughout the year.
- Value of technology increases, too, when it is possible for a complete system to contain fewer dependencies or components. For example, a sensor with built-in solar power conversion and communications capabilities is easier to deploy than a sensor that requires a datalogger, modem, batteries, and all of the external parts that connect these together.
- Performance of these sensors need to be tracked. To help this, sensor readings sampled at various times (including extreme weather events) will be corroborated with readings or observations from other sources, including other sensors of alternative technologies deployed in similar locations as part of this project.

As evaluations are conducted, considerations should be made for how a larger network of sensors could be put to the best use. Lessons learned from this project's deployments will help with this. Acquisition, deployment, analysis and visualization processes documented within this project may therefore be scalable to potentially hundreds of sensors within a given region.

As partially noted in earlier chapters with new information here, the following districts will be targets for deployment. Most considered locations will be rural, small community urban, or suburban:

- **Abilene:** Freezing and flooding detection. Candidate locations may be centered around the City of Abilene, the IH-20 frontage road and the TxDOT district office.
- **Austin:** Flooding and wildfire detection. Candidate locations may be centered around the Lonely Pines area of US 290 in Bastrop County for fire detection, and various flood-prone areas including Smithville and the Dry Creek crossing on SH 71 for flood detection.

4.8.2 Data

For the value of sensors to be demonstrated, sensors must be tied to data analysis and information dissemination activities. For that reason, at least a minimal set of data proof-of-concepts need to be created to support deployed sensors. These are the use cases that will be explored, along with respective proof-of-concepts:

- Observing various locations' road surface temperatures from a centralized location. These will appear as points on a map, as well as numbers in a table.
- Logging road surface temperatures from a moving vehicle. These will appear as numbers in a table.
- Observing various locations' roadway water depth from a centralized location. These will appear as points on a map, as well as numbers in a table.
- Observing nearby river/creek water level from a centralized location. These will appear as points on a map, as well as numbers in a table.
- Observing and alerting various locations' unusual temperatures from a centralized location. These will appear as points on a map, as well as numbers in a table.
- Monitoring traffic density in similar locations. (This may be a viable byproduct of the sensing technology used in some of the sensor units). These will appear as numbers in a table.

To facilitate the viewing of map-based and table-based information, the representation format will be structured as a data mart feeding a dashboard. This offers the most flexibility and simplicity in proving concepts and will facilitate discussion on additional practical uses for the sensors and data.

4.8.3 Activities for Sensor Deployments

Given the requirements and insights collected so far, sensor deployment activities cover the following:

- Specifying sensors and related software/hardware through requirements-gathering.
- Consulting with vendors to obtain quotes for integrated systems.
- Ordering sensors.
- Consulting TxDOT personnel in respective districts to plan on deployments. This includes sharing as much information as possible about sensors so that the necessary mounts can be fabricated and constructed for when the sensors are ready to deploy.
- Test sensors in lab environments.
- Create and test data collection and visualization software and procedures.
- With TxDOT assistance, deploy sensors. Verify proper operation.
- Co-locate data visualization software and procedures within respective district traffic management centers.

- Document relevant findings.

From these deployments, insights and reporting can focus on the following areas:

- Specifying sensors and expected use cases;
- Deploying sensors;
- Identification of performance metrics that can be used in future efforts to justify further sensor deployments;
- Demonstrations of sensors in action;
- Implications on roadway operations; and,
- Processes necessary for reproducing data use cases that are similar to what is used for this project. For example, steps will outline the creation of a data mart view of a sensor and accessing status and data through a dashboard. Attention can also be given to the underlying raw data that originates from sensors.

In summary, these activities are intended to help all project participants arrive at preliminary end-to-end proof of concepts that facilitate further conversation and ease the deployment of future sensors.

Chapter 5. Data Analysis for Decision-Making

Processing and visualizing data are very important tasks which contribute to proper data analysis. Data processing includes cleaning up the dataset (removing bad measurement points), and generating estimates. Another activity commonly performed is data aggregation. Visual interpretations such as dashboards serve as a communication portal as well as a user friendly way to monitor roadway conditions. The implementation of processing and visualizing data was conducted in this project through existing data as well as through collected sensor data. Processing and visualizing data are outlined in the background of this chapter and lead into the applied techniques and project findings conducted.

5.1 Background to Processing and Visualizing Data

Data cleanup is usually relatively simple, and consists of excluding data points that do not meet specific requirements. These requirements are designed such that faulty measurement data fails one or multiple of these requirements, while non faulty data meets all of the requirements. Several criteria are usually taken into account:

- Measurement range (do the readings fall into an allowable range?)
- Criteria on variability (are the sensors stuck with a constant value? Does the amount of variation over time (derivative) fall into an allowable range?)
- Criteria on spatial correlations (are sensors that are close reporting similar measurements?)

If sensor faults are infrequent (in time), which is the case of most sensor networks, moving median filtering is one of the easiest way to remove the faulty measurement points, without affecting the time constant of the measurements much. Median filtering is very robust to outliers; hence, provided that outliers are few and spaced far in time, they will be easily removed by this process.

Generating estimates is another data processing activity. It depends heavily on the application (traffic sensing, flood sensing, temperature monitoring) as each application has a very different dynamical model. However, some processing methods are common to all dynamical models:

1. Ensemble Kalman Filtering (EnKF), provided that the sensor and process noise are Gaussian
2. Particle Filtering (PF), that works with any type of sensor and process noises (though PF is much slower in practice than EnKF)

The idea behind these processing methods is to have an accurate model of how the phenomenon evolves in space and time (for example, how does traffic propagate for traffic sensing applications, or how do floods propagate for flood monitoring applications), and use the measurement data to

“nudge” an entire estimation map towards the observations of the sensors. The output consists of estimates everywhere across the map, even in areas that are not covered by sensors. These estimates are realistic in that they take into account the dynamics of the phenomenon being monitored. The parameters used to model the phenomenon can also be estimated using the measurement data, through a process called inverse modeling.

Data aggregation is another activity that may happen around processing. Specifically, aggregation is the reduction of high-frequency samples through an averaging process. The following outcomes are achieved:

- Reducing the amount of data, which can speed up analysis and visualization activities
- Reducing noise
- Exposing average values

While aggregation is a useful tool, it must be performed carefully within a data processing and archiving scheme. After aggregation, many high-frequency features of the original data are lost. Unless one is certain that this loss is acceptable for all possible future analyses, it is best to keep a copy of the original, raw data, and to aggregate a copy in preparation for visualization and analysis activities.

5.2 Road Weather Data Processing, Visualization, and Analysis Using Tableau

In this project, archived data including weather, traffic, and crash reports were integrated and analyzed to provide practical findings and tools related to road weather management. The primary visualization tool utilized was Tableau software which enabled the demonstration of data fusion for the workshops held in Abilene and Austin. The processing and visualizing tasks discussed in this chapter were implemented through Tableau and the discoveries and means necessary are further detailed here. The demonstrations shared in the workshops are outlined and discussed later in Chapter 7. Additional analysis was conducted using intel from the weather data used to evaluate the impact on traffic using INRIX and WKZ (WKZ) data.

5.2.1 Tableau as Visualization Tool

Tableau allows the creation and presentation of visuals as a means of communication. An introduction to Tableau is included in Appendix A and further findings from archived data and creating a visualization are included in Chapter 5.2.2. The purpose of this section is to give an overview of the sharing capabilities allowed through Tableau.

Sharing Information among Officials

Interacting with a Published Dashboard

Once a dashboard has been created and published, you can interact with the information that’s on the report. If you’d like to point out something of note on the dashboard, you can create and share

a custom view of the dashboard. Here you also have the ability to add comments on a view or download aspects of the dashboard. Dashboards can be shared through email, although users will be prompted to enter credentials in order to view. Online profiles can be created for free, but free online profiles do not have the ability to download and view unless existing Tableau software is available on their computer. However, free profiles do have the ability to view and interact with the visuals on the website.

Subscriptions are also available whether it is to the dashboard itself or to the user. Emails sent from the subscription will contain an image of the workbook at that time and a link to the live version.

Email Communication

Static visualizations or reports created can be published as PDFs or images to communicate via email with agencies or to the public without Tableau access.

Sharing Information to the Public

Publishing Visualizations to the Web

Tableau Public enables anyone to publish interactive data visualizations to the web for free. These publications are called “vizzes” and can be embedded into webpages and blogs or shared through social media and email. Once shared, vizzes can be downloaded by anyone. The constraint to Tableau Public limits the data to 15,000,000 rows per workbook. A publicly accessible Tableau page was created for this project to demonstrate the use of Tableau as a communication portal (Figure 5.1).

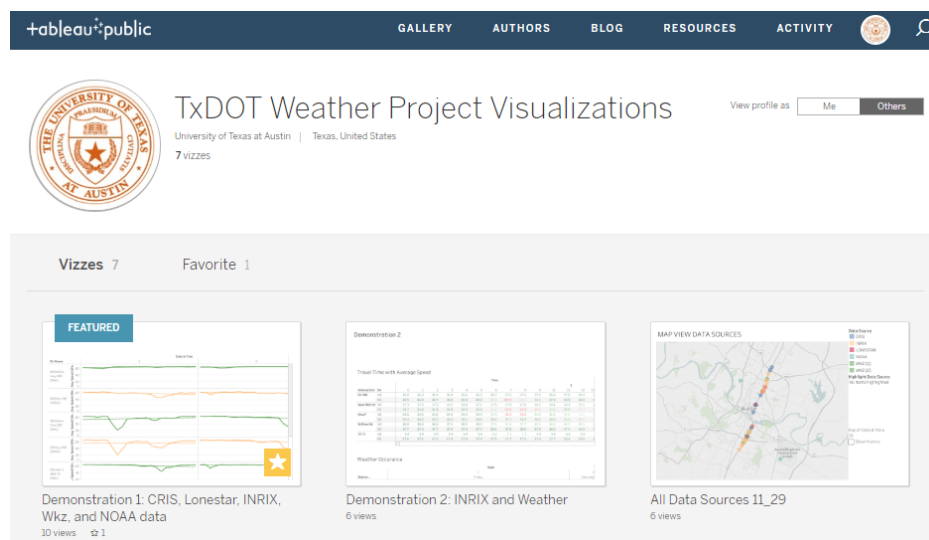


Figure 5.1 Tableau publications created for the TxDOT Weather Project

Tableau to PowerPoint

Tableau provides steps to embed a dashboard into a PowerPoint in cases where someone might not have a user log-in or needs to present and share the information. The transitions between the

modes involves downloading a zip file with coding to facilitate the connection. This is as an eight-step process that is not as straightforward as the Tableau software and is detailed through Tableau support.

Online Data Sources

The Web Data Connector option in Tableau enables online dataset connections to the application. The caveats to this appeal are the advanced steps to set up a web data connector and the inability to connect live. While the Tableau Community provides a few examples of connectors previously made and tips to create a new connector, this process involves understanding the coding used and requires further somewhat difficult steps. If a connection does not already exist, someone new to the process would have difficulty creating a connector. Also, web connection through Tableau is not live, meaning the dataset will not automatically update throughout as the online data set changes. Transferring updates from web to Tableau is possible but must be done through the refresh option on the connection pane.

5.2.2 Case Example Using Tableau

The capabilities of Tableau as a visualization tool were explored through data fusion. The data used was selected not only in the interest of accessible data, but more importantly it was selected based on proximity to available weather sensing stations. The abundance of data and overall importance of IH 35 in Austin made a great candidate for analysis. And while the NOAA provides historical climate data online, the number of available weather stations in the Austin area is underwhelming. For this reason, the study was constrained to available data within a reasonable distance to the two weather stations available (located near Camp Mabry and the Austin Bergstrom Airport). Data used to conduct the analysis include INRIX traffic data, IH-35 WKZ trailer station traffic data, Lonestar traffic incident data, Crash Records Information System (CRIS) data, and NOAA weather condition data. The location of the sensors are shown in Figure 5.2 and depict the results over the entire month. For example, during this month 138 crashes were reported on the segment, shown as occurrences in blue.

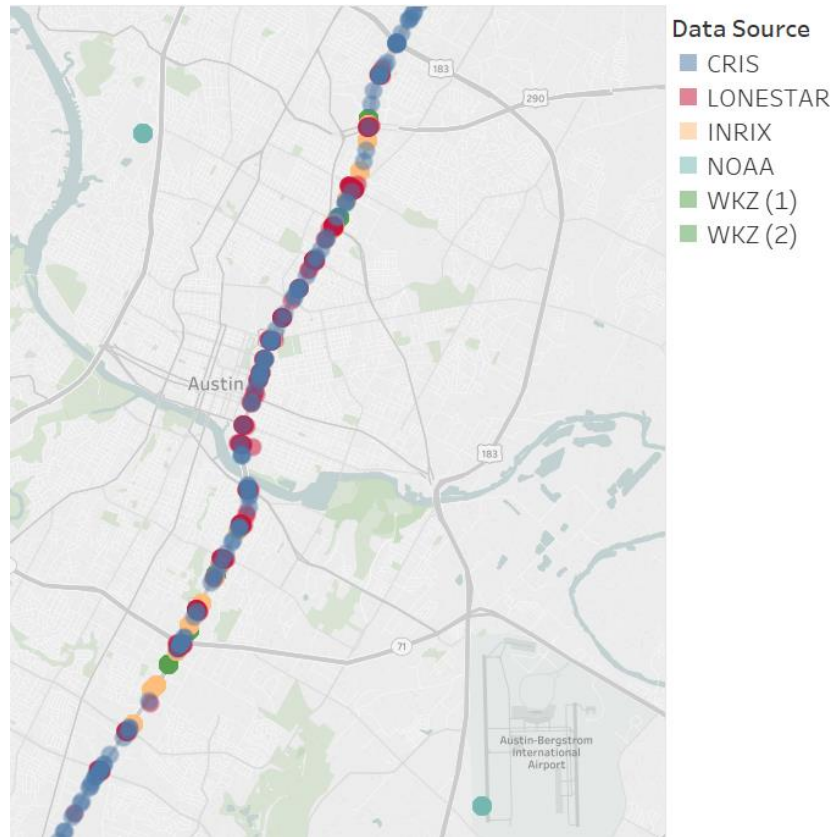


Figure 5.2 Map of IH-35 case example using Tableau

Findings from Data Visualization Creation Using Tableau

The discoveries found using Tableau and multi-sourced data include difficulty with joining data sets, processing high volume data, and limited geographic capabilities. Valuable findings from Tableau include the ability to present a clear message and the general overall friendly user interface.

Joining Data by Time

When selecting variables to ‘join by’ among data sets, Tableau prefers the column IDs to match perfectly—which presents an obstacle if a user is interested in combining data by timestamp. Tableau reads the timestamps as unassociated values if either the exact minute or second do not align. For example, if combining data by timestamp from two different sensors—one monitoring traffic counts and speeds and another monitoring weather conditions (precipitation levels, temperature, etc.)—the user is unable to see the effects relative to one another over time. The timestamp for each data set will only show what is connected to its exact ID match. Other joining issues arise when different sources have different formats, such as the connection shown in Figure 5.3. And even if the connection was permitted, the timestamps do not align properly and will cause issues with later analysis.

- Tableau prefers the date (or any joining variable) to exist in the primary data source or it will not come through from any secondary source.

