UNIVERSITY OF TEXAS ARLINGTON

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Snowplow Operations Management System Final Report

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16. Abstract

Winter road maintenance accounts for approximately 20% of state departments of transportation's maintenance budgets; states and local highway agencies spend an average of $2.3 billion on winter operations every year. Nevertheless, over 5 million vehicle crashes occur in the U.S. each year, and approximately 21% of these crashes happen in the presence of adverse weather (e.g., sleet, snow, etc.). According to the National Highway Traffic Safety Administration, about 5,000 people are killed and over 418,000 are injured in weather-related crashes each year. These crashes also contribute to approximately $70.7 billion in property damages, including damages to the road infrastructure.

Real-time road conditions information, especially road conditions images, provide valuable information to transportation operations managers to enhance their winter operations practices and improve road safety. The primary objective of this project was to develop a Snowplow Operations Management System to (1) collect and display a live feed of road conditions images from tablets mounted on snowplows; (2) collect and display on-demand road conditions images upon request by TxDOT staff either in field or office for real-time analysis; (3) collect weather information that facilitates snowplow operations decisions from national weather services for visualization alongside snowplow locations and road conditions images; (4) estimate road surface temperatures and visualize the road segments prone to icing hazards; (5) develop an easy-to-use, map-based ArcGIS interface displaying the collected real-time road conditions images, weather information from national weather services, road surface temperatures, and roads prone to icing hazards for safe and efficient operations of snowplows; and (6) estimate the implementation cost of the Snowplow Operations Management System in TxDOT, including the capital cost and operating cost.

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Table of Contents

List of Tables

List of Figures

EXECUTIVE SUMMARY

Winter road maintenance accounts for approximately 20 percent of state Departments of Transportation's maintenance budgets; states and local highway agencies spend an average of $2.3 billion on winter operations every year (FHWA, 2020). Nevertheless, over 5 million vehicle crashes occur in the U.S. each year, and approximately 21% of these crashes happen in the presence of adverse weather (i.e., sleet, snow, etc.) (FHWA, 2020). According to the National Highway Traffic Safety Administration (NHTSA), about 5,000 people are killed and over 418,000 are injured in weather-related crashes each year (FHWA, 2020). These crashes also contribute to approximately $70.7 billion in property damages, including damages to the road infrastructure (Miller and Zaloshnja, 2009). Real-time road conditions information, especially road conditions images, provide valuable information to transportation operations managers to enhance their winter operations practices and improve the safety of the roads (Ameen et al., 2022; Shahandashti et al., 2019).

The primary objective of this project was to develop a Snowplow Operations Management System to (1) collect and display a live feed of road conditions images from tablets mounted on snowplows; (2) collect and display on-demand road conditions images upon requests by TxDOT staff either in field or office for real-time analysis; (3) collect weather information that facilitates snowplow operations decisions from national weather services in order to be visualized along with snowplow locations and road conditions images; (4) estimate road surface temperatures and visualize the road segments prone to icing hazards; (5) develop an easy-to-use map-based ArcGIS interface displaying the collected real-time road conditions images, weather information from national weather services, road surface temperatures, and roads prone to icing hazards for safe and efficient operations of snowplows; and (6) estimate the implementation cost of the Snowplow Operations Management System in TxDOT, including the capital cost and operating cost.

The research team developed an approach to turn tablets into snowplow operations management devices to automatically collect and transfer road conditions images at predetermined time intervals (e.g., every 10 minutes) when the snowplows are moving at the speed of 5 mph. The collected road conditions images were further processed and visualized in an ArcGIS map-based interface for a predetermined period of time (i.e., one hour). Also, the research team developed a feature in the system that facilitates providing on-demand images of road conditions upon requests from TxDOT staff either in field or office for real-time analysis.

In addition, the helpful weather information for managing the snowplows operations was identified from national weather services and integrated into the map-based interface using Esri map services to be displayed along with snowplow locations and road conditions images.

The research team also estimated road surface temperatures by developing sets of statistical models, which allowed estimating the road surface temperatures using forecasts weather data from national weather services. From extensive data collection and statistical data analysis on actual road surface temperatures and ambient weather data during the winter season 2021-22 in North Texas, the research team concluded that the ambient temperature, relative humidity, wind speed, average temperature of the previous day, and road surface condition (wet/dry) are correlated with the road surface temperatures. The estimated road surface temperatures were further visualized on the map-based interface for up to five (5) days.

With the help of TxDOT, the research team set up a pilot test in the Wichita Falls district to evaluate the performance of the system for the 2020-21 and 2021-22 winter seasons. The collected images, along with other road conditions information, were visualized in an ArcGIS map-based interface with interactive maps.

This implementation project helps communicate adverse road conditions, improve snowplow operational decisions, and consequently decrease weather-related crashes. Real-time images of road conditions help transportation operations managers visually monitor road conditions and make well-informed decisions during snowstorms. In addition, access to certain weather information that facilitates snowplow operations decisions, as well as information about road surface temperatures provide essential information to TxDOT operations managers about possible locations of low road surface temperatures and potential ice and snow hazards on roads. This information could improve decision-making for deploying snowplows to administer anti-icing and snow-removal measures on roads during winter operations.

CHAPTER 1. INTRODUCTION

Winter road maintenance accounts for approximately 20 percent of State Departments of Transportation's (State DOTs) maintenance budgets; states and local agencies spend over $2.3 billion on winter operations annually (FHWA, 2020). Adverse weather will act through low visibility, precipitation, high winds, and extreme temperature to affect driver capabilities and vehicle performance (FHWA, 2020). Table 1.1 summarizes the impacts of various weather events on roadways, traffic flow, and operational decisions.

Table 1.1 Weather impacts on roads, traffic, and operational decisions (FHWA, 2020)

Road Weather Variables	Impacts on Roadway	Impacts on Traffic Flow	Operational Impacts
Air temperature and humidity	N/A	N/A	▪ Road treatment strategy (e.g., snow and ice control) ▪ Construction planning (e.g., paving and striping)
Wind speed	▪ Visibility distance (due to blowing snow, dust) ▪ Lane obstruction (due to wind-blown snow, debris)	▪ Traffic speed ▪ Travel time delay ▪ Crash risk	▪ Vehicle performance (e.g., stability) ▪ Access control (e.g., restrict vehicle type, close road) ▪ Evacuation decision support
Precipitation (type, rate, start/end times)	▪ Visibility distance ▪ Pavement friction ▪ Lane obstruction	▪ Roadway capacity ▪ Traffic speed ▪ Travel time delay ▪ Crash risk	▪ Vehicle performance (e.g., traction) ▪ Driver capabilities/behavior ▪ Road treatment strategy ▪ Traffic signal timing ▪ Speed limit control ▪ Evacuation decision support ▪ Institutional coordination
Fog	▪ Visibility distance	▪ Traffic speed ▪ Speed variance ▪ Travel time delay ▪ Crash risk	▪ Driver capabilities/behavior ▪ Road treatment strategy ▪ Access control ▪ Speed limit control
Pavement temperature	▪ Infrastructure damage	N/A	▪ Road treatment strategy

Road Weather Variables	Impacts on Roadway	Impacts on Traffic Flow	Operational Impacts
Pavement condition	▪ Pavement friction ▪ Infrastructure damage	▪ Roadway capacity ▪ Traffic speed ▪ Travel time delay ▪ Crash risk	▪ Vehicle performance ▪ Driver capabilities/behavior (e.g., route choice) ▪ Road treatment strategy ▪ Traffic signal timing ▪ Speed limit control
Water level	▪ Lane submersion	▪ Traffic speed ▪ Travel time delay ▪ Crash risk	▪ Access control ▪ Evacuation decision support ▪ Institutional coordination

According to the Federal Highway Administration, over 5,891,000 vehicle crashes occur in the U.S. each year, and approximately 21% of these crashes happen in the presence of adverse weather (i.e., rain, sleet, snow, fog, etc.) (FHWA, 2020). Moreover, about 5,000 people are killed and over 418,000 are injured in weather-related crashes each year (FHWA, 2020). These crashes also contribute to approximately $70.7 billion in property damages, including damages to the road infrastructure (Miller and Zaloshnja, 2009). Table 1.2 summarizes weather-related crash statistics from 2007 to 2016 analyzed by Booz Allen Hamilton, based on the data provided by National Highway Traffic Safety Administration. In order to improve transportation features, such as roadways safety, transportation agencies sponsor a variety of transportation research projects (Ashuri et al., 2017; Ashuri et al., 2014).

Table 1.2 Weather-related crash statistics from 2007 to 2016 (FHWA, 2020)

Road Weather Conditions	Category	Weather-Related Crash Statistics (10 Year Statistics)		
		Number of Crashes	**Percentage of Total Vehicle Crashes**	**Percentage of Total Weather-Related Crashes**
Wet Pavement	Vehicle crashes	860,286	15%	70%
	Crash injuries	324,394	15%	78%
	Crash fatalities	4,050	12%	76%
Rain	Vehicle crashes	556,151	10%	46%
	Crash injuries	212,647	10%	51%
	Crash fatalities	2,473	8%	46%
Snow/Sleet	Vehicle crashes	219,942	4%	18%
	Crash injuries	54,839	3%	14%
	Crash fatalities	688	2%	13%
Icy Pavement	Vehicle crashes	156,164	3%	13%
	Crash injuries	41,860	2%	11%
	Crash fatalities	521	2%	10%
Snow/Slushy Pavement	Vehicle crashes	186,076	4%	16%
	Crash injuries	42,036	2%	11%
	Crash fatalities	496	2%	10%
Fog	Vehicle crashes	25,451	1%	3%
	Crash injuries	8,902	1%	3%
	Crash fatalities	464	2%	9%

The overall objective of this project is to create a Snowplow Operations Management System to (1) collect and display a live feed of road conditions images from tablets mounted on snowplows; (2) collect and display on-demand road conditions images upon requests by TxDOT staff either in field or office for real-time analysis; (3) collect weather information that facilitates snowplow operations decisions from national weather services in order to be visualized along with snowplow locations and road conditions images; (4) estimate road surface temperatures and visualize the road segments prone to icing hazards; (5) develop an easy-to-use map-based ArcGIS interface displaying the collected real-time road conditions images, weather information from national weather services, road surface temperatures, and roads prone to icing hazards for safe and efficient operations of snowplows; and (6) estimate the implementation cost of the Snowplow Operations Management System in TxDOT, including the capital cost and operating cost. Figure 1.1 shows an overview of the Snowplow Operations Management System. This implementation project helps communicate adverse road conditions, improve snowplow operational decisions, and consequently decrease weather-related crashes.

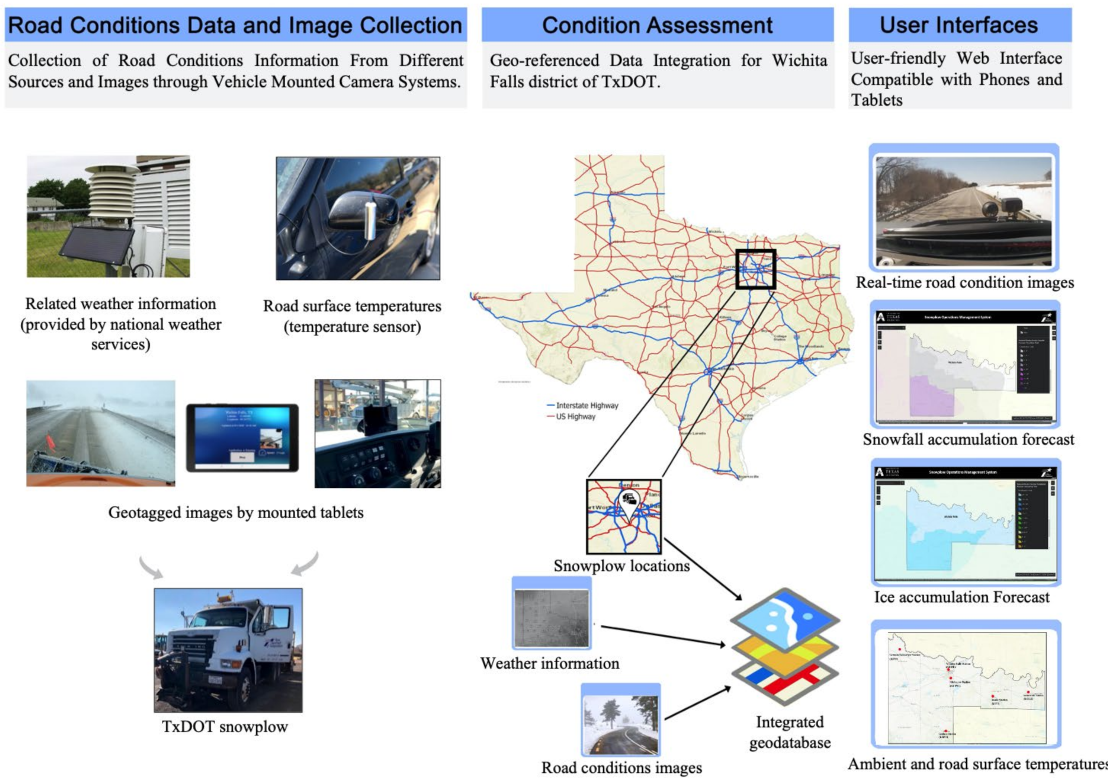


Figure 1.1 An overview of Snowplow Operations Management System, from data sources to user interface

This technical report explains all the Tasks performed in developing the Snowplow Operations Management System for the TxDOT Wichita Falls district. The report is organized as follows:

Chapter 1 is this introductory chapter.

Chapter 2 explains turning tablets into snowplow operations management devices to provide a live feed of road conditions images.

Chapter 3 explains collecting weather information that facilitates snowplow operations decisions from national weather services in order to be visualized in a map-based interface.

Chapter 4 explains developing sets of statistical models to estimate the road surface temperatures and describes the approach used to visualize the road segments prone to icing hazards.

Chapter 5 explains the Map-based ArcGIS Interface.

Chapter 6 explains the implementation cost of the Snowplow Operations Management System

Chapter 7 explains developing an on-demand road conditions image collection feature for the system.

Chapter 8 is the summary of the pilot district's feedback during the implementation period.

Chapter 9 is the summary and conclusion of this technical report.

CHAPTER 2. LIVE FEED OF ROAD CONDITIONS IMAGES

This chapter explains how the research team turned tablets into snowplow operations management devices to provide real-time images of road conditions. The research team developed a custom Android application, running on mounted tablets on snowplows, to collect geotagged images as a snowplow moves over five (5) mph. These tablets facilitate collecting and transferring real-time road conditions images as snowplows operate in field. The research team employed this technology in the TxDOT Wichita Falls district to provide road conditions images to the district's transportation managers during 2020-21 and 2021-22 winter seasons. Figure 2.1 shows a TxDOT snowplow in the Wichita Falls district and a programmed tablet mounted on the snowplow's windshield to collect real-time road conditions images.

(a) (b)

Figure 2.1 (a) Wichita Falls' snowplow; (b) Mounted tablet in the snowplow

2.1 Introduction

Winter road conditions is one of the most often requested information by the transportation operations managers (Deeter et al., 2014). The road conditions images can provide valuable information for transportation operations managers in enhancing their winter operations practices (Ameen et al., 2022). This information can be collected through snapshots of road conditions by a mounted camera on transportation agencies' snowplows (Shahandashti et al., 2019). The research team developed a custom Android application, running on mounted tablets on snowplows, to collect geotagged images of road conditions in TxDOT's Wichita Falls district. The collected images were further displayed on a user-friendly map-based interface.

The research team tested and debugged the custom Android application on a Samsung Galaxy tablet, shown in Figure 2.2, similar to the device that the Oklahoma DOT employed on its snowplow fleet. Table 2.1 summarizes the technical specification of the tablet used in this project.

Figure 2.2 Samsung Galaxy Tab A 8-inch tablet

Table 2.1 Technical specifications of the tablet used to test the custom Android application (Source: Samsung website)

	Element	Description
Processor	CPU Speed	2GHz
	CPU Type	Quad-Core
Display	Size (Main Display)	8.0" (203.1mm)
	Resolution (Main Display)	1280 x 800 (WXGA)
	Technology (Main Display)	TFT
	Color Depth (Main Display)	16M
Camera	Main Camera - Resolution	8.0 MP
	Main Camera - Auto Focus	Yes
	Front Camera - Resolution	2.0 MP
	Main Camera - Flash	No
	Video Recording Resolution	FHD (1920 x 1080) @30fps
Memory	RAM Size	2 GB
	ROM Size	32 GB
	Available Memory	21.3 GB
	External Memory Support	MicroSD (Up to 512GB)
Network / Bearer	2G GSM	GSM850, GSM900, DCS1800, PCS1900
	3G UMTS	B1(2100), B2(1900), B4(AWS), B5(850), B8(900)
	4G FDD LTE	B1(2100), B2(1900), B3(1800), B4(AWS), B5(850), B7(2600), B8(900), B12(700), B17(700), B20(800), B28(700)
	4G TDD LTE	B38(2600), B40(2300), B41(2500)
Connectivity	USB Version	USB 2.0
	Location Technology	GPS, Glonass, Beidou, Galileo
	Ear jack	3.5mm Stereo
	Wi-Fi	802.11 a/b/g/n 2.4+5GHz
	Wi-Fi Direct	Yes
	Bluetooth Version	Bluetooth v4.2
	NFC	No
	Bluetooth Profiles	A2DP, AVRCP, DI, HID, HOGP, HSP, OPP, PAN
Operating System	Android Version	Android 9.0 Pie
Sensors	Motion	Accelerometer
	Environment	Light
Physical specification	Dimension (H x W x D, inch)	8.27×4.9×0.31
	Weight (oz)	12.24
Battery	Battery Capacity	5100 mAh
	Removable	No
Audio and Video	Video Playing Format	MP4, M4V, 3GP, 3G2, WMV, ASF, AVI, FLV, MKV, WEBM
	Video Playing Resolution	FHD (1920 x 1080) @30fps
	Audio Playing Format	MP3, M4A, 3GA, AAC, OGG, OGA, WAV, WMA, AMR, AWB, FLAC, MID, MIDI, XMF, MXMF, IMY, RTTTL, RTX, OTA

Rugged tablets could also be used for this project. The rugged tablets meet certain requirements, especially in terms of protection against extreme and rough environments. They might be slightly more expensive; however, these tablets are designed to handle heavy-duty tasks and are more durable. Figure 2.3 shows an example of a rugged tablet in the market (Galaxy Tab Active 3).

Figure 2.3 Example of a rugged tablet (source: www.gpslockbox.com)

2.2 Developing a Custom Android Application to Collect and Transfer Images

The research team developed a custom Android application to facilitate collecting geotagged images by mounted tablets on snowplows. The custom application was designed to collect and transfer geotagged images of road conditions at predetermined time intervals (i.e., every 10 minutes) when a snowplow operates at a speed of 5 mph or more. Figure 2.4 shows the data flow from a tablet device to the map-based interface.

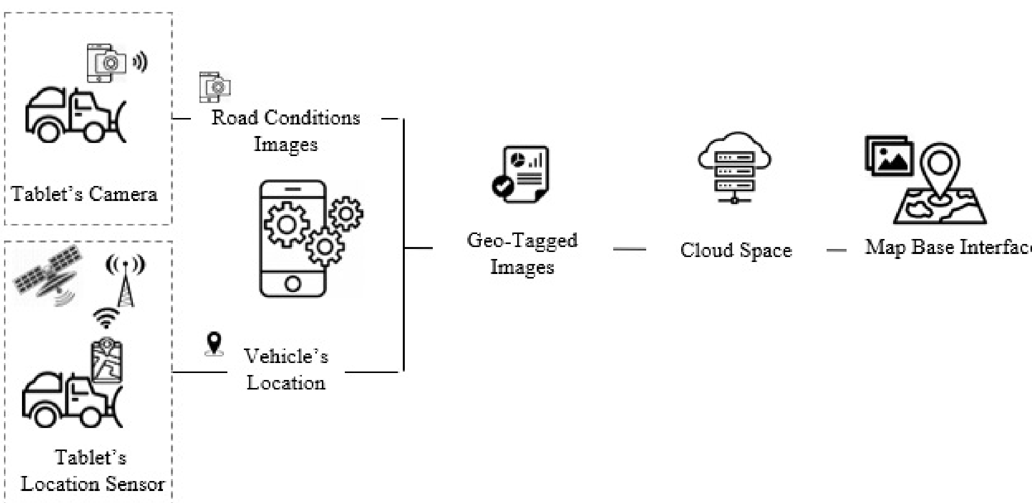


Figure 2.4 Data flow from the tablet to a map-based interface

The custom Android application was developed in Java, the official language for Android development. To develop the custom application, the research team used different application programming interfaces (APIs), Java classes, and object methods to execute various tasks, such as retrieving the vehicle speed, capturing the images, determining the vehicle location, constructing metadata, and uploading the data to cloud space. Figure 2.5 shows the function modeling methodology used to develop the custom Android application, which runs on Android tablets.

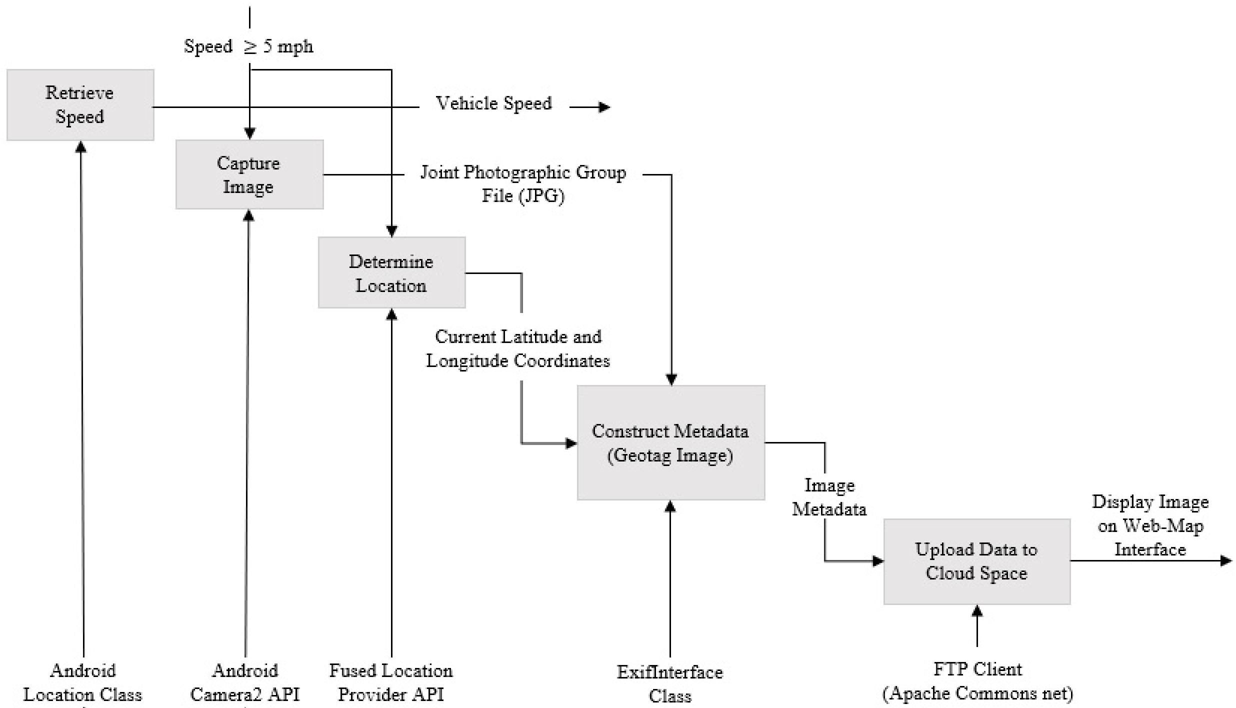


Figure 2.5 Function modeling methodology for custom Android application in Java language

The following subsections provide more details about each task of the custom Android application.

