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Down-to-Earth Winter Operations Sensing and Data Applications

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16. Abstract

Weather-responsive management strategies (WRMS) are innovative approaches to utilizing data in making decisions for roadway operations and maintenance. Texas Department of Transportation (TxDOT) has been evaluating low-cost approaches for enhancing WRMS, with special emphasis on suburban and rural environments. The main focus of Project 0-7007 is to find a sustainable approach for automatically and passively sensing winter weather operations treatment activity through detection of plowing, sand spreading, and brine spraying, and to utilize live and historic data for spreadsheets, reports, and GIS applications. A pilot was conducted where six winter operations vehicles were equipped with sensors to detect where and when key equipment is switched on or off. General-purpose sensor inputs on the existing fleet telemetry system were then utilized to send those events through the same pipeline that supplies live-vehicle position data to TxDOT GIS apps. Successful results from the pilot, lessons learned, and findings from evaluations on fixed- and mobile-sensor devices are reported. Similar strategies are applied to events that extend beyond winter weather.

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weather, winter, ice storms, sensors, data, information dissemination, telemetry, operations, maintenance, management, geographic information systems

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Products

Because of changes in fleet tracking technology utilized by the Receiving Agency, the first product developed by this project, "Mounting and Basic Operation Manual" (0-7007-P1), has been superseded by the contents of Chapter 3 in this report.

The second product is a set of PowerPoint slides presented in the Aug. 24, 2021 project workshop (0-7007-P2).

The third product is a set of PowerPoint slides, notes, and videos from the April 24, 2023 project workshop (0-7007-P3).

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Chapter 1. Executive Summary

In operating and maintaining a transportation system, one of the most important factors that must be reckoned with is weather. Extreme weather imposes significant safety, economic, environmental, and quality-of-life implications on all travelers. It also costs billions of dollars to the traveling public, DOTs, and business (FHWA, 2018). Of all crashes across the United States, 21 percent is attributable to weather, of which 26 percent is ice-related, and 72 percent is linked to wet pavements (NHTSA, n.d.). Of all causes of non-recurring delays, 25 percent is due to weather (Schrank, 2015), impacting the mobility of travelers and freight alike.

Weather-responsive management and maintenance strategies (WRMS) are innovative approaches to traffic operations management and roadway maintenance that mitigate the effects of adverse weather on the transportation system. WRMS includes establishing effective data tools that help managers in planning and decision-making, especially with respect to extreme weather. Desired outcomes of these strategies include reduced weather-related vehicle crashes, decreased delays, improved mobility, and environmental benefits. Texas Department of Transportation (TxDOT) with support from the United States Federal Highways (FHWA) Every Day Counts (EDC) program has been evaluating new weather-related data sources including those that come from low-cost sensors and data services for purposes of enhancing WRMS, with special emphasis on suburban and rural environments.

This project was designed to lay groundwork for enhancing the value of current and future strategies by showcasing data processes that fit within existing IT architecture and cybersecurity models. A cornerstone of the project is to find how to automatically and passively sense winter weather operations treatment activity such as plowing, sand spreading, and brine spraying. Data from these activities are then analyzed and visualized within a demonstration environment using ArcGIS Pro. Tenets that guide the project include:

- Hands-free, passive data collection that does not require any awareness or intervention from equipment operators;
- GPS benefits available where equipment sensing is not available;
- Fallback path to manual procedures when technology fails; and
- Intent to enhance current operations capabilities, not to entirely replace existing processes.

Chapter 2 illustrates the broad landscape of WRMS, both in data inputs and applications. Data may originate from a variety of sources, including roadside sensors, on-vehicle equipment, data services, and combinations of these. Prior research and implementations around WRMS have focused on the use of roadside weather information systems (RWIS) and software that facilitates the collection, analysis, and visualization of data, and decision support. Systems across the nation range from dash cams on snowplows to fully integrated materials-deployment tracking and optimization solutions. Along with WRMS, the use of crowdsourced data and effective dissemination of quality information continue to be active areas of interest for DOTs.

Chapter 3 describes a process that project researchers have established for piloting the capability of sensing winter operations (WinterOps). The Geotab fleet tracking system installed on TxDOT's ~11,000 vehicles offers a set of general-purpose auxiliary input channels that can be accessed through a custom-wired peripheral attached via cable harness. The wiring allows for detecting when sensed equipment is switched on or off. Inputs are timestamped, geolocated, and sent to the same data back-end that supplies live vehicle position data for Texas Emergency Response Application (TxERA) and related GIS-based tools. Sensing is often achieved by tapping off of +12V lines that activate when respective equipment is used. Detecting plowing activity through the use of external sensors on the plow rig has offered challenges, but a post-processed heuristic has shown improved ease of installation and resiliency. Through the course of the project, six vehicles (four from the Abilene District and two from the Lubbock District) were equipped with WinterOps sensing capabilities and shown to produce data that was recorded by the Geotab system. During the project's pilot, those vehicles in service produced data throughout the Winter 2023 season.

Chapter 4 offers background information on earlier stages of the project where strategies for WinterOps sensing had been developed. It offers explanations to supplement the installation process described in Chapter 3.

Chapter 5 extensively looks at the use of WinterOps data for the purposes of diagnosing sensing status, collecting live or historic data in comma-separated value (CSV) format, and performing advanced analysis in ArcGIS Pro. The advanced analysis includes functions for mapping vehicle tracks to underlying map geometry, identifying historic treatment activity for a given roadway segment, and producing graphical reports of region-wide treatment activity. Capabilities demonstrated in ArcGIS were written in a modular fashion to facilitate eventual integration into new applications including TxERA and operations dashboards. Chapter 5 concludes with a case study on utilizing semi-automated WinterOps data for improving brine usage tracking processes that currently rely upon hand-written records.

Chapter 6 presents roadside and on-vehicle weather sensor solutions that were evaluated for the project. Capabilities and experiences are offered for each product, followed by data visualizations and insights discovered by project researchers. Chapter 6 concludes with an in-depth look at strategies for predicting roadway surface freezing from prior weather data.

Finally, Chapter 7 describes non-winter applications for many of the WRMS previously presented. Applications include herbicide application, incident response, and rainfall detection (to include observations on how speed can be affected by adverse weather and roadway operations).

Through its duration, Project 0-7007 facilitated the presentation of two workshops and one major demonstration that presented the evolution of the WinterOps sensing installation process and practical uses for data. The intent was to illustrate how a traffic operations center's capabilities for understanding exactly what is happening on the roadways can be significantly improved through WinterOps sensing.

While TxDOT may seek to move toward new digital capabilities offered on vehicles that are acquired in the future, most of TxDOT's existing WinterOps fleet (to include some vehicles of significant age) will remain in service for many years. A process that allows for the low-cost addition of WinterOps sensing capabilities and a suite of IT solutions on the back-end would equip older vehicles with similar feature-sets as the newest. For live winter operations and pre-season planning, consistent technology across fleet vehicles allows TxDOT to manage WinterOps effectively, increase coverage of winter treatment, optimize the usage of treatment materials such as brine, and improve safety for the traveling public.

Chapter 2. Introduction

This chapter presents an introduction to Weather-responsive management Strategies (WRMS). To define WRMS and the initiating drive for the project, the United States Federal Highway Administration (FHWA) states (FHWA, 2015):

> The Weather-Responsive Management Strategies initiative under the Federal Highway Administration Every Day Counts – Round 5 (EDC-5) program promotes the use of road weather data from mobile and connected vehicle (CV) technologies to support traffic and maintenance management strategies during inclement weather. The goal is to improve safety and reliability, as well as to reduce environmental impacts on the transportation system resulting from adverse weather.

WRMS strategies have the potential to reduce weather-related vehicle crashes, decrease delays, improve mobility, and provide benefits to the environment. Key outcomes of interest to a DOT are reductions in costs and improvements in dissemination of information to travelers. A compelling demonstration of new strategies would leverage the latest weather-related data sources, roadside sensing technologies, and on-vehicle equipment to enhance a department of transportation's (DOT) ice prevention and response activities.

The project described in this report brings an improved understanding of WRMS to Texas Department of Transportation (TxDOT), focusing upon the sensing of winter operations (WinterOps) at times of inclement weather, and practical uses of various data sources, especially within the context of a GIS system. In this chapter, a literature search surveys and synthesizes relevant efforts across the United States and internationally to highlight examples that are relevant to the needs of Texas. Special attention is given to those that leverage emerging mobile technologies. The intention is that the background material can help inform how the WRMS demonstration platform for freezing weather should be designed and operated in subsequent stages of this project.

The FHWA EDC-5 program that provided sponsorship for this project was intended to further states' investment and practice in providing traffic advisories and warnings to travelers, as well as improving the ability to control the flow of traffic on highways during inclement weather. A recent focus of the program used mobile observations and connected vehicle (CV) data to support traffic and maintenance management. This project continued activities that were begun under the EDC-4 program and TxDOT Project 5-9053-01 (Bhat, 2019). That earlier program emphasized the use and development of capabilities in Integrating Mobile Observations (IMO) applications and clear communications among agencies and messages to the traveling public through Pathfinder. Further elaboration on program objectives, as well as work conducted by other state DOTs, are summarized in Section 2.2.4, as well as other portions of Section 2.4.

The next section provides an overview of WRMS as well as road-weather information systems (RWIS) that provide data for WRMS. Section 2.2 then explores maintenance decision support systems (MDSS) that are actively pursued by a number of state DOTs for actively optimizing their winter weather operations. Finally, Section 2.3 looks at how outcomes from WRMS are helping to better inform the travelling public.

2.1. WRMS and RWIS

WRMS pertains to activities around acquiring relevant and timely information about weather (current and forecast) and road conditions for the purpose of implementing appropriate maintenance measures by the transportation agencies and disseminating information to road users. Figure 2.1 shows a typical WRMS schematic concept.

RWIS is a common mechanism for supplying data for WRMS. According to the Federal Highway Administration (FHWA, 2023):

> [RWIS] is comprised of Environmental Sensor Stations (ESS) in the field, a communication system for data transfer, and central systems to collect field data from numerous ESSs. These stations measure atmospheric, pavement and/or water level conditions. Central RWIS hardware and software are used to process observations from ESS to develop nowcasts or forecasts, and display or disseminate road-weather information in a format that can be easily interpreted by a manager.

There are three kinds of RWIS, including those for atmospheric data (air temperature and humidity, visibility distance, wind speed and direction, precipitation type and rate, cloud cover, tornado or waterspout occurrence, lightning, storm cell location and tracking, and air quality), pavement data (pavement temperature, freezing point and condition, chemical concentration, and subsurface conditions), and water level data (stream, river, and lake levels near roads and tide levels). As seen below, RWIS may be located at the roadside, or on board DOT vehicles.

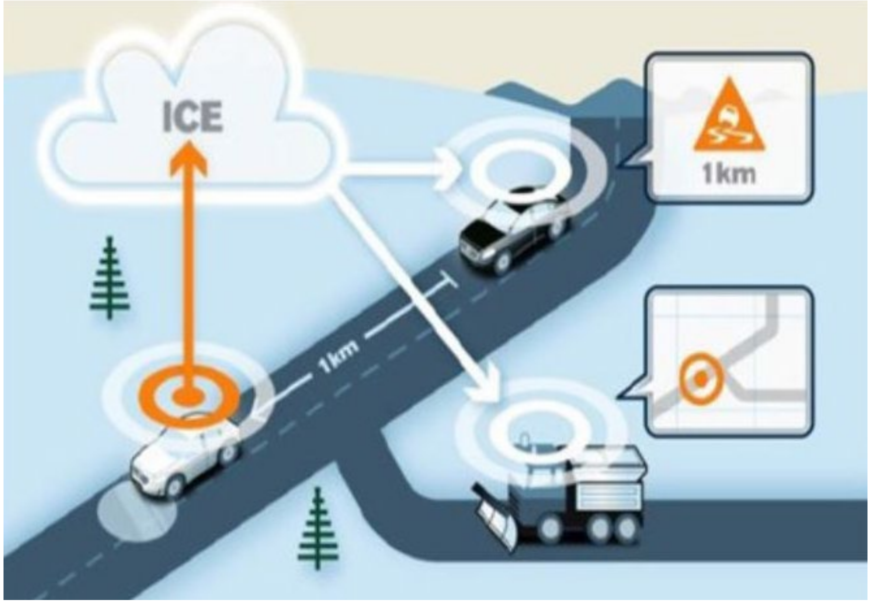


Figure 2.1: Winter Weather-responsive Management Concept Example (Source: FHWA)

2.1.1. Types of WRMS and Uses for RWIS

This section briefly outlines the strategies and sources that comprise WRMS that are implemented by various DOTs. A variety of strategies exemplify the diversity of WRMS applications:

Traffic Management Strategies

- Motorist advisory and warning systems: 511, Highway Advisory Radio (HAR), variable message signs (VMS), dynamic message signs (DMS), website, kiosk, in-vehicle application, smartphone application
- Signal timing and ramp metering
- Variable speed limit
- Road/lane closure
- Traffic diversion
- Vehicle restriction

Maintenance Management Strategies

- Anti-icing and de-icing
- Plowing and snow removal
- Route optimization/vehicle tracking
- Debris removal
- Water drainage maintenance
- Vegetation control

Mobile and CV WRMS Data Sources

- Vehicle-based road-weather sensors: friction, temperature, precipitation, snow depth, etc.
- Onboard cameras
- Electronic tablets and smartphones
- Global Positioning System (GPS) receivers/AVL systems
- Vehicle Controller Area Network (CAN) bus

2.1.2. Vehicle-based Sensor Technologies for WinterOps

Ye et al. (2011) synthesized the information regarding the development and implementations of various vehicle-based technologies for winter road management practices. They are listed in the following subsections.

2.1.2.1. Automatic Vehicle Location (AVL)

Automatic Vehicle Location (AVL) is a technology that integrates information produced by a maintenance vehicle, such as location, to provide temporally and spatially referenced information on that vehicle's activities. This allows faster responses to storms through vehicle tracking and dispatching capabilities. AVL can also help simplify tracking and reporting requirements, thus decreasing the time and paperwork required to manage winter maintenance activities. Figure 2.2 represents a typical AVL implementation concept.

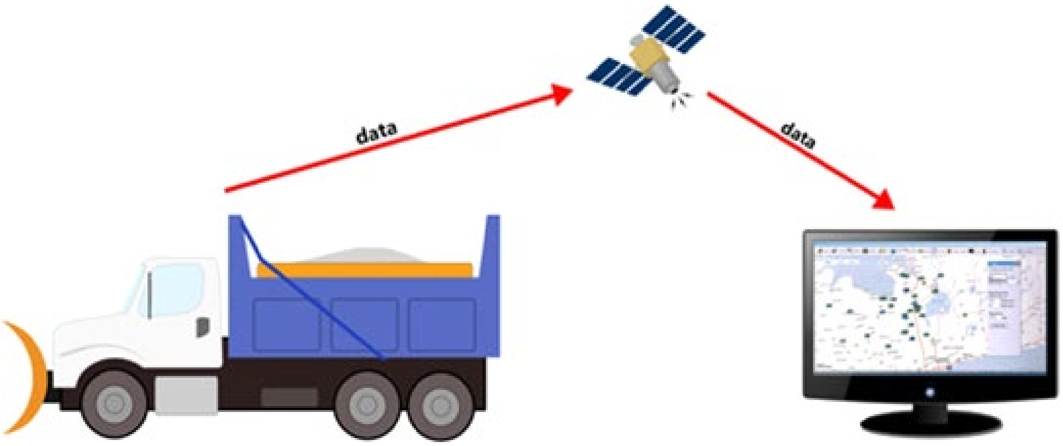


Figure 2.2: AVL Concept Diagram (Source: CDOT)

2.1.2.2. Mobile RWIS Technologies

Vehicle-based RWIS includes technologies like surface temperature measurement devices, onboard freezing point and ice-presence detection systems, and salinity measuring devices. Figure 2.3 shows an example of a plow-mounted onboard unit used as mobile RWIS.

Surface temperature measurement devices

Surface temperature measurement devices usually use vehicle-based, non-contact infrared (IR) sensors, which absorb the infrared emissions from the road surface. The quantification provides an indirect measure of surface temperature. These devices generally consist of an IR sensor, a processor, and a display unit. The entire sensor assembly can be mounted on the maintenance vehicle.

Onboard freezing point and ice-presence detection systems

This technology allows mapping of the road surface conditions along an entire roadway network, detects localized ice patches, and provides greater knowledge of the effects of de-icing and anti-icing chemicals on the road surface.

Salinity measuring device

Salinity measuring devices are used to monitor the residual salt concentrations on the road surface, which helps maintenance managers make informed decisions related to chemical application and reapplication. Monitoring the concentration of the solution on a road surface along entire stretches of roadways would allow for more accurate chemical application rates; integrating measurements from salinity sensors to automatic spreader controls allows the spreader to apply the right amount of chemicals in the correct location.

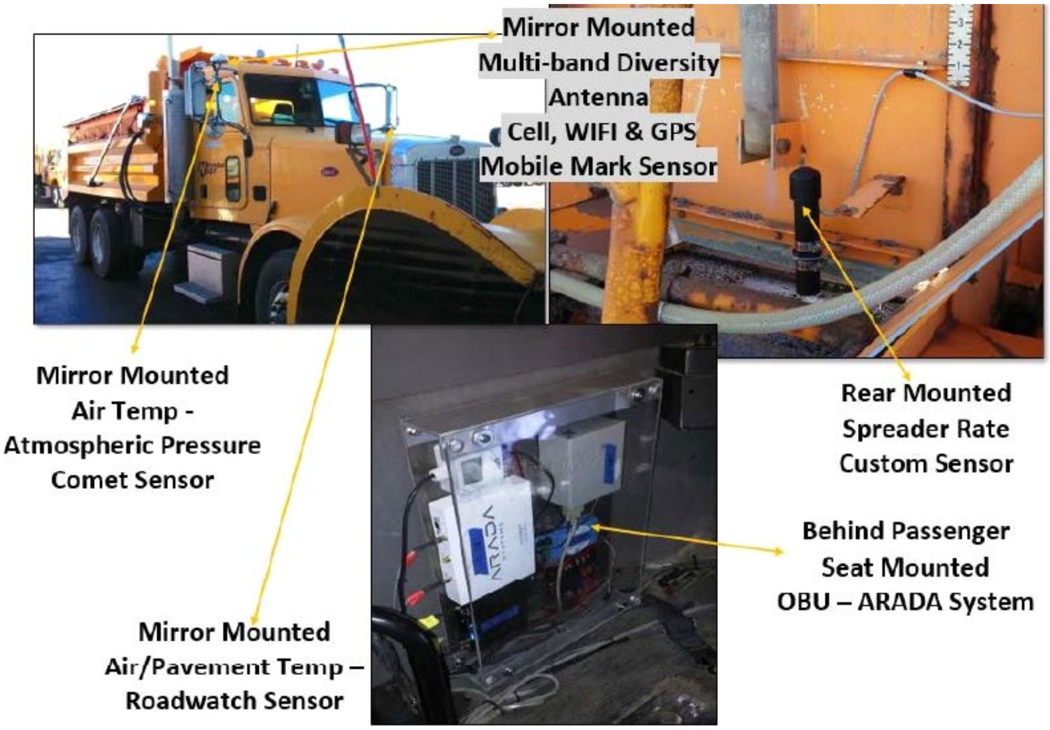


Figure 2.3: Plow Onboard Hardware and Sensor Placement (Source: NDOT)

2.1.2.3. Millimeter Wave Radar System

The millimeter wave radar system (MWRS) works by sending out signals that reflect off objects in their path; the radar system detects the echoes of signals that return. MWRS specifically employs electromagnetic waves with wavelengths from 1 to 10 mm. An advantage offered by this system is that it works over long ranges and also in extreme conditions such as heavy rain and snowstorms.

2.1.2.4. Visual and Multi-spectral System

This system uses sensors that employ electromagnetic energy at various wavelengths, particularly in the infrared and visible wavelength spectrum. Multi-modal sensing, or the use of multiple wavelengths or even multiple technologies in a single sensing system, has shown substantial problem-solving attributes. Collision warning system and roadway sensing devices are examples of such a system.

Collision warning system

The use of active sensor systems such as lidar are predominant in production vehicles as adaptive cruise control (ACC) components. The ACC technology overlaps collision warning technologies to a great extent, as it uses lasers or radar to monitor and maintain vehicle speed as well as the distance to the other vehicles.

Roadway condition sensing devices

most vehicle-mounted roadway condition sensors are developed for pavement evaluation Roadway conditions sensing devices, but they can be used by winter maintenance agencies to predict evolving roadway surface conditions. There are a few challenges to using the devices, as the data collected by these sensors can be compromised by wind, air temperature, visibility, and even pavement structural conditions.

2.1.3. Environmental Sensor Station for RWIS

The Environmental Sensor Station (ESS), an important part of the RWIS, mainly consists of the following components (Haas et al., 1997; Boon and Cluett, 2002):

- **Sensors**: ice detection, water level, atmospheric sensors
- **Remote processing units**: process raw data from sensors
- **Central processing units**: analyzes, stores and arranged RPUs data
- **Telecommunications equipment to transmit data**: transmits RWIS information that comes to it in all kinds of forms
- **Computer workstations equipped with software:** has software that can be used to access the stored RWIS data and present it in many forms such as text, geographical info systems, maps and voice messages
- **Forecasts from the National Weather Service (NWS) or other meteorological services:** include both weather and pavement condition forecasts. They take information from other sources like the NWS in order to estimate any future problems due to temperature

2.1.4. Integrating Mobile Observations (IMO)

Through EDC-4, two distinct road-weather management solutions are deployed that allow state and local agencies to be proactive in managing the surface transportation system ahead and during adverse weather events (FHWA, n.d.). These two solutions are IMO and Pathfinder.

IMO implementations provide the potential for real-time access to road-weather data at all points along a route through CV technology or sensor-fitted vehicles. This enhances traffic management center (TMC) situational awareness, provides new data sources for Weather-Responsive Traffic Management and Maintenance of Decision Support System applications, and allows for objective condition reporting for performance measurement. CV technologies dramatically expand the amount of data that can be used to assess, forecast, and address the impacts that weather has on roads, vehicles, and travelers. Deriving useful road-weather applications from vehicle data is challenging.

Three state DOTs—Michigan, Minnesota, and Nevada—utilized standardized installations, common lexicons, and normalized data formats as referenced by the USDOT Intelligent Transportation Systems (ITS) Joint Program Office (JPO) National ITS Architecture tools (U.S. Department of Transportation, 2023).

2.1.4.1. Michigan Department of Transportation (MDOT)

MDOT's IMO 3.0 project was aimed at improving road-weather data collection sources and evaluating their benefits in terms of cost-effectiveness and reliability. The focus of this project was to collect weather-related data from CVs and mobile data acquisition platforms such as Vehicle-based Information and Data Acquisition System (VIDAS). This data collection strategy necessitated collaboration with other agencies to pull in data from their systems, such as the National Center for Atmospheric Research (NCAR) Pikalert Vehicle Data Translator, FHWA Weather Data Environment (WxDE), and MDOT's Weather-Responsive Traveler Information System (Wx-TINFO). It was found that an increase in CV data availability coupled with the expansion of existing transportation and infrastructure data continuously improves the quality of information available to the agency. This enhanced MDOT's Data Use and Analysis Processing (DUAP) project with weather-related information, which improved the data pool for formulating road-weather management decisions.

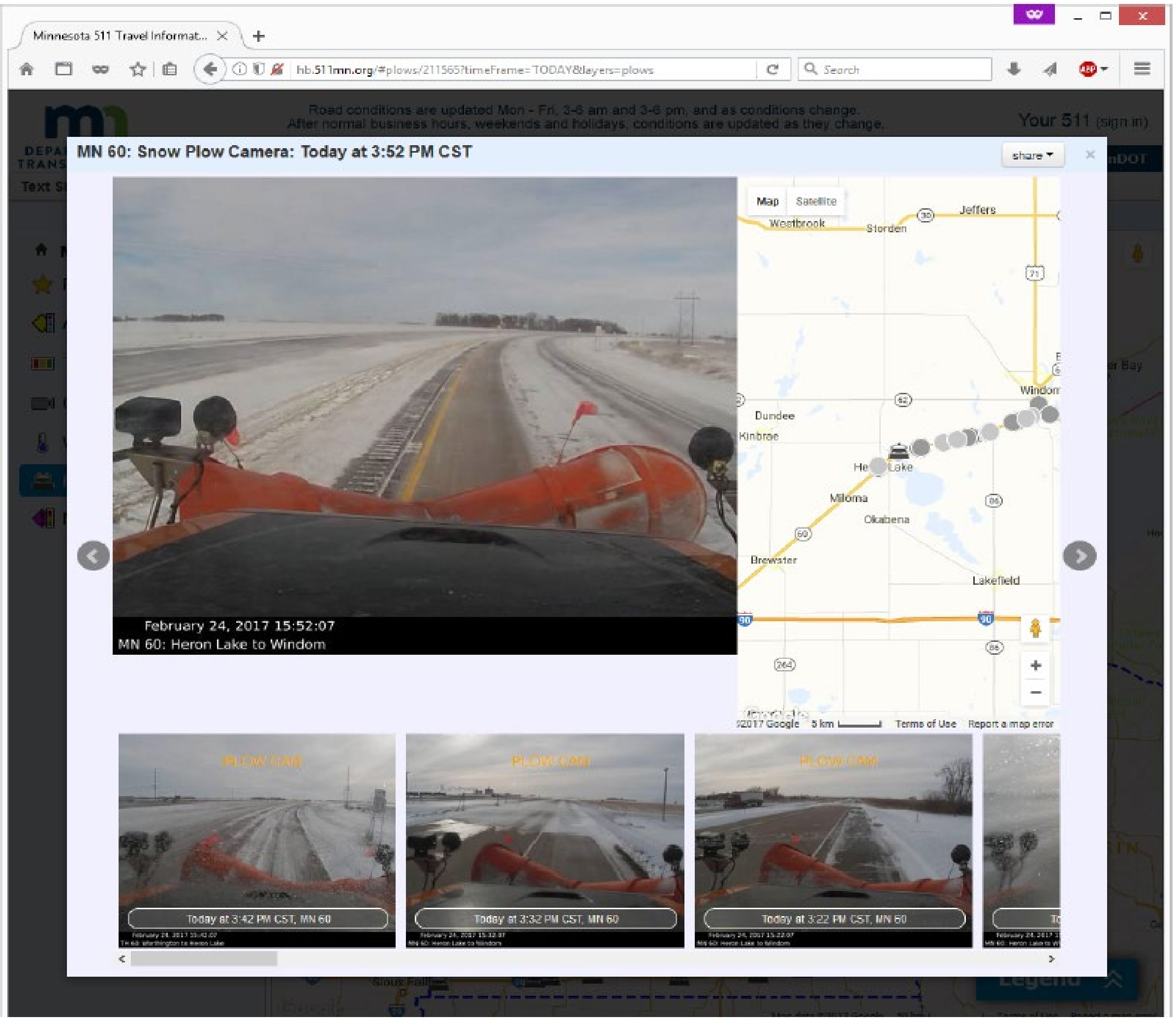
The overall coverage of weather observations was enhanced significantly by the addition of mobile methods to the data collected from fixed sensors. Sensors installed on the vehicles measured weather conditions such as ambient temperature, surface temperature, humidity, barometric pressure, and dew point, along with vehicle data such as position, speed, and acceleration. The VIDAS devices installed on the agency fleet can collect data from sensors on the vehicle, and the vehicle itself. Availability of a variety of sensors improves the reliability of the information. Apart from the VIDAS platform, vehicles were also equipped with Surface Patrol sensors and accelerometers, which aided the collection of information regarding the pavement surface apart from just the weather conditions. VIDAS relays information to the back office via cellular networks, providing DUAP with the latest information that helps forecast the weather impact to the user in almost real time in addition to aiding agencies in their weather management responses and plans. Additionally, onboard units (OBU) were also placed in fourteen such vehicles and integrated with VIDAS for V2V and V2I communication capabilities to further provide information such as current traffic flow or changes in traffic flow caused by incidents, weather impacts, traffic signals, etc. The DUAP system was responsible for forwarding the weather data received from the CVs and the VIDAS platform to both NCAR and WxDE external systems in support of these related weather initiatives with the FHWA.

2.1.4.2. Minnesota Department of Transportation (MnDOT)

MnDOT's IMO 1.0 phase focused on the installation of AVL and mobile data computer (MDC) collection units on 80 snowplows; MnDOT used the mobile data collected to achieve significant improvements of data quality and labor savings. Phase 2.0 of the IMO project built upon the previous work and continued to refine equipment and software for statewide deployment of these units. A major component of the IMO 3.0 phase was the development, installation, and operation of a hybrid communication method on an urban corridor that included both cellular communications and dedicated short-range communications (DSRC). This project involved DSRC hardware installation for six roadside units (RSUs) and five OBUs in vehicles, and the development of new network and software protocols to meet communications and data collection objectives. Each demonstration vehicle could communicate through cellular networks as well as DSRC; however, the preferred mode of communication was through DSRC. In regions where DSRC was unavailable or out of range, the vehicles were to automatically revert to cellular network communication. The DSRC components of this project were also required to be integrated with the AVL and MDC to ensure seamless communication among OBUs, RSUs, and the back-end server.

Another major focus of MnDOT's IMO 3.0 was the enhancement of mobile applications. MnDOT supported NCAR's efforts by providing field data and feedback aimed at enhancing the existing Pikalert System; this included improved diagnosis, better forecast accuracy, and improved Pikalert display. MnDOT used NCAR's Enhanced Maintenance Decision Support System (EMDSS), which provides the road maintenance agencies with road conditions, warning, and suggested treatment information for winter road maintenance purposes. The EMDSS is equipped to provide a 72-hour forecast of weather conditions, enabling the maintenance operator to strategically plan their maintenance operation and undertake improved and informed decision-making. This helps minimize road disruptions during winter through efficient planning, thus reducing labor costs and improving road safety. Further, the NCAR's Motorist Advisory and Warning (MAW) tool provides motorists with prior road warnings for pre-trip planning and early decision-making.

MnDOT also installed network video dash-mounted and ceiling-mounted cameras on 226 snowplows, which were integrated with the onboard MDC/AVL. These cameras were capable of automatically capturing snapshots of road conditions during plowing, set to a specific time interval (e.g., a snapshot every 5 or 10 minutes). The system then sent these captured images—along with other information like the geolocation, maintenance status, and road condition—to be relayed to several MnDOT 511 travel information systems, including the desktop website, mobile website, and 511 app. Figure 2.9 shows plow image examples and map on MnDOT's 511 website.



Road conditions are updated Mon - Fri, 3-6 am and 3-6 pm, and as conditions change.
After normal business hours, weekends and holidays, conditions are updated as they change.

Figure 2.4: Plow Image and Map on MnDOT's 511 Website

2.1.4.3. Nevada Department of Transportation (NDOT) – IMO 3.0

The evolution of the three phases of the IMO project undertaken by NDOT was similar to that of MnDOT. NDOT's primary motivation in incorporating the IMO initiative was to lay the foundation for the implementation of an MDSS and a Material Management System (MMS), which would help NDOT to optimally allocate resources during winter maintenance operations. Phase 1 of the IMO project involved evaluating NDOT's data telemetry capabilities for leveraging AVL and weather data acquisition. Due to the low cellular connectivity in the rural regions, there was a need to develop all the hardware and software to telemeter data using the statewide Enhanced Digital Access Communication System (EDACS) radio network that allowed NDOT to communicate with snowplows and maintenance vehicles across the state. During the IMO 1.0 phase of the project, NDOT instrumented 20 vehicles, including 11 snowplow trucks and nine light-duty vehicles.

Phase 2 of the IMO project saw almost a complete redesign of the hardware system—the EDACS system was replaced by the cellular communication system. Around 25 NDOT vehicles were equipped during this phase of the project. The development and implementation of EMDSS and subsequently the MMS were secondary objectives of NDOT during this phase.

Phase 3 of the IMO initiative was designed to leverage earlier learnings and resources from Phase 1 and 2, implementing a DSRC system. The IMO equipment mounted on the vehicles during this phase was used for sensing data (such as location data, weather parameters, and vehicle parameters), temporarily storing the data while preparing for transmission, and transmitting the data by selecting a telemetry mode of either cellular modem or DSRC. As these vehicles travel along the test corridor, the telemetry mode is selected using the best possible mode, with priority given to DSRC. Figure 2.10 represents the IMO architecture adopted by Nevada.

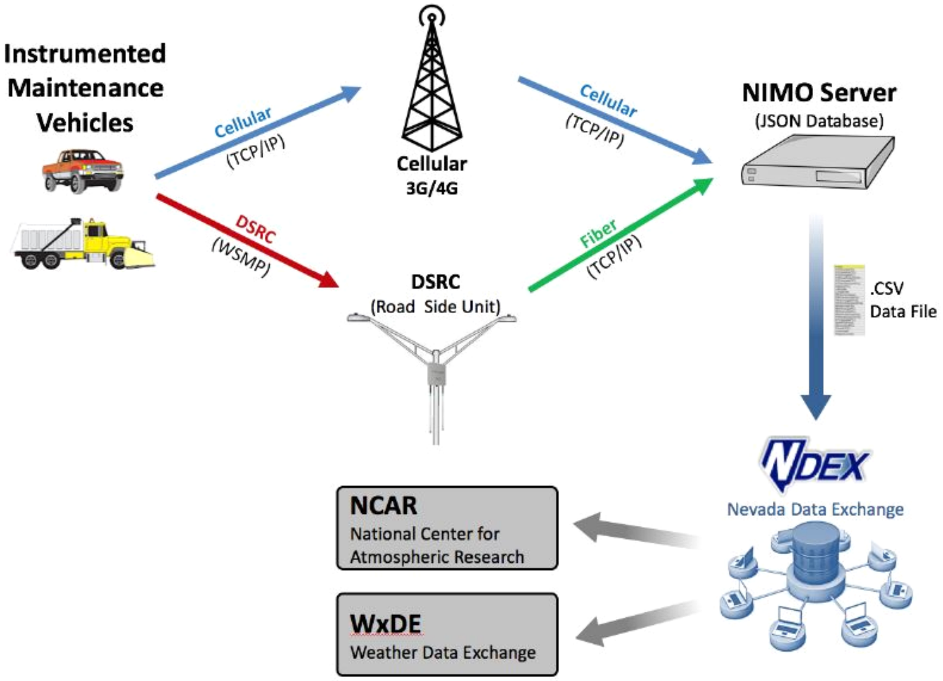


Figure 2.5: IMO Concept of Operation and Data Flow Paths Adopted by NDOT

2.1.5. Pathfinder

The goal of Pathfinder is to fortify the communication and working relationship between state DOTs, NWS, and other major players in weather and transportation enterprises for the effective dissemination of road-weather information to travelers. The information provided should be “clear,” “concise,” “impact-based,” and “consistent,” so that drivers are well informed and able to make safe and efficient travel decisions. Popular information dissemination methods used during Pathfinder implementations include DMS, VMS, 511 websites, social media, smartphone apps, HAR, and DOT web portal.

Benefits include reliable and consistent messages to road users; increased communication, shared resources, and shared tools through collaboration between organizations; efficient management strategies; and improved safety and mobility.

The steps to incorporate Pathfinder include the following: (i) identify partners, (ii) determine qualifying collaborative events, (iii) select communication mediums and procedures, (iv) establish point person at each participating entity, (v) synchronize forecast schedule, (vi) establish definitions and create shared resources, (vii) create shared impact message for the public, (viii) conduct post event review, archive data, and document operating procedure. The Pathfinder implementations in Utah, California, and Colorado are outlined below.

2.1.5.1. Utah Pathfinder Project

Events considered: snow, freezing rain, high winds

Partners involved in Utah Pathfinder initiative

- NWS – Salt Lake City, Grand Junction
- Utah Department of Transportation (UDOT) – Utah Emergency Manager, UDOT Communications (High Impact Events)

Types of message dissemination strategies

- UDOT – VMS, road-weather alert, Travelwise Alert (push), 511 weather forecasts, TV interviews
- NWS – Watches, warnings, and advisories products, weather stories, TV interviews

Benefits and outcomes

- Reliable and consistent forecast helped in transmitting unified messages to the road users causing reduction in vehicle miles travelled (VMT)
- Enabled the public to be more flexible with their travel plans—changed schedule, changed route, used transit, or did not travel
- Increase in shared resources like weather observations (NWS weather spotters, snowplow reports, citizen reporting program, traffic cameras) and shared tools (NWS high resolution local modeling, UDOT pan/tilt/zoom camera access, portable RWIS trailers, satellite communications)
- Trust and reliability increased among public since all sources stated the same road impacts
- DOT maintenance is more effective which helped in congestion reduction
- Improved overall safety and mobility

2.1.5.2. California Pathfinder Project

The Pathfinder initiative was implemented in Truckee, a small rural municipality in California. This section briefly describes the collaboration, applications, and benefits achieved through this initiative.

Stakeholder collaboration

- NWS through the Weather Forecast Office
- California Department of Transportation (CalTrans)
- Truckee Police Department and the California Highway Patrol

Technology applications

- All snow removal equipment includes AVL
- The location of snow removal equipment is also displayed on a public web portal (map-based) in real time
- The town's website (www.511portal.com/truckee) provides road-weather and weather information, traffic conditions, and important related messages and alerts
- Truckee's Facebook account is used to disseminate this information
- The Truckee Police Department uses a text blast system, called NIXLE, to alert the public of emergencies

Benefits experienced

- Enhanced weather knowledge through collaboration with the NWS Weather Forecast Office
- Enhanced safety and public relations through expansion of public information and outreach
- Better allocation of resources, improved efficiency and effectiveness of road operations
- Public is better prepared for severe weather conditions and appreciates better road conditions during severe events

2.1.5.3. Colorado Pathfinder Project

The key partners involved in Colorado's Pathfinder project include the following:

- Colorado Department of Transportation (CDOT)
- Colorado NWS Forecast Offices
- CDOT Road-Weather Management
- Iteris, Inc.
- Colorado Avalanche Information Center (CAIC)

The Colorado Pathfinder initiative involves five key steps:

1. **Weather and road-condition forecast briefing**
    - The briefing is prepared by the NWS, CDOT Road-Weather Manager, CAIC, and Iteris, Inc., highlighting the weather event overview, conditions, and commutes affected.
    - Forecasts include beginning and end times of the event, temperatures, precipitation types and amounts, and wind speeds.
    - The forecast is generally reviewed by the road-weather manager to gain a complete understanding of the event and host the pre-storm conference call if appropriate.

2. **Pre-storm conference call**

   A pre-storm conference call generally happens 24 to 48 hours prior to the forecasted event and involves three key topics that aid in developing an action plan:

   - Weather and road condition forecast information, based on which a storm level is agreed upon by the attendees.
   - Assessment of operational readiness by CDOT maintenance sections throughout the state and the traffic management centers.
   - Development of impact-based and consistent messages to be disseminated to the public by both CDOT and NWS.

3. **Implementation plan development**

   The action plan includes the following.

   - Possible strategies to coordinate activities and allocate maintenance forces to tackle the intensity and extent of the weather event.
   - Maintenance strategies to be adopted to keep the roads safe, which includes plowing, treatments, and other operational strategies.
   - The timing, location, and content of DMS and any specific warnings that are required to be transmitted to the road users. Coordination with the media to disseminate consistent messages is also vital.

4. **Plan execution**

   This step includes carrying out the developed plan arrived at in the previous step. Proper execution of maintenance plans, dissemination of consistent messages to the users, and performance of the treatments as strategized form the core of this step.

5. **After-action reviews**

   The after-action reviews are aimed at evaluating the action plan to continuously improve treatment strategies, readiness, and sharing of resources.

Benefits realized

- More focused and efficient treatment strategies by CDOT to implement effective management methods.
- The road users, who are now well-informed about the impacts of the event on their travel with consistent messages, are benefitted by making safe travel decisions.
- Increased communication and collaboration during storm events

2.1.6. Other Winter Maintenance Strategies

Apart from the IMO and Pathfinder initiatives, a few other DOTs domestically and internationally have used various strategies to tackle winter weather events.

2.1.6.1. Wisconsin Department of Transportation (WisDOT)

WisDOT's RWIS (Wisconsin Department of Transportation, 2019) is designed to provide winter management personnel with the most accurate information about present and future weather conditions. Their RWIS includes these components:

- 68 weather and pavement condition sensors along state highways
- Detailed weather forecasts by MDSS
- A winter storm warning service for WisDOT and county highway departments
- More than 1,000 mobile infrared pavement temperature sensors on patrol trucks around the state.

WisDOT uses AVL-GPS to determine the location of a vehicle and allows management to monitor the location of an entire fleet. This system can assist in the management of labor, equipment and materials. WisDOT primarily uses data from AVL-GPS to improve MDSS recommendations and record and transmit operational data (such as application rates, pavement temperatures, position of blades) from snowplows.

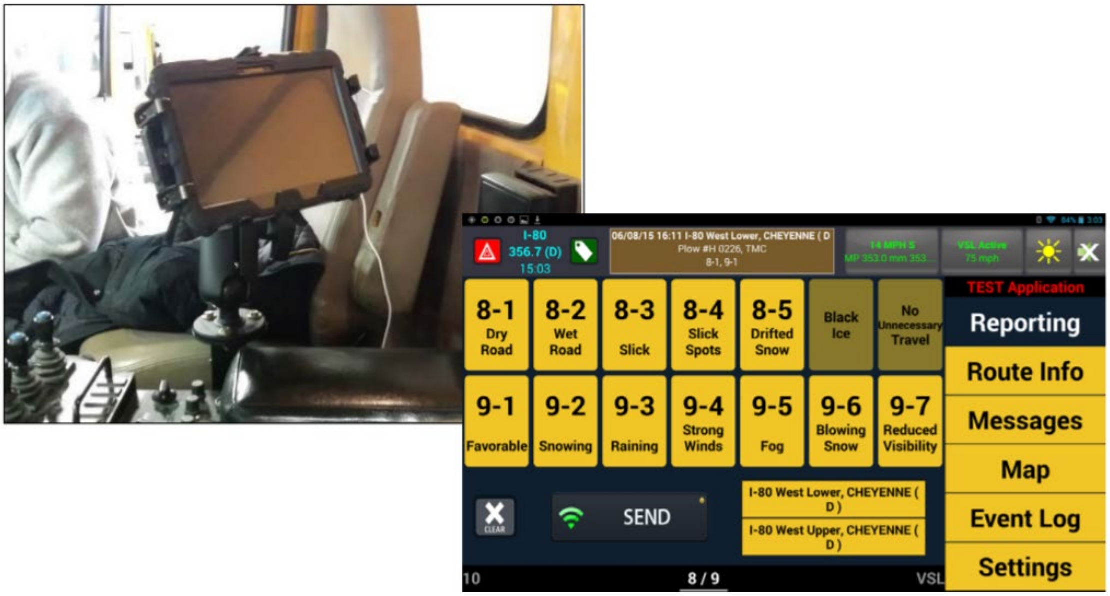
2.1.6.2. Oregon Department of Transportation (ODOT)

Given the importance of driver behavior and preparedness in reducing winter crashes, ODOT emphasizes driver awareness and produces travel information tools (Oregon Department of Transportation, 2018). ODOT's TripCheck platform provides real-time information and road conditions along with forecasted events to warn travelers of any impending hazardous conditions so that they can plan their trips accordingly. Additionally, the ODOT's RWIS network provides localized weather conditions with the help of cameras, which allow for weather-triggered variable speed limit signs (tested in one of its interstate highways), an example of which is shown in Figure 2.11. The variable speed sign is triggered by certain weather events or visibility restrictions such as heavy fog, reducing the posted speed limit and warning travelers of inclement conditions and the need to travel cautiously. Further, ODOT focuses on improving its knowledge about how to influence driver behavior and its role in preventing crashes.

Figure 2.6: ODOT Variable Speed Sign

2.1.6.3. WYDOT Road Condition Reporting and Traffic Management

Wyoming DOT (WYDOT) Mobile Road Condition Reporting app (shown in Figure 2.13) is available on tablets installed on maintenance vehicles, allowing the field crew to report information and update databases remotely, reduce radio traffic, save labor cost and time, and provide almost real-time information to the public (Kitchener et al., 2015). Use of this app has resulted in a more efficient road and traffic condition reporting by maintenance employees and TMC operators. Traffic management capabilities were also enhanced during weather events, resulting in more accurate DMS and variable speed limit recommendations.



06/08/15 16:11 I-80 West Lower, CHEYENNE (D
Plow #H 0226, TMC
8-1, 9-1

I-80 West Lower, CHEYENNE (D)
I-80 West Upper, CHEYENNE (D)

Figure 2.7: WYDOT Mobile Tablet Installation and Interface

2.1.6.4. WRMS in Slovakia

Kociánová (2015) describes a multi-level solution for intelligent winter road maintenance management based on monitoring and forecasting of weather conditions and the road surface conditions at selected road locations in Slovakia. The winter road maintenance management comprises the following components and interactions that are diagrammed in Kociánová's paper:

1. **Dispatcher, driver, and maintenance vehicles**

    - The primary task of a dispatcher is to manage maintenance by continuously monitoring weather and road conditions and making key decisions regarding deployment of maintenance crew, technology, and amount of treatment using appropriate software tool.
    - The driver is equally important as he/she is responsible for performing the maintenance treatment on site.
    - Intelligent maintenance vehicles are necessary to optimize maintenance circuit configuration for applying de-icing and anti-icing agents. The vehicles should have an onboard electronic unit and must be equipped with AVL.

2. **Information about road-weather and surface conditions**

Better decision-making can occur only when accurate and relevant information can be collected about road and weather conditions.

- The most important sources of real-time meteorological and pavement data are road-weather stations, ensuring automatic data collection and transmission. Sensors provided at such stations can measure meteorological data such as air temperature, relative humidity, wind speed and direction, precipitation, and visibility, and road conditions like surface temperature, status (dry, wet, moist, snow, etc.), water layer thickness, salt concentration, friction, and others.
- Weather stations can be equipped with overview camera for visual monitoring of the road and weather conditions.
- Other sources of weather and road data are meteorological radars and satellites, Slovakia's National Weather Service, and mobile weather data.

3. **Software support for dispatchers**

    - RWIS includes ESSs, a software tool that accumulates available data from all sources and communicates the relevant information to road users and maintenance managers. This information helps the dispatchers make better-informed decisions regarding winter road maintenance strategies and prompts motorists to re-consider their travel plans.
    - MDSS is a part of RWIS that generate predictive outputs depending on the specific inputs (which are basically the road and weather data). These road-weather forecasts are crucial for the efficient timing of winter maintenance and assist the dispatcher in decision-making

with respect to weather-situation development. With the latest set of information, MDSS produces treatment recommendations for winter maintenance operators.

- Road-weather forecast, as the name suggests, is a mechanism for predicting future road and weather conditions on the basis of historical, current, and predicted geographically localized information through computational modeling.

2.1.7. Integrating Maintenance Management

A study by Hinkka et al. (2016) primarily discusses the importance of integrating two important facets of winter road maintenance: (i) winter road maintenance techniques and (ii) road-weather and surface-condition monitoring.

- **Winter road management treatments** include chemical methods (use of de-icing, anti-icing agents), mechanical methods (removal of ice or snow by ploughing or scraping), and thermal methods (application of heat to remove ice and snow).
- **Road-weather and surface-condition monitoring** generally includes RWIS, which consists of meteorological stations strategically located alongside the roadway to monitor roadside weather or pavement conditions or both); thermal mapping (remotely measuring road temperature using infrared sensors mounted on vehicles); continuous friction measurement (determining the coefficient of friction using advanced friction measuring devices); and web-based surveillance and automatic road surface image recognition.

This study also describes the two different approaches to managing maintenance operations of winter roads: (i) process-controlled and (ii) results-oriented:

- In the **process-controlled** (or ad-hoc) **approach**, the agency or the authorities strictly define the way the maintenance is required to be carried out (type of vehicle fleet to use, how fast to mobilize, section of the road where maintenance is required, where to use chemicals, etc.) and they pay the contractors based on the type of actions/treatments laid out at a pre-determined price. This process is mostly used in countries/regions where snow and icy weather is an occasional event that occurs several times in a year.
- In the **results-oriented** (or collaborative) **approach**, the authorities define the quality and performance criteria for maintenance operations but the contractors are free to use any methods according to their judgement. The maintenance work is generally awarded by the authorities to the cheapest offer from the contractor that meets their criteria wherein the contractor is free to choose the equipment, treatments and the working method. This process is mostly adopted in regions/countries where snow and icy weather events are a regular phenomenon and occur throughout the winter.

Figure 2.16 categorizes the types of approaches to winter road maintenance management.

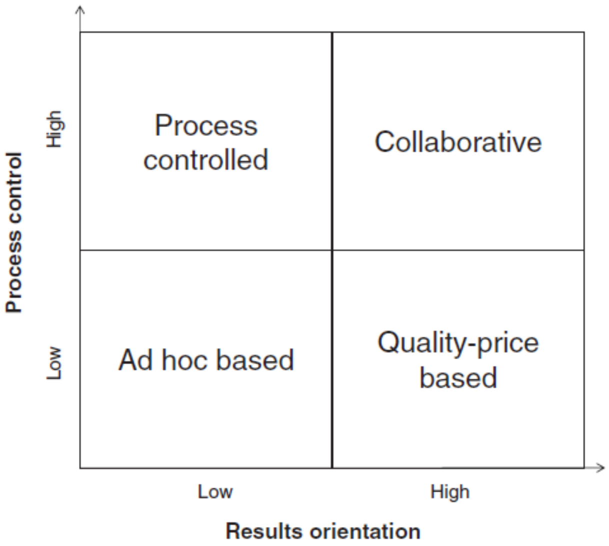


Figure 2.8: Matrix Classifying Approaches to the Management of Winter Road Maintenance

The ad-hoc approach is generally adopted when the country or region experiences snowy or icy weather rarely, or where transportation systems and agencies are under-developed or non-existent. Meanwhile, the collaborative approach has the benefits of both. It gives the contractor freedom to develop its own working methods simultaneously involving the authorities in key decision-making so that the sustainability issues are considered. However, combining these two approaches requires collaboration between actors, i.e., means of effective communication between both the parties. Integrated winter road maintenance enables this type of interaction.

2.1.8. Non-winter Relevant Topics/Studies

There are several studies that do not specifically deal with winter maintenance strategies but are relevant to the procedures and operations concerning winter road management.