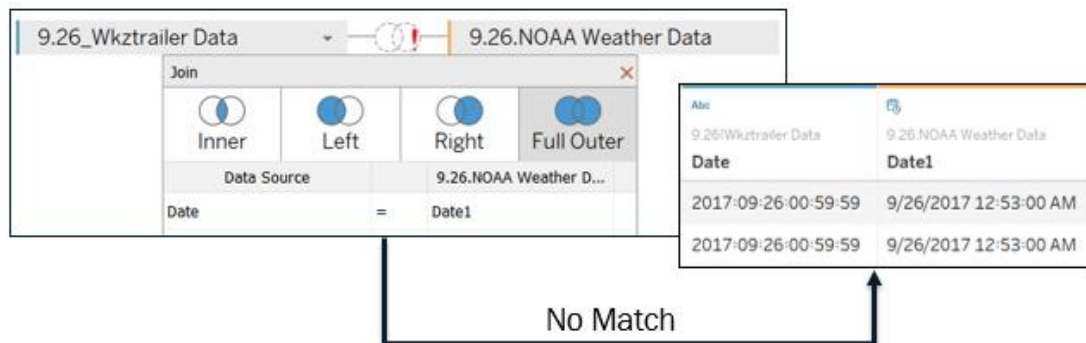


Figure 5.3 Limitation in Tableau joins

Processing High Volume Data

The more data is added, the more cleaning and processing becomes necessary. Even though the sample size used was based on a small segment of IH 35 for just one month (December 2017), each data source was heavily saturated with frequent outputs per hour and exponentially increased the rows of data involved. Additionally, each data source has its own variable output scheme. These differences impact the integration process as there can be various time formats present, confusion between variable definitions, and unknown shorthand terms included. For example, the NOAA uses shorthand notation to represent the present weather condition such as “RA:63” to stand for heavy rain with no freezing. These notations are not always intuitive and must be addressed to be able to quickly assess information.

Plotting Data

The general GIS capabilities of the Tableau software are limited. In order to plot coordinates in this project, only one data source could be used to create a map’s display. To overcome this issue the data was combined into one data set, so that all coordinates appear in the primary data source. Another work around would be to plot separate maps. The latest update of Tableau, however, does address this issue by enabling connections to spatial file types (e.g., shapefiles, KML, etc). However, this addition was added as a part of a November 2018 version update and has not been explored further.

Communicating Information

Using Tableau to create visuals from data fusion allows the presentation of a clear message. The interactive nature of the visuals shows the value of analysis through a dashboard set up for decision-making. An example of a clear message presented using road weather data is shown in Figure 5.4. The depiction of average speeds and vehicle counts (from WKZ data) overlaid by hourly precipitation, directly observes the impacts of rain as a weather event compared to a clear day. The discussion of the demonstrations included in the report further support the use of Tableau as a communication portal and visual analysis tool.

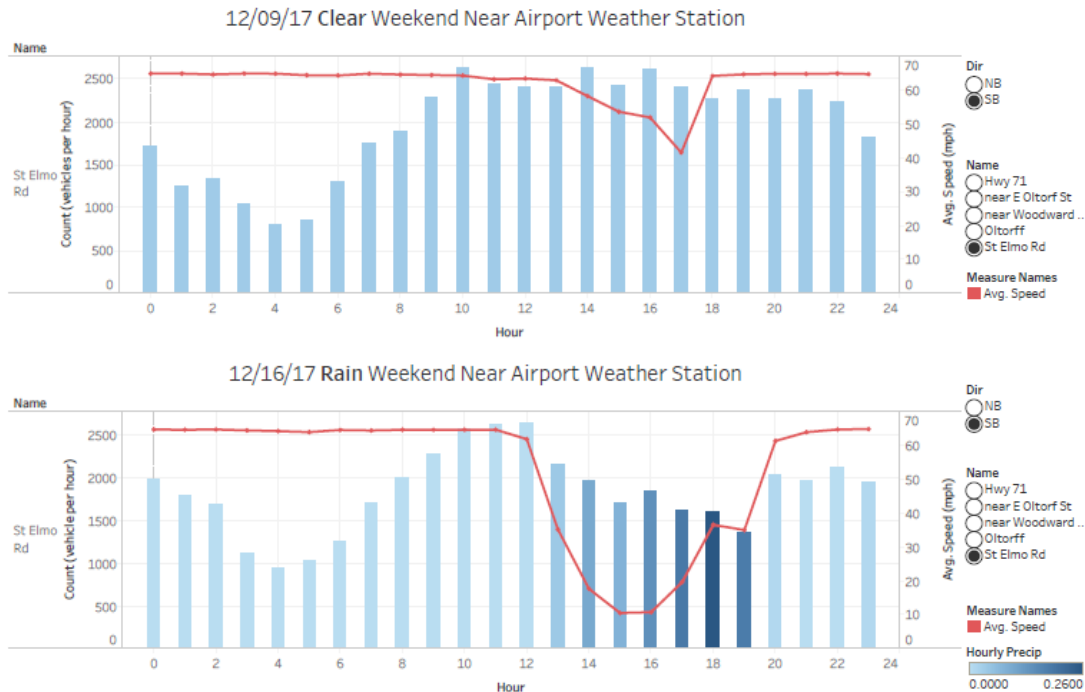


Figure 5.4 Rain effect comparison on speed and vehicle counts on IH 35

5.2.3 Historical-Data-Based Performance Metrics

Initial weather-responsive traffic calculations were performed in this project similar to previously mentioned performance metrics evaluated by other states over larger data. This data was calculated for December 2017 based on the same segment of IH 35 mentioned earlier in this chapter. Sensor locations from INRIX data and WKZ data were selected due to proximity of available NOAA weather station data, and they also correspond closely to one another along IH 35. The impact of weather on average travel speeds was calculated for both data sources while the impact on travel time was only calculated from the available data provided by INRIX.

Weather Impacts on Average Speeds

In Table 5.1 the impact of weather on average travel speeds shows the differences between WKZ and INRIX data calculations in both percent change and miles per hour. Three different scenarios existed in the month of the data set, including the occurrence of rain on a weekday or weekend and snow on a weekday. These events were then compared to the weekdays or weekends that experienced little to no rain or snow.

The differences between results shown for the two data sources are also shown in the table and are likely attributed to a few causes. The sensors selected are not in precisely the exact locations but are closely positioned (INRIX is also taken over a short range to capture travel time rather than a single source). Examining the sensor stations between the two data sources in Tableau for the same day and time range shows obvious differences. The WKZ data appears to vary less than the INRIX data. In many cases INRIX data captures additional changes in speed that the WKZ data does not.

Both data sets have portions of date missing, so these gaps on both ends will also contribute to varying calculations.

There was only one snow event in this month and it occurred from about 5PM to 7PM during the PM peak while the AM peak received light rain. In general, it makes sense from the table that snow has the biggest impact on travelers speed, because it is a rare event in Austin and drivers are not used to experiencing on their commute.

There were multiple occurrences of rain during the month analyzed and southbound traffic on IH 35 seemed to suffer the most over both the AM and PM peaks for a weekday rain event. Yet on the weekend, all traffic was impacted negatively.

Table 5.1 Analyzing the Impact of Weather on Average Travel Speeds

Weather Impact	Time Frame	Average Speed Difference (%)				Average Speed Difference (mph)			
		Northbound		Southbound		Northbound		Southbound	
		WKZ	INRIX	WKZ	INRIX	WKZ	INRIX	WKZ	INRIX
Snow (Weekday)	AM (6AM-9AM)	-13%	-16%	-19%	-29%	-0.2	-1.7	-3.9	-4.3
	PM (4PM-7PM)	-20%	-31%	-70%	-126%	-5.9	-10.6	-14.9	-15.5
	Off-Peak (9AM-4PM)	1%	-1%	-13%	-10%	1.2	0.2	-3.6	-0.5
Rain (Weekday)	AM (6AM-9AM)	-18%	-25%	-14%	-34%	-2.6	-6.2	-2.7	-7.2
	PM (4PM-7PM)	4%	4%	-32%	-39%	2.5	2.3	-6.0	-5.3
	Off-Peak (9AM-4PM)	-2%	-4%	-2%	-10%	-0.5	-0.9	-0.2	-2.5
Rain (Weekend)	Peak (12PM-6PM)	-40%	-40%	-49%	-49%	-12	-12	-12	-12

Weather Impacts on Average Travel Times

The impact to travel time is recorded only through INRIX data and is therefore the dataset shown in Table 5.2. Travel times typically reflect similar trends to that of the existing roadway speeds. So, travel times are dramatically high during the reported snow event in the PM peak period. Again, typical Austin drivers are not accustomed to snow and therefore could benefit from the dissemination of more action-based information. Rain overall increases travel times no doubt in part from slower travel speeds for safety reasons, but in any case, the impact of rain is apparent.

Table 5.2 Analyzing the Impact of Weather on INRIX Data Average Travel Times

Weather Impact	Time Frame	Average Travel Time Difference (%)		Average Travel Time Difference (min)	
		Northbound	Southbound	Northbound	Southbound
Snow (Weekday)	AM (6AM-9AM)	10%	17%	8	18
	PM (4PM-7PM)	32%	42%	17	71
	Off-Peak (9AM-4PM)	8%	2%	3	7
Rain (Weekday)	AM (6AM-9AM)	23%	24%	13	24
	PM (4PM-7PM)	7%	14%	2	21
	Off-Peak (9AM-4PM)	10%	10%	4	10
Rain (Weekend)	Peak (12PM-6PM)	24%	24%	14	25

- Performing baseline performance metrics for weather impacts on traffic characteristics, such as the example shown here, are important for tracking effective road weather management.

Chapter 6. Implementation Plan

6.1 Introduction

This implementation plan outlines the planning and actions necessary to deploy the sensors that were purchased and evaluated for this project. The sensor activities are intended to provide these actions for the project:

- Specifying sensors and related software/hardware through requirements-gathering.
- Consulting with vendors to obtain quotes for integrated systems.
- Ordering sensors.
- Consulting TxDOT personnel in respective districts to plan on deployments. This includes sharing as much information as possible about sensors so that the necessary mounts can be fabricated and constructed for when the sensors are ready to deploy.
- Testing sensors in lab environments.
- Creating and testing data collection and visualization software and procedures.
- With TxDOT assistance, deploying sensors.
- Verifying proper operation.
- Co-locating data visualization software and procedures within respective district traffic management centers.
- Documenting relevant findings.

From these deployments, a number of insights are discovered that were reported through workshop training materials and this document. These focus on the following areas:

- Specifying sensors and expected use cases;
- Deploying sensors;
- Identifying performance metrics that can be used in future efforts to justify further sensor deployments;
- Demonstrating sensors in action; and,
- Understanding implications on roadway operations.

In summary, these activities are intended to help arrive at preliminary end-to-end proof of concepts that facilitate further conversation and ease the deployment of future sensors. These can be performed with specific attention to enhancing roadway operations during times of extreme weather.

6.1.1 Purpose

The purpose of this specific system is to sense several environmental parameters, including the following:

- Road temperature (Sadeem Equa)
- Presence of ice, water, or slush on road (Icesight 2020E and Mobile Icesight)
- Road water level (Sadeem Equa)
- River water level (OTT Sutron)
- Air pollution (particulates, CO and CO₂) to detect wildfires (Troposphere)
- Weather parameters (air temperature, wind direction and speed, precipitation rate) (HOBO RX3000)

6.1.2 System Overview

The system implemented consists of several independent wireless sensor networks connected to respective backend databases (cloud-based) with multiple tables for each parameter category.

Sensor nodes within each sensor network are independent of one another (no multi-hop communications), and are either fixed or mobile:

- Road temperature (Sadeem Equa), presence of ice, water or slush on roads (Icesight 2020E), River water level (OTT Sutron), Air pollution sensors (Troposphere) and weather sensors (HOBO RX3000) are all fixed sensors
- Some presence of ice, water, and slush sensors (Mobile Icesight) are mobile sensors

All fixed sensors are solar-powered, and connected to their respective databases through a wireless connection (IEEE 802.15.4, IEEE 802.11, or cellular). Sensors without a cellular interface broadcast their data to solar-powered cellular gateways that interface them with the cellular network.

The mobile sensors are powered by the vehicle 12V DC supply, and are connected to their own cellular interface (Icesight MPU).

System Description

The sensors used in this system consist in either cellular-enabled sensors that will transmit their data over the cellular network, or dedicated sensors using another protocol (WiFi (802.11), IEEE 802.15.4) and connected to corresponding cellular gateways. The data sent to the database will consist in a string of numbers in CSV format or other similar format with other delimiters, and will be entered in the corresponding tables.

Assumptions and Constraints

Budget

The total equipment budget required to purchase the sensors and supporting equipment is \$129K.

Resource availability and skill sets

The deployment is supported by several students familiar with systems engineering, wireless sensor networks, and solar-powered systems. Equipment such as power supplies, voltage/current meters, and oscilloscopes are used to check the performance of batteries and sensors respectively.

Software and other technology to be reused or purchased

This system can use several pieces of software for storing data in the cloud, and for visualizing data on a map (GIS software). Cloud storage services are purchased as part of this system, to avoid the costs of building and maintaining a dedicated server.

Constraints associated with product interfaces

Most of the sensors used in this project have cell communication capabilities; the sensors that do not have to be interfaced with corresponding gateways that have cellular communication capabilities. These interfaces require the gateways (or cell-based sensor nodes) to be in range with the cellular network associated with their SIM cards, which limits deployment possibilities.

The mobile sensors are powered by the 12V DC supply onboard a vehicle, and are well within the maximal current allowed by these systems, drawing only 0.5 A in operation.

The fixed sensors and gateways are solar-powered and are thus not interfaced with the power grid.

6.1.3 System Organization

The following sensors are used:

- OTT Sutron radar water level sensors
- Sadeem WSS water level and ground temperature sensors (1)
- Icesight 2020 road temperature and contaminant presence sensors
- Mobile Icesight road temperature and contaminant presence sensors (2)
- Troposphere air pollution sensors (3)

- Weather monitoring stations (HOBO RX3000)

These sensors require the following interfaces:

- (1) Raspberry Pi based gateways to interface with the IEEE 802.15.4 output of the sensors with the cell network, or with the WiFi network
- (2) Mobile Icesight MPUs are used to interface the Mobile Icesight sensors with the cellular network, and also provide GPS position and time data
- (3) Custom developed solar-powered WiFi gateways provide a WiFi to Cellular interface for the Troposphere sensors

6.2 Management Overview

The management of the deployment plan involves several phases, outlined below.

6.2.1 Description of Implementation

The project was implemented over a one-year period. The first step was the identification of the sensing needs. Given the project objectives, our sensing needs fell into three categories:

- Detection of icing and water on roads
- Measurement of water levels in rivers
- Measurements of air pollutants associated with wildfires—in particular, carbon dioxide (CO₂), carbon monoxide (CO), and particulate matter (PM 2.5 and PM 10)

Additional relevant data for all of the above included weather measurement data, including rain rate (which is used as a predictor variable for flooding), humidity and air temperature (which can predict icing conditions), and wind direction and speed (associated with the interpretation of pollutant concentration data, given the actual location of the wildfires).