2.2.1 Vehicle Speed

Tablets come with built-in location sensors that determine the device's location, elevation, and speed. The developed application, running on tablets, utilized the "Location Manager" class in Android development to retrieve the device's speed. The speed is calculated by dividing the distance the device travels by the total time it takes to travel that distance. To retrieve the speed, first, the Android "Location Manager" class obtains periodic updates of the tablet's geographical location at specific time intervals and provides access to the device's system location services (Android developers, 2020a). Then, the "LocationListener," another Java class, receives notifications from the LocationManager when the location of the device changes. The LocationListener gets notified based on the specified distance intervals or number of seconds. By having location updates, a Java location object method, “getSpeed,” returns the device's speed in metric units (Android developers, 2020a). Furthermore, appropriate conversion factor converts the metric unit (km/h) to the imperial unit (mph) within the application. The required permissions, including access to “Fine Location,” “Coarse Location,” and “Internet,” were granted in the Android manifest file to access the location services of the device to retrieve the speed.

2.2.2 Capture Image

The built-in camera in the tablet is used to capture the images. The “android.hardware.camera2” package uses the tablet’s camera device as a pipeline, which takes input requests for capturing a single frame in order to output one capture result as a metadata packet (Android developers, 2020b). The developed application uses the “android.hardware.camera2” package to create a “camera capture session” with a set of output surfaces within the camera device.

First, the application constructs a CaptureRequest, which defines all the camera device's capture parameters to capture a single image (Android developers, 2020b). Once the request is set up, it is handed to the active capture session. After processing the request, the camera device produces a TotalCaptureResult object, which contains information about the state of the camera device at the time of capture, and the final settings used (Android developers, 2020b). Lastly, the captured image is sent to TextureView target surface to preview (Android developers, 2020b). Appropriate permissions, including “access to the camera” and “write to external storage,” were granted in the Android manifest file to access the camera device to capture and save the images to the storage space.

2.2.3 Vehicle Location

Most Android devices take advantage of the signals provided by multiple sensors to determine the location. However, choosing the right combination of signals for a specific task in different conditions remains essential (Android developers, 2020c). Finding a battery-efficient solution is also critical. This custom Android application uses the “Fused Location Provider;” a Google Play Service that combines different signals (i.e., GPS and cell tower) to determine the location information of the tablet at predetermined time intervals.

First, a Location Service client is created to retrieve the device location within the application. Once the Location Service client is created, the application can determine the last known location of the tablet by the "getLastLocation" Java object method. This method returns the current latitude and longitude of the device location (Android developers, 2020c). Appropriate permissions, including access to "fine location" and "coarse location," were granted in the Android manifest file to provide access to the location services of the tablet.

2.2.4 Construct Image Metadata

Metadata describes data about data. Specifically, image metadata is the information embedded into an image that includes details about the image itself and information about its creation. The image metadata allows information to be transferred together with an image in a way that can be understood by software, hardware, and humans, regardless of the format. While the tablet generates default (i.e., time, camera model, focal length, etc.) metadata during the capturing process, other required metadata (i.e., location information) should be added. To integrate the required location data (longitude and latitude coordinates) into the image metadata, the Android "ExifInterface" class was used to geotag the captured images and add the location information to the image metadata. This class facilitated reading and writing Exchangeable Image File (EXIF) tags into a JPEG file or a RAW image file (Android developers, 2020d).

The standard form of GPS coordinates for the image EXIF file is in "Degree, Minutes and Seconds (DMS)" format; however, the latitude and longitude coordinates that the Fused Location Provider class provides are in decimal. Therefore, a local Java method was implemented in the application to convert the decimal coordinates to DMS format. Lastly, an ExifInterface object method known as "setAttribute" added the current latitude and longitude coordinates to the image file at the time when the image was captured. Table 2.2 shows examples of metadata created by the custom Android application for a captured image.

Table 2.2 Example metadata for a captured image by the custom application

Property	Value
Camera Make	Samsung
Camera Model	SM-T295
Exposure	1/33
Focal Length	3.8 mm
ISO Speed	176
Flash	Off
Image Width	1920
Image Height	1080
Orientation	Rotate 90 CW
Date and Time	2020:06:10 15:52:21
GPS Latitude	32.732814
GPSLatitudeRef	North
GPSLongitude	97.113237
GPSLongitudeRef	West

2.2.5 Upload Image Metadata to Cloud Space

The developed application uses the "File Transfer Protocol (FTP)" method to upload the image metadata to cloud space. FTP is a secure network protocol to transfer data between a host device (i.e., tablet) and a remote server (i.e., cloud space). Through the FTP connection between the application and the server, the application can upload, download, or delete files from the cloud space. To establish an FTP connection, the application implements the "Apache Commons Net" library. The Apache Commons Net library contains a collection of network utilities and protocol implementations, including FTP, to set up the connection between host device and server (Apache Software Foundation, 2020). In this application, the host device is the tablet, and the server is the University of Texas at Arlington (UTA) cloud space, which temporarily stores the images to be further processed and displayed on the map-based interface.

Every FTP client needs information about the server, including "Host Address," "Port," "Username," and "Password" to establish the connection. This information was extracted from the UTA cloud account and implemented in the application development. To prevent images from backlogging in the cloud, this connection was designed to delete images older than an hour in the cloud. The appropriate permissions, including access to "network state" and "internet," were granted in the Android manifest file to set up the FTP connection.

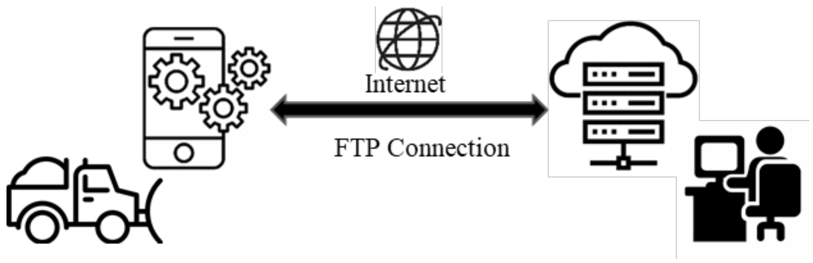


Figure 2.6 Uploading image metadata to cloud space

2.2.6 The Custom Android Application's User Interface

Collecting data using the custom application is relatively self-sufficient with minimum distraction for the snowplow operators. Figure 2.7 shows the user interface of the developed application. The user starts the data collection by pressing the "Run" button. As the button is pressed, the application begins to collect geotagged images and upload them to the cloud space if the snowplow operates at a speed of 5 mph or more. The process described in Subsections 2.2.1 to 2.2.6 would be repeated every 10 minutes unless the user presses the "Stop" button.

Figure 2.7 The user interface of custom Android application

2.3 Results

With the help of TxDOT, the research team set up a pilot test for the developed system in the TxDOT Wichita Falls district as a proof of concept and provided road conditions images, collected from mounted tablets on snowplows, to the district's transportation managers during 2020-21 and 2021-22 winter seasons. The tablets were mounted on the front windshield of the snowplows using suction-cup mounts in a location with no distraction for the drivers. The tablets were powered using a USB power outlet in the snowplows. Figure 2.8 shows a mounted tablet on a TXDOT snowplow and the snowplow's power outlet, which powered the tablets during the operations time using a USB cable.

a **b**

Figure 2.8 (a) Tablet mounted on the front windshield using a suction-cup mount, and (b) USB cable and power outlet used to provide power for the tablets

Each tablet used a data plan to transfer data to the developed snowplow operations management system for displaying the road condition images on the map-based ArcGIS interface.Figure 2.9 and Figure 2.10 show examples of collected road condition images during the 2020-21 and 2021-22 winter seasons in the Wichita Falls district.

Figure 2.9 Examples of collected road condition images 2020–21 winter season

(a) Wichita County, 1/1/2021, 7:36 AM; (b) Young County, 1/1/2021, 8:53 AM,

(c) Wichita County, 1/1/2021, 7:06 AM; (d) Wilbarger County, 1/1/2021, 1:38 PM,

(e) Wilbarger County. 12/31/2020, 3:57 PM; (f) Wichita County, 1/1/2021, 7:46 AM

Figure 2.10 Examples of collected road condition images 2021–22 winter season

(a) Young County, 2/27/2022, 5:50 PM; (b) Cooke County 2/2/2022, 9:53 AM,
(c) Baylor County, 2/24/2022, 7:06 AM; (d) Wilbarger County, 2/23/2022, 1:38 PM,
(e) Montague County, 2/25/2022, 3:57 PM; (f) Archer County, 2/27/2022, 2:29 PM

2.4 Summary

Real-time road conditions images, provided by mounted tablets on snowplows, help transportation operations managers, snowplow operators, and the traveling public to make well-informed decisions during snowstorms. This chapter explained how the research team developed a custom Android application for mounted tablets on snowplows to collect real-time images of road conditions and transfer them to cloud space. The custom Android application automatically takes geotagged images every ten (10) minutes while the snowplow operates at a speed of five (5) mph or more. The image metadata was temporarily uploaded in UTA cloud space.

The developed custom application facilitates collecting road conditions images automatically through mounted tablets on snowplows. The collected images will be further processed using python scripts to feed the ArcGIS map-based interface to visualize them through interactive maps for the transportation operations managers.

CHAPTER 3. CURRENT AND FORECAST WEATHER INFORMATION

This chapter provides information about collecting and displaying weather information that facilitates snowplow operations management decisions. The research team developed an approach to (1) automatically collect weather information from official national sources, such as the National Oceanic and Atmospheric Administration (NOAA) and National Weather Service (NWS), and (2) display them on the ArcGIS map-based interface developed for facilitating the real-time visualization of geotagged data during snowplow operations. Figure 3.1 shows an overview of data sources, geo-referenced GIS layers, and a map-based interface for displaying weather data.

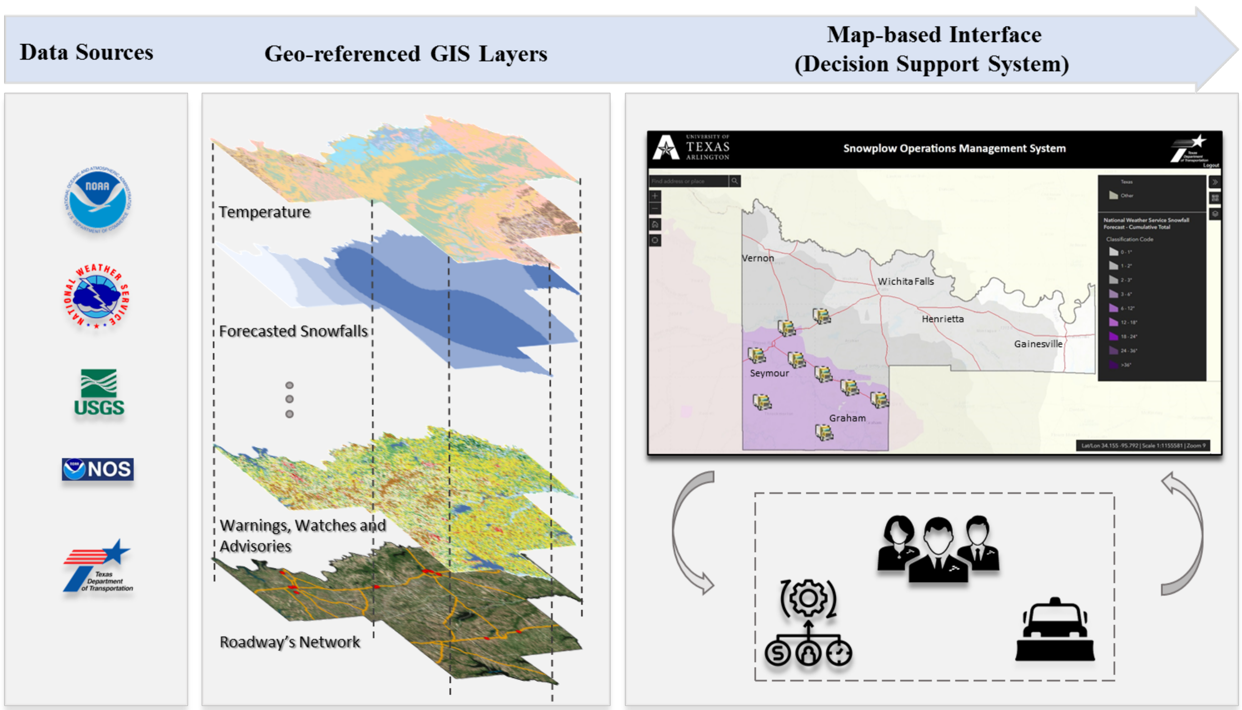


Figure 3.1- Overview of data sources, geo-referenced GIS layers, and map-based interface for collecting and displaying weather data

3.1 Current Weather Information

The current weather information (e.g., ambient temperatures) is collected from hourly Meteorological Aerodrome Reports (METAR) administered by NOAA. Typical METAR data contain information about several weather variables for each land-based Environmental Sensor Station location (Federal Aviation Administration, 2017):

- Air Temperature
- Dew Point
- Wind Speed and Direction
- Relative Humidity
- Horizontal Visibility
- Weather Condition
- Precipitation
- Sky Condition (Cloud Cover and Heights)
- Barometric Pressure

The research team used the information from the land-based Environmental Sensor Stations (i.e., METAR) to visualize the current weather information in the system. The following subsection describes the land-based Environmental Sensor Stations used to obtain the hourly meteorological data in the TxDOT Wichita Falls district.

3.1.1 Environmental Sensor Stations

Environmental Sensor Stations are utilized across the United States to provide weather data for the public and government agencies. An Environmental Sensor Station contains various types of instrumentation such as temperature sensors, wind sensors, and barometric pressure sensors to collect meteorological data from the field. The Environmental Sensor Stations are mainly administered by external agencies such as the National Weather Service, the Federal Aviation Administration, the US Geological Survey, the Department of Agriculture, the Forest Service, and the Environmental Protection Agency.

The research team developed an approach to automatically collect current weather information from the available Environmental Sensor Stations in the TxDOT Wichita Falls district and display the related data on the ArcGIS map-based interface. The Environmental Sensor Stations, administered by NOAA, report meteorological data on an hourly basis. Figure 3.2 shows the locations of the available Environmental Sensor Stations in the TxDOT Wichita Falls district.

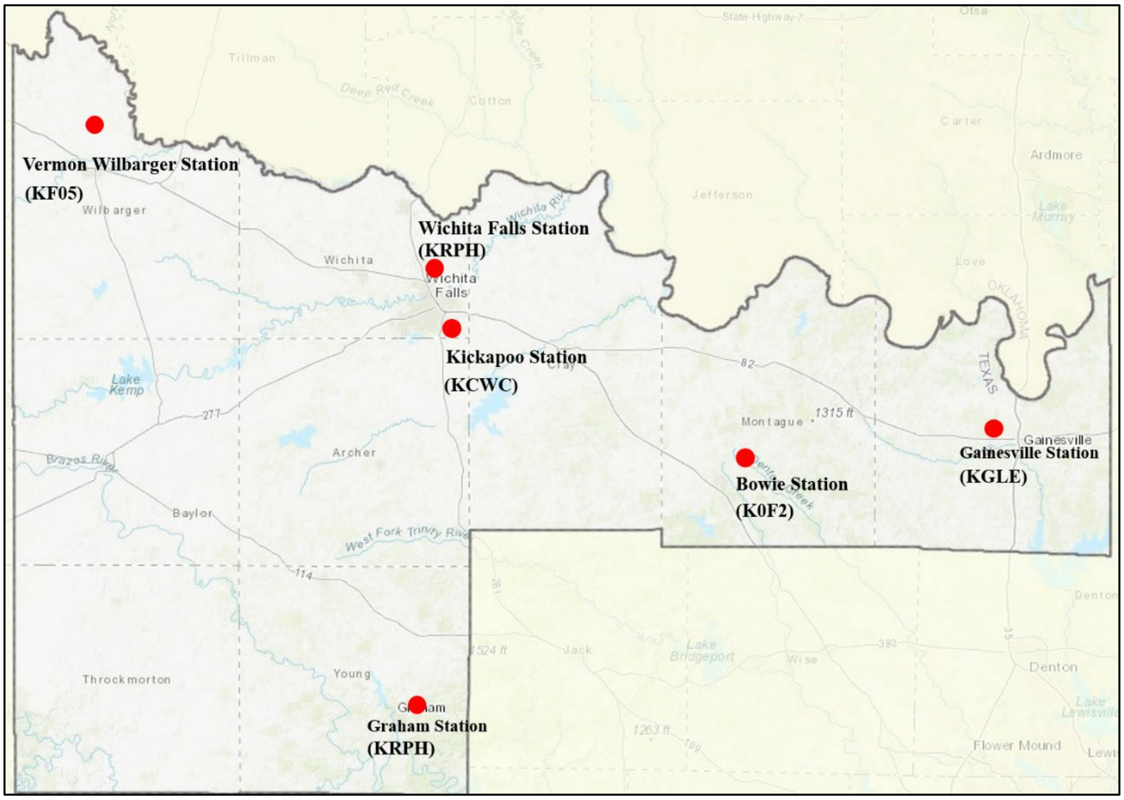


Figure 3.2 Environmental sensor stations in TxDOT Wichita Falls district

Table 3.1 provides more detailed information (i.e., identifier, elevation, latitude, and longitude) about each Environmental Sensor Station in the TxDOT Wichita Falls district.

Table 3.1 Information about environmental sensor stations in TxDOT Wichita Falls district

Observation Station Name	Identifier	Elevation	Latitude	Longitude
Sheppard Air Force Base, Wichita Falls, TX	KSPS	1014 ft	33.97861	-98.49278
Wilbarger County Airport, Vernon, TX	KF05	1266 ft	34.22556	-99.28361
Kickapoo Downtown Airport, Wichita Falls, TX	KCWC	1003	33.8647	-98.4918
Bowie Municipal Airport, Bowie, TX	K0F2	1100	33.6017	-97.7756
Gainesville Municipal Airport, Gainesville, TX	KGLE	840	33.65139	-97.19694
Graham Municipal Airport, Graham, TX	KRPH	1122	33.11000	-98.55528

3.2 Graphical Forecast Maps

The National Weather Service (NWS) is an agency of the United States federal government that provides graphical forecast maps to visualize weather forecasts, warnings of hazardous weather, and other weather-related products for organizations and the public to enhance protection, safety, and general information. The NWS's National Digital Forecast Database (NDFD) uses data from regional NWS Weather Forecast Offices and the National Centers for Environmental Prediction. Below are some examples of forecast weather data provided by the NDFD:

- Precipitation forecast
- Snowfall forecast
- Dew point forecast
- Ice accumulation forecast
- Wind speed forecast
- Relative humidity forecast

The graphical forecast maps include incremental and cumulative data for snowfall, precipitation, and ice accumulation in 6-hour intervals. The incremental and cumulative data facilitate determining the intensity and average of forecasted weather data, such as snowfall over a specific period of time.

Weather forecasts use a variety of terminologies. Table 3.2 explains the sky condition terminologies used in the forecast reports. The sky condition describes the predominant or average sky cover based on the percent of the sky covered by opaque (not transparent) clouds. If a high probability of precipitation (60% or greater) is expected, the sky condition may be omitted since it is inferred from the precipitation forecast (NOAA, 2021a).

Table 3.2 Sky condition terminology description (NOAA, 2021)

Sky Condition	Opaque Cloud Coverage
Clear/Sunny	1/8 or less
Mostly Clear/Mostly Sunny	1/8 to 3/8
Partly Cloudy/Partly Sunny	3/8 to 5/8
Mostly Cloudy	5/8 to 7/8
Cloudy	7/8 to 8/8

Table 3.3 explains the temperature forecast terminologies in the forecast reports. The temperature in a forecast report is used to describe the forecast maximum and minimum temperature, or in some cases, the temperature at a specific time (NOAA, 2021a).

Table 3.3 Temperature forecast terminology description (NOAA, 2021a)

Temperature Description	Forecast Meaning
Around 50/Near 50	A range of temperatures from 48 to 52
The lower 50s	Temperatures of 50, 51, 52, 53, 54
The Mid 50s	Temperatures of 53, 54, 55, 56, 57
The Upper 50s	Temperatures of 56, 57, 58, 59
The 50s	A range of temperatures from 50 to 59
50 to 55	Temperatures of 50, 51, 52, 53, 54, 55

Table 3.4 explains the wind forecast terminologies in the forecast reports. The wind forecast report describes the prevailing direction from which the wind is blowing with speeds presented in miles per hour (NOAA, 2021a).

Table 3.4 Wind forecast terminology description (NOAA, 2021a)

Sustained Wind (mph)	Speed Descriptive Term
0-5 mph	Light/ light and variable wind
5-10 / 10-15 / 10-20	None
15-25	Breezy (mild weather) Brisk or Blustery (cold weather)
20-30	Windy
30-40	Very Windy
40 greater	Strong, dangerous, high, damaging (High Wind Warning Criteria)

Table 3.5 explains the precipitation forecast terminologies in the forecast reports. The probability of precipitation (POP) is the likelihood of a measurable amount of liquid rainfall during a specified period at any given point in the forecast area. The forecast area, or zone, is generally considered a county (NOAA, 2021a).

Table 3.5 Precipitation probability terminology description (NOAA, 2021)

Probability of Precipitation (%)	Expression of Uncertainty	Equivalent Areal Qualifier
10	(None used)	Isolated/ Few
20	Slight Chance	Widely Scattered
30, 40, and 50	Chance	Scattered
60 & 70	Likely	Numerous (or none used)
80, 90, & 100	(None used)	Occasional, periods of, or none

Table 3.6 describes the time periods terminologies in the forecast reports.