2.1.8.1. Crowdsourcing for Transportation Operations

According to the FHWA, “Crowdsourcing turns transportation system users into real-time sensors on system performance, providing low-cost, high-quality data on traffic operations, roadway conditions, travel patterns, and more” (FHWA, 2019). Examples of crowdsourcing applications in transportation are diagrammed in Figure 2.17:

Sources of crowdsourced data:

- Data extracted from social media platforms (Facebook, Twitter, etc.)
- Data extracted from third-party apps and websites containing crowdsourced data
- Specially developed mobile or tablet app designed for collecting crowdsourced information

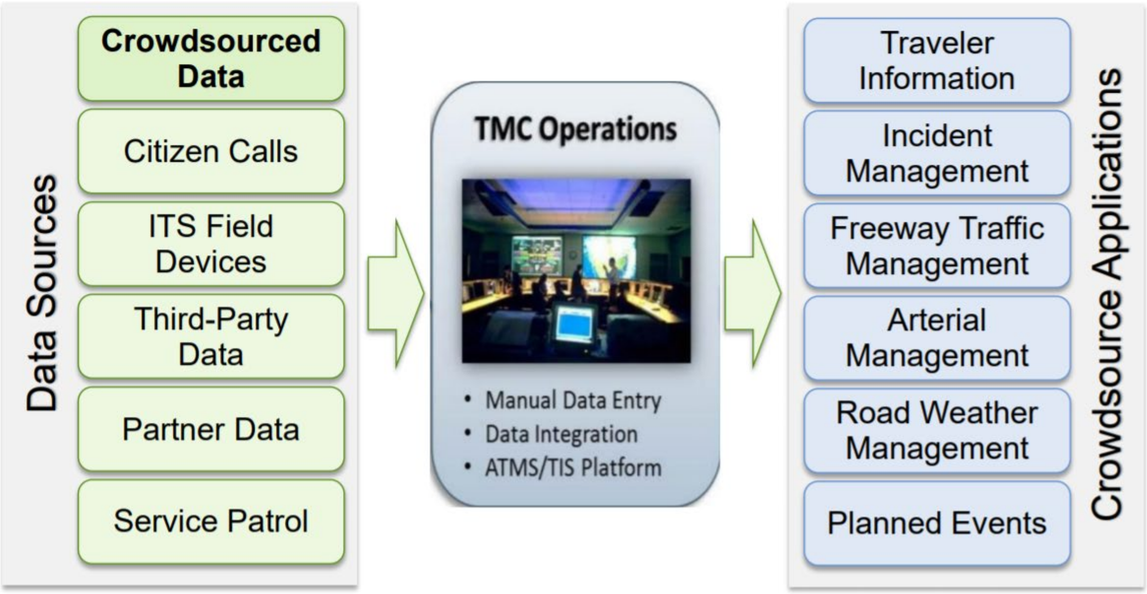
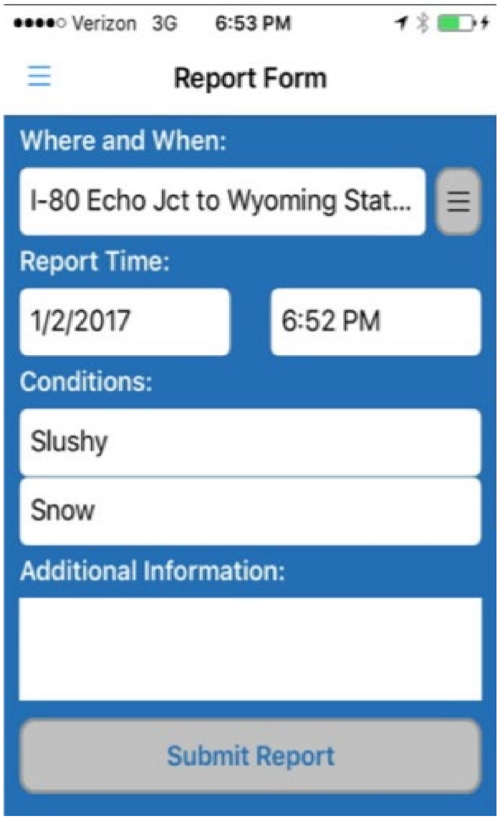


Figure 2.9: Crowdsourcing Application in Transportation

As an example of crowdsourcing application in transportation, Utah DOT (UDOT) launched a dedicated mobile app known as the *Citizen Reporter Program* (Figure 2.18) to collect information from the general public through crowdsourcing.



Report Form

Where and When:
I-80 Echo Jct to Wyoming Stat...

Report Time:
1/2/2017
6:52 PM

Conditions:
Slushy
Snow

Additional Information:

Figure 2.10: UDOT Citizen Reporter Program App Interface

Bhat et al. (2019) summarizes few other crowd-sourcing applications in transportation:

- Crowdsourced apps like **Waze** have become popular resources for drivers to obtain traffic information, which also encourages partnered agreements with the DOTs.
- The collaborative design of **CARS (Condition Acquisition and Reporting System)** allows integration of ITS applications, public information web sites, and other information dissemination platforms. Users can manually enter roadway events or import from a third party like Waze, NWS, or from a traffic management system.
- The Community Collaborative Rain, Hail and Snow Network (**CoCoRaHS**), sponsored by NOAA and National Science Foundation (NSF), is a citizen reporting network in which volunteers collect and report precipitation measurements. Weather-monitoring agencies use this date to measure, map, and share precipitation levels. CoCoRaHS is dedicated to providing free quality data available for weather prediction and alerts.

2.1.8.2. Using Vehicle Speed Data to Measure WRMS Impact

Lee et al. (2008) suggested that vehicle speed data can be used as a good measure for representing driving conditions during winter weather events and a handy measure for winter maintenance performance as well. In this study, the 954 winter maintenance log entries recorded in Wisconsin during various winter events over three years were used in conjunction with the automatic traffic recorders (ATR) to investigate the relationship between speed variation and weather maintenance performance. The winter storm reports contain the details of each storm event, including the duration and type of precipitation and details regarding maintenance start and end times. The speed data was obtained from the ATRs. Speed data variables, such as time after the snowstorm, starts at the time at which traffic begins to slow down, time to maximum speed reduction (MSR), and time to speed normalcy were computed from the ATR data. The time duration between the MSR point and the moment vehicle speed recovers to normal winter speeds is termed as the speed recovery duration (SRD), which was used as a potential measure for maintenance performance indicator. A regression tree analysis revealed that delay time for crew dispatch, MSR percent, and time to MSR point after the storm starts are the major independent variables explaining the SRD. Vehicle speed during winter weather appears to closely relate to the prevalent pavement conditions; therefore, vehicle speed appears to be a potent measure of quality of winter maintenance operations.

2.1.8.3. Other Studies

Bogren and Gustavsson (A Weather Model for Variable Speed Limits, 2006) emphasize the importance of having variable speed limits during severe winter weather conditions using RWIS. Their paper argues that simply providing information to the driver regarding the slippery conditions of the road is insufficient, since drivers are found to have poor judgement of the prevalent risk conditions; guiding them through variable speed limits is a more effective instrument. Based on the amount of snow, rain, and ice formation, the slipperiness of road can be classified into several risk categories, and dynamic speed limits can be applied according to the climatological condition of the road. The paper also states the possibility of integrating a weather prediction model to the automatic setting of the variable speed limits.

In another study by Gustavsson and Bogren (Development of RWIS—a New Approach Using Accident Data, 2006), the authors relate the winter road incidents to weather and slipperiness. They found that rain during very low temperature or snow with surface temperatures 3^{o}C were the two weather situations where the greatest number of incidents occurred, followed by general ice and cold snow events. It was also found that the frequency of incidents increased with the severity level of the weather (measured in terms of accumulation of snow, amount of precipitation of snow events, and the probability of the temperature dropping below freezing point).

The study by Ewan et al. (Remote Sensing of Weather and Road Surface Conditions, 2013) investigates the reliability of DSC-111 and DST-111 sensors for their application in the weather-responsive system. Four parameters of interest were tested as the main outputs: pavement surface test, ice and snow depth, water depth, and grip level.

- The sensor was found to be accurate and reliable in detecting the road surface condition which matched with the actual rad surface condition precisely.
- The sensor could consistently determine the pavement grip levels corresponding to the changing patterns of coefficient of static friction as measured.
- The snow or ice depth readings were found to be inaccurate in most cases; however, the sensor could accurately detect the presence of snow or ice, which could be sufficient for most of ITS applications for winter road management.
- The water depth measurements could be accurately measured after rigorous calibration of the sensor. As a matter of fact, proper calibration of the sensors significantly improved the accuracy level of its measurements when compared to the original installation settings. Hence, it is highly recommended that agencies undergo rigorous calibration checks before actually implementing sensors on the road.

This study investigated the non-invasive technology for measuring road-weather conditions through the reliability and accuracy tests of the sensor DSC-111 and DST-111, which could be successfully implemented to obtain valuable information about road conditions.

2.1.9. RWIS Network Planning: Optimal Density and Location

Road-maintenance operations require reliable and timely information about road and weather conditions from the RWIS in order to efficiently schedule and manage maintenance tasks during winter weather. However, the RWIS installation and maintenance expenses are often very high and require strategical allocation. The study by Kwon and Fu (2016), sponsored by the USDOT, developed three methods of optimizing the density and location of such RWIS stations on a road network. These three methods were (i) surrogate-based method, (ii) cost-benefit-based method, and (iii) spatial-inference based method.

- The surrogate measure-based approach optimizes the RWIS location by allocating the higher priorities to locations that are more prone to have severe weather conditions. This method, in fact, formalizes the general practice by many transportation agencies for locating RWIS stations. Two types of location ranking criteria were considered for this method: (1) weather-related factors such as variability of surface temperature, mean surface temperature, and snow water equivalent and (2) traffic-related factors like winter average daily traffic, average crash rate, and highway type. The locations can be ranked based on either using these factors individually or using a weighted average.

- The second approach, namely the cost-benefit method, explicitly accounts for the potential benefits of the RWIS system at each location. This method assumes that the costs and benefits of installing a RWIS system at a location can be determined; therefore, this method is mostly applicable when detailed data of weather, traffic, collisions, and costs for winter maintenance operations are available so that the benefits of the RWIS system (reduction in collision and maintenance costs) can be evaluated for each location. Using these benefit estimates and costs of maintenance operations, the life cycle net benefits can be estimated for all the locations thereby facilitating objective prioritization. A case study conducted as a part of this project based on the current RWIS network in northern Minnesota shows that the highest projected 25-year net benefits are approximately $6.5 million, with a cost-benefit ratio of 3.5, given the network of 45 RWIS stations.

- The third approach, the spatial inference method, is more comprehensive with the objective of maximizing the use of RWIS information to determine winter road-weather conditions. The optimization problem considers dual criteria representing the value of RWIS information for spatial inference and travel demand distribution. The Spatial-Simulated Annealing (SSA) algorithm was employed to solve the optimization problem for this method.

Case studies involving four regions—Ontario (Canada), Utah, Minnesota, and Iowa—were conducted wherein the three methods of RWIS station optimization were implemented for these regions. For example, when the spatial-inference method was implemented for all four regions, the Figure 2.19 curves were obtained to chart RWIS density. The number of RWIS stations per unit area (10,000 km^2) required to provide adequate coverage was found to be 2.0, 2.2, 2.9, and 4.5 for Iowa, Minnesota, Ontario, and Utah, respectively. There appears to be a significant correlation between RWIS density and spatial parameters. It was also observed that regions with less varied topography have longer spatial correlation and vice-versa.

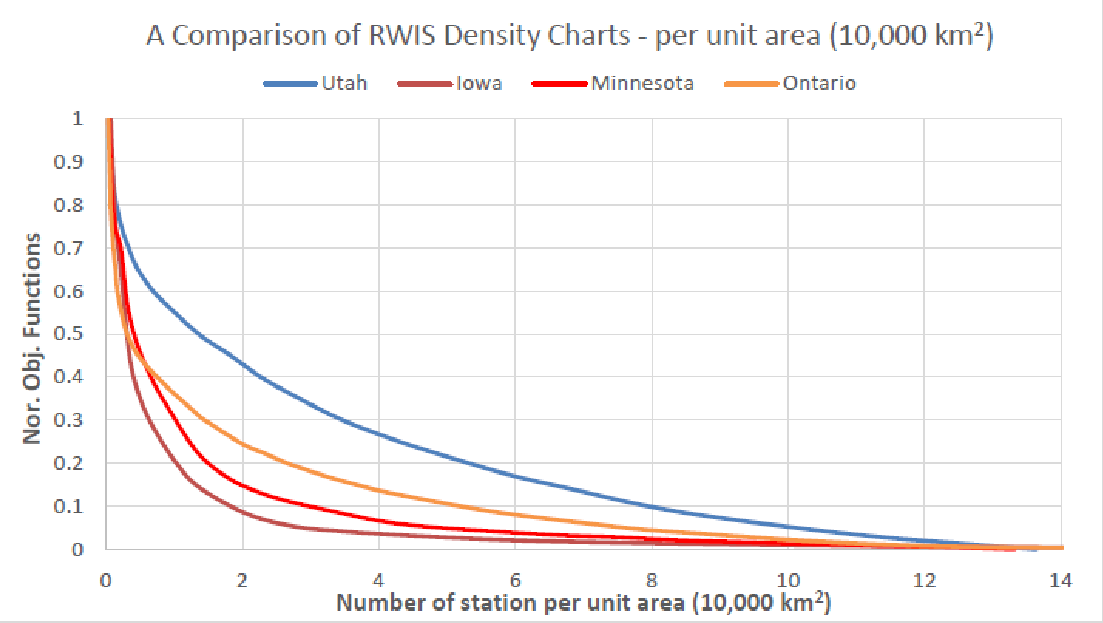


Figure 2.11: Comparison of RWIS Density Charts – per unit area (10,000 km^2)

2.2. MDSS

According to the FHWA, a "Maintenance Decision Support System (MDSS) is a computer-based, customizable tool that provides winter maintenance personnel with route-specific weather forecast information and treatment recommendations" (Dye et al., 2008). Essentially, the concept of MDSS can be thought to be intertwined with that of WRMS; however, due to its ever-growing importance, it is worthwhile to highlight the salient features and implementations of MDSS separately. MDSS can benefit local and state agencies in multiple ways, such as reducing costs for labor, material, and equipment; improving public safety; improving mobility; increasing the level of service on roads; maintaining decision-making consistencies over regions; providing training to new and experienced DOT personnel; enhancing collaboration between DOTs; and providing a way to review maintenance actions during past storms.

Figure 2.12: MDSS overview

The functional flow prototype of MDSS (Dye et al., 2008) is shown in Figure 2.12, and prototype/example of an MDSS main screen display is shown in Figure 2.13.

- The inputs consist of the weather and road conditions and output from weather prediction model primarily from NWS and DOTs. The inputs also include observations from maintenance trucks regarding their location and treatment activities.

- Information is fed to the Road-Weather Forecast System that synthesizes the information based on certain predefined formulas to create a forecast to aid the treatment recommendation process. This forecasted information includes air temperatures, wind speeds, precipitation types, and their probabilities.

- The Road Condition and Treatment Module uses these forecasted weather elements to predict road conditions like snow depth and pavement temperature by computer modeling. Alternative treatment procedures and their effectiveness can be evaluated in this step.

- Once the treatment plan is decided, MDSS presents recommendations to the user in the form of graphics and maps. If the agency is using mobile data communication or AVL technology, the treatment recommendation can be directly communicated to an operator in the truck/ maintenance vehicle.

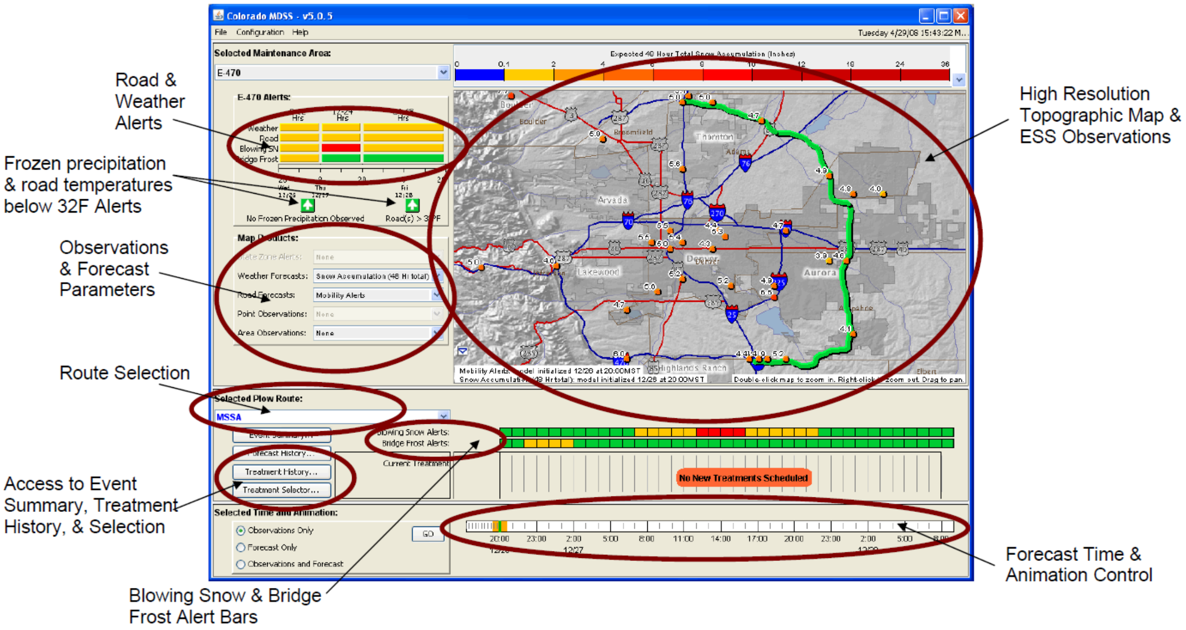
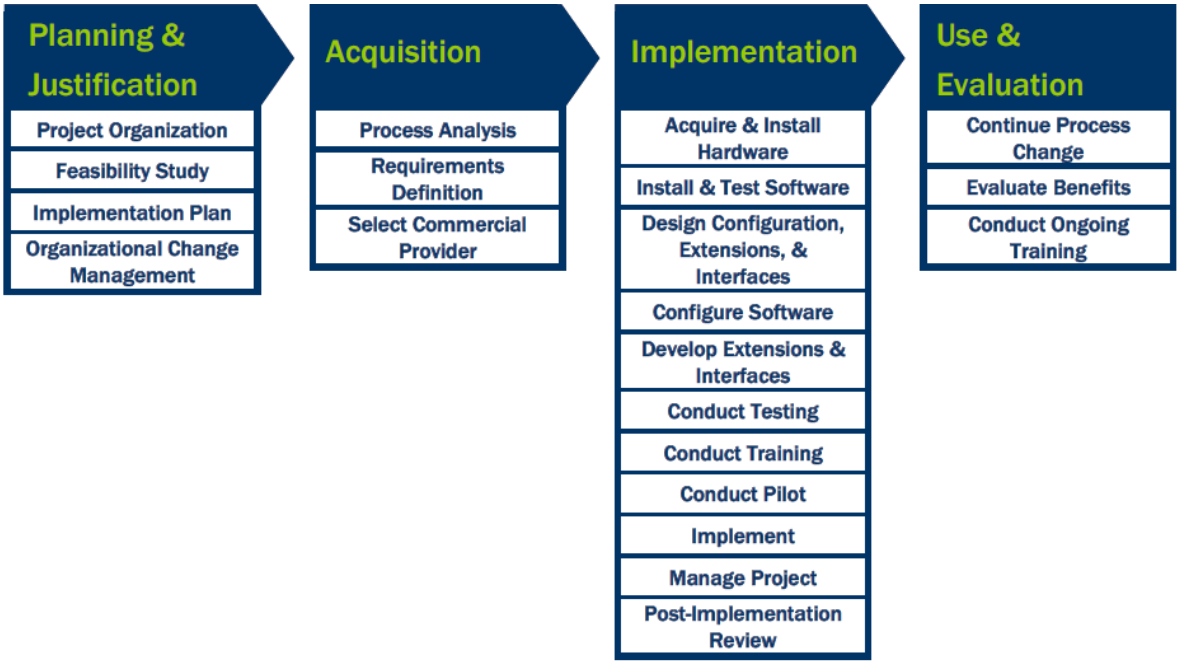


Figure 2.13: Example of an MDSS Main Display Screen (from a FHWA functional prototype)

There are four phases for deploying MDSS: planning and justification, acquisition, implementation, and use and evaluation. Each of the phases has its own set of tasks. The specific tasks and resources required vary depending on the DOT; however, the tasks under each phase can be summarized as shown in Figure 2.14.



Planning & Justification	Acquisition	Implementation	Use & Evaluation
Project Organization	Process Analysis	Acquire & Install Hardware	Continue Process Change
Feasibility Study	Requirements Definition	Install & Test Software	Evaluate Benefits
Implementation Plan	Select Commercial Provider	Design Configuration, Extensions, & Interfaces	Conduct Ongoing Training
Organizational Change Management		Configure Software	
		Develop Extensions & Interfaces	
		Conduct Testing	
		Conduct Training	
		Conduct Pilot	
		Implement	
		Manage Project	
		Post-Implementation Review	

Figure 2.14: MDSS Deployment Phases

2.2.1. Benefits of MDSS and RWIS

MDSS (or Road Decision Support Systems) and RWIS have proven to be effective in improving road safety, mobility, and efficiency while minimizing maintenance-related costs. The paper by Atallah (2012) describes the potential benefits of such a system and discusses a tool that aid in estimating the potential benefits of RWIS and MDSS when the known operational and economic parameters are plugged in. The paper also details the types of benefits achieved by RWIS and MDSS, summarized below.

2.2.1.1. Application User benefits

- **Labor time savings** can be achieved through various means such as time spent in decision-making, time taken to treat or not to treat sections of roads during actionable events, and other indirect savings in terms of stress-related absences, clean-up time improvements, and IT labor savings.
- **Decision-making** involves analyzing the road conditions, current and future weather forecasts, status and availability of vehicles, materials, budget constraints, traffic conditions, and communication aspects, which are time-consuming. Using MDSS can save more than 50 percent of such time. Also, RWIS coupled with camera networks can help decision-makers be aware of the immediate road conditions, eliminating the need for manual inspection.
- **Actionable events.** Not all weather events call for maintenance or treatment. However, without the presence of RWIS and MDSS, it is difficult to estimate the road conditions and temperature of the pavement during each storm, thus requiring an actionable call-out for every storm, even for those for which treatment is not required. Users of a road-decision support system will see a treatment call-out reduction of as much as 30 percent, and sometimes more.
- **Maintenance operator driving time.** With a reduced number of actionable events and full road treatment, there would a considerable amount of drive-time savings (as much as 50 percent) with the RWIS and MDSS mechanisms.
- **Other time savings.** Use of RWIS and MDSS would result in consistent decision-making, improve accuracy of the decisions, and reduce stress on the decision-makers. This in turn would reduce the number of stress-related absences and help improve satisfaction and motivation of the employers. Also, efficient application of de-icing and anti-icing materials would reduce the amount of clean-up tasks.
- **Material cost savings.** Three main type of materials are used in the treatment process, including dry and wet de-icing materials, and also fuel to power maintenance vehicles.

The use of RWIS and road MDSS would significantly reduce the consumption of these materials through efficient decision-making and optimum treatment practices.

- **Maintenance and wear savings.** Fleet maintenance costs include vehicle cleaning costs, servicing costs, and maintenance and repair costs. With optimum usage of vehicles, several such costs can be substantially reduced.
- **Other efficiency benefits.** Publicity and litigation benefits include reductions in complaint costs and litigation costs that occur when a considerable number of complaints arise due to weather-induced road situations.

2.2.1.2. Community Benefits

"Community" generally refers to the end-users and the general public who would benefit from the use of the decision support system. These benefits include the following.

- **Safety.** The number of crashes attributable to inclement weather is likely to substantially decline when the road decision support system and RWIS facilities are adopted by the transportation agencies. Crashes caused by slippery conditions or low visibility during winter storms sometimes involve multiple vehicles, resulting in significant material loss, time loss, injury, and fatality cost. Road-weather decision support systems coupled with RWIS can allow agencies to realize significant savings, sometimes in the range of several million dollars.
- **Mobility.** Traffic flow can be improved by adopting better winter maintenance strategies aided by RWIS and MDSS. Slowdown of traffic caused by congested highways, slow moving treatment vehicles, crashes, and overcapacity due to highway closures during winter weather can be ameliorated by efficient and informed decision-making.
- **Environment.** Road decision support systems offer major benefits to the environment, including decreased use of maintenance vehicles, reduction of chemicals on the road that may run off into water system, and reducing start-stop activities that add to air pollution. Minimizing the usage of salts through a decision support system minimizes the pollution as well as the direct cost.

2.2.1.3. Indirect Benefits

Indirect benefits include efficiency, publicity, and safety benefits that may not have a direct monetary evaluation but provide accountability and tracking benefits, improving the system as a whole.

- **Efficiency.** The performance and cost benefits are already apparent. A decision-support system further helps in tracking the status of resources, material use, year-to-date expenses, driving time, contractor use, etc. Such efficiency results in better future planning, performance tracking, and streamlined operations.
- **Publicity.** A road support system helps in publishing information to the general public regarding measures taken by the agency and allows for a comprehensive management plan that will withstand scrutiny in legal matters. This makes the management process

transparent to the general public. Additionally, it provides assurances to drivers about the safety of the road, which may increase the revenue generated from tolls.

- **Safety.** Better communication leads to richer information being transmitted to the general public, which can increase safety levels on multiple fronts through more accurate expectations and fewer encounters with unexpected situations.

2.2.2. Applications of MDSS

2.2.2.1. Maine

The FHWA Road-Weather Management Program has sponsored development of a prototype MDSS. A case study evaluation was conducted by Cluett and Jenq (2017) and funded by the USDOT ITS Joint Program. The MDSS prototype software modules developed are commercially available and can be tailored to the decision support applications required by different DOTs. This case study involves the use of MDSS by the Maine DOT in the Scarborough region with the help of Meteorlogix/DTN. The objective was to evaluate the potential institutional issues and the potential benefits of the MDSS and compare the improvements in winter management operations before and after the implementation of MDSS.

To identify benefits and lessons, the researchers monitored winter management operations during the winter of 2006–2007 in Scarborough using the MDSS approach. Using a detailed event reconstruction approach, data were collected for 12 winter storm events that required a maintenance response in order to characterize the uses of the MDSS as a maintenance tool, versus not using MDSS (i.e., how maintenance operations would have been conducted prior to having access to MDSS).

Several benefits of using MDSS were documented, including improved productivity in terms of efficient use of labor and material costs, enhanced mobility, and improved safety. Moreover, MDSS provided important educational input to the users and an additional tool for decision-making. Overall, the MDSS was found to be an effective GIS incorporated tool that provided forecasts of weather and pavement conditions and guided manager and engineers through better maintenance treatment strategies.

2.2.2.2. Wisconsin

WisDOT deployed the MDSS through more than one phase in all Wisconsin counties, although it is primarily used for tracking purposes only, i.e., AVL data tracking. An MDSS-based five-year weather severity index is computed by WisDOT to compare the present weather severity to the recent past and determine the appropriate course of action. Monitoring of the monthly MDSS usage statistics and potential pavement buckling episodes are also carried out by WisDOT (Wisconsin Department of Transportation, 2019).

2.2.2.3. Sapporo

The MDSS makes use of weather forecasts and pavement condition information to improve decision-making during winter maintenance tasks, which includes deciding the timing and amount of de-icing agent to be applied and when to mobilize the snow removal vehicles. A significant cost reduction in winter maintenance operations is generally observed as a result of MDSS, since it helps optimize the amount of de-icing agent to be used and reduces labor costs by accurately timing snow removal operations. This in turn helps improve road safety, as the snow removal process is expedited. A prototype MDSS framework was set up in the Sapporo region via website (Yamagiwa et al. 2006); this framework provided current and forecast weather conditions and operation support information. The information includes notices on snowfall, snowstorm visibility, temperature, and precipitation for current conditions; forecasts up to six hours in advance; and maintains records up to 48 hours in the past. In a snowstorm event, two types of information are generally required: the snowfall visibility and the snowfall intensity. Therefore, the MDSS framework was required to provide information on both those factors. The MDSS frame has leapfrogged since this prototype implementation in 2004/2005 and the current forms of MDSS platform used in several DOTs are far more sophisticated and data rich.

2.3. Dissemination

The dissemination of information mechanism is operationally embedded within the WRMS and RWIS framework (including IMO and Pathfinder initiatives); however, it is worthwhile to make a separate brief note of it. The information needs to be effectively communicated to the road users/motorists and the maintenance managers such that it is readily and easily available and accessible to them. Generally, the process of disseminating the collected data follows these steps:

- Data is collected at a district or local level and then inputted to a central system where it may be directly published for the public or transmitted to maintenance authorities for further processing.
- Some states feed the data to third-party vendors to then make available to the public.
- Some states skip the local connection and instead have all information go straight to the central database.
- Types of information outlets are discussed below.

The information gathered by RWIS must be delivered to those who need it; these “customers” can be broadly classified into two categories: (i) maintenance personnel who make winter maintenance decisions, and (ii) the motoring public-at-large who require the information to adjust/make travel plans. RWIS information is disseminated via the following outlets.

- Information to motorists/road users can be communicated through the following travel information outlets (Koon and Galarus, 2016), which include but aren't limited to:
    - 511 phone system
    - 511 website
    - Statewide traveler information websites
    - Road condition maps
    - Social media (Facebook, Twitter)
    - Mobile websites
    - Media outlets (e.g., local TV)
    - Link to transit operators
    - Smart phone apps
    - VMS; DMS
    - HAR
- Information can be communicated to maintenance personnel via similar platforms as mentioned above in addition to the following outlets:
    - Specialized password-protected websites for more detailed information that is not being released to the public
    - Emails or internal websites/communication platforms

Two forms of weather-responsive traffic management strategies pertain to information dissemination: pre-trip road condition information dissemination and en-route weather dissemination (Gopalakrishna et al., 2011).

- The **Pre-trip Condition Dissemination**, in which agencies send out information about current and forecasted weather and pavement conditions. If roadway users see this information prior trip initiation, it can strongly influence their choice of mode, departure time, and travel route. The greatest challenge to this form of information dissemination is ensuring that travelers actively check for it before beginning their trips. Providing relevant information is useless if people are not checking and therefore following it.
- The **En-Route Weather Alerts** obviously have less of an effect on travel time and mode but do affect travel route. This kind of information gives drivers the option to change routes before hitting a problem area. The biggest challenge with this form of dissemination is relaying accurate information when the information is dynamic and changing.

Issues that decrease the quality of traveler information include the following:

- Errors or failures in VMS feeds (e.g., misspellings or typos, incorrect abbreviations, cultural variations, sign limitations)
- Equipment failure or equipment end of life
- Camera failures: offline, communications, power issues, potential old or partial pictures, pixels out.
- Field element location
- Lack of timeliness (e.g., old or stale information, inaccurate conditions reported, missing report, wrong start date on construction project)

- Operator input error
- Sensor failures and mis-calibration
- Breakdowns in connectivity and communications
- Missing information regarding an incident, construction, lane closures, etc.

Methods to check data quality and solve such errors range from fully manual procedures to semi-automatic procedures to almost fully automatic means. In order to mitigate these problems, stricter quality control checklists need to be added as RWIS is becoming more widely available in user-friendlier forms.

2.3.1. Clarus

The Clarus Initiative began in 2004 as a multiyear program funded by the USDOT (Gopalakrishna et al., 2012). The ultimate goal of this program was to create a new way to assimilate data, check data quality, and disseminate data in order to provide real-time weather and pavement conditions. The program used different states' RWIS and ESS stations along with mobile observations from AVL-equipped trucks.

Clarus employed a web portal to display weather and other relevant travel conditions. The information is produced on a map where the user can select points along a roadway to see photos and read different weather sensor readings. The program also includes a trip planning function. Once enough background weather/pavement data is gathered, this function could greatly assist drivers for future trips.

Clarus did face troubles in accuracy of some of the data taken from RWIS and ESS stations, most specifically the roadway temperature, which is critical in estimating whether a road is frozen. This created PR issues as the public was less likely to trust the information given from the portal. Furthermore, not all the information given on the site was easily understandable by the public, so the public often misunderstood the readings. Overall, this database was most useful with traffic management personnel, as they could relay information to and from the public regarding road conditions so people could change their routes immediately.

2.3.2. Examples of DOT Dissemination Mechanisms

Bhat et al. (2019) lists methods of information dissemination that are currently in practice in some cities or counties in Texas that include the following:

- **511 systems and websites** such as 511DFW are used to disseminate information directly or through linking with agency websites. Active traffic information sources such as DriveTexas (https://drivetexas.org/) and TxDOT's ITS website (http://www.transguide.dot.state.tx.us/) can be effective in information dissemination.
- **Social Media or Mobile Apps:** TxDOT uses social media to provide road-weather information updates through Twitter and Facebook, which provide a virtually free source

of information dissemination. Figure 2.15 shows an example of information dissemination through Twitter. More details can be found in the report by Bhat et al. (2019)

- **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. CodeRed and Everbridge Mass Notification System are examples of such systems that are used in several Texas towns and cities. Details can be found in Bhat et al. (2019).

The dissemination mechanisms adopted by a few other DOTs (Wyoming, Florida, Oregon, Idaho, and Alabama) are briefly summarized in Table 1, along with the data sources and the impact of the road-weather management system.

TxDOT Austin
@TxDOTAustin

The power of water: RM 2900 bridge in Kingsland washed away. #TurnAroundDontDrown #atxtraffic Road closures at drivetexas.org

10:26 AM - 16 Oct 2018

70 Retweets 59 Likes

4 70 59

Figure 2.15: Example of information disseminated via Twitter

Table 2.1: Examples of DOT Dissemination Mechanisms Along with Technology and Impact

DOT	Technology/Data	Dissemination	Impact
Wyoming	Speed detection, RWIS, CCTV, historical and current crash data	DMS, variable speed limit, 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 variable speed limit	Safety & traffic flow – decreased speed variance and reported crashes
Oregon	Weather sensors, crash data	Variable speed limit/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

Chapter 3. WinterOps Sensing Pilot

Across its 25 districts and 269 maintenance sections, TxDOT's fleet of vehicles used for winter operations (WinterOps) are diverse in type and age, ranging from brand new to 20 years old and older. Most trucks are used for different purposes year-round but equipped with WinterOps equipment for only part of the year. Adding minimally invasive sensing capabilities to each vintage of truck requires close teamwork with maintenance personnel.

The ability to automatically sense winter-weather-operations treatment activity (through detection of plowing, spreading, or spraying) is the cornerstone for this project. The general idea is to leverage existing fleet-wide on-vehicle telemetry ("GPS black box") equipment to send signals that indicate when respective WinterOps-related equipment is activated. Once such signals are obtained by that infrastructure, activations of plowing, spreading, spraying, and other equipment wired to the general sensor inputs are automatically archived and made available to live and historic data services that can utilize data for various forms of monitoring and reporting. This chapter compiles together successful experiences from installations on the project's six pilot vehicles into a step-by-step process that outlines a general recipe relevant for all vehicles.

While the project's earlier installation design utilizing the Verizon Connect fleet telemetry system was documented in project deliverable P1, "Mounting and Basic Operation Manual" submitted in September 2020, the TxDOT fleet-wide installation of Geotab products in late 2022 necessitated a number of revisions in strategies for piloting in Winter 2022–2023. As noted in this chapter, this allowed the sensing scheme and supporting hardware to be simplified. The equipment installation efforts utilizing Geotab were conducted among four trucks in the TxDOT Abilene District and two trucks in the Lubbock District, listed in Figure 3.1.

Lubbock: 871221071 *and* 871220088:

- Ch. 1: PTO on (via pressure switch)
- Ch. 2: Spreader control box on
- Ch. 3: Plow moving down or down in "float" mode (via plow control box)
- Ch. 4: Plow moving up (via plow control box)

Abilene: 871221063:

- Ch. 2: Spreader control box on
- Ch. 3: Plow moving down or down in "float" mode (via plow control box)
- Ch. 4: Plow moving up (via plow control box)

Abilene: 4793-G:

- Ch. 2: Sprayer on (via control box)

Abilene: 3300-K:

- Ch. 2: Spreader on (measured from the spreader solenoid)
- Ch. 3: Plow moving down or down in "float" mode (via plow control box)

- Ch. 4: Plow moving up (via plow control box)

Abilene: 4498-H:

- Ch. 2: Spreader control is on (via mechanical switch at the control lever)
- Ch. 3: Plow is down (via mechanical rotating plow level switch on the plow rig)

Figure 3.1: Installations completed for the project pilot

3.1. Sensing Signaling

WinterOps sensing capabilities focused by the project includes plowing, spreading, and spraying. Detection of plowing was achieved through either the use of a switch that makes contact when the plow is lowered, or through detecting when the plow is in motion being raised or lowered (in which case, a heuristic can be used to estimate when the plow is actually down). Spreading and spraying actions are signaled through the detection of power to the respective control boxes. In later stages of the project, the activation of the Power Take-off (PTO) was also considered as an important event to be sensed. Not only is the PTO used for other truck functions during non-winter seasons (for example, a dump truck dumping), but it also provides a precise indication of when a spreader is actually utilizing the PTO to actively put material onto the roadway.

3.1.1. Channel Assignment Scheme

Each of the Geotab IOX-AUXM cable harnesses that allow for general-purpose “on/off” sensor inputs have 4 channels, labeled “AUX 1” through “AUX 4”. It is also possible to daisy-chain cable harnesses to achieve up to “AUX 12”. To ease the challenge of keeping track of which channel maps to which function across all of the trucks, a “quasi-standard” was devised that has the capacity to commonly associate each AUX channel number with a known set of possible functions, as indicated in Table 3.1:

Table 3.1: “Quasi-standard” for typical channel assignments

AUX	Purpose
1	PTO on
2	Spreader or sprayer control box power on
3	Plow down (if plow rig level switch is used), plow *moving* down, or plow down in “float” mode
4	Plow *moving* up

Because it may be rare for a vehicle to have both a spreader and a sprayer, Channel 2 is allocated for either of these. On trucks that may have both, an exception would need to be made for the channel number assignment scheme. For equipment that is subject to be removed during the off-season, it is appropriate to consider the use of a connector on the sensed activation line that allows for a quick, clean disconnect. (If these are hard-wired, maintenance personnel under tight schedules may rip out or clip wires used for WinterOps sensing). In the case of the plow status, only Channel 3 would be needed if a physical plow level switch/sensor is used to indicate when the plow is in the down position; otherwise, a signal for the plow moving upwards is necessary on Channel 4.

In the future, other channel assignments can be sought for other types of equipment, whether they are assigned among Channels 1-4, or they utilize a daisy-chained cable harness. Other types of equipment could include arrow boards, flow meters, and individual booms on an advanced sprayer vehicle.

3.1.2. Caveats

This section clarifies what can be expected of the precision of signals for each type of WinterOps equipment. The activation of a signal depends upon characteristics of the equipment on each truck, and how the operator utilizes the equipment. Some ambiguities can be helped or resolved by additional processing on the IT back-end.

3.1.2.1. Plow Blade

When both Channels 3 and 4 are utilized to measure from the in-cab control box when the plow blade is in motion going down, or in motion going up, no raw signal is activated when the plow is resting in the lowered position. To gain a sense of when the plow is likely in the lowered position, heuristics must be leveraged on the IT back-end that act upon the Channel 3 and 4 signals. In short, the series of “down” and “up” activations are analyzed by how long each is activated over a length of time. After a plow blade is lowered onto the pavement surface, a challenge is to differentiate between when a vehicle operator quickly taps on the “up” control to raise the blade half an inch above the roadway versus when the operator presses the “up” control long enough at the end of a plowing operation to drive to the next destination. After an unknown start state, the heuristics utilize sequences of up/down events and thresholds of time to estimate when the plow blade is down on the roadway. Since all trucks are different, and the plow moves up and down at different speeds on different trucks, a calibration process may still be needed to allow the heuristic to work as intended. The heuristic used for the pilot is found in Appendix B.

Another style of operation to be detected in the absence of a physical plow level detector is the use of “float mode”. This “float mode” is activated when the “down” control is constantly engaged, allowing the gravity of the plow blade to keep it in contact with the road surface. Personnel in both Lubbock and Abilene districts said that the use of “float mode” is deterred because the scraping action puts excessive wear-and-tear on both the plow blade and the road surface.

3.1.2.2. Spreader

On piloted trucks, researchers learned of different styles that operators may use to activate spreading on a roadway.

First, the operator may turn a spreader control box on (such as the one pictured in Figure 3.6), set the spread rate knob to zero and "blast" where necessary. The "blast" function exists on some control boxes, allowing the operator to push a knob to suddenly spread within small areas, such as short bridges, ramps, or intersections. Alternatively, the spread rate knob can be turned up to selectively spread. In these cases, it is not possible to know for sure when spreading is happening without utilizing another means of sensing that directly monitors the physical dispensing action.

Second, the operator may keep spreader control box on, and engage the spreader with the PTO. Some trucks then automatically disengage (or, "kick off") the PTO when the operator drives above a certain speed. To detect time and location of spreading action precisely, it's necessary to utilize the spreader box power signal *and* the PTO signal together.

If some of the signals necessary for detecting precise time and location of spreading are missing, the sensing of the spreader control box power is enough to at least know that spreading very likely happened *sometime* during the course of a trip. This can still be useful for operations and planning purposes.

3.1.2.3. Sprayer

The sprayers and control boxes encountered during the project appeared simpler than the spreader controls. The PTO was not necessary, and activation lines were readily accessible. A challenge would come if multiple sprayer booms are utilized, as each boom may operate independently. In this case, power to the spreader box is not enough to allow for precise sensing. It could be possible to utilize a parallel set of relays to know when at least one boom is activated. Another approach is to daisy-chain enough IOX-AUXM cable harnesses to individually detect the activation of each boom, and to then utilize logic on the IT back-end to know when at least one is activated.

3.1.2.4. PTO

Sensing of the PTO was achieved on the two trucks in Lubbock by utilizing pressure switches that close a contact when pneumatic pressure enters the switch. Maintenance personnel readily tapped these pressure switches into the tube that pressurizes when the PTO control is engaged by the operator. While this pressure switch was found to be readily available at a local auto parts store, additional parts are needed to adapt the pneumatic connections of different sizes.

In Abilene on a similar vehicle ("871221063"), such pressure switches were not available at the time of installation. Researchers evaluated whether wires to the PTO indicator lamp next to the control could be "tapped" to obtain a positive signal whenever the PTO is activated. However, because of the way the indicator lamp's circuit was designed, tapping a direct signal either caused the indicator lamp to never extinguish, or introduced grounding problems into the vehicle. Researchers then considered that it would likely be possible to wire some kind of sensing in-series with the PTO indicator lamp rather than "tapping off". However, because an accidental break or short in this kind of wiring would have the potential to entirely break the PTO, maintenance personnel were resistant to allow in-series wiring. Another method would be needed for sensing off of the PTO indicator lamp that could potentially require the use of diodes, resistors, or relays.

On Abilene District's "3300-K" vehicle, there was no success in finding a place to obtain an electrical signal that activated whenever the PTO control on the dashboard was engaged. The dashboard switch bank used a proprietary serial signal that could not be deciphered. On this vehicle, sensing of PTO activation was achieved by running a wire from the solenoid on the exterior of the cab that engages PTO activation.

3.2. Installation Process

This section presents a step-by-step process for performing an installation of WinterOps sensing capabilities on a truck. Because each truck is different in terms of wiring, and makes/models of equipment, the process is to act as a general framework. The same process is provided in slide show format for the end-of-project "Product P3" workshop. In the next chapter, this process is supplemented with further notes on discoveries and challenges encountered during the course of the project.

3.2.1. Checklist

The installation process, plus steps leading up to it are roughly outlined through the following checklist:

- ☐ **Choose target vehicles.** The choice should be based upon the needs of the district or maintenance section and can be influenced by estimating the ease of installation. Installation complexity can depend upon how new the truck is, how familiar maintenance personnel are with the vehicle model and vintage, and how accessible equipment on the vehicle appears to be. As hinted in the next chapter, no truck should immediately be considered as "too old".

- ☐ **Order IOX-AUXM cable harnesses.** This step must allow for enough time to find a supplier that has these in stock, and for the delivery time prior to installation. While the fleet tracking contract vendor should have these readily available for ordering, researchers did not find this to be true at the time of the pilot.

- ☐ **Order junction boxes and other parts.** As described below, junction boxes allow sensor lines to be accessed for testing and maintenance purposes.

- ☐ **Install sensing capabilities.** The next section describes the steps in detail.

- ☐ **Verify signals in shop.** The MyGeotab web application allows for this. Further details are found in Section 5.1.

- ☐ **Perform simple road test and verify signals.** This final step verifies that the WinterOps sensing installation is ready for use in the field.

3.2.2. Steps

This section spells out common activities that pertain to the installation itself. Figure 3.2 shows the overall structure of the final installation, where +12V sensing activations from pieces of equipment pass through a junction box, and then enter the IOX-AUXM cable harness attached to the Geotab "GPS black box".

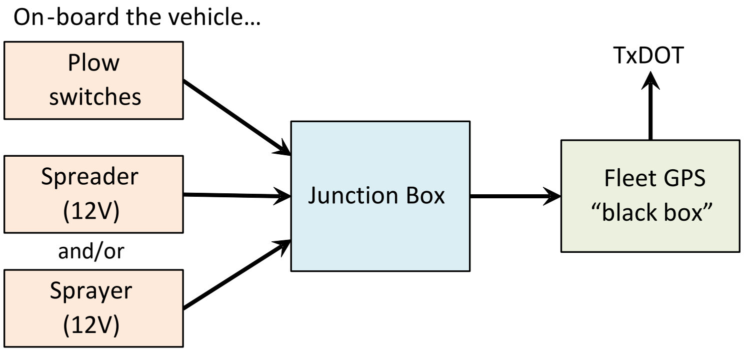


Figure 3.2: Structure of WinterOps sensing equipment

While performing the installation steps, it is important to remember:

- Every truck is different;
- Types of equipment among trucks are different;
- Steps described below should be modified or skipped as needed; and
- Engineering judgement should be used through the entire process.

After the installation is complete, Geotab will passively record WinterOps activities along with vehicle position and timestamps. Data are guaranteed to be stored with Geotab for at least a year. (Geotab personnel informally told researchers that in the multi-year history of Geotab's product offering, they had never deleted customers' historic data.)

3.2.2.1. Position the Junction Box

In this step, locate a mounting position for a junction box such as the one shown in Figure 3.3 to allow for future access. During the course of this project, positions have included underneath the passenger seat, or on the passenger side of the in-cab central control column found on newer trucks. This junction box will have sensor input and data lines run to it, plus optional +12V supply that is only active when vehicle ignition is engaged. Also consider that it can be helpful to run power or data lines in anticipation of potential future expansion of sensing capabilities.

Label four terminals in the box as Channels 1, 2, 3, and 4. Also label ignition supply voltage if that is to be provided to the junction box. Until the end of the installation process, do not mount or screw down the box until wiring is finished and sensor inputs have been tested in the shop.

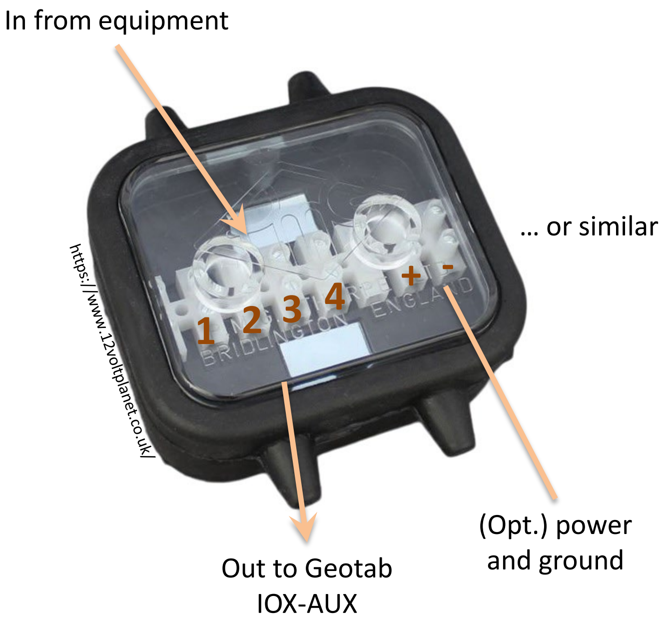


Figure 3.3: Simple junction box design appropriate for in-vehicle installation

3.2.2.2. Provide Power (if Needed)

In cases where sensing is to be accomplished with the installation of switches or mechanical contacts, it is necessary to run a wire that serves as a +12V supply only when ignition is applied to the vehicle. This can be accomplished by finding such a supply in the vehicle's fuse box and tapping off of it, or using a plug adapter that can plug into the +12V cigarette lighter-style jack. Run such a supply to the corresponding terminal in the junction box.

3.2.2.3. Attach to Cable Harness and "GPS Black Box"

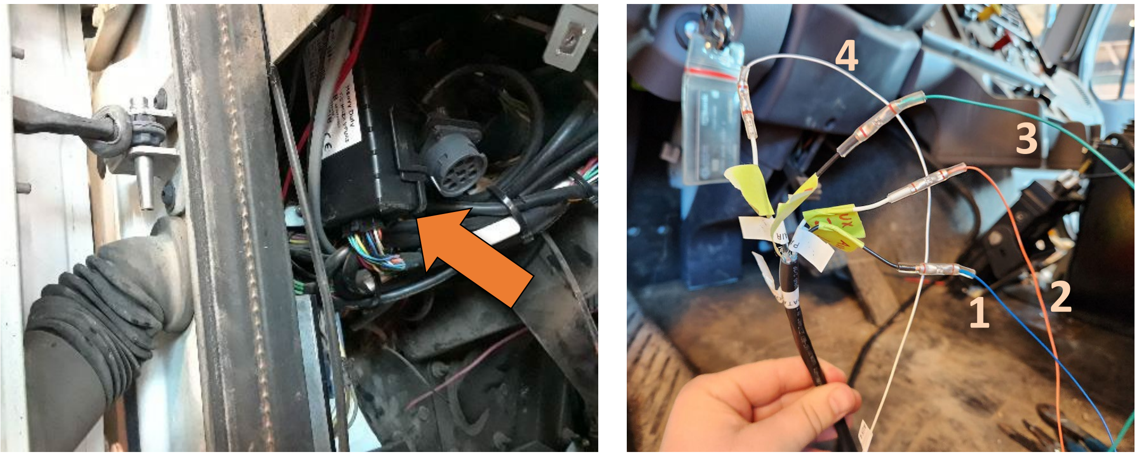
Now, locate the Geotab "GPS black box" that should have already been installed in the vehicle by the fleet tracking contractors. This should be located underneath the driver side dashboard, as in Figure 3.4a. Loosen any zip-ties that are holding the "GPS black box" in place so that the expansion port is visible. (The expansion port looks like a USB mini jack).

In preparation for attaching the IOX-AUXM cable harness to the expansion port, and in anticipation of zip-tying the cable harness to the "GPS black box" so that it can be secured, attach data lines to the "AUX" inputs of the cable harness:

1. Run at least four wires from the junction box to the place that the wires can attach to the IOX-AUXM cable harness colored "AUX" wires. It is best to use a cable that contains four wires bundled together. Connect four of these wires at the junction box to respective "AUX

1”, “AUX 2”, etc. terminals. Then, on the other end of the data cable, split apart the individual wires and use a voltmeter to determine which “AUX” terminal each is connect to. Label them “1”, “2”, etc. with tape.