Based on the above, we identified the following sensor candidates:

- Passive infrared remote temperature sensors (PIR) for monitoring road temperature (associated with icing conditions)
- Laser-based ice presence sensors for monitoring ice or snow presence on roads directly
- Contact based water level sensors (for roads)
- Pressure based water level sensors (for rivers)
- Ultrasonic-based water level sensors (for roads)
- Ultrasonic wind sensors and dysdrometers

- Mechanical wind vanes and wind speed sensors
- Dedicated wildfire sensors (optical + infrared)
- Air pollution sensors (to detect CO₂, CO, and PM 2.5 and 10)

The mechanical (contact-based) flood sensors were not considered for two reasons. First, many of these sensors are already in place in various cities (including Austin and San Antonio), while newer non-contact-based sensors (radars, sonars) are more recent technologies that should be investigated further. In addition, the sensors would not provide useful measurement data in the highly probable event that no flood is actually detected over the test period.

Similarly, pressure-based water level sensors were not considered for rivers, since they measure a mix of static and dynamic pressure (dependent on their orientation) that is difficult to interpret, and require specific mounting with waterproof conduits and grilles (to prevent large rocks from hitting them).

Dedicated wildfire sensors were considered (Fire Alert from Vigily); however, the manufacturer did not respond to our requests for quotations.

The remaining technologies were considered and requests for quotes were sent to various sensor manufacturers. Price and specifications were the driving factors affecting the purchase decision.

The various sensors were received and tested in the lab to evaluate the following:

- Solar panel output and battery charging
- Sensor functionality
- Data transmission to the server

In parallel, the WiFi and 802.15.4 gateways required by two of the purchased sensors were assembled and tested.

6.2.2 Major Tasks

The implementation involved the following tasks:

- Identification of the sensing needs
- Identification of the most appropriate types of sensors to meet the sensing needs
- Selection of the sensor deployment sites
- Selection of sensor providers
- Procurement process

- Unboxing of the sensor nodes and bench testing
- Assembly of the custom-developed gateways
- Sensor deployment. Devices were handed over to TxDOT for these activities:
 - o Investigating the sensor site
 - o Mounting
- Operational verification

The selection of sensor deployment sites could be done in parallel with the other tasks; however, all other tasks were sequential.

The unboxing and assembly of the sensor nodes required specific tooling and supplies, including:

- Fastening tools
- SIM cards for cellular devices
- Voltage meters and current meters to test the solar panel outputs (open circuit voltage and short circuit current)
- Voltage meters and current meters to test battery charge (open circuit voltage charging current)
- Oscilloscopes (to check the presence of digital signals generated by the sensors)
- Power supplies

6.2.3 Implementation Schedule

This section shows the project schedule.

- Identification of the sensing needs: Jul. 2017–May 2018
- Identification of the most appropriate types of sensors to meet the sensing needs: Jul. 2017–May 2018
- Selection of the sensor deployment sites: Aug. 2017, revised in May–Oct. 2018. (While this timeline was originally dictated by the picking of flood-prone areas, it was amended based on technical challenges that would have slowed the project progress. Findings from this project will ease future site selections, however).
- Selection of sensor providers: Aug. 2017–May 2018

- Procurement process: Aug–Oct. 2017 (Sadeem); May–Aug. 2018 (others)
- Unboxing of the sensor nodes and bench testing: Aug.–Nov. 2018
- Assembly of the custom-developed gateways: Sept.–Oct. 2018
- Sensor deployment: Devices were handed over to TxDOT for these activities:
 - o Investigating the sensor site: Oct.–Nov. 2018
 - o Mounting: Oct.–Nov. 2018
- Operational verification: Dec. 2018–Jan. 2019

6.2.4 Security and Privacy

Security: no specific cybersecurity provisions are in place given the experimental nature of the project. The sensors are sending data to a cloud database, but no system or software is in place to detect or prevent data spoofing. The proposed systems do not have security certifications or features.

Privacy: the system does not generate privacy sensitive data. The traffic measurement data generated by some sensors (Sadeem Equa) is aggregated and does not contain any privacy sensitive information.

6.3 Implementation Support

This section conveys additional information important to consider for implementation purposes.

6.3.1 Hardware

The following hardware was developed:

- OTT Sutron radar water level sensors, consisting of:
 - o A radar
 - o A cellular-enabled datalogger
 - o A battery
 - o A solar panel
 - o A weatherproof enclosure
- Sadeem WSS water level and ground temperature sensors, consisting of:
 - o A dual ultrasonic/PIR sensor

- o A solar panel/battery charge controller
- o A microcontroller board with a 802.15.4 transceiver
- o A battery
- o A solar panel
- o A weatherproof enclosure
- Icesight 2020 road temperature and contaminant presence sensors, consisting of:
 - o A cabinet with mounting brackets
 - o A datalogger
 - o A cellular modem
 - o Two 12V Lead acid gel batteries
 - o A solar panel
- Mobile Icesight road temperature and contaminant presence sensors, consisting of:
 - o A mobile Icesight road temperature sensor
 - o A mobile Icesight MPU (Mobile processing unit) with WiFi to cellular interface and GPS
- Troposphere air pollution sensors, consisting of:
 - o A microcontroller board with WiFi (802.11) interface
 - o An air pollution sensor board
 - o A integrated battery and solar panel system
 - o A weatherproof enclosure
- Weather monitoring stations (HOBO RX3000), consisting of:
 - o A microcontroller board with cellular interface
 - o A weather sensor instrument including mechanical airspeed, wind direction and rain rate sensors, one air temperature sensor and one relative humidity sensor
 - o A weatherproof enclosure

In addition to the sensors, we needed the following interfaces:

- The Sadeem sensors require either a backend computer with a 802.15.4 compatible transceiver (such as a USB digi interface), or a range-extending gateway developed from a Raspberry Pi computer, and including:
 - o A Raspberry Pi 3 computer
 - o A 802.15.4 transceiver
 - o A cellular network shield
 - o A weatherproof enclosure
- The mobile Icesight sensors require a Mobile Icesight MPU, which is a device from the same manufacturer
- The Troposphere sensors require either to be in range of a WiFi-enabled computer connected to the internet, or to be in range of a WiFi gateway. We developed WiFi gateways using the following:
 - o A weatherproof battery and 5V power supply
 - o A WiFi-to-cellular gateway
 - o A solar panel compatible with the battery/power supply assembly
 - o A weatherproof enclosure

6.3.2 Software

In addition to the firmware used to operate the sensors themselves, we needed the following software to operate some of the sensors:

- Autopoll (to operate the OTT Sutron sensors)
- Cradlepoint (to operate the Sadeem sensors)

Custom software was supplied by the manufacturer (Sadeem) to operate the Raspberry-Pi-based 802.15.4 gateway.

Software was developed to operate the WiFi gateways associated with the Troposphere sensors.

6.3.3 Facilities

The testing was carried out in engineering labs on the UT Austin campus, involving the following equipment:

- embedded computers
- power supplies
- function generators
- oscilloscopes
- voltage and current meters

6.3.4 Materials

The systems required the following materials:

- SIM cards (for all cellular devices)
- Batteries (for the 802.15.4 gateways and 802.11 gateways)
- Enclosures (for the 802.15.4 gateways and 802.11 gateways)
- Solar panels (for the 802.15.4 gateways and 802.11 gateways)

6.3.5 Personnel

Staffing Requirements

Sensor specification, purchasing, testing, and integration require at minimum a person who is familiar with electrical engineering and computer technical knowledge that is covered in this project's workshop training material. Familiarity is needed insofar as that person can coordinate technical staff, learn and perform activities him/herself, and/or communicate effectively with the vendor's technical integration staff. Indeed, vendors provide valuable services because their staff are already familiar with their products and implementations. In some cases, vendors provide such services as part of their product cost; others charge extra for these services.

Each sensor node deployment requires three to four persons. The sensors are light enough to be carried by a single person, except for the fixed Icesight 2020 cabinet, which requires two persons to handle.

For deployments of sensor at human-height level, the operators need to lift the sensors and mount them on a pole or on a bridge structure, requiring the use of basic assembly tooling (screwdrivers, bolts, drillers). For deployments at higher heights, the operators furthermore need to bring the sensors to the required height (possibly requiring the operation of equipment such as a man-lift).

Training of Implementation Staff

Staff members already familiar (whether peripherally or in-depth) with ITS equipment deployment, signal control systems, or technological mechanics are best candidates for training

for technical aspects of sensor testing and integration. For those performing installations, the following training is required:

- Working above ground (safety, use of man-lift equipment)
- Handling of heavy items (Icesight 2020)
- High voltage operations

The high voltage training is required for connecting some batteries (such as the 12V lead acid batteries of the Icesight 2020E), and to handle solar panel connectors properly (open circuit voltages of solar panels are on the order of 20V).

These DC voltages are not very dangerous, since the lowest recorded electrocution occurred at 30V DC), though some training and protective equipment (insulating gloves) would be desirable.

6.3.6 Outstanding Risks

This list captures risks and challenges that were encountered through the course of this work.

- Vendor integration time must be accounted for. It may take several months.
- Items in shipment may be lost.
- Restrictions on international shipping may delay or impede a delivery.
- Wireless communications standards or other protocols may change and be incompatible with predecessor versions.
- Device documentation may be incomplete or missing.
- Required personnel may have challenging schedules; the task of coordinating schedules may be substantial.

In addition to these risks, the projects carries the risks of medium DC voltages (for the batteries of some sensors, and the voltage and current outputs of some solar panels). However, the sensors are safe to work with overall:

- The PIR sensors do not emit radiation
- The IR lasers of the IceSight sensors are class 1 (eye safe under all conditions)
- The ultrasonic sensors are inaudible
- The radar sensors use a centimetric wavelength at a very low power, and are expected to have no impact on health

- The weather sensors pose no specific risk given that their edges are rounded and made of a soft plastic material, and unlikely to cause accidental injuries.

6.3.7 Implementation Impact: Cost-Benefit

The total cost associated with the deployment of the proposed sensors within this project is about \$126,000. The sensors have various sensing capabilities (applicable to flooding, icing, other weather and fire) that provide the following benefits:

- Detection of icing conditions (combination of weather sensors and ice detection sensors)
- Detection of high water levels on roads, and in creeks (combination of weather sensors and non-contact water level sensors)
- Assessment of fire risk (weather and solar irradiance sensors)
- Fire detection (particulate and CO sensor)

To estimate this benefit, we estimated the probability of successful detection of a high impact event, and the associated savings related to this detection. For this, we use the following statistics:

Icing: We consider the case of Dallas and its surroundings in this study. Dallas County has 1,412,852 workers (U.S. Census Bureau, 2015), i.e., potential daily commuters. In the case of a snow event, the welfare cost would be \$522,755.24. Considering that Dallas has approximately 0.7 serious snow-days per year (iWeatherNet LLC, 2017), the annual loss is \$366,000. We estimate that the Dallas area could be fully covered by two mobile IceSight sensors inside TxDOT vehicles. Assuming that better icing information from sensors could reduce 10% of these crashes, the benefits would exceed \$256,000 over the expected seven-year lifetime of the sensors

Fire detection: The average wildfire response is estimated to cost Texas \$30,000, with Texas experiencing 9,300 wildfires in 2016. The Insurance Information Institute recognizes that Texas is ranked second among the top ten most wildfire prone states in 2017 with more than 715,000 homes at risk (“Wildfires,” 2017). While not all this cost savings would accrue to TxDOT alone, it could achieve a significant cost reduction by cutting 5% of required responses, resulting in estimated savings of \$2800 per year. Over the five-year lifetime of the sensors, the expected savings exceed \$14,000.

Flooding: In 2016, TxDOT expenditures related to floods and high rains exceeded \$36 million, with a 10% increase compared to the previous year (Engineers, 2016). Assuming that this trend will hold for the next decade (as already reinforced by Hurricane Harvey), the total cost of flooding over the coming decade would exceed \$573 million. The localized deployment of eight flooding sensors and six weather sensors (including rain rate sensors) in high risk areas is expected to reduce the expenditure by 0.2%, resulting in \$1,146K in savings

Sensor-selection related benefits: All these savings would correspond to direct savings associated with actual detections over the sensor lifetimes. Additional savings would be obtained by developing best practices and sensor selection guidelines to help TxDOT identify the best solutions. We expect these benefits to provide 10% overall savings in total sensor related expenditures through better sensor selection. Assuming a conservative sensor budget for TxDOT of \$200,000 per year for the entire state, this would result in a cumulated saving of \$200,000 over the course of 10 years.

This analysis is a preliminary estimate, and only looks at the budgeting impact of this project and only external costs that have explicitly been analyzed. This does not take into consideration other costs, such as economic (e.g., freight mobility, impact to other types of commercial vehicles, commuter accessibility to workplaces), value of travel time, or cost to the environment. With the metrics analyzed, the overall cost-benefit ratio is \$1,616K:\$615K, or approx. **2.6:1**. If the additional items were analyzed, this ratio is expected to be significantly greater.

6.3.8 Performance Monitoring

To conduct the analysis, performance metrics need to be chosen and measured on the sensors and as a result of the sensors' operation. Feasible performance metrics include:

- Uptime (fraction of the time where sensors are operational and providing non-faulty data)
- Rates of false positives and false negatives, which require cross-validation with other sensors, and/or verifications performed by hand measurements.

If possible, human or environmental factors such as casualty reduction, saved travel time, or saved emissions can be measured. With archived data and analysis, these can be evident at the end of a duration of time that the sensors are deployed.

6.4 Additional Implementation Requirements

Sensor devices should be high-grade products (e.g., weather resistant, hardened) that utilize an open, accessible format for data representation.

In the future, sensor devices will need to abide by the TxDOT's rules on systems security if those devices will be integrated with TxDOT operations, especially if they feed directly into the traffic operations center ATMS.

Each sensor type has requirements on mounting that are largely dictated by physical properties of their sensing technologies. Sensor data sheets and supplemental documentation produced within this project contain details on these known requirements (provided in Appendix D).

6.4.1 Site Requirements

Each site must be carefully evaluated to determine optimal sensor location, and whether a solution exists for a particular sensor type. Things that must be considered include:

- Is a candidate location within the TxDOT right-of-way?
- If the device sits close to the ground, is it prone to collision, vandals, or debris?
- If the sensor requires mounting on a dedicated pole, is the pole configuration crash-tested, protected by a guardrail, or far enough away from the road for it to be safe for traffic?
- If the sensor is mounted on an existing pole, such as a streetlight, does the pole have the capacity to support the weight, especially in wind?
- If the device is mounted on a bridge, does it interfere with bridge structure integrity? Can it be cleared by bridge engineers?
- Will the solar panel withstand a severe storm?

6.4.2 Implementation Verification and Validation

The field installation verification will require the following checks:

- Adequate power supply (positive charging current when the solar panel is exposed to full sunlight)
- Sensor functionality (data generated by the sensor must fall in the expected measurement range)
- Batteries are initially fully charged
- Sensor data correctly reaches the input database, and at the correct (expected) measurement rate

6.4.3 Acceptance Criteria

Once the sensors were deployed, the following criteria was used to accept the deployment as is or possibly request additional work:

- Overall packet delivery ratio has to exceed 90%
- Solar panel charging current has to be sufficient to ensure permanent operation, as per the energy budget estimates
- Sensor output has to exhibit some variability (as per the datasheet) to ensure that the system is working properly

Chapter 7. Workshop Sensor and Data Demonstrations

Two half-day training workshops were delivered on December 13 and 14, 2018, in Abilene and Austin, respectively. Invitees included TxDOT personnel and representatives from partnering agencies. The intent for hosting the workshop, titled “Weather Savvy Roads: Sensors and Data for Enhancing Road Weather Management,” in two locations was to make the workshop accessible within two distinct Central Texas locations, and to facilitate discussion on topics and concerns that are particular to each region.