Table 3.6 Time periods terminology description (NOAA, 2021a)

Forecast Time Period	NWS Definition (LST)
Today	6 am-6 pm
This Morning	6 am-noon
This Afternoon	Noon-6 pm
This Evening	6 pm-midnight
Overnight	Midnight-6 am
Tonight	6 pm-6 am

Figure 3.3 shows a graphical forecast map for snowfall, provided by the National Weather Service, during a winter storm over Texas on January 8, 2021, at 4:15 PM. According to the forecast map, snow accumulation is predicted to affect some areas of Texas.

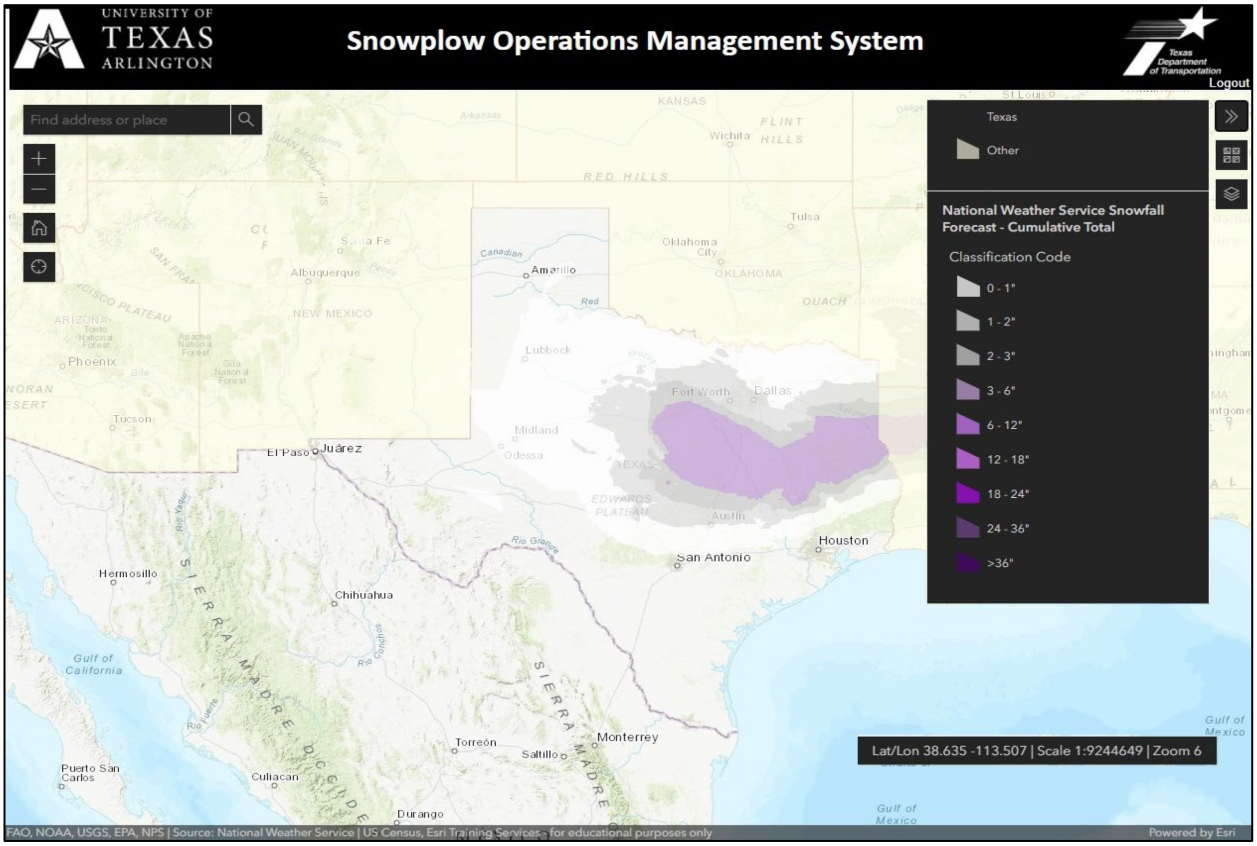


Figure 3.3 Snowfall forecast by the National Weather Service (Texas, January 8, 2021, 4:15 PM)

Figure 3.4 shows a graphical forecast map for snowfall over the TxDOT Wichita Falls district on January 8, 2021, at 4:23 PM. As the graphical forecast map shows, the Southwestern regions of the district are predicted to have more snowfall compared to the other regions. Moreover, Figure 3.5 shows a graphical forecast map for precipitation over the TxDOT Wichita Falls district on January 8, 2021, at 4:37 PM. According to the graphical forecast map, the Southwestern regions of the district are predicted to get more precipitation compared to the other regions.

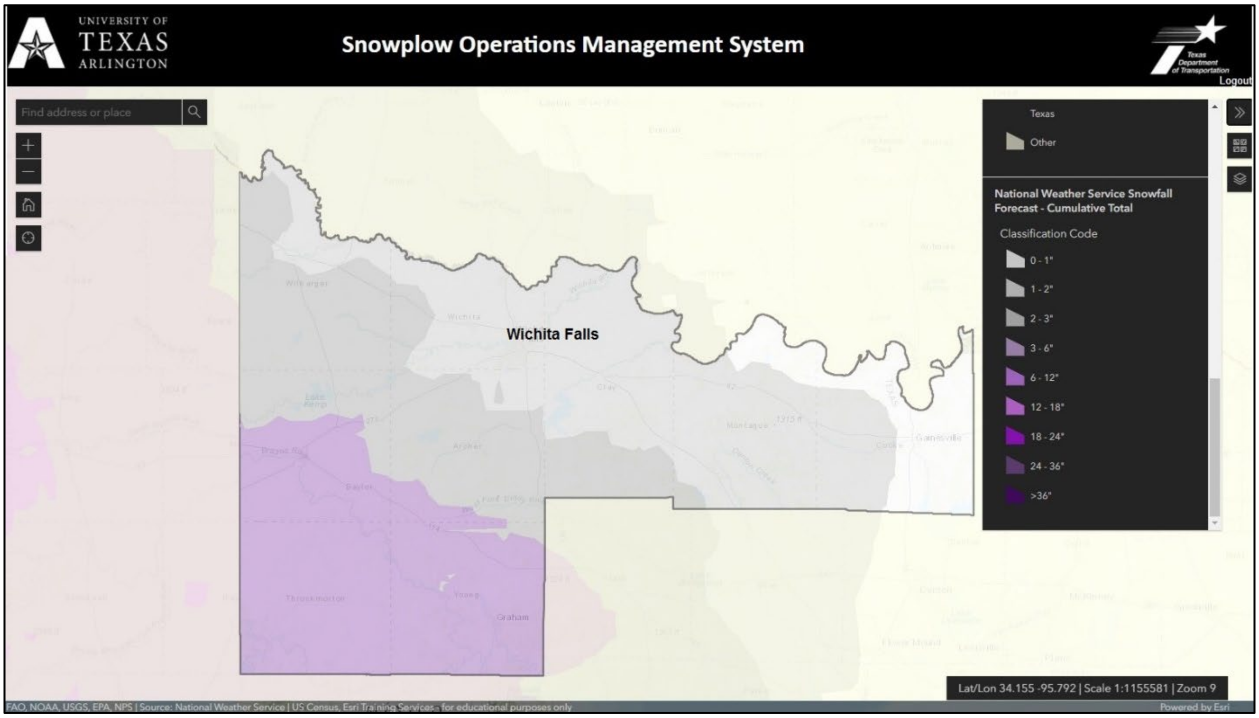


Figure 3.4 Snowfall forecast by the National Weather Service (TxDOT Wichita Falls district, January 8, 2021, 4:23 PM)

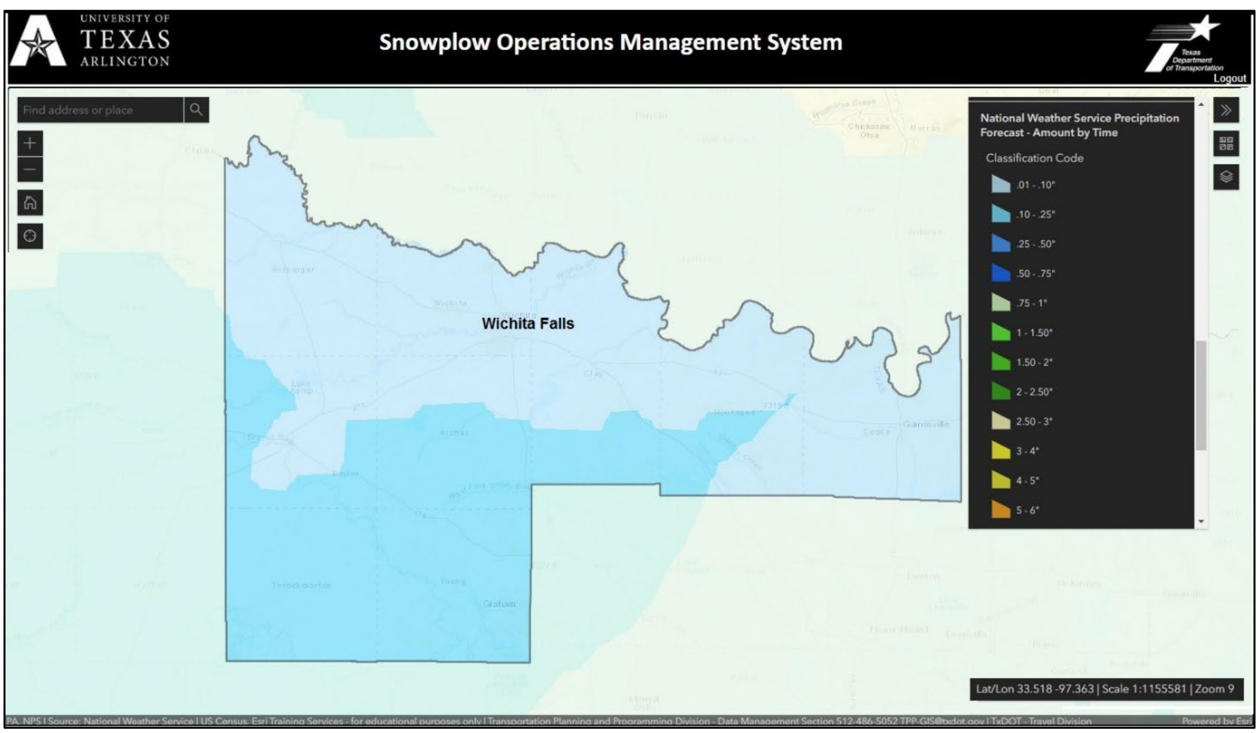


Figure 3.5 Precipitation forecast by the National Weather Service (TxDOT Wichita Falls district, January 8, 2021, 4:37 PM)

3.3 Warnings, Watches, and Advisories

The National Weather Service uses weather data, radar, and satellite analysis to alert the public and related agencies to a potentially threatening weather event. Warnings, watches, and advisories are mainly issued for events such as winter storms, blizzards, ice storms, frost, and wind chill during wintertime. The issued warnings, watches, and advisories by National Weather Service can help transportation managers have their resources ready for winter operations ahead of time and deploy them to locations where the watches, warnings, and advisories are issued for. Below is the description of the terminologies used by the National Weather Service for waning, watch, and advisory (NOAA, 2021b).

- Warning

  A warning is issued by National Weather Service when hazardous weather or hydrologic event is likely or imminent to occur. A warning means weather conditions pose a threat to life or property. People in the path of the storm need to take protective action.

- Watch

  A watch is issued by National Weather Service when the risk of hazardous weather or hydrologic event has increased significantly, but its occurrence, location, or timing is still uncertain. It is intended to provide enough lead time so that the public or officials will be able to set preparation plans ahead of the adverse weather condition.

- Advisory

  An advisory is issued by National Weather Service when hazardous weather or hydrologic event is likely or imminent to occur. Advisories are for less severe conditions than warnings that cause significant inconvenience and, if caution is not exercised, could lead to situations that may threaten life or property.

The research team identified maps visualizing the warnings, watches, and advisories issued by the National Weather Service and integrated them into the ArcGIS map-based interface to facilitate displaying forecasted weather data on adverse weather conditions for TxDOT transportation managers. Figure 3.6 shows an advisory issued by the National Weather Service during a winter storm in Texas on January 8, 2021, at 1:31 PM.

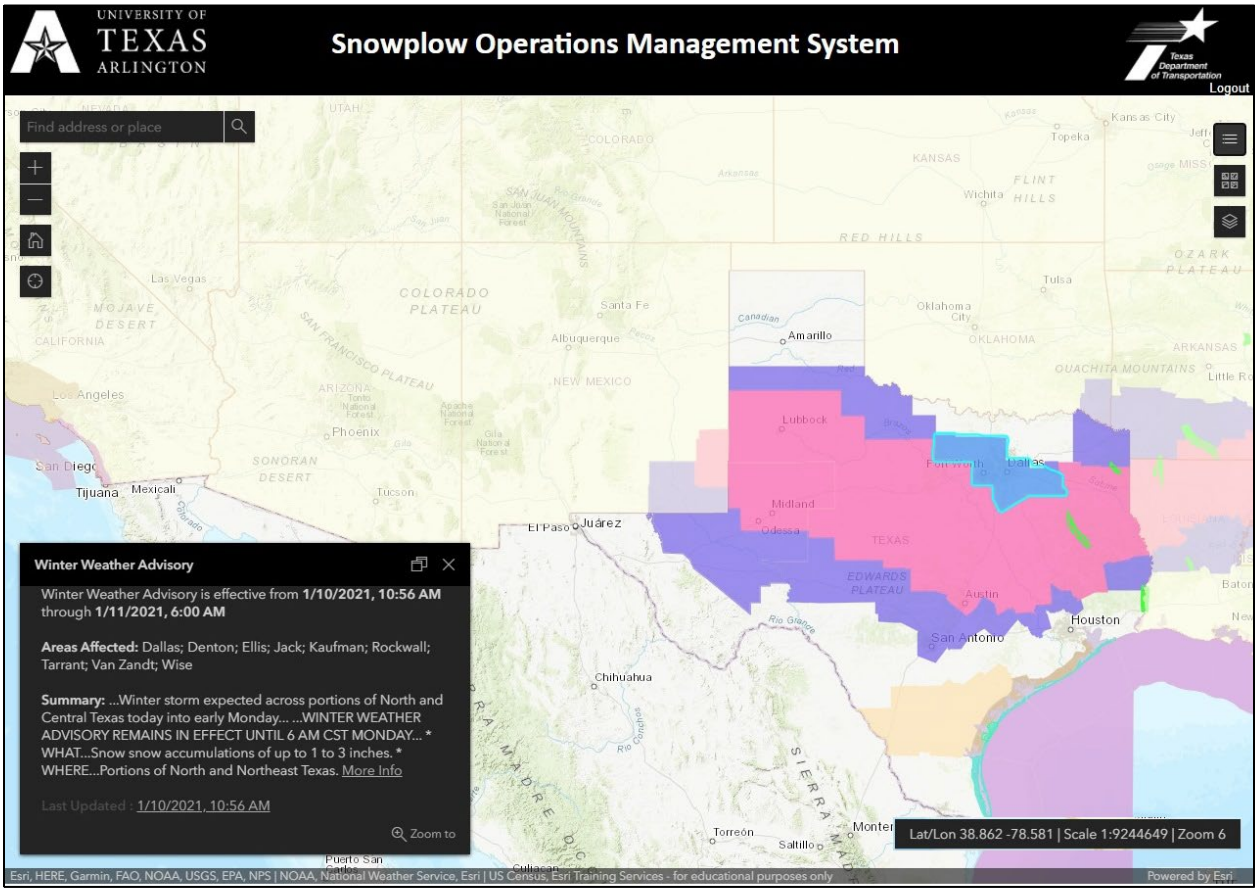


Figure 3.6 Advisory from the National Weather Service for During a Winter Storm in Texas (January 8, 2021, 1:31 PM)

Figure 3.7 shows a warning issued by National Weather Service for the TxDOT Wichita Falls district on January 8, 2021, at 1:50 PM. According to the issued warning, the Western area of the district is predicted to be affected by a snowstorm during the following 24 hours.

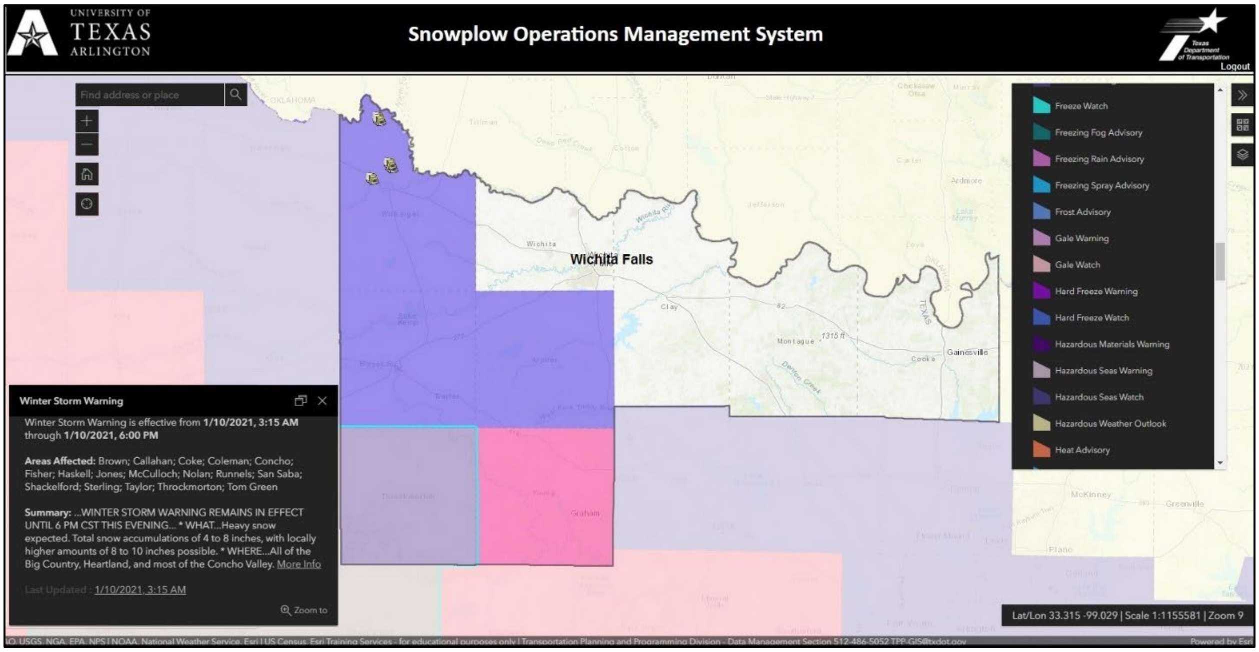


Figure 3.7 Warning from the National Weather Service during in TxDOT Wichita Falls district (January 8, 2021, 1:50 PM)

3.4 Useful Weather Information for Snowplow Operations

A valuable geo-referenced database should include as many practical entities to summarize the data in a meaningful way. Having too few data entities might not provide enough information, while too many data entities might make the database overwhelming and confusing for end users (Onstad, 2008, Baral et al., 2021). To select the most useful weather information that facilitates snowplow operations decisions, the research team reviewed the state-of-practice in other state DOTs across the U.S. to identify practical weather parameters that help enhance the snowplow operations decisions. Table 3.7 summarizes examples of weather information that different state DOTs used in their road condition map interfaces (i.e., states travelers' information websites).

Table 3.7 Examples of related weather information used in other state DOTs' road condition map interfaces

Department of Transportation	Related weather data entities					
	Fixed Weather Stations	Weather radar and Warnings (NWS)	Snowfall forecast (NWS)	Ice forecast (NWS)	Wind Forecast (NWS)	Precipitation Forecast (NWS)
Iowa	✓	✓	✗	✗	✗	✗
Colorado	✓	✗	✗	✗	✗	✗
Arizona	✓	✓	✗	✗	✗	✗
Pennsylvania	✓	✓	✗	✗	✗	✗
Minnesota	✓	✓	✗	✗	✗	✗
Alaska	✓	✓	✗	✗	✗	✗
New York	✓	✓	✗	✗	✗	✗
North Dakota	✓	✓	✗	✗	✗	✗
Ohio	✓	✗	✗	✗	✗	✗
Delaware	✓	✓	✓	✗	✗	✗
Oregon	✓	✓	✓	✗	✗	✗
Montana	✓	✓	✓	✓	✓	✓

Based on the frequency and application of the related weather data information used in other state DOTs, the research team shortlisted the related weather information in the SOMS to include:

1. Ambient Temperatures, provided by NOAA,
2. Warnings, Watches, and Advisories, provided by NWS,
3. Snowfall Forecast-Cumulative Total, provided by NWS, and
4. Ice Forecast-Cumulative Total, provided by NWS

3.5 Summary

In the United States, National Oceanic and Atmospheric Administration (NOAA) and National Weather Service (NWS) are responsible for providing accurate weather data for the public and agencies. The weather information, such as current temperatures, forecast snowfall and ice accumulation, as well as watches, warnings, and advisories from NWS, provide useful information for managing snowplow operations. This chapter provided information about collecting the weather information that facilitates snowplow operations management decisions. The UTA research team integrated the available GIS layers of these weather information from NOAA and

NWS into the ArcGIS map-based interface to automatically display the related weather information on the map-based interface as a part of the developed decision support system.

CHAPTER 4. ROAD SURFACE TEMPERATURES AND ROAD SEGMENTS PRONE TO ICING HAZARDS

4.1 Introduction

According to Federal Highway Administration (FHWA), about 13% of weather-related crashes occur due to icy roads in the United States — which translates into over 150,000 vehicle crashes each year (FHWA, 2020). Therefore, monitoring road surface temperature is crucial for transportation managers to develop proactive anti-icing strategies for winter operations (Yun et al., 2018). Road surface temperature data in the road networks provide essential information to transportation operations managers about possible locations of low road surface temperature and potential road icing hazards. This information could improve decision-making for deploying snowplows to administer anti-icing measures on roads during winter operations.

The objectives of this chapter are to (1) develop an approach to automatically collect actual road surface temperature data through a mounted temperature sensor, (2) develop a methodology to estimate road surface temperature on TxDOT on-system road segments using the collected sensory data and influencing forecast weather data (e.g., ambient temperature, relative humidity) for up to 5 days, and (3) display the actual and estimated road surface temperatures on the map-based interface along with the snowplow locations. Figure 4.1 shows an overview of the approach used in this chapter to estimate the road surface temperatures and display them on a map-based interface.