2. The IOX-AUXM cable harnesses used in the project were manufactured with the colored “AUX” cables attached to an 8-position female header. On existing vehicles, maintenance personnel elected to do away with the header and use shrink-tubed solder joints to attach the individual “AUX” wires (see Figure 3.4b). Clip off the header and ensure that the colored wires are labeled as “1”, “2”, etc. as they were prior to clipping. Then attach to the data lines, ensuring that the channel assignment is consistent.
3. Two additional cables (red and black) are found coming from the IOX-AUXM that are shrink-tubed together. These are used by the IOX-AUXM for termination purposes when multiple IOX-AUXM cable harnesses are daisy-chained together. For the purposes of this installation, if no daisy-chaining is intended, these should simply be tucked away when the Geotab equipment is placed back underneath the dashboard. Refer to the IOX-AUXM documentation for further details.
4. Plug the IOX-AUXM harness into the “GPS black box”. Leave the “GPS black box” out until it has been verified that Geotab receives the “AUX” inputs.



a.

b.

Figure 3.4: The cable harness connects to the telemetry device (a), and data lines should be labeled (b).

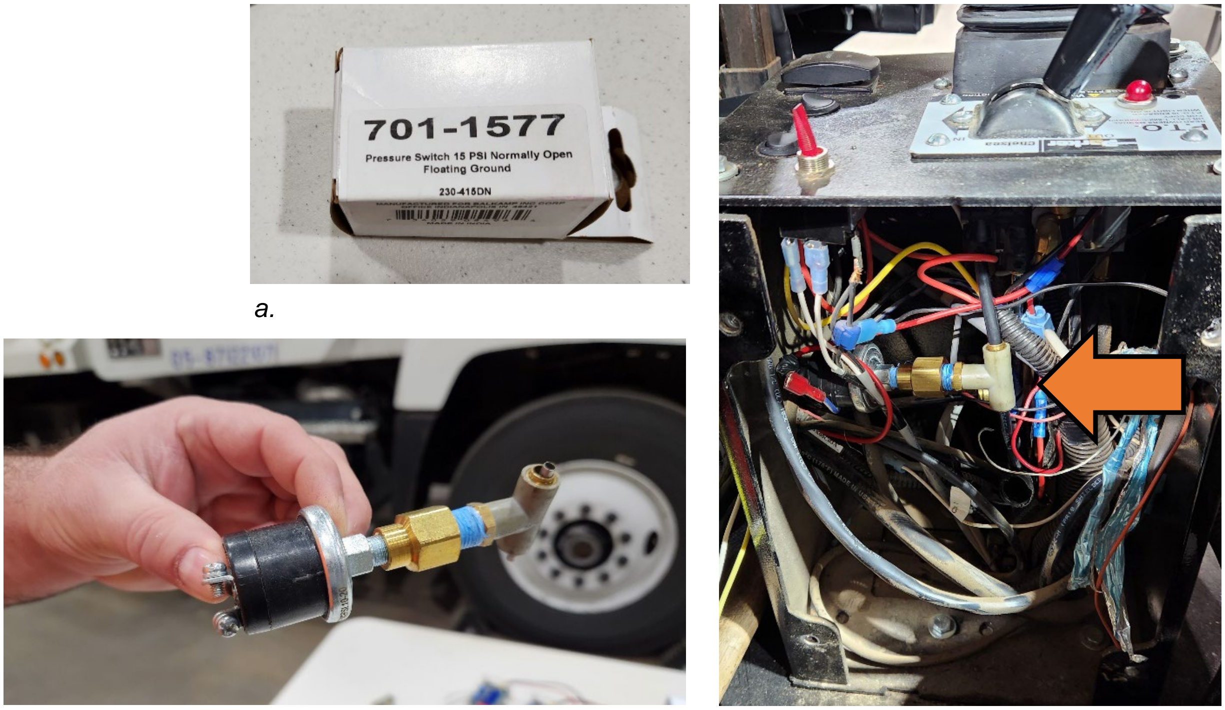
3.2.2.4. Connect Equipment Sensing

This section describes details on connecting sensing for the PTO, sprayer, spreader, and/or the plow blade. Processes described here should be used as needed, with the caveat that some unique characteristics of trucks not encountered in the pilot study may require new ingenuity.

PTO (Channel 1):

Option 1: Pressure Switch:

Maintenance personnel in Lubbock implemented a solution for both trucks used in the pilot study that involved the use of a “normally open” pressure switch. The switch could be placed in-line of the PTO pneumatic tube (see Figure 3.5). The activation pressure is adjustable. When pressure is applied, an electrical switch inside closes. As a result, wiring +12V through the switch and attaching the other terminal to the AUX Input #1 allowed for clean, affirmative detection of PTO activation.



a.

b.

c.

Figure 3.5: Pressure switch for PTO sensing (a and b), installed in the console column (c)

Option 2: Electrical Activation:

On the “871221063”, “871220088”, and “871221071” vehicles, an indicator lights up on the central console when the PTO switch is engaged. While it was tempting to believe that a signal could be pulled off of the indicator, maintenance personnel discovered that the lamp sits in series between the PTO console switch and other circuitry, causing problems described in the “Caveats” Section 3.1.2. It is conceivable that an electronic PTO detection could still be achieved, perhaps with a resistor or diode, but was not attempted for the pilot.

Brine sprayer or V-box spreader (Channel 2):

For devices such as these, locate a +12V line that is activated when the brine sprayer or V-box spreader is switched on. Places within the cab to “tap off” of such a line may include inside the vehicle's fuse box, or within the bundle of cables that are attached to a control box such as the spreader control shown in Figure 3.6. Vehicle wiring diagrams and a sharp probe can help in this search. If a candidate signal wire is found, a crimp-on "T" junction can be used, or other means of securely splicing such as solder joints and shrink tube. If neither of these in-cab options can be identified, and no other way is feasible for equipping the cab (e.g., "ingenious" methods described at the end of Section 4.2), then it may be necessary to run a wire out to the solenoid that activates when the equipment is switched on, as was necessary for the "3300-K" vehicle. Exterior cables are subjected to a harsh environment, and are advised to only be used if it is absolutely necessary. During the process of finding and making the connection, check expected operation using a voltmeter, and be aware of whether a chance exists for undesired battery drain when equipment is activated after the vehicle's ignition is shut off.

Figure 3.6: Spreader control box

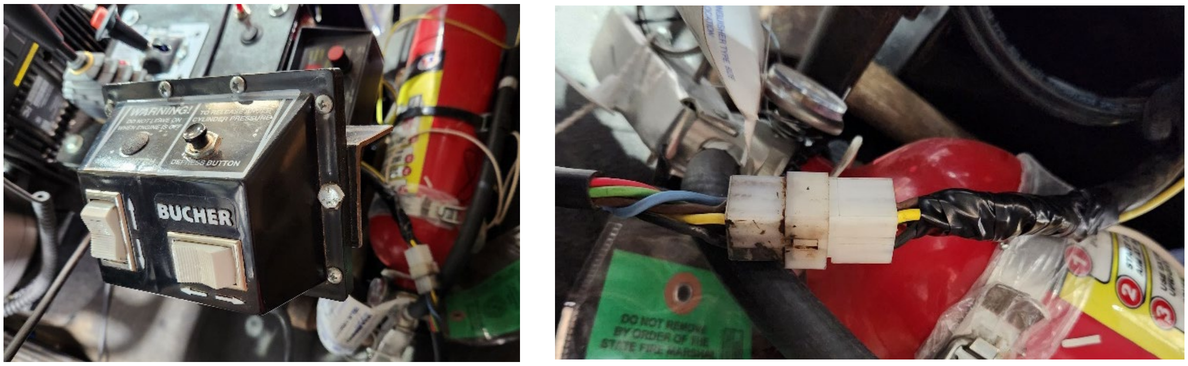
Plow blade up/down sensing (Channels 3 and 4):

During the project, two approaches were used for sensing when a truck is plowing. The first involves detecting when the plow blade up/down controls are used by the vehicle operator by tapping directly off of the +12V lines tied to the control box's rocking switches. Here, determination of the plow blade being in the down position depends upon the use of heuristics run on the sensing data, or the assumption that the plow is operated in "float mode". The second involves using an external rotating switch mounted to the plow rig that closes when the plow is lowered toward the roadway.

Option 1: In-cab control

Vehicles with plows used for this study contained a Bucher control box, as seen in Figure 3.6a. The control box features two large rocker switches. One is used to raise and lower the plow blade, and the other is used to angle the plow parallel to the roadway's surface. For the purposes of the project, only the up/down control is of interest. On some models, the "down" switch can be intentionally stuck in that position to operate the plow in "float mode", where the plow constantly rests on the road surface while the vehicle is in motion. Inside the control box, terminals extrude from the rear of each switch, allowing for +12V to appear terminals that correspond to each plow motion. The positions of the terminals are counterintuitive to the switch's operation, and should be verified with a voltmeter. Also, coming from the control box is a pigtail connector shown in Figure 3.6b. It is possible to either connect directly to terminals on the rear of each switch, or at the pigtail connector.

Note that unless the plow is operated in "float mode", no signal exists from this control box that indicates at any given time whether the plow blade is resting raised or lowered. As explained in Section 3.1.2, for this to be estimated, a calibrated heuristic that considers historic switch press patterns can be run against the raw up/down switch signals to determine when the plow is *likely* in the up position or the down position.



a.

b.

Figure 3.7: In-cab plow controls: a) Bucher plow control box, and b) connections to control box pigtail

Option 2: Exterior plow level sensing

Prior to devising the plow level heuristic that allows for the in-cab up/down plow controls to be used, the method used for the project involved attaching a mechanical switch or sensor to the exterior plow assembly that would activate (e.g., switch closed with +12V) when the plow blade is lowered toward the ground. To accomplish this, +12V ignition power (only active when vehicle ignition is engaged) and return wires must be run from the junction box to the front bumper area, where it is possible to plug in a plow rig position sensing switch to connect to the junction box.

A plug is necessary because the plow rig may be removed from the truck during off-season times. In choosing how to facilitate this, it is possible to either attach in-wire connectors and secure them near the front bumper using heavy-duty zip ties, or to drill out a place on the front bumper for mounting a cable jack (Figure 3.10). It is important to choose a cable plug type that is resilient to the harsh environmental conditions encountered on the front of the vehicle when it is performing WinterOps activities.

Figure 3.8: A hole is drilled on the bumper to install the cable plug assembly.

Next, a mechanism for signaling when the plow blade is in the “down” position needs to be attached to the plow rig. Two vehicles in Abilene were first equipped with the rotating limit switch pictured in Figure 3.9. The switch is designed for harsh environments, and the armature is adjustable. It is also possible to unscrew the cover of the switch and rewire it to rest in the “on” position instead of the “off” position. Other options for mechanical plow level sensing that were tried included ball-bearing sensors (consisting of a non-airtight cylinder containing a small metal ball), but the ball bounced too excessively within the casing for a solid signal to be achieved. A mercury switch was out of the question because of cost and environmental concerns.

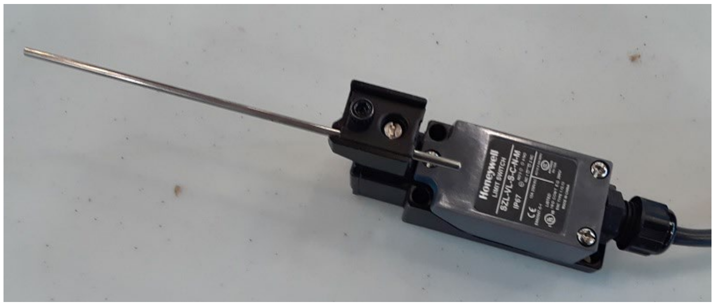


Figure 3.9: This limit switch must be attached to the plow assembly for the “down” position to be detected.

The limit switch must be installed such that it activates (e.g., deflects enough that it “clicks on”) when the plow is completely lowered. Enough tolerance should be given so that the plow is still considered “lowered” even if it is an inch off of the road surface, and that the plow blade may bounce whenever the vehicle passes over bumps. Furthermore, it is important to keep in mind that the plow rig “down” position may slightly change depending upon how the blade is mounted at the start of each season; e.g., how much chain is used in suspending it from the rig.

As pictured in Figure 3.10 and Figure 3.11, it may be necessary to weld a metal “extension” to the plow rig so that the limit switch is positively activated without there being a chance of the armature slipping. Finally, to protect the switch from ice build-up that can happen during plowing, a “shield” as shown in Figure 3.11 is welded above the switch location to protect it.

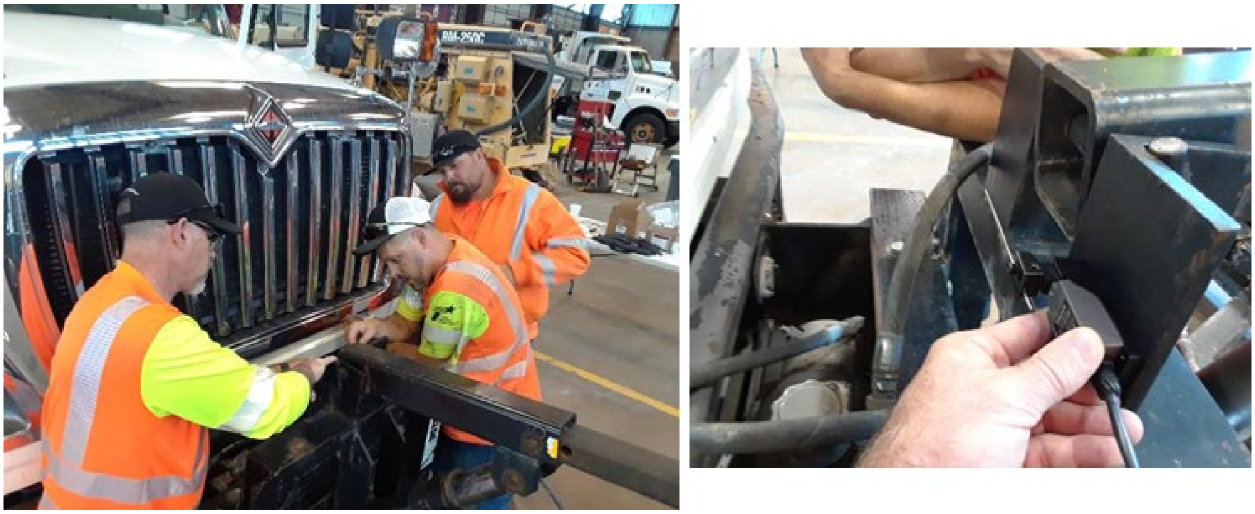


Figure 3.10: Maintenance personnel determine how to mount the limit switch.

Figure 3.11: Successful plow rig extension and rotating limit switch on 4498-H

3.2.2.5. Test Sensing in the Maintenance Facility

In the maintenance garage or bay, start the vehicle, wait for half of a minute for the Geotab equipment to boot up, and activate and deactivate several times each piece of equipment that has been connected for sensing. Wait a couple of seconds between each activation or deactivation. Especially after the second activation, listen for a series of beeps coming from the IOX-AUXM cable harness that indicate which AUX channel is being sensed. (For example, a series of 3 beeps will correspond with positive identification of activation on Channel 3). These beeps will be heard for a handful of activation events until the IOX-AUXM “learns” about the signaling scheme that is to be used in the future.

If no beeps are heard for a particular channel, then that may indicate that the signal is not appearing from its source. It may be helpful to check for expected +12V activations at the junction box’s terminals.

Power down the ignition and use the process in Section 5.1 to verify in MyGeotab that each of the channel activations were received by Geotab. Ensure that the timestamp provided with each event is roughly within the time period that the garage testing was taking place.

3.2.2.6. Final Mounting

Use screws and mounting hardware to secure the junction box to its permanent location. Also, zip-tie the IOX-AUXM cable harness to the “GPS black box”. Return the “GPS black box” to its place under the dashboard and use a zip tie or two to keep everything secured in its original place. Then, tuck data and sensing signal cables under doorframes, floor mats, etc. as much as possible to keep cables in the cab from interfering from vehicle operation.

3.2.2.7. Simple Road Test

This step is best performed with one driver and one observer sitting in the passenger seat. Plan ahead on a short route that would allow for testing WinterOps sensing capabilities. If a plow is involved, the plow rig and blade should be mounted on the truck, and lowered in a safe place while the vehicle is in motion. For example, Abilene District personnel used an area in the Taylor County Maintenance Facility where loose asphalt is on the ground; there may be other places where the road surface is expendable. If a spreader is involved, the trucks tested for the project only required the control boxes to be powered even without a slide-in V-box spreader installed. If a sprayer is involved, the Abilene District truck’s sprayer used for the study was run for short periods of time while the brine tank was empty. It is also helpful to consider places where two or more pieces of equipment are operated simultaneously, such as having the PTO engaged while powering the spreader control.

The observer in the passenger seat should have a smartphone app or other means of reading accurate time down to the second, and a means of logging event types and times. Researchers in the project used a notepad (even though writing legible notes on a notepad while trucks are in motion is tricky, as the truck’s suspension jerks and shakes the cab considerably). After the truck starts on its journey, make a note of every time a piece of sensed equipment is switched on or off. Particularly for the plow blade, make a note of when the plow is put into motion going up or down, and when it is stopped, even if the plow blade control is engaged for barely a second; try to simulate the operation that would be exercised in winter weather, noting whether the plow is lowered enough to functionally plow a snowy roadway.

At the end of the journey, use the method described in Section 5.1 to view events in MyGeotab diagnostics, and verify times to those that were logged. If each event occurs within a second or two of the logged time, then the outcome is considered good. If a channel never activates as would have been expected, then sensing on that channel plus that channel's connection to the IOX-AUXM cable harness should be checked and repaired.

After this is complete, it is also possible to obtain data using the method described in Section 5.2, and use GIS software to visualize the vehicle track combined with equipment operation events, as seen in Figure 3.7.

3.3. Road Testing Results

Road tests were conducted in December 2022, aimed at assessing the accuracy of Geotab readings shortly after WinterOps sensing installations. The goal was to verify the precision of Geotab readings by comparing them with actual records obtained from the road tests. For each vehicle, signal presence was first checked in the respective garages. Then, short road tests around the maintenance yards were conducted for the 871221071, 871220088, 4793-G, and 3300-K vehicles. The 4498-H vehicle was also similarly road tested, but without the use of the plow, because time for testing was limited.

Figure 3.12 to Figure 3.15 sample the results of two of the vehicles. Each figure showcases the path taken by the vehicle during the test on the left side, while on the right side, a plot depicts the ground truth status recorded by an observer inside the vehicle (in orange) alongside the status indicated by Geotab measurements (in blue). To record the precise timings of specific actions, such as moving the plow blade up or down and turning the spreader on or off, the observer inside the vehicle utilized a stopwatch mobile app. Various aspects of the Geotab service can be evaluated by analyzing these records, including the possibility of missed signals, the precision of timing, and accuracy of the plow level heuristic.

The plot in Figure 3.12 demonstrates a seamless alignment between the Geotab status indication and the ground truth. Notably, at approximately 10:06:30, the observer's report confirms that the plow blade is in the lowered position, coinciding with the plow level heuristic's status transition from "unknown" to "down". Likewise, another instance of synchrony occurs at approximately 10:07:00, where the observer indicates the plow blade being moved up, which is accurately reflected in Geotab's corresponding status update.

It is important to highlight that both Figure 3.13 and Figure 3.14 exhibit a scenario where the observer reports a change in the plow and spreader status, which goes unreported by the heuristic measurements. This specific occurrence arises when the truck operator briefly presses the plow blade up or down button, making minor adjustments to the plow position while keeping it in the same overall state (up or down). To account for these cases, a filtering mechanism is implemented in the plow level heuristic processing code to disregard such transient events and improve the likelihood of accurate status representation.

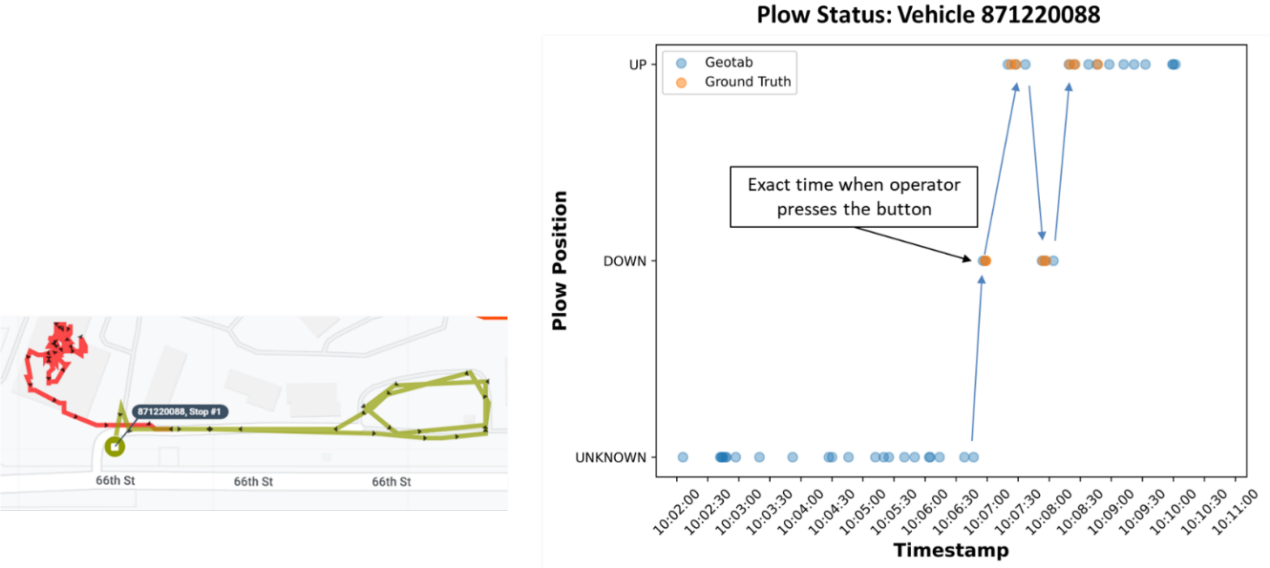


Figure 3.12: Vehicle 871220088 Geotab versus ground truth plow (heuristic) status

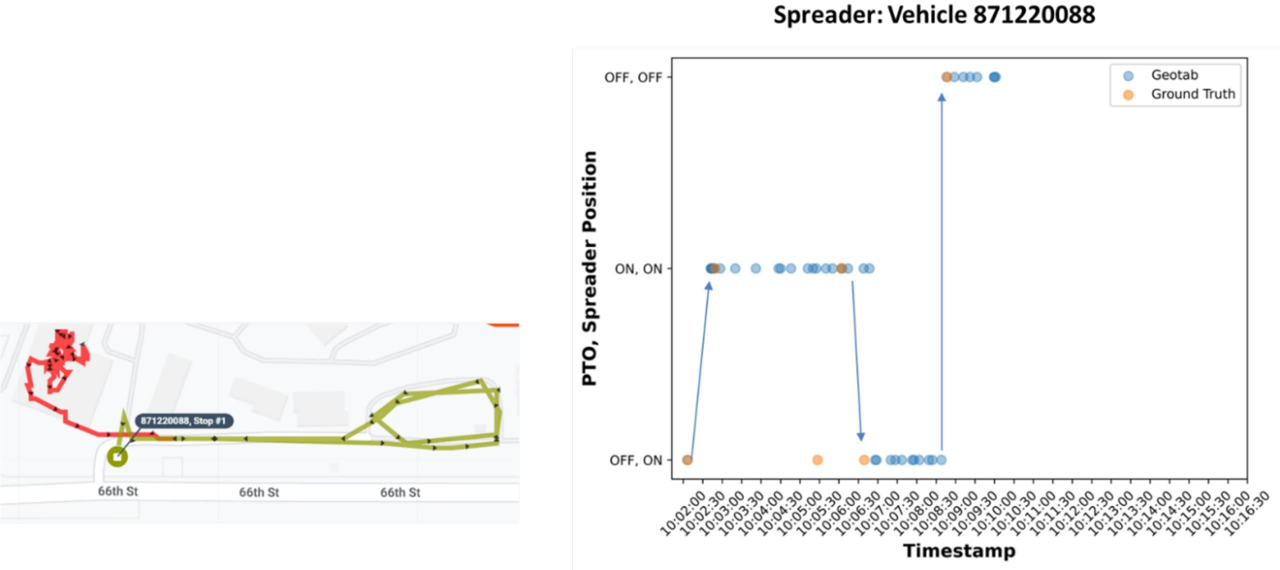


Figure 3.13: Vehicle 871220088 Geotab versus ground truth spreader status

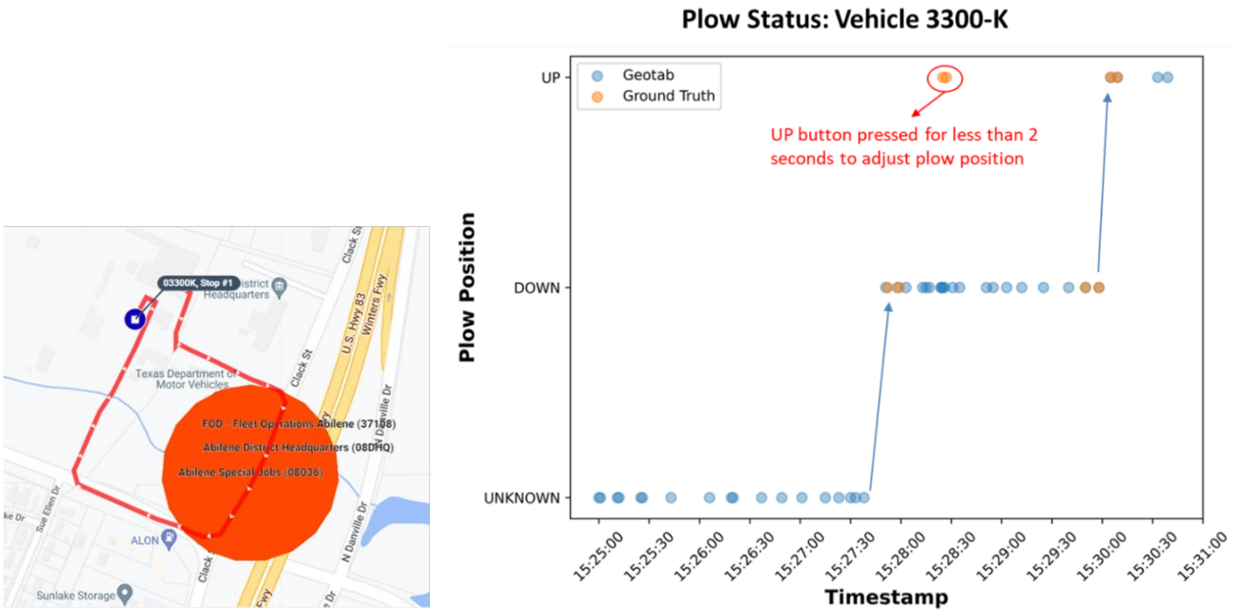


Figure 3.14: Vehicle 3300-K Geotab versus ground truth plow (heuristic) status

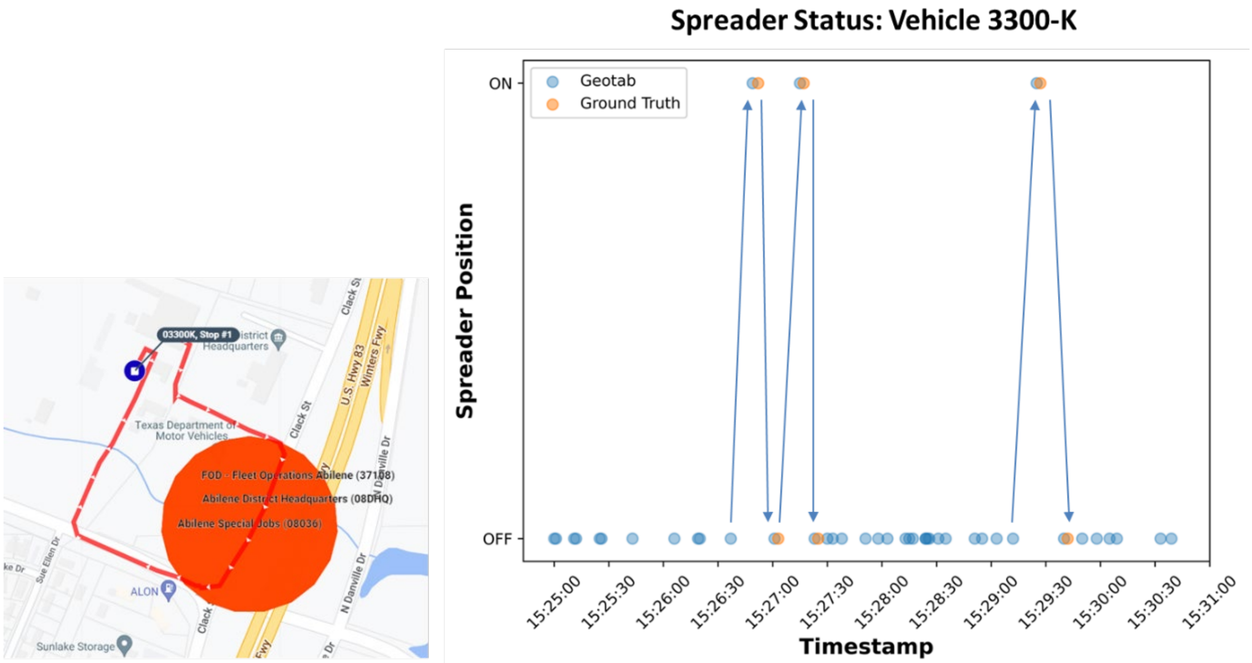


Figure 3.15: Vehicle 3300-K Geotab versus ground truth spreader status

3.4. Vehicles in Winter 2023

For the vehicles in service, WinterOps sensing signals were read by the Geotab system and accessible as historic data through the MyGeotab web app or the API. However, the 4793-G sprayer vehicle was not observed during the winter season because it was out of commission for repairs during two time periods of freezing activity, including Jan. 26-Feb. 3, and then Feb. 16-18, 2023.

Three-dimensional plots such as the one shown in Figure 3.16 have been instrumental in depicting winter operations. They exhibit a unique ability for vehicle position, equipment activation, and time passage to all be visualized in a single graph.

More samples of the WinterOps data appear in Chapter 5, both for purposes of extracting as comma-separated value (CSV) format that can be imported into a wide variety of tools including Excel, and analyzing/visualizing within GIS software.

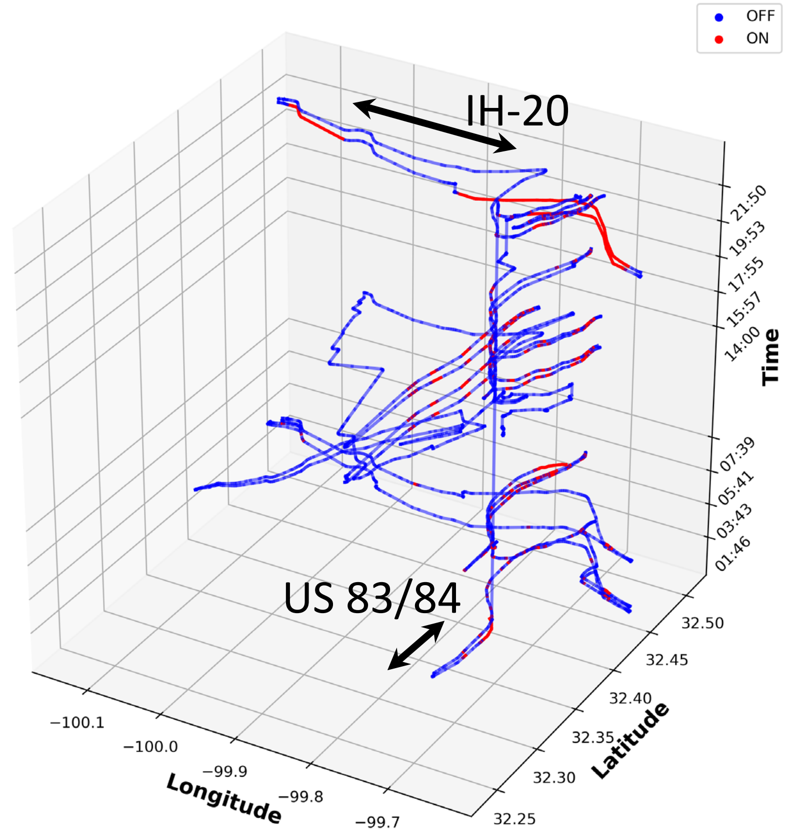


Figure 3.16: Three-dimensional time plot of spreading, Jan. 29-Feb. 2, 2023

Chapter 4. WinterOps Sensing Experiences

This chapter summarizes experiences that researchers and TxDOT personnel gained in various stages of installation and usage of on-vehicle WinterOps sensing.

4.1. Ramping Up the Project

When project stakeholders were identifying the priority for obtaining pretreatment and treatment operations data from fleet vehicles, and researchers had opportunities to speak with maintenance and operations personnel, researchers proposed the following tenets:

Equipment must be operated passively and hands-free. Operators gave the impression that it is difficult to reliably go out of one's way to specifically interact with a data system when the main task at hand is to treat many miles of roadway, often over long hours. For that purpose, researchers could not require operators to hit buttons on tablets, for example, to indicate where a plowing operation was executed or where brine was being loaded. Sensing equipment must be assumed to be "out of sight, out of mind."

Leverage existing equipment and processes as much as possible. Districts and maintenance sections use equipment and processes that have been in place for many years. To maximize the usefulness of new strategies and likelihood of acceptance, they must be introduced in a way that minimizes negative impact to what's been "tried and true." The strategies are tools to help do the job better, not create a major paradigm shift.

Vehicle tracking capabilities are still beneficial when the detection of winter operations equipment is not available. While the Geotab fleet tracking system is enabled on all ~11,000 TxDOT fleet vehicles that allow for the recording of vehicle positions and engine status, the addition of the ability to track specific WinterOps equipment is very new. For as much as possible, processes designed to utilize WinterOps sensing data should also provide value when WinterOps equipment sensing capabilities are absent.

There should always be a clear means to "fall back" to manual procedures. Even though they've been piloted, the methods for collecting WinterOps data are not widespread, and it would be appropriate to maintain the pre-existing practice of recording handwritten brine logs until semi-automation is more widely available. Meanwhile, the semi-automation provided by WinterOps sensing can be helpful for cross-validating and correcting the handwritten records.

Project researchers are not trying to replace any existing practice. The intention of the project is to offer new tools that have the capacity for improving winter operations, potentially through time savings in maintaining records and more accurate precision.

Clear benefits are sought in research opportunities that hold the most promise. Project stakeholders agreed that having a basic capability of understanding where and when equipment is switched on or off is an important first step. Further opportunities can be investigated for other more advanced sensing capabilities that would require advancement in equipment, such as flow meters and equipment control boxes with digital interfaces. With such support available from products offered by Geotab, TxDOT is likely to eventually pilot the use of such newer control equipment. It is expected that older control equipment relevant to this project will exist on hundreds of fleet vehicles for as long as those vehicles are in service, which can be 20 years or more.

4.2. Prior to September 2023

Up until September 2023, TxDOT employed the fleet-wide use of the Verizon Connect telemetry system. This involved "GPS black box" devices on board vehicles, cell data communications, and a back-end IT service that included a web app for viewing live and historic vehicle telemetry data. A method was also in place to provide a feed of live vehicle information to the ArcGIS Geoevents Server used for in-house dashboards and apps created on the ArcGIS Enterprise platform, including TxERA. Administrators of the back-end were able to add metadata for each vehicle to help describe vehicle function and signaling scheme for general-purpose sensor inputs. These were stored within the Verizon Connect system. The fleet contained a mixture of telemetry devices, some of which offered two general-purpose sensor inputs, and some that offered four.

After a number of challenges in obtaining the cable harness required to connect sensor signal lines to the "GPS black box" and obtaining information on cable harness pinouts, the first installation of WinterOps sensing capability was accomplished on the "3300-K" International 7600 plow/spreader truck in Abilene in May of 2021. In preparation for this installation, researchers identified a local engineering company, Meers Engineering (now disbanded) to design and build "sensor kits" consisting of electrical terminal blocks, relays, and isolated power regulators designed to feed necessary equipment activation signals to the Verizon Connect cable harnesses. Meers Engineering also investigated strategies for sensing the plow level position, and offered the rotating switch in Figure 3.9 as the first strategy to try out.

The installation of these sensing capabilities on "3300-K" ended up taking the entire day. Most of the time was in figuring out how to reliably obtain power that was only activated when vehicle ignition was on, and also determining how to consistently know when the spreader is activated. Technicians working on the effort extensively used wire probes and electrical schematics to find viable signals. The fuse box located in the dashboard surprisingly did not readily offer such signals, and the switch built into the dashboard console that engaged the PTO and spreader was mounted in a module that utilized a proprietary serial data communications scheme to the vehicle's computer. In the end, technicians had to run a wire along the exterior of the cab to the solenoid that activates the spreader. That allowed for 12V to show up on that wire whenever the spreader was operating.

Another intensive activity was in determining where to mount the rotating switch to positively know when the plow blade was close enough to the ground to assume that the vehicle was plowing. The rotating switch has an adjustable "arm" as shown in Figure 3.9. Unfortunately, it was not immediately possible to mount the switch in a place where the arm would not slip off. One strategy considered was to bend the arm so that a section of the plow rig would sufficiently rotate the switch. It became apparent that the screw that tightens the arm to the switch was not strong enough to keep it in position. The final strategy was to weld a metal rod to the end of a portion of the plow rig that would positively push on the arm without slipping out of place when the plow lowered (Figure 3.11). Maintenance personnel followed that welding operation with another that placed a metal shield above the switch and rod to protect it from ice that can pack behind the plow.

At the end of the day, no time remained for testing with the Verizon Connect system; this had to be conducted at a later time. The time required for the detective-work and engineering was extensive, but once maintenance personnel learned how to tap into the correct signal and positively determine when the plow was lowered, the process could be repeated much quicker on a similar vehicle. This happened both in Abilene and Lubbock Districts. Of all 6 trucks utilized for the project, the "0-3300K" was the most difficult and time-consuming to equip for WinterOps sensing. Two more trucks in the Abilene District were since then updated with WinterOps sensing capabilities for use on the Verizon Connect system.

When opportunities came to road-test with the Verizon Connect system, maintenance personnel and researchers discovered that latency of communications from the "GPS black boxes" sometimes exceeded 30 minutes when testing within the shop, and sensor events were recorded at about a 10-second accuracy on the road. While this could offer capabilities to record lengthy stretches of plowing activities, it would offer too little precision to reliably record "spot treatments", such as spreading through intersections and over short bridges.

The winter of 2021-2022 offered some experiences in WinterOps sensing that would need to be subsequently addressed. First, the strategy of using external equipment for plow level sensing needed to be revisited. Even though it was protected with a welded-on shield, the rotating arm switch mechanism used on the 3300-K vehicle ended up bending out of shape. Additionally, the connector provided by the local engineering firm corroded in the harsh environmental conditions found on the roadway. Another vehicle, 4498-H also had a rotating switch style plow level sensing mechanism, but the welded extension arm was larger and the shield was stronger. This plow level sensing mechanism survived that winter season, and was used in the same way for Winter 2022-2023 despite other vehicles being updated to the in-cab plow up/down sensing that required the use of heuristics to predict plow level position.

Other problems occurred during the winter of 2021-2022. One sensor kit failed and shorted out the vehicle. Operations personnel actively in the field ripped out the sensing equipment to immediately remedy the problem. Later investigation found that the power regulator within the sensor kit had failed, possibly caused by a lightning strike. Researchers began to consider how to simplify the sensor kits and do away with the power supplies. In addition, after some time after the first storm in 2022, the sensing of WinterOps equipment stopped working. It was later determined that the Verizon Connect "GPS black boxes" were expecting a different signaling scheme, perhaps after a firmware update.

After that winter, the means of detecting plow level was revisited. At that time, the engineering firm offered non-airtight ball-bearing style sensors that could be mounted to the plow rig. In subsequent tests, it was determined that the sensor was too "glitchy" to reliably sense plow level; it also never rotated enough to eliminate false readings when the vehicle was on a hill, or when the vehicle came to a stop. Researchers inquired about the use of mercury sensors, but TxDOT personnel stated environmental concerns over "mercury on the roadway", for example, if the vehicle suffered an accident. Plus, the engineering firm found that mercury sensors were fairly expensive and in low supply, on the order of $400 per piece. These factors led to the idea of using the "plow moving up" and "plow moving down" signals from the controls in the cab, and sending them through the plow level heuristic (Appendix B).

Finally, while Abilene District personnel equipped additional vehicles, maintenance personnel offered ingenuity in detecting WinterOps activations. First, on an older vehicle that required the use of a mechanical lever in the cab to activate the spreader, a small contact switch was installed near the lever that engaged whenever the lever was swung low enough to touch it, as shown in Figure 4.1. Second, another vehicle's equipment was controlled using a simple electric toggle switch that had exposed wire contacts (Figure 4.2). It was straightforward to solder to the contacts to obtain a 12V indication of when that toggle switch was engaged.

Figure 4.1: A contact switch is used to sense when the lever is pulled down.

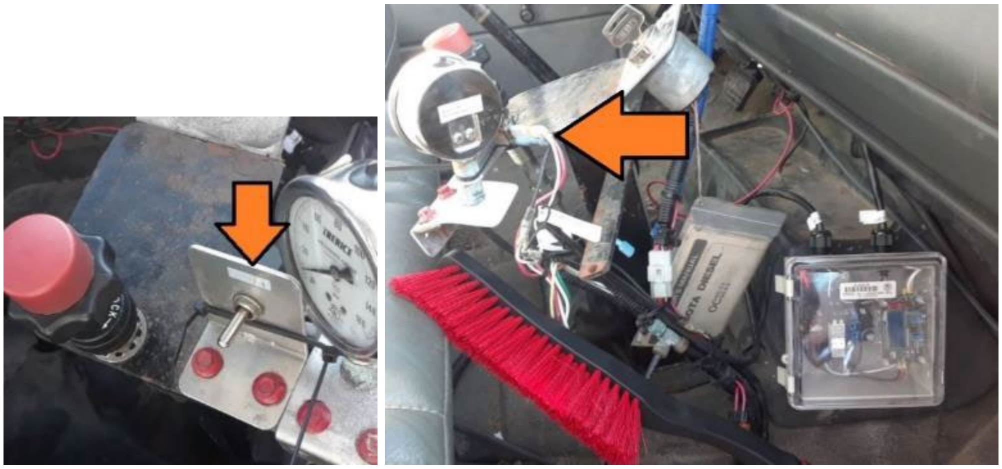


Figure 4.2: A toggle switch offers rear terminals that can be soldered.

4.3. Recent Experiences with Geotab

TxDOT announced a new contract with Geotab around September, 2023, replacing the earlier Verizon Connect contract. All of the Verizon "GPS black boxes" were replaced with Geotab Go devices, and online access to data was switched to the MyGeotab web app. Meanwhile, since few vehicles up to that time had WinterOps sensing capabilities completed or producing data, it was agreed that the project would be extended through Winter 2022-2023, not only to update installations on all 6 vehicles chosen for the pilot, but to also transition WinterOps sensing capabilities to the new Geotab system.

While Geotab personnel installed MyGeotab equipment on vehicles, the data lines from sensor kits on vehicles used for this project were cut and taped off. The project amendment allowed for these connections to be restored, using a simpler kind of signaling scheme supported by the Geotab IOX-AUXM cable harnesses (see Section 4.3.1). While the Verizon Connect system encouraged the use of relays to "close the loop" between input and output data cable pairs, the Geotab system simply needed a +12V signal with respect to chassis ground to enter into the respective channel on the IOX-AUXM cable harness. This allowed the power supplies in the sensor kits to be removed, and relays to be bypassed. Sensor kits simply then became passive junction boxes to provide access to data lines and optional ignition power where needed.

Other positive discoveries were made of the Geotab system. First, the MyGeotab web app allowed for consistent in-shop testing of sensing capabilities. Second, the Geotab IOX-AUXM devices emitted audio tones to signal when general purpose inputs were being successfully received, a great feature that helped to reduce the need for going back and forth to a laptop or telephoned technician to verify signal quality. On road tests, it became apparent that Geotab offered accuracy down to the second, allowing for precise measuring of where spot treatments occur in the field. Finally, Geotab personnel were very helpful about familiarizing researchers with their extensive and friendly software API for accessing historic data.

A feature that the Verizon Connect system offered that TxDOT's Geotab system lacks is a way to label auxiliary sensor input channels per vehicle. While more advanced product offerings from Geotab may offer this feature, the current approach for keeping track of vehicle equipment would need to be maintained somewhere else.

In the end, after adapting to the Geotab system, the total cost of WinterOps sensing equipment was found to be fairly minimal: on the order of $70 for an IOX-AUXM cable harness, and $20 for a terminal block enclosure. Wires, connectors, and shrink tubing were nominal. The PTO pressure switch and connector ran about $50, obtainable online or at a local auto shop. If a rotating switch were used for plow level sensing on the plow rig, that would add about $100. (All told so far: $240). The largest expense would be the labor for determining where and how to obtain signals and run wires. The newest trucks included in this pilot appeared to be much more uniform than the older trucks, allowing for the use of similar processes for equipping WinterOps sensing capabilities. After spending time with the first such vehicle 871220088 in the Lubbock District (taking a little over half a day), maintenance personnel could then perform all wiring and connections to the Geotab system on the second truck within 2 hours without a sense of rush.

4.3.1. Electrical Signaling Scheme

The Geotab GO devices ("GPS units") installed in each vehicle take an optional "IOX-AUXM" cable harness that contains four colored wires that end at a connector. Each of the colored wires is labeled according to its respective AUX input channel. There's also a black and red cable pair used for IOX-AUXM daisy-chaining purposes, and these were left alone. Although the IOX-AUXM cable harness was supposedly available through TxDOT's contracted vendor, it wasn't listed on their website, and a supplier in Cedar Park[*] was located that had them in stock.

After consultation with Geotab, researchers learned that the IOX-AUXM takes one of three signaling schemes, and self-learning logic allows for two them to be automatically detected. (It is also possible to set a parameter to force a certain scheme). The first scheme is "Ground-High Circuit", which is used for the purposes here, and the other two are "Float-High Circuit", and "Ground-Float Circuit". High voltage to these can be anywhere from around +2V to nominal +12V.

This differs significantly from the method used by Verizon, where a loop is closed by a relay to signal an activation. As a result, this Geotab "Ground-High Circuit" presented an opportunity to simplify the internals of the Sensor Kits, making them easier to work on, and reducing the chance for electrical failure. In each of the Sensor Kits, the power regulators were removed, the relays were left disconnected, power and ground were run solely to respective blocks for use if required, and the terminal block for each AUX input was clearly accessible and labeled (as in Figure 3.3 and Figure 3.4). While this took away the feature where green indicator lights on each relay

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[*] https://canamwireless.com/

illuminate when sensor activations occur, the IOX-AUXM had an audible series of beeps while learning the signaling schemes. In addition, sensor activations could be measured by using a voltmeter on the exposed terminal blocks.

4.4. Lessons to Learn

This section is a compilation of lessons that either came with experiences while performing installations, or from feedback given at project workshops and other events.

4.4.1. Operations and Logistics

This project required on-site visits to Abilene and Lubbock Districts to perform WinterOps sensing installations and to conduct road tests. The onsite contact person who schedules resources should be properly forewarned that these installations require expertise from onsite TxDOT mechanics and technicians. Implying this within e-mails is not adequate for successful communication.

Researchers did well to recognize that the vehicles are active fleet vehicles, and should not be overly compromised by modifications that have a risky potential to fail. Final decisions on strategies for installations must be made by the appropriate TxDOT fleet maintenance personnel.

As noted earlier, the methods for operating the spreader and other equipment may differ from vehicle to vehicle and even from operator to operator. Findings from this project should be taken as general advice that is subject to the nuances of individual vehicles and district procedures. Actual operators should be consulted to fully understand how they prefer to operate the vehicles and equipment.

It is ideal to not hard-wire to equipment (e.g., in-cab control boxes) that may be seasonally uninstalled. A compelling idea is to use a connector that allows for the wiring to be neatly unplugged until the equipment is reinstalled. Plug styles should be such that personnel unfamiliar with the workings of the WinterOps sensing installations can intuitively know to detach and reattach at the plug (as opposed to ripping out or cutting wires).

4.4.2. Installations and Equipment

When positioning plow level sensors, part of the process involves raising and lowering the plow rig such that one can observe when the plow is considered “lowered”. Then, the placement or tilt of the sensing device is adjusted to ensure that it engaged and disengages accordingly. In the end, the sensing device is to be screwed into holes that are tapped into the heavy metal that comprises the plow rig. To avoid the possibility of tapping holes in the wrong place and causing the sensing device to be misaligned, a strategy that worked well was to first tap one hole on one corner, screw down the sensing device on just that one corner, and then pivot the sensing device while finding the ideal orientation. By “locking down” that corner, the sensing device is far less likely to move around in such a way that additional tap positions are misaligned.

An auxiliary sensor input that is disconnected or unpopulated shows up as a "0" in Geotab data. This allows for robustness against the possibility that some sensing channels are not populated, especially for processes that always assume an "active-high" when each type of sensed equipment is used. If junction boxes and cable harnesses are pre-wired for supporting all channels, it is straightforward to later add sensing capabilities for additional equipment by simply screwing into the junction box.

For this project, maintenance personnel generally needed to spend a considerable amount of time (e.g., half of a day) to install WinterOps sensing capabilities to a first truck of its kind. However, subsequent installations to similar trucks of the same vintage occurred much faster. Much time would be saved among repeated installations if maintenance personnel document how installations are achieved so that knowledge can be shared with other districts or maintenance sections and remembered for new installations in years ahead.

Environmental conditions behind a plow blade are very harsh. Ice, grit, and brine can become packed and cause poor connections in exposed cables and jacks. Do everything reasonable to protect those connections when it is necessary to run exterior cables.

It became apparent that fixed-location sensors are more valuable than mobile sensors. While fixed sensors are intended to always produce data at known locations in expected environments, mobile sensors are only useful when the vehicle it is attached to is being used, and happens to be in a useful location. On vehicles, the precise location of a mobile sensor is generally not repeatable across any given length of time, making it difficult to arbitrarily compare data from different time periods.

Researchers should exercise caution when climbing in and out; one researcher had a "close call". The passenger seats ride high above the road, and a misstep on the ladder may lead to an injury if care is not taken. Because of where cables, junction boxes, and connections are located, it is often necessary during installations to partially enter the cab at awkward angles, which makes the elevation even more dangerous. Some trucks have caution signs that advise keeping at least two points of contact with the vehicle when climbing in and out.

4.5. Future Directions

In addition to offering lessons and cautionary notes, participants at workshops and meetings also offered a number of ideas on potential areas of future work.

One of the biggest topics and challenges is in being able to accurately sense when the spreader is working. As noted in Section 3.1.2, it is possible on vehicles utilized for the pilot to know when the spreader control box is switched on, and also to know when the PTO is engaged. However, if the spread rate is set to zero while everything else is on, a false signal can be registered. In addition, there is desire to know whether the equipment is properly working. Similar ideas have been expressed about the sprayer. For example, it was mentioned that sometimes it is useful for a vehicle to follow the truck performing the spraying so that the driver of that vehicle can roughly verify proper performance through observation. Other strategies have included having the operator turn on the rear floodlights and look in the side mirrors for a cloud of material while dispensing. From a sensing perspective, a solution used in other industries involving dumping grain through a chute consists of a paddle that swings open during dispensing. Another observation is that the PTO and the conveyor in the spreader each make noise, and the spreading action has its own unique sound. A research question that could be interesting for those who specialize in signal processing or machine learning is whether these sounds can be automatically identified as an indication of dispensing action.