Although the workshops contained lecture and discussion sections, a significant component of both workshops was the live sensor and data demonstrations during the lunch break. The demonstrations were set up at stations along tables, where each station could have a prop of the sensor device, as well as a view of its live operation. Some stations were attended by a knowledge expert who could engage in one-on-one conversations with participants. The motivation for this was to allow participants to consider how similar sensor or data analytics solutions could be used in their own districts or organizations. This document describes each of the demonstrations and the use cases they intend to convey.

7.1 Data Analysis Demonstrations

One set of demo stations focused on data fusion experiments, which are further documented in Chapter 5. There were multiple displays in both demonstrations, including an assortment of maps and charts. Demonstration 1 showed the value of data fusion of multiple sources to access traffic and weather impacts on a larger scale. Demonstration 2 focused on the impact of weather on traffic and highlighted the need for additional roadway weather information for accurate information dissemination.

7.1.1 Demonstration 1: Data Fusion

Data Sources

- CRIS
- INRIX
- LONESTAR
- NOAA
- Work Zone (Wkz)

IH-35 Merged Data Map: This map (Figure 7.1) shows all of the data collected for the sample month of December 2017 on a segment of IH 35. It shows the data points for each day by a side filter and includes data from all the above listed sources. This map is beneficial to analyze the network visually and target specific days to see what events have taken place.

The CRIS data includes 138 total crashes during this time frame and the time of the plot as well as the contributing crash factor are displayed. The Lonestar data shows events such as vehicle stalls, maintenance issues, and collisions. INRIX data and WKZ Trailer data show traffic characteristics such as average travel times, speeds, and vehicle occupancy. NOAA weather data included in this map showcases average hourly rain, wind speeds, visibility, and present weather conditions. The information taken from each source does not include all available data but rather portions of data for simplification.

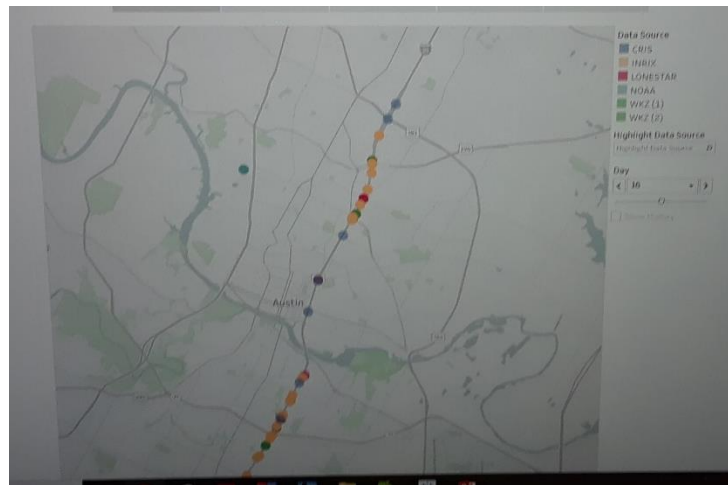


Figure 7.1 Data fusion demonstration

Variations of the map of IH 35 are included to breakdown the events of each hour visibly. Rather than looking at the entire day, each hour allows an easy recognition of a Lonestar or CRIS event as an influence on traffic.

Other charts of the merged data set include a display of weather conditions and traffic characteristics in a continuous stream to monitor differences. Lastly, there is also included a quick data check figure to show where gaps exist between the INRIX data and WKZ Trailer data.

7.1.2 Demonstration 2: Weather and Traffic Data

Data Sources

- INRIX
- NOAA

The first view of this demonstration shows the map of IH 35 with the INRIX sensors distinctly separated by color and proximity to the only available weather information sources. The next graph showcases a day which received rain, and the differences between the reported amounts relative to the sensor stations. This difference is shown on top of average travel times and speeds. Knowing that there is a rain event is one important aspect of roadway weather management, but it is also important to know where the event is happening. Accuracy in the location of the event helps to communicate the proper information.

The last dashboard shows average travel times and speeds over the course of the entire month compared to what weather occurrence exists. Weather occurrences in this case include not only rain but various other weather types such as fog, snow, or thunderstorms. This is another way to monitor changes in traffic in relation to present weather type.

7.2 Sensor Demonstrations

The other set of demo stations focused on sensor products and capabilities, to convey to workshop participants a “hands-on” means to consider how sensors and data can enhance roadway operations within their own districts or organizations.

7.2.1 OTT Sutron RLS

The OTT Sutron RLS uses radar to measure water height. The use case is to detect the presence of water in flood-prone areas, and to characterize how high that flood level is. While other flood detection technologies may use on/off contact switches or electromechanical parts, the use of radar to detect water presence in a roadside environment is a novel application that promises to offer higher accuracy and a lower device cost.

The unit, depicted in Figure 7.2 consists of the following:

- Radar unit
- Cellular-enabled datalogger and battery in a weatherproof enclosure
- Solar panel



Figure 7.2 OTT Sutron RLS with supporting equipment

Live feeds of activated OTT Sutron RLS stations in a laboratory environment, as well as in the Abilene District Headquarters maintenance yard are viewed in a terminal window for the purposes of the demonstration. While this display method is basic, it is possible to capture the data and display it within a graphical interface such as WxDE or other utility.

At the December 14 workshop in Austin, the demo station was attended by David Procyk, Territory Manager for OTT/Sutron, who has in-depth knowledge of the radar technology used in the sensors. His involvement was requested to add value for attendees (in an academic, non-commercial fashion) on understanding the operation of the sensor.

7.2.2 Sadeem WSS

The Sadeem WSS uses ultrasound and infrared detection to report water level and ground temperature. The use case is to detect the presence of water in flood-prone areas, but to also report upon icy conditions. Each station is therefore dual-purpose. A distinguishing characteristic of the Sadeem WSS is its minimalistic footprint: one only needs to install a lightweight box and small solar panel to have a functional station. The unit, depicted in Figure 7.3, contains:

- A dual ultrasonic/PIR sensor, solar panel/battery charge controller, microcontroller board with an 802.15.4 transceiver, and battery within a weatherproof enclosure.
- A solar panel

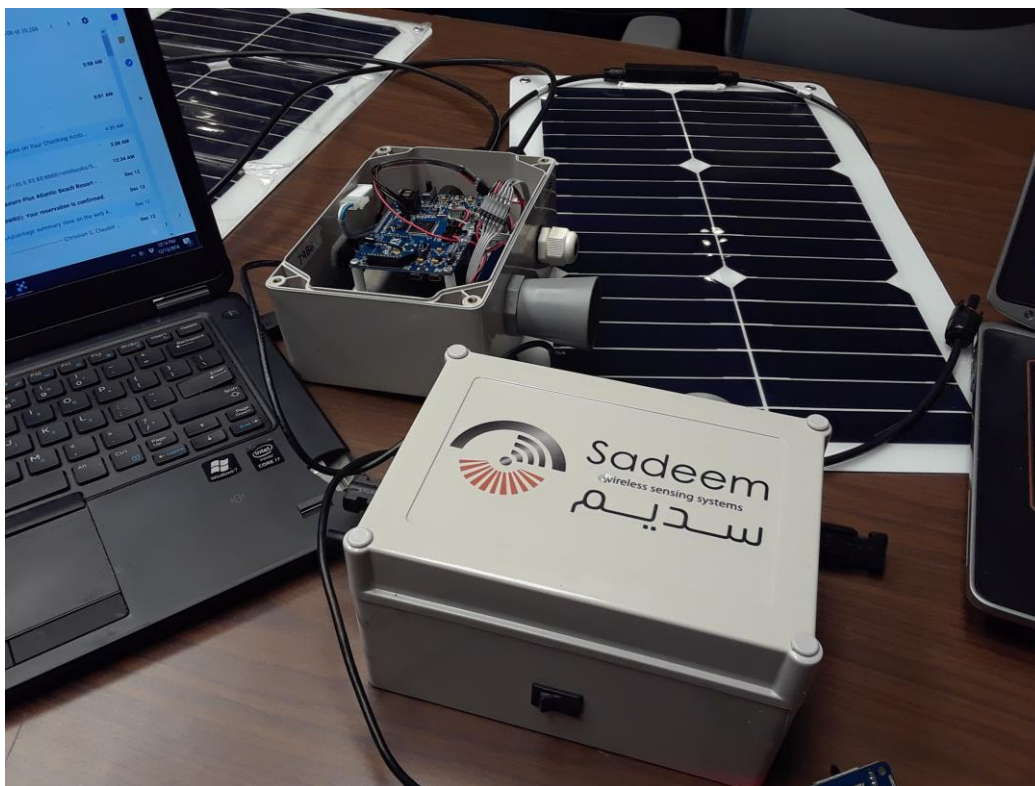


Figure 7.3 Sadeem WSS unit and solar panel

One limitation of the Sadeem WSS evaluated for the project is its communication range. While marketed for urban environments, the range of the Sadeem WSS model proved to be challenging for semi-rural environments within flood-prone or freeze-prone locations of the Abilene District. Further work was performed to evaluate the feasibility of extending the range with gateways, but no solution was reached. Meanwhile, the Sadeem manufacturer has created updated products that provide longer-distance cellular network communications, which were not able to be purchased for the project.

A live feed from a Sadeem WSS was facilitated by capturing data from the 802.15.4 communications onto a laptop and displaying the data that is provided by the device. While this display method is low-level and basic, it is possible to capture the data and display it within a graphical interface such as WxDE or other utility.

7.2.3 IceSight 2020

The IceSight 2020 is a remote road surface condition sensor that uses laser and infrared optical technology to read the temperature of a specific spot of pavement while characterizing the surface conditions: dry, wet, slushy, or icy. The use case is to remotely detect the temperature of a vulnerable section of roadway and to understand the water condition of the surface.

The unit depicted in Figure 7.4 consists of the sensor unit attached to a power supply. In a field installation, the sensor would also be supported by a sizeable solar panel, and a cabinet containing a datalogger, cellular modem, and two 12V lead-acid batteries.



Figure 7.4 IceSight 2020 in its demo station

The live demonstration consisted of a laptop attached to the activated sensor, and displaying its raw output. Most use cases would allow for processing of that output and rendition of the information in a more graphical form.

7.2.4 Mobile IceSight

The Mobile IceSight uses the same technology as the IceSight 2020, but in a more compact form factor that is meant to be mounted to a vehicle (Figure 7.5). Meanwhile, the device is connected to a mobile processing unit (MPU). Inside the MPU is a GPS receiver and a cellular network modem. These are powered by the 12V outlet in the vehicle. The theory of operation is that when the power is applied to the MPU, measurements of surface conditions and temperatures will be immediately sent wirelessly to a vendor-provided cloud service that collects the data. As data is collected, it appears within the “Glance” web app that displays the vehicle position on a map along with a trail that depicts the roadway conditions (Figure 7.6). The same web app allows recorded data to be downloaded for further analysis.

A use case for the Mobile IceSight is to record roadway surface conditions to understand the conditions during a susceptible time, such as shortly before freezing conditions are predicted to set in. Insight can be gained on whether specific sections of vulnerable roadway (e.g., bridges and flyovers, as well as curves) need immediate treating for ice prevention.



Figure 7.5 Mobile IceSight mounted on vehicle

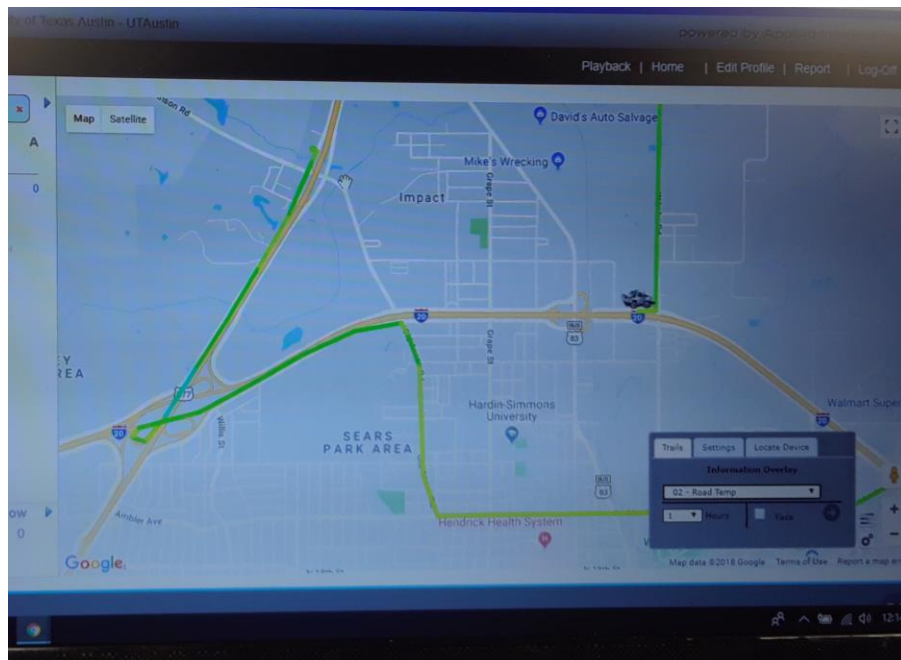


Figure 7.6 Mobile IceSight and web app as demonstrated

The demonstration involved mounting the Mobile IceSight on the vehicle in Abilene and driving it around the district office maintenance yard. Participants viewed the live output from the Mobile IceSight on the projected screen.

7.2.5 Troposphere

The Troposphere is an air pollution detector. It is created by an Austin-based start-up business, and currently comes in prototype enclosures. While it can be used on its own to detect pollution, the use case for this project was to combine it with weather station data to detect the presence of wildfires. Visualizations can be produced of its various readings, as seen in Figure 7.7.

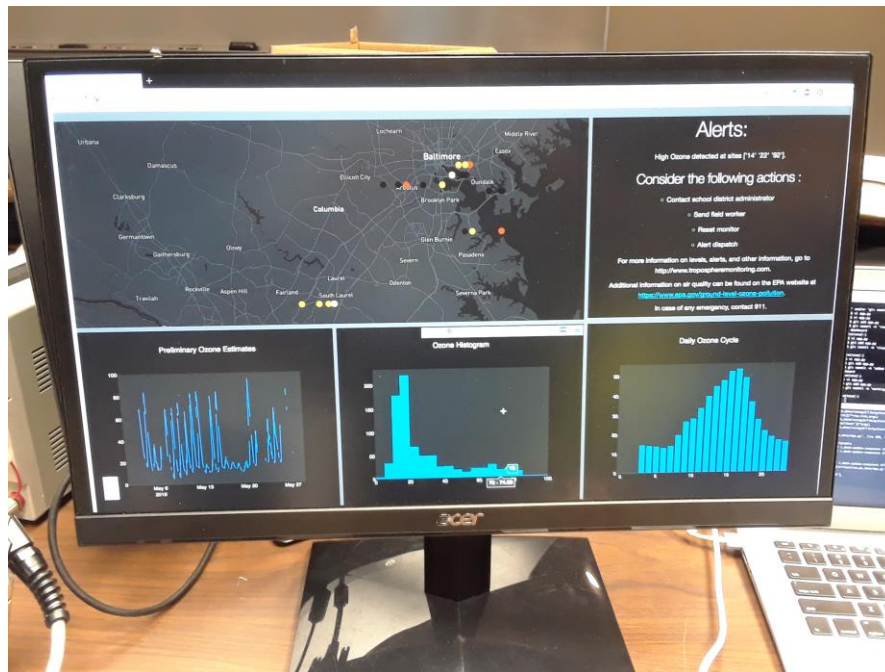


Figure 7.7 Visualizations of Troposphere at its demo station data at the demo station

Each Troposphere pollution sensor consists of a microcontroller board with WiFi (802.11) interface and an air pollution sensor board. These are packaged along with an integrated battery and solar panel system in a weatherproof enclosure. Each unit measures air temperature, as well as the concentration of several species:

- H₂O (relative humidity)
- CO (Carbon monoxide)
- NO_x (not used in the present work, but can be used for pollution monitoring)
- O₃ (not used here, but can be used for pollution monitoring)
- Particulate matter, in the categories:

- o PM 2.5 (2.5 μm)
- o PM 10 (10 μm)

Fires are expected to generate CO, PM 2.5, and PM 10 (in smoke). Detected levels for each pollutant type are then available for visualization and analysis.