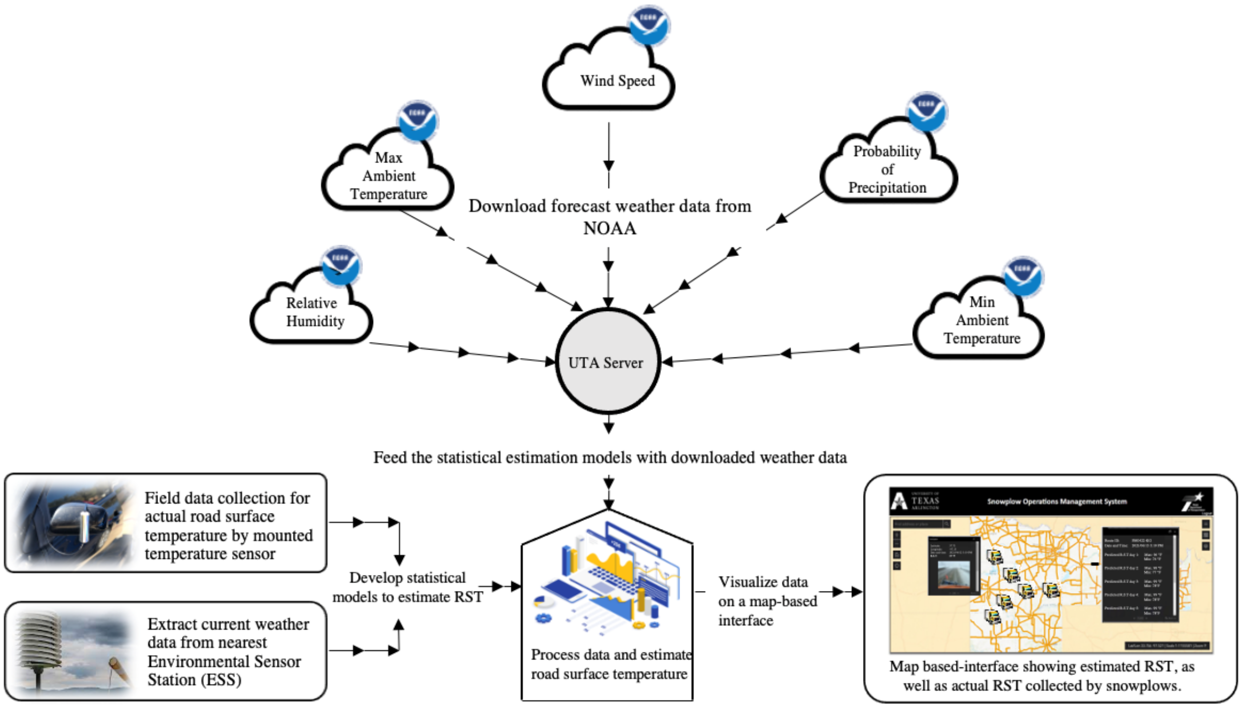


Figure 4.1 Overview of the methodology from data collection to the estimation of road surface temperatures along with the locations of snowplows

4.2 Automatic Collection of Actual Road Surface Temperatures Using Sensors

This section provides information about collecting actual road surface temperature data and displaying the collected field data on the map-based interface, along with the locations of snowplows. A vehicle-mounted temperature sensor collects the road surface temperature data and transfers it to the UTA cloud space using a custom application running on tablets as a communication system. The collected actual road surface temperatures are then processed and displayed on the map-based interface, along with the locations of snowplows.

4.2.1 Temperature Sensor

The UTA research team developed an approach to employ a RoadWatch® temperature sensor kit to collect actual road surface temperature data automatically. The RoadWatch® sensor uses infrared measuring to capture the road surface temperatures. This sensor can detect a one-degree change in road surface temperature in one-tenth of a second (RoadWatch manual, 2020). According to the temperature sensor manual, the accuracy of the temperature measurements is within ± 2°F (± 1°C) when the ambient air temperature is between 23°F and 41°F (-5°C to +5°C)

(RoadWatch manual, 2020). The RoadWatch® sensor could be mounted to a snowplow side mirror using a mirror bracket that clamps onto the snowplow mirror. It could be powered by a 12V DC and 0.05 amperage current. Figure 4.2 shows the RoadWatch® sensor kit that was employed to collect actual road surface temperature data. The UTA research team mounted this sensor on personal vehicles during the data collection period. Table 4.1 summarizes the technical specifications of the RoadWatch® sensor kit that the research team employed to collect actual road surface temperature data.

(a) (b)

Figure 4.2 Temperature sensor used to collect road surface temperature data; (a) RoadWatch® sensor kit; (b) mounted sensor on vehicle's side mirror

Table 4.1 Technical specifications of the RoadWatch® temperature sensor used to collect actual road surface temperature data (RoadWatch® manual, 2020)

Properties	Description
Road surface temperature accuracy	± 2 °F (23°F to 41°F ambient temperature) ± 6 °F (-40°F to 23°F ambient temperature)
Operating voltage	12 VDC (vehicle power)
Current requirement	0.05 Amp
System operating temperature range	-40°F to +150 °F
Sensor sample rate	Ten (10) samples per second
Sensor weight	11 oz
Vibration	Four (4) g's two axis

4.3 Upgrade Android Application

The research team upgraded the Android application, previously explained in chapter 2, to communicate with the RoadWatch® temperature sensor via Bluetooth technology and transfer the collected actual road surface temperature data to the UTA cloud space. The updated Android application receives the actual road surface temperature data from the temperature sensor at predetermined time intervals (i.e., 10 minutes) when the snowplow operates at a speed of 5 mph or more and transfers them to UTA cloud space to be further processed. Figure 4.3 shows the data flow from the temperature sensor and tablet device to the UTA cloud space.

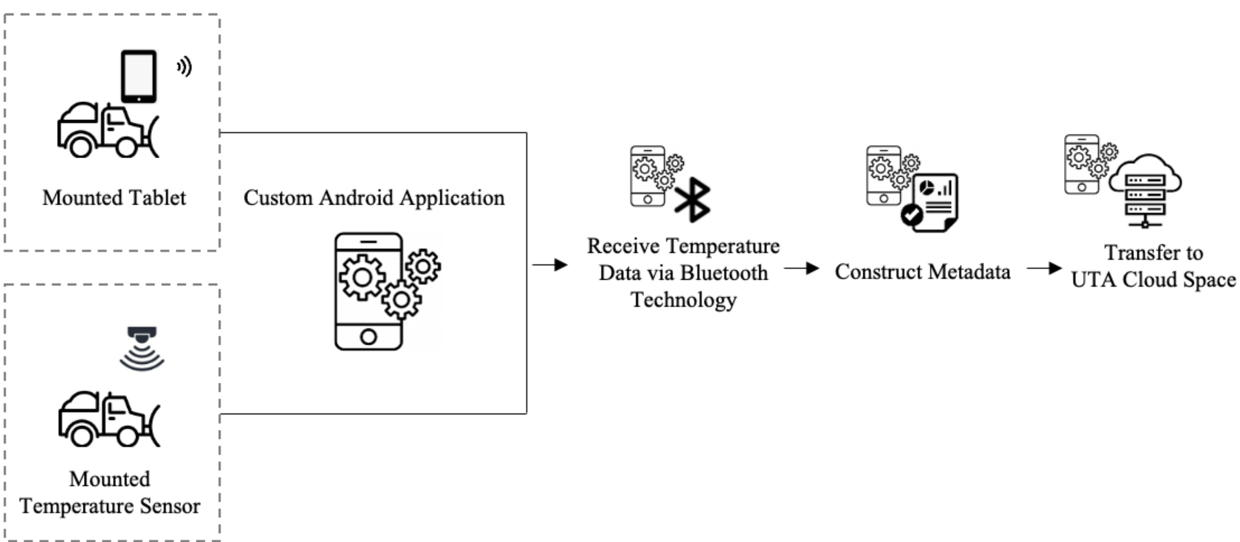


Figure 4.3 Data flow from the temperature sensor and tablet device to UTA cloud space

The Android application was designed to automatically connect to the RoadWatch® temperature sensor, receive the actual road surface temperature data, and transfer them to UTA cloud space at the predetermined time intervals. To upgrade the custom Android application, the research team used different application programming interfaces (APIs), Java classes, and methods to execute various tasks, such as scanning the nearby Bluetooth devices, discovering and connecting to the RoadWatch® temperature sensor, reading the road surface temperature when the sensor advertises new data, constructing metadata, and uploading the data to the cloud space. The application retrieves and transfers the road surface temperatures when the vehicle is moving at the speed of 5 mph or above. Figure 4.4 shows the Function Modeling Methodology (IDEF0 figure) to illustrate how the research team upgraded the Android application running on tablets.

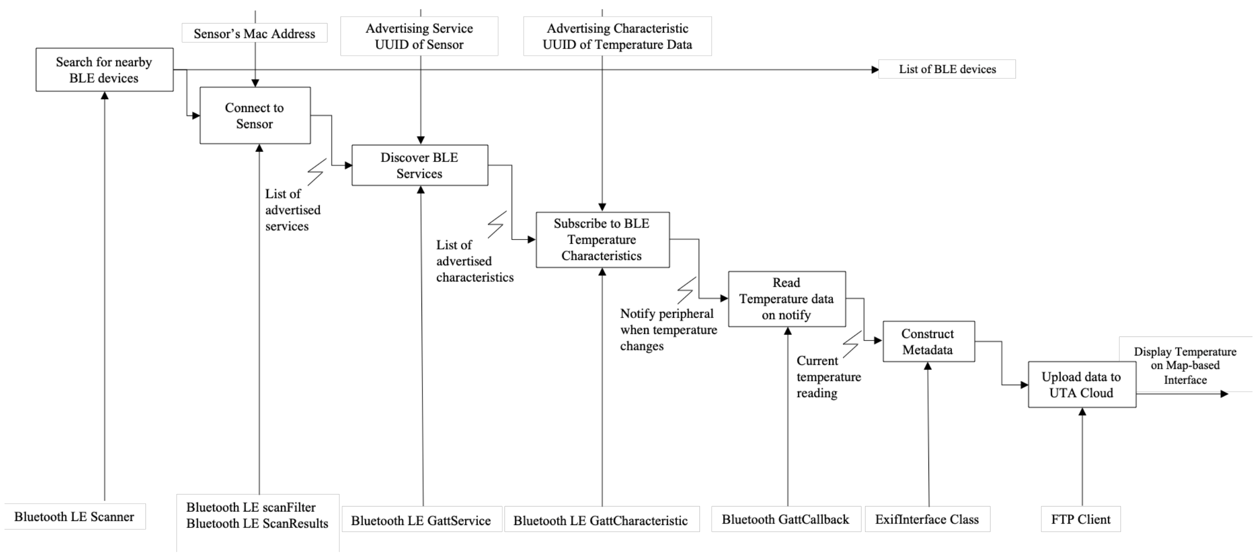


Figure 4.4 IDEF0 diagram for updating the Android application in Java programming language

Collecting data using the temperature sensor is relatively self-sufficient with minimum distraction for the driver. Figure 4.5 shows the Android application's user interface. As the user starts the application by pressing the "Run" button, the application connects to the temperature sensor via Bluetooth, receives the road surface temperature data at predetermined time intervals, and transfers them to the UTA cloud space when the snowplow operates at a speed of 5 mph or above. Figure 4.6 illustrates a schematic view of the map-based interface showing the actual road surface temperature data collected by the mounted temperature sensor.

Figure 4.5 User interface of the upgraded Android application (Version 2.0)

Figure 4.6 Schematic view of the map-based interface displaying the actual road surface temperature, collected by the temperature sensor, along with snowplow location

4.4 Development of Statistical Models to Estimate Road Surface Temperatures Wherever the Actual Temperatures Are Not Available

This section discusses statistical models to estimate road surface temperature using the Multiple Linear Regression (MLR) method. Statistical models are widely used in practice to estimate road surface temperature because of the opportunity that they provide for a fast real-time estimation of road surface temperature for winter operations decision-making purposes (Chi et al., 2019). Although statistical models are simple and provide a fast solution, they need to be calibrated and validated to be reliable for their intended purpose (Chi et al., 2019). Table 4.2 shows examples of statistical models developed to estimate the road surface temperature for different purposes.

Table 4.2 Examples of statistical models for estimation of road surface temperature

Model	Objective	Affecting Parameters	Data collection	Researcher(s)
Stepwise regression model	Determine the pavement surface temperature in cold climates	Air temperature, Relative humidity, wind speed during rainfall and snowfall	Data was collected based on the meteorological data of icy pavement in Jinhua from December 2010 to January 2016	Qiu Xin et al., 2018
Stepwise regression model	Determine road surface temperature along a test road concerning weather data and pavement depth	Air temperature, solar radiation, depth of pavement	Data collected from several sensors along a 500 m road segment in Edmonton, Alberta, Canada, from Sep 2014 to Sep 2014	Asefzadeh et al., 2017
Disaggregate regression model	Determine the pavement surface temperature in a low-speed low, traffic parking lot	Pavement surface temperature, air temperature, solar radiation, wind speed	All the tests were conducted in parking lot C at the University of Waterloo, Ontario, Canada, in the winter season of 2012-2013	Hosseini et al., 2015
Linear regression model	Determine pavement temperature for concrete and asphalt pavement	Ambient temperature	Data were collected from 32 environmental sensor stations in Utah during 2009	Guthrie et al., 2014
Linear regression model	Determine the pavement surface temperature in cold climates	Air temperature, dew point, lag dependent variable (the surface temperature at earlier times)	Data were collected every 10 minutes from nine stations in Ottawa for the winter season 2001-2002.	Sherif et al., 2011
Linear Regression model	Determine pavement temperature at different depths considering weather data	Air temperature, solar radiation, thermal history	Data was collected from two test sections on an hourly basis in Wisconsin at different pavement depths.	Boshcher et al., 1998
Neural Network	Increase the accuracy of road surface nowcast by a numerical model	Time of day, earlier surface temperature variation, Dew point, wind speed, road surface state	Data were collected from different sites in different countries, including Japan, England, Switzerland, Norway, Italy, Austria, between 1992-1994	Shao et al., 1997

Despite the importance of previous prediction models to estimate pavement temperatures, these models are mainly developed for specific applications in specific temporal and spatial circumstances other than the scope of the current study. For example, the estimation models developed by Sherif et al. (2011) and Asefzadeh et al. (2017) use input data from specific environmental sensors (e.g., road weather information systems) to estimate the temperatures at different pavement depths, which are not available in the current study to be used as input for estimating road surface temperatures along the roads in North Texas. Therefore, it is crucial to develop estimation models that use available parameters (i.e., influencing forecast weather data from NOAA) to estimate road surface temperature over the temporal and spatial extent pertinent to this study (i.e., winter season in North Texas).

As the National Weather Service provides gridded (i.e., 5km resolution) forecasts of sensible weather data (e.g., ambient temperature, relative humidity), it is of interest to develop statistical models and perform a data fusion on the available weather data to estimate the road surface temperatures along roadways. The process of combining data or information to estimate the state of an entity is defined as data fusion (Shahandashti et al., 2011). The following section elaborates how the research team used the Multiple Linear Regression method and performed data fusion to estimate road surface temperatures along North Texas roads using the forecast weather data.

4.4.1 Multiple Linear Regression

Multiple Linear Regression (MLR) is popularly used as a prediction model with a linear combination of several predictors (Wilks, 2011). The general formula for MLR can be described as follows (Wilks, 2011):

$$\hat{y} = \beta_0 + \sum_{i=1}^{K} \beta_i x_i + \varepsilon \qquad \text{(Eq. 1)}$$

Where K is the number of predictors, x_i is predictor, β_i is the coefficient of predictors, β_0 is intercept constant, ε is the model's residual, and $\hat{y}$ is the response variable.

During the winter season 2021-22 in North Texas, the research team collected actual road surface temperature data using the RoadWatch® temperature sensor along with the associated ambient weather data to develop statistical models to estimate the road surface temperature using the MLR method. The actual road surface temperatures were randomly collected from the roads located in North Texas. The associated ambient weather data (e.g., ambient temperature, relative humidity, etc.) were downloaded from the closest NOAA weather station to the location where the actual road surface temperatures were collected. The research team conducted statistical analysis on the collected data to find the significant predictors in the dataset to estimate the road surface temperature. A summary of the weather data collected from the weather stations is shown in Table 4.3.

The collected weather data were chosen based on the frequency of their applications in the previous models for estimating road surface temperature and the availability of NOAA's forecast weather data.

Table 4.3 Predictors used in the statistical analysis to estimate road surface temperature

Parameter	Abbreviation
Ambient temperature (°F)	$T_{current}$
Relative humidity (%)	Rh
Dew point temperature (°F)	$T_{dewpoint}$
Wind speed (mph)	Wsd
Wind gust (mph)	Wgt
Road Surface Condition (wet/dry)	RSC
24-hour precipitation (in)	Pr
Pressure (in)	P
Maximum temperature of the previous day (°F)	T_{max24}
Minimum temperature of the previous day (°F)	T_{min24}
Average temperature of the previous day (°F)	T_{avg24}

In Figure 4.7, the data frequency distribution illustrates the range and frequency of the collected data.

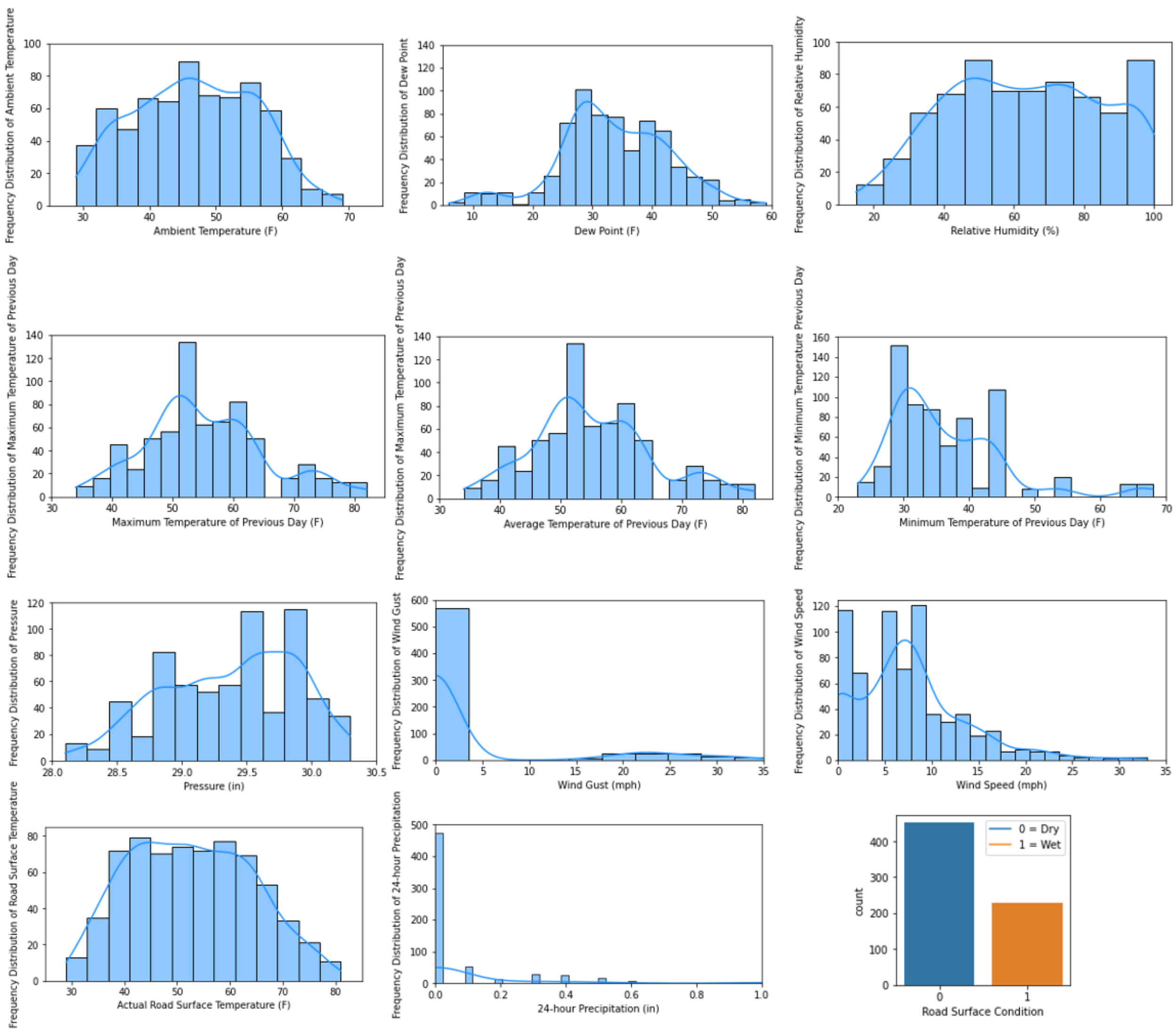


Figure 4.7 Frequency distribution of the collected data

Furthermore, the correlation matrix is calculated using Pearson's method to determine the correlation between variables. Figure 4.8 shows the correlations matrix between all variables. A Pearson coefficient of |R| > 0.7 is commonly used as the multicollinearity threshold (Dormann et al., 2013). Therefore, the selected predictors should have a correlation of less than 0.7 to avoid multicollinearity in the model.