Interest was expressed about automatically understanding and verifying the dispensing rate of brine. Similarly, there was mention about the need to know how full the V-box spreader is while on the road. Sensing technologies exist such as flow meters or depth detectors that can either send serial data or send series of pulses that correspond with ranges of values. Pulses can likely be successfully handled by the existing Geotab IOX-AUXM devices and interpreted within the IT back-end. It is important to consider that Geotab also has other general-purpose input peripherals that can take serial data, in which case Geotab or the contracting vendor would need to be consulted to ensure that the agency agreements and corresponding data plans allow for the use of these peripherals.

Especially if more advanced sensing is being used, a strategy for managing ground truth would need to be established. Flow meters, depth detectors, and other sensors need to be periodically calibrated, especially in environments such as these where dust and debris can accumulate, flying debris can hit a sensor, and equipment is subject to seasonal removal and reinstallation. Resilience significantly increases when more than one sensor is utilized for making the same measurements.

GPS signals and speed data can be indicators of treatment activity. It had been mentioned that traffic operations centers have raised alerts about slow traffic being measured via INRIX probe vehicle cloud service on I-20 through Abilene, which is actually caused by treatment activity. Brine sprayers are likely to drive at a certain speed (e.g., 45 MPH) to ensure that the right concentration is applied to the roadway. Plows may traverse a road back and forth in predictable ways, especially on multi-lane highways where there is possibility for multiple plows to operate in tandem.

The idea of plow cams keeps on surfacing, even those that are not integrated in any way with other telemetry systems, and those that only update once every 10 minutes. Plow cams appear to have appeal for traffic operations personnel and the public travelers alike.

Chapter 5. Utilizing WinterOps Sensing Data

Winter weather operations benefit from effective visualization and analysis of data for several reasons. Weather conditions are highly dynamic and unpredictable. By visualizing and analyzing data in real-time using tools like ArcGIS, agencies can have a comprehensive understanding of the current conditions and make informed decisions accordingly. Additionally, winter weather operations involve managing a variety of resources, including snowplows, salt trucks, brine sprayers, and manpower. By visualizing data on a dashboard, agencies can track the location and status of their fleets in real-time. Also, historical data about vehicle trajectories and activities can be made available and utilized to develop route optimization strategies and ensure effective resource allocation.

Analysis and visualization requirements make ArcGIS and other mapping software essential tools. Even many analyses and reporting activities are greatly assisted by the use of spreadsheet software such as Microsoft Excel. Therefore, a major effort within the project focused on how the data could be accessed and utilized. In addition to identifying compelling use cases that could exemplify new abilities brought by automation, researchers also sought to determine best approaches that data could be leveraged within processes and initiatives already underway within TxDOT. Researchers and project stakeholders collaborated with Information Technology Division personnel who were working to provide new GIS capabilities to TxDOT. The major focus was on eventual integration into TxERA that leverages the Esri ArcGIS Enterprise platform. Additionally, researchers explored other potential uses of automated WinterOps data concerned with reducing time and adding accuracy to paper logs that have to do with the use of brine in winter storm pre-treatment.

In this chapter we discuss how project stakeholders can leverage ArcGIS and Geotab tools to access capabilities. While the initial objective was to develop a real-time operations dashboard, internal technical challenges encountered by TxDOT ultimately made this objective infeasible to achieve within the time allowed for the project. Instead, project researchers implemented several tools within ArcGIS Pro to provide comparable capabilities. This chapter shows how to visualize snowplow, spreader, and brine sprayer truck data in the MyGeotab web app, call Geotab's API to retrieve comma-separated value (CSV) format data, visualize the data in ArcGIS Pro, and export summary reports.

5.1. MyGeotab and Direct CSV Data

In MyGeotab, users are able to track the real-time location of their equipped fleet on a live map, see the detailed trip history of their vehicles, and view dashboard reports that summarize trends in fuel consumption, idling, and more. The MyGeotab web app can be accessed from any location with Internet access, where users can login using their TxDOT email credentials after acquiring the necessary permissions (see Figure 5.1).

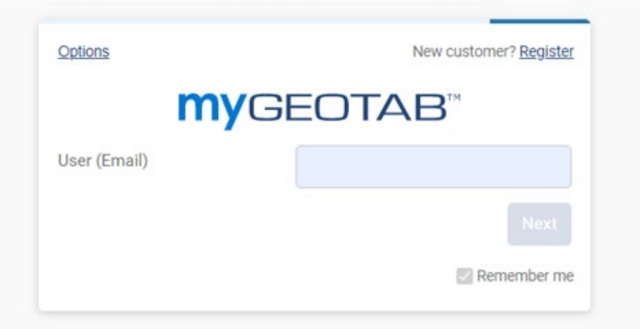


Figure 5.1: MyGeotab login interface

Within MyGeotab, users have access to multiple functionalities and visualization that can be accessed through the multiple tabs shown in Figure 5.2. This includes five main tabs:

- Vehicles & Assets
- Dashboard
- Map
- Activity
- Engine & Devices

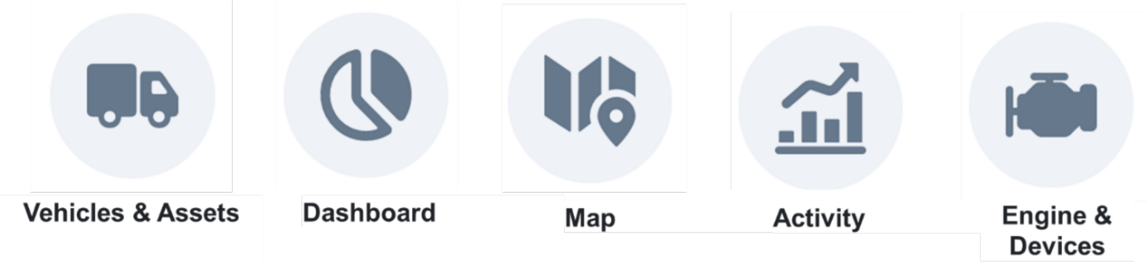
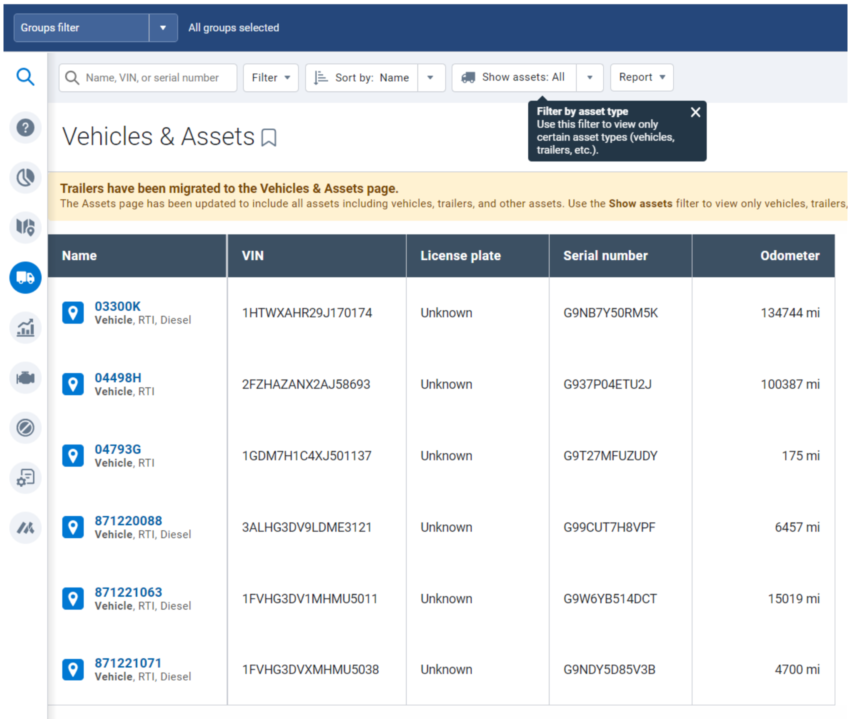


Figure 5.2: MyGeotab tabs

5.1.1. Vehicles and Assets Tab

The Vehicle and Assets page in MyGeotab provides users with a comprehensive list of vehicles equipped with Geotab GPS devices. As part of the pilot project in the Abilene and Lubbock Districts, a total of six vehicles were equipped, as depicted in Figure 5.3. By selecting a specific vehicle (e.g., vehicle 0300K in Figure 5.4) and clicking on the location button, users can access a real-time map visualization of the truck’s current location. Furthermore, users have the option to review the trip history of the vehicle or explore the area activity. By default, only the most recent trip is displayed on the map when viewing the vehicle’s trip history, as shown in Figure 5.4. However, users can visualize additional trips by selecting them from the list. Conversely, when examining area activity, previous trips conducted by other trucks in the vicinity of the selected truck are previewed, as illustrated in Figure 5.4.

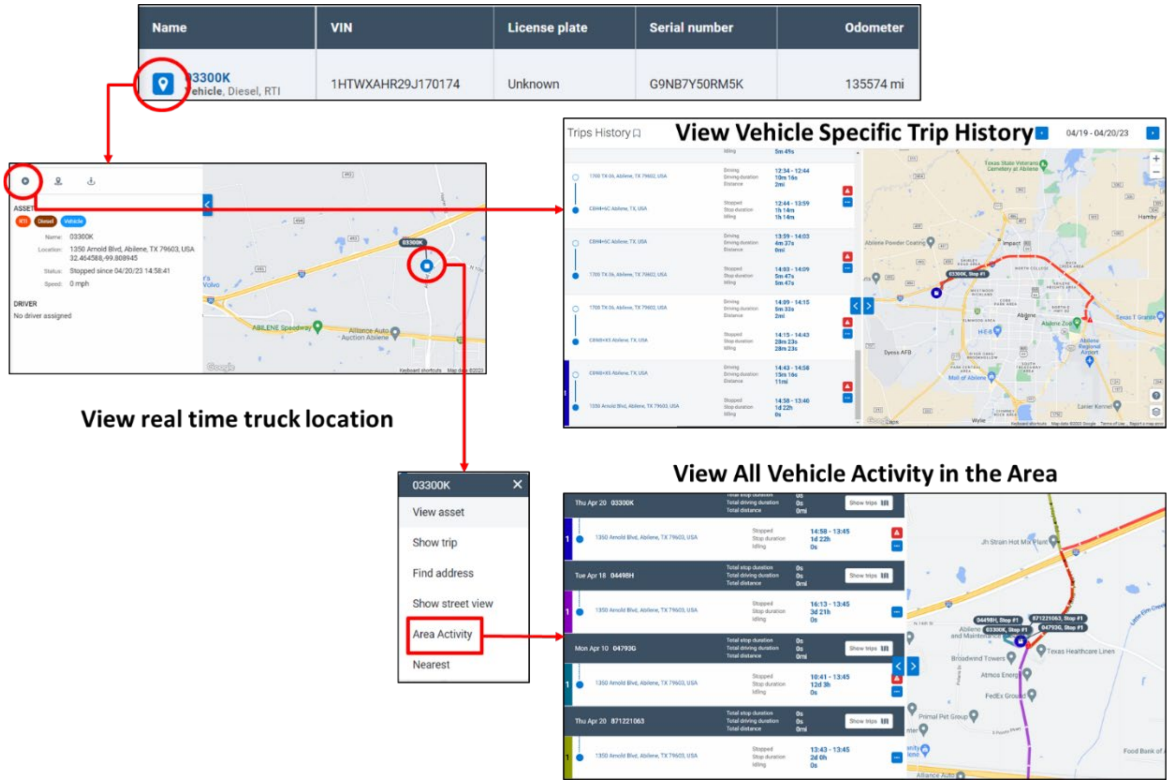


Filter by asset type
Use this filter to view only certain asset types (vehicles, trailers, etc.).

Trailers have been migrated to the Vehicles & Assets page.
The Assets page has been updated to include all assets including vehicles, trailers, and other assets. Use the **Show assets** filter to view only vehicles, trailers,

Name	VIN	License plate	Serial number	Odometer
03300K **Vehicle**, RTI, Diesel	1HTWXAHR29J170174	Unknown	G9NB7Y50RM5K	134744 mi
04498H **Vehicle**, RTI	2FZHAZANX2AJ58693	Unknown	G937P04ETU2J	100387 mi
04793G **Vehicle**, RTI	1GDM7H1C4XJ501137	Unknown	G9T27MFUZUDY	175 mi
871220088 **Vehicle**, RTI, Diesel	3ALHG3DV9LDME3121	Unknown	G99CUT7H8VPF	6457 mi
871221063 **Vehicle**, RTI, Diesel	1FVHG3DV1MHMU5011	Unknown	G9W6YB514DCT	15019 mi
871221071 **Vehicle**, RTI, Diesel	1FVHG3DVXMHMU5038	Unknown	G9NDY5D85V3B	4700 mi

Figure 5.3: Vehicles and Assets interface in MyGeotab



Name	VIN	License plate	Serial number	Odometer
03300K Vehicle, Diesel, RTI	1HTWXAHR29J170174	Unknown	G9NB7Y50RM5K	135574 mi

ASSET

Name: 03300K
Location: 1350 Arnold Blvd, Abilene, TX 79603, USA 32.464588,-99.808945
Status: Stopped since 04/20/23 14:58:41
Speed: 0 mph

DRIVER
No driver assigned

View real time truck location

View Vehicle Specific Trip History

View All Vehicle Activity in the Area

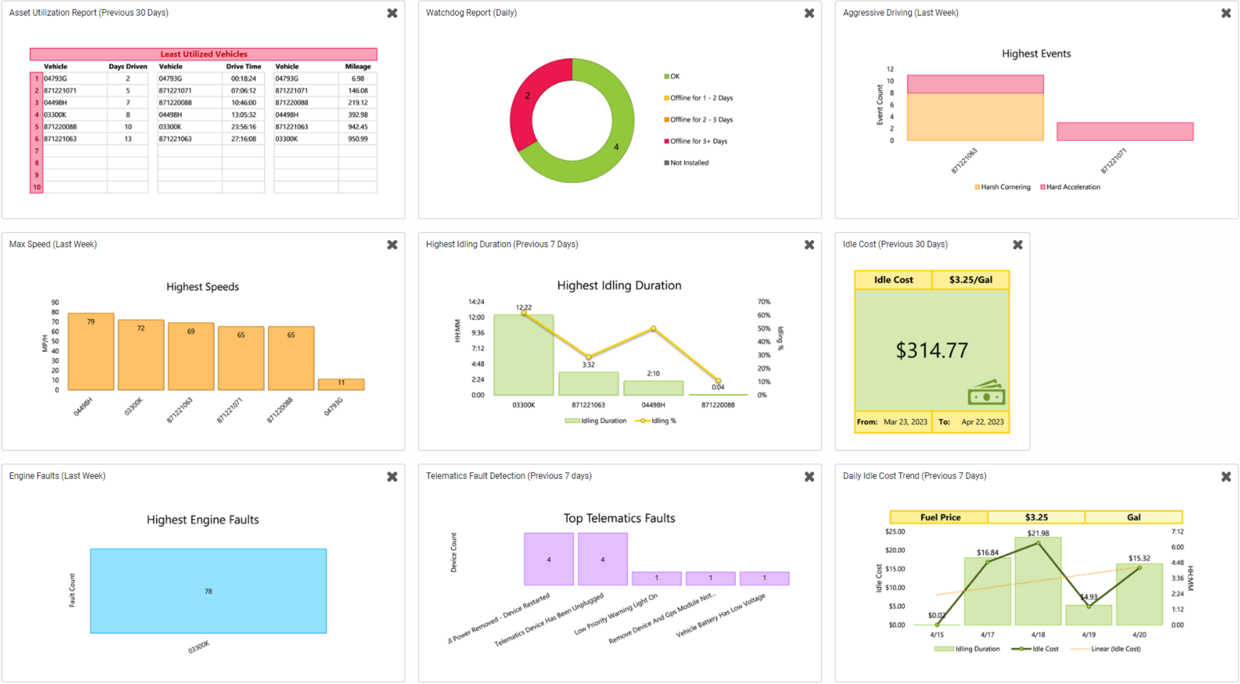
Figure 5.4: View vehicle and area activity from the Vehicles and Assets tab

5.1.2. Dashboard Tab

The Dashboard tab provides a quick and comprehensive overview by sharing essential data about fleet utilization, driving behavior, speed trends, idling durations, fuel consumption, and others, as shown in Figure 5.5.

To assess fleet utilization, the asset utilization report provides statistics on key performance indicators (KPIs) including days driven, drive time, and mileage. This report can uncover which vehicles are hardly used, overused, or in downtime for maintenance or repair. The Watchdog report provides information about device communication and status. This allows users to identify devices that need to be investigated from ones that are reporting as healthy. For example, in Figure 5.5 two devices stopped communicating and need to be investigated. The aggressive driving report shows the number of harsh cornering and hard acceleration events by vehicle. The max speed report provides the highest reported speed for each vehicle in the last week. The idling duration report presents the longest idling duration (When the engine is running, but the vehicle does not change position) for each vehicle over the past week. Since vehicle idling increases fuel consumption and costs, the dashboard also reports the total idling costs in the past month. Additionally, the dashboard reports the idle cost trends which illustrates idling cost per day over a seven-day period.

Moreover, MyGeotab allows users to export all these reports to Microsoft Excel for further quantitative analysis. Geotab also provides documentation for creating custom dashboard reports (see for example https://www.geotab.com/blog/custom-dashboard-report/)



Asset Utilization Report (Previous 30 Days)

Least Utilized Vehicles

	Vehicle	Days Driven	Vehicle	Drive Time	Vehicle	Mileage
1	04793G	2	04793G	00:18:24	04793G	6.98
2	871221071	5	871221071	07:06:12	871221071	146.08
3	04498H	7	871220088	10:46:00	871220088	219.12
4	03300K	8	04498H	13:05:32	04498H	392.98
5	871220088	10	03300K	23:56:16	871221063	942.45
6	871221063	13	871221063	27:16:08	03300K	950.99
7						
8						
9						
10						

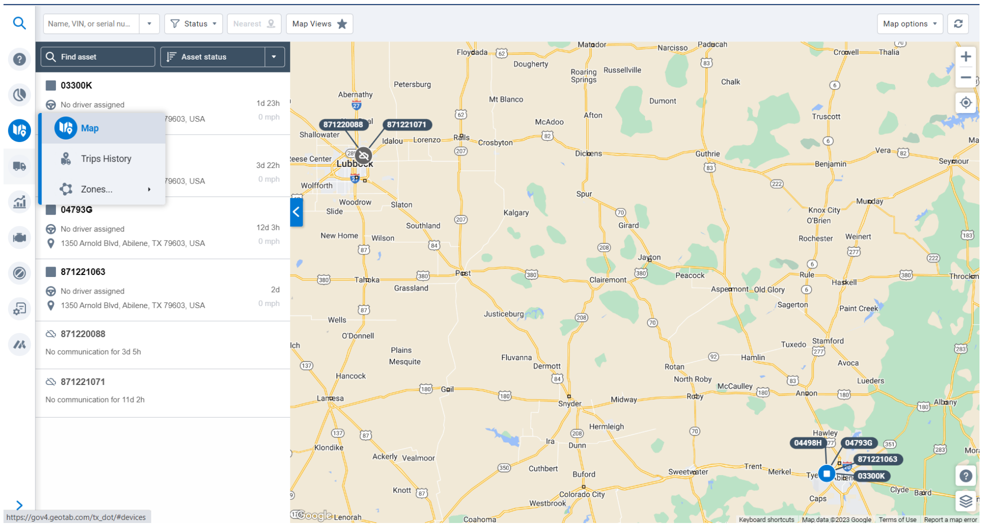
Idle Cost (Previous 30 Days)

Idle Cost	$3.25/Gal
$314.77	
From: Mar 23, 2023	To: Apr 22, 2023

Figure 5.5: Visualizations in the Dashboard Tab in MyGeotab

5.1.3. Map Tab

In the map tab, users can view live location for all vehicles. The list of vehicles on the left of the map, as shown in Figure 5.6, provides information about current vehicle speed and the time since it was last operated. For example, Figure 5.6 shows that vehicle 871221063 was last operated 2 days ago.



03300K
No driver assigned
79603, USA
1d 23h
0 mph

79603, USA
3d 22h
0 mph

04793G
No driver assigned
1350 Arnold Blvd, Abilene, TX 79603, USA
12d 3h
0 mph

871221063
No driver assigned
1350 Arnold Blvd, Abilene, TX 79603, USA
2d
0 mph

871220088
No communication for 3d 5h

871221071
No communication for 11d 2h

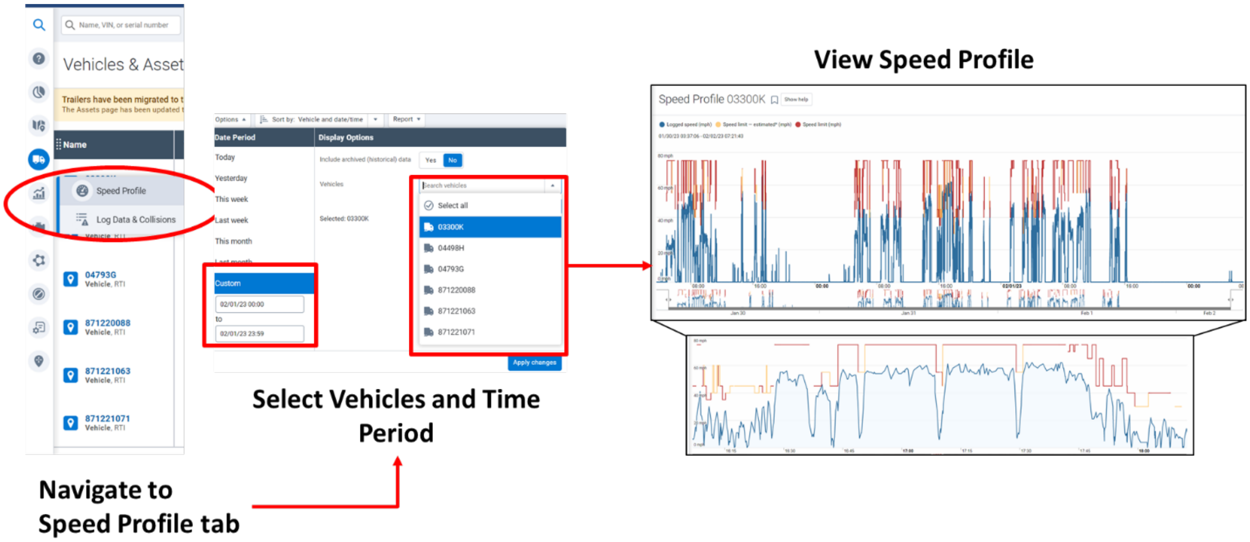
Figure 5.6. Map tab in MyGeotab

5.1.4. Activity Tab

The Activity tab in MyGeotab provides data about vehicle speeds and trajectories.

5.1.4.1. Speed Profile

In the vehicle speed profile tab, MyGeotab prompts users to select the vehicles and date range of interest before generating the speed profile. Figure 5.7 details the steps to be followed for viewing the speed profile of vehicle 0300K between January 30 and February 2 of 2023. First, they need to navigate to the vehicle speed profile tab within MyGeotab. Then, they should locate and select vehicle 0300K from the available options. Next, they need to input the desired date range, starting from January 30th and ending on February 2nd, 2023. This feature allows users to analyze the vehicle's speed patterns, identify any irregularities, and gain insights into its performance during the selected dates.



View Speed Profile

Select Vehicles and Time Period

Navigate to Speed Profile tab

Figure 5.7: Steps to navigate to the Speed Profile in MyGeotab

5.1.4.2. Log Data and Collisions

The log data and collisions page within MyGeotab serves as a crucial resource for viewing truck activity. To access this data, users can follow the steps outlined in Figure 5.8. First, within MyGeotab, navigate to the “Activity” section and then proceed to the “Log Data & Collisions” tab. On the top left corner of the page, locate the options menu and click on it to specify the desired date period and vehicle(s) of interest. Once the options are set, users can apply them to generate a comprehensive list of all vehicle trips within the selected time period, as demonstrated on the right side of Figure 5.8. This list provides essential information about the trips, including dates, durations, distances, and any recorded collisions.

To further explore a specific trip, users can click on the location icon located to the right side of each row in the list. By doing so, a map of the selected trip will be displayed, as depicted in Figure 5.9. Also note that more than one trip can be displayed at once simply by selecting the trips of interest from the list displayed in Figure 5.9. This map visualization provides a clear visual representation of the trip’s route and enables users to analyze the specific locations visited during that trip. It helps in understanding the spatial context of the truck’s activity and provides valuable insights for route optimization, identifying potential issues or incidents, and improving overall fleet management.

To further visualize the activity of each vehicle, the “Summary” menu, located to the right of the “Options” menu, provides a summary of the selected vehicle’s activity. Within the “Activity and Trips Summary Report” available in the “Summary” menu, the user can access key metrics that provide insights into the vehicle's operations, as shown in Figure 5.10. These metrics include:

- **Total Miles Traveled:** This metric indicates the cumulative distance covered by the vehicle during the selected duration. It provides a clear understanding of the vehicle’s overall travel distance. For example, vehicle 871221063 traveled a total of 1,833 miles from January 24 to February 3, 2023.

- **Total Driving Time:** This metric represents the total duration for which the vehicle was in motion or actively driving. It accounts for the combined time spent on trips and other driving activities. For example, vehicle 871221063 was in motion for a total duration of 2 days, 14 hours, and 39 minutes from January 24 to February 3, 2023.

- **Total Stopped Time:** This metric reflects the total duration during which the vehicle was stationary or completely stopped. It includes time spent at traffic lights, stop signs, or any other instances where the vehicle was not in motion. For example, vehicle 871221063 was stopped for 8 days, 9 hours, and 19 minutes from January 24 to February 3, 2023.

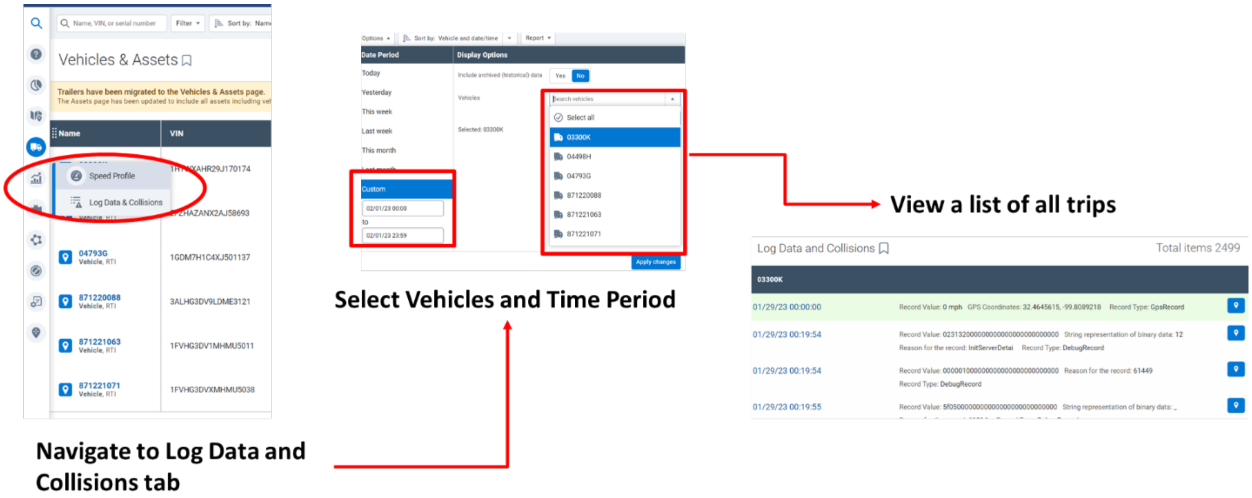
- **Total Idling Time:** This metric denotes the cumulative time that the vehicle's engine was running but the vehicle remained stationary. It captures instances when the engine was idle, such as during extended stops or waiting periods. For example, vehicle 871221063 was idling for a total duration of 1 day, 11 hours, and 32 minutes from January 24 to February 3, 2023.

In addition to the valuable features provided by the log data and collisions page in MyGeotab, users also have the option to export an Advanced Log Data & Collisions Report in Excel format. This report offers enhanced functionality and flexibility in analyzing and processing the data further. To generate the Advanced Log Data & Collisions Report, users can navigate to the desired time period and vehicle(s) of interest within MyGeotab's log data and collisions section. Once the relevant filters and parameters are set, users can click on the Report button to initiate the export process then click on "Advanced", as shown in Figure 5.11. Figure 5.11 also shows a preview of the exported Excel file. The output file includes several columns with important information about the logged data. Here are the main columns that will be included in the Excel output:

- **Device:** This column identifies the specific device or GPS unit associated with the recorded data.
- **Device Group:** This column categorizes the device into a specific group or category within the fleet management system.
- **First Name:** This column provides the first name associated with the driver or operator of the vehicle.
- **Date:** This column indicates the date of the recorded activity or event.
- **Log Time:** This column specifies the time at which the event or activity was logged.
- **Record Type:** This column classifies the type of record or event, such as Debug Record, Engine Status Record, and GPS Record. GPS records are the ones of interest for visualizing and analyzing truck activity.
- **Speed:** This column displays the recorded speed of the vehicle at the given timestamp.

- **Longitude** and **Latitude:** These columns represent the GPS coordinates of the vehicle's location at the given timestamp.
- **Reason for Log:** This column provides information regarding the reason for the log entry including:
    - **CurveBased:** This GPS point was logged due to a change in position cause by curve
    - **CruveSpeed:** This GPS point was logged due to a change in speed
    - **CurvePositionEstimateError:** This GPS point was logged because the difference between the actual position of the vehicle and the estimated position of the vehicle is greater than the allowed threshold.
    - **CurveTimeOut:** This GPS point was logged because the timeout value of 100 seconds was reached.
    - **CurveOtherEvent:** This GPS point was logged to report a non-GPS based event, such as signals from the AUX channels.
    - **CurveZeroSpeed:** This GPS point was logged because the vehicle either came to a stop or started moving from a stop.
- **Ignition:** This column indicates the ignition status of the vehicle, whether it is on or off.
- **Aux1** (PTO): This column denotes the status of the auxiliary function 1, often associated with Power Take-Off (PTO) operations (e.g., a value of 1 indicates that PTO is on).
- **Aux2** (Spreader/Sprayer): This column represents the status of the auxiliary function 2, typically associated with spreader or sprayer equipment (e.g., a value of 1 indicates that Spreader or Sprayer is on).
- **Aux3** (Plow-related): This column signifies the status of the auxiliary function 3, commonly related to plow operations (e.g., a value of 1 indicates that the plow is going down).
- **Aux4** (Plow-related): This column represents the status of the auxiliary function 4, also typically associated with plow-related operations (e.g., a value of 1 indicates that the plow is going up).
- **Valid:** This column indicates the validity or accuracy of the logged data.
- **Valid GPS:** This column specifies whether the GPS data associated with the record is considered valid or accurate.
- **Debug Record:** This column highlights any debug or diagnostic records related to the vehicle’s performance or operations.
- **Engine Diagnostic:** This column provides diagnostic information or codes associated with the vehicle’s engine.
- **Controller:** This column denotes the status or data related to the vehicle’s controller unit.
- **Engine Status:** This column represents the status or condition of the vehicle’s engine.

Overall, the Advanced Log Data & Collisions Report in Excel format empowers users to extract maximum insights from the collected data, enabling them to identify trends, patterns, and areas for improvement in truck activity and safety. With the ability to customize and manipulate the data, users can unlock the full potential of the log data and collisions information, contributing to more efficient and informed decision-making within their organization.

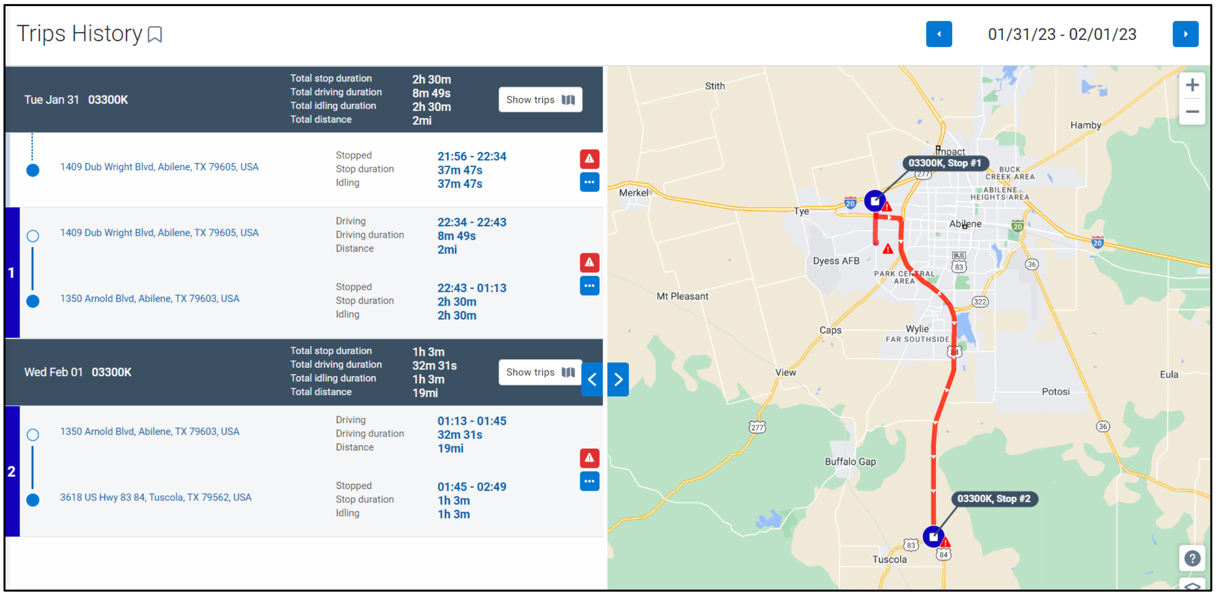


Navigate to Log Data and Collisions tab

Select Vehicles and Time Period

View a list of all trips

Figure 5.8: Steps to navigate to the Log Data and Collisions tab in MyGeotab



Trips History

01/31/23 - 02/01/23

Tue Jan 31 03300K
Total stop duration 2h 30m
Total driving duration 8m 49s
Total idling duration 2h 30m
Total distance 2mi

1409 Dub Wright Blvd, Abilene, TX 79605, USA
Stopped 21:56 - 22:34
Stop duration 37m 47s
Idling 37m 47s

1
1409 Dub Wright Blvd, Abilene, TX 79605, USA
Driving 22:34 - 22:43
Driving duration 8m 49s
Distance 2mi

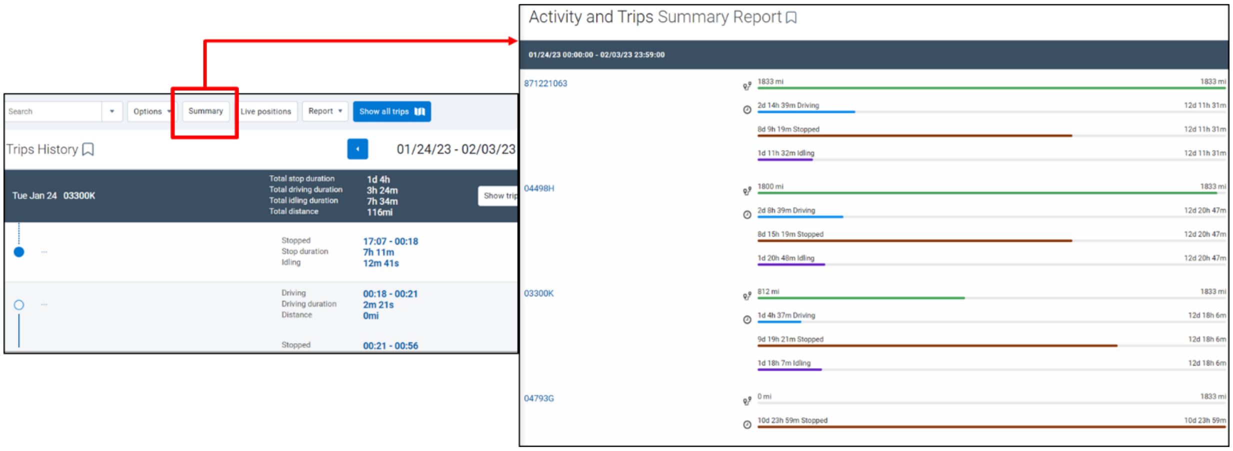
1350 Arnold Blvd, Abilene, TX 79603, USA
Stopped 22:43 - 01:13
Stop duration 2h 30m
Idling 2h 30m

Wed Feb 01 03300K
Total stop duration 1h 3m
Total driving duration 32m 31s
Total idling duration 1h 3m
Total distance 19mi

2
1350 Arnold Blvd, Abilene, TX 79603, USA
Driving 01:13 - 01:45
Driving duration 32m 31s
Distance 19mi

3618 US Hwy 83 84, Tuscola, TX 79562, USA
Stopped 01:45 - 02:49
Stop duration 1h 3m
Idling 1h 3m

Figure 5.9: Viewing trip history in MyGeotab



Tue Jan 24 03300K

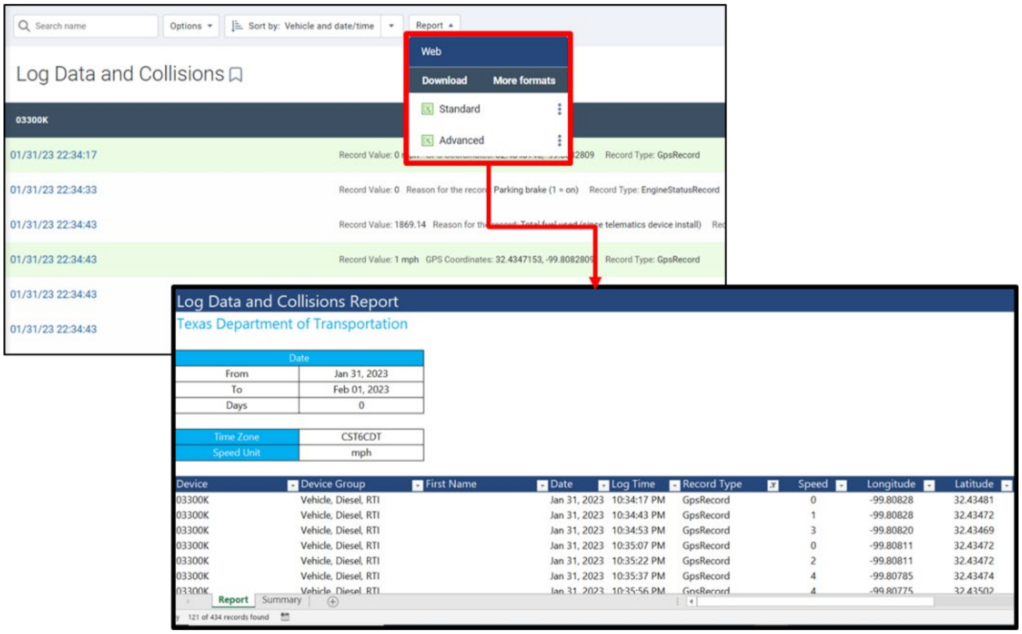
Total stop duration	1d 4h
Total driving duration	3h 24m
Total idling duration	7h 34m
Total distance	116mi

Stopped	17:07 - 00:18
Stop duration	7h 11m
Idling	12m 41s
Driving	00:18 - 00:21
Driving duration	2m 21s
Distance	0mi
Stopped	00:21 - 00:56

01/24/23 00:00:00 - 02/03/23 23:59:00

Device	Value	Total
871221063	1833 mi	1833 mi
	2d 14h 39m Driving	12d 11h 31m
	8d 9h 19m Stopped	12d 11h 31m
	1d 11h 32m Idling	12d 11h 31m
04498H	1800 mi	1833 mi
	2d 8h 39m Driving	12d 20h 47m
	8d 15h 19m Stopped	12d 20h 47m
	1d 20h 48m Idling	12d 20h 47m
03300K	812 mi	1833 mi
	1d 4h 37m Driving	12d 18h 6m
	9d 19h 21m Stopped	12d 18h 6m
	1d 18h 7m Idling	12d 18h 6m
04793G	0 mi	1833 mi
	10d 23h 59m Stopped	10d 23h 59m

Figure 5.10: Activity and Trips Summary Report



03300K

01/31/23 22:34:17 Record Value: 0 2809 Record Type: GpsRecord
01/31/23 22:34:33 Record Value: 0 Reason for the recor Parking brake (1 = on) Record Type: EngineStatusRecord
01/31/23 22:34:43 Record Value: 1869.14 Reason for th e telematics device install) Re
01/31/23 22:34:43 Record Value: 1 mph GPS Coordinates: 32.4347153, -99.8082809 Record Type: GpsRecord
01/31/23 22:34:43
01/31/23 22:34:43

Log Data and Collisions Report

Texas Department of Transportation

Date	
From	Jan 31, 2023
To	Feb 01, 2023
Days	0

Time Zone	CST6CDT
Speed Unit	mph

Device	Device Group	First Name	Date	Log Time	Record Type	Speed	Longitude	Latitude
03300K	Vehicle, Diesel, RTI		Jan 31, 2023	10:34:17 PM	GpsRecord	0	-99.80828	32.43481
03300K	Vehicle, Diesel, RTI		Jan 31, 2023	10:34:43 PM	GpsRecord	1	-99.80828	32.43472
03300K	Vehicle, Diesel, RTI		Jan 31, 2023	10:34:53 PM	GpsRecord	3	-99.80820	32.43469
03300K	Vehicle, Diesel, RTI		Jan 31, 2023	10:35:07 PM	GpsRecord	0	-99.80811	32.43472
03300K	Vehicle, Diesel, RTI		Jan 31, 2023	10:35:22 PM	GpsRecord	2	-99.80811	32.43472
03300K	Vehicle, Diesel, RTI		Jan 31, 2023	10:35:37 PM	GpsRecord	4	-99.80785	32.43474
03300K	Vehicle, Diesel, RTI		Jan 31, 2023	10:35:56 PM	GpsRecord	4	-99.80775	32.43502

121 of 434 records found

Figure 5.11: Steps to export the Advanced Log Data and Collisions Report

5.1.5. Engine and Devices Tab

The Measurements section within the Engine and Devices tab in MyGeotab provides users with a detailed view of various measurements and parameters related to the vehicles' engine performance and efficiency. This is specifically where inquiries may be made within MyGeotab about the WinterOps sensing capabilities installed in Chapter 3.

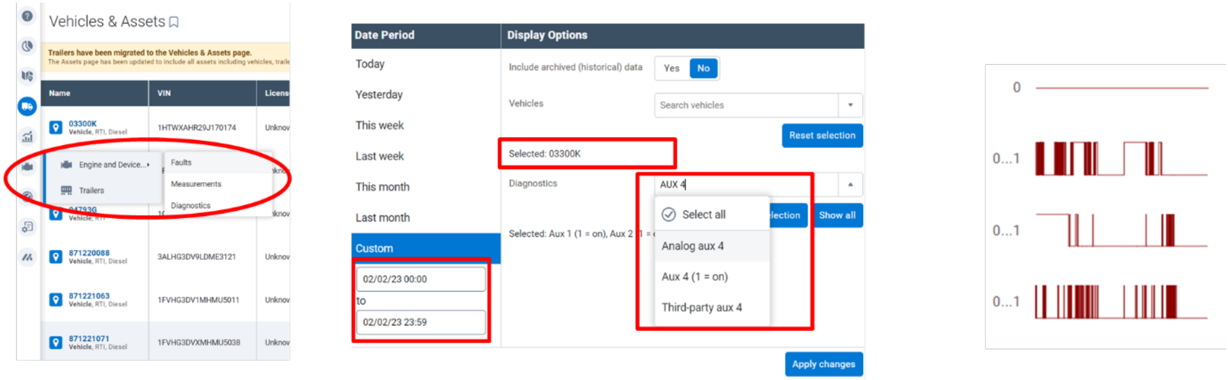
Within MyGeotab, navigate to the Engine and Device section proceed to the "Measurements" tab. On the top left corner of the page, locate the options menu and click on it to specify the desired date period and vehicle(s) of interest. In addition to date and vehicle selection, diagnostics related to PTO, spreader, sprayer, and plows also need to be specified. Refer to the middle picture in

Figure 5.12 for a visual guide on selecting the appropriate diagnostics. To obtain the status of the PTO, spreader, sprayer, and plows, ensure the following diagnostics are selected:

- Aux 1 (1=on)
- Aux 2 (1=on)
- Aux 3 (1=on)
- Aux 4 (1=on)

Once you have made the necessary diagnostic selections, apply the changes. The measurements page will now display a preview of the data for each AUX channel, allowing you to assess the status and activity of the selected auxiliary devices, as shown on the left side of Figure 5.12. One can also select a measurement to view individual events, or the graph to view the data in a visual format, as shown in Figure 5.13. Viewing individual events allows for a detailed examination of each event associated with the chosen measurement. By clicking on an event, users can access additional information such as the timestamp, value, and any relevant details pertaining to that specific event (left side of Figure 5.13). This level of granularity facilitates a deeper analysis and troubleshooting of engine-related activities and performance. To gain a visual representation of the data, MyGeotab has a graphing feature available in the Measurements section. By selecting the desired measurement, users can generate a graph that displays the data over time. The graph provides a visual overview of how the measurement values fluctuate, allowing for trend identification, pattern recognition, and performance analysis. Visualizing the data in this manner can highlight anomalies, outliers, and trends that may not be immediately apparent when examining the raw numerical values (right side of Figure 5.13).

Similar to the export capability for Log and Collisions Data, MyGeotab also allows users to export an Engine Status Report in Excel format. This report provides valuable insights into the status of the engine and its auxiliary signals. This report provides information about the device name, as well as timestamps indicating when each signal was detected, as well as the corresponding value. This enables fleet managers to analyze the timing and duration of auxiliary device activations or any relevant changes in their status, as shown in Figure 5.14.



Vehicles & Assets

Trailers have been migrated to the Vehicles & Assets page.
The Assets page has been updated to include all assets including vehicles, traile

Name	VIN	Licens
03300K Vehicle, RTI, Diesel	1HTWXAHR29J170174	Unknov
871220088 Vehicle, RTI, Diesel	3ALHG3DV9LDME3121	Unknov
871221063 Vehicle, RTI, Diesel	1FVHG3DV1MHMU5011	Unknov
871221071 Vehicle, RTI, Diesel	1FVHG3DVXMHMU5038	Unknov

Include archived (historical) data: Yes **No**

Vehicles: Search vehicles

Selected: 03300K

Diagnostics: AUX 4

Selected: Aux 1 (1 = on), Aux 2

Custom: 02/02/23 00:00 to 02/02/23 23:59

Navigate to Engine and Device Measurements

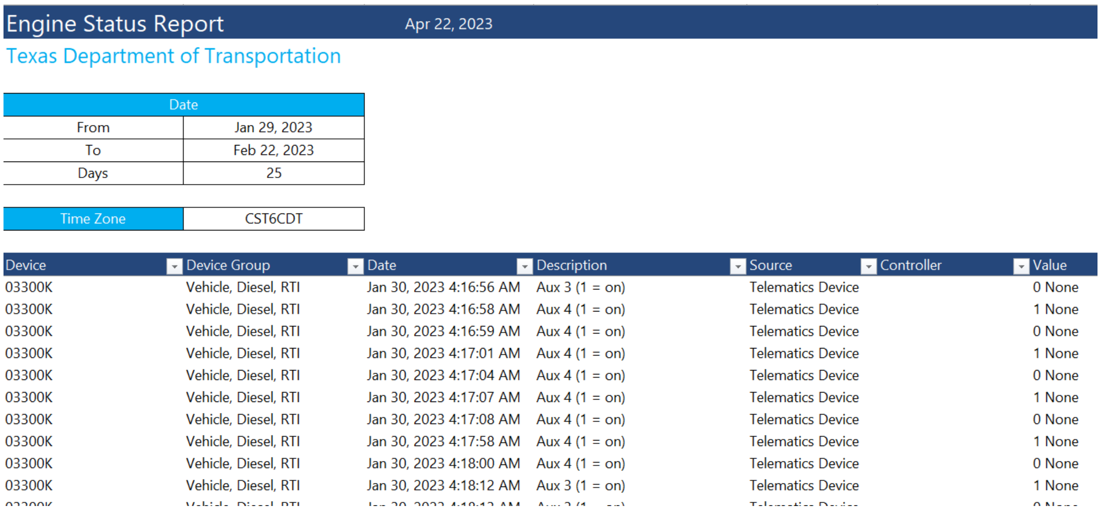
Select Vehicles, Time Period, and Diagnostics

View data

Figure 5.12: Steps to navigate to Engine and Devices Measurements

01/29/23 00:00:00	0
01/30/23 04:28:05	1
01/30/23 04:28:27	0
01/30/23 04:47:49	1
01/30/23 04:47:56	0
01/30/23 04:47:58	1
01/30/23 04:47:59	0
01/30/23 04:59:17	1
01/30/23 05:02:53	0
01/30/23 05:04:09	1
01/30/23 05:04:22	0
01/30/23 05:05:35	1
01/30/23 05:08:03	0
01/30/23 05:08:34	1
01/30/23 05:10:06	0
01/30/23 05:11:11	1
01/30/23 05:11:27	0
01/30/23 05:11:47	1
01/30/23 05:12:05	0
01/30/23 05:14:10	1
01/30/23 05:15:41	0
01/30/23 05:18:58	1
01/30/23 05:20:36	0
01/30/23 05:21:33	1
01/30/23 05:21:49	0
01/30/23 05:24:08	1

Figure 5.13: Engine Data Profile



Engine Status Report Apr 22, 2023

Texas Department of Transportation

Date	
From	Jan 29, 2023
To	Feb 22, 2023
Days	25

Time Zone	CST6CDT

Device	Device Group	Date	Description	Source	Controller	Value
03300K	Vehicle, Diesel, RTI	Jan 30, 2023 4:16:56 AM	Aux 3 (1 = on)	Telematics Device		0 None
03300K	Vehicle, Diesel, RTI	Jan 30, 2023 4:16:58 AM	Aux 4 (1 = on)	Telematics Device		1 None
03300K	Vehicle, Diesel, RTI	Jan 30, 2023 4:16:59 AM	Aux 4 (1 = on)	Telematics Device		0 None
03300K	Vehicle, Diesel, RTI	Jan 30, 2023 4:17:01 AM	Aux 4 (1 = on)	Telematics Device		1 None
03300K	Vehicle, Diesel, RTI	Jan 30, 2023 4:17:04 AM	Aux 4 (1 = on)	Telematics Device		0 None
03300K	Vehicle, Diesel, RTI	Jan 30, 2023 4:17:07 AM	Aux 4 (1 = on)	Telematics Device		1 None
03300K	Vehicle, Diesel, RTI	Jan 30, 2023 4:17:08 AM	Aux 4 (1 = on)	Telematics Device		0 None
03300K	Vehicle, Diesel, RTI	Jan 30, 2023 4:17:58 AM	Aux 4 (1 = on)	Telematics Device		1 None
03300K	Vehicle, Diesel, RTI	Jan 30, 2023 4:18:00 AM	Aux 4 (1 = on)	Telematics Device		0 None
03300K	Vehicle, Diesel, RTI	Jan 30, 2023 4:18:12 AM	Aux 3 (1 = on)	Telematics Device		1 None

Figure 5.14: Excel output of the Engine Status Report

5.1.6. MyGeotab: Case Study

In this section we utilize the above tools to examine how Abilene's fleet operated during the winter events that took place between January and February of 2023. Historical weather data was examined to identify the dates during which Abilene experienced the most severe winter weather. This data is presented in Figure 5.15. With this information, we can now proceed with analyzing Abilene's fleet performance during these winter events using MyGeotab.