For both of the workshops, the demo station was attended by Chris Kelley, CTO of Troposphere Monitoring. His involvement was requested to add value of for attendees (in an academic, non-commercial fashion) on understanding the operation of the sensor.

7.2.6 HOBO RX3000 Weather Monitoring

The HOBO RX3000 is a standalone weather station. Each station consists of:

- A microcontroller board with cellular interface contained within a weatherproof enclosure
- A set of weather sensor instruments including mechanical airspeed, wind direction and rain rate sensors, air temperature sensor and relative humidity sensor.

Figure 7.8 and Figure 7.9 show the HOBO RX3000 and its instruments. Typical use cases for transportation applications is to understand the temperature of surrounding regions that aren't adequately covered by existing instrumentation. Data from these weather stations can be used in conjunction with the more sparsely situation NOAA weather stations in applications such as the data fusion experiments documented in Chapter 5. Weather conditions can also be monitored in near real time (updates are sent over the cell phone network at 15-minute intervals).

The demonstration involved showing the weather data and graphical visualizations in the vendor cloud web app, HOBOLink, for both the Austin District and Abilene District locations. While HOBOLink offers features for showing the latest data, graphing historic data, creating dashboards and alerts, and downloading data files, the vendor also offers a web-based API for retrieving data, which opens opportunities for integrating weather data into other systems and workflows.



Figure 7.8 HOBOTek RX3000 at its demo station



Figure 7.9 Deployment of the HOBOTek RX3000 at the TxDOT Austin District Headquarters maintenance yard

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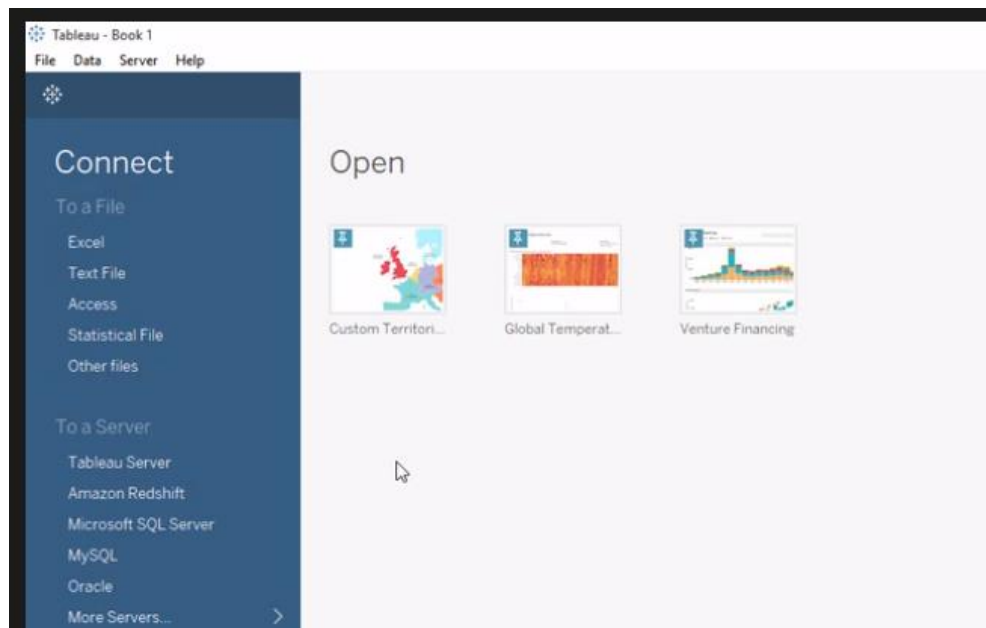
Appendix A: Getting Started with Tableau

From the onset, Tableau provides links to tutorial videos, sample data sets, and step-by-step instructions to learn how to use the software. The best way to get to know the application is to watch a tutorial or you can always jump into the software and search a specific question in the forums sections of Tableau when needed.

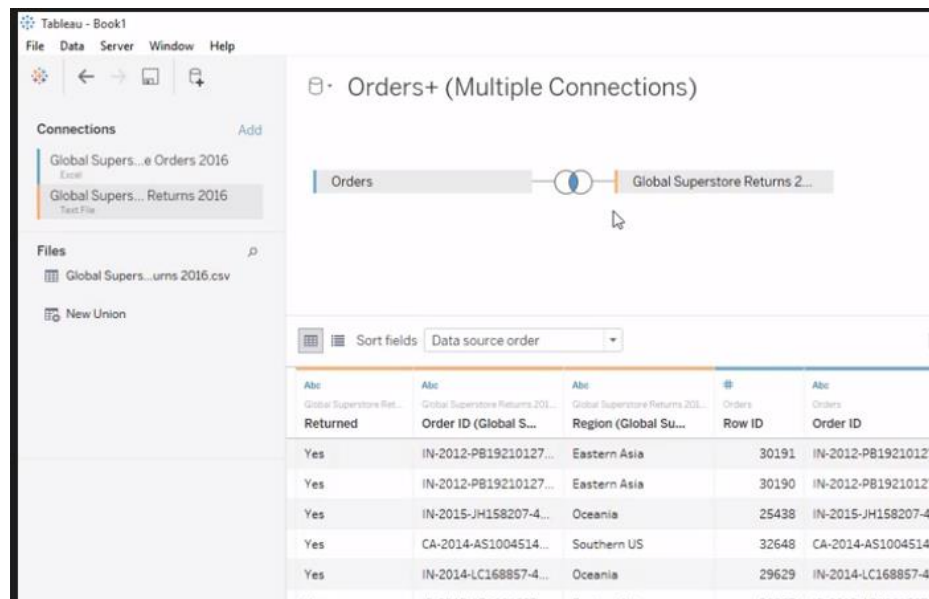
Introduction Video Walkthrough

The introduction tutorial will allow you to follow along with the sample data set to introduce some key features:

- **Connecting to Data:** Selecting the data sources from the Connect pane is simple with drag and drop placement into the canvas. The Data Source Page will allow you to select which sheets or tables to use and allows the creation of integrated data sources by adding a connection.



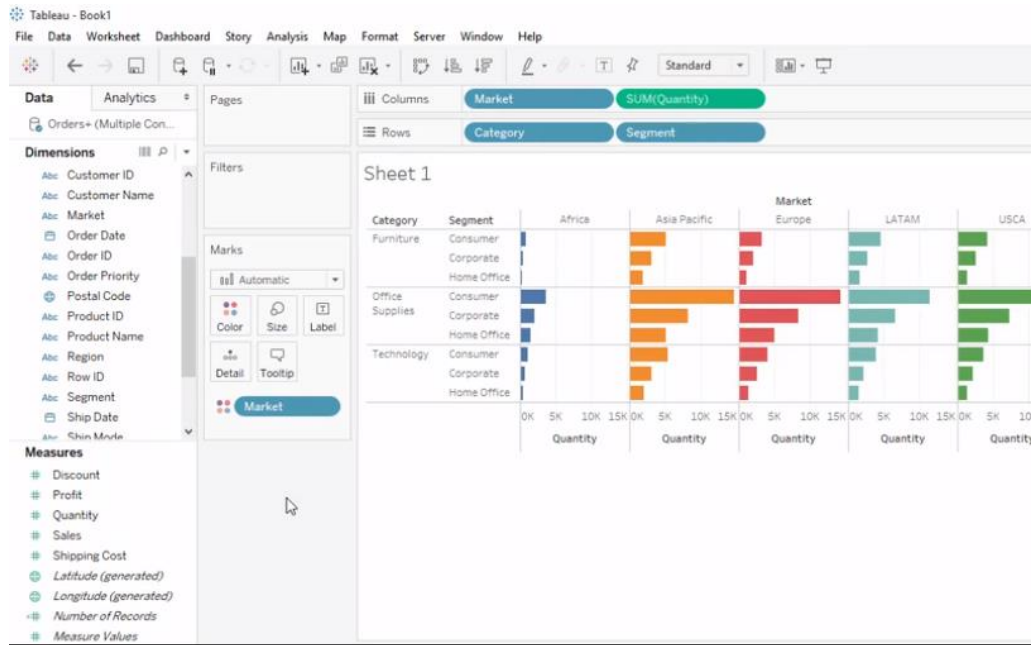
- **Joins & Data Preparation:** The options to Join tables in different ways is allowed and easy manipulation of the data such as splitting fields, changing from number to a string, and simple changes can be made.



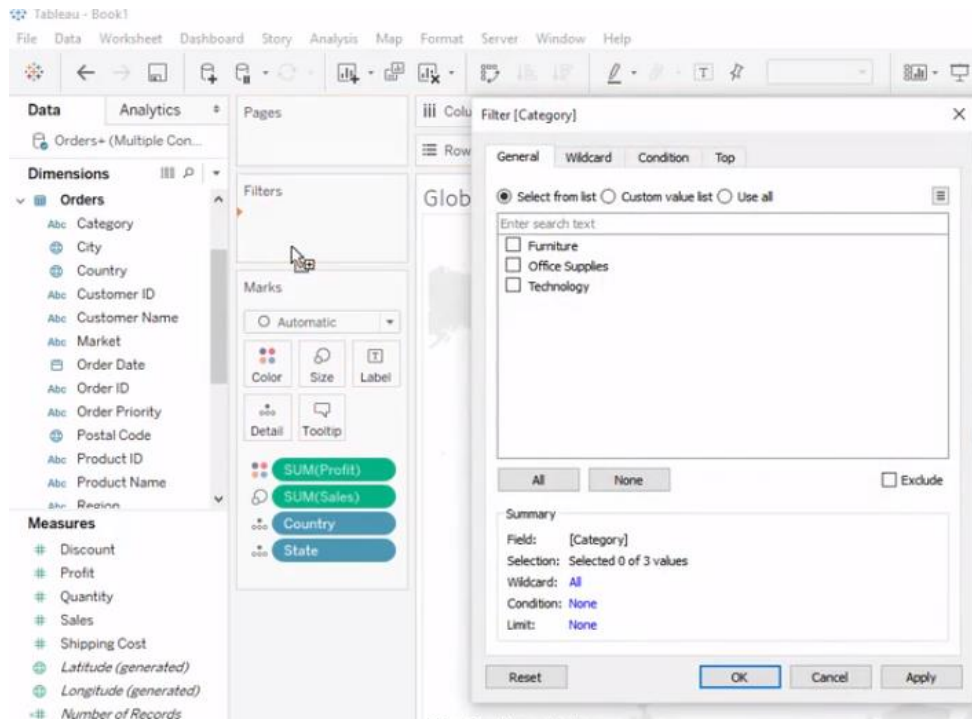
- **Connecting Live vs Extracting:** When connecting to the data you can either connect live or extract. Connecting live is great when we have constantly changing data.



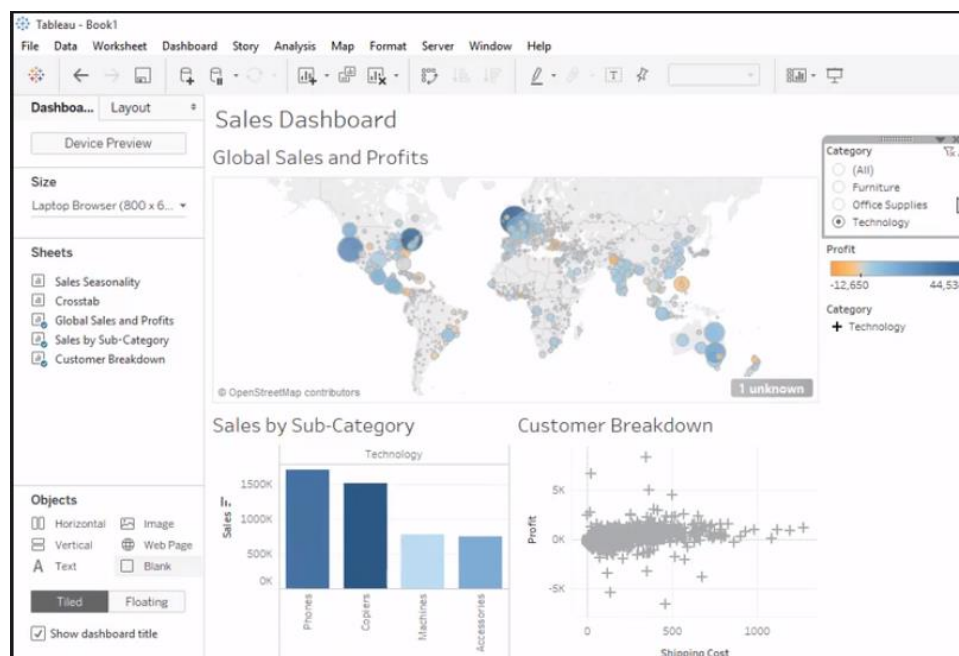
- **Dimensions and Measures:** Dragging fields into rows and columns instantly create a visualization. *Dimensions* are categorical fields and often discrete (e.g., date, customer, and Category). These are fields that we want to slice and dice our numerical data by. *Measures*, on the other hand, are our metrics and often continuous. They are the numbers we want to analyze. Continuous fields create axes in the chart.



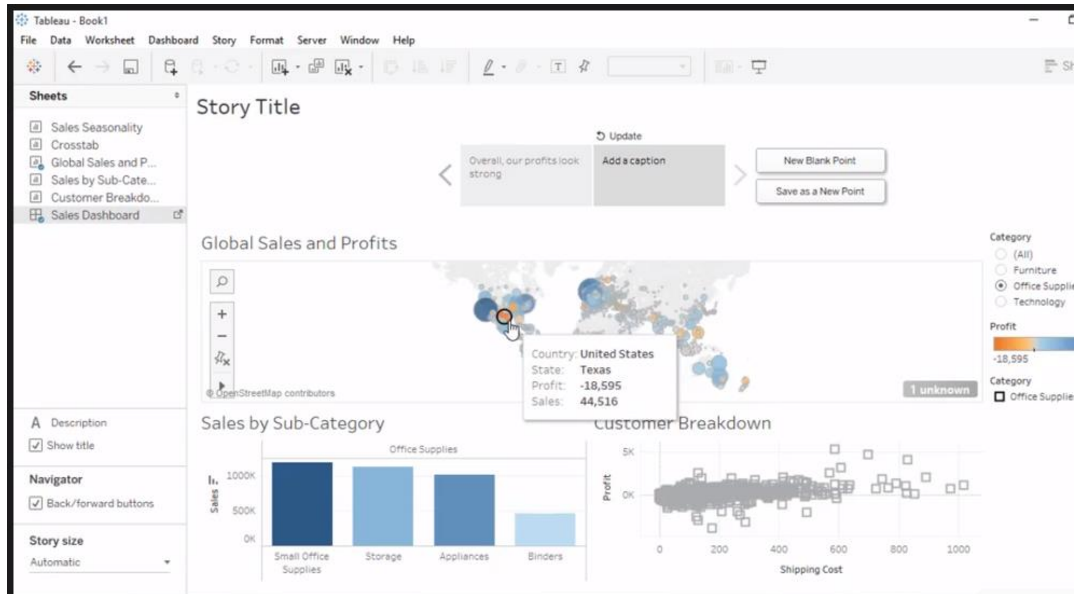
- **Crosstab and Exporting Data:** From the edits made to the visualization we can right click on the viz and copy to paste into excel or “Duplicate as a Crosstab.” This easily flips from one view to another while still allowing for edits in both areas.
- **Show Me:** The Show Me feature contains a list of common chart types to help you start your analysis or best represent the data. It is only the one-click options, as there are many possibilities.
- **Filters:** Dragging a field or a “pill” to the filter shelf allows the content of the field to become interactive. In a generic Category filter including Furniture or Technology, this feature allows you to highlight specific points within that category.