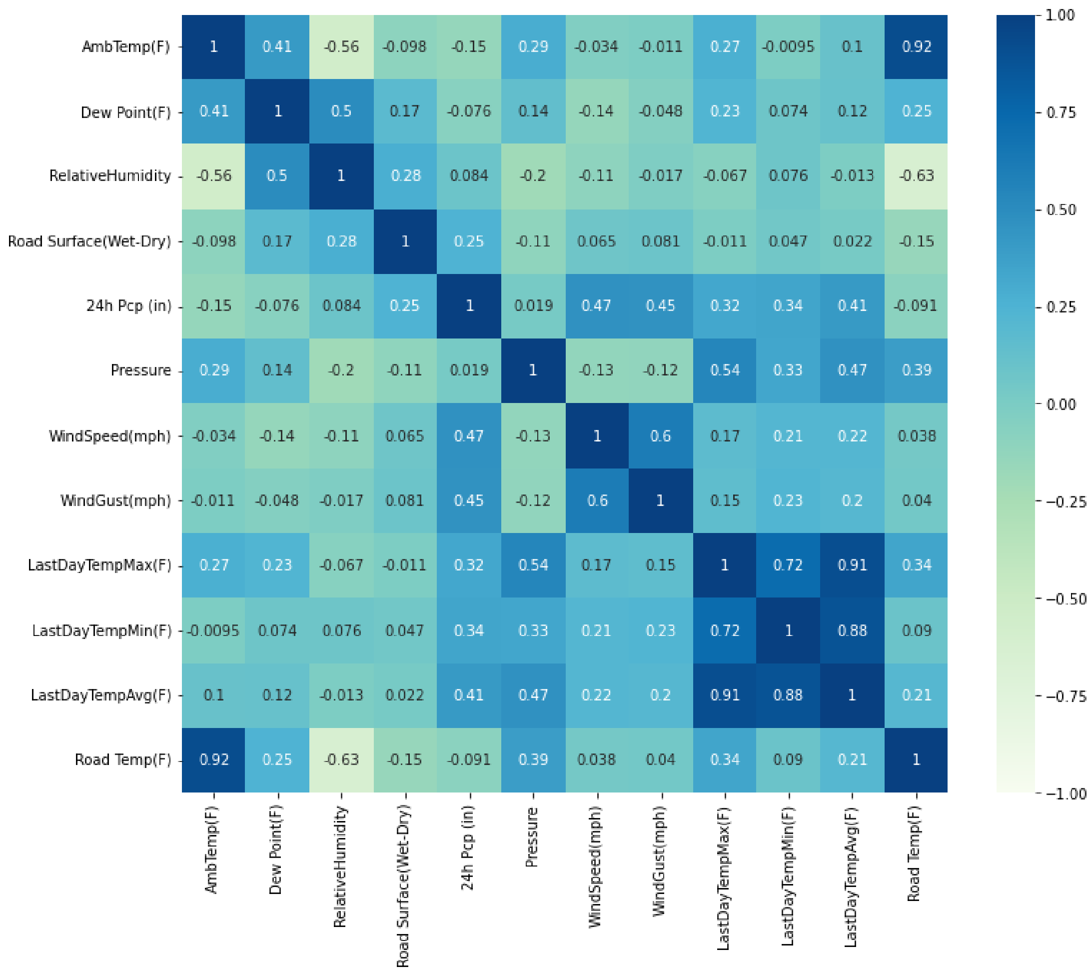


Figure 4.8 Pearson's correlation coefficient between all variables

To find the most significant set of variables to estimate the road surface temperatures, the M5 Regression Tree attribute selection method was performed on the dataset. M5 Regression Tree attribute selection method selects the best subset of variables that most improve the Akaike information criterion (Massana et al., 2015). Using the M5 Regression Tree method, the following attributes were selected:

- Ambient Temperature
- Relative Humidity
- Road Surface Condition
- Wind Speed
- Average Ambient Temperature of Previous Day

Moreover, the collected data were categorized into two groups: dark and light, to consider the effect of time-of-day in the road surface temperature estimation models. Dark starts two hours after the sunset and ends one hour after sunrise, and light starts one hour after the sunrise and ends two hours after the sunset (Guthrie 2014). Table 4.4 shows the dark and light hours in North Texas based on the sunrise and sunset time during different months of the year.

Table 4.4 Light and dark hours in Texas during different months of the year

Month	Light	Dark
January	9 AM to 8 PM	8 PM to 9 AM
February	8 AM to 8 PM	8 PM to 8 AM
March	9 AM to 10 PM	10 PM to 9 AM
April	8 AM to 10 PM	10 PM to 8 AM
May	8 AM to 10 PM	10 PM to 8 AM
June	7 AM to 11 PM	11 PM to 7 AM
July	8 AM to 11 PM	11 PM to 8 AM
August	8 AM to 10 PM	10 PM to 8 AM
September	8 AM to 10 PM	10 PM to 8 AM
October	9 AM to 9 PM	9 PM to 9 AM
November	8 AM to 8 PM	8 PM to 8 AM
December	9 AM to 7 PM	7 PM to 8 AM

Data ranges for the continuous and binary attributes are shown in Table 4.5 and Table 4.6, respectively. The data were collected in North Texas from November 2021 to March 2022.

Table 4.5 Data ranges for the significant continuous attributes

Continuous Variable	Description	Light			Dark		
		Max	Min	Standard Deviation	Max	Min	Standard Deviation
RST	Road Surface Temperature (°F)	81	29	11.5	63	29	7.6
$T_{current}$	Ambient Temperature (°F)	69	29	8.8	60	26	7.4
Rh	Relative Humidity (%)	100	15	20	100	24	16.5
T_{avg24}	Average Ambient Temperature of Past Day (°F)	72	32	9	72	30	8.6
Wsd	Wind Speed (mph)	24	0	5.1	26	0	5.7

Table 4.6 Data range for the significant binary attribute

Binary Variable	Description	Light		Dark	
		Wet	Dry	Wet	Dry
RSC	Road Surface Condition	158	304	70	148

The UTA research team conducted two MLR analyses on the collected data for light and dark datasets to develop the statistical models to estimate the road surface temperature. Table 4.7 shows the resulting statistical models developed to estimate the road surface temperature for Light and Dark datasets using the MLR approach based on the Akaike information criterion (AIC). The 10-fold cross-validation method was performed to calculate the accuracy metrics of the models (i.e., coefficient of correlation and mean absolute error).

Table 4.7 Statistical models developed to estimate the road surface temperature

Light / Dark	Statistical Prediction Model	Coefficient of Correlation (R)	Mean Absolute Error (°F)
Dark	$RST = 0.97T_{current} + 0.024Rh - 1.21RSC - 0.059Wsd + 0.13T_{avg24} - 1.89$	0.97	1.45
Light	$RST = 1.01T_{current} - 0.11Rh - 0.67RSC - 0.11Wsd + 0.18T_{avg24} + 4.5$	0.92	4.5

4.4.2 Estimate and Display Road Surface Temperatures

The UTA research team used the National Digital Forecast Database (NDFD), administered by NOAA, to extract the influencing forecast weather data as the inputs of the estimation models. The influencing forecast weather data are downloaded from the NDFD database and processed in UTA servers for the next five (5) days to estimate the road surface temperatures on TxDOT on-system roadways in the Wichita Falls district. The TxDOT on-system roadways are the routes that TxDOT maintains. These routes include (TxDOT, 2021b):

- Interstate highways
- U.S. highways
- State highways
- Farm and ranch roads

- Park roads
- Recreational roads

The TxDOT on-system route inventory was downloaded in GIS format from the TxDOT open data portal. The research team developed an approach to automatically download the influencing forecast weather data from the NDFD and process them to feed the estimation models. NDFD is a suite of products administered by NOAA to make forecasts of weather data available to weather enterprises (e.g., academia and government) so that the weather enterprises can use them to develop new products (NWS, 2019). NDFD data is based on grids that cover the Continental U.S. as well as separate grids that cover Hawaii, Alaska, the U.S. Virgin Islands, and Puerto Rico. Each grid cell has information to generate a point-specific forecast for any cell-based geographic coordinate location (NWS, 2021). NDFD forecast weather data are provided in GRIB2 files and updated hourly to daily depending on the weather variable. A GRIB2 file is a binary file saved in the World Meteorological Organization (WMO) format. It contains gridded meteorological data and is the primary format used to transmit NDFD data to NWS customers. The flowchart in Figure 4.9 shows how data from NDFD is downloaded and processed on the UTA server to feed the statistical models developed in Section 4.4.1 to estimate the road surface temperatures along TxDOT on-system roadways in the Wichita Falls district, wherever actual road surface temperatures are not available.

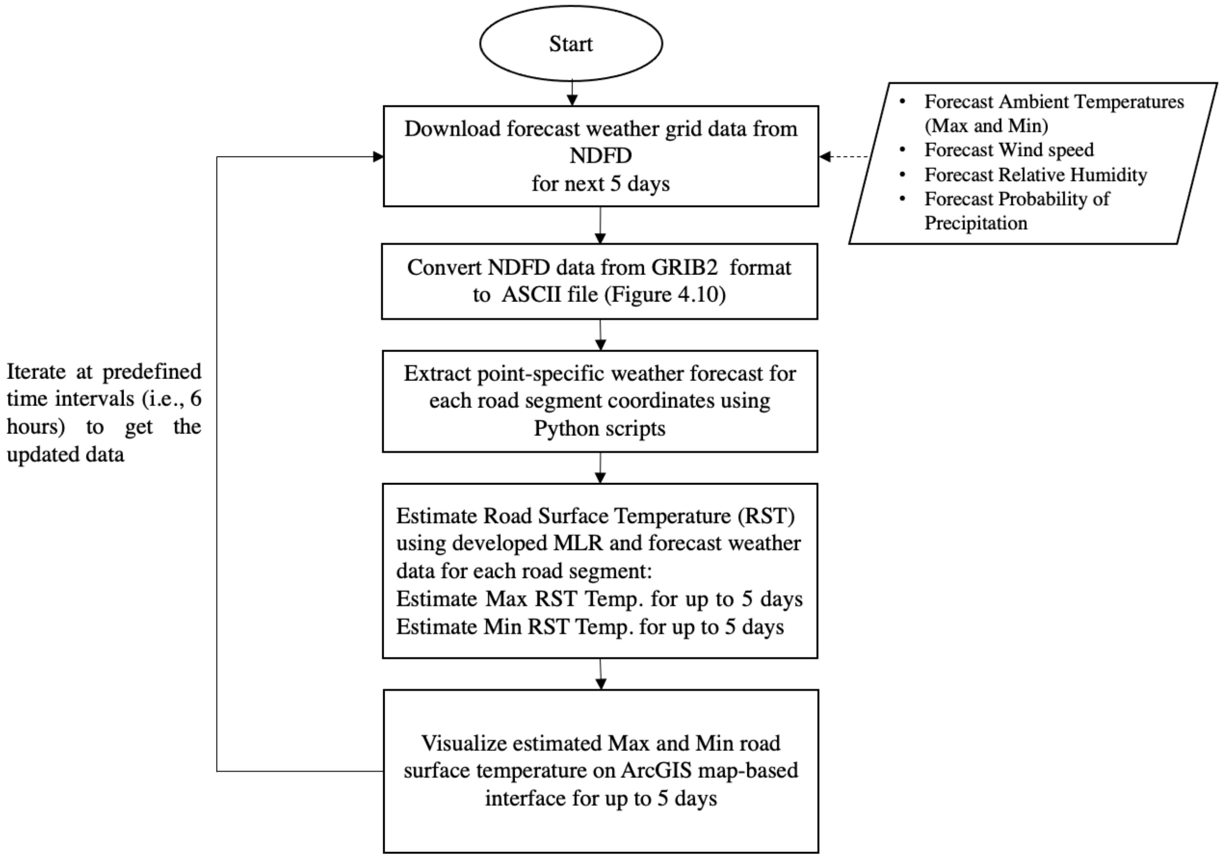


Figure 4.9 Flowchart for estimation of road surface temperature using forecast weather data from the NDFD

The forecast weather data downloaded from NDFD for the five (5) following days is as below:

- Relative humidity: expected ratio (%) of present atmospheric moisture amount to the required amount to make the air saturated (NWS, 2019).
- Wind speed: expected sustained 10-meter wind speed in knots (NWS, 2019).
- Maximum temperature: expected daytime maximum temperature in °F (NWS, 2019).
- Minimum temperature: expected overnight minimum temperature in °F (NWS, 2019).
- Probability of precipitation: the likelihood of a measurable precipitation event (1/100th of an inch or more) (NWS, 2019).

The average temperature for the previous day is taken as the average of the maximum and minimum temperatures of the day before the desired day, and the binary variable of the Road Surface Condition (RSC) is considered “dry” when the probability of precipitation is 0%, and “wet” when the probability of precipitation is more than 0%.

The downloaded forecast weather data from NDFD is in GRIB2 format and should be converted to ASCII comma-separated format (CSV) to be further processed. Figure 4.10 shows the Function Modeling Methodology (IDEF0 figure) to convert the GRIB2 file to the ASCII comma-separated file. The CSV file, which contains the forecast weather variables in 5 km resolutions, is then processed using Python scripts to feed the statistical models to estimate maximum and minimum road surface temperatures up to 5 days. The whole process is iterated at predefined time intervals (e.g., 6 hours) to get the most updated forecast weather data at each time.

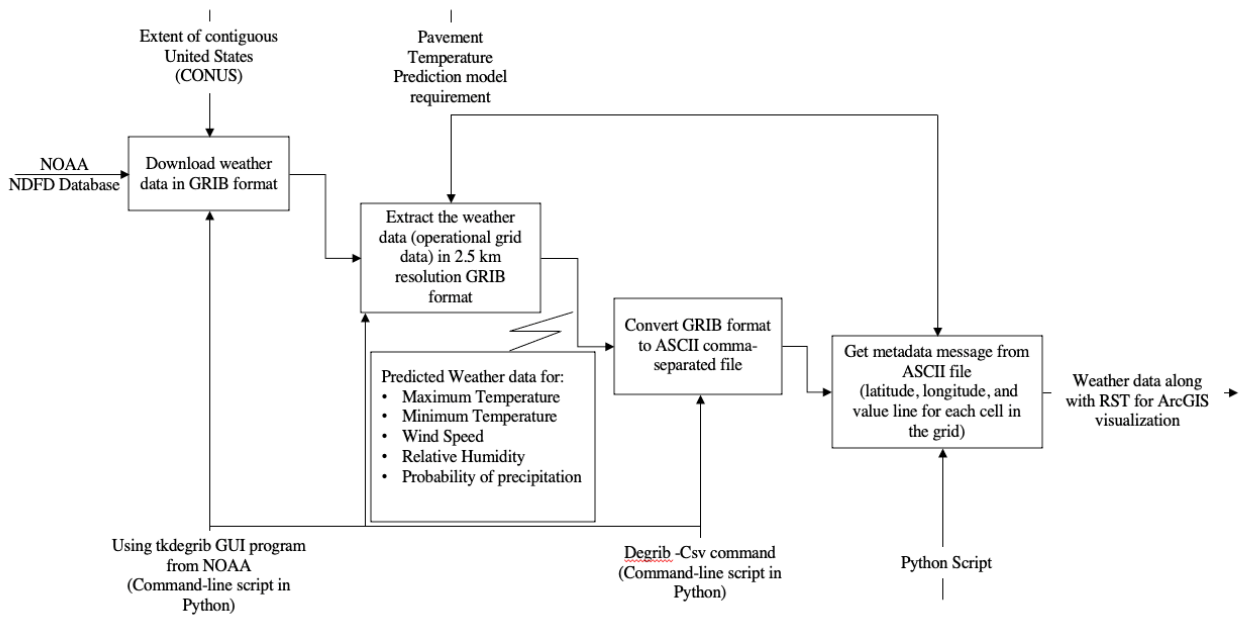


Figure 4.10 IDEF0 diagram for converting GRIB2 file downloaded from NDFD to ASCII comma-separated

Finally, the estimated road surface temperatures for the next five (5) days will be mapped onto the TxDOT on-system roadways and visualized on the map-based interface. Figure 4.11 shows the map-based interface displaying snowplow locations, as well as the estimated road surface temperatures for each segment of road in a pop-up window.

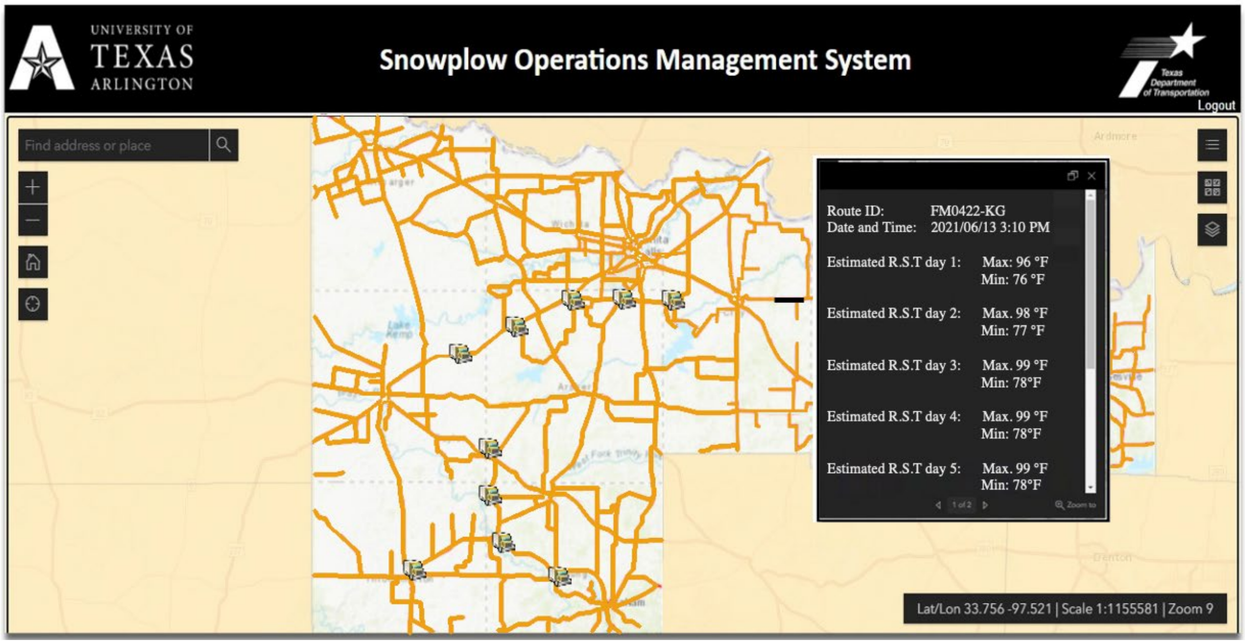


Figure 4.11 Screenshot of the map-based interface showing estimated road surface temperatures for TxDOT on-system roadways in the Wichita Falls

Furthermore, the research team utilized the Esri map service to visualize road segments prone to icing hazards in the next 72 hours using NOAA ice accumulation forecasts. The Esri map services use the National Digital Forecast Database (NDFD), National Data Buoy Center, National Weather Service RSS-CAP Warnings and Advisories, and National Weather Service Boundary Overlays, all administered by NOAA, to create data entities that contain information about current and forecast weather information (i.e., ice accumulation). The Esri map services download the source data and parse them using Aggregated Live Feeds methodology to return information that can be served through the ArcGIS server as a map service (Esri, 2022). Figure 4.12 shows a screenshot of the map-based interface showing the ice accumulation forecast in North Texas on February 2, 2022, at 5:30 PM.

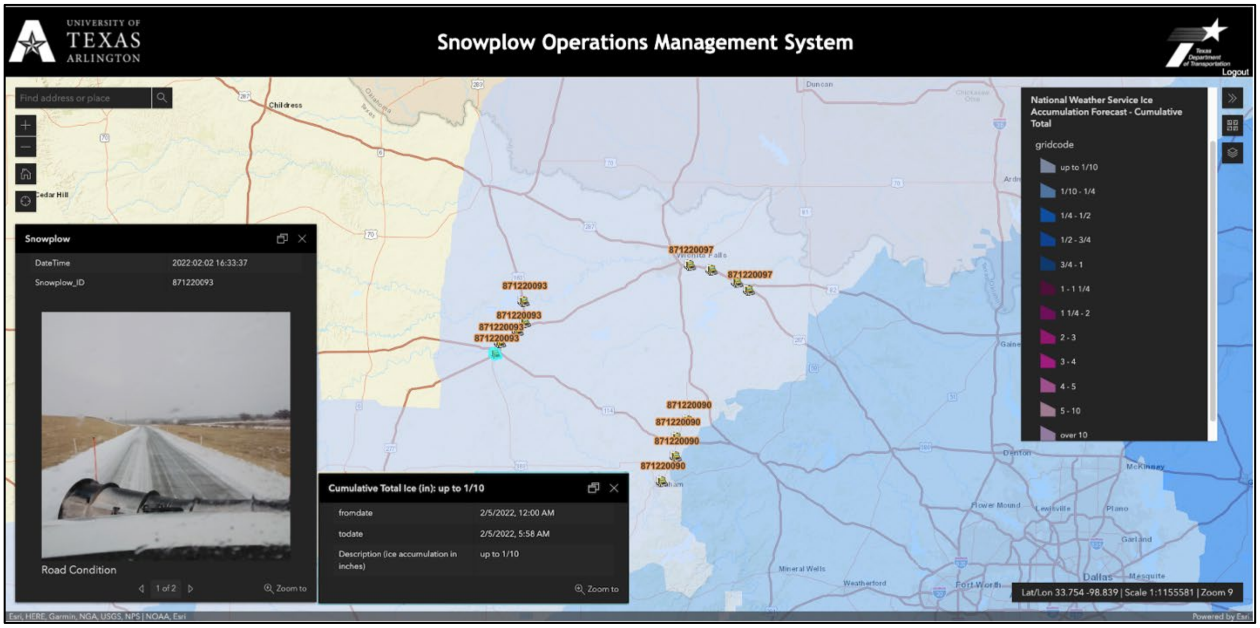


Figure 4.12 Map-based interface showing the ice accumulation forecast in North Texas (February 2, 2022, at 5:30 PM)

4.5 Summary

Monitoring road surface temperature is crucial to establishing winter maintenance strategies. The National Weather Service provides forecasts for specific weather parameters, such as ambient temperature, relative humidity, wind speed, and precipitation. However, it does not provide road surface temperature forecasts. This chapter explained statistical modeling using a Multiple Linear Regression approach to estimate road surface temperatures using weather forecasts from the National Weather Service. The research team used forecast weather data from NDFD, administered by NOAA, to feed into the developed statistical models to estimate the road surface temperature on the TxDOT on-system road segments where actual road surface temperatures are not available. Furthermore, the road segments prone to icing hazards were visualized on the map-based interface using the Esri map service for ice accumulation forecasts. This information provides valuable information for transportation operations managers assisting their decision-making process during snowplow operations.

CHAPTER 5. ARCGIS MAP-BASED INTERFACE

5.1 Introduction

One of the essential components of the Snowplow Operations Management System (SOMS) is a platform to view the collected data for transportation operations managers. Since the data are collected from multiple sources with different data structures, it is critical to integrate them into a single map-based interface to share spatial information through interactive maps. Sharing data through interactive maps allows transportation operations managers to visually monitor and overlay road conditions information through a web browser, mobile device, or desktop viewer. Overlaying geospatial data in forms of different data entities facilitates decision-making and planning for transportation asset management (Shahandashti et al. 2020).

The objectives of this chapter are to develop an easy-to-use map-based ArcGIS interface in Esri to visualize (1) live feed of road conditions images, collected from mounted tablets on snowplows; (2) related weather information provided by national weather services (i.e., NOAA and NWS); and (3) road surface temperatures for TxDOT Wichita Falls on-system road segments. Figure 5.1 shows an overview of the approach from data sources to data visualization in the ArcGIS interface.