In Figure 5.16, the trip trajectories and AUX signals of three vehicles operating in Abilene on January 30 are shown. The vehicles featured in the figure are 04498H (left figure), 03300K (middle figure), and 871221063 (right figure). A close examination of Figure 16 reveals notable insights regarding the activities of these vehicles on that specific day. Specifically, the graph showcases that vehicles 03300K and 871221063 were engaged in extensive salt spreading operations. This conclusion is drawn from the conspicuous spikes observed in the respective graphs associated with these vehicles.

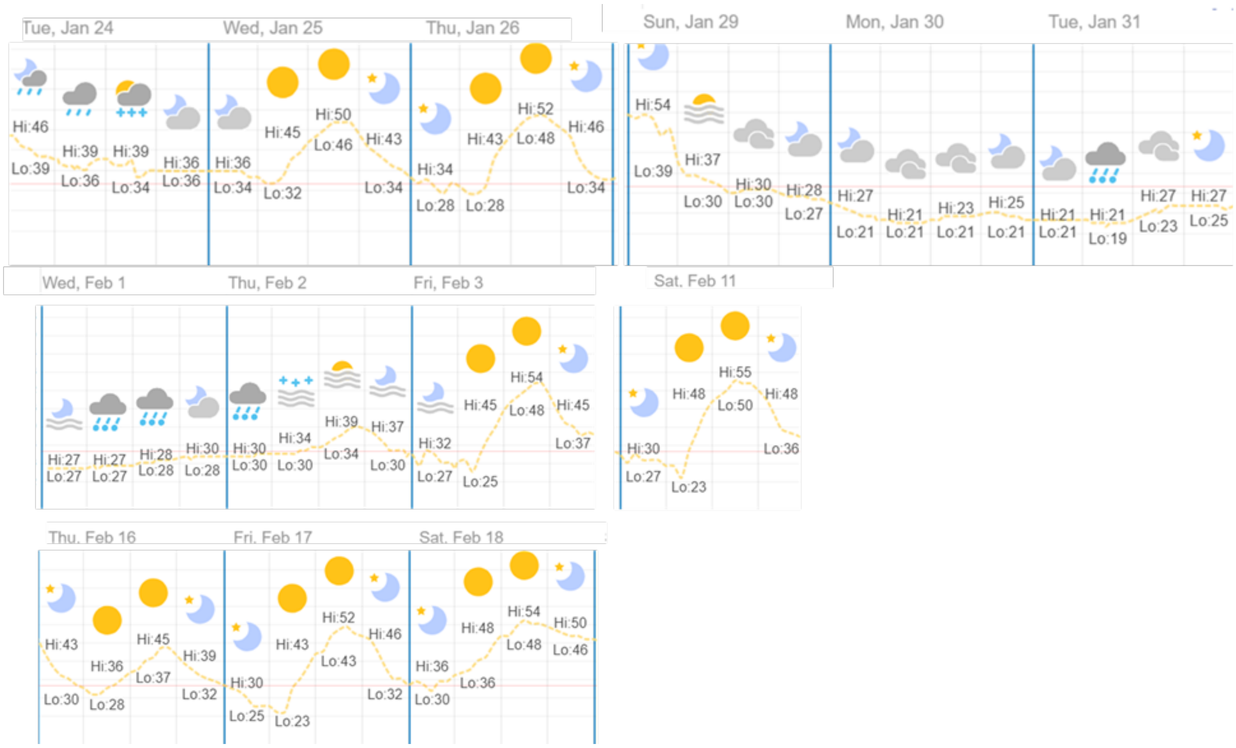


Figure 5.15: Historical weather data in Abilene on January and February of 2023

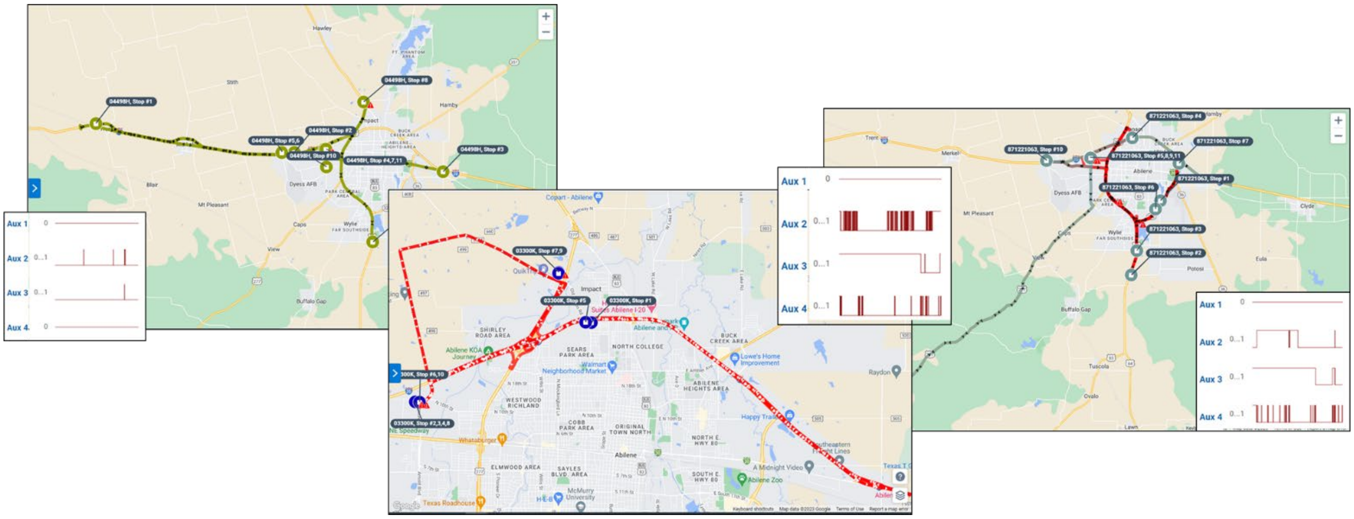


Figure 5.16: Vehicle trip history in January 30th, 2023

5.2. GIS Integration

The objectives of ArcGIS data applications in this project include:

1. **Retrieve data from Geotab API:** ArcGIS data applications aim to seamlessly access and retrieve data from Geotab. This integration allows for the utilization of Geotab's data within ArcGIS for further analysis and visualization.

2. **Visualize data on a map:** ArcGIS provides powerful mapping capabilities, enabling users to visualize Geotab data on a map. This allows for a spatial representation of vehicle locations, routes, and other relevant information, providing a comprehensive view of fleet operations.

3. **Apply symbology to monitor plowing, spreading, and spraying:** ArcGIS data applications allow users to apply customized symbology to the map layers representing plowing, spreading, and spraying activities. This enables easy monitoring and identification of areas that have been treated or require attention during winter weather operations.

4. **Apply spatial join with roadways to analyze treated roads and perform other analyses:** By performing a spatial join between Geotab data and roadway datasets, ArcGIS enables the analysis of which roads have been treated or are in need of treatment. This spatial analysis helps identify patterns, prioritize road maintenance, and optimize winter weather operations.

5. **Export reports:** ArcGIS data applications offer the ability to generate and export reports based on the analyzed Geotab data. These reports can include detailed information about vehicle activities, treatment effectiveness, resource allocation, and other relevant metrics for reporting and decision-making purposes.

6. **Integrate with TxERA:** ArcGIS data applications can be integrated with the TxERA system, a platform used by TxDOT for managing emergency scenarios and related roadway maintenance and operations. This integration facilitates seamless data sharing and collaboration between ArcGIS and TxERA, streamlining winter weather operations and enhancing efficiency.

By focusing on these objectives, ArcGIS data applications provide a comprehensive suite of tools and functionalities to effectively utilize Geotab data, visualize it spatially, analyze roadway treatment, generate reports, and integrate with existing systems for enhanced winter weather operations management.

5.2.1. Retrieve Data from Geotab API

The Geotab API, also known as MyGeotab SDK, provides a means for programmers or technologically savvy users to access Geotab data through third-party applications. It offers a robust set of tools and functionalities for automating tasks and working with data within the

MyGeotab environment. In the specific context of this study, the MyGeotab SDK played a pivotal role in facilitating the display of vehicle trips and WinterOps activities on ArcGIS maps.

To get started, one must install the MyGeotab Python 3 language library and command line tool. If one is using Pip, the command line to install the library may look like this:

```
$ pip install mygeotab
```

The following code snippet shows the initial steps taken to access Geotab data through the MyGeotab SDK, demonstrating the setup process and the authentication of the client. This code initializes the Geotab API with the specified credentials, including the username and password for authentication. The server parameter denotes the Geotab server address, in this case, “gov4.geotab.com”. The database parameter represents the database, “tx_dot”, being accessed.

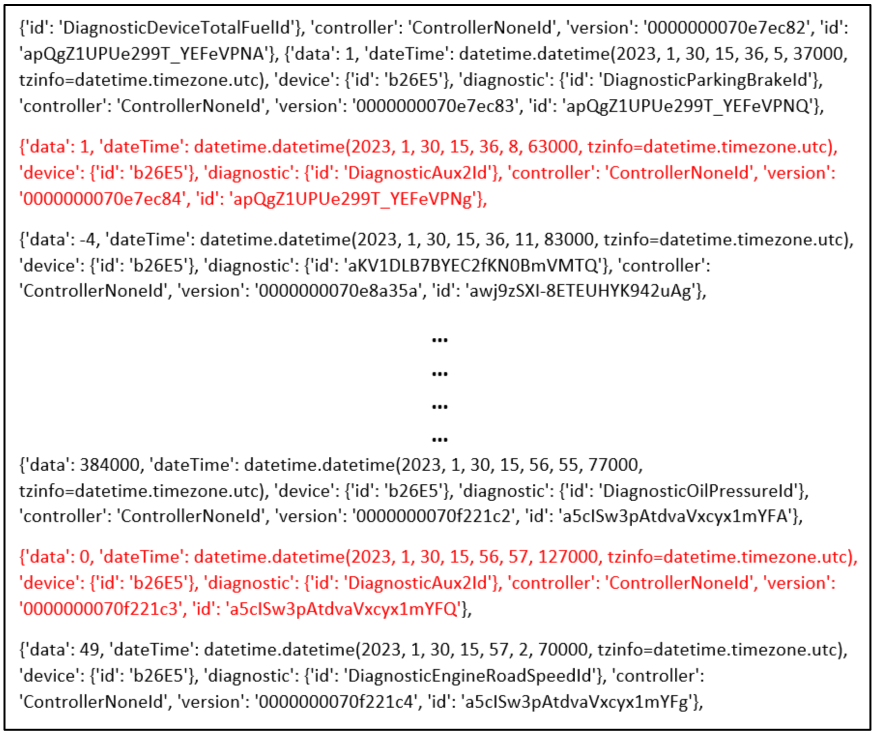
```
client = mygeotab.API(username='[insert username]',
                      password='[insert password]',
                      server='gov4.geotab.com',
                      database='tx_dot')
client.authenticate()
```

Next, we define a function “get_device_data()” to retrieve device data. This function takes three parameters: device_id, from_date, and to_date. It retrieves the status data for a specific device within the specified time period. The client.get() method is used to make a request to the Geotab API, querying the “StatusData” resource and applying search filters for the device ID and date range. This function returns the status of the vehicle whenever a change is detected (for example, a value of 1 for AUX 2 indicates that the spreader is being turned on).

```
# Define a function to get the device data
def get_device_data(device_id, from_date, to_date):
    results = client.get('StatusData', search={'deviceSearch': {'id':
              device_id}, 'fromDate':   from_date, 'toDate': to_date})
    return results

from_date = '2023-01-30T00:00:00' # start of time period
to_date = '2023-01-30T23:59:59' # end of time period
status_data = get_device_data(device_id, from_date, to_date)
```

Figure 5.17 shows a snapshot of the outputs of the “get_device_data()” function. The data elements corresponding to the status of AUX 2 (spreader) are colored to stand out. The first timestamp where AUX2 has a value of 1 is (2023,1,20,15,36,8,63000). After that there are no data outputs corresponding to AUX2 until 20 minutes later where the timestamp is (2023,1,20,15,56,57,127000). This implies that the spreader was turned on at 15:36:08 and was kept on until 15:56:57. Thus, the outputs of this function represent the change in status and not the status itself. These considerations were carefully integrated in the GIS tools that we will discuss later.



```
{'id': 'DiagnosticDeviceTotalFuelId'}, 'controller': 'ControllerNoneId', 'version': '0000000070e7ec82', 'id':
'apQgZ1UPUe299T_YEFeVPNA'}, {'data': 1, 'dateTime': datetime.datetime(2023, 1, 30, 15, 36, 5, 37000,
tzinfo=datetime.timezone.utc), 'device': {'id': 'b26E5'}, 'diagnostic': {'id': 'DiagnosticParkingBrakeId'},
'controller': 'ControllerNoneId', 'version': '0000000070e7ec83', 'id': 'apQgZ1UPUe299T_YEFeVPNQ'},

{'data': 1, 'dateTime': datetime.datetime(2023, 1, 30, 15, 36, 8, 63000, tzinfo=datetime.timezone.utc),
'device': {'id': 'b26E5'}, 'diagnostic': {'id': 'DiagnosticAux2Id'}, 'controller': 'ControllerNoneId', 'version':
'0000000070e7ec84', 'id': 'apQgZ1UPUe299T_YEFeVPNg'},

{'data': -4, 'dateTime': datetime.datetime(2023, 1, 30, 15, 36, 11, 83000, tzinfo=datetime.timezone.utc),
'device': {'id': 'b26E5'}, 'diagnostic': {'id': 'aKV1DLB7BYEC2fKN0BmVMTQ'}, 'controller':
'ControllerNoneId', 'version': '0000000070e8a35a', 'id': 'awj9zSXI-8ETEUHYK942uAg'},

                                              ...
                                              ...
                                              ...
                                              ...
{'data': 384000, 'dateTime': datetime.datetime(2023, 1, 30, 15, 56, 55, 77000,
tzinfo=datetime.timezone.utc), 'device': {'id': 'b26E5'}, 'diagnostic': {'id': 'DiagnosticOilPressureId'},
'controller': 'ControllerNoneId', 'version': '0000000070f221c2', 'id': 'a5cISw3pAtdvaVxcyx1mYFA'},

{'data': 0, 'dateTime': datetime.datetime(2023, 1, 30, 15, 56, 57, 127000, tzinfo=datetime.timezone.utc),
'device': {'id': 'b26E5'}, 'diagnostic': {'id': 'DiagnosticAux2Id'}, 'controller': 'ControllerNoneId', 'version':
'0000000070f221c3', 'id': 'a5cISw3pAtdvaVxcyx1mYFQ'},

{'data': 49, 'dateTime': datetime.datetime(2023, 1, 30, 15, 57, 2, 70000, tzinfo=datetime.timezone.utc),
'device': {'id': 'b26E5'}, 'diagnostic': {'id': 'DiagnosticEngineRoadSpeedId'}, 'controller':
'ControllerNoneId', 'version': '0000000070f221c4', 'id': 'a5cISw3pAtdvaVxcyx1mYFg'},
```

Figure 5.17: Device Status Data output example

Next, we discuss a function that retrieves GPS records for a specific device within a specified time period using the Geotab API. The following code defines the function get_gps_records() and demonstrates its usage. The function takes device_id, from_date, and to_date as parameters. It makes use of the client.get() method to query the Geotab API for GPS records. The function returns the results obtained from the API call, which represent the GPS data for the specified device and time period. Note that this output does not include information about the status of the plow, spreader, or sprayer. It only includes GPS coordinates associated with the vehicle trajectory.

```
# Define a function to get the GPS records
def get_gps_records(device_id, from_date, to_date):
   results = client.get('LogRecord', search={'deviceSearch': {'id':
             device_id}, 'fromDate':  from_date, 'toDate': to_date})

   return results

# Define the parameters for retrieving GPS records
from_date = '2023-01-30T00:00:00'  # start of the time period
to_date = '2023-01-30T23:59:59'  # end of the time period

# Call the function to retrieve GPS records
gps_data = get_gps_records(device_id, from_date, to_date)
```

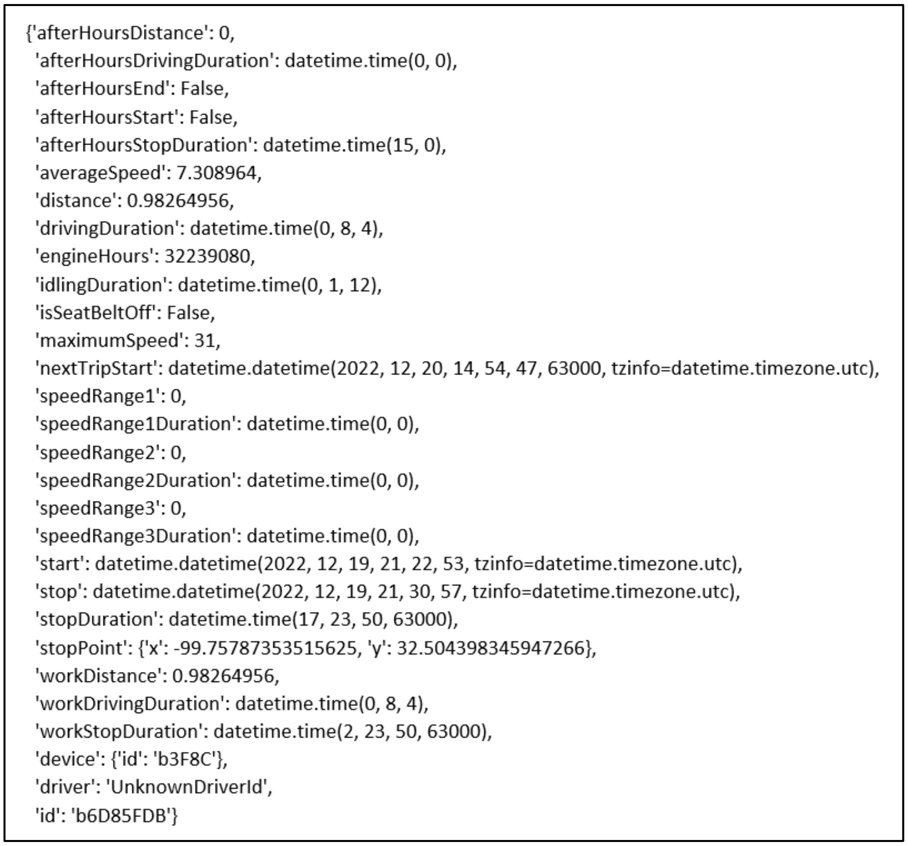
The following code defines the function get_trip_records() and demonstrates its usage. The function takes device_id, from_date, and to_date as parameters.

```
# Define a function to get trip records
def get_trip_records(device_id, from_date, to_date):
   results = client.get('Trip', search={'deviceSearch': {'id': device_id},
            'fromDate': from_date, 'toDate': to_date})
   return results

# Define the parameters for retrieving trip records
device_id = vehicle_list[5]  # device ID for the vehicle you want trip
                               records for
from_date = '2023-01-30T00:00:00'  # start of the time period
to_date = '2023-01-30T23:59:59'    # end of the time period

# Call the function to retrieve trip records
trip_data = get_trip_records(device_id, from_date, to_date)
```

Figure 5.18 shows an example output of the "get_trip_records()" function. For each trip, the output provides information about the distance, duration, idling and stopping times, as well as other insights. This output is especially beneficial to identify the times trips were taken and extract data for only these timeframes from the "get_gps_records()" and the "get_device_data()" functions.



```
{'afterHoursDistance': 0,
 'afterHoursDrivingDuration': datetime.time(0, 0),
 'afterHoursEnd': False,
 'afterHoursStart': False,
 'afterHoursStopDuration': datetime.time(15, 0),
 'averageSpeed': 7.308964,
 'distance': 0.98264956,
 'drivingDuration': datetime.time(0, 8, 4),
 'engineHours': 32239080,
 'idlingDuration': datetime.time(0, 1, 12),
 'isSeatBeltOff': False,
 'maximumSpeed': 31,
 'nextTripStart': datetime.datetime(2022, 12, 20, 14, 54, 47, 63000, tzinfo=datetime.timezone.utc),
 'speedRange1': 0,
 'speedRange1Duration': datetime.time(0, 0),
 'speedRange2': 0,
 'speedRange2Duration': datetime.time(0, 0),
 'speedRange3': 0,
 'speedRange3Duration': datetime.time(0, 0),
 'start': datetime.datetime(2022, 12, 19, 21, 22, 53, tzinfo=datetime.timezone.utc),
 'stop': datetime.datetime(2022, 12, 19, 21, 30, 57, tzinfo=datetime.timezone.utc),
 'stopDuration': datetime.time(17, 23, 50, 63000),
 'stopPoint': {'x': -99.75787353515625, 'y': 32.504398345947266},
 'workDistance': 0.98264956,
 'workDrivingDuration': datetime.time(0, 8, 4),
 'workStopDuration': datetime.time(2, 23, 50, 63000),
 'device': {'id': 'b3F8C'},
 'driver': 'UnknownDriverId',
 'id': 'b6D85FDB'}
```

Figure 5.18: Trip Data output example

5.2.2. Preparing the Roadway Segments Layer

This section discusses the various steps and considerations that were considered before delving into the application of winter weather maintenance operations in ArcGIS.

5.2.2.1. Appending Tier System

The TxDOT Roadway Inventory serves as the foundational feature class for this project's roadway segment layer. It displays a polyline layer that encompasses the roadway attributes of roads throughout the state of Texas. Unlike typical transportation practices, winter maintenance operations in each district utilizes a tier system for prioritizing roadways. Tier 1 roads have the highest priority, while Tier 4 roads have the lowest priority. Therefore, each road segment in the TxDOT Roadway Inventory used for this study was assigned a tier level based upon maps provided by Abilene and Lubbock District personnel.

5.2.2.2. Dividing Segments at Intersections

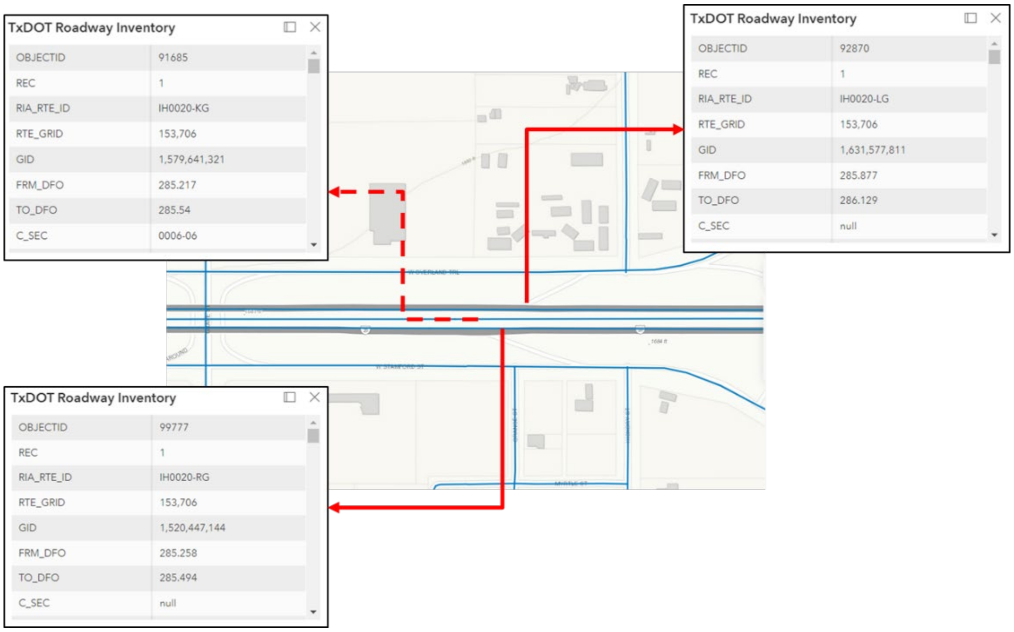
Additionally, the roadway segment lines in the TxDOT Roadway Inventory are not always divided at intersection locations. This omission of intersection divisions can lead to inaccuracies in both visualization and analysis.

To illustrate this point, consider the scenario where a winter maintenance truck plows only a portion of a roadway segment and then exits the segment at an intersection. Without the proper division of the segment at the intersection, subsequent analysis could mistakenly indicate that the entire segment was treated. This oversight can result in misleading conclusions and hinder effective decision-making.

To address this issue, all intersections were located using various ArcGIS tools and all ramps were identified by querying data from the OpenStreetMaps (OSM) API. (See Perrine, 2021 for strategies, code, and data set that can help accomplish this). Then, the polylines in the TxDOT Roadway Inventory were divided at these points. By accurately dividing the segments at intersection points, the system can provide a more precise representation of the treated sections, enabling better assessment of winter maintenance operations and optimizing resource allocation.

5.2.2.3. Deleting Unnecessary Lines

The TxDOT Roadway Inventory encompasses various classifications for roadbeds in different line sections. For instance, there are designations such as LG (Left Roadbed), RG (Right Roadbed), and KG (Centerline or Single Roadbed). In Figure 5.19, a section of interstate highway I-20 in Abilene is depicted, presenting three distinct segments that only differ in their roadbed classification, while everything else remains the same. It is evident from the figure that the middle segment, assigned the KG designation, does not accurately represent an actual road segment. Instead, it merely serves as the midpoint between the LG and RG segments. As a result, this middle KG segment should be excluded from the analysis. However, it should be noted that there are other instances where the KG segment accurately represents the actual road location. Consequently, the TxDOT Roadway Inventory was adjusted by removing KG segments that do not correspond to real roadway alignments.



TxDOT Roadway Inventory

OBJECTID	91685
REC	1
RIA_RTE_ID	IH0020-KG
RTE_GRID	153,706
GID	1,579,641,321
FRM_DFO	285.217
TO_DFO	285.54
C_SEC	0006-06

TxDOT Roadway Inventory

OBJECTID	92870
REC	1
RIA_RTE_ID	IH0020-LG
RTE_GRID	153,706
GID	1,631,577,811
FRM_DFO	285.877
TO_DFO	286.129
C_SEC	null

TxDOT Roadway Inventory

OBJECTID	99777
REC	1
RIA_RTE_ID	IH0020-RG
RTE_GRID	153,706
GID	1,520,447,144
FRM_DFO	285.258
TO_DFO	285.494
C_SEC	null

Figure 5.19: Polyline snapshot from TxDOT Roadway Inventory

5.2.3. Preparing Facility Geofences

Various feature classes were generated to encompass all facilities managed by the Texas Department of Transportation (TxDOT), including buildings, maintenance facilities, fueling stations, salt reserves, and brine making locations. These feature classes are stored within a file geodatabase named “Geofences_US_V3.gdb”. In Figure 5.20, the Abilene District Headquarters is depicted. The green polygon signifies the overall boundary of the facility, while the pink polygons represent buildings and the blue polygon represents a fueling facility. These geofences play a vital role in future endeavors aimed at detecting vehicle entries into the facilities. By detecting such events, it becomes possible to gain insights into the frequency of vehicle visits, their duration of stay, and the specific activities conducted within the facility. Furthermore, similar information is provided for salt reserves, which proves essential in determining the frequency of restocking for spreaders, as well as tracking the amount of salt distributed and amount remaining in reserves.

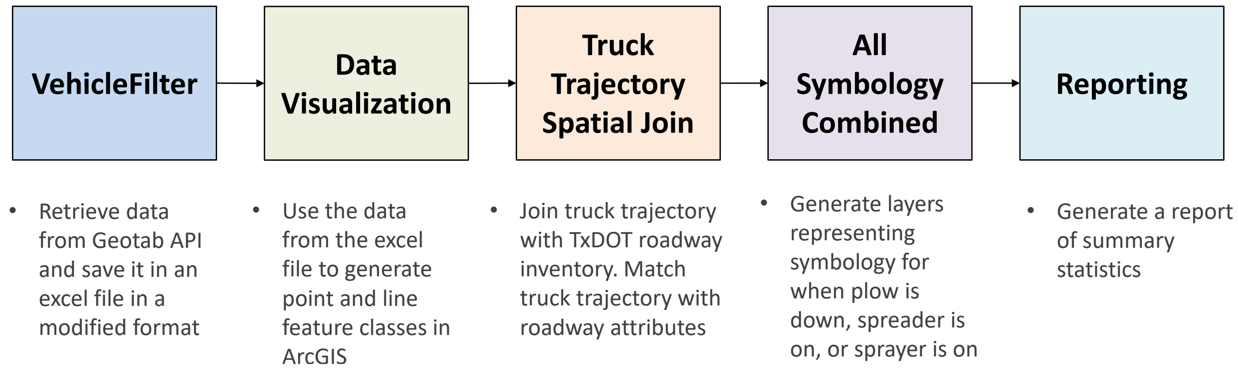
Figure 5.20: Abilene District Headquarters geofence

5.2.4. ArcGIS Integrated Solutions

After completing the necessary prerequisites outlined in the previous section, a set of toolboxes was developed within ArcGIS Pro using Python scripts and Model Builder to encompass various winter weather maintenance-related functionalities. A total of five distinct tools were created, each serving a specific purpose:

- Vehicle Filter;
- Data Visualization;
- Truck Trajectory Spatial Join;
- All Symbology combined; and
- Reporting.

These tools follow a sequential workflow, as presented in Figure 5.21, to achieve the desired outcome. Figure 5.21 also provides a brief description of each of the five tools. Subsequent sections will delve into the intricate workings of each tool and underlying coding considerations. While these are presented as distinct tools, they can be scripted as an automated string of events.



- Retrieve data from Geotab API and save it in an excel file in a modified format
- Use the data from the excel file to generate point and line feature classes in ArcGIS
- Join truck trajectory with TxDOT roadway inventory. Match truck trajectory with roadway attributes
- Generate layers representing symbology for when plow is down, spreader is on, or sprayer is on
- Generate a report of summary statistics

Figure 5.21: Workflow in ArcGIS Pro

5.2.4.1. Vehicle Filter

The Vehicle Filter function is a vital component of the winter weather maintenance toolbox. Its primary purpose is to extract relevant WinterOps data from the Geotab API and save it in a CSV file format.

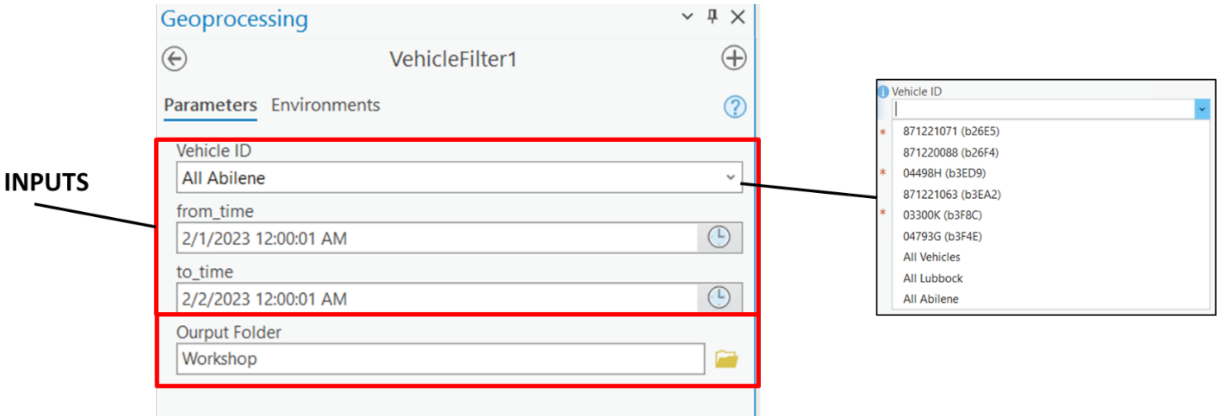
To accomplish this task, the Vehicle Filter function utilizes the Geotab API, which serves as a data source for retrieving real-time vehicle data. The function initiates a connection to the Geotab API using appropriate credentials and authentication mechanisms. It then specifies the desired data parameters, such as the time range, geographical boundaries, and specific vehicle attributes to be extracted. Once the data extraction process is initiated, the Vehicle Filter function receives a stream of vehicle data from the Geotab API. It applies predefined filters and criteria to selectively extract the desired data based on specific requirements. It also applies the heuristic to accurately determine the plow state. Upon extracting the filtered data, the Vehicle Filter function proceeds to save the extracted information in a CSV (comma-separated values) file format. The CSV file format is commonly used for storing tabular data in a plain text format, making it easily readable and accessible within ArcGIS. By saving the extracted vehicle data in a CSV file within ArcGIS, the Vehicle Filter function ensures that the data is readily available for subsequent analysis and integration with other winter weather maintenance tools within the toolbox. This streamlined approach facilitates the seamless flow of data, enabling further processing, visualization, and decision-making in winter weather maintenance operations.

This toolbox is created through a Python script that incorporates the functions and considerations that were discussed earlier. The user interface for the Vehicle Filter toolbox in ArcGIS Pro is presented in Figure 5.22. It provides a convenient and intuitive interface for users to interact with the tool. The inputs required to perform the vehicle filtering are as follows:

- **Vehicle ID:** This input is selected from a drop-down menu located on the right side of Figure 5.22. Users can choose the specific vehicle for which they want to extract data.
- **Start Time (from_time):** Users need to specify the desired start time for the data extraction. This parameter defines the beginning of the time period from which the vehicle data will be filtered.

- **End Time (to_time):** This input requires users to define the end time for the data extraction. It marks the conclusion of the time period for which vehicle data will be filtered.
- **Output Folder Directory:** Users need to specify the directory or location where the output CSV file will be saved. This allows for organization of the extracted data.

Upon providing these inputs, the Vehicle Filter toolbox processes the data based on the selected vehicle, start time, and end time. It then generates a CSV file as the output, containing the data specific to the selected vehicle and the designated time period.



Vehicle ID: All Abilene
from_time: 2/1/2023 12:00:01 AM
to_time: 2/2/2023 12:00:01 AM
Ourput Folder: Workshop

Figure 5.22: Interface of the Vehicle Filter toolbox within ArcGIS Pro

5.2.4.2. Data Visualization

The Data Visualization toolbox is a powerful tool within ArcGIS that leverages data from the CSV file obtained from the Vehicle Filter tool to generate point and line feature classes. This functionality enables the visual representation of the WinterOps data in a spatial context, facilitating better understanding and analysis. The toolbox is developed using ArcGIS' Model Builder and adheres to the workflow presented in Figure 5.23.

Specifically, the Data Visualization toolbox employs two preexisting tools within the ArcGIS toolbox: "XY to Line" and "XY to Point". These tools play a crucial role in converting the data from the CSV file into spatial features. The XY to Line tool is utilized to generate line feature classes. It takes the coordinates from the Excel file and constructs lines based on the sequential order of the points. This enables the visualization of trajectories, paths, or any other spatial patterns present in the data. On the other hand, the XY to Point tool is employed to create point feature classes. It extracts the coordinates from the Excel file and generates individual points corresponding to each set of coordinates. These points represent specific locations or events captured in the data. To enhance the visual representation of the output points and lines, the Data Visualization toolbox utilizes the "Apply Symbology from Layer" tool. This tool enables the formatting of the generated points and lines to match a specific symbology or visual style (preloaded into the toolbox), as shown on the right of Figure 5.24. It ensures that the output features are presented in a clear and consistent manner, enhancing their interpretability. Figure 5.25 displays an example of the output feature class generated by this tool.

By leveraging the capabilities of ArcGIS and incorporating the Data Visualization toolbox into the workflow, users can effectively transform Excel-based data into visually compelling representations, facilitating deeper understanding and analysis of the spatial aspects within the dataset.

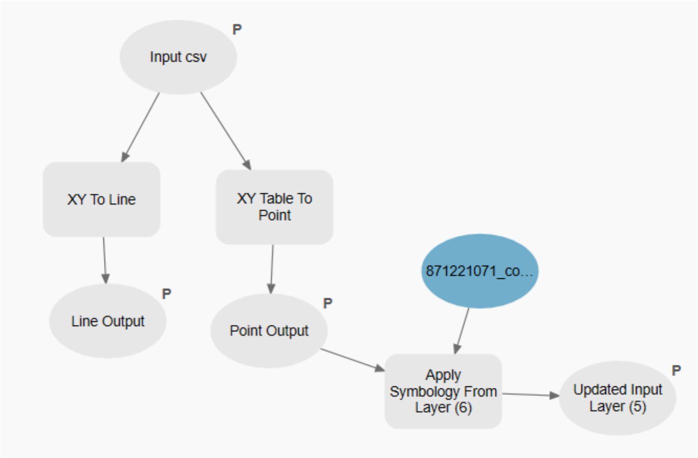
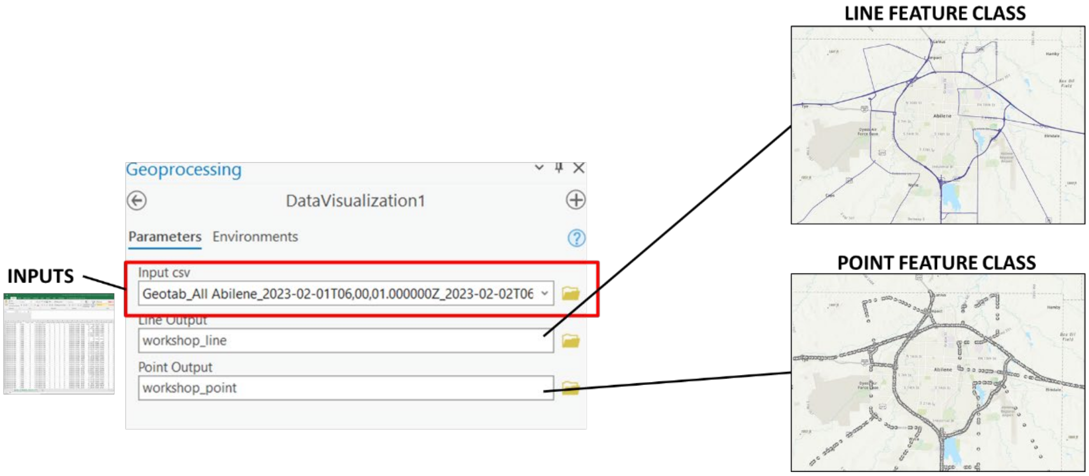


Figure 5.23: Model Builder workflow for the Data Visualization tool



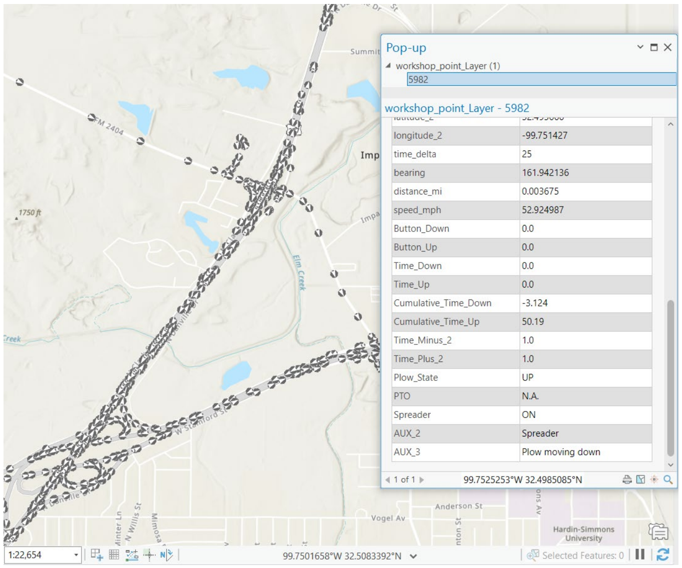
DataVisualization1

Input csv: Geotab_All Abilene_2023-02-01T06,00,01.000000Z_2023-02-02T06

Line Output: workshop_line

Point Output: workshop_point

Figure 5.24: Interface of the Data Visualization toolbox within ArcGIS Pro



longitude_2	-99.751427
time_delta	25
bearing	161.942136
distance_mi	0.003675
speed_mph	52.924987
Button_Down	0.0
Button_Up	0.0
Time_Down	0.0
Time_Up	0.0
Cumulative_Time_Down	-3.124
Cumulative_Time_Up	50.19
Time_Minus_2	1.0
Time_Plus_2	1.0
Plow_State	UP
PTO	N.A.
Spreader	ON
AUX_2	Spreader
AUX_3	Plow moving down

Figure 5.25: Example output of the Data Visualization tool

5.2.4.3. Truck Trajectory Spatial Join and All Symbology Combined

This toolbox incorporates two main components: the "Truck Trajectory Spatial Join" and the "All Symbology Combined" tool. The Truck Trajectory Spatial Join and All Symbology Combined tools have been merged into a single toolbox to streamline the workflow. This framework is implemented in Model Builder as shown in Figure 5.26.

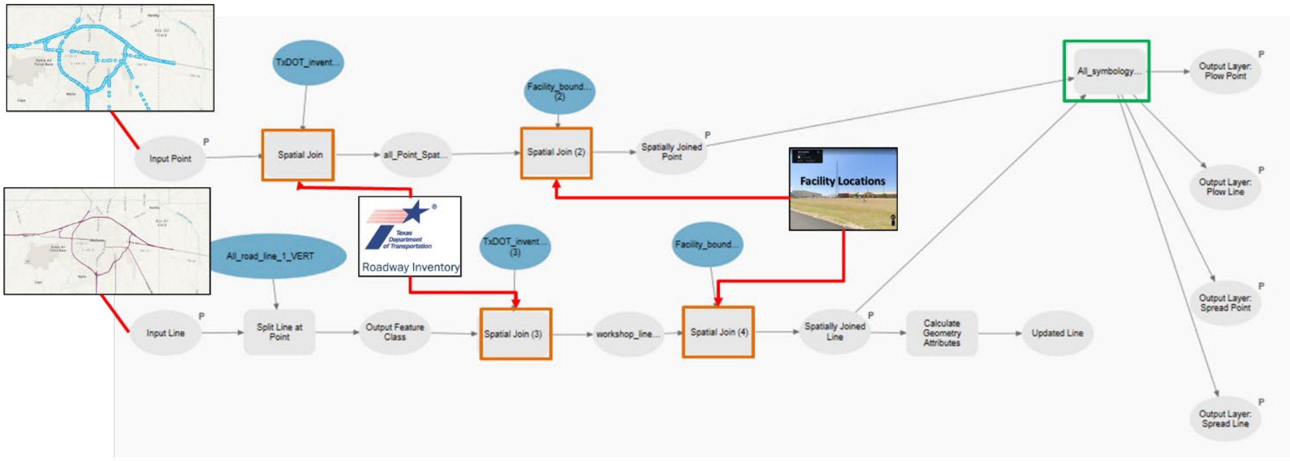


Figure 5.26: Model Builder workflow for the Truck Trajectory Spatial Join and the All Symbology Combined tools

The Truck Trajectory Spatial Join component is responsible for matching truck trajectories with roadway attributes provided within the TxDOT Roadway Inventory feature class. This feature class has been modified based on considerations discussed earlier. By performing this spatial join, the tool connects the truck trajectories with relevant roadway information, such as road names, tier levels, and operation status. Additionally, the spatial join is repeated with the facility boundaries layer. The output of this component is a point feature class that includes truck trajectories, operation status, road name and tier level, and whether the point is located within a facility.

The line feature class is also inputted into the toolbox and joined with the TxDOT Roadway Inventory layer and the facility boundaries layer. However, before the joining process, the TxDOT Roadway Inventory line feature class is split at the start and end vertices of the truck trajectory feature class using ArcGIS' "Split Line at Point" tool. This is crucial for accurately capturing instances where treatment changes along the road segment, such as when a truck is spreading salt only on a specific portion of the road. This is illustrated in Figure 5.27 that shows a scenario where a truck is spreading salt on particular portion of the road. In that case only a quarter of the road segment in treated. By splitting the line segments at the treatment change points, the spatial join can correctly indicate the treated portions of the road. This step ensures more accurate visualization and analysis. The output of this component is a line feature class that includes truck trajectories, operation status, road name and tier level, and whether the point is located within a facility.

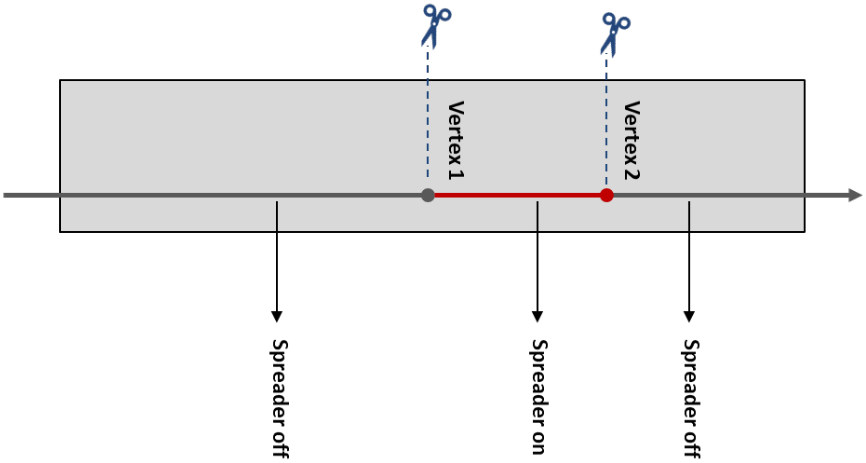
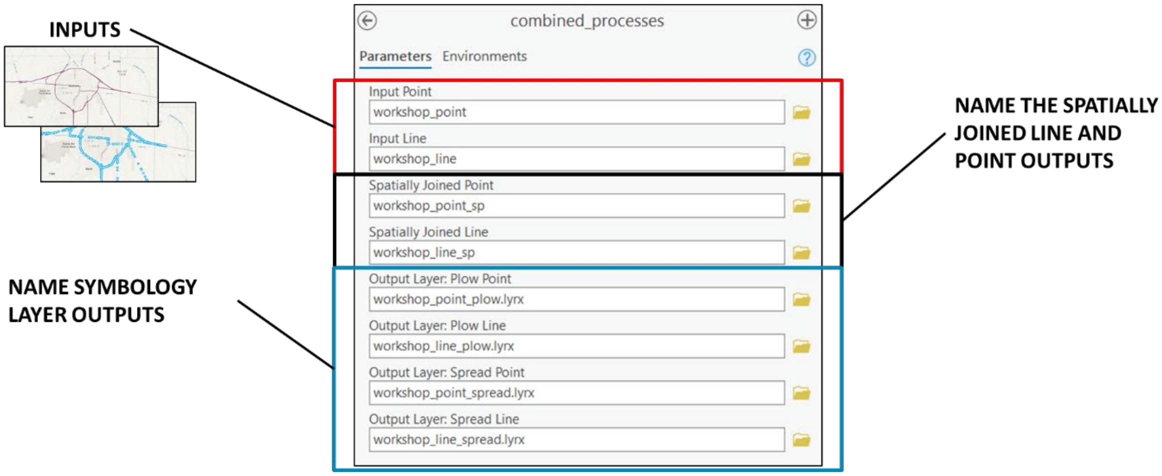


Figure 5.27: Illustration of splitting roadway line at truck trajectory vertices

After completing the spatial joins, multiple symbologies are applied to the output feature classes. The "All Symbology Combined" tool component generates separate symbology layers for the plowing state and the spreading state. These symbology layers enhance the visual representation of the line and point feature classes, clearly indicating when the plow is down or when the spreader is on. The user interface for this tool, as shown in Figure 5.28, allows users to input the point and line feature class files, specify the output joined files, and name the four symbology layers. It's worth noting that the spraying symbology was not included in this tool due to the sprayer being in maintenance for most of the winter season in 2023, but adding it would involve minimal intervention.

Overall, this integrated approach ensures that truck trajectories are effectively linked with relevant roadway attributes, and the resulting symbology layers enable clear representation of plowing and spreading activities. Figure 5.29 and Figure 5.30 show the outputs emerging from this toolbox.

Figure 5.29 displays the truck trajectories in point format, capturing the PTO and Spreader states, as well as the plowing status. This visualization offers a concise overview of the locations and states of the trucks during the winter weather maintenance operations. By examining this figure, it becomes easier to identify patterns, clusters, and the distribution of plowing and spreading activities across the designated roadways. Figure 5.30 showcases both the line and point feature classes for a specific ramp on I-20 in Abilene. This illustration provides a detailed visualization of the overlapping trajectories of the trucks. It allows for a deeper understanding of how multiple trucks navigate and treat the same roadway segment, enabling the identification of any potential inefficiencies or opportunities for optimization in winter weather maintenance operations.