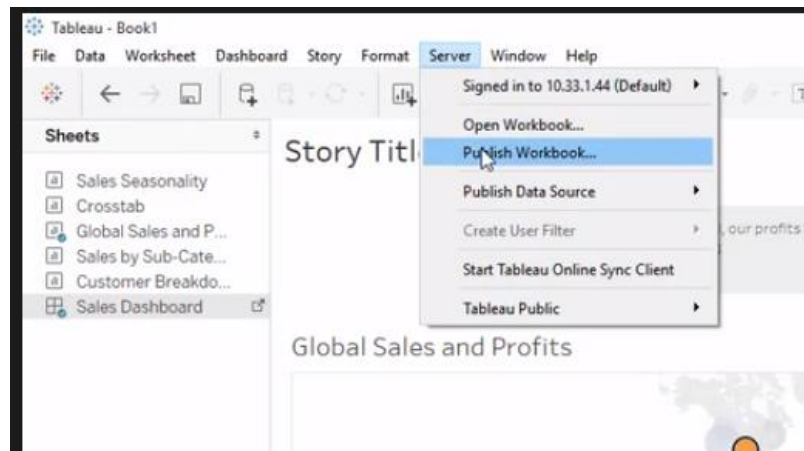
- **Sorting, Grouping**, creating **Hierarchies** and **Trend lines** within the viz are all possible as well.
- **Dashboards:** Once a viz is created, you can compile a dashboard to share with the team. Multiple individual views can be combined into a single dashboard. Click the new dashboard tab.



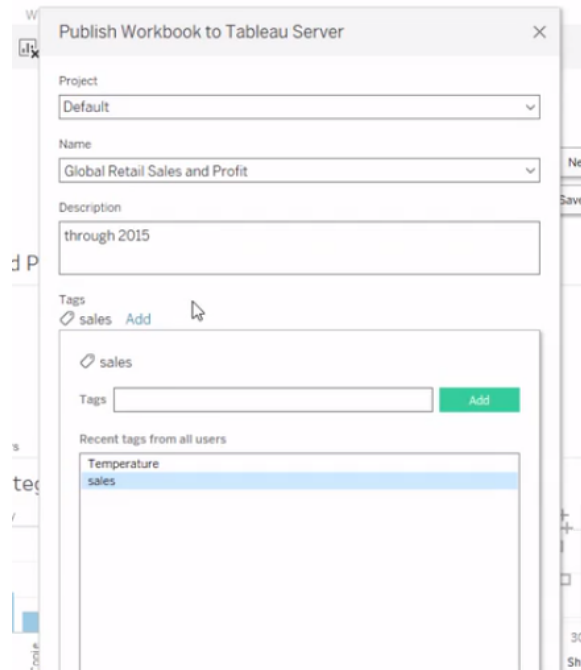
- **Story Points:** This feature leads an audience through the path of the discovery of the information and assembles a series of views to do so. Clicking New Story will allow you to bring in the visualizations desired. A key aspect of Story Points allows you to snapshot a specific visualization while still maintaining interactivity.



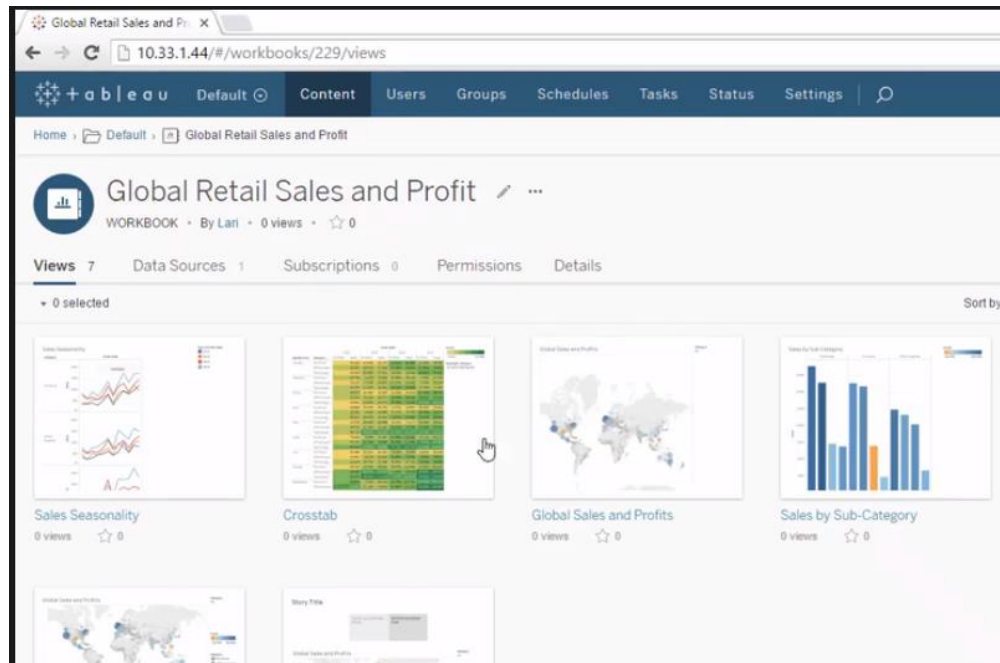
- **Collaboration:** The most effective way to share a workbook is to publish it with Tableau Server or Tableau online. Published workbooks are fully interactive, up-to-date, secure, and can be accessed by browser or mobile app.



To publish, open the Server menu and select Publish Workbook. We could also choose to publish the data source, if we only want to publish the data itself for others to use. We can publish to a specific project, name the workbook, enter a description, tag the content, choose exactly what to publish, and control permissions.



Once published, interacting with content is easy, and everything is still fully interactive, right in the browser. We can subscribe to content to get updates emailed on a set schedule, favorite content, and search and filter.



Additional Resources

Further resources can be found in the righthand panel at the start of Tableau as well as online.

Discover

Training

[Getting Started](#)

[Connecting to Data](#)

[Visual Analytics](#)

[Understanding Tableau](#)

[More training videos...](#)

Sharing

[Learn more about ways to share](#)

Resources

[Blog - 7 reasons LinkedIn just named Tableau a top company to work for... again!](#)

[Tableau Conference - Register Now](#)

[Forums](#)

Appendix B. Cataloged Data Sources

During the course of the project, a number of data sources were identified and added to the Data Catalog (Figure B.1) and categorized according to topic, format, and location. While it can be reasoned that many datasets in one way or another have the potential of providing information that helps with extreme weather management and evacuation planning, a number of key datasets are included that are considered to be potentially relevant to TxDOT. Many of the datasets are local to the Travis County area, and are included to exemplify the positive and negative aspects of cataloging local data. With determined schemes for tagging, organizing, geographic filtering, and description-writing, hundreds of additional datasets can be added to the Data Catalog.

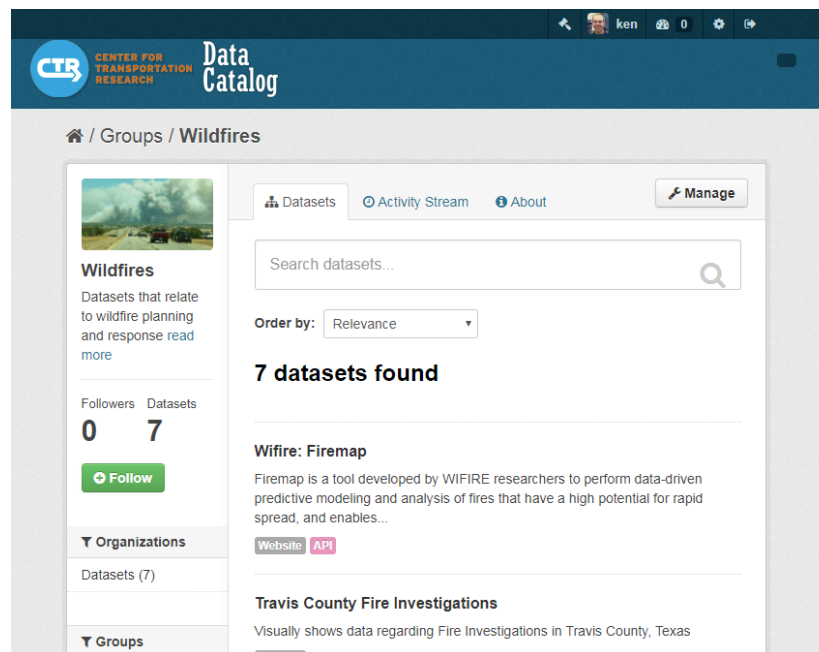


Figure B.1: Screenshot of the preliminary Data Catalog

Datasets

TxDOT C.R.I.S.

<https://cris.dot.state.tx.us/public/Purchase/>
This provides historic crash data, which can be informative for evacuation planning.

TxDOT DISCOS

<http://www.txdot.gov/inside-txdot/division/finance/discos.html>
District and County Statistics publication provides selected transportation-related statistics for each of the 254 counties and 25 TxDOT districts.

TxDOT Roadway Inventory

<https://www.txdot.gov/inside-txdot/division/transportation-planning/roadway-inventory.html>

NOAA: SWDI

<https://www.ncdc.noaa.gov/swdi/#TileSearch>
Provides historic severe weather events for a selected location.

Austin Fire Stations

<https://data.austintexas.gov/Public-Safety/Austin-Fire-Stations/64cq-wf5u>
Identifies locations of fire stations.

AFD Response Area Polygons – 2015

<https://data.austintexas.gov/Locations-and-Maps/AFD-Response-Area-Polygons-Zip-2015/y95t-brjh>

This is a standard set of polygons that delimit AFD response regions.

COA: Creek Lines

<https://data.austintexas.gov/Locations-and-Maps/Creek-Lines/hqpf-kr96>

This identifies all of the creek lines within the Travis County area, which can be useful for vulnerability assessment.

Hydrography Polygons 2006

<https://data.austintexas.gov/Locations-and-Maps/Hydrography-Polygons-2006/99y8-6pgc>

This identifies areas of bodies of water in the Travis County area.

COA: Watersheds

<https://data.austintexas.gov/Environment/Watersheds/ec78-i9z5>

This provides a list of watersheds and identifies which bodies of water are discharged into.

Travis County Fire Investigations

<https://www.traviscountytexas.gov/maps/gis-fire-investigations>

Shows locations of fires by month in Travis County, gives type of fire (structure, vehicle, etc.), address, date, and incident number.

Travis County Building Footprints

<https://data.austintexas.gov/Locations-and-Maps/Building-Footprints-2013/d9te-zi9f>

This geographically depicts all of the structures within the Travis County area,

which can be useful for understanding building density.

COA: Traffic Count Study

<https://data.austintexas.gov/Transportation-and-Mobility/Traffic-Count-Study-Area/cqdh-farx>

This provides historic traffic counts for sampled roadway spot locations and can be informative for understanding roadway usage patterns and background traffic.

USDOT: BTS: Geography Resources

<https://www.bts.gov/explore-topics-and-geography/geography/national>

A collection of books and articles describing a broad variety of transportation statistics.

USDOT: BTS: Freight Transportation: Freight Flows by Highway, Railroad, and Waterway: 2012

<http://w-catalog.utnmc.org/dataset/usdot-bts-freight-transportation-freight-flows-by-highway-railroad-and-waterway-2012>

A series of tabular resources providing freight transportation data

USDOT: BTS Map Transportation Map Gallery

<https://maps.bts.dot.gov/MapGallery/>

Provides an open and easily accessible/downloadable series of maps related to transportation. Provided by the USDOT: BTS.

USDOT: BTS: Transportation Safety: Highway Crash Fatalities 2015

<https://www.bts.gov/topics/transportation-safety>

A series of visual and tabular resources providing transportation safety data

Organizations

National Weather Service: National Oceanic and Atmospheric Administration

<http://www.weather.gov/>

Informs and keeps track of weather conditions and warnings. Provides historic data.

Data.gov: Data Mart COA

<https://catalog.data.gov/dataset?organization=city-of-austin&tags=transit>

Data hosted by Data.gov containing material related to the City of the Austin, particularly aimed at Transit.

USDOT: BTS Open Data Portal

<http://osav-usdot.opendata.arcgis.com/>

A portal for various transportation data, not limited to just roads but rail, aviation and marine.

TTU: NWI: West Texas Mesonet

<http://www.depts.ttu.edu/nwi/research/facilities/wtm/index.php>

Apps and Tools

TX A&M Forest Service: TXWRAP

<https://www.texaswildfirerisk.com/>

Allows wildfire risk data to be obtained for an area, which can then be used to inform the public. This may be of interest for preventative measures.

TxDOT: DriveTexas.org

<https://drivetexas.org>

This site informs citizens of highway conditions, which may be of interest for long-distance evacuation planning.

TxDOT GIS Open Data Portal

<http://gis-txdot.opendata.arcgis.com/>

State of Texas Open Data Portal

<https://data.texas.gov/>

ATX Floods

<https://www.atxfloods.com/>

Provides data for low water crossings and floodplains. Evacuations performed around such locations should be checked for flooding vulnerability.

COA: GIS Department

<http://www.austintexas.gov/department/gis-and-maps>

General resources for mapping and georeferencing.

COA: Open Data Portal

<https://data.austintexas.gov/>

City of Austin's open data portal contains a variety of resources that may be useful for evacuation planning, including infrastructure data and demographics.

RtePM

<http://rtepm.vmasc.odu.edu/>

A graphical web application for planning evacuations and predicting the total evacuation time for a given zone.

Google: Waze

<https://www.waze.com/livemap>

An app for roadway information and travel planning that utilizes crowd-sourced information. It is worthwhile to determine whether partnerships with this app can lead to dissemination opportunities.

NOAA: GIS Map

[http://www.wrh.noaa.gov/map/?&zoom=8&scroll_zoom=true¢er=27.829360859789794,-](http://www.wrh.noaa.gov/map/?&zoom=8&scroll_zoom=true¢er=27.829360859789794,-99.2449951171875&basemap=OpenStreetMap&boundaries=true,false,false&obs=true&obs_type=weather&elements=temp,wind,gust&obs_popup=true&obs_density=1)

[99.2449951171875&basemap=OpenStreetMap&boundaries=true,false,false&obs=true&obs_type=weather&elements=temp,wind,gust&obs_popup=true&obs_density=1](http://www.wrh.noaa.gov/map/?&zoom=8&scroll_zoom=true¢er=27.829360859789794,-99.2449951171875&basemap=OpenStreetMap&boundaries=true,false,false&obs=true&obs_type=weather&elements=temp,wind,gust&obs_popup=true&obs_density=1)

Offers a geographic view of current weather and reported hazards.