The developed ArcGIS map-based interface is accessible through a password-protected webpage. This webpage is available at https://axb9294.uta.cloud/SOMSNOV/login.php and is only accessible for TxDOT and UTA staff currently. Section 5.4 explains how a user interacts with the system. Further details about the developed system have been presented in the following sections.

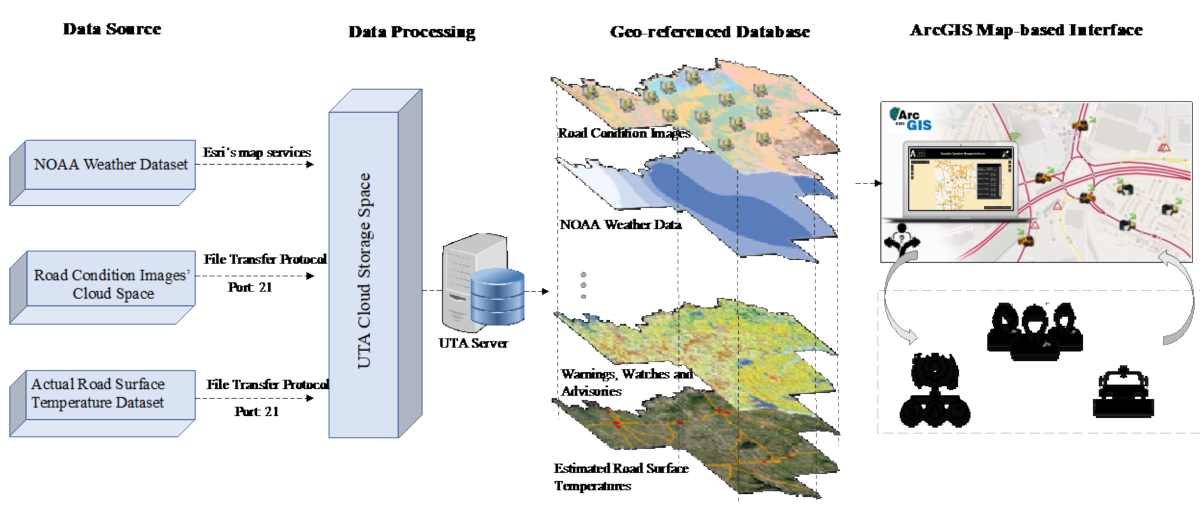


Figure 5.1 Overview of the methodology from data sources to data visualization in ArcGIS interface

5.2 Spatial Data Collection and Processing

The Snowplow Operations Management System (SOMS) uses spatial data (e.g., geotagged images, weather-related information from national weather services, and road surface temperatures) to visualize road condition information on the ArcGIS map-based interface. Also, other spatial data such as influencing weather parameters on the road surface temperatures (e.g., ambient temperatures and wind speed) must be collected to estimate road surface temperatures. Spatial data collection and processing for visualization, data cleaning, and data organization are explained in this chapter.

5.2.1 Road Condition Images

The research team developed a geo-referenced database to facilitate the real-time visualization of road condition images on the map-based interface during snowplow operations. The map-based interface uses the capabilities of the ArcGIS Application Programming Interface (API) for JavaScript and ArcGIS online. A spatial data entity, representing snowplows as point features, was hosted in the ArcGIS online and included in the map-based interface. The spatial data entity will be updated as the road condition images are received from operating snowplows in the field and are processed using the Exchangeable Image File (EXIF) information associated with the geotagged images. The map-based interface displays the snowplows' updated location and road condition images associated with the snowplows. The map-based application runs in a web browser and can be accessed from desktops, smartphones, and tablets, which use windows, macOS, Android, iOS, and Linux operating systems. Figure 5.2 shows the flowchart used to process the collected road condition images to visualize them in the map-based interface. An example screenshot of the map-based interface displaying the road conditions images is shown in Figure 5.3.

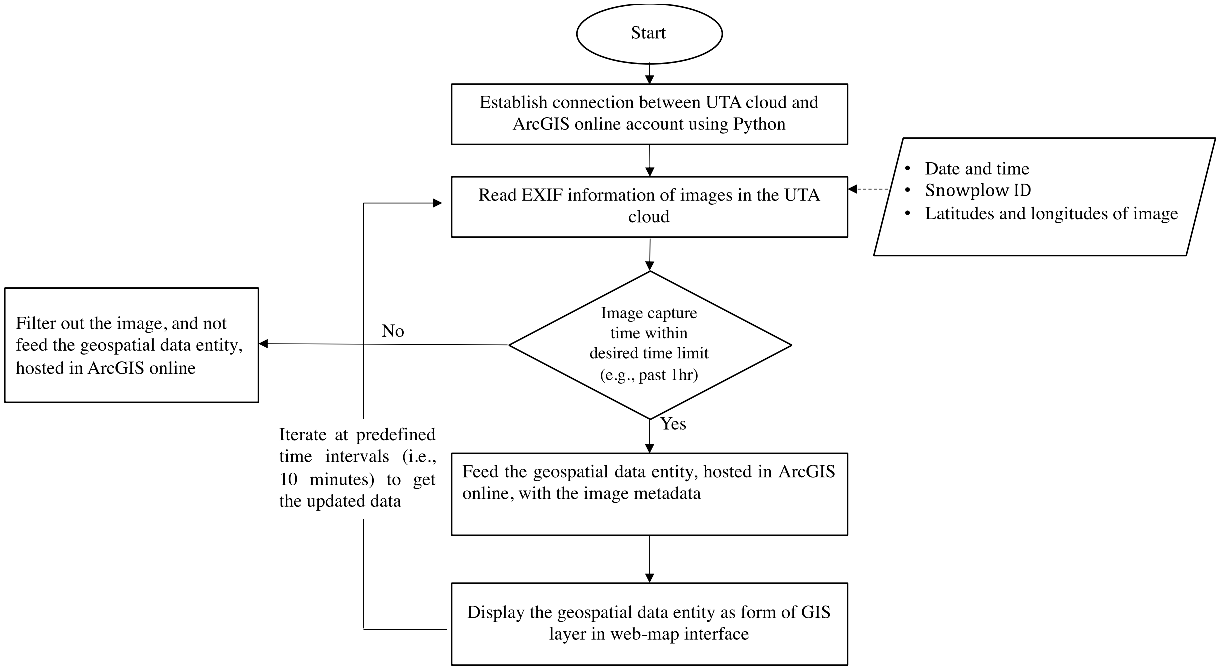


Figure 5.2 Flowchart to visualize the road condition images in the map-based interface

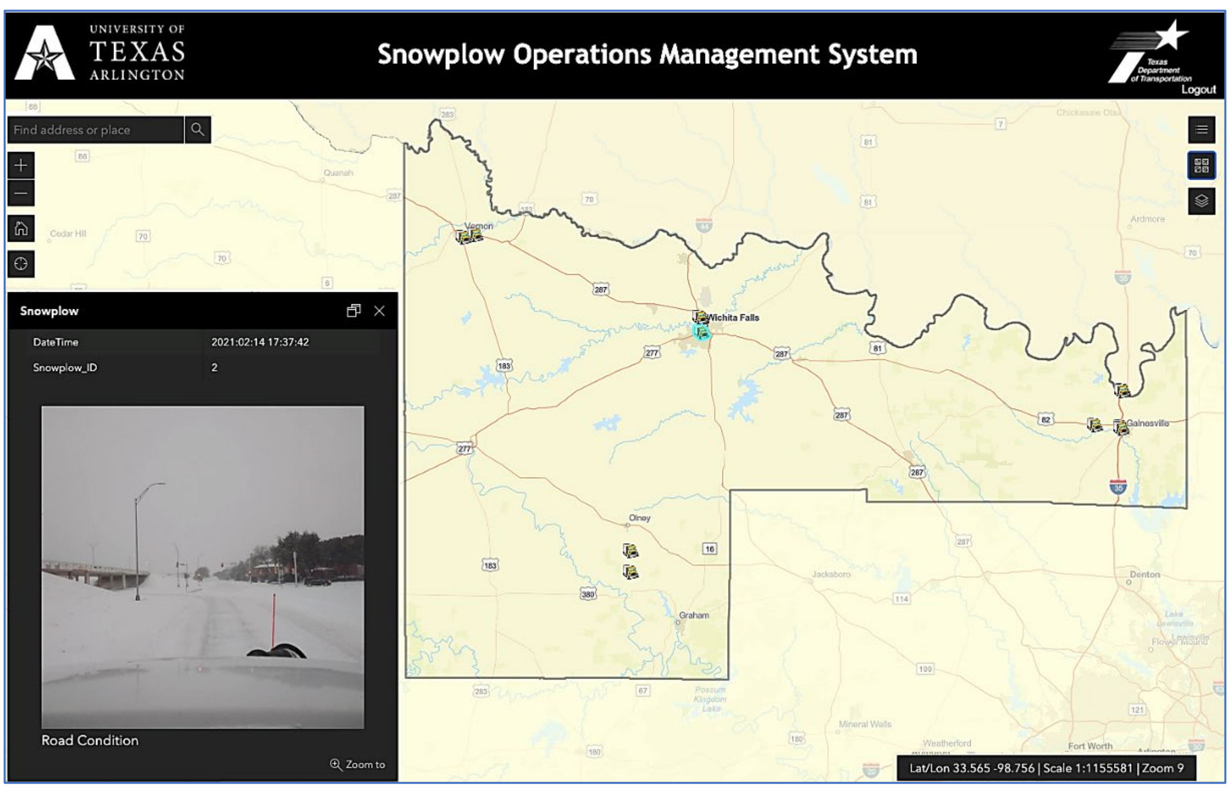


Figure 5.3 Road condition images data entity; displaying road condition images collected by operating snowplows (February 14, 2021, at 5:37 PM).

System Capacity

The existing system has been designed to handle the data received from approximately ten (10) snowplows at the project's current phase. However, it can be scaled depending on the data received from snowplows in the field if needed in the next phases. The research team used UTA cloud space to store the data received from snowplows and a desktop computer (Intel® Xeon® Processor E3-1240, 3.5GHz, and 16 GB RAM) as a server, stationed at the University of Texas at Arlington, to maintain the system. To measure the system's capacity, UTA research team conducted load testing on the system to find the maximum number of snowplows that the system under different assumptions can handle. The conducted load testing was evaluated from two aspects:

1. Cloud storage space
2. Computational performance of the server

In the following paragraphs, the load testing results will be presented.

(1) Cloud Storage Space Aspect

The research team used the UTA cloud storage with approximately 400 M.B. free space to store the data received from snowplows in field. Table 5.1 shows the load testing results under different assumptions, including the timespan that images will remain posted on the map-based interface and the time intervals between capturing images by the tablets in snowplows.

Table 5.1- Maximum number of snowplows that the existing system can handle from the cloud storage space aspect.

The time interval between capturing images by tablet	The timespan that images will remain posted on the map-based interface		
	The past one-hour	The past two-hour	The past four-hour
Every 5 minutes	30 snowplows	15 snowplows	7 snowplows
Every 10 minutes	65 snowplows	32 snowplows	15 snowplows
Every 15 minutes	100 snowplows	50 snowplows	25 snowplows

Note: Currently, the past one-hour images, captured every 10 minutes, are displayed on the map-based interface.

(2) Computational Performance of the Server Aspect

The research team developed Python scripts running on the server stationed at the University of Texas at Arlington to process the collected images to be further visualized on the ArcGIS map-based interface. The server processes the collected data, stored in the cloud space, at predetermined time intervals to feed ArcGIS online map-based interface. Table 5.2 shows the results of load testing under different assumptions, including the time intervals that the server processes collected data in the cloud space and the time intervals between capturing the images by the tablets in snowplows. The timespan that the images will remain posted on the map-based interface is assumed to be one hour.

Table 5.2 Maximum number of snowplows that the system can handle from the computational performance of server aspect— images will remain posted on the map-based interface for one hour.

Time intervals for data processing in the sever	Time intervals between capturing images		
	5 minutes	10 minutes	15 minutes
2 minutes	5 snowplows	10 snowplows	15 snowplows
5 minutes	13 snowplows	25 snowplows	38 snowplows
10 minutes	25 snowplows	50 snowplows	75 snowplows
15 minutes	38 snowplows	75 snowplows	100 snowplows

Note: Currently, the time interval between both data processing in server and image capturing from tablets is 10 minutes.

The results of the load testing show that with the current system setting (displaying the last one-hour images, received every 10 minutes from snowplows, with data processing time interval of 10 minutes), the computational performance of the server controls the system capacity and is responsive to handle the data received from approximately 50 snowplows.

5.2.2 Related Weather Information

The UTA research team developed an approach to visualize the related weather information for snowplow operations on the ArcGIS map-based interface. Using Esri's map services, the research team visualized the related weather information on the map-based interface. Esri's map services use the National Digital Forecast Database (NDFD), National Data Buoy Center, National Weather Service RSS-CAP Warnings and Advisories, and National Weather Service Boundary Overlays, all maintained by NOAA, to create data entities that contain information about current and forecast weather information. Esri's map services download the source data and parse them using Aggregated Live Feeds methodology to return information that can be served through the ArcGIS server as a map service.

The research team used official Esri's map services to import the related weather information into the geo-referenced database in the Snowplow Operations Management System.

Based on the frequency and application of the related weather data entities used in other state DOTs, the research team shortlisted the related weather data entities in the SOMS to include: (1) Ambient Temperatures from NOAA; (2) Warnings, Watches, and Advisories from NWS; (3) Snowfall Forecast Cumulative Total from NWS; and (4) Ice Forecast-Cumulative Total from NWS. Figure 5.4 to Figure 5.6 shows examples of related weather information visualized in the Snowplow Operations Management System's map-based interface.

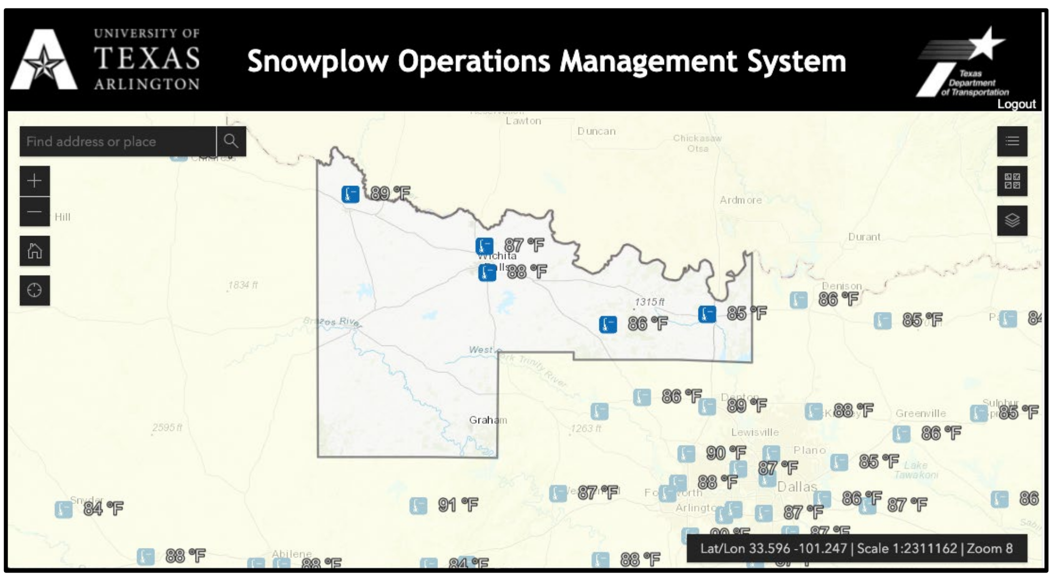


Figure 5.4 Current ambient temperatures from NOAA in the TxDOT Wichita Falls district (October 4, 2021, 4:23 PM)

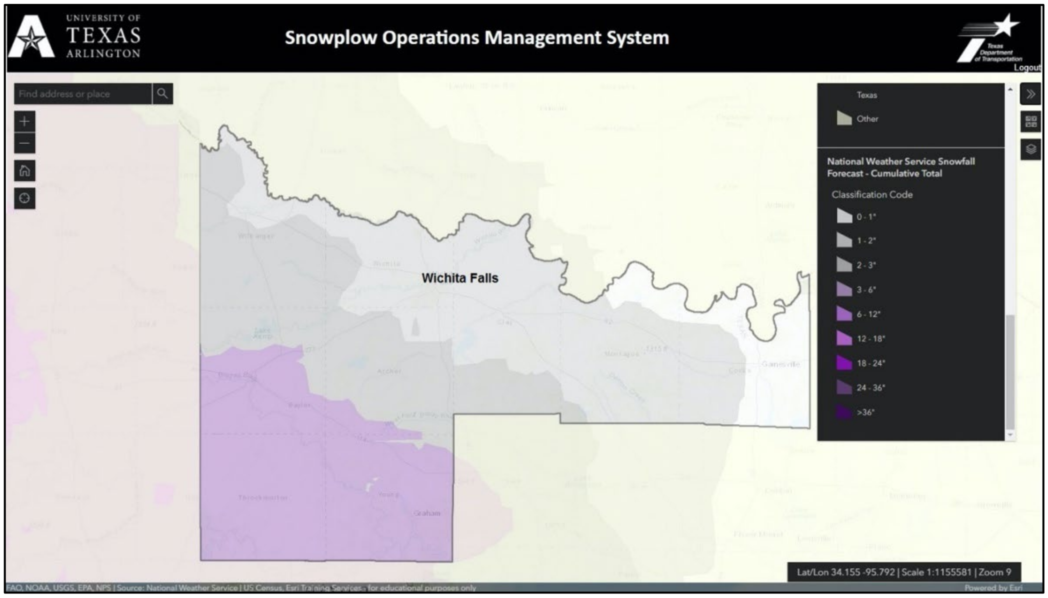


Figure 5.5 Snowfall forecast from the National Weather Service in the TxDOT Wichita Falls district (January 8, 2021, 4:23 PM)

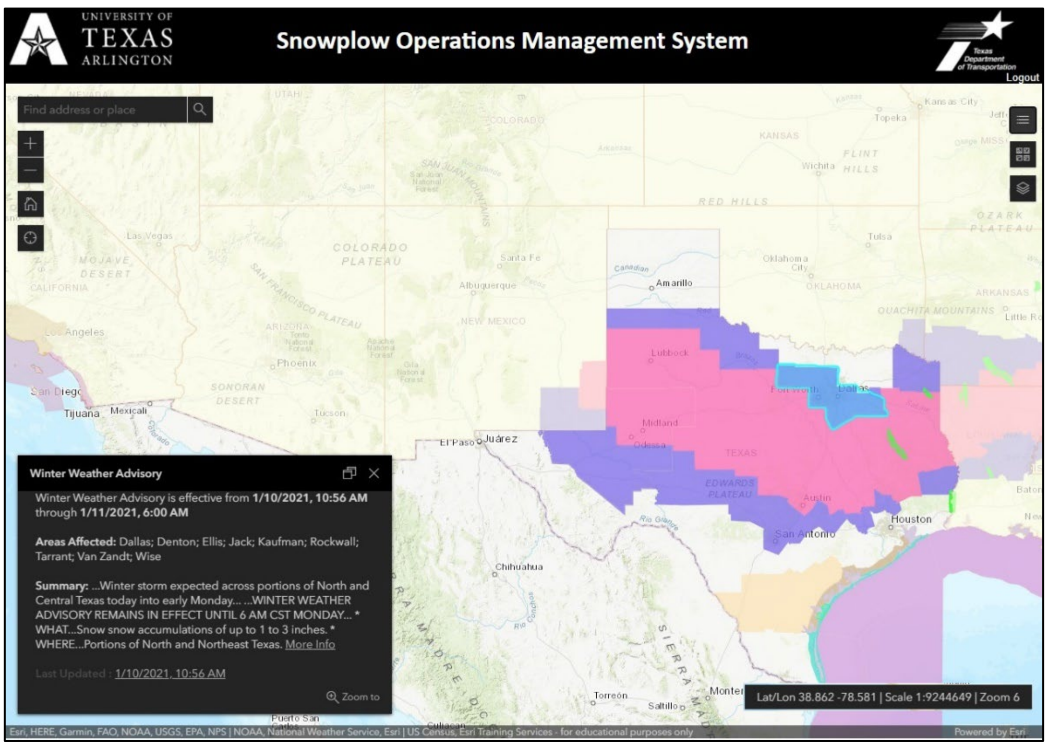


Figure 5.6 Advisory from the National Weather Service during a winter storm in Texas (January 8, 2021, 1:31 PM)

5.2.3 Road Surface Temperatures

The UTA research team estimated road surface temperatures by downloading the influencing weather parameters required for feeding the statistical predictive models (discussed in chapter 4) from the National Digital Forecast Database (NDFD). The data, downloaded in GRIB 2 format, would be converted to ASCII comma-separated format (CSV) to be processed to visualize the estimated road surface temperature on the map-based interface. The research team developed an approach to download and store the data in the server stationed at UTA and process them to visualize the estimated maximum and minimum road surface temperatures on the map-based interface for up to 5 days. Figure 5.7 shows the Function Modeling illustration (IDEF0 figure) of the methodology from downloading the data to visualizing the road surface temperatures on ArcGIS map-based interface.

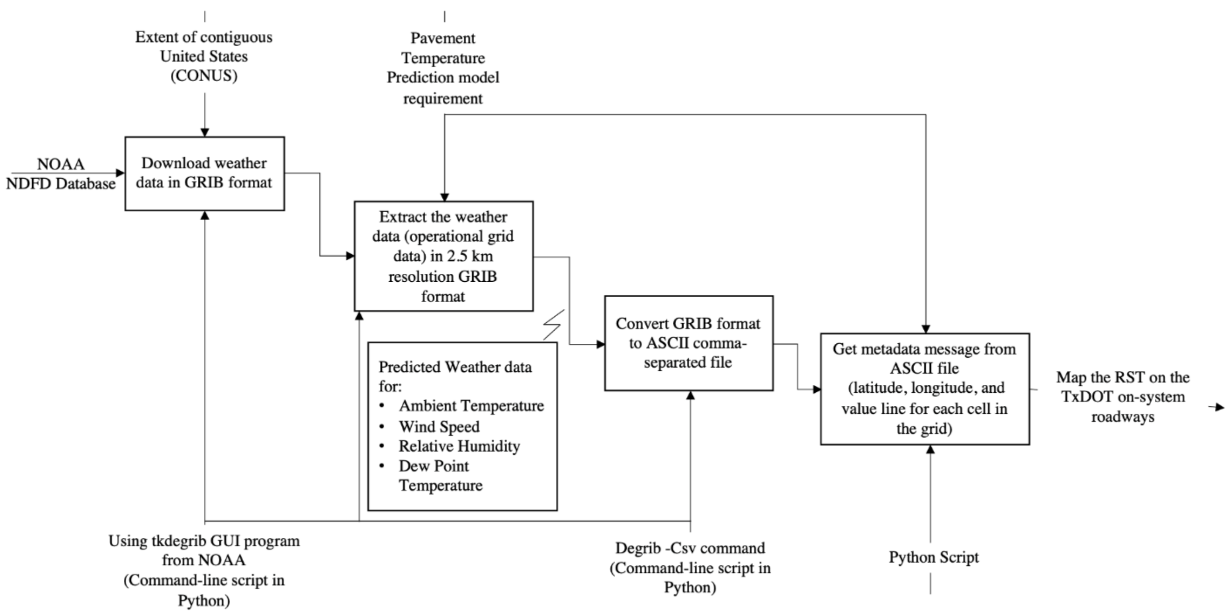


Figure 5.7 IDEF0 diagram from downloading the data to visualizing the road surface temperatures on the map-based interface.