Input Point: workshop_point

Input Line: workshop_line

Spatially Joined Point: workshop_point_sp

Spatially Joined Line: workshop_line_sp

Output Layer: Plow Point: workshop_point_plow.lyrx

Output Layer: Plow Line: workshop_line_plow.lyrx

Output Layer: Spread Point: workshop_point_spread.lyrx

Output Layer: Spread Line: workshop_line_spread.lyrx

Figure 5.28: Interface of the Truck Trajectory Spatial Join and the All Symbology Combined tools

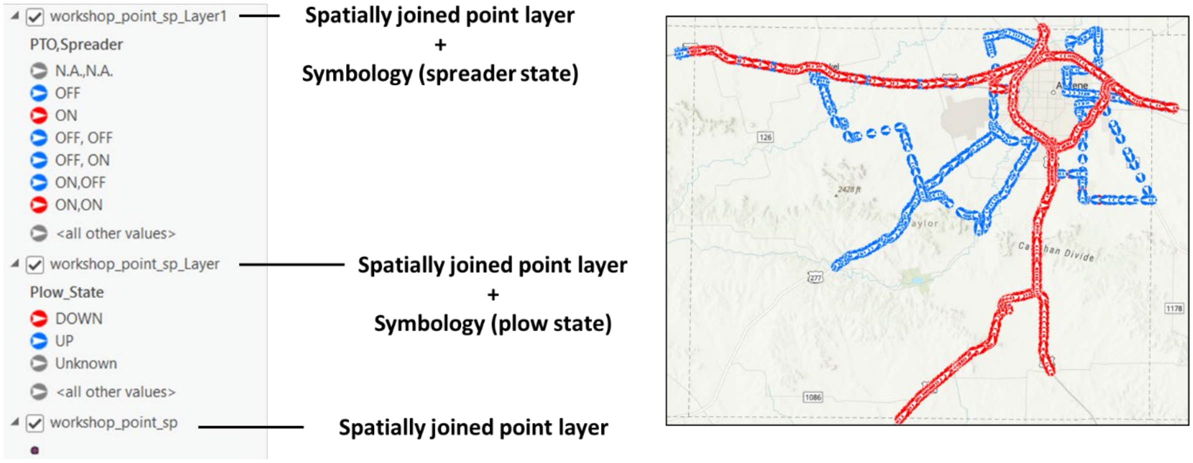


Figure 5.29: Example output of the Truck Trajectory Spatial Join and the All Symbology Combined tools

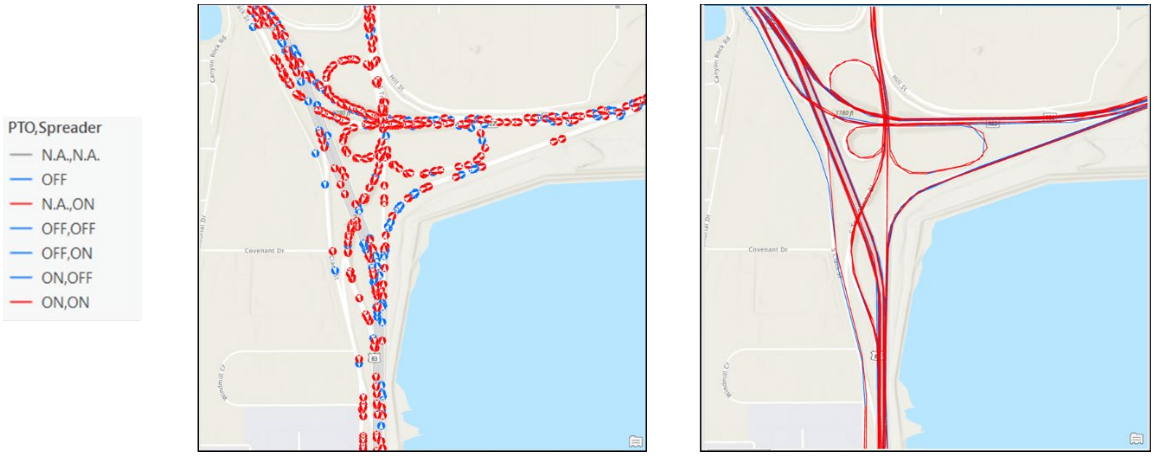


Figure 5.30: Example of overlapping trajectories

5.2.4.4. Reporting

The Reporting toolbox serves as the final step in the workflow, aiming to generate a comprehensive report of summary statistics. This functionality is implemented through a custom Python script specifically tailored for this project, ensuring accurate and relevant information. Figure 5.31 illustrates the user interface of the reporting tool, offering a user-friendly experience.

To generate the report, the tool requires the spatially joined line feature class obtained from the previous “Truck Trajectory Spatial Join and All Symbology Combined” toolbox as the input. This feature class contains the integrated information of truck trajectories, operation status, road name and tier level, and facility location. In addition to the input feature class, the user needs to specify the output path location, providing a directory where the generated report will be saved. Furthermore, the user is prompted to provide a file name for the report. This allows for organization and retrieval of the generated reports. To further refine the report, the user is required to select the district of interest from a drop-down menu. In the provided example (Figure 5.31), the district chosen is Abilene. This selection allows the report to focus specifically on the designated district, providing district-specific insights and summary statistics.

The final summary report provides comprehensive information and visualizations to facilitate analysis and decision-making in winter weather maintenance. The report is divided into three sections, each offering valuable insights into different aspects of the data, as shown in Figure 5.32.

Section 1 of the report includes essential information about the duration covered by the report, the district being analyzed, and key distance metrics. These metrics consist of:

- The duration of activity covered by the report: start time and end time.
- The district covered by the report.
- The total distance traveled across all districts during the selected period.
- The total distance traveled specifically within the district.

- A bar chart is included to visually showcase the total travel miles versus the district travel miles.
- A pie chart illustrates the distribution of district miles traveled across the four tier levels, enabling an understanding of how treatments are distributed within the district.

Section 2 focuses on individual vehicles within the selected district. It provides:

- A table indicating the miles traveled per vehicle and the proportion of total miles traversed by each vehicle. This information allows for an assessment of the contribution of each vehicle to the overall distance traveled.
- A bar chart presenting the miles traveled by each vehicle, categorized by the four tier levels, providing insights into the distribution of activities across different vehicles and treatment types.

Section 3 delves into more detailed analysis of the treatment activities and speed distributions. It includes:

- A bar chart that displays the percentage of total miles traveled within the district for various treatment states, including when the plow is down, spreader is on, and sprayer is on. This visual representation offers a quick overview of the prevalence of each treatment state during the selected period.
- A boxplot representing the speed distribution under different treatment conditions. The plots depict the overall speed distribution, as well as distributions specific to when the plow is down, spreader is on, sprayer is on, and when no treatment is being applied. This allows for a comparison of speed profiles under varying treatment scenarios.
- Three boxes are provided, each reflecting statistics for when the plow is down, spreader is on, and sprayer is on. Within each box, the first line displays the total miles traveled in the specific treatment state across all roads within the district. Adjacent to this value is the corresponding percentage, representing the proportion of those miles compared to the overall distance traveled in all treatment states within the district. The subsequent four lines of each box represent the total miles traveled in the specific treatment state (e.g., plow down) on each tier level. Next to each distance value is the percentage, indicating the proportion of that distance compared to the total distance covered in the respective treatment state (as mentioned in line 1). Importantly, the sum of the percentages presented in the last four lines should always amount to 100 percent, ensuring a comprehensive representation of the distribution of miles traveled within each treatment state across the tier levels.
- A three-dimensional plot showcasing the trajectories of all selected trucks within the given district over the specified time period. The plot provides a comprehensive visualization by incorporating the location and time dimensions simultaneously. In this plot, the trajectories of the trucks are color-coded to represent different treatment types, enhancing the

understanding of the activities performed by each truck. The color scheme employed is as follows: red is used to depict instances when the plow is down, blue signifies when the spreader is on, green indicates the sprayer is on, and grey represents situations where no treatment is being applied. By incorporating both the spatial and temporal dimensions, this plot enhances the comprehension of the data, enabling stakeholders to make informed decisions based on a comprehensive understanding of truck movements and treatment activities throughout the selected period.

- A horizontal bar chart illustrates the different activities of each truck during the selected period. The chart utilizes the same color scheme as the three-dimensional plot to represent treatment types, while black indicates the time spent by the vehicle in a facility. This visualization enables a detailed analysis of individual truck activities over time.

The final report is generated in a user-friendly PNG format, optimized for easy printing and sharing with stakeholders. The report is designed to fit within a single page, ensuring convenient access to all the relevant information. By choosing the PNG format, the report maintains high-quality graphics and visual elements while offering compatibility across different devices and platforms. Also, with its concise and compact layout, the report serves as a comprehensive summary of the analysis, making it an effective communication tool for conveying key findings, insights, and recommendations. It provides a visually appealing and accessible format for stakeholders to review, discuss, and act upon the information presented.

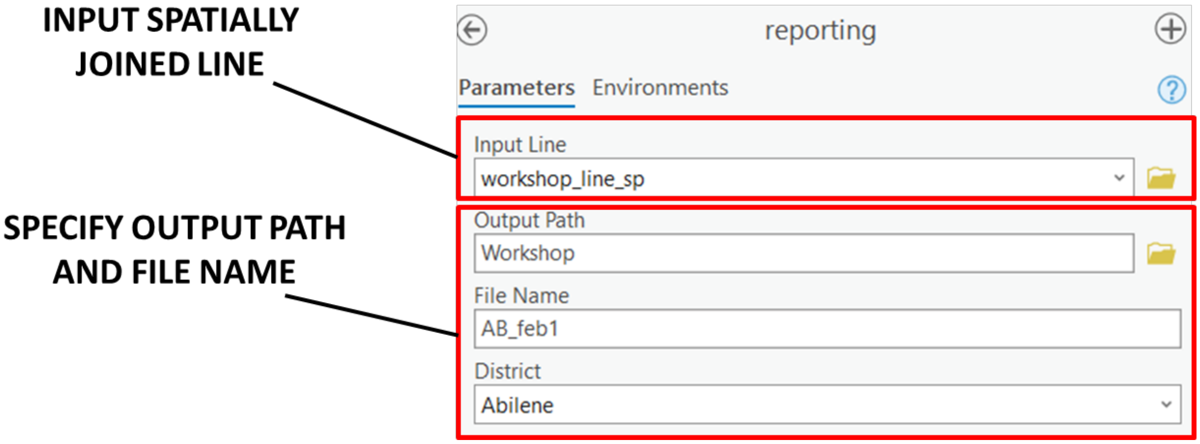
In addition to the concise one-page summary report, the reporting toolbox also generates a comprehensive CSV file containing detailed data that corresponds to the various plots. Having this comprehensive CSV file alongside the summary report ensures transparency and enables stakeholders to explore and validate the findings and conclusions presented in the report. It also allows for customized analyses and tailored visualizations based on specific research questions or areas of interest, enhancing the overall value and utility of the generated data. The CSV file is named the same as the PNG report and is organized into four distinct sheets, providing comprehensive information for further analysis

The first sheet in the dataset, labeled “Raw Data”, encompasses the attribute table that is associated with the spatially joined line output obtained from the “Truck Trajectory Spatial Join” toolbox. This sheet serves as a comprehensive source of information regarding the truck trajectories, providing relevant attributes and additional data for in-depth analysis. For each line segment representing a truck trajectory, the sheet includes the latitude and longitude coordinates of the start (columns latitude and longitude) and end points (columns latitude_2, and longitude_2), along with their respective timestamps (columns dateTime_1 and dateTime_2). The time difference (column time_delta) between the start and end points is also recorded, aiding in the analysis of the duration of each trajectory. Other essential attributes include the speed of the vehicle (column speed for the Geotab estimated speed and column speed_mph for calculated speed), a unique vehicle ID (column ID), the bearing or direction of travel (column bearing), the distance between the start and end points (column distance_mi), the spreader or sprayer state (column Spreader or Sprayer), the plow state (column Plow_State), the PTO state (column PTO) the type of AUX connection (column AUX_2 and AUX_3), the presence or absence of a PTO sensor (column id_DiagnosticAux1Id), the road ID based on TxDOT roadway inventory (column RIA_RTE_ID), the functional class of the road (column F_SYSTEM), the number of lanes (column NUM_LANES), the district name (column District), the tier level (column Tier), the site name of the corresponding TxDOT facility (if the road segment overlaps with one otherwise the cell in the csv file will be blank) (column SITE_NM), and the cardinal direction of the vehicle movement (column cardinal_dir).

The second sheet, titled "Passes Data", focuses specifically on providing information about the traversals made by vehicles on each line segment of the truck trajectories. It includes details such as the district name, the vehicle ID, a unique identifier generated by concatenating the cardinal direction, road segment ID, start and end linear referencing, and the vehicle ID. Additionally, a column labeled "p_section" indicates the percentage of the road segment between the starting and ending linear referencing points that was traversed by the truck, effectively indicating the extent to which the road segment was treated or passed by the vehicle. Figure 5.33 in the dataset visually demonstrates the analysis of the passes data. By filtering the data corresponding to vehicle ID b3F8C (i.e., vehicle 3300K) within the linear referencing range of 259.48 and 260.909, the sum of the elements in the "p_section" column amounts to approximately one, indicating that this specific road segment was passed once. Similar conclusions can be drawn by filtering the data based on vehicle b3ED9 (i.e., 4498H), further reinforcing the analysis of road segment passes.

The third sheet, labeled "Plow Grouping", provides a concise summary of the total distance plowed, categorized by district, vehicle ID, date, and road tier level. By aggregating the data, the sheet presents a comprehensive overview of the cumulative distance covered by plowing operations. The information is organized based on the specific district responsible for the plowing, the unique identifier of each vehicle involved, the date on which the plowing occurred, and the road tier level corresponding to the plowed segment.

Similarly, the fourth sheet titled "Spread Spray Grouping" aggregates the data, presenting a consolidated view of the distances covered based on specific parameters. It provides a comprehensive summary of spreading or spraying distances, categorized by district, vehicle, date, and road tier level. It offers valuable insights into the cumulative distances covered during spreading or spraying operations, allowing for a detailed analysis of these activities, specifically focusing on aggregating distances based on unique combinations of PTO and spreader/sprayer states. By analyzing these combinations, the sheet provides insights into the distribution and utilization of equipment, helping identify variations in spreading or spraying techniques and their impact on the overall distance covered. This level of detail aids in optimizing resource allocation and improving operational practices for more effective road treatment.



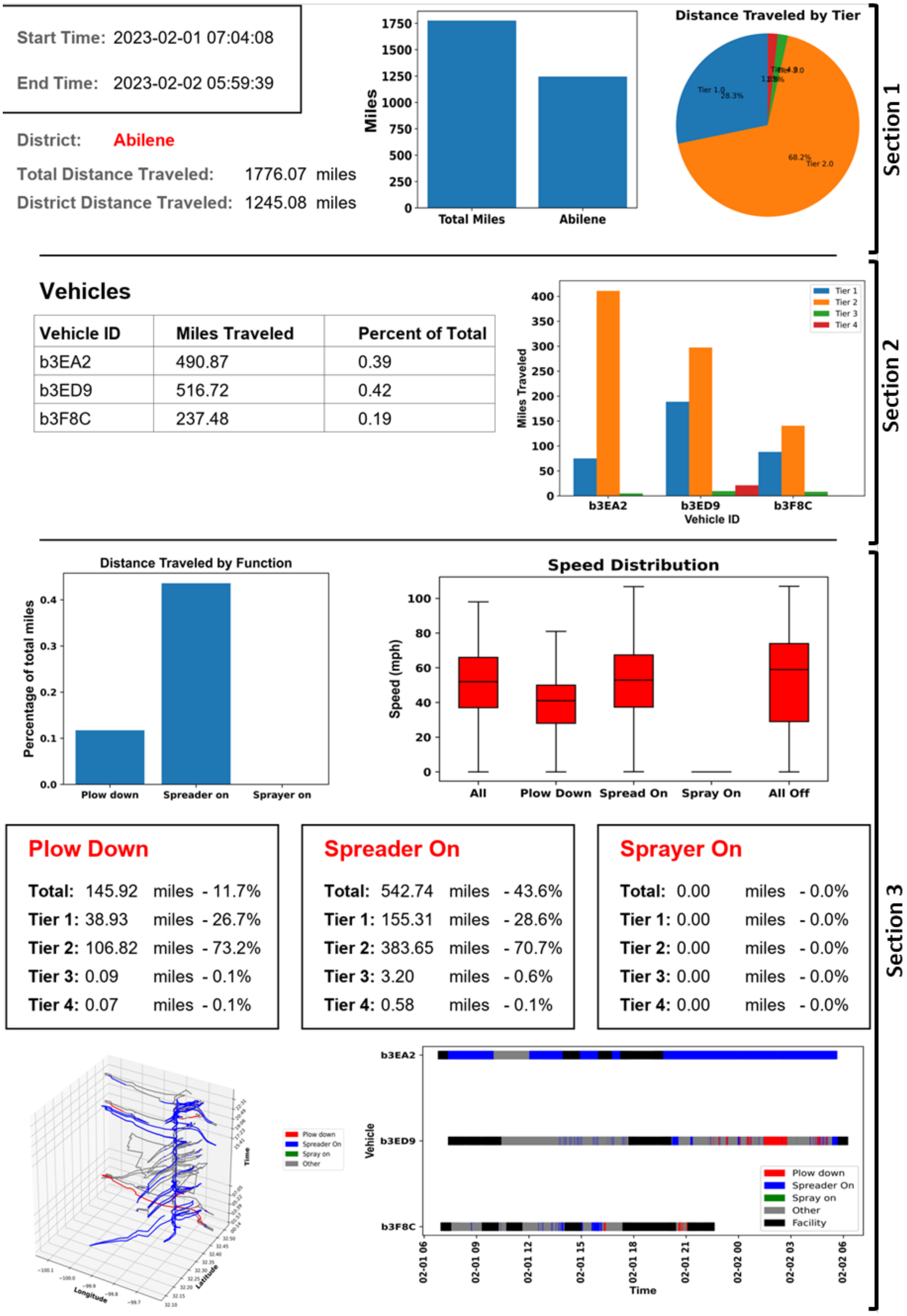
Input Line
workshop_line_sp

Output Path
Workshop

File Name
AB_feb1

District
Abilene

Figure 5.31: Interface of the Reporting tool



Start Time: 2023-02-01 07:04:08

End Time: 2023-02-02 05:59:39

District: Abilene

Total Distance Traveled: 1776.07 miles

District Distance Traveled: 1245.08 miles

Vehicles

Vehicle ID	Miles Traveled	Percent of Total
b3EA2	490.87	0.39
b3ED9	516.72	0.42
b3F8C	237.48	0.19

Plow Down

Total: 145.92 miles - 11.7%
Tier 1: 38.93 miles - 26.7%
Tier 2: 106.82 miles - 73.2%
Tier 3: 0.09 miles - 0.1%
Tier 4: 0.07 miles - 0.1%

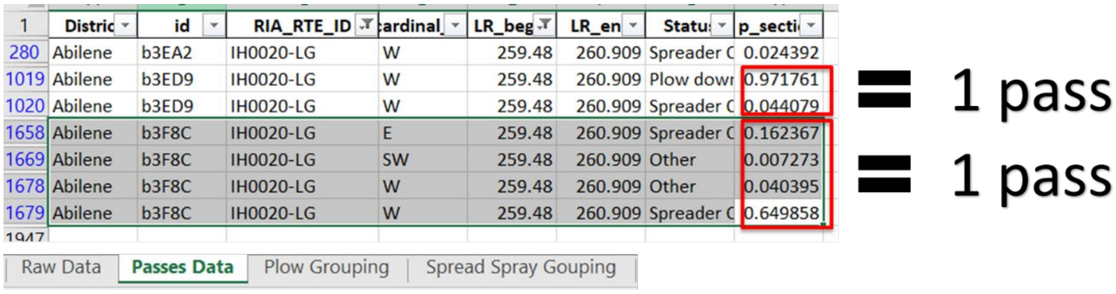
Spreader On

Total: 542.74 miles - 43.6%
Tier 1: 155.31 miles - 28.6%
Tier 2: 383.65 miles - 70.7%
Tier 3: 3.20 miles - 0.6%
Tier 4: 0.58 miles - 0.1%

Sprayer On

Total: 0.00 miles - 0.0%
Tier 1: 0.00 miles - 0.0%
Tier 2: 0.00 miles - 0.0%
Tier 3: 0.00 miles - 0.0%
Tier 4: 0.00 miles - 0.0%

Figure 5.32: Final Report format



1	Distric	id	RIA_RTE_ID	:ardinal_	LR_beg	LR_en	Statu:	p_secti
280	Abilene	b3EA2	IH0020-LG	W	259.48	260.909	Spreader C	0.024392
1019	Abilene	b3ED9	IH0020-LG	W	259.48	260.909	Plow dowr	0.971761
1020	Abilene	b3ED9	IH0020-LG	W	259.48	260.909	Spreader C	0.044079
1658	Abilene	b3F8C	IH0020-LG	E	259.48	260.909	Spreader C	0.162367
1669	Abilene	b3F8C	IH0020-LG	SW	259.48	260.909	Other	0.007273
1678	Abilene	b3F8C	IH0020-LG	W	259.48	260.909	Other	0.040395
1679	Abilene	b3F8C	IH0020-LG	W	259.48	260.909	Spreader C	0.649858
1947								

Figure 5.33: Passes Data Sheet in the output CSV file

5.2.5. Next Steps: GIS Dashboarding

The GIS application can be extended in several directions. From a metrics perspective, expanding the GIS application can involve incorporating data on spreading rates. By including this information, the application can assess the quantity of material used for winter maintenance operations and determine if overspreading has occurred. This allows for better control and management of resources, optimizing material usage and reducing waste. Moreover, connecting these spreading rates with cost calculation tools enables accurate estimation of the expenses associated with winter maintenance operations. This data can be leveraged to improve future planning, budgeting, and cost optimization strategies.

Additionally, correlating treatment applications with weather data presents another valuable direction for extending the GIS application. By integrating real-time or historical weather data, the application can analyze the relationship between treatment applications and weather conditions. This correlation allows for the prediction of when roads will require service or reservice in the future. For instance, if the application determines that a combination of snowfall and temperature below freezing is expected, it can recommend a specific type and quantity of deicing material to be applied. Also, after applying the material, based on traffic and weather conditions the application can predict when material needs to be reapplied. Such predictive capabilities enhance proactive maintenance planning, ensuring timely treatment and reducing the risk of adverse road conditions.

Integration of routing optimization algorithms into the GIS application can significantly enhance winter maintenance operations. These algorithms can optimize treatment trajectories by considering factors such as road conditions, weather forecasts, and the location of facilities. By minimizing travel distances and optimizing routes, fuel costs can be reduced, and trips to the facility can be streamlined. This integration improves resource allocation, enhances operational efficiency, and reduces the environmental impact of winter maintenance activities.

Most importantly, to facilitate seamless data sharing and collaboration, it is essential to integrate the GIS application with an online real-time dashboard that can also be connected to the TxERA system. This integration allows for the exchange of data between ArcGIS and TxERA, enabling stakeholders to access real-time information, monitor winter weather operations, and make informed decisions. The online dashboard provides a centralized platform for visualizing and analyzing data, enhancing coordination, and promoting effective collaboration among teams involved in winter maintenance operations.

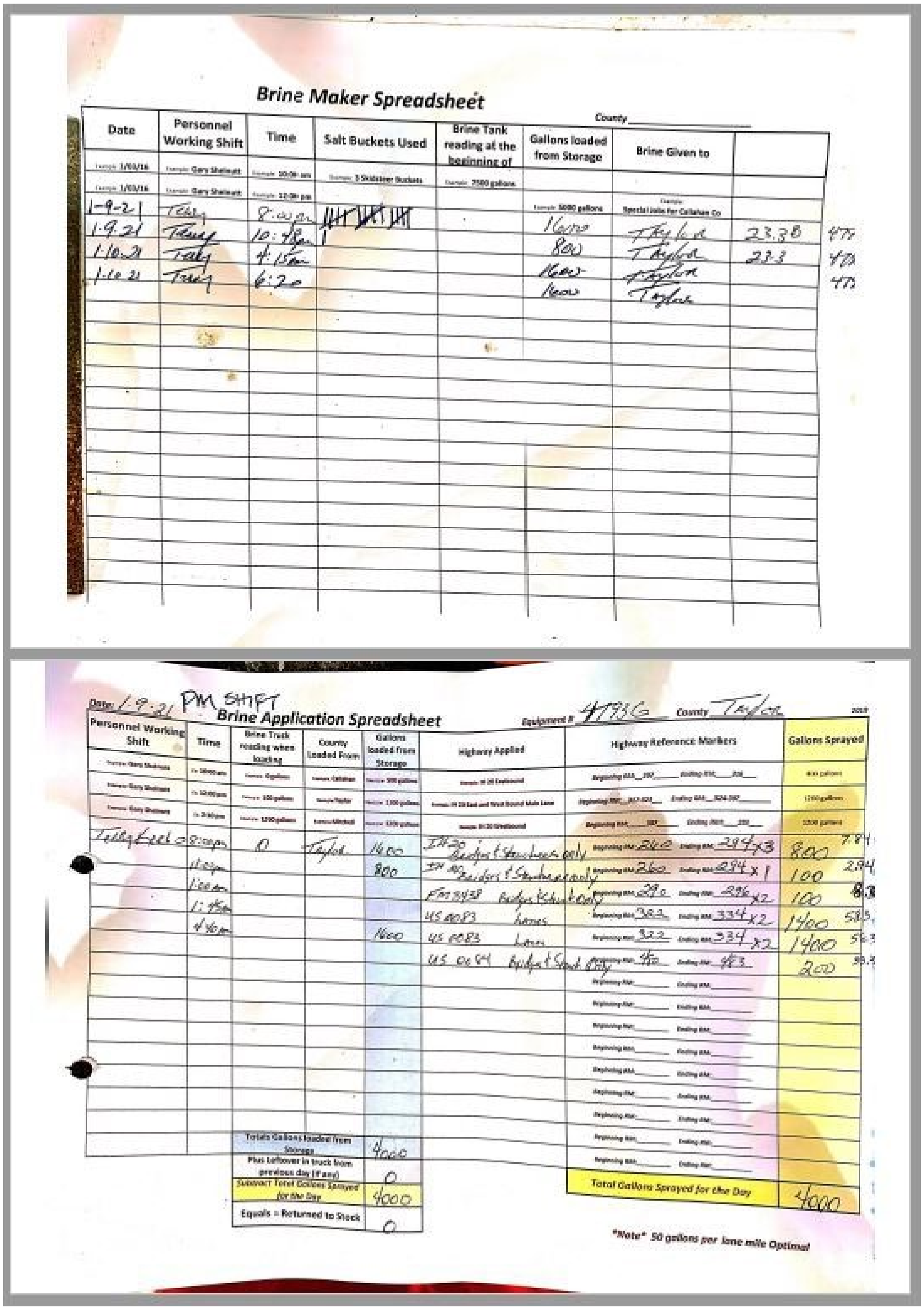
5.3. Future Data Applications: Brine Logs

This section uses current and possible future practices involving brine logs to exemplify future applications and uses for automatically collected WinterOps data. Brine logs in the TxDOT Abilene District are records of brine production and brine deployment during times of winter storm pretreatment and ice removal treatment. Current methods involve manually-written records as shown in Figure 5.34, including:

- **Brine Maker Spreadsheet:** Date, personnel working shift, time, salt buckets used, brine tank reading at the beginning of production, gallons of material loaded from storage, and where the brine is given to
- **Brine Application Spreadsheet:** Personnel working shift, brine truck reading when loading, county facility loaded from, gallons loaded from storage, highway applied, highway reference markers, and gallons sprayed

Vehicle operators are expected to maintain these records shortly around the time of performing winter treatment or pretreatment, but are not to record these while driving. Operators then may need to resort to their own recollection to write records, with possibility of approximating. Sometime after the treatment operation, these records may then be transcribed to an Excel spreadsheet, where calculations and analyses are made on the cost of materials deployed.

For reference, a vehicle telemetry report can appear as shown in Figure 5.35. This example comes from the Verizon Connect system that TxDOT utilized fleet-wide prior to Fall/Winter 2022, showing time, geocoded location, battery voltage, GPS coordinates (latitudes and longitudes), speed, and heading. Entries appear in the report as the vehicle traverses distinct places or other changes in vehicle status occur such as stopping.



Brine Maker Spreadsheet

County ____________

Date	Personnel Working Shift	Time	Salt Buckets Used	Brine Tank reading at the beginning of	Gallons loaded from Storage	Brine Given to		
Example: 1/03/16	Example: Gary Shelnutt	Example: 10:30 am	Example: 3 Skidsteer Buckets	Example: 7500 gallons				
Example: 1/03/16	Example: Gary Shelnutt	Example: 12:30 pm			Example: 5000 gallons	Example: Special Jobs for Callahan Co		
1-9-21	Terry	8:00 am	卌 卌 卌		1600	Taylor	23.38	47
1.9.21	Terry	10:48 pm	1		800	Taylor	23.3	47
1.10.21	Terry	4:15 am			1600	Taylor		47
1.10.21	Terry	6:20			1600	Taylor		

Date: 1.9.21 PM SHIFT

Brine Application Spreadsheet

Equipment # 4793G County Taylor 2017

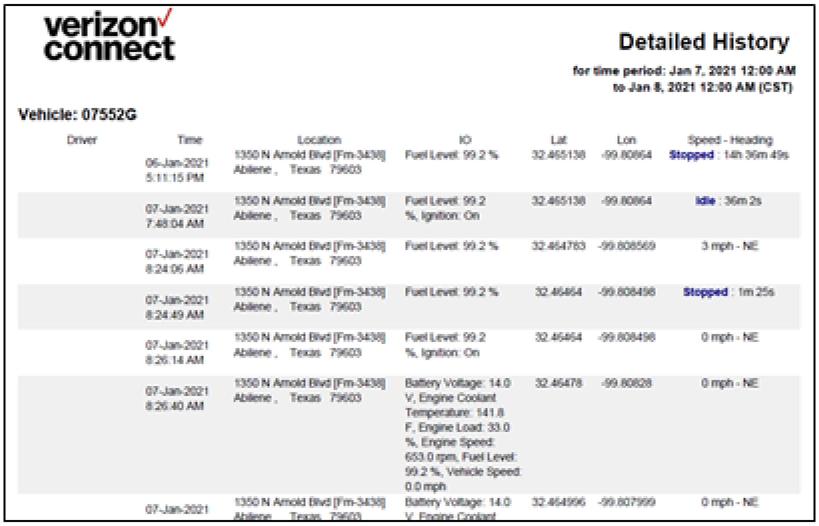
Personnel Working Shift	Time	Brine Truck reading when loading	County Loaded From	Gallons loaded from Storage	Highway Applied	Highway Reference Markers	Gallons Sprayed	
Example: Gary Shelnutt	Ex: 10:00 am	Example: 0 gallons	Example: Callahan	Example: 300 gallons	Example: IH 20 Eastbound	Beginning RM: 297 Ending RM: [illegible]	400 gallons	
Example: Gary Shelnutt	Ex: 12:00 pm	Example: 100 gallons	Example: Taylor	Example: 1300 gallons	Example: IH 20 East and West Bound Main Lane	Beginning RM: 317-323 Ending RM: 324-[illegible]	1200 gallons	
Example: Gary Shelnutt	Ex: 2:00 pm	Example: 1200 gallons	Example: Mitchell	Example: 1200 gallons	Example: IH 20 Westbound	Beginning RM: [illegible] Ending RM: [illegible]	1200 gallons	
Terry Keel	8:00 pm	0	Taylor	1600	IH 20 Bridges & Structures only	Beginning RM: 260 Ending RM: 294 x3	800	7.84
	11:00 pm			800	IH 20 Bridges & Structures only	Beginning RM: 260 Ending RM: 294 x 1	100	2.94
	1:00 am				FM 3438 Bridges & Structures only	Beginning RM: 290 Ending RM: 296 x2	100	8.3
	1:45 am				US 0083 Lanes	Beginning RM: 322 Ending RM: 334 x2	1400	58.5
	4:40 am			1600	US 0083 Lanes	Beginning RM: 322 Ending RM: 334 x2	1400	56.3
					US 0084 Bridges & Struct only	Beginning RM: 450 Ending RM: 453	200	39.5
						Beginning RM: Ending RM:		
						Beginning RM: Ending RM:		
						Beginning RM: Ending RM:		
						Beginning RM: Ending RM:		
						Beginning RM: Ending RM:		
						Beginning RM: Ending RM:		
						Beginning RM: Ending RM:		
						Beginning RM: Ending RM:		
						Beginning RM: Ending RM:		

Totals Gallons loaded from Storage	4000
Plus Leftover in truck from previous day (if any)	0
Subtract Total Gallons Sprayed for the Day	4000
Equals = Returned to Stock	0

Total Gallons Sprayed for the Day	4000

Note 50 gallons per lane mile Optimal

Figure 5.34: Current hand-written brine logs



verizon connect

Detailed History

for time period: Jan 7, 2021 12:00 AM
to Jan 8, 2021 12:00 AM (CST)

Vehicle: 07552G

Driver	Time	Location	IO	Lat	Lon	Speed - Heading
	06-Jan-2021 5:11:15 PM	1350 N Arnold Blvd [Fm-3438] Abilene , Texas 79603	Fuel Level: 99.2 %	32.465138	-99.80864	Stopped : 14h 36m 49s
	07-Jan-2021 7:48:04 AM	1350 N Arnold Blvd [Fm-3438] Abilene , Texas 79603	Fuel Level: 99.2 %, Ignition: On	32.465138	-99.80864	Idle : 36m 2s
	07-Jan-2021 8:24:06 AM	1350 N Arnold Blvd [Fm-3438] Abilene , Texas 79603	Fuel Level: 99.2 %	32.464783	-99.808569	3 mph - NE
	07-Jan-2021 8:24:49 AM	1350 N Arnold Blvd [Fm-3438] Abilene , Texas 79603	Fuel Level: 99.2 %	32.46464	-99.808498	Stopped : 1m 25s
	07-Jan-2021 8:26:14 AM	1350 N Arnold Blvd [Fm-3438] Abilene , Texas 79603	Fuel Level: 99.2 %, Ignition: On	32.46464	-99.808498	0 mph - NE
	07-Jan-2021 8:26:40 AM	1350 N Arnold Blvd [Fm-3438] Abilene , Texas 79603	Battery Voltage: 14.0 V, Engine Coolant Temperature: 141.8 F, Engine Load: 33.0 %, Engine Speed: 653.0 rpm, Fuel Level: 99.2 %, Vehicle Speed: 0.0 mph	32.46478	-99.80828	0 mph - NE
	07-Jan-2021	1350 N Arnold Blvd [Fm-3438] Abilene , Texas 79603	Battery Voltage: 14.0 V, Engine Coolant	32.464996	-99.807999	0 mph - NE

Figure 5.35: Verizon Connect vehicle telemetry report

The data contained within such logs and reports can be utilized together for advanced purposes such as the following examples:

1. **Analyze the impact of the treatment activity on the level of service of the section (for example, changes in speed or flow)**: This can be done by analyzing the speed data (obtained from NPMRDS or INRIX) prior to the treatment, during the treatment and after the treatment of the segment. Additionally, comparing similar segments (in terms of link-types and usage) with one set of segments consisting of the treated segments and the other set of treatments that are untreated, can be useful in estimating the effectiveness of the treatment activity. Over a period of time, this analysis exercise would add on to the knowledge-base of the maintenance department, providing greater information and intuition about the type of treatment (and amount of brine usage) necessary for different types of winter storms, and can act as a maintenance decision support system.

2. **Create effective visualization of the treatment activity for a better understanding of current and historical activities**: Visualizations are often the best and the most effective way to understand available information. If available in a convenient form, the treatment activity logs can be used to make useful visualization during a period of severe winter weather. If automated in real-time, this could aid decision makers with visual information about links or roadway segments where treatment activities have recently taken place or currently underway. This could also aid in quicker planning and decision-making, especially when used in conjunction with real-time speed data. In addition, visualizing historical treatment activities (in terms of location and quantity of treatment material used) could provide a powerful tool for quick understanding of past decisions and actions.

5.3.1. Manual Analysis Process

If one were to perform a full, computer-assisted analysis of the handwritten brine sheets, the current process would include a substantial amount of manual intervention. As a one-time exercise, researchers performed the following activities. The manual steps were found to be time-consuming and tedious:

- **Digitalize brine sheets for analysis and visualization:** The brine sheets are presently available as hand-written forms shown in Figure 5.34. The entries are then required to be translated to a machine-readable format for any possible analysis. This may be done by manually entering the brine-sheet contents in a spreadsheet for performing any analysis.
- **Plot the activity locations for visualization:** Manually plotting the link locations from handwritten logs on a GIS map as shown in Figure 5.36 is especially time-consuming. This can be done using ArcGIS in the following way:
    - Load the TxDOT Roadway Inventory geodatabase onto a new ArcGIS project. The file to be loaded is named "TxDOT_Roadway_Linework_wAssets" which is a Geodatabase Feature Class file.
    - To identify the links treated, the highway name and the reference markers are required. This is done by the "Select Layer by Attributes" option in ArcGIS and entering the expression for the highway name and the reference marker points.
    - Once the list of expressions for reference marker queries are loaded, run the feature and the line segments treated will be highlighted (shown in cyan in Figure 5.36).
- **Fleet location data cross-verification:** The link locations can be cross-verified using the fleet tracking (e.g. Verizon Connect or Geotab) reporting functionality to produce a report as in Figure 5.35. However, in Verizon Connect, this is only available in PDF format which needs to be converted to tables for any analysis purpose. This can be done using Tabula or any other open-source online portals but requires care to ensure proper outcomes. Currently, the Verizon data tracks the location of the maintenance truck continuously at small intervals of time, therefore, the data contains point coordinates (latitudes and longitudes) of the vehicle on the automated log sheet. This can be plotted on any GIS platform by using the converted table (e.g., as a CSV file) as an input (Figure 5.37).
- **Associate brine usage/treatment action with the links:** To undertake any form of analysis or visualization, we must find a way to associate the brine usage to the links treated. On vehicles that lack WinterOps sensing, this process needs to be incorporated manually due to the lack of automated association of treatment activity in the CSV data.
- **Analyze speed data (example, mean speed recovery time):** As a measure of treatment effectiveness, the speed data of the treated links can be tracked (from NPMRDS or INRIX database) during and after the treatment activity (See Figure 5.38 as an example). Over a period of time, the speed recovery pattern can help optimize the amount of brine solution to be used as more and more data is added to the knowledge base.

Figure 5.36: Plot of maintenance activity recorded in a log sheet

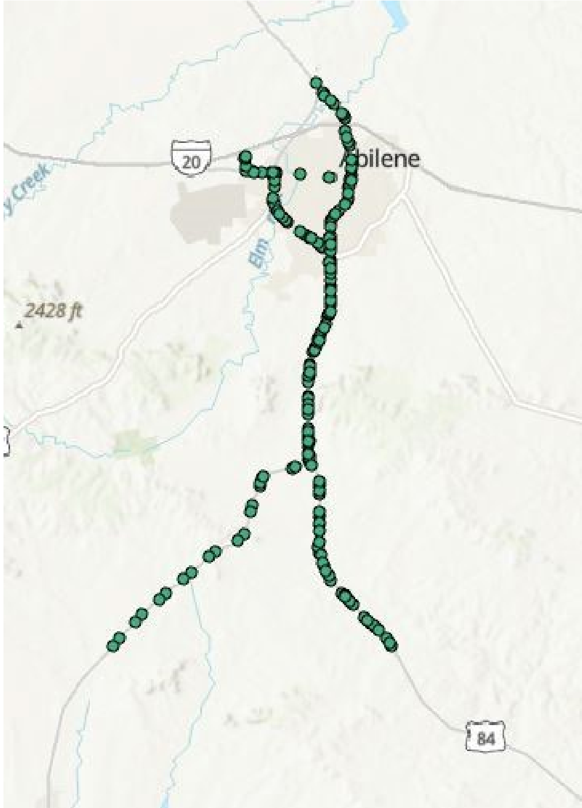


Figure 5.37: Plot of automated Verizon Connect vehicle

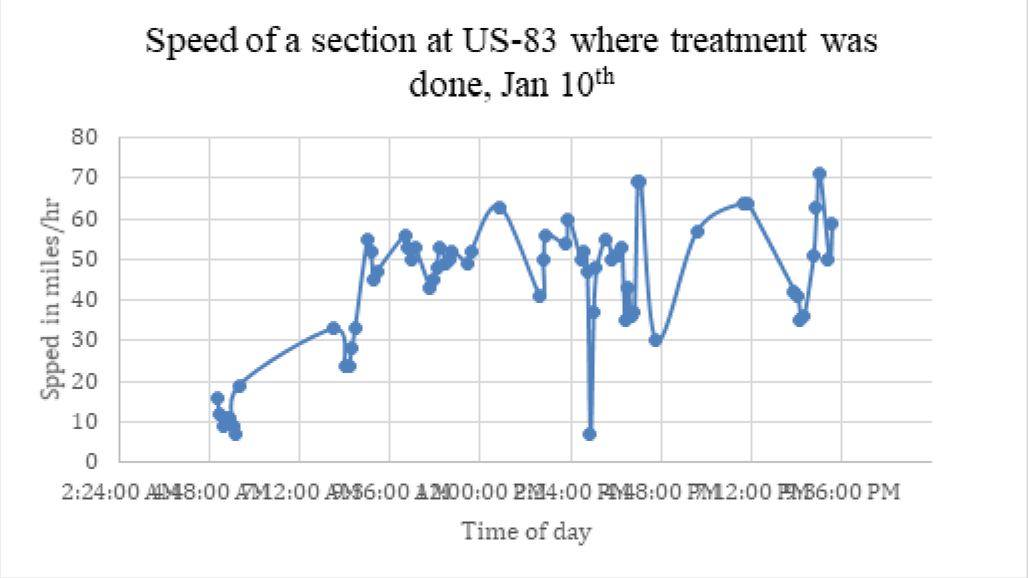


Figure 5.38: Example of speed recovery profile post-treatment

A number of disadvantages are apparent when no automated winter roadway treatment activity sensing is present:

- **Possibility of manual errors:** Since the brine logs are handwritten, there is always a possibility for manual errors. This may include incorrect or imprecise information about the time, location (segment and road mark-up points) or brine application quantities. Also, for post-analysis, handwritten logs must be manually read and transcribed to a machine-readable document. Some cases of poor legibility had been found in the handwritten logs. In most other cases, transcription become substantially tedious and time-consuming.
- **Lack of locational precision:** The handwritten notes contain information of only the starting and ending reference markers and the approximate brine solution spread throughout the segment without disaggregate information about the amount spread specific to a location. This may not be useful for effective post-analysis.
- **Loss of information due to aggregation:** The brine solution used information is available in aggregate quantities. Similar to the lack of locational precision, the lack of availability of brine solution usage at a disaggregate level causes hindrance in effective analysis of treatment data.
- **Excessive time consumption in data processing:** The transcription of the data from the handwritten form to machine readable format is substantially time-consuming. Moreover, as mentioned earlier, plotting the roadway segments on a GIS platform is also tedious and takes a significant amount of time.

5.3.2. Semi-Automation and Analysis

It is anticipated that the automatic collection of roadway treatment activity data makes analysis much more accessible and useful. This could potentially eliminate the need to manually transcribe hand-written logs to aid in post-analysis of the data collected. The advantages of these automated maintenance logs are:

- No possibility of manual errors since data is automatically recorded.
- Precise location information as the vehicle trajectory is automatically recorded along with the time-stamp instead of only start and end reference markers (as is done in handwritten logs).
- Disaggregated maintenance information is now recorded as each point in the vehicle location trajectory can be associated with the treatment status.
- Very convenient to plot on a GIS platform since each location point is timestamp as well as the amount sprayed attributes, thus aiding effective and efficient analysis.
- Historic data can be automatically and easily archived.

This brings several opportunities for distinct improvements in roadway weather operations. For example:

- Historic logging of treatment activity: "Breadcrumbs" visualization of vehicle trajectories.
- With weather precipitation data, discern when de-icing agent needs to be re-applied to the roadway.
  - "Breadcrumbs" that fade away after a few days (Figure 5.39).
  - Replenishment optimization based on aggregation of such analysis over time.
- Helpful for reviewing selective treatments, such as bridges. This allows for better tracking through visualization of treatment intensity in such critical segments.

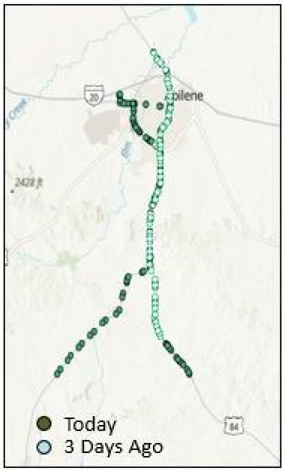


Figure 5.39: Time-enhanced "breadcrumbs" example

Chapter 6. Sensor Technologies and Data

During the course of the project, researchers deployed and utilized data from various sensor products and third-party services. Experiences with technologies allowed for an understanding of sensor/data reliability, and potential value for future efforts in improving winter weather response strategies.

6.1. Sensor and Data Retrospectives

This subsection summarizes sensor and data-related project efforts from the perspective of systems reliability and functionality. Specific sensors and data sources are explored first, followed by a summary of the live data fusion efforts that researchers undertook within the recent project tasks.

6.1.1. Sadeem WSS Surface Temperature

Figure 6.1 shows the solar-powered Sadeem WSS installed in the Abilene District Headquarters maintenance yard. The sensor contains a passive infrared array that can be used to measure the surface temperature of the pavement below it. It also contains an ultrasonic water level sensor. It communicates over the cell phone network. An AT&T Prepaid SIM card and data plan have been maintained for this project. A web page interface had been established on a CTR server for viewing the live data, and further work had been performed in recording the live data to a database hosted on the same system. Because of strengthened IT security policies put into place during the course of the project, the web page interface could not be accessed from outside of UT.

As winter approached, researchers noticed that the sensor lost cell phone communications for several hours each day. The manufacturer analyzed the situation and suggested to realign the solar panel to catch more exposure to the winter position of the sun. This largely resolved the problem. Other, smaller sporadic outages were still observed that could be attributed to the cell phone carrier and the sensor's location at the edge of the Abilene urban area.

Another challenge researchers encountered was in keeping the live data service that records data to the database up and running reliably. For unknown reasons, the Python-based process that uses a library for supporting the sensor's MQTT data protocol stalled after several days of running. Researchers had to restart the process in order to resume the recording of data. A viable mitigation is to implement a "keepalive" mechanism that automatically restarts the process when it is detected to stall for a specific amount of time. Another solution is to preemptively restart the process nightly. Regardless of the method used to keep the data flowing, the main lesson is that redundancy, or the co-location of sensors that provide similar functions, is the most sustainable way to ensure the availability of data.

Finally, the process of converting sensor-specific numeric readings to temperature measurements used a complex, proprietary methodology that took time to receive from the manufacturer. Both the passive infrared array and the onboard ambient temperature sensor produce numbers that do not apparently correspond with temperature readings linearly. The complex model that converts these numbers to temperature readings is interdependent upon ambient temperature and system voltage. The web-based interface for viewing live data had been converted to show degrees Fahrenheit, and the contents of the database had been converted retroactively.

The device once again ceased working, this time at the start of 2023. This time, the manufacturer stopped their back-end support of the unit, and did not end up restarting the plan. While in principle the passive infrared sensing concept was compelling, the incident was a sign that long-term guarantees on back-end support should be established with a manufacturer prior to purchasing.

Figure 6.1: Sadeem WSS in the Abilene District maintenance yard

6.1.2. RX3000 Weather Stations

Figure 6.2 shows one of five weather stations that are installed in TxDOT facilities within the Abilene District. A split sign pole was utilized to achieve this installation, supporting the anemometer, wind vane, and tipping bucket at the highest points, with solar panel, solar sensor, and temperature sensors also mounted.

These weather stations are supported by the HOBOLink cloud service, and annual payments to renew data plans support both the cell phone carrier and the service. The products do not offer the ability to connect through other means, making them possibly less attractive than a more open product. However, the reliability of connections and the user-friendly features offered by the cloud service had made the weather stations an attractive choice for evaluating the capabilities of new sensing technologies and products within the context of this project.

Despite the features they bring, the station installed in Snyder had troubles enumerating all of its connected sensors for several weeks, and also proceeded to not connect at all. A couple of calls to the tech support resulted in a reset signal being sent to the unit to resolve the issue. The advice given was that whenever power is to be disconnected from the unit, or when peripherals are to be added or removed, the unit should be placed into pause mode through the front panel before disconnecting power; otherwise, the state of connections can be out of sync.

Another problem arose when researchers attempted to retrieve historic data. Problems were encountered in authenticating for programmatic downloads, and the tech support personnel also reported that the web-based interface for the HOBOLink cloud service was temporarily imposing difficulties on downloads of several days' worth of data across multiple units. Researchers persisted by reducing the size of each requested download. The programmatic live data retrieval functionality was shortly restored thereafter.

Into 2023, the manufacturer cautioned that cell phone carriers are phasing out 3G service in lieu of 4G. The RX3000 units originally deployed in the Abilene District were 3G units, and the only way of upgrading to 4G was to replace the base units. The project funded the replacement of three of these units while reusing the weather sensing peripherals.

Figure 6.2: RX3000 weather station installed at a TxDOT facility in the Abilene area

6.1.3. IceSight Surface Condition

Two different types of IceSight sensors were attempted to be used for the project—two Mobile IceSight sensors (one of which is shown in Figure 6.3, mounted to the front of a pickup truck in

Abilene District), and the fixed IceSight (shown in Figure 6.4, protruding above the "IH-35 SVC-RD" street sign on a TxDOT traffic signal mast arm at the edge of the 11th St. Bridge over IH-35 in downtown Austin). The Mobile IceSight devices were complemented with a "Mobile Processing Unit" that performed GPS tracking and reporting to a cloud-based web UI. This service and data plan required an annual subscription fee. The Mobile IceSight also had a built-in WiFi server that hosted a webpage reporting live status, and researchers were able to identify a web-based stream of data that could be leveraged in other applications. With some custom work, it would be possible to show status on a smartphone in the vehicle or to log the data with no subscription service.

Prior to Winter 2019, both of the Mobile IceSight sensors were recalled by the manufacturer for a water leak issue; the sensors were to receive complementary fixes. The manufacturer did not return the units until well into 2020 after the winter season ended. Since then, one of the units was installed on an Abilene District pickup truck, and the other was lent to the HERO vehicle operations in Austin for mounting to a vehicle. Unfortunately, the unit in Abilene produced zeros during the Winter 2020-2021 season, showing malfunctioning behavior. While the manufacturer has offered to provide technical support over the phone, researchers took the unit back to UT in order to troubleshoot it. Meanwhile, the other unit destined for the HERO vehicle was never installed, partially because the vehicle that it was targeted for suffered a traffic accident. Researchers retrieved the unit late into the Winter 2020–2021 season with the intent of swapping it with the malfunctioning one in Abilene. In the end, no data were produced by either Mobile IceSight device during the 2020-2021 winter season.

Meanwhile, the fixed IceSight in downtown Austin over IH-35 performed much better, steadily producing data and communicating over a cell phone modem to the City of Austin traffic operations network. The first observed outage was between February 15 and February 18, 2021, which was during an extreme, deep-freeze ice storm where power outages were experienced in great magnitude across the state. While better performance may have been possible if the IceSight were powered with solar instead of a hard-wired power feed, any power loss or network disruption experienced in other areas of the data chain would have resulted in a similar data outage. This is because the IceSight does not have its own onboard data caching capabilities, and otherwise relies upon an external data logger.

City of Austin personnel implemented a process within their IT systems to collect the live data stream (temperatures and road surface characterizations produced once every two seconds, reported once every minute), and post those data to the city's open data portal that is hosted by Socrata. As of May 2023, this can be accessed at: https://data.austintexas.gov/dataset/Real-Time-Road-Conditions/ypbq-i42h. City of Austin personnel presented their solution at the project's August 2021 workshop.

Toward the first part of 2022, the IceSight over IH-35 stopped working. City of Austin personnel inquired about the cost for repairing it, but the cost was deemed too expensive. While the city declined this repair, the interest still remains to see from a remote location whether critical infrastructure is freezing, and the search shall continue for economical sensing hardware that will provide a long period of service.

Figure 6.3: Mobile IceSight mounted on the front of an Abilene District pickup truck

Figure 6.4: Fixed IceSight mounted on a signal mast arm adjacent to the 11th St. Bridge over IH-35 in downtown Austin, Texas

6.1.4. ARHIS Surface Condition

In the ongoing interest of finding ways to determine roadway icing in remote locations, toward the end of 2022 the project facilitated the evaluation of a sensing technology offered by Korean company SK Planet— "ARHIS"—that uses audio, ambient temperature, and advanced processing "in the cloud" to characterize road surface freezing condition. As part of the installation process, the system is calibrated to the unique characteristics of its fixed location. While the manufacturer and TxDOT Abilene District personnel sought to rush the installation by the start of 2023, challenges in cell modem communications, equipment operation, and personnel availability did not allow the system to come online until freezing conditions were finished for the season. However, at the time of this writing, the device was verified to properly characterize a wet roadway surface as seen in Figure 6.5, and researchers look forward to learning more about ARHIS performance next winter.