InciWeb

<https://inciweb.nwcg.gov/maps/>

Incident Information System across entire USA. Shows fires throughout USA on maps.

USGS Wildfire

USDOT: BTS Interactive Transportation Statistics Map

<https://www.bts.gov/content/state-transportation-numbers>

Provides an interactive GIS interface to quickly get access to transportation-related reports across entire US.

Harris County FWS

<https://www.harriscountyfws.org/>

Harris County Flood Warning System shows both current and historical flood and water related data throughout Harris County, Texas.

Wolfram Alpha

<https://www.wolframalpha.com/>

This provides a query interface for gathering information and performing calculations and provides a means to quickly retrieve basic statistics for any region.

Appendix C. Stakeholder Activities and Communications

The following section outlines feedback provided by stakeholders on current practices in responding to extreme weather events. The feedback was elicited through questions and surveys administered at stakeholder meetings, as well as phone interviews. This is summarized based on the standard template presented below:

Organization (Stakeholders and job titles)

Activities:

- Duties (relevant to this project) performed by the stakeholder and the stakeholder's organization

Proactive Efforts:

- Efforts that help in preparing for weather events before they occur

Reactive Efforts:

- Activities that are performed in response to a weather event that is occurring or had occurred

Other Organizations:

- Outside departments and agencies that share data or are contacted

Data:

- Data sources and methods that are used in conducting these activities

The list is divided into three sections: (1) practitioners who address all emergency events, and then those who contributed specifically to procedures associated with (2) freezing/flooding, and (3) wildfires.

General

This section pertains to stakeholders who address all types of emergencies within their jurisdictions, including freezing, flooding, and wildfires.

TxDOT Traffic Ops. (Brian Fariello, Director, Traffic Management Section)

Activities:

- If the TxDOT EOC is activated, shift to EOC work.
- Stay in touch with district traffic ops staff, identify their needs, liaison with TxDOT administration.
- Ensure TMS ATMS is up and running.

Proactive Efforts:

- Work as needed on evacuation plans.

- Ensure statewide emergency Dynamic Message Sign notification process is up to date.

Reactive Efforts:

- Work with districts on recovery plans, and repair plans that include support from other districts, and statewide contract.
- Create an After Action Assessment.

Other Organizations:

- Other TxDOT districts not impacted by event.
- TxDOT purchasing.

Data:

- Travel speeds, including point speed traffic sensors, and Bluetooth sensors. Data is also obtained from the private sector.
- Roadway volumes.
- Road closures.
- High water detection systems.

Travis County (Brian Burk, Senior Engineer)

Activities:

- Monitor road/weather conditions.
- Manage response to requests for assistance.

Proactive Efforts:

- Locate contract lists and select service providers.
- Identify common flooding crossings.
- Coordinate staffing with other organizations.
- Log in to support systems (WEB EDC, ATXfloods).
- Assist with traffic, specifically with signing.
- Monitor status of developing weather scenarios.

Reactive Efforts:

- Calling/texting contacts to assist in response efforts.
- Completing reports and charge accounts.

- Surveying damage, and assisting with restoration.

Other Organizations:

- TxDOT Austin District
- Travis County Sheriff
- City of Austin Street and Bridge
- Austin/Travis County Office of Emergency Management.

Data:

- On-line third party weather forecasts and data.
- On-site personal report by phone.
- Enterprise data for roads maintenance etc. within GIS.
- Very limited fixed flood gauge data.

CAPCOG (Eric Carter, Capital Area Council of Governments)

Activities:

- Support for regional notification system and web EOC application

Proactive Efforts:

- Planning related to regional collaboration system maintenance/readiness

Reactive Efforts:

- Support as required

Other Organizations:

- County/city emergency management community

Data:

- GIS data (available online and can be field collected)
- Field reports via phone or web browser

FHWA (Kirk Fauver, Planning and Research Engineer)

Activities:

- Damage assessment reviews with TxDOT.
- Recovery efforts with state and local officials.
- Finding sources identified through federal aid highway program for emergency relief.

- Coordination with TxDOT and FEMA during recovery and rebuilding efforts related to transportation systems.

Proactive Efforts:

- Risk assessment for impact and severity; understand the breadth of impact (scope) and magnitude, as well as the types of impacts.
- Identify resources and tools.
- Create a GIS map of evacuation routes with TxDOT.

Reactive Efforts:

- Early and continuous communications.
- Interagency coordination.
- Timely response and action.
- Inform local decision-makers and elected officials.
- Upward coordination with FHWA and USDOT headquarters.

Other Organizations:

- FEMA
- TxDOT
- Texas Commission on Environmental Quality (TCEQ) and EPA
- Small Business Administration (SBA)
- University Research Centers

Data:

- HPMS (pavement condition)
- Traffic volumes (AADT).
- GIS mapping for fire, transportation, and flooding) with GIS-ST (EPA's tool).
- Detailed Damage Inspection Report (DDIR) uploaded to web by area engineers.
- Real-time traffic data.
- Air Quality from TCEQ monitoring/EPA reporting.
- RWIS: road weather information system to measure ice/water, including floods.

Travis County Sheriff's Office (Meg Seville, Planner)

Activities:

- Responding to calls related to roadway issues.
- Blocking roadways when hazards are present.
- Attempting to rescue individuals stuck on roadways.
- Notify Travis County Transportation and Natural Resources (TNR) and TxDOT of needs for barricades and road closures.

Proactive Efforts:

- Monitoring area that are known problems.
- Staff the Emergency Operations Center.
- Prepare extra staffing as needed.

Reactive Efforts:

- Work with partners, TNR, and fire departments, to determine how to better respond in future.
- Participate in groups to identify problem areas.

Other Organizations:

- TNR.
- TxDOT
- Office of Emergency Managemet.
- ESO – Emergency Services District.

Data:

- Simple observations make in the field
- Reports from the public
- Past experience
- River levels from LCRA and the Flood Early Warning System (FEWS).

FHWA (Millie Hayes, Safety and Traffic Operations Specialist)

Activities:

- Reporting road closures to our headquarters and other Federal Government requestors, for use in reporting to superiors and in routing resources into the impacted area.

Proactive Efforts:

- When we know an event is coming, we try to ensure we know of the proper internal and state (TxDOT) counterparts.

Reactive Efforts:

- Usually we do a “lessons learned” session both internally and with TxDOT counterparts to make the process more effective and efficient in the future.

Other Organizations:

- We have one single point of contact for TxDOT and one TxDOT backup.
- Nearly all requests go through these individuals.

Data:

- During and after each incident we pull data from TxDOT’s system, where data is available online for our download.
- After the incident (such as subsequent emergency relief efforts), we create data in the form of reports created while in the field. We use a Federal Government app for emergency relief efforts.
- No sensor data is used except from those partners.

Travis County Roadway Maintenance (Scott Lambert, Engineer)

Activities:

- Preparing special maps that address key issues or impending events.
- Attend shifts at CTECC.
- Coordinate after Hours Response (ART) crew locations.
- Support traffic signage for shelters/routes.

Proactive Efforts:

- Map locations with issues that had been identified in the past.
- Review ART contacts and check with primary contacts.

Reactive Efforts:

- Coordinate pickup of barricades.

- Drive to damaged area and review road conditions.
- Plan long term repairs where needed.

Other Organizations:

- Other road maintenance departments
- Law enforcement.

Data:

- Jurisdiction maps
- ATXfloods
- Weather radar
- Google traffic flow maps

City of Austin Office of Sustainability (Rodrigo Leal, Research Analyst)

Activities:

- Interviews w/ response stakeholders to compile lessons-learned/best practices. (Office of sustainability is more involved in research AND policy recommendations not directly involved in incident response).

Proactive Efforts:

- Currently working on a set of recommendations/strategies focused on citywide climate change including adaptation and preparedness. Those will hopefully inform future disaster response

Reactive Efforts:

- Try to understand lessons-learned.
- On case-by-case basis, contribute to EOC staff at CTECC

Other Organizations:

- Within City of Austin: Homeland Security and Emergency Management (HSEM), Watershed Protection, Austin Fire Department, Austin Energy, Austin Water, Public Works, Austin Transport, Austin Public Health

Data:

- Neighborhood-specific evacuation plans for locations at greatest risk of flooding/wildfire. These are often considered in terms of developments, not predefined zones.
- For real-time flood/road closure info, ATXfloods GIS maps.

- For flood risk, FEMA floodplains and maps on localized flooding from Watershed Protection.
- For fire risk, fire risk maps from AFD and TXWRAP. This information has been collected for a preliminary risk assessment of Austin's 33 critical arterial roads

Roadway Operations: Freezing and Flooding

TxDOT (Daniel Richardson, TxDOT Director of Operations, and Carl Johnson, District Engineer, TxDOT Abilene District)

Activities:

- Winter roadway maintenance, sand, salt, and brine application, plowing snow.
- Flood response

Proactive Efforts:

- Pre-treat roads 2-3 days with brine before an expected weather event, or shorter turnaround pre-treating.
- Equipment maintenance and preparations ahead of season.
- Set up and open an emergency operations center as needed.
- Create an SOP or “Plan” for the emergency.
- Place employees “on call” on the front end of the event. Uploading information into DriveTexas.org

Reactive Efforts:

- Plowing snow
- Coordinating movement of equipment from neighboring districts
- Mitigating freezing
- For flooding, drive to problem areas and make assessments. Barricade if necessary.
- After Action Reporting
- Repairing and cleaning equipment

Other Organizations:

- Neighboring TxDOT districts
- Texas Department of Public Safety

- Texas Forest Service
- National Weather Service

Data:

- NOAA, National Weather Service (website and personnel consultations) that shows NOAA data plus private weather stations.
- Assessments out on the roadway.
- No sensors available except for a couple of weather stations.

TxDOT (Brian Dodge, TxDOT Emergency Management Coordinator, TxDOT Maintenance)

Activities:

- Coordinating preparation and responses for winter treating.
- At time of interview, coordinating at the emergency operations center in Houston because of Harvey.

Proactive Efforts:

- Pretreating
- Coordinating the movement of resources from neighboring districts. The TxDOT snow and ice procedure manual informs some of the processes.

Reactive Efforts:

- Removal of debris caused by Harvey

Other Organizations:

- Emergency responders
- FHWA
- National Weather Service (via online data resources and direct communications with analysts).

Data:

- Weather maps
- Flood level readings
- Corps of Engineers dam operations and water releases
- A&M Texas Forest Service drought potential data and potential wildfire fuel

Wildfires

City of Austin (David Ginnich, Water-Wildland Conservation)

Activities:

- GIS emergency response team.
- Responder to CTECC (the Austin area emergency response center and EOC facility).
- Make maps upon request.

Proactive Efforts:

- Monitor weather.
- Prepare for the GIS transition to a new commercial provider.
- Check that data is up to date.

Reactive Efforts:

- Respond to CTECC and make maps upon request.
- Supporting shelter response with maps.

Other Organizations:

- Homeland Security and Emergency Management (HSEM).
- Watershed Protection.
- Austin Fire Department Wildfire Division.
- Travis County GIS group.
- Austin Police Department.

Data:

- City internal data.
- Online and field collected fire risk.
- Map-based data that are critical for evaluating fire progression and land accessibility, including floodplains, slope, structure density, and fire fuel sources.
- Work is mainly done with LIDAR data to model fire risk, so it is from a fixed point in time.

Austin Fire Department (Nate Casebeer, Forester)

Activities:

- Providing data for maps regarding each incident (including wildfires) to AFD or other incident command centers

Proactive Efforts:

- Identifying hazardous areas and potential risk

Reactive Efforts:

- Incident mapping, visually representing the effects/impacts of the incident

Other Organizations:

- Others in AFD
- Austin Water Utility
- City of Austin Communications
- City of Austin Office of Sustainability

Data:

- Field collected data
- Online data
- Data shared through interdepartmental cooperation, as well as in-house data.
- AFD response zones, neighborhood boundaries, land use, roads
- Mobile data collector (ArcCollector) application for cell phones/tablets.
- Drone Imagery

Austin Fire Department (William Weldon)

Activities:

- Operationally engage an incident on the fire-line as well as planning and coordinating support.

Proactive Efforts:

- Follow the Texas Forest Service fire weather and predictive services.

Reactive Efforts:

- Observe how a fire burned in an area under weather, fuels and topographic inputs.

Other Organizations:

- TFS
- USFWS
- Other ESDs
- Other Federal agencies (such as BLM and USFS).

Data:

- City of Austin infrastructures.
- Community Wildfire Protection Plan (CWPP) data, which is developed by a third party.
- Critical infrastructure data.
- Records of fire-line intensity that can be used to better understand fire behavior under conditions.
- Fuels mapping.

Appendix D: Specifications for Sensor Deployments

Introduction

This appendix contains specifications for mounting various sensor types that are referred to within this project and report.

Radar sensors (OTT/Sutron)

Specifications

- Minimal measurement range (height): 3 ft
- Maximal range (height): 100 ft
- Max tilt: 15 degrees with respect to vertical
- Beam angle: 12 degrees
- Weight: 4.6 lbs

Suggested Deployment Configurations

- On bridge: bolted under the bridge, at least 6 feet away (and less than 100 feet) from water. (See Figure D.1).
- On bridge: bolted to the side. If mounted to a pole/mast, use an arm of around 4 ft to reduce possible interference.



Figure D.1: Under bridge mounting configuration

- On a pole/mast. The pole/mast needs to be at least 10 ft tall, with a cantilever of at least 4 ft, capable of supporting the weight of the sensor (4.6 lbs). The solar panel, battery and datalogger are mounted on the pole, while the sensor is mounted at the end of the cantilever. Poles taller than 30 ft may require a longer cantilever depending upon sensor tilt. (See Figure D.2.)



Figure D.2: Mast/arm mounting configuration

Multiple sensors can be mounted on the same pole, provided that the pole is able to carry their weight.

The radar water level sensor is designed to be mounted over water, but it can also be mounted over ground—e.g., a creek bed, creek shore, or nearby flood-prone patch of rocks or pavement. Light vegetation (e.g., long grass) is expected to not significantly interfere with operation. To measure water level directly on a roadway, the beam area would need to cover a portion of the road that is not regularly driven on, such as the shoulder. The beam area would need to be well clear of guardrails.

Mounting Parameters

Please refer to the following diagram (Figure 3) for clarification on mounting parameters and requirements. Please note that the beam area is approximate.

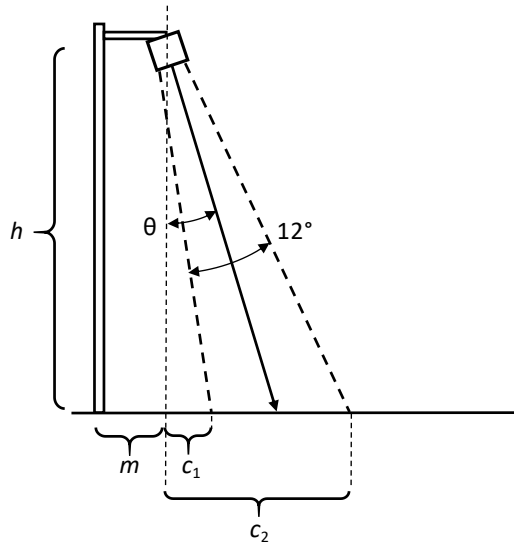


Figure D.3: Mounting parameters for OTT/Sutron radar water level sensors

In the diagram:

h = height above ground ($\geq 3'$, $< 100'$)

m = arm/cantilever length (if mounted on pole, $\geq 4'$)

θ = sensor tilt angle with respect to vertical ($< 15^\circ$)

c_1 = approx. beam extent, near-side with respect to sensor vertical: $h \times \sin(\theta - 6^\circ)$

c_2 = approx. beam extent, far-side with respect to sensor vertical: $h \times \sin(\theta + 6^\circ)$

Table D.1 shows calculated values for near-side and far-side beam extents.