Figure 5.8 shows the map-based interface showing the estimated road surface temperatures along with snowplow locations.

Figure 5.8 Estimated road surface temperatures along with snowplow locations in the Wichita Falls district

Moreover, Figure 5.8 shows the map-based interface displaying the ice accumulation forecast from NWS overlayed with the road networks in the Wichita Falls district on February 2, 2022, at 2:47 PM.

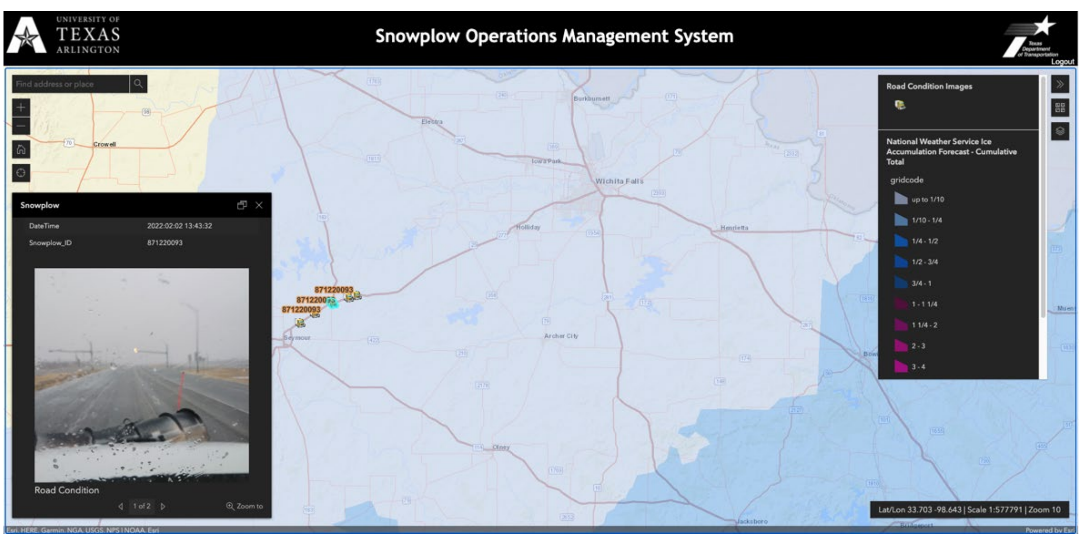


Figure 5.9 Ice accumulation forecast from NWS overlaid with the road networks in the Wichita Falls district on February 2, 2022, at 2:47 PM.

5.3 Data Model Development for Snowplow Operations Management System

The development of a prototype data model for the Snowplow Operations Management System (SOMS) has been summarized in this section. TxDOT Data Architecture was used to create a logical data model based on the collected data. This section includes two sub-sections: (1) a conceptual data model, which represents the general idea of the SOMS, and (2) a logical data model, which provides detailed information about entities and attributes used in the SOMS.

5.3.1 Conceptual Data Model

Figure 5.10 shows the conceptual data model of the SOMS. All the data entities are imported to the SOMS geo-referenced database and are spatially matched. Data could be imported into the geo-referenced database and exported out of the geo-referenced database. Verified users can access and use spatial data by a map-based interface (created and designed to be used in the SOMS) through their computers and phones and contribute to the database by uploading road condition images. An administrator is needed to manage and verify data for the users.

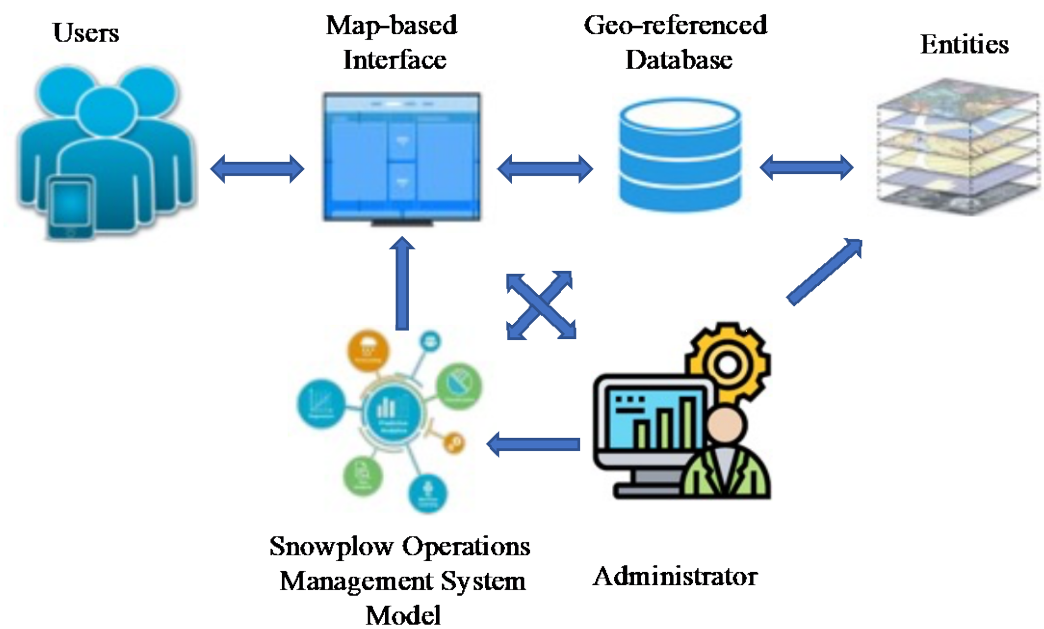


Figure 5.10 Conceptual Data Model

Data Dictionary

Conceptual data model terms are described in Table 5.3.

Table 5.3 Conceptual data model terms description

Term	Description
Entity	**Definition:** an entity is the detailed representation of an object of interest (e.g., road condition images).

Term	Description
Snowplow Operations Management System Geo-Reference Database	**Definition:** A Snowplow Operations Management System is a georeferenced database created using ESRI ArcGIS Online to store and organize GIS-based entities. Geo-referenced databases use an efficient data structure optimized for performance and storage.
Snowplow Operations Management System Model	**Definition:** A Snowplow Operations Management System model is a model that uses data such as road condition images metadata and influencing weather parameters as the inputs, processes the input data, and represents the desired output in the map-based interface.
The SOMS map-based interface	**Definition:** The SOMS map-based interface is a map-based interface that is based on ESRI ArcGIS online that obtains data from a geo-referenced database
User	**Definition:** a user is a TxDOT employee granted the authority to interact with the SOMS map-based interface.
Administrator	**Definition:** an administrator is a TxDOT employee, or a person authorized by TxDOT who has knowledge about Snowplow Operations Management System (SOMS) and oversees managing and organizing the system as well as updating data and verifying data and users.

5.3.2 Logical Data Model

Collected spatial data were used to develop entities for the logical data model based on TxDOT Data Architecture (TxDOT, 2010). Figure 5.11 illustrates the different data entities developed for the Snowplow Operations Management System. The definitions of entities and their associated attributes are provided in the following subsection.

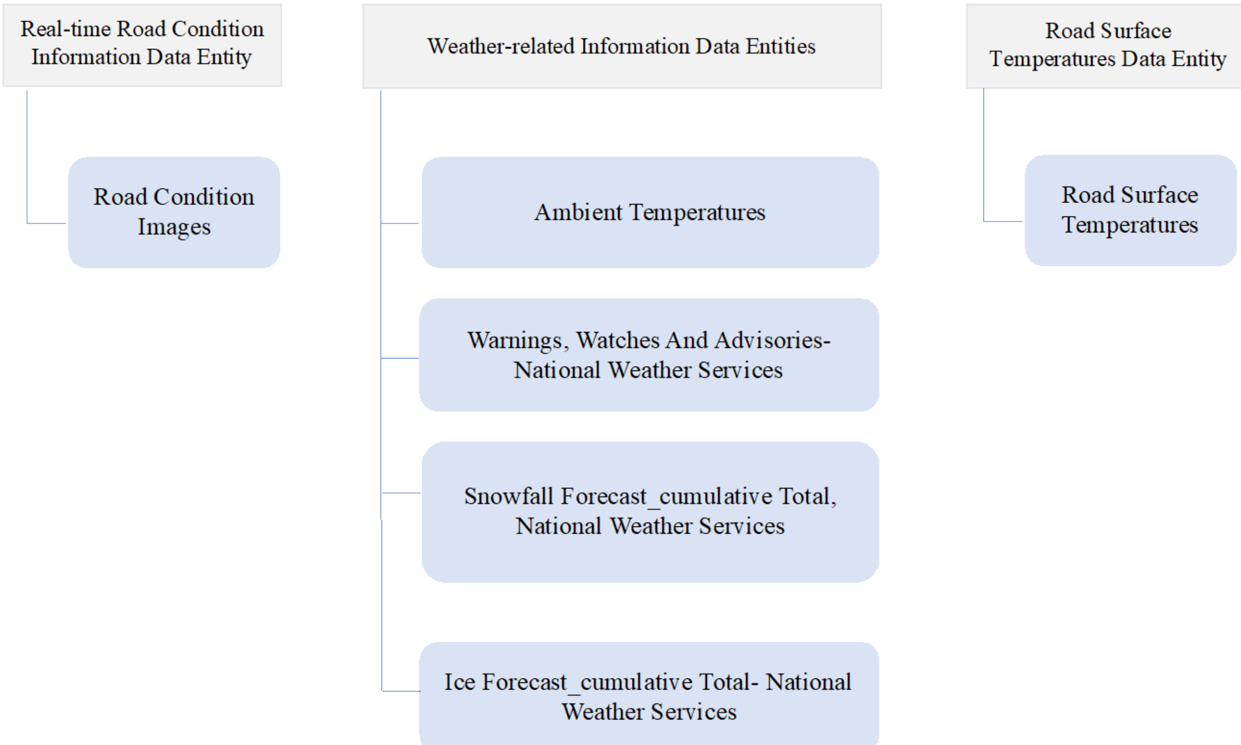


Figure 5.11- The Snowplow Operations Management System's data entities

Data Dictionary

All entities in the logical data model for the SOMS are described in Table 5.4 based on TxDOT Data Architecture.

Table 5.4 Description of the Snowplow Operations Management System's data entities

Entity	Attribute	Description
ROAD CONDITION IMAGES	LATITUDE	**Definition:** LATITUDE is a float number that defines the angular distance of the image location from north/south of the Equator. **Purpose:** LATITUDE coordinate provides an accurate locational relay from north/south of the Equator using the Global Position System (GPS) **Example:** 37.73 **Valid values:** -90 to +90 **Format:** number
ROAD CONDITION IMAGES	LONGITUDE	**Definition:** LONGITUDE is a float number that defines the angular distance of the image location from the East/West of the meridian at Greenwich, England. **Purpose:** Longitude coordinate provides an accurate locational relay from East/West of the meridian at Greenwich, England, using the Global Position System (GPS) **Example:** 96.7 **Valid Values:** -180 to +180 **Format:** number
ROAD CONDITION IMAGES	DATE AND TIME	**Definition:** DATE AND TIME provides information about the time in which the image has been captured. **Purpose:** DATE AND TIME identifies the exact time the image has been captured. **Example:** 2021/02/28 1:28 PM **Valid Values:** N/A **Format:** string
ROAD CONDITION IMAGES	COMMENT	**Definition:** COMMENT is a combination of words that express the written remark of the user. **Purpose:** COMMENT expresses the user's opinion or reaction to a condition in the road captured in the image. **Example:** "Ice observed on the road" **Valid Values:** N/A **Format:** string
AMBIENT TEMPERATURES	STATION NAME	**Definition:** STATION NAME is a word that defines the name of the weather station. **Purpose:** STATION NAME identifies the weather station by its name. **Example:** Wichita Falls **Valid Values:** N/A **Format:** string

Entity	Attribute	Description
AMBIENT TEMPERATURES	DATE AND TIME	**Definition:** DATE AND TIME provides information about the observation time of the weather information. **Purpose:** DATE AND TIME identifies the exact time that weather information (e.g., ambient temperature) has been observed. **Example:** 10/3/2021, 5:51 PM **Valid Values:** N/A **Format:** string
AMBIENT TEMPERATURES	AIR TEMPERATURE (ºF)	**Definition:** AIR TEMPERATURE is a number that defines the temperature of the air surrounding an individual, typically measured in degrees Fahrenheit (ºF). **Purpose:** AIR TEMPERATURE is to measure how cold/hot the weather is. **Example:** 86 (ºF). **Valid Values:** N/A **Format:** number
AMBIENT TEMPERATURES	SKY CONDITION	**Definition:** SKY CONDITION is a combination of words describing the predominant or average sky cover based on the percent of the sky covered by opaque (not transparent) clouds. **Purpose:** SKY CONDITION could be used as an indicator of precipitation occurrence in the near future. **Example:** Cloudy **Valid Values:** N/A **Format:** string
AMBIENT TEMPERATURES	WEATHER CONDITION	**Definition:** WEATHER CONDITION is a combination of words describing the atmosphere. **Purpose:** WEATHER CONDITION provides the state of current atmospheric condition. **Example:** Light Rain **Valid Values:** N/A **Format:** string
WARNINGS, WATCHES, AND ADVISORIES, NATIONAL WEATHER SERVICES	TYPE	**Definition:** TYPE is a combination of words that identifies the type of the issued warnings, watches, and advisories. **Purpose:** TYPE describes the class of the issued warnings, watches, and advisories defined by National Weather Services. **Example:** Winter Storm Watch **Valid Values:** N/A **Format:** string
WARNINGS, WATCHES, AND ADVISORIES, NATIONAL WEATHER SERVICES	SEVERITY	**Definition:** SEVERITY is a combination of words that identifies the severity of the issued warnings, watches, and advisories from National Weather Services. **Purpose:** SEVERITY describes how extreme the forecast event is expected to be.

Entity	Attribute	Description
		Example: Mild **Valid Values:** N/A **Format:** string
WARNINGS, WATCHES, AND ADVISORIES, NATIONAL WEATHER SERVICES	SUMMARY	**Definition:** SUMMARY is a combination of words giving information about the issued warnings, watches, and advisories. **Purpose:** SUMMARY shows what should be expected during the event that the warnings, watches, or advisory is issued for. **Example:** N/A **Valid Values:** N/A **Format:** string
WARNINGS, WATCHES, AND ADVISORIES, NATIONAL WEATHER SERVICES	DETAILS	**Definition:** DETAILS is a web address (URL) to the source of the issued warning, watches, or advisories. **Purpose:** DETAILS redirect the user to the source of the issued warnings, watches, or advisory on the web to provide more detailed information about the event. **Example:** N/A **Valid Values:** N/A **Format:** string
WARNINGS, WATCHES, AND ADVISORIES, NATIONAL WEATHER SERVICES	UPDATED (STORED IN UTC)	**Definition:** UPDATED is the last time that the issued warnings, watches, or advisory has been updated, and is reported in Coordinated Universal Time UTC). **Purpose:** UPDATED shows how recent the issued warnings, watches, or advisory is. **Example:** 10/3/2021, 10:18 AM **Valid Values:** N/A **Format:** string
WARNINGS, WATCHES, AND ADVISORIES, NATIONAL WEATHER SERVICES	EFFECTIVE (STORED IN UTC)	**Definition:** EFFECTIVE is the date and time that the issued warnings, watches, or advisory take into effect. **Purpose:** EXPIRATION shows the date and time that the issued alert is expected to take into effect. **Example:** 10/3/2021, 10:18 AM **Valid Values:** N/A **Format:** string
WARNINGS, WATCHES, AND ADVISORIES, NATIONAL WEATHER SERVICES	EXPIRATION (STORED IN UTC)	**Definition:** EXPIRATION is the date and time that the issued warnings, watches, or advisory expires. **Purpose:** EXPIRATION shows the date and time that the issued alert is expected to expire. **Example:** 10/5/2021, 10:18 AM **Valid Values:** N/A **Format:** string
WARNINGS, WATCHES, AND ADVISORIES, NATIONAL WEATHER SERVICES	AREAS AFFECTED	**Definition:** AREAS AFFECTED is a list of affected areas in the issued warnings, watches, or advisory. **Purpose:** AREAS AFFECTED shows which areas are expected to be affected by the issued alert. **Example:** Wichita falls; Olney.

Entity	Attribute	Description
		Valid Values: N/A **Format:** string
SNOWFALL FORECAST_CUMULATIVE TOTAL, NATIONAL WEATHER SERVICES	FROM DATE	**Definition:** FROM DATE is the starting date and time of the snowfall precipitation forecast. **Purpose:** FROM DATE shows the date and time that the forecast snowfall precipitation is expected to start. **Example:** 10/5/2021, 10:18 AM **Valid Values:** N/A **Format:** string
SNOWFALL FORECAST_CUMULATIVE TOTAL, NATIONAL WEATHER SERVICES	TO DATE	**Definition:** TO DATE is the ending date and time of the forecast snowfall precipitation. **Purpose:** TO DATE shows the date and time that the forecast snowfall precipitation is expected to end. **Example:** 10/8/2021, 11:28 AM **Valid Values:** N/A **Format:** string
SNOWFALL FORECAST_CUMULATIVE TOTAL, NATIONAL WEATHER SERVICES	DESCRIPTION	**Definition:** DESCRIPTION is a combination of words describing the amount of total cumulative snowfall between the FROM DATE and TO DATE. **Purpose:** DESCRIPTION provides information on how much total snow is expected to accumulate on the surface between the FROM DATE and TO DATE. **Example:** Up to 1 inch of snowfall is expected **Valid Values:** N/A **Format:** string
ICE FORECAST_CUMULATIVE TOTAL, NATIONAL WEATHER SERVICES	FROM DATE	**Definition:** FROM DATE is the starting date and time of the ice accumulation. **Purpose:** FROM DATE shows the date and time that the forecast ice accumulation is expected to start. **Example:** N/A **Valid Values:** N/A **Format:** string
ICE FORECAST_CUMULATIVE TOTAL, NATIONAL WEATHER SERVICES	TO DATE	**Definition:** TO DATE is the ending date and time of the ice accumulation. **Purpose:** TO DATE shows the date and time that the forecast ice accumulation is expected to end. **Example:** N/A **Valid Values:** N/A **Format:** string
ICE FORECAST_CUMULATIVE TOTAL, NATIONAL WEATHER SERVICES	DESCRIPTION	**Definition:** DESCRIPTION is a combination of words describing the amount of total ice accumulation (inches) between the FROM DATE and TO DATE. **Purpose:** DESCRIPTION provides information on how much total ice (inches) is expected to accumulate on the surface between the FROM DATE and TO DATE. **Example:** Up to 1 inch of snowfall is expected **Valid Values:** N/A

Entity	Attribute	Description
		Format: string
ROAD SURFACE TEMPERATURE	ROUTE NAME	**Definition:** a ROUTE NAME is a word that defines the name of the route based on the TxDOT road naming convention. **Purpose:** ROUTE NAME identifies road by a unique designated name. **Example:** FM-2224 **Valid Values:** N/A **Format:** string
ROAD SURFACE TEMPERATURE	MAX TEMP Day1 (ºF)	**Definition:** MAX TEMP Day 1 is a number which is an estimation of the maximum road surface temperature for the next day; estimated in degrees Fahrenheit (ºF). **Purpose:** MAX TEMP Day 1 shows the estimated maximum road surface temperature for the following day. **Example:** 67 (ºF) **Valid Values:** N/A **Format:** number
ROAD SURFACE TEMPERATURE	MIN TEMP Day1 (ºF)	**Definition:** MIN TEMP Day 1 is a number which is an estimation of the minimum road surface temperature for the next day; estimated in degrees Fahrenheit (ºF). **Purpose:** MIN TEMP Day 1 shows the estimated minimum road surface temperature for the following day. **Example:** 45 (ºF) **Valid Values:** N/A **Format:** number
ROAD SURFACE TEMPERATURE	MAX TEMP Day 2 (ºF)	**Definition:** MAX TEMP Day 2 is a number which is an estimation of the maximum road surface temperature for the following second day; estimated in degrees Fahrenheit (ºF). **Purpose:** MAX TEMP Day 2 shows the estimated maximum road surface temperature for the following second day. **Example:** 67 (ºF) **Valid Values:** N/A **Format:** number
ROAD SURFACE TEMPERATURE	MIN TEMP Day 2 (ºF)	**Definition:** MIN TEMP Day 2 is a number which is an estimation of the minimum road surface temperature for the following second day; estimated in degrees Fahrenheit (ºF). **Purpose:** MIN TEMP Day 2 shows the estimated minimum road surface temperature for the following second day. **Example:** 45 (ºF) **Valid Values:** N/A **Format:** number

Entity	Attribute	Description
ROAD SURFACE TEMPERATURE	MAX TEMP Day 3 (ºF)	**Definition:** MAX TEMP Day 3 is a number which is an estimation of the maximum road surface temperature for the following third day; estimated in degrees Fahrenheit (ºF). **Purpose:** MAX TEMP Day 3 shows the estimated maximum road surface temperature for the following third day. **Example:** 67 (ºF) **Valid Values:** N/A **Format:** number
ROAD SURFACE TEMPERATURE	MIN TEMP Day 3 (ºF)	**Definition:** MIN TEMP Day 3 is a number which is an estimation of the minimum road surface temperature for the following third day; estimated in degrees Fahrenheit (ºF). **Purpose:** MIN TEMP Day 3 shows the estimated minimum road surface temperature for the following third day. **Example:** 45 (ºF) **Valid Values:** N/A **Format:** number
ROAD SURFACE TEMPERATURE	MAX TEMP Day 4 (ºF)	**Definition:** MAX TEMP Day 4 is a number which is an estimation of the maximum road surface temperature for the following fourth day; estimated in degrees Fahrenheit (ºF). **Purpose:** MAX TEMP Day 4 shows the estimated maximum road surface temperature for the following fourth day. **Example:** 67 (ºF) **Valid Values:** N/A **Format:** number
ROAD SURFACE TEMPERATURE	MIN TEMP Day 4 (ºF)	**Definition:** MIN TEMP Day 4 is a number which is an estimation of the minimum road surface temperature for the following fourth day; estimated in degrees Fahrenheit (ºF). **Purpose:** MIN TEMP Day 4 shows the estimated minimum road surface temperature for the following fourth day. **Example:** 45 (ºF) **Valid Values:** N/A **Format:** number
ROAD SURFACE TEMPERATURE	MAX TEMP Day 5 (ºF)	**Definition:** MAX TEMP Day 5 is a number which is an estimation of the maximum road surface temperature for the following fifth day; estimated in degrees Fahrenheit (ºF). **Purpose:** MAX TEMP 5 shows the estimated maximum road surface temperature for the following fifth day. **Example:** 67 (ºF)

Entity	Attribute	Description
		Valid Values: N/A **Format:** number
ROAD SURFACE TEMPERATURE	MIN TEMP Day 5 (ºF)	**Definition:** MIN TEMP Day 5 is a number which is an estimation of the minimum road surface temperature for the following fifth day; estimated in degrees Fahrenheit (ºF). **Purpose:** MIN TEMP Day 5 shows the estimated minimum road surface temperature for the following fifth day. **Example:** 45 (ºF) **Valid Values:** N/A **Format:** number
SNOWPLOW OPERATIONS MANAGEMENT SYSTEM INTERFACE USER	USER FIRST NAME	**Definition:** a USER FIRST NAME is a word that identifies the first name of a user who signs up for the interface **Purpose:** USER FIRST NAME is used to identify a user. **Example:** N/A **Valid Values:** N/A **Format:** string
SNOWPLOW OPERATIONS MANAGEMENT SYSTEM INTERFACE USER	USER LAST NAME	**Definition:** a USER LAST NAME is a word that identifies the last name of a user who signs up to the interface **Purpose:** USER LAST NAME is used to identify a user. **Example:** N/A **Valid Values:** N/A **Format:** string
SNOWPLOW OPERATIONS MANAGEMENT SYSTEM INTERFACE USER	USER EMAIL	**Definition:** a USER EMAIL is a word that defines the email address of a user, and must be used by a user to gain access to the map-based interface **Purpose:** USER EMAIL is used as contact information as well as sign up and sign into the map-based interface. **Example:** John@txdot.com **Valid Values:** N/A **Format:** string
SNOWPLOW OPERATIONS MANAGEMENT SYSTEM INTERFACE USER	USER PASSWORD	**Definition:** a USER PASSWORD is a word that must be used by a user to gain access to the map-based interface **Purpose:** USER PASSWORD is used to sign up and sign into the map-based interface. **Example:** a-32B_74r **Valid Values:** N/A **Format:** string

5.4 Map-Based ArcGIS Interface Development

This section explains developing a map-based ArcGIS interface for visualizing the road condition images collected from snowplows, road surface temperatures, and related weather information provided by national weather services. This map-based interface is accessible through a password-protected web page that is only accessible for TxDOT and UTA staff. Figure 5.12 shows the sign-in web page to access the interface. Moreover, Figure 5.13 illustrates the developed Snowplow Operations Management System's map-based interface.