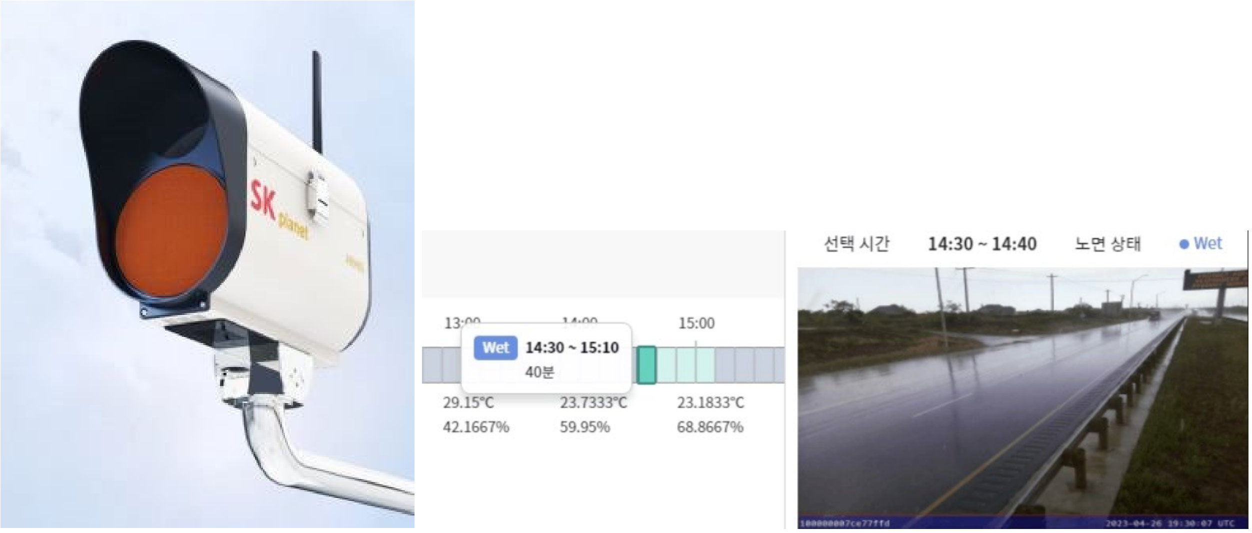


Figure 6.5: ARHIS audio-based road surface sensor and diagnostic "wet" reading on US 83/84

6.1.5. Data Fusion

An experiment of combining together speed data and processed temperature measurements is shown in Figure 6.6. This example was rendered in ArcGIS Pro using data files that were produced by Python-based solutions that retrieved live data. These and later efforts produced codes that allow for retrieval of live data from:

- TxDOT Lonestar C2C feed (INRIX speeds) with database storage
- The 5 HOBOLink weather stations with database storage
- ~4 good weather stations including West Texas Mesonet and TCEQ (Texas Commission on Environmental Quality) via Synoptic Data (a commercial online data source for a variety of weather stations) with database storage
- Sadeem WSS with database storage
- National Weather Service

The Python implementations that provide the live data was run on research systems at CTR. With security review, migration of these implementations could be helpful in allowing TxDOT to achieve the same functionality internally. For example, these can run to feed data to the Geoevents server that provides data to ArcGIS Enterprise applications such as TxERA.

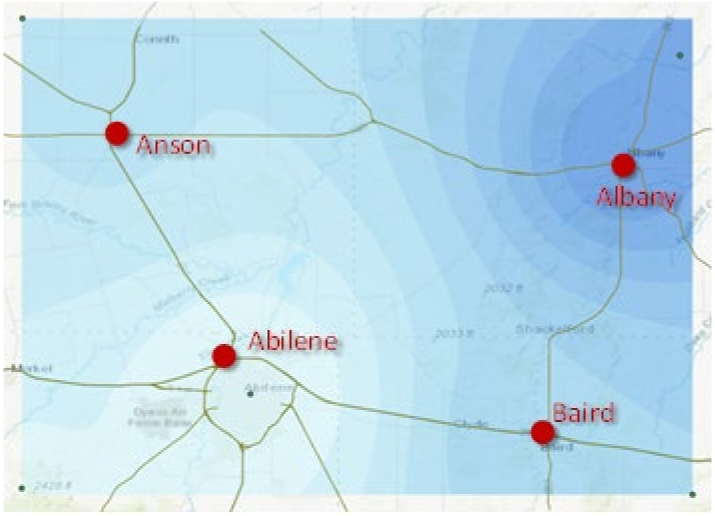


Figure 6.6: Data fusion combining roadway speeds with interpolated temperatures

6.2. Insights

A selection of analysis examples is provided in this subsection to illustrate the data capabilities that are provided by sensor and data sources, and also to highlight key findings that can help in understanding how to best leverage the data sources for operational decisions.

6.2.1. Sadeem Sensor Analysis

To better understand the capabilities of the Sadeem WSS sensor located in the Abilene District Headquarters maintenance yard, Figure 6.7 provides a comparison between the ambient temperature and the surface temperature as measured onboard the sensor. The surface temperature is observed to slightly lead the ambient temperature. This is primarily because the IR sensor is very sensitive to immediate fluctuations, especially because of solar radiance. Better stability can be found during times that direct sunlight is not hitting the road surface, such as when clouds are present or when it is nighttime. This surface temperature measurement can be used to calibrate other critical segments in the network.

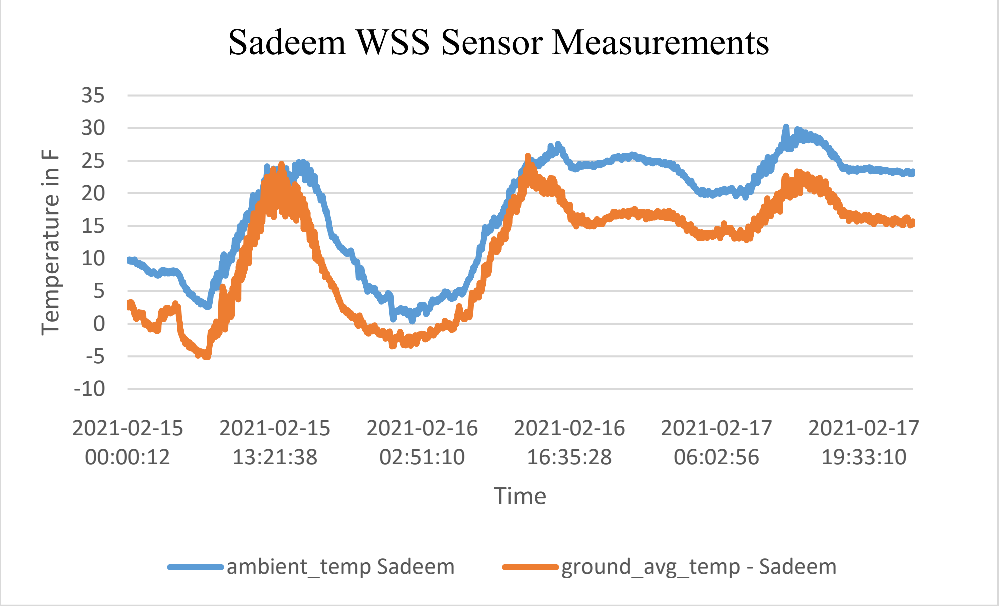


Figure 6.7: Sadeem WSS ambient vs. surface temperature

In looking further at the sensitivity of the passive infrared array to sunlight reflection off of pavement, Figure 6.8 provides a comparative plot between solar radiance and the Sadeem surface temperature. The solar radiance is measured from the nearest RX3000 station (ABL-HQ), which is about 300 feet away from the Sadeem sensor's location. The surface temperature follows the solar radiance pattern during the day.

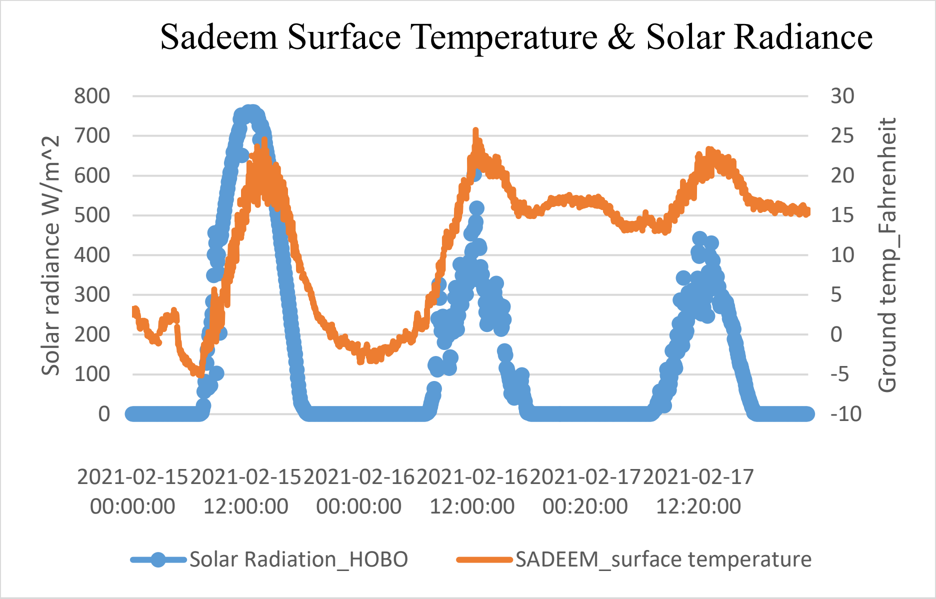


Figure 6.8: Sadeem surface temperature and solar radiance

6.2.2. RX3000 Soil Temperature

Figure 6.9 provides an example comparison between the ambient temperature and the soil temperature as measured by the RX3000 station at TxDOT Abilene District Headquarters. Interestingly, the soil temperature does not seem to be affected much by the ambient temperature, even during the extreme February winter storm. This is likely because of the position of the probe which is 4" below the surface. Since the variation of the soil temperature probe is negligible during this storm's unusually cold temperature, this secondary probe appears to best be buried in a shallower position, or coupled to an item that may be more helpful for observing possible ice formation, such as a concrete pad, bridge structure, or metal pole or guardrail.

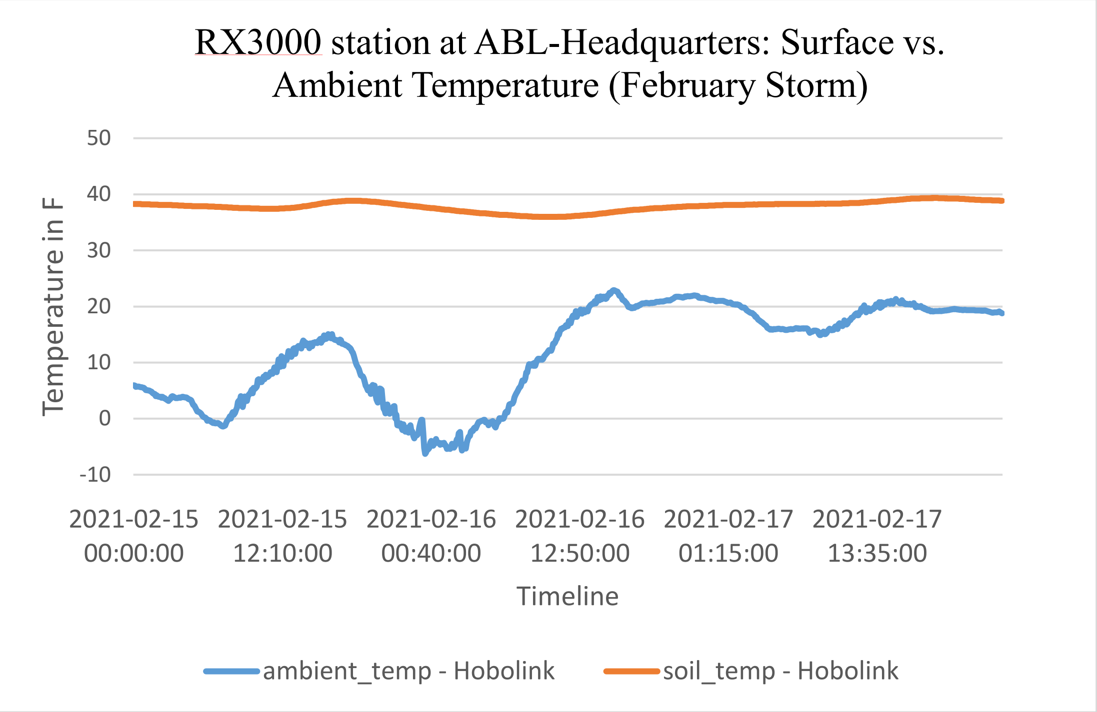


Figure 6.9: RX3000 ambient vs. 4-inch-deep soil temperature

6.2.3. Sadeem vs. RX3000 Comparison

It is important and interesting to compare surface temperature across different sensors/stations to check consistencies and calibration requirements. Figure 6.10 provides an ambient temperature comparison between the Sadeem and the Abilene-HQ RX3000 station (separated by ~300 feet). The Sadeem sensor is found to consistently report a higher temperature compared to the nearest RX3000 station measurements which may be a calibration issue.

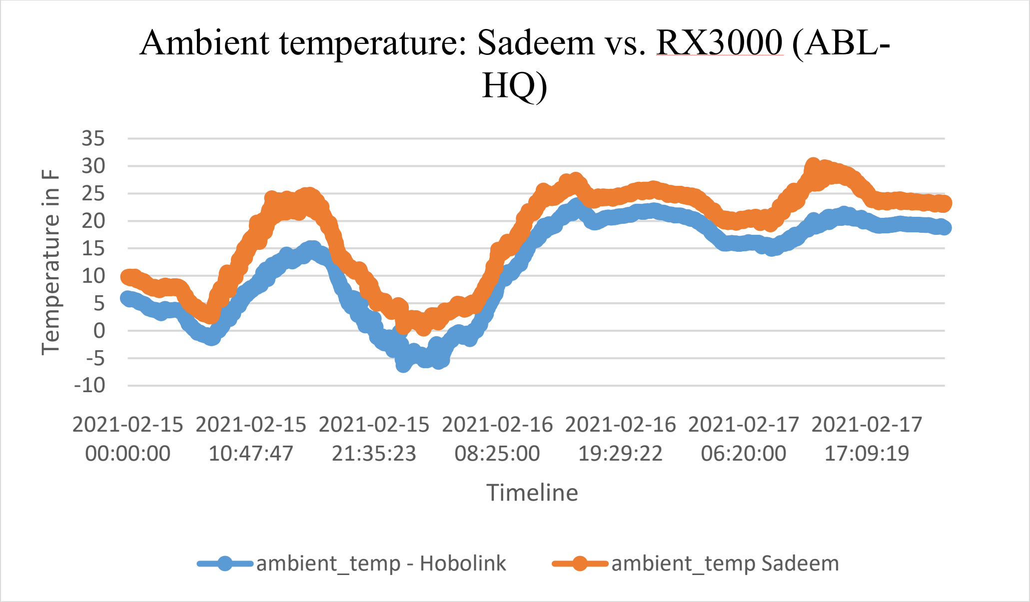


Figure 6.10: Ambient temperature comparison between Sadeem and RX3000 sensors

6.2.4. Austin Fixed IceSight

The fixed IceSight sensor under analysis for this project is located above the 11th Street bridge in downtown Austin. Figure 6.11 provides an example analysis of the January winter storm which included times of snow accumulation. The figure compares the air and surface temperature reported by the device. The surface conditions reported by the device are also plotted. Continuous surface condition and ambient temperature information for a fixed point can be used to calibrate the surface conditions at other places during future storms. Surface condition information can also be used for ice-formation prediction.

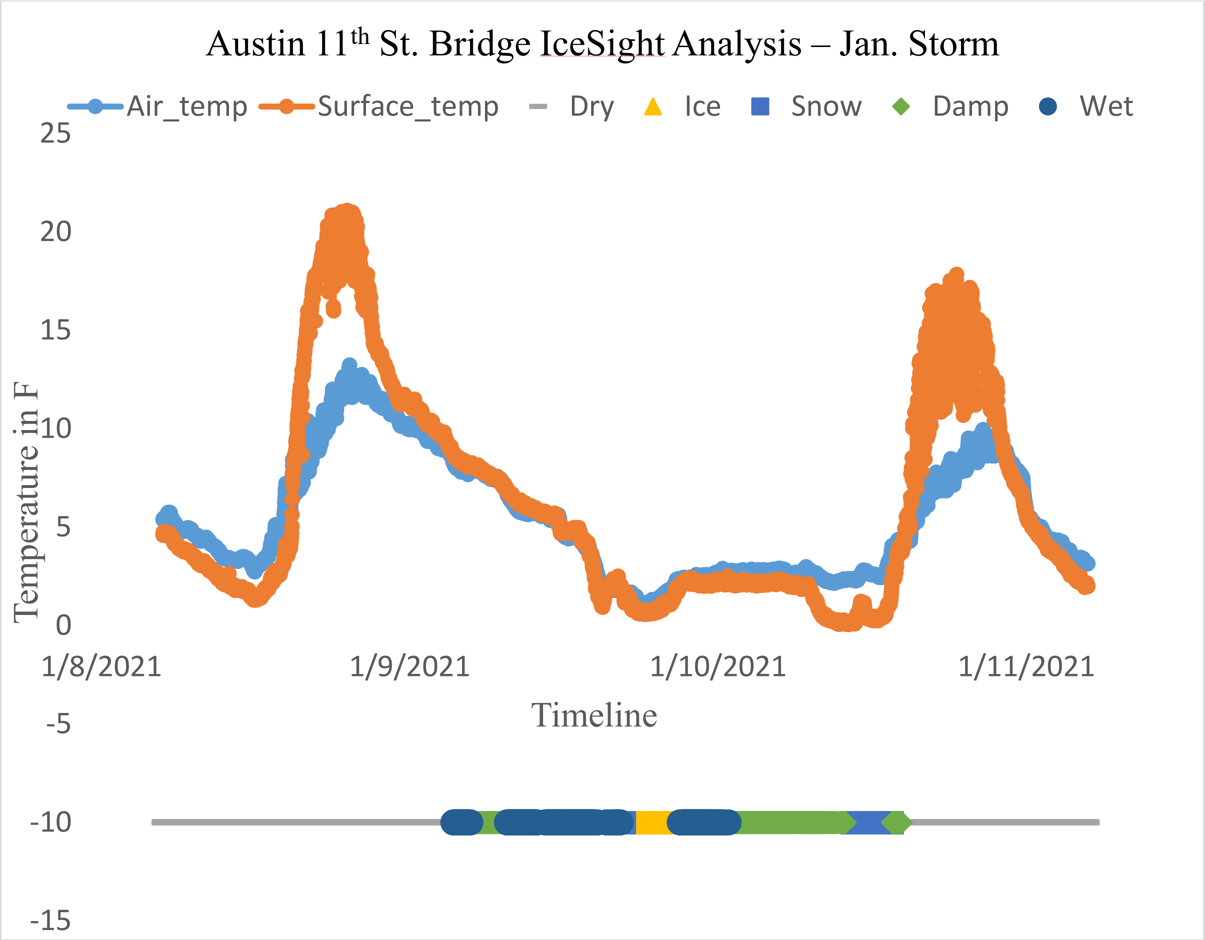


Figure 6.11: Austin IceSight air temperature, surface temperature and surface conditions

6.2.5. Real-time Spatial Analysis

The purpose of spatial analysis is to estimate weather conditions between measurements made from known locations. In effect, the theory is to calculate the expected measurement that would be made if a sensor were able to be placed at any arbitrary location within the spatial analysis area. In this exercise, spatial plots generated from sensors and data sources are based on information from the RX3000/HOBOLink stations and Synoptic data (only for temperature). These shown in Figure 6.12 and Figure 6.13 are auto-generated using a Python script, showing spatial temperature and dewpoints. Based upon types of sensors available on weather stations and other data sources, available live weather information plots may include:

- Temperature
- Relative Humidity
- Wind speed
- Wind direction
- Rainfall
- Solar Radiance
- Dew point
- Soil Temperature

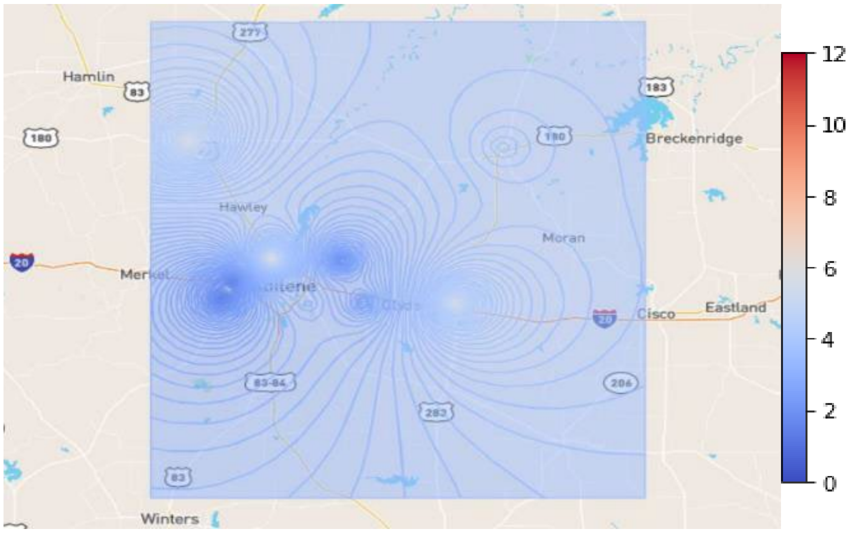


Figure 6.12: Spatial temperature plot

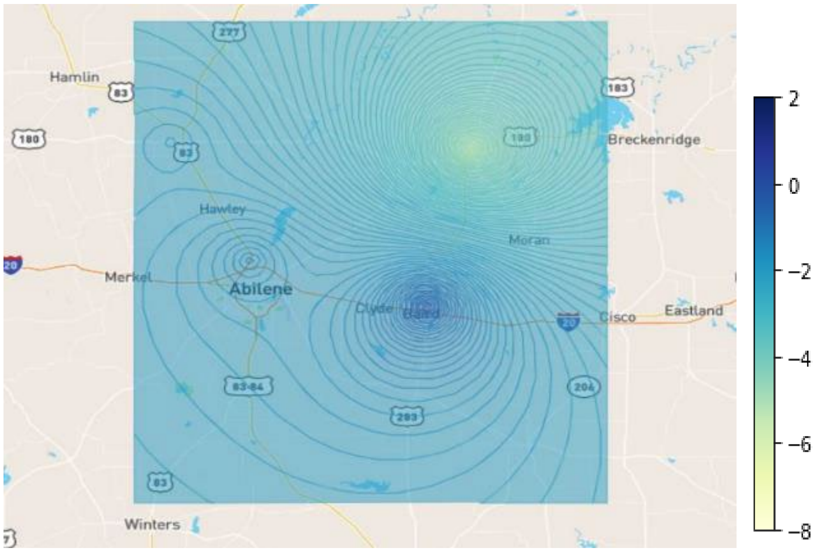


Figure 6.13: Spatial dew-point plot

6.2.6. Time Series Resolution

Measurements from Synoptic Data are queried, stored and analyzed to observe trends during the winter storm in January. Although data from all Synoptic stations within the Abilene area are available and analyzed, observations from Synoptic station AN600, a station operated by TCEQ (Texas Commission on Environmental Quality) at the Abilene Regional Airport are presented here in Figure 6.14. New data samples are made available once per hour.

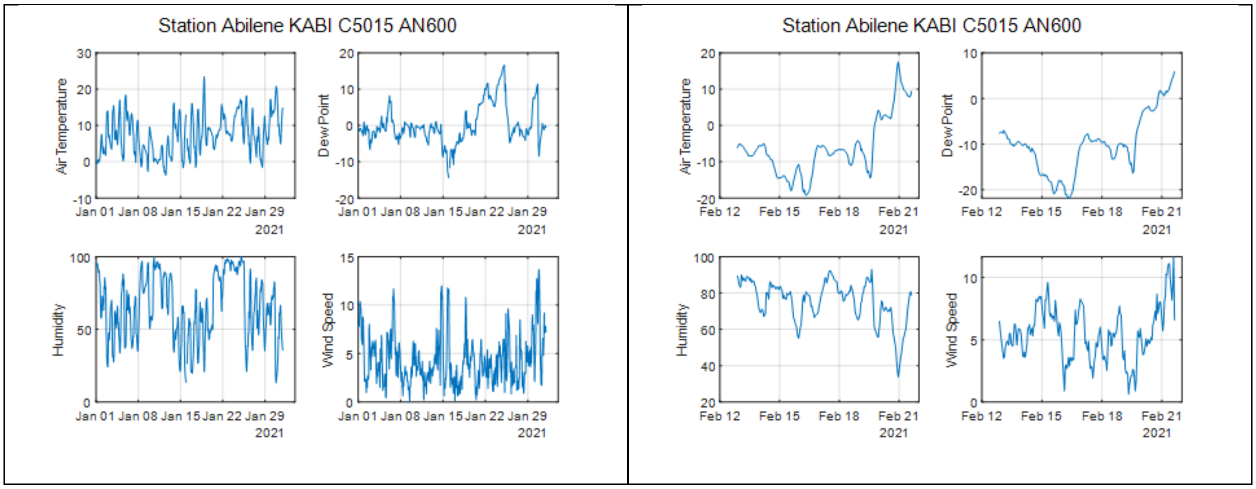


Figure 6.14: Abilene Regional Airport weather station data via Synoptic Data

Similarly, measurements from the project's RX3000/HOBOLink sensors are also shown in Figure 6.14. In this case, it can be observed that these data are of much higher resolution—samples are provided at every 10 minutes. This allows more insights sooner into weather and environmental conditions happening at the site. These specific plots in Figure 6.15 are for the RX3000 station housed in Baird at different times in January and February 2021 respectively.

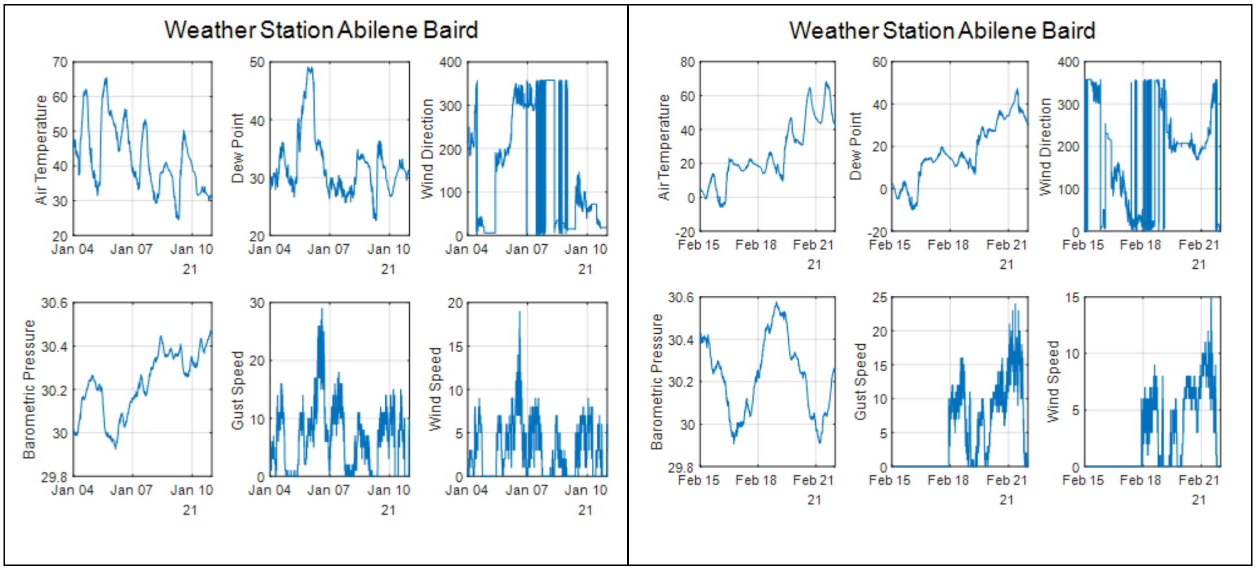


Figure 6.15: Data samples for the Baird RX3000 weather station

Since the capacity to store and access measurements were developed from different kinds of sensors that are each in a similar geographic location, it was possible to perform analysis and study variances among them. With further work, this would allow for intelligent calibration, removal of bias from sensors, and automatic alerting if one of the weather stations is detected to be dysfunctional. Overall, assimilating data from multiple sources increases robustness of the monitoring system as well as estimation accuracy of the phenomenon happening on-ground. To demonstrate differences in measurements from different sources, in the same time duration, the following graphs are presented in Figure 6.16:

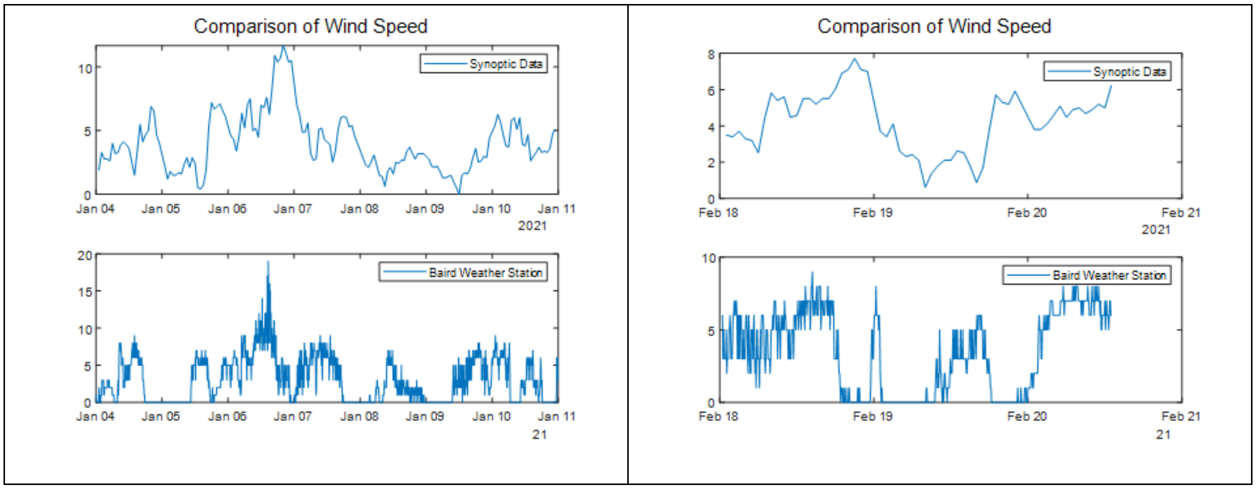


Figure 6.16: Comparison of wind speeds from the RX3000 Baird station and nearby Synoptic Data station

The high-resolution data from the RX3000 stations allow us to understand the correlation of different parameters among each other. For example, plots in Figure 6.17 visualize the variation of wind speed as a function of ambient air temperature and pressure. The curved surface is obtained by quadratic fit and provides an average for the fluctuating wind speed data as a function of ambient temperature and pressure. For the months of January and February, the wind speed is observed to be parabolic with rising pressure and increases at larger temperatures.

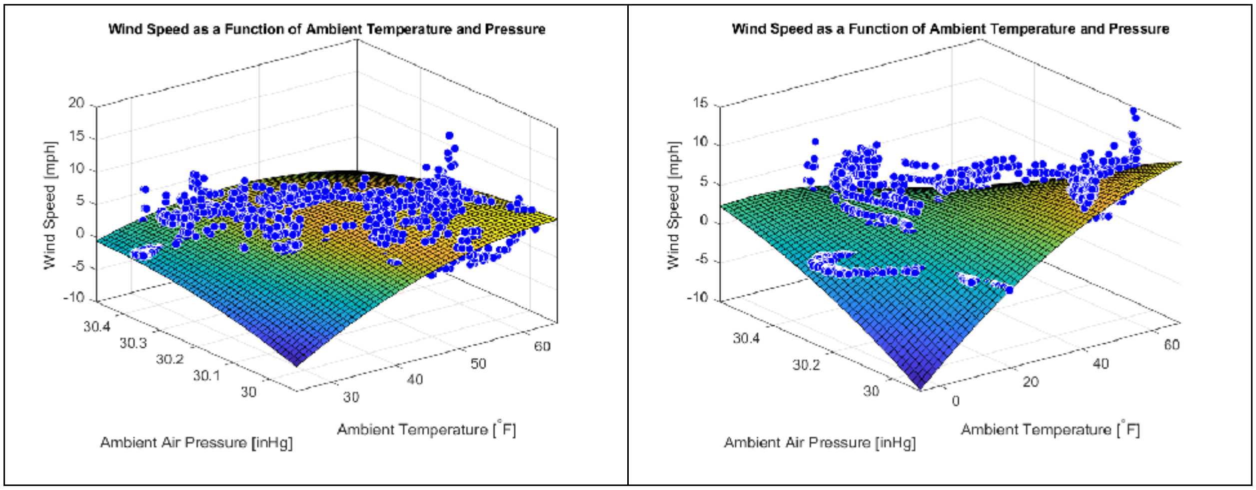


Figure 6.17: Wind speed as a function of ambient temperature and pressure with quadratic fit

6.3. Road Surface Freezing Prediction

For effective transportation planning and management, it is important to reliably predict ice formation on road surface during extreme events. By predicting when ice will form on the road surface and its spatial distribution, transportation agencies can take appropriate action to ensure that the roads are safe for travel. This can include making informed decisions for spraying brine or sanding the road surface, closing the road to traffic, or advising drivers to take alternative routes. In addition, predicting ice formation on road surfaces can help reduce the cost of maintaining and operating the road network. By knowing when and where ice is likely to form, transportation agencies can optimize their use of resources, such as brine and sand, and reduce the amount of time and money spent on road maintenance. Ice formation prediction and timely dissemination of this information can help raise public awareness. Moreover, by making the ice formation predictions and sharing the data, the public can plan their activities accordingly.

6.3.1. Prior Data

The Modern-Era Retrospective Analysis for Research and Applications (MERRA), developed by NASA, offers extensive weather data starting from 1980. This dataset is characterized by its fine-grained and uniform grid, providing valuable information on a global scale. The MERRA data is available at an hourly temporal resolution, ensuring continuous coverage throughout the analyzed period. In terms of spatial resolution, each data point represents a 0.5º latitude by 0.67º longitude area, which corresponds to approximately 50 km by 60 km at mid-latitudes.

MERRA data was included in InfoPave in 2016 (Elkins et al., 2021). InfoPave is a comprehensive platform that offers researchers and users a user-friendly interface to explore and analyze pavement information. It was established as part of the Long-Term Pavement Performance (LTPP) program which aimed to study the behavior of pavement test sections located on in-service roadways across the U.S. The platform offers a wide range of datasets covering diverse domains such as weather, traffic, pavement structure and construction, pavement materials, and pavement performance.

Within the InfoPave platform, users have access to a wide range of MERRA data, offering valuable insights into various meteorological variables. This includes hourly measurements of essential parameters such as precipitation, evaporation, soil moisture profiles, layer-specific soil moisture content, and water infiltration rates. In addition, the dataset provides detailed hourly readings of air temperature, soil temperature at multiple depths with a six-layer resolution, as well as temperature data within the unsaturated zone. Moreover, the dataset includes hourly information on wind velocity vectors, air density, specific humidity, estimated relative humidity, and air pressure. Regarding radiative properties, the MERRA data covers various parameters such as hourly shortwave radiation at the surface, shortwave radiation at the top of the atmosphere, cloud cover, surface emissivity, and surface albedo. These measurements contribute to a comprehensive understanding of radiative processes and their impact on the Earth's surface. The inclusion of such diverse and detailed variables in the MERRA dataset makes it a valuable resource for researchers and applications across various fields.

The LTPP database not only provides MERRA data but also incorporates roadway freezing data for specific test sections. For certain LTPP test sections, a combination of subsurface temperature and electrical resistivity is utilized to estimate frost penetration (Elkins et al., 2021). Consequently, a Freeze Stata variable is generated, encompassing the calculated parameters required to ascertain the frozen or unfrozen state of pavement layers at a specific depth.

To develop road surface freezing prediction models, extensive data from both MERRA weather data and LTPP freeze data were carefully extracted and utilized. A comprehensive dataset of 20,847 observations was meticulously gathered from the LTPP database, ensuring a robust foundation for analysis and model development. Recognizing the influence of weather conditions in the near past on today's freezing state, an expanded approach was adopted. In addition to the data for the current day of interest, weather data for the two preceding dates were also included. This decision was made to capture the significant impact of previous weather conditions, as they play a crucial role in determining the present freezing state of the road surface. By encompassing a broader time range, the predictive models were able to consider the historical context of weather patterns and their effect on freezing conditions. This comprehensive approach enables a more accurate and reliable prediction of the road surface freezing state, accounting for the complex interplay between past and present weather conditions.

6.3.2. Methodology

There are two main research areas in latest literature on estimation or prediction. In recent years, researchers are trying to merge these two, as well as devising application specific, more robust and efficient methods than their respective vanilla versions.

The first approach is **physical model-based**, known commonly as data-assimilation. In this approach, observations from sensors are systematically assimilated with predictions from a physical model explaining the underlying process. This way, we not only use sensors (data) but also our knowledge of structure of the environment, to produce the "best" estimate.

The other approach is **purely data-based**. One of the more commonly known techniques are machine learning and deep learning employing neural networks. There are other models, which are explained in subsequent sections, that can be employed. The idea is to first train these models with a large sum of data, and later use the trained model to predict ice formation based on measurements received in real-time.

There are trade-offs with either approach, and the distinction is increasingly blurred in recent research. In general, model-based methods are more robust; they quantify uncertainty in their predictions and can be run online if well-formulated. Uncertainty in their predictions in principle should be less than in predictions made by data-driven approaches. Data-driven approaches are simpler to devise and tune and may be computationally more efficient. However, in cases like ice formation, it may not provide good measures of uncertainty in results.

In this work, both of these methods are explored. Results are shown with the data-driven approach. The metrics to evaluate and grade different approaches in making ice formation prediction, for our case, will include accuracy; i.e., if the prediction made by the model was correct or not. The goal is to predict state of ice on roads based on current weather data. Weather data can be used to make consistent and precise predictions, and the models can provide other valuable information such as the level of confidence in their predictions.

In the following, both the model-based and data-driven approaches for predicting ice formation on roads are explained. This is followed by possible future steps and conclusion drawn from the study.

6.3.3. Model-Based Estimation

Physical models for ice formation prediction are based on theories of energy balance at the ground surface. Using these energy fluxes at the road surface for predicting ice risk over a time period is made possible by modelling hydro-meteorological processes using partial differential equations. The road temperature or ice prediction models first calculate atmospheric surface heat fluxes of radiation, observable and latent heats, and then forecast road conditions.

As input, such models employ numerical weather forecasts, either directly or after modifications made by meteorologists, as well as observations from road-weather stations and the radar precipitation measurement network. As output, the model produces not only road surface temperature measurements, but also road surface condition classification and a traffic index describing the driving conditions in more general terms, including an assessment of road surface friction. A flow chart describing inputs and outputs of the ice prediction model is provided in Figure 6.18.

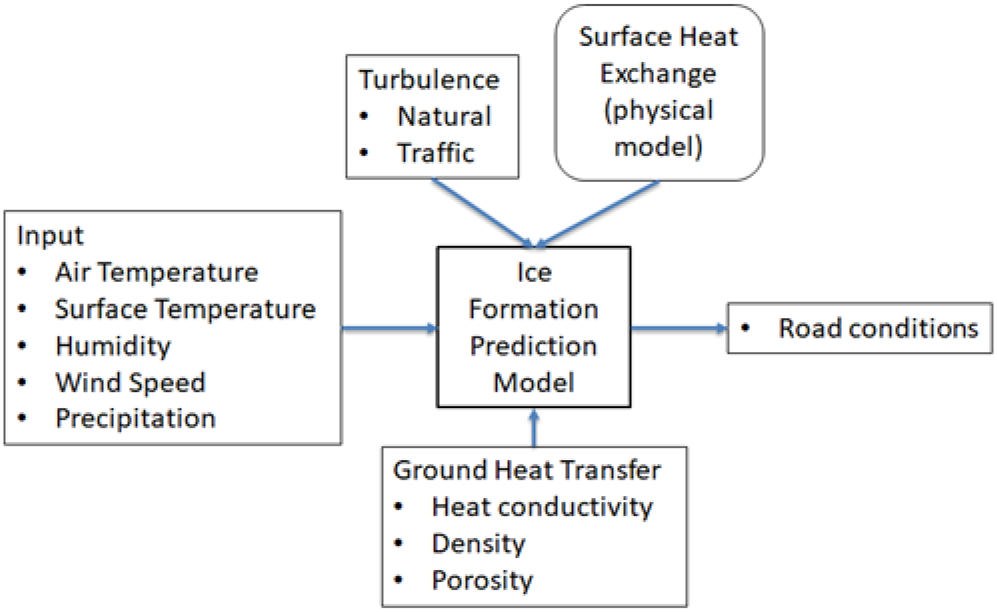


Figure 6.18: Inputs and Outputs of the ice prediction model

These models, as research has shown, can also play a crucial role in understanding the phenomenon of energy exchange between soil, vegetation, and atmosphere; such prediction is relevant for other purposes, such as agricultural management and irrigation system control.

Building on top of these models by incorporating the time dependency among the measurement data, we can automatically identify road surface states in a continuous manner. In the future, it is possible to build onto the data analytics algorithms to first identify states of a road surface within a particular area, and then model consecutive road surface conditions by leveraging each prior measurement. The accuracy of this incremental modeling is helped by the idea that road surface conditions do not dramatically change within a short period but change relatively slowly in most cases.

6.3.3.1. Robustness

A prerequisite for accurate forecasts is information about the current conditions at the forecast area. It is important that the initial conditions in the forecasting model represent real conditions because even small deviations can change the forecast. The observations collected and processed from this project's weather stations and external sources have the potential to improve the forecast accuracy for road stretches and ice prediction models. As a step further, these kinds of measurements distributed over space and time in high resolution enables the creation of a dedicated road-weather service to deliver timely and localized forecasts of hydro-meteorological conditions at the road surface, as well as the ability to issue warnings about adverse road conditions with a lead time from a few hours up to 2 days or longer.

Model-based estimation can be used to introduce the concept of robustness in measuring how much a road surface temperature or ice prediction model is capable of yielding stable results over time. The work performed can be used to build and verify an optimal system that balances precision and robustness. Moreover, the model is aimed to be robust to noisy data when the initial bias in the atmospheric forecast is reduced before applying to the ice prediction model. This is particularly important for accurate short-range forecasts. As explored in a 2006 study by Karsisto et al., even the first forecast hours often include error because the atmospheric forecast is taken from a numerical weather prediction model representing conditions integrated over large areas. The resolution of models is often too coarse to account for all local features, and this can lead to road surface temperature differences of up to 10°C across a road network. Even the smallest variations in atmospheric forcing can affect the freezing of roads at near-zero temperatures (Shao et al., 1996; Bogren et al., 2000). Keeping this in mind, one or more of the following techniques are applied to improve the accuracy of forecasts:

- **RoadSurf** was developed at the Finnish Meteorological Institute. It is single-dimensioned and uses the heat balance equation to calculate the road surface temperature. In addition, RoadSurf calculates the amount of water, snow, and ice on the road. It also predicts road surface friction using a numerical-statistical equation. As input, RoadSurf requires the forecasts of air temperature, relative humidity or dew point temperature, wind, precipitation, and incoming radiation. A more detailed description of the model can be found in Kangas et al. (2015).

- In the **LAM50 NWP model**, the biggest attraction point is that researchers in Homleid's 1995 study used a Kalman filter to address systemic deviations between surface temperature forecasts produced by the model and corresponding observations. Since corrections are continuously issued in response to the latest observations in a Kalman filter, the model is allowed to adapt when major changes are observed. Another advantage is its simplicity as shown in the work cited above.

- A Canadian open-source road-weather information system called **METRo** (Model of the Environment and Temperature of Roads) incorporates a full road-condition forecasting system that can predict the road surface temperature as well as the pavement condition. METRo also contains an observation assimilation mechanism to help to initialize the forecast and a local bias-correcting mechanism. This capability allows the model to be deployed easily over a large number of stations in similar local environments without the need for too much calibration effort across every station and region.

6.3.4. Data Driven Estimation

In order to employ artificial intelligence (AI) based solutions to predict ice formation, the models must be trained on large amounts of data. Here, the MERRA dataset is leveraged. The aim is to first train the AI models using the large dataset, and then fine-tune the model based on relatively smaller but spatially precise measurements available from the RX3000 HOBOLink weather stations deployed for the project described in Section 6.1.2. The large dataset (and later the measurements collected from local weather stations) is preprocessed to a format that can be ingested by the models. Various pre-processing strategies and their motivation are explained in the following sections.

Once the models are trained on large dataset and appropriate weights are computed, predictions are rigorously validated by performing a quantitative analysis of results. This involves computing predictions for the scenarios that the AI model has not seen during the training process. The quantitative analysis is used to narrow down the model that probabilistically gives the most consistent and accurate predictions. The architecture of these models and their respective results is explained in subsequent sections.

6.3.4.1. Binary classification

The framework employed to predict ice formation on roads uses binary classification models under supervised learning. This implies that the dataset must be labelled correctly—i.e., noted whether there was ice formed on the road at the respective data and time—before the models can be trained on it. Once trained, the models can then (hopefully) predict if there will be ice on road or not, based on weather data. The prediction from the AI model is computationally efficient and faster than classical physical model. This allows the AI model to be integrated into an online estimation process to make real-time predictions.

6.3.4.2. Transfer Learning

Once the AI models are trained on a large national dataset, and the models are analyzed and found to be consistently making accurate predictions, the research intent is to fine-tune the models for localized predictions by using the relatively small dataset compiled from measurements obtained directly from the HOBOLink local weather stations. Although this work is reserved for later, the framework is designed keeping this extension in mind. While challenges exist in integrating the large public dataset and HOBOLink measurements, this transfer learning strategy can be feasible.

6.3.4.3. Data Preparation

Before feeding to the AI models, data sources were analyzed and preprocessed to achieve the best prediction performance in terms of classification accuracy. Specifically, exploratory data analysis was performed, addressing anomalies (e.g., invalid entries), replacing null values, and dropping highly correlated measurements. Entities which had less than 60 percent of the rows populated were dropped. Subsequently, with analysis of correlation of variables among each other and with respect to themselves at a previous time (as shown in Figure 6.19), columns that were highly correlated were dropped, to avoid giving the AI models a false sense of accuracy on predicting next-day ice formation. Missing values of columns that weren't dropped were replaced with mean or most frequent values.

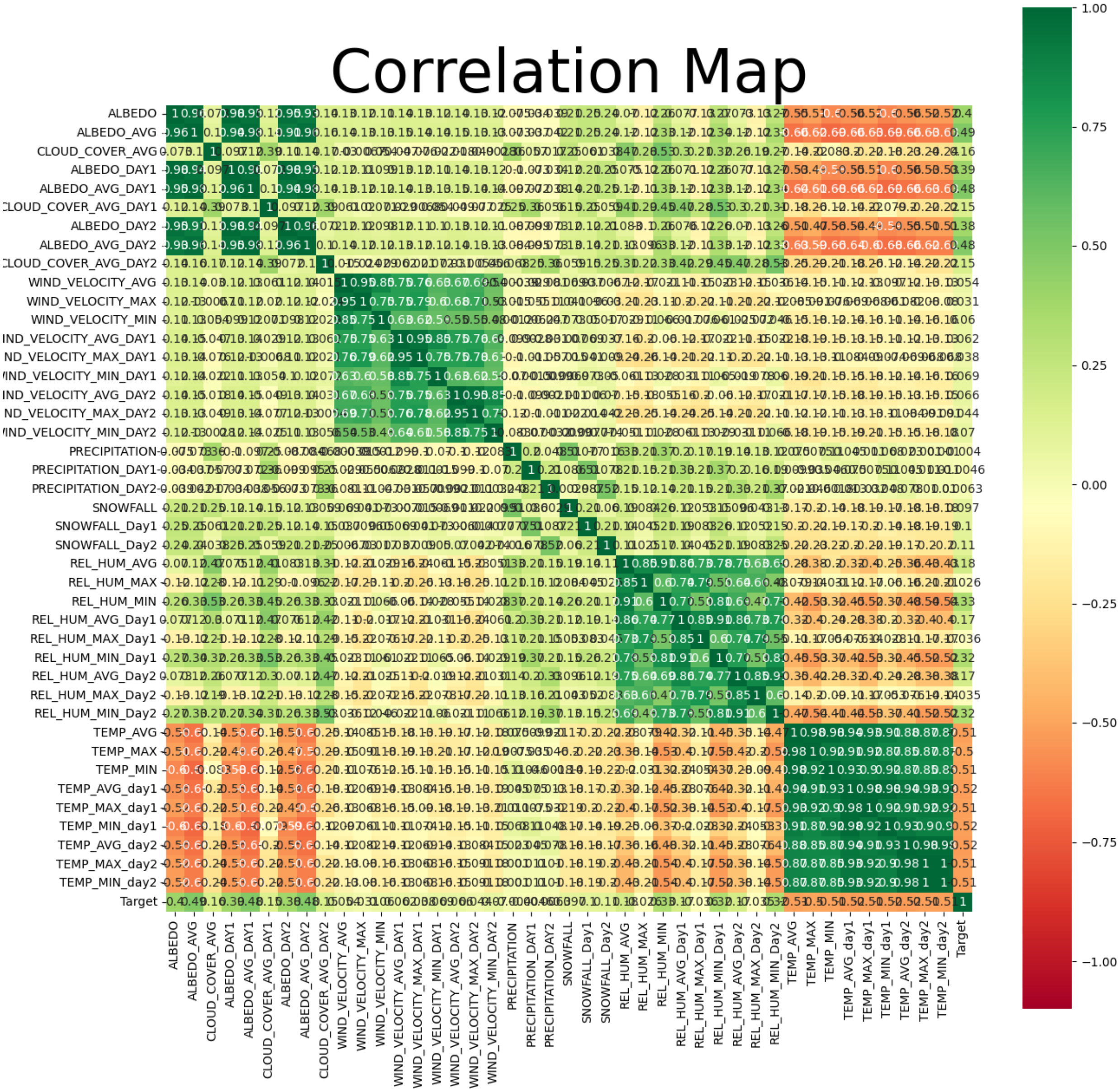


Figure 6.19: Correlation map derived from the national dataset

6.3.4.4. Examples of Data-driven Models

Area Under the ROC Curve (AUC) was chosen as the metric to measure the performance of each model. AUC provides an aggregate measure of performance across all possible classification thresholds. One way of interpreting AUC is as the probability that the model ranks a random positive example more highly than a random negative example. This metric is chosen because of the need to identify as many possible positive cases as possible (e.g., there is ice formation on the road tomorrow versus there is no ice formation on the road tomorrow).

The use of AUC is desirable for the following two reasons:

- It is scale-invariant. It measures how well predictions are ranked, rather than their absolute values.
- It is classification-threshold-invariant. It measures the quality of the model's predictions irrespective of what classification threshold is chosen.