Table D.1: Approximate values for near-side c_1 and far-side c_2 with respect with the sensor vertical

		Near-side c_1 (approx. feet)						Far-side c_2 (approx. feet)					
		Tilt Angle θ (degrees)						Tilt Angle θ (degrees)					
		0	3	6	9	12	15	0	3	6	9	12	15
Height h (feet)	5	-0.5	-0.3	0.0	0.3	0.5	0.8	0.5	0.8	1.0	1.3	1.5	1.8
	10	-1.0	-0.5	0.0	0.5	1.0	1.6	1.0	1.6	2.1	2.6	3.1	3.6
	15	-1.6	-0.8	0.0	0.8	1.6	2.3	1.6	2.3	3.1	3.9	4.6	5.4
	20	-2.1	-1.0	0.0	1.0	2.1	3.1	2.1	3.1	4.2	5.2	6.2	7.2
	25	-2.6	-1.3	0.0	1.3	2.6	3.9	2.6	3.9	5.2	6.5	7.7	9.0
	30	-3.1	-1.6	0.0	1.6	3.1	4.7	3.1	4.7	6.2	7.8	9.3	11
	40	-4.2	-2.1	0.0	2.1	4.2	6.3	4.2	6.3	8.3	10	12	14
	50	-5.2	-2.6	0.0	2.6	5.2	7.8	5.2	7.8	10	13	15	18
	60	-6.3	-3.1	0.0	3.1	6.3	9.4	6.3	9.4	12	16	19	22
	80	-8.4	-4.2	0.0	4.2	8.4	13	8.4	13	17	21	25	29
	100	-10	-5.2	0.0	5.2	10	16	10	16	21	26	31	36

Sadeem WSS

Because of continued communications issues, our original long-range plans for the Sadeem sensors requires some alteration. To summarize, the gateways that we intended to interface between the sensors and the cell phone network don't have the correct protocol to speak with the Sadeem sensors. To make these work, we have come up with a plan to use "homebrewed" computing hardware to act as viable gateways.

The main implication of this is that we need to provide power to one or two of these updated gateways; solar won't work. While 110V is easiest to use for power, we can potentially find other power transformers that can provide the 5V that the gateway equipment needs. Possibilities include signal control cabinets, DMS sign cabinets, or other field stations that receive power. The Sadeem sensors themselves continue to be solar-powered.

Figure D.3 shows deployment options for the three Sadeem sensors. There are a variety of options based upon whether we can find one or more sufficient powered bases of operation for the gateways. Each gateway can wirelessly connect multiple Sadeem sensors with a maximum range of 1000 ft (rural), or 300 ft (urban). We can provide one or two gateways. Two may be preferable if power can be found in two interesting field locations. Furthermore, if there's a consideration for it, we do have the option of deploying one of the sensors in the maintenance yard, similar to what had been done in the past.

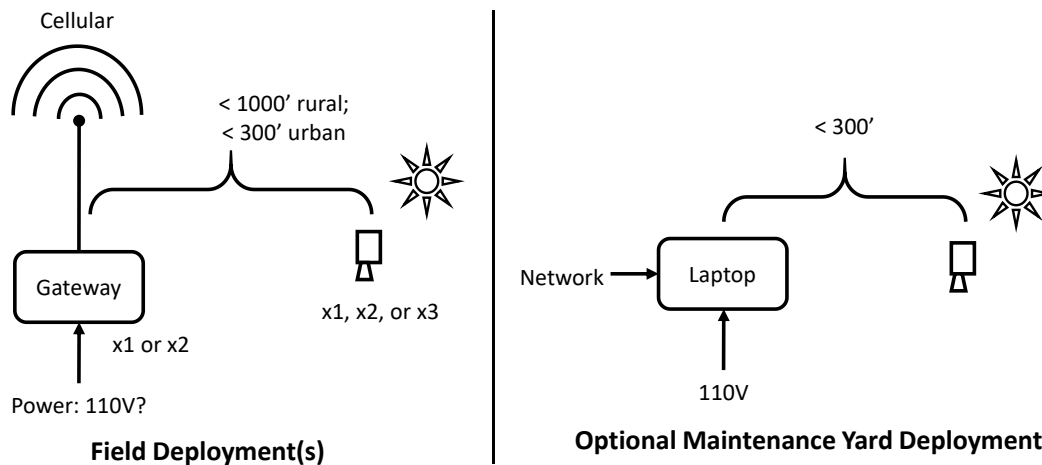


Figure D.3: Deployment options for Sadeem sensors

Figure D.4 shows possible mounting configurations for the Sadeem sensors. The left side of Figure D.6 (on the left side) is also viable, along with bridges, signal crossbars, and sign bridges.

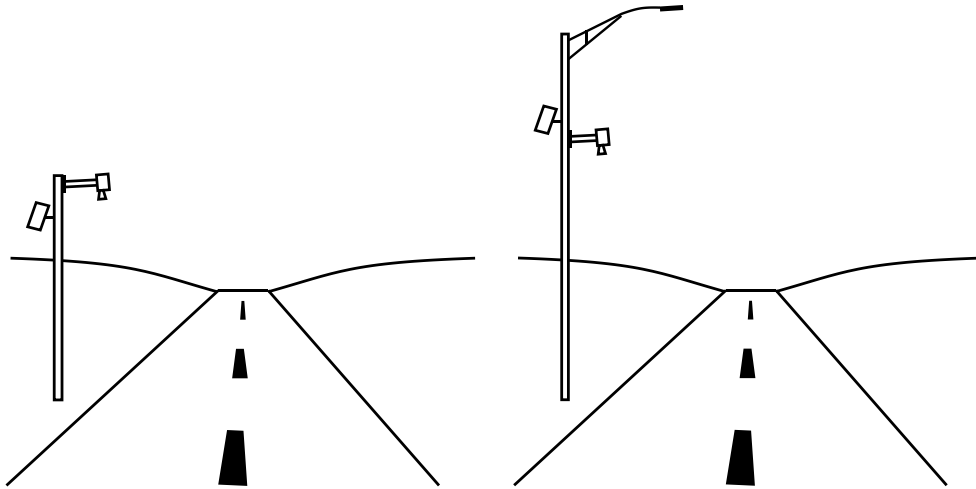


Figure D.4: Possible mounting configurations for Sadeem sensors and solar panels; also see the left side of Figure D.6

Specifications:

Max. communications range from gateway: 300 ft (urban); 1000 ft (rural)

Max. beam distance to measured surface: 18 ft

Max. tilt: 10° with respect to sensor vertical

Beam angle: ~15°

Min. clearance of beam: 1 ft. Keep at least a foot clearance around the beam area for all distance the beam travels from the sensor, including poles and guardrails.

Fixed IceSight 2020E

The Fixed IceSight will now come equipped with a 26" x 17" x 16" aluminum weather resistant locking cabinet (see Figure D.5) that houses data-logging equipment, a cell phone modem, and a pair of sealed batteries that are about the size and weight of car batteries. The complete system will be solar-powered and will need to be within cell phone reception.



Figure D.5: Cabinet for Fixed IceSight equipment

Figure D.6 shows possible mounting configurations for the Fixed IceSight. While a signal mast arm configuration is shown on the left, other configurations could be a sign bridge, a roadway bridge, or other strong overhead structure.

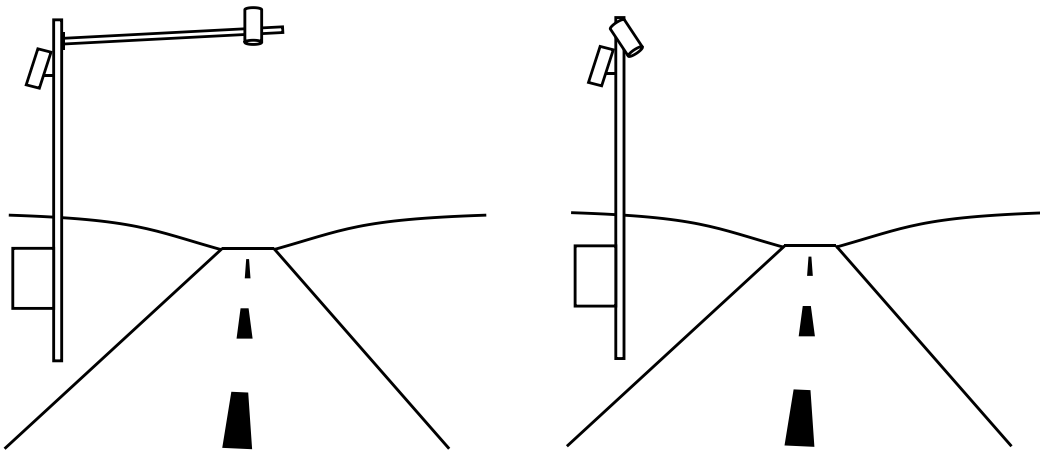


Figure D.6: Possible mounting configurations for Fixed IceSight 2020E, solar panel, and cabinet

Specifications:

Max. range: 50 ft

Spot size: 36 in. at 30 ft

Elevation angle: 30° to 85°

Weight (of the elevated sensor): 8 lb.

Mobile IceSight 2017

The Mobile IceSight now shall be equipped with an “MPU”, a self-contained “mobile processing unit” that sits in the vehicle. The MPU is powered from the vehicle and has attached to it a GPS receiver and a cell phone modem. This will allow independent operation of the Mobile IceSight. The theory is that when the MPU is switched on, the vehicle’s location and roadway surface temperature measurement will show up on the laptop back in the District Office, and perhaps in a Web interface that can be accessed from anywhere online.

Other Sensors (Troposphere and Weather Stations)

Sensors may be mounted on poles. Minimum height of each sensor: 7 ft. Higher heights may reduce the risk of vandalism and also have a higher chance of accurate temperature measurements. A good target is at least 10 ft.

There is no specific requirement in sensor orientation (except for the wind vanes and wind speed sensors, and rain rate sensors, which must be upright).

Appendix E: Training Workshop Presenter Overview

This appendix introduces and summarizes the training workshop material that was produced during the course of this project to disseminate project content and findings to interested practitioners. Figure E.1 provides the presentation title slide. The full presentations are available in a separate publication: 5-9053-01-P2, *PowerPoint Presentations for the Training Workshop*.

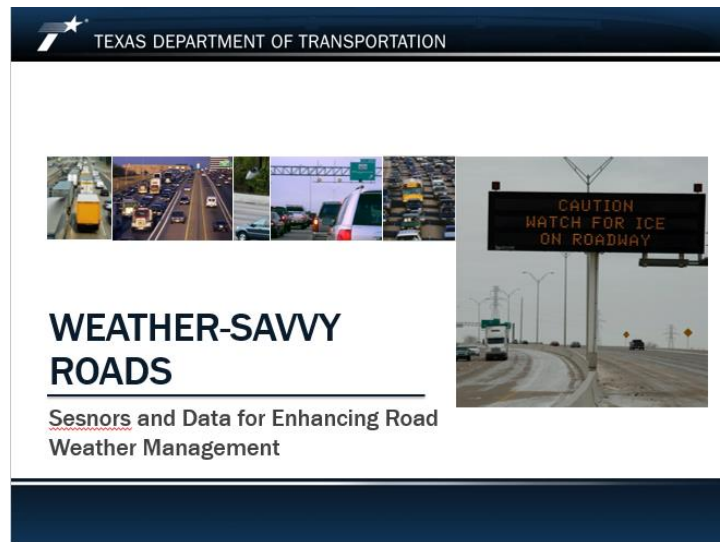


Figure E.1: Title slide for the presentation materials

Overview

- **Title:** Weather Savvy Roads: Sensors and Data for Enhancing Road Weather Management
- **Purpose:** To introduce processes and challenges for deploying sensors and using data
- **Objective:** After the workshop, participants should be informed on key concepts needed for a successful sensor deployment.
- **Contents:**
 - o Introduction (15 minutes)
 - o Part 1: Technologies for Road Sensing (1 hour, 30 minutes)
 - o Lunch break and demonstrations (1 hour)
 - o Part 2: Data, Decision-Making, and Dissemination (1 hour, 15 minutes)
 - o Dismissal and additional one-on-one conversations

Part 1: Technologies for Road Sensing

This first section of the workshop focuses upon sensors: operation, deployment, and maintenance. Although this section is to be delivered in lecture format, discussion throughout the section is encouraged. The technical level of the audience should be gauged to adjust the depth of technical details that are to be delivered. The presenter should be at least moderately familiar with sensor capabilities and installations. While this presentation does not substitute the knowledge and experience of a vendor or agency personnel who have had significant experience with sensor devices, this presentation is intended to convey the most common challenges and concerns of any sensor deployment. The goal is for participants to achieve a working level of familiarity such that they can ask well-informed questions and have feasible expectations when working with knowledgeable personnel on implementing a sensor deployment.

Part 1 is divided into the following sections:

- **Present a high level overview of sensors:** types, topology styles, measureable phenomenon, and total sensor cost
- **Important sensor specifications to select appropriate solutions:** understanding features, sampling rates, and what to look for on a sensor product's datasheet
- **Power considerations:** a primer for understanding power requirements for sensors in the field, with emphasis on operating "off the grid" with solar panels, batteries, and an energy budget
- **Wireless communications considerations:** an overview of the wireless spectrum, communications technologies, expected distances, and international standards
- **Lessons learned:** challenges encountered within this project that may also be relevant to future sensor purchases, integrations, and deployments
- **Five assessment questions** are included at the end of Part 1 to satisfy training material requirements. These may be used in training delivery as group discussion exercises, depending upon the needs of the participants.

Lunch Break and Demonstrations

This is an opportunity to demonstrate live sensor operation at distinct stations, and to engage in one-on-one conversations with workshop participants.

Part 2: Data, Decision-Making, and Dissemination

The second section of the workshop transitions over to several topics that have to do with effectively using data that comes from sensors or other sources. Much of this conveys best practices that have been documented in other agencies across the United States, as well as

experimental results from efforts conducted through the course of the project. The presenter should be at least moderately familiar with the data topics contained within the materials. Again, while the slide content can be delivered in lecture format, discussion should be encouraged as the wide topic areas of the lecture content may pique thoughts and realizations among the participants.

Part 2 addresses the following:

- **Sensors and IT architecture:** looking at methods for accessing sensor data given IT security policies
- **Low water crossing study:** a review of two low-water crossing studies, including survey results in a 2011 TTI study
- **Case studies:** road weather data: an overview of practices from other DOTs as reported by the FHWA
- **Dissemination to the public:** a look at current and emerging methods for facilitating the dissemination of information to the public, including an introduction to social media, and Pathfinder DMS message guidelines
- **Data analysis:** A look at data fusion experiments that add value to data by combining data sources with novel visualizations
- **Discussion topics** are prompted at the tail end of the section, but may occur throughout as desired and facilitated.