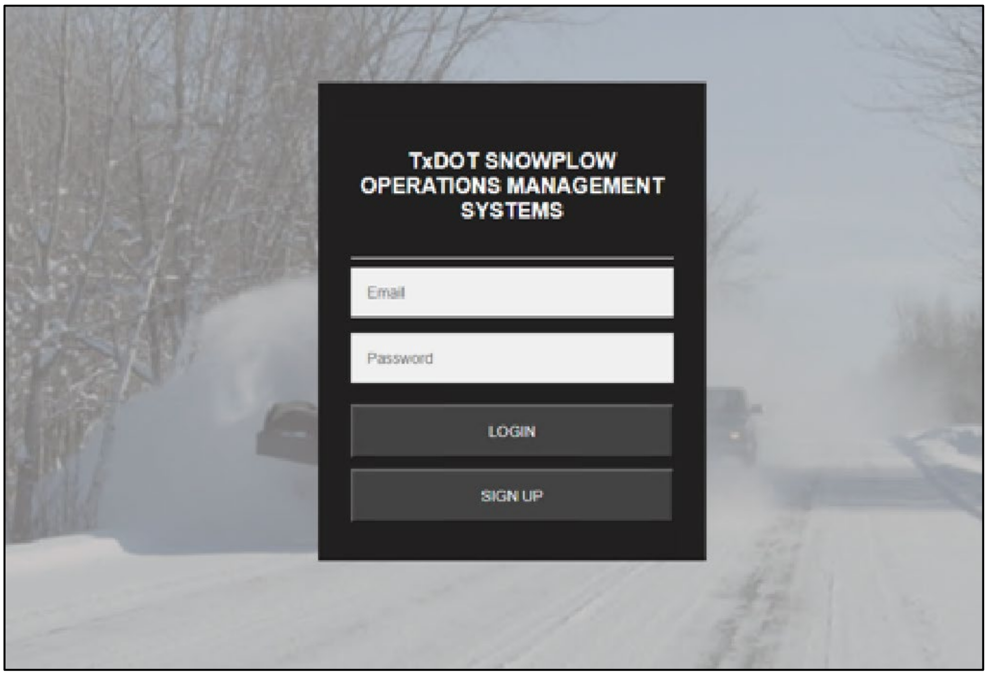


Figure 5.12 Sign-in webpage to access the map-based interface

Figure 5.13 Map-based interface for Snowplow Operations Management System

Descriptions of the widgets in the map-based interface are shown in Table 5.5. The entity widget helps the user control the required entity's display in the interface, i.e., the entity containing the information on road condition images can be turned on or off using the entity widget. By clicking on the displayed data on the map-based interface, the users can see information about the data (i.e., road condition images or related weather information).

The legend widget displays the legend of the entities, which are turned on in the map-based interface. The base map in the map-based interface can be changed using the base map widget. The widgets on the top-left of the interface, such as the zoom widget, home, and locator widget, help the user navigate the interface. Table 5.5 describes the functionality of the widgets available in the map-based interface.

Table 5.5 Description of widgets in the map-based Interface

Widget Name	Description
Search	This widget helps to find a specific location in the map-based interface.
Zoom In	This widget helps zoom in on the map view in the map-based interface.
Zoom Out	This widget helps to zoom out of the current map view in the map-based interface.

Widget Name	Description
Home	This widget brings the map view to the initial view extent.
Locator	This widget helps to find the location of the user.
Base map	This widget allows the user to select the base map to be displayed in the map view of the map-based interface.
Entity	This widget displays the list of spatial data entities that can be visualized in the map-based interface.
Legend	This widget displays the legends of the spatial data entities displayed in the map-based interface.

5.4.1 Use Cases

A use case is a set of possible sequences of interactions between a user and a system and indicates the system's action in response to a user's action. The use case diagram is a graphical table of contents for individual use cases and defines a system boundary. Figure 5.14 represents the use case diagram for the snowplow operations management system. Use cases for the map-based application are detailed in Table 5.6 to Table 5.16.

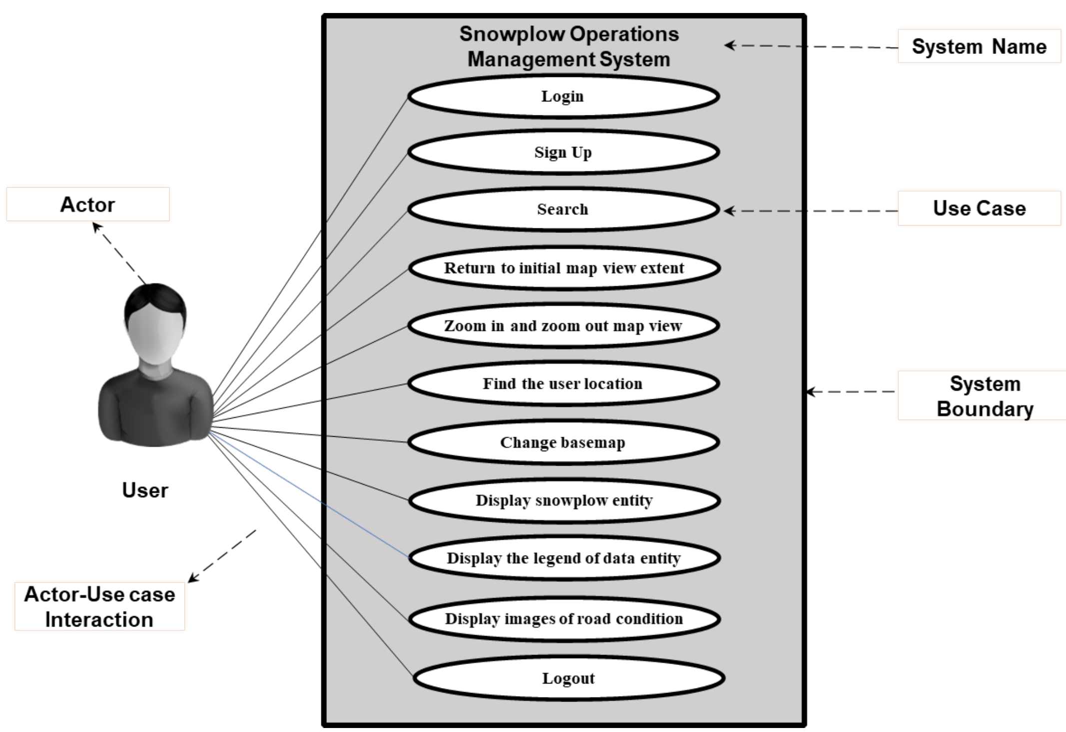


Figure 5.14 Use case diagram

Table 5.6 UC1: Login

Actor: User	**System: Snowplow operations management system**
	0. The browser displays a web page.
1. The user enters the web address in the address bar and press enter. URL: https://axb9294.uta.cloud/SOMSNOV/login.php	2. The system displays the login page, which prompts the user to log in using a username and password.
3. The user enters the username and password, then clicks the login button.	4. The system displays a. The map-based interface if the username and password are entered correctly. b. A message requesting to recheck inputs if the username or password is incorrect.
5. The user sees the map-based interface, or a login error is displayed.	

Table 5.7 UC2: Sign up

Actor: User	**System: Snowplow operations management system**
	0. The browser displays a web page.
1. The user enters the web address in the address bar, and presses enter.	2. The system displays the login page, which prompts the user to log in using a username and password along with the option to sign up for a new account.
3. The user clicks on the signup button.	4. The system prompts the user to sign up page.
5. The user fills in the information (First Name, Last Name, Email address, Password) requested on the sign-up page and clicks the signup button to complete the process.	6. The system sends an email to the user's email address to activate the account.
7. The user opens the email and clicks the activation link to activate the account.	8. The system registers the user and displays the confirmation of registration.

Table 5.8 UC3: Search

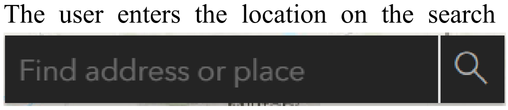
Actor: User	**System: Snowplow operations management system**
	0. The system displays the map-based interface.
1. The user enters the location on the search bar. 	2. The system displays the searched location.

Table 5.9 UC4: Return to initial map view extent

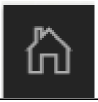
Actor: User	System: Snowplow operations management system
	0. The system displays the map-based interface.
1. The user clicks the home button. 	2. The system returns to the initial map view extent.

Table 5.10 UC5: Zoom-in and zoom-out of the map view

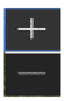
Actor: User	System: Snowplow operations management system
	0. The system displays the map-based interface.
1. The user clicks the zoom button. 	2. The system zooms in or zooms out in the map view of the map-based interface.

Table 5.11 UC6: Find the user location

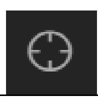
Actor: User	System: SRMMS
	0. The system displays the map-based interface.
1. The user clicks the locator widget. 	2. The system displays the location of the user in the map-based interface.

Table 5.12 UC7: Change base map

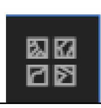
Actor: User	System: Snowplow operations management system
	0. The system displays the map-based interface.
1. The user clicks the base map widget. 	2. The system displays the available base maps from which the user can select.
3. The user clicks on the desired base map.	4. The system changes the existing base map to the base map selected by the user.
5. The user clicks on the base map widget.	6. The system closes the expanded base map widget.

Table 5.13 UC8: Display data entity

Actor: User	**System: Snowplow operations management system**
	0. The system displays the map-based interface.
1. The user clicks the entity widget. 	2. The system expands the entity widget and displays the data entities, including the road condition images, related weather information, and estimated road surface temperatures' entities.
3. The user clicks on the entity to turn it on and off.	4. The system displays or removes the entity from the map view.
5. The user clicks on the entity widget.	6. The system closes the expanded entity widget.

Table 5.14 UC9: Display the legend of the data entity

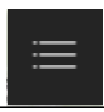
Actor: User	**System: Snowplow operations management system**
	0. The system displays the map-based interface.
1. The user clicks the legend widget. 	2. The system displays the legend of the entity displayed in the map-based interface.

Table 5.15 UC10: Display road condition data

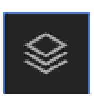
Actor: User	**System: Snowplow operations management system**
	0. The system displays the map-based interface.
1. The user clicks the entity widget. 	2. The system expands the entity widget and displays the data entities, including road condition images, related weather information, and estimated road surface temperatures' entities.
3. The user turns on the data entities to ensure required entities are displayed on the map.	4. The system displays the snowplows in the map-based interface.
5. The user clicks on the data in the map-based interface.	6. The system displays a pop-up window containing related information about the data.
7. The user clicks on the close bottom in the pop-up.	8. The system closes the pop-up window.

Table 5.16 UC11: Logout

Actor: User	**System: Snowplow operations management system**
	0. The system displays the map-based interface.
1. The user clicks the logout out button located on the top-right of the application.	2. The system exits the application.

5.5 Summary

As the collected data are from multiple sources with different data structures, it is important to integrate all the collected data into a single map-based interface to share the spatial information through interactive maps. The UTA research team developed an ArcGIS map-based interface to facilitate the real-time visualization of the spatial data during snowplow operations based on TxDOT data architecture. The map-based interface, hosted in ArcGIS Online, displays (1) the road condition images along with snowplow location, (2) related weather information from national weather services, (3) and road surface temperatures on TxDOT on-system road segments in the Wichita Falls district. The map-based application runs in a web browser and can be accessed from desktops, smartphones, and tablets, which use windows, macOS, Android, iOS, and Linux operating systems. Sharing and matching spatial data through interactive maps allows transportation operations managers to monitor road condition information graphically and facilitate decision-making on snowplows' deployments during winter operations.

CHAPTER 6. COST ANALYSIS AND SCHEDULE

6.1 Introduction

The objectives of this chapter are to (1) estimate the implementation cost of the Snowplow Operations Management System (SOMS), including the capital cost and operating cost, and (2) propose a schedule for the SOMS implementation in TxDOT.

6.2 Implementation Cost of the Developed System

In this chapter, the implementation cost of the SOMS, including the capital cost and operating cost, for equipping the snowplows and maintaining the SOMS has been explained. Also, the total cost of the SOMS implementation in one sample district in TxDOT with 30 snowplows has been discussed.

6.2.1 Capital Cost

The capital cost of the SOMS implementation includes the one-time cost for acquiring the required equipment. The equipment needed for the SOMS includes (1) data acquisition equipment which would be installed on the snowplows to collect road condition images, and (2) server equipment to process the collected data to be further visualized on a map-based interface. The following sub-sections explain the cost of the equipment.

Data Acquisition Equipment

The data acquisition equipment needed to be installed on the snowplows includes (1) a tablet device to collect geotagged road condition images and (2) auxiliary equipment, including the tablet mount and cable to mount the tablet on the snowplow and power it during the snowplow operations. Figure 6.1 illustrates the data acquisition equipment needed for implementing the SOMS.

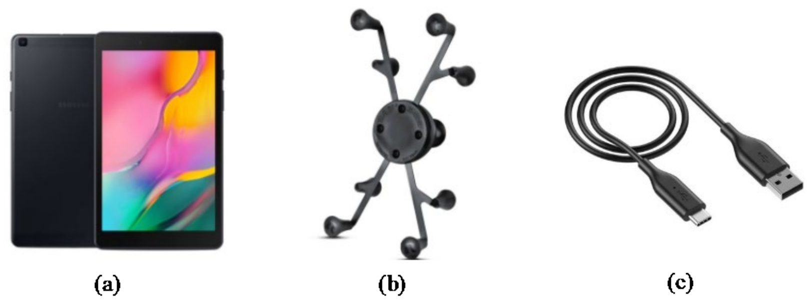


Figure 6.1 Data acquisition equipment required for implementing the SOMS: (a) Tablet device, (b) Tablet mount, and (c) USB cables

Table 6.1 shows the cost breakdown of the data acquisition equipment based on the suggested specification for each piece of equipment. The total cost of data acquisition equipment would be approximately $290 for each snowplow.

Table 6.1 The capital cost of data acquisition equipment for the SOMS implementation—for each snowplow

Description	Specification	Cost ($)
Tablet	Samsung Galaxy Tab A 8 inches (LTE)	~ $200
Installation mount	RAM suction cup mount	~ $80
Charging cable	2A and 5V USB cable	~ $10
The total capital cost of data acquisition per snowplow		~$290

The research team recommend that the tablets are replaced every 5 years. Rugged tablets could also be used for this system. Rugged tablets could have a longer lifespan, but they might be slightly more expensive. These tablets are designed to handle heavy-duty tasks and are more durable.

Server Equipment

The UTA research team used a high-end desktop computer stationed at the UTA to maintain the developed system during snowplow operations. TxDOT owns a fleet of engineering grade computers which can be used to maintain the system. However, if TxDOT decides to use external resources for this project, Table 6.2 shows the approximate cost of a high-end desktop computer that could be used to maintain the SOMS.

Table 6.2 The capital cost of the server equipment for the SOMS implementation—for snowplow fleet

Description	Cost ($)
High-end desktop computer (including the monitor, mouse, and keyboard)	~$5,000*

*This cost may be waived if TxDOT decides to use its engineering grade computers to maintain the system

6.3 Operating Cost

The operating cost of the SOMS would be the ongoing cost of running and maintaining the system during the snowplow operations. The operating cost includes the cost of (1) a data plan, (2) web hosting services and software licensing, and (3) system administration. The following sub-sections explain the cost breakdown for each item.

6.3.1 Data Plan

An Internet connection should be provided for the tablets to transfer the collected data to the server. The research team used a cellular data plan on the tablets to provide the Internet connection. Table 6.3 shows the approximate cost of the data plan based on the average price of unlimited data plans offered by U.S. wireless carriers. The data plan could be used only for the months that the SOMS is under operation during the winter season. According to the snowfall history in North Texas, it is assumed that the winter season lasts from December to April (5 months) (NOAA, 2021c). Therefore, the annual operating cost of the SOMS for the data plan would be approximately $185 for each snowplow— assuming the approximate $40 monthly cost for the data plan.

Table 6.3 Data plan cost the SOMS implementation—for each snowplow

The average cost of a monthly data plan	The annual cost for each snowplow ($)
$40 / line	~$200

6.3.2 Web Hosting Services and Software Licensing

The UTA research team developed a map-based application using the capabilities of ArcGIS software. Furthermore, the research team hosted the developed map-based application on a password-protected web page to facilitate accessing the collected information for the authorized TxDOT staff. Currently, the research team are using the existing internal resources of UTA (e.g., cloud space, web hosting services, and software licensing) to store the collected data and host the map-based application on the web. The cost of web hosting services and software licensing may be waived if TxDOT uses its internal resources to provide access to web hosting services and software licensing for this project. However, if TxDOT decides to use external resources for this project, the cost of required services would be approximately as shown in Table 6.4. The price of web hosting services is based on the average price of available third-party web-hosting providers.

Table 6.4 Web hosting services and software licensing cost for the SOMS implementation—for snowplow fleet

Description	Annual cost ($)
ArcGIS license	~$700*
Web hosting services	~$100*

* This cost may be waived if TxDOT decides to use its internal resources for web hosting and GIS software licensing

6.3.3 System Administration Cost

The SOMS needs an administrator to maintain the system during the snowplow operations. An administrator is a TxDOT employee, or a person authorized by TxDOT who has knowledge about the SOMS and oversees managing and organizing the system, updating data, and verifying data and users. Assuming that the system administrator, with an average hourly wage of $39/hr., needs to spend 2 hr./day for the system maintenance, the yearly operating cost of the system would be approximately $11,700 as shown in Table 6.5 —for five (5) months of maintaining the SOMS in the winter season.

Table 6.5 System administration cost—for snowplow fleet

Description	Amount
System administrator’s hourly wage	~$39/hr.
Hours per day required for system maintenance	~2 hours
The total number of hours for five (5) months of the system administration	~300 hours
The total operating cost of the system administration	~$11,700/ year

6.4 Implementation Cost of the SOMS in One Sample District in TxDOT with 30 Snowplows

According to TxDOT, approximately 700 snowplows are available in TxDOT to operate during winter storms for snow removal purposes (TxDOT, 2021a). If these snowplows are evenly distributed between all 25 TxDOT districts, each district has approximately 30 snowplows available to equip with the SOMS for winter operations. Table 6.6 summarizes the total cost of the SOMS implementation in one sample district in TxDOT— It is assumed that TxDOT provides access to a desktop computer, as well as web hosting services and software licensing through their internal resources at no additional cost.

Table 6.6 Cost summary for the SOMS implementation in one TxDOT district—for 30 snowplows

	Description	The total cost of the SOMS implementation in one sample TxDOT district
Capital Cost	Data acquisition equipment ($290 for each snowplow)	~$8700
	Desktop computer	*No additional cost*
Operating Cost	Data plan ($200/year for each snowplow)	~$6,000/ year
	Administration cost ($11,700 for total fleet)	~$11,700/ year
	Web hosting and software licensing	*No additional cost*

6.5 Proposed Implementation Schedule

In this section, the UTA research team proposed a schedule for the SOMS implementation in TxDOT. This schedule is proposed based on the experiences during the pilot test period of the project, and it could be adjusted in any way to serve the TxDOT needs in the future. The research team recommend collecting the tablets from the trucks before the summer between April to May in order to prevent damage to the tablets.

Table 6.7 Proposed schedule for implementing the SOMS in TxDOT

Implementation Phases	Fiscal Year											
	Septemb	**October**	**Novembe**	**Decembe**	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**
Phase 1: Acquiring the