This is a short-list of promising models that use the AUC metric:

- **Logistic Regression** is appropriate to conduct regression analysis when the dependent variable is dichotomous (binary).
- A **Random Forest** is a classifier that fits a number of decision tree classifiers on various sub-samples of the dataset and uses averaging to improve the predictive accuracy and to control over-fitting. It can also be used to determine feature importance, as shown in Figure 6.20.
- **Light GBM** is a gradient boosting framework that uses a tree-based learning algorithm. It grows its tree vertically while other algorithms grow trees horizontally, meaning that Light GBM grows leaf-wise while other algorithms grow level-wise. It will choose the leaf that exhibits the least loss in accuracy.
- **Neural Network:** Deep Learning is a subfield of machine learning concerned with algorithms inspired by the structure and function of the human brain, called artificial neural networks. A Sequential Neural Network was tried with various numbers of nodes and layers until a fairly optimal configuration was found.

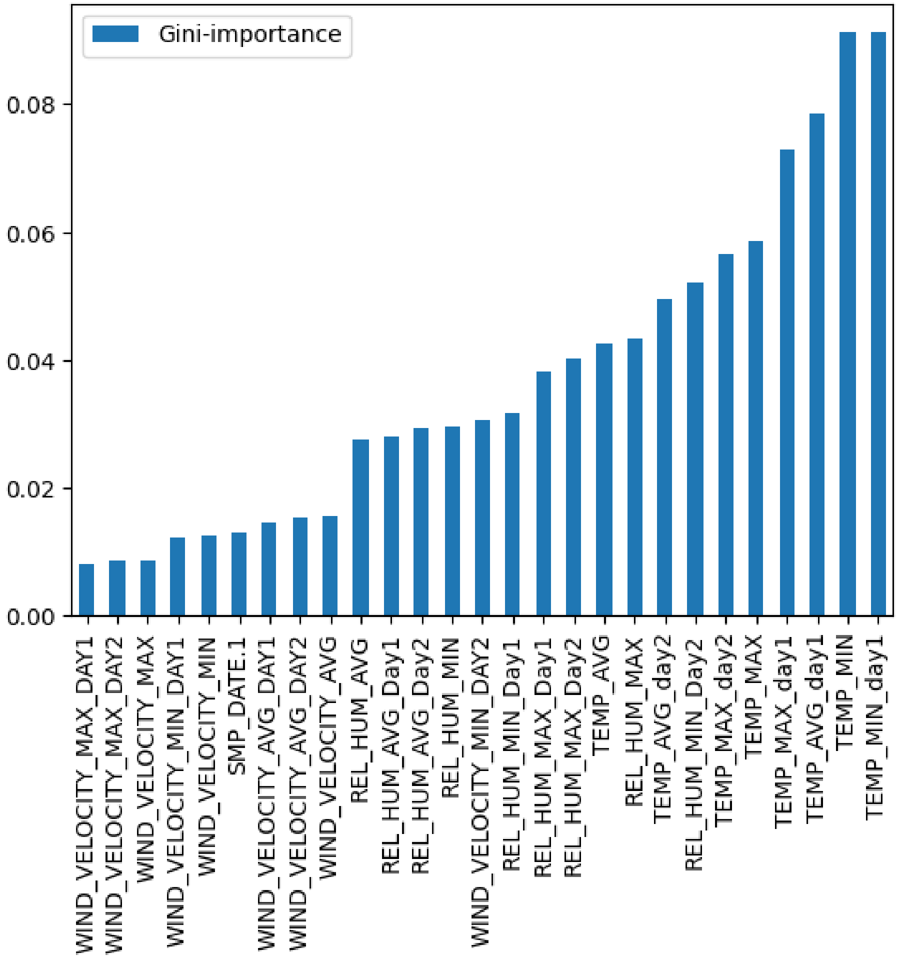


Figure 6.20: Relative significance of each input variable as reported by the Random Forest classifier

6.3.5. Results

After trying these models, the best classifier was found to be the Random Forest classifier (with parameters *bootstrap*=True, *max_depth*=60, and *n_estimators*=300). It gave the best AUC value, indicating the highest probability in identifying positive cases. AUC values for each of the models converted to percentages are shown in Table 6.1.

Table 6.1: Results of Accuracy Among Four Tested Models

Logistic Regression	**Random Forest Classifier**	**LGBM Classifier**	**Neural Network**
86.20%	91.00%	90.95%	90.07%

To exemplify the automated classification process, Figure 6.21 shows actual and predicted values from the Neural Network model. The model is shown to correctly predict the actual outcome (again, a binary indication that there will be freezing roads on the next day) more than 90 percent of occurrences.

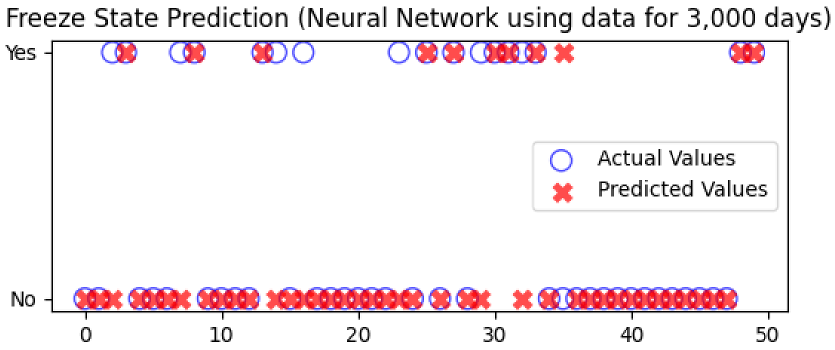


Figure 6.21: Neural Network prediction accuracy visualization

6.3.6. Next Steps

All of the data-driven techniques need more data from the sensors to be able to be trained to reliably deliver predictions. Adding more sensors and gathering data for larger periods of time would improve data-based classification for scenarios that the models haven't seen in the past. This makes the solution more robust.

A future plan is to explore the quantification of uncertainty with the neural network and other data-driven models, such as seen with model-based estimation techniques. Recently, researchers have been increasingly trying to systemically incorporate into the prediction the uncertainty introduced due to sensors, training data, test data and weights of the models. Quantifying uncertainty in data-driven models would allow operators at TxDOT and other agencies to be informed how much confidence can be instilled in a model concerning its prediction for icing on a particular road segment at a particular time.

A natural extension of uncertainty quantification is to compute optimal placements for the sensors, or to devise optimal travel plans for vehicles equipped with sensors to improve current understanding of the environment and to make reliable estimates. This process would be run in a loop in an online fashion to estimate best locations for the small number of fixed or mobile sensors.

Chapter 7. Non-Winter Weather Applications

This chapter explores applying principles explained earlier toward types of weather or environmental events beyond winter. In addition, some of the research areas around sensors and data are further explored for the purpose of adding value to the core capabilities that project sensors and related data sources can offer.

The following section extends the operations sensing capabilities to other non-winter weather phenomenon, focusing primarily upon springtime pesticide application. Further sensor analysis on rain detection, and data analysis to determine how traffic speed may be affected by weather events is included.

7.1. Operations Sensing for Non-Winter Weather

A major activity within this project is to establish a means to automatically track winter weather-related roadway operations. The method for this is to equip sand spreaders, brine sprayers, and snowplows with sensing capabilities that send simple sensor "on/off" indications over the vehicle telemetry system along with the current timestamped vehicle position and engine health data.

While this sensing capability was targeted for winter weather operations, it was also apparent that these tracking capabilities can apply to responses to other types of weather or environmental phenomenon. Task 7 was created in the project Work Plan to identify extensions on project successes to other domains, with the motivation of providing a broader value to TxDOT. In brainstorming, the following applications are apparent:

- **Pesticide and herbicide application** along rights-of-way, for example, to control vegetation growth through the spraying of liquid chemicals; and
- **Incident response** for broken-down vehicles or emergency roadway facility repair.

7.1.1. Pesticide and Herbicide Application

This section further explores the pesticide application use case, reporting upon earlier applicable work in the project and summarizing conversations with personnel in the Abilene District. Several vendors listed below provide capabilities that involve the tracking of vehicles specifically for pesticide and herbicide application activities. Each of these vendors was approached earlier in the project to determine if their offerings could fulfill the requirements for winter operations sensing. While investigating, the following was found for each of these vendors:

- **Clearion** (https://clearion.com/) markets for pesticide application and infrastructure management. In focusing upon application development and usability, they rely upon third-party hardware solutions to assist in supporting their software features. As of June 2021, no third-party hardware solution was found that would integrate with vehicle systems and perform live winter operations sensing over the existing telemetry system.

- **TeeJet** (https://www.teejet.com/) offers a wide variety of hardware that assists in spraying applications, some of which are used by TxDOT for brine spraying. A handful of product offerings feature technological capabilities for automatic tracking vehicle position and sprayer status. However, the ability to retrieve a live stream of activity data, let alone integrate into the existing telemetry system, was not found.
- **AgTerra** (https://www.agterra.com/) applies to farming applications. While they do offer hardware solutions for tracking vehicle position and an intuitive software application, the integration with existing systems and ability to operate independent from proprietary software was not sufficient for further exploration.
- **FarmerGPS** (now appearing to be defunct, as of May 2023) was mostly centered around a smartphone app that tracked farming activities, but also offered an optional interface box that could tie into spraying systems. The operator was left with many steps that were necessary for further integration. In an e-mail conversation, the vendor concluded that the control box was not sufficient for this project's application.

In hypothetically applying the WinterOps sensing functions to pesticide application, it is clear that the ability to track pesticide spraying activity is similar to that of brine application:

- The same strategy for tapping into the spraying system would be exercised.
- Sprayers would need to be identified in back-end system appropriately.
- The same reporting functionality would be used within GIS visualizations to see evidence of pesticide spraying activity, tied with timestamps and roadway positions.
- The same mechanism within TxERA could be applied to change the appearance of live and historic vehicle position icons on the map based upon spraying activity.
- In further research, historic "breadcrumbs" could show which stretches of roadway had been sprayed for the season, allowing identification of stretches remaining to be treated.

In conversing with TxDOT Abilene District personnel, a valuable capability specific to pesticide application has to do with disputes around alleged effects of herbicide on nearby farmers' crops. A scenario could arise where a crop owner blames the DOT district for poor crop performance, stating that roadside herbicide drift is the cause. If the DOT were to equip all vehicles with the ability to automatically track the application of herbicide, with the ability to see historic activity breadcrumbs along roadways, the DOT could verify and show evidence of all herbicide treatment activities in the district, including the absence of treatment near specific sites.

Another application for historic breadcrumbs is in ensuring the health of people who work alongside the roadway for various purposes, including volunteer litter pickup crews. Prior to the arrival of such crews, potential work sites can be evaluated to determine if recent pesticide application had taken place. If recent activity is found, then crews can be advised to reschedule or reposition work. (While these statements are not intended to draw any conclusion on whether chemicals sprayed along a roadway are harmful to humans, individuals—especially those with compromised health conditions—may still desire to know all potential risks prior to engaging in any roadside activity.)

7.1.2. Incident Response

Operations sensing for incident response was not explored to the level pursued for pesticide application, but the following capabilities were evaluated for the purposes of the project:

- For an incident response fleet that attends to broken-down vehicles along rights-of-way, the current vehicle fleet tracking system can provide the positions of individual response vehicles.
- An attempt was made to equip a HERO vehicle in the Austin District with a Mobile IceSight sensor that would measure road surface freezing condition wherever the HERO vehicle travels. This was not achieved because the HERO vehicle that was targeted suffered damage from a traffic accident.

The tracking of operations activity can add another dimension of utility to the existing capabilities. For example, the automatic logging of flashing lights or arrow board activity on an incident response vehicle can help assess operator activity, such as whether the incident response vehicle is rushing to an incident scene or is already parked and attempting to divert traffic away from the incident location. Operations activity data could be analyzed alongside roadway speed data to assess impacts of incidents and response activities. For road crews performing emergency roadway repair, such as clearing fallen trees or sweeping away flood damage, the use of heavy machinery can be automatically logged to assess the intensity of work.

This concludes the evaluation of operations sensing for non-winter-weather-related activities. The next section outlines the exploration of a new, solid-state rain detection technology.

7.2. Lower-Cost Rain Detection

All five RX3000 weather stations deployed in the Abilene District have rainfall measurement capabilities. Two product offerings from the vendor use variations on the “tipping bucket” methodology for measuring the amount of rainfall: when enough rainwater falls into a receptacle, the receptacle tips over, allowing a known amount of rainwater to be added to a cumulative measure. While this methodology is commonly used, it has potential drawbacks:

- Rainfall measurements can be attained only when the bucket fills up enough to tip over;
- Bird and insect nests can interfere with the operation of the tipping bucket, and thus the buckets require at least annual inspection;
- Freezing or overly dusty conditions can cause the moving parts to seize up;
- These rain gauges cost approximately $300 or more each; and,

- The bucket rig is the size of a football or larger, imposing limits on where it can be installed.

In collaboration with Texas Advanced Computing Center, an idea was researched at no cost to this project to leverage newer, low-cost IoT (Internet of Things) technologies to reduce costs for physical materials and eliminate the need for moving parts. This concept involved equipping a traffic signal control cabinet with an IoT platform that could record sound and thus detect the presence of rain. The microphone would potentially be coupled to the ceiling of the signal control cabinet, in theory recording the metallic "tapping" or "plipping" sounds that raindrops would make against the metal surface. For proper processing and characterization of sound (e.g., to differentiate against nearby loud traffic or pedestrians banging against the side of the cabinet), machine learning would need to be applied on live samples.

While exploring this idea, a relatively new product offering was discovered that is marketed for sprinkler systems and "do it yourself" projects—the Hydreon RG-9, a solid-state rain detection device that looks at the diffraction of infrared light against a 3-inch clear, plastic dome (Hydreon, 2021) and retails for $50. As the dome becomes wet, or exhibits rapidly shifting changes in diffraction, the device reports on three grades of rainfall intensity approximately once per second. While the Hydreon does not have the capability to directly report rain accumulation, it does report the presence of rain in a way that is more immediate than a tipping bucket.

Two such devices were acquired. In a preliminary test, one of them was verified to function as advertised when activated outdoors. At the time of this writing, no further tests were conducted on the RG-9. In considering possible use cases, the small, solid-state form factor offers a compelling alternative to the tipping bucket counterpart. It is conceivable that such a device could be mounted to the top or the side of a pole or signal control cabinet and be attached to a base device or endpoint that collects data.

The next section analyzes sensitivity of speed data against various weather events, including intense rainfall.

7.3. Weather Elements and Speed Relationship

Understanding the relationship between speed and weather events may not only help in predicting the level of service of a road network based on weather forecast (which can then be integrated as a road-weather information component), but also help in optimizing treatment activities. In this section, a basic exploratory analysis is undertaken to understand the correlation between weather events and speed of travel. The weather elements considered are rainfall, temperature, relative humidity, and solar radiance. Though rainfall is likely to have the most immediate impact on traveler speed due to its direct effect on road conditions, the isolated relationship with other elements concerning speed may not be immediate (as we also observe in our basic analysis). However, different combinations of these weather elements may have varying impacts on the speed and level of service of road segments. Such multivariate analysis can be a part of future research to understand weather-speed relationship. We provide a few univariate analyses of the relationship between speed and weather elements for different days of the month under different weather conditions for a section of the I-20 interstate highway on the northern side of Abilene, Texas. The link segment and the HOBOLink RX3000 station ("Abilene-HQ") under consideration for this analysis are shown in Figure 7.1. The speed and weather relationship can be further explored to identify any patterns of crashes associated with certain weather conditions and related speed profiles.

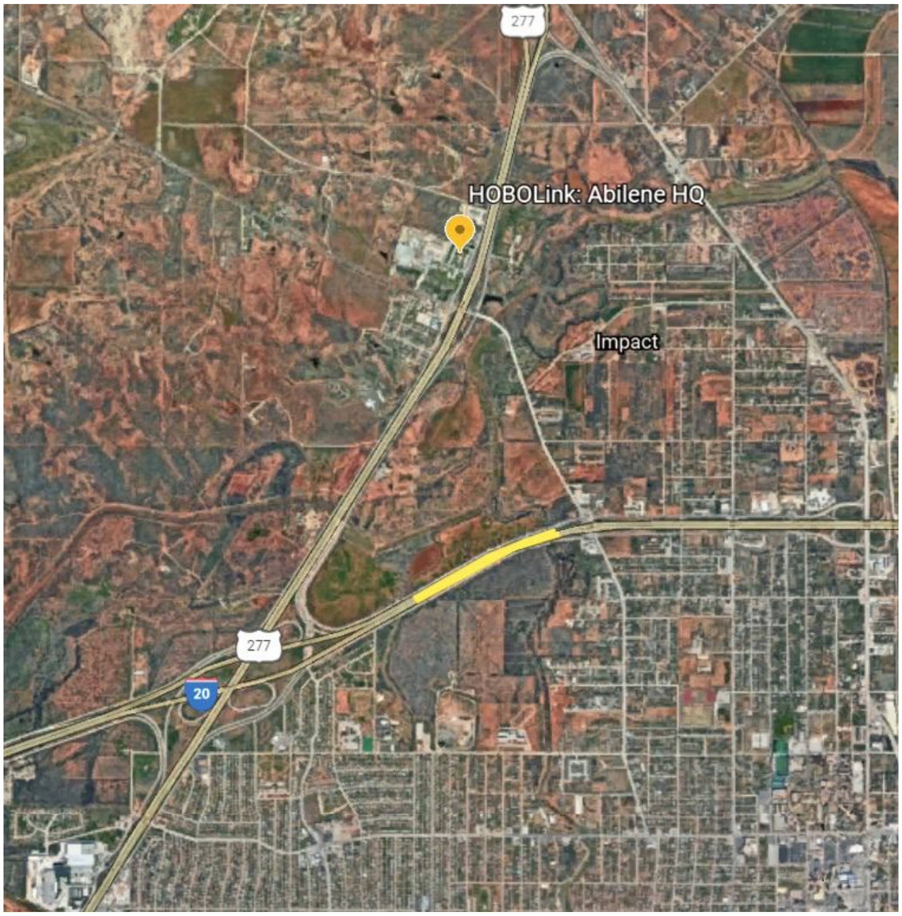


Figure 7.1: Link and weather station used for analysis (highlighted in yellow) (source: Google Maps)

7.3.1. Speed vs. Rainfall

The following set of graphs (Figure 7.2 and Figure 7.3) represent the speed and rainfall profile for the days between and including May 22, 2021, to May 25, 2021. While no rainfall is recorded in the graphs for May 22-24, minor amounts were observed in other measurements. In these graphs, the speed data for a normal period (during which there was no rainfall)—May 8 to May 11—is also plotted.

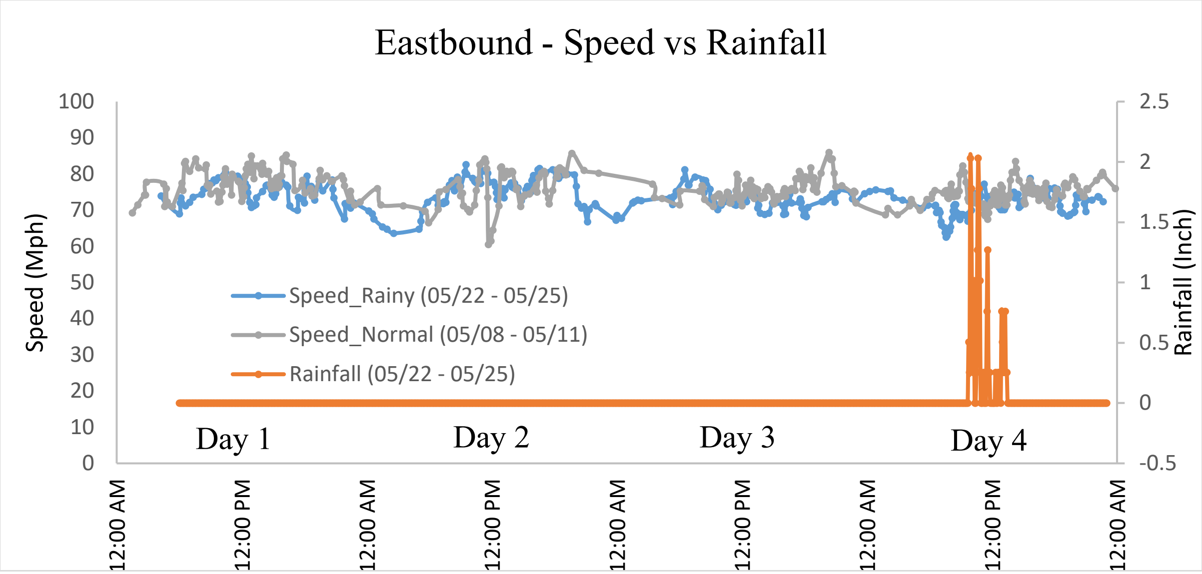


Figure 7.2: Speed vs. Rainfall, Eastbound I-20

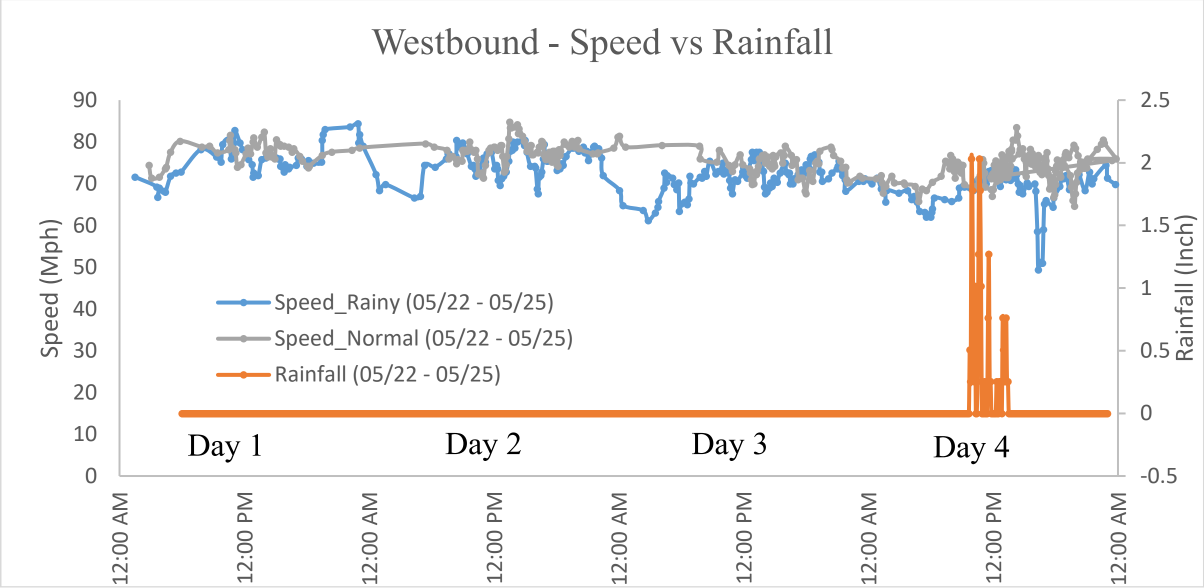


Figure 7.3: Speed vs. Rainfall, Westbound I-20

From the speed profile, it can be seen that the rainy day of May 25 is characterized by a reduction in speed compared to a normal period—in particular, a marked reduction after intense rainfall in the westbound direction. The eastbound direction is not as distincive. A similar analysis was also conducted for another period in May that also received considerable rainfall. The following set of graphs (Figure 7.4 and Figure 7.5) represent the speed and rainfall profile for the days between and including May 15, 2021, to May 18, 2021. The base case (a day with no rainfall) is also plotted similar to the earlier graphs.

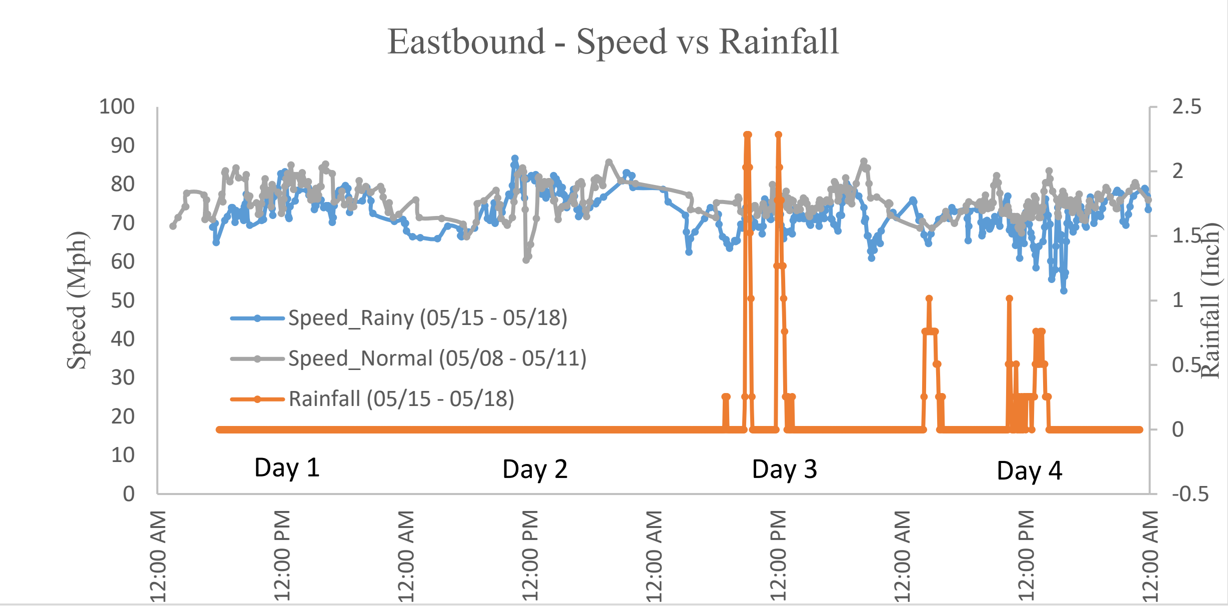


Figure 7.4: Speed vs. Rainfall, Eastbound I-20

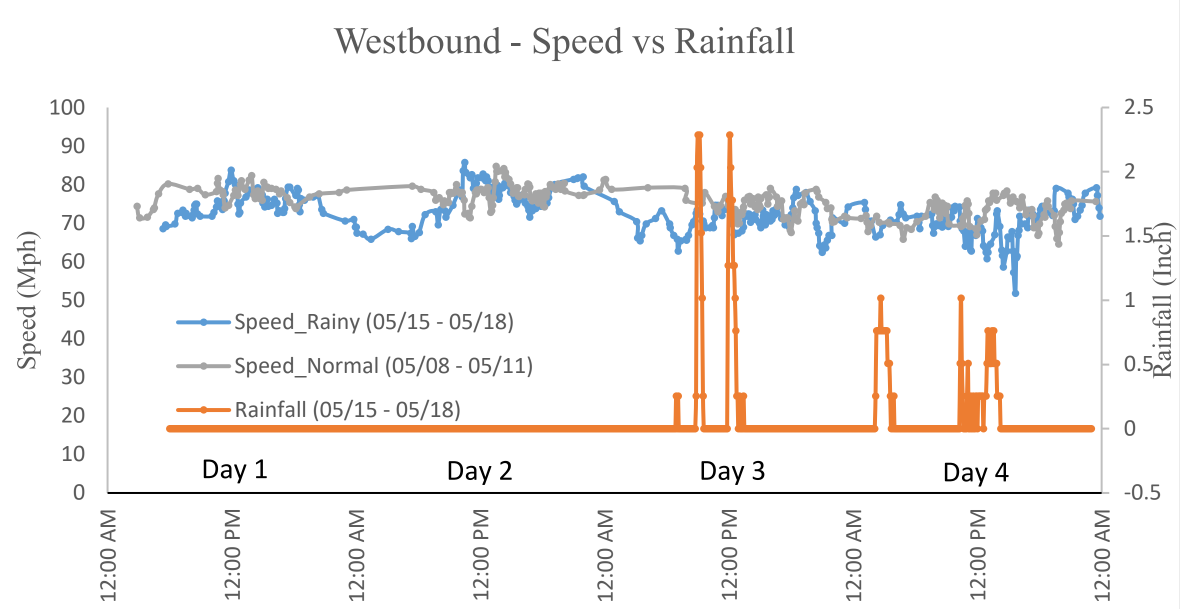


Figure 7.5: Speed vs. Rainfall, Westbound I-20

Similar to our earlier observation, it is observed that the days of May 18, 2021, is characterized by a reduction in speed compared to a normal period; however, a distinct speed reduction is not as apparent on the prior data. Further analysis and research direction can focus on understanding this relationship between rainfall and speed for various intensity and rainfall amount.

7.3.2. Speed vs. Other Weather Elements

The relationship between speed and other weather elements may not be direct or immediate, but a combination of these elements may impact speed. However, as a part of the basic exploratory analysis we plot speed profile against temperature, relative humidity, and solar radiance for the days of May 6 and 7, 2021 (when there were no other weather events).

7.3.2.1. Speed vs. Temperature

Figure 7.6 and Figure 7.7 represent the speed profile for varying temperature. No significant pattern was observed between link speed and the ambient temperature for the analyzed period.

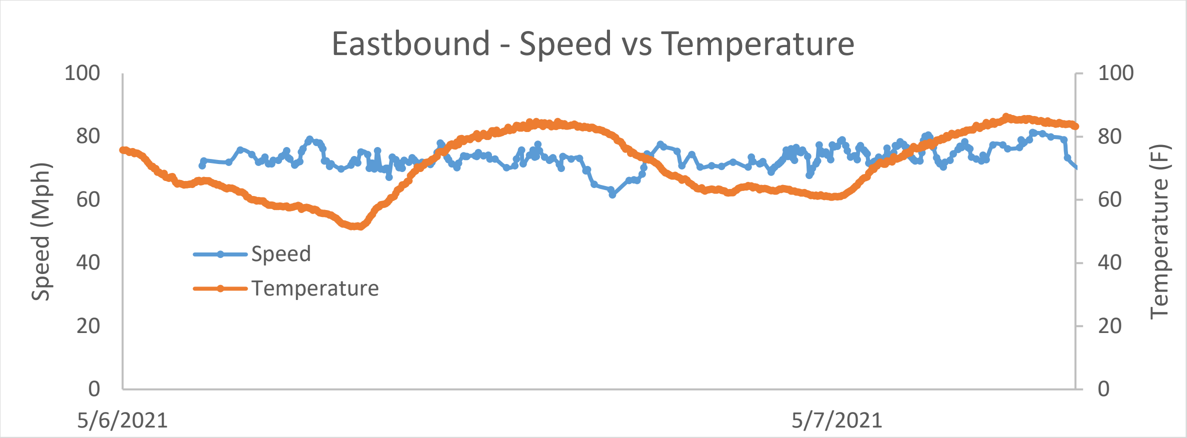


Figure 7.6: Speed vs. Temperature, Eastbound I-20

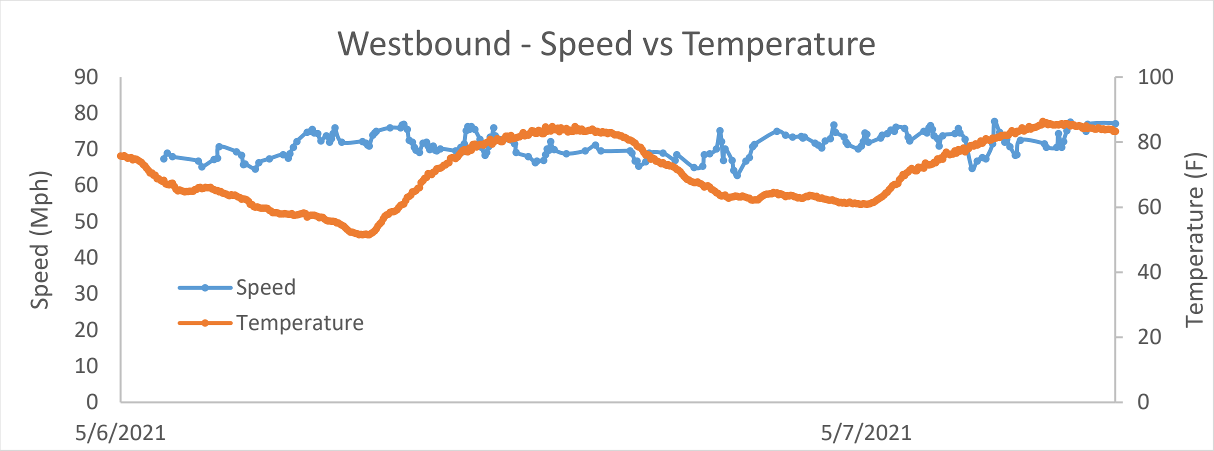


Figure 7.7: Speed vs. Temperature, Westbound I-20

7.3.2.2. Speed vs. Relative Humidity

Figure 7.8 and Figure 7.9 represent the speed profile for varying relative humidity. No significant pattern was observed between link speed and the relative humidity for the analyzed period.

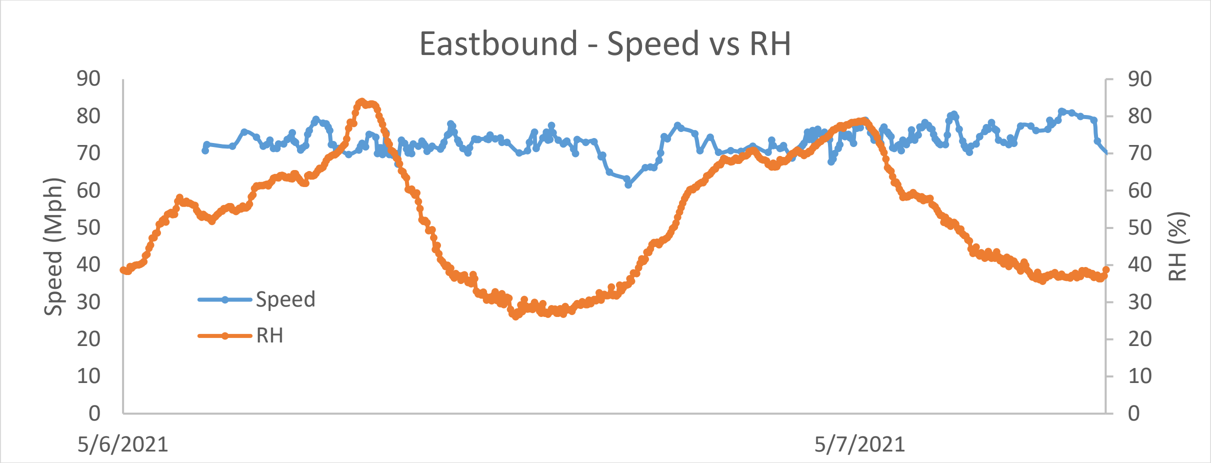


Figure 7.8: Speed vs. Relative Humidity, Eastbound I-20

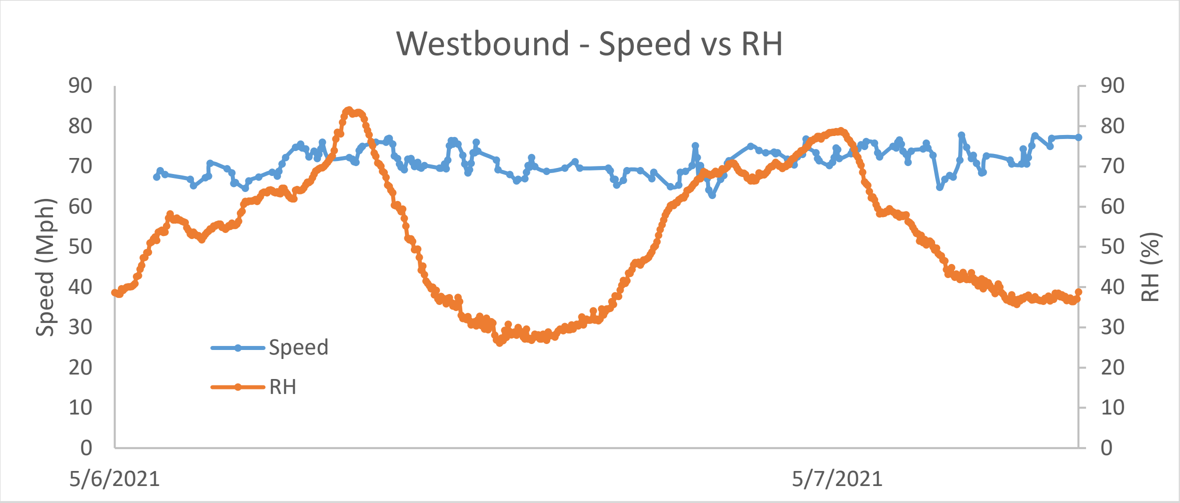


Figure 7.9: Speed vs. Relative Humidity, Westbound I-20

7.3.2.3. Speed vs. Solar Radiance

Figure 7.10 and Figure 7.11 represent the speed profile for varying solar radiance. No significant pattern was observed between link speed and the solar radiance for the analyzed period. As far as the other weather elements are concerned, our preliminary exploratory analysis suggests that no significant pattern between these elements and the speed of the network when examined in a univariate analysis.

In conclusion, among these analyses, decreased speed is sometimes observed during and after the rain spells for both the time periods considered as compared to normal days without rainfall. The drop in speed may be influenced by the amount and intensity of rain, and future research can focus on analyzing rainfall and speed data across several such events. Such analysis can result in the production of a mean speed recovery profile, improved assessment of adverse effects caused by combinations of weather events, better understanding of drainage requirements in certain road segments, and exploration of the relationships between crashes and multivariate weather data.

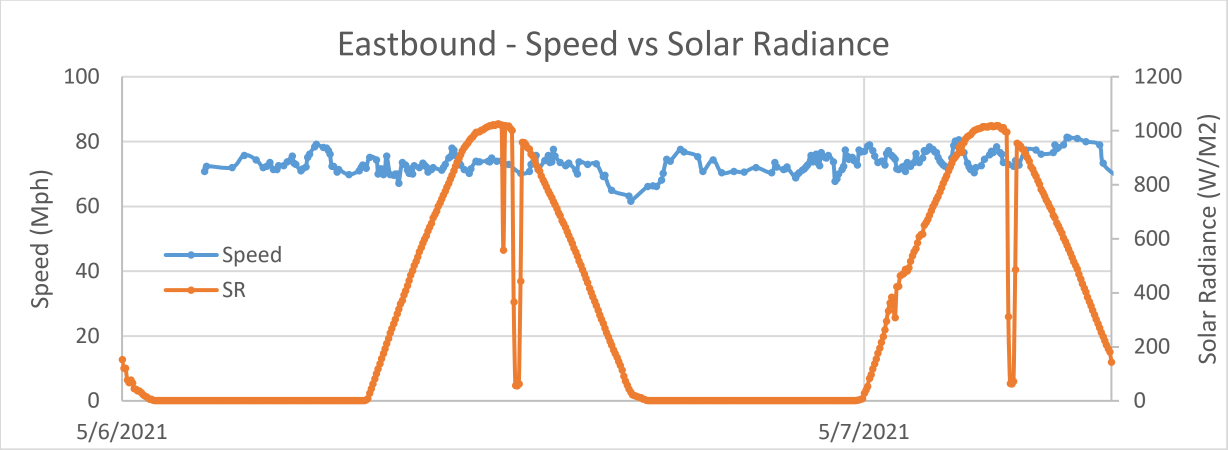


Figure 7.10: Speed vs. Solar Radiance, Eastbound I-20

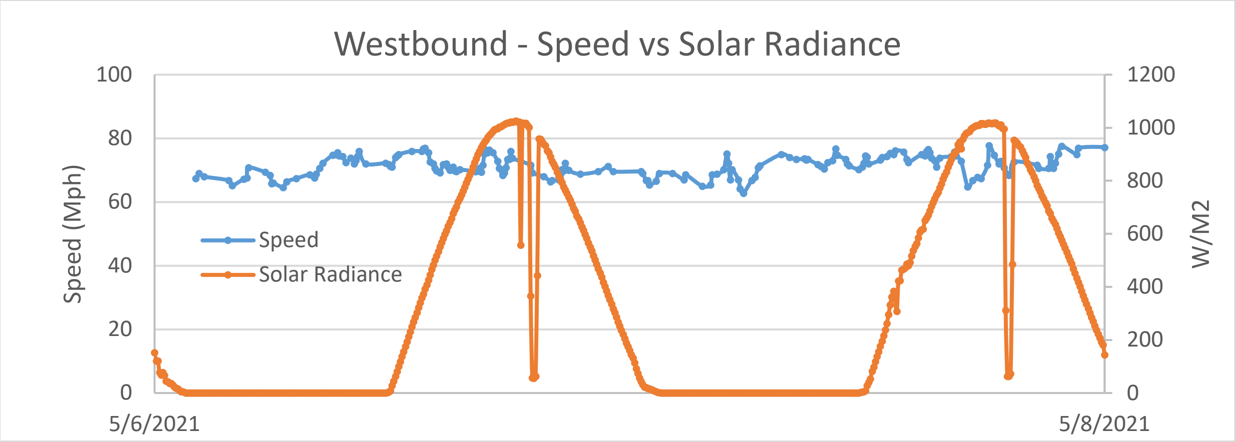


Figure 7.11: Speed vs. Solar Radiance, Westbound I-20

7.3.3. Other Applications of Ice Prediction Models

Optimal Task Allocation: When an extreme event happens, ice treatment vehicles' paths can be planned and adapted in real time. Each treatment vehicle can be allocated tasks in an optimal manner. The metric for optimality could be the shortest path, clearing up roads of highest priority, and maximizing traffic flow in road networks. Informed decisions for ice treatment vehicles are made possible by designing a mixed-integer optimization program that incorporates all financial and dynamical constraints of the vehicle, as well as data from weather stations, to understand external weather and road surface conditions.

Agriculture Applications: Since the model plays a crucial role in understanding the phenomenon of energy exchange between soil, vegetation, and atmosphere, the model's predictions are relevant for non-transportation purposes, such as agricultural management and irrigation system control.

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Appendix A. Value of Research

The value of research for this project comes from the mitigation of the safety and mobility impacts of weather on roadways. Weather-responsive decision making can improve traffic-flow and safety. Moreover, with the sensing and information dissemination frameworks that are designed and deployed as part of this project, opportunities are created to improve the performance of existing roadway networks, to develop better ice treatment strategies and to improve resource management.

Plan and Assumptions

In the following, we quantify the value of research by evaluating improvements in productivity and prevention of road crashes due to operations sensing and information system.

In the United States, 21% crashes in US are attributable to weather, of which 26% is ice-related, and 72% is tied to wet pavements [1]. The same source also explains that 20% road crashes are weather related. Of all causes of non-recurring delays, 25% are due to weather (Schrank, 2015), impacting the mobility of travelers and freight alike

We assume that with the science and technology introduced in this project, about 5% of **ice-related and wet-pavement crashes** can be avoided. This is made possible with real-time measurements and information provided by solution proposed in the project.

The costs associated with **reduced road salt** use with weather-responsive roadway management is quantified and presented.

Decision-making involves analyzing the road conditions, current and future weather forecasts, status and availability of vehicles, materials, budget constraints, traffic conditions, and communication aspects, which are time-consuming. Also, RWIS coupled with camera networks can help decision-makers be aware of the immediate road conditions, eliminating the need for manual inspection. We assume that with the solution proposed in the project, 50% of such **labor time** can be saved.

Not all weather events call for maintenance or treatment. However, without the presence of RWIS and MDSS, it is difficult to estimate the road conditions and temperature of the pavement during each storm, thus requiring an actionable call-out for every storm, even for those for which treatment is not required. We assume **a treatment call-out** reduction of as much as 30%. We remark this is a conservative estimate and the percentage may be higher if the proposed solution is effectively designed and deployed.

Maintenance operator **driving time**: With a reduced number of actionable events and full road treatment, there would a considerable amount of driving time saving (as much as 50%) with proposed mechanisms.

Material cost savings: Three main type of materials are used in the treatment process, including dry and wet de-icing materials, and also fuel to power maintenance vehicles. We assume 30% reduction in all these.

We discuss the cost of deployment of such a sensor network, and argue that **cost-to-benefit** is much favorable.

Beyond these, other assessments are possible with further work, and are not quantified in this analysis. For example,

- Winter operations sensing and data also reduce negative environmental impacts associated with excessive salt usage
- Use of RWIS and MDSS would result in consistent decision-making, improve accuracy of the decisions, and reduce stress on the decision-makers. This in turn would reduce the number of stress-related absences and help improve satisfaction and motivation of employers
- Efficient application of de-icing and anti-icing materials would reduce the amount of clean-up tasks.
- Maintenance cost savings as a result of timely road treatment thereby reduce damage to bridges and concrete pavements
- Indirect savings such as stress-related absences and IT labor costs
- Lower salt usage reduces vehicle corrosion and associated costs for drivers

Quantitative Analysis

Road Crashes

The National Highway Traffic Safety Administration (NHTSA) reported that motor vehicle crashes cost American society $340 billion in 2019, which is equivalent to $1,035 for each of the 328 million people in the United States. More than 150,000 auto crashes occur annually due to icy roads, which can result in property damage, injuries, and fatalities [2]. The Road Safety Foundation reported that effective snow fighting on roads cuts injury accidents by 88.3% [7]. According to another study, road salt can reduce crashes by 88%, injuries by 85%, and accident costs by 85% [10].

The Centers for Disease Control and Prevention (CDC) estimated that the cost of medical care and productivity losses associated with occupant injuries and deaths from motor vehicle traffic crashes exceeded $75 billion for crashes that occurred in 2017 [4].

In 2021, in Texas, 2849 crashes occurred over icy road surfaces [12]. Assuming that we can reduce the number of crashes by 5%, we have

$$5\%\ of\ 2849 = 2564\ accidents\ avoided\ per\ year$$

In average, the cost of an accident is \$5,700 for accidents that involve no injuries or casualties [13]. The yearly savings are thus in excess of \$811K/year. Assuming a discount factor of 10% on future benefits of the technology (incorporating the fact that new driver assist systems will further reduce the impact of accidents in the future), the total savings are in excess of \$9 M over a 10-year period.

Salt Usage

TxDOT uses brine to treat roads, which costs about 25 cents per gallon [5]. The North Carolina Department of Transportation reported that rock salt costs about \$14 per mile per lane to apply, while brine costs about half as much [6]. The Minnesota Pollution Control Agency reported that current road salt costs for MnDOT in the Twin Cities Metropolitan Area are \$60 to \$70/ton for snow and ice control, which makes up 20 to 30% of the total costs [7]. The Minnesota Department of Transportation used 1,832,487 gallons of salt brine in one year [4]. The Minnesota Department of Transportation (MnDOT) spent nearly \$116 million dollars to clear roads during the 2020-2021 winter season, according to a report [11].

Assuming a 30% reduction in salt or brine usage, and assuming usage of Texas would be 10% of the usage of Minnesota, we reach the savings of \$3,480,000.

Labor and Environmental Costs

The United States currently spends approximately \$2.3 billion annually to keep highways free of snow and ice, which includes labor cost. The associated corrosion and environmental impacts add at least \$5 billion to the cost [8]. The Minnesota Pollution Control Agency reported that labor costs for snow and ice control make up 40% of the total costs [7]. The cost of keeping roads snow and ice-free throughout a storm's duration was estimated at around \$4 million in one instance [9].

We assume that our proposed solution can make a reduction of 10% in the labor costs. This is made possible by time and money savings as explained in the Plan and Assumptions section. We combine these savings with savings due to treatment call-outs and maintenance driving costs savings and assume that Texas costs would be comparable to Minnesota costs. This yields labor cost savings to be $10\%\ of\ 40\%\ of\ \$(5+2.3)\ billion = \$292{,}000{,}000$

Benefit-to-Cost Ratio

The winter op vehicles can be equipped with weather operation sensing equipment, at the approximate cost of \$200/vehicle. Assuming that 5,000 vehicles are equipped, the total equipment cost is \$1M. This project cost a total of \$708,537.

Total Savings are given as

$$\$292{,}000{,}000\ + \$3{,}480{,}000\ + \$9{,}000{,}000 = \$304{,}480{,}000$$

This gives the benefit to cost ratio to be about 178:1.

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Appendix B. Plow Level Heuristic

The plow level heuristic derives an indication on whether a snowplow blade is likely resting in the up or down position from inputs that signify only when the blade is *in the process of moving* up or the blade is *in the process of moving* down. By allowing for this up/down resting position to be estimated, it reduces the need to use a physical sensor attached to the plow rig to sense the position.

Step 1: Calculate time difference at time i: $\Delta T_i = T_{i+1} - T_i$

Step 2: Create $Button_{down}$ variable where $Button_{Down} = \begin{cases} -1 & \text{if Aux3 = True} \\ 0 & \text{if Aux3 = False} \end{cases}$.

Also, create $Button_{up}$ variable where $Button_{up} = \begin{cases} +1 & \text{if Aux4 = True} \\ 0 & \text{if Aux4 = False} \end{cases}$

Step 3: Calculate the number of seconds the down or up button was pressed for.

$$Time_{down;\,i} = \Delta T_i \times Button_{down;\,i}$$
$$Time_{up;\,i} = \Delta T_i \times Button_{up;\,i}$$

Step 4: Calculate a variable that keeps track of the cumulative number of seconds each button is pressed for since the beginning of the trip.

$$Time - Cumulative_{down;\,i} = Time_{down;\,i} + Time - Cumulative_{down;\,i-1}$$
$$Time - Cumulative_{up;\,i} = Time_{up;\,i} + Time - Cumulative_{up;\,i-1}$$

Step 5: Search for the first time during the trip where the cumulative time the down button is pressed exceeds than 2 seconds

$IF \quad Time - Cumulative_{down;\,i} < -2 \ \rightarrow \ Time_{-2;\,i} = Time_{-2;\,i-1} + 1$

Else $Time_{-2;\,i} = 0$
Where $Time_{-2;\,i=0} = 0$

Step 6: Similarly, search for the first time during the trip where the cumulative time the up button is pressed exceeds than 2 seconds:

$IF \quad Time - Cumulative_{up;\,i} > 2 \ \rightarrow \ Time_{+2;\,i} = Time_{+2;\,i-1} + 1$
Else $Time_{+2;\,i} = 0$
Where $Time_{+2;\,i=0} = 0$

Step 7: Define when the state of the plow is "unknown":

IF $Time_{+2;\,i} = 0$ and $Time_{-2;\,i} = 0$ → Plow State = Unknown

Step 8: Find the timestamp with the first known plow state.

IF $Time_{+2;\,i} = 1$ and $Time_{-2;\,i} = 0$ → Plow State = Up
IF $Time_{+2;\,i} = 0$ and $Time_{-2;\,i} = 1$ → Plow State = Down

Step 9: Find the plow state corresponding to each timestamp i:

IF $Button_{down;\,i} = 0$ and $Button_{up;\,i} = 0 \rightarrow \text{Plow State}_i = \text{Plow State}_{i-1}$
IF $Button_{down;\,i} = -1$ and $Time_{-2;\,i} < -2 \rightarrow \text{Plow State}_i = \text{Down}$
IF $Button_{up;\,i} = +1$ and $Time_{+2;\,i} > 2 \rightarrow \text{Plow State}_i = \text{Up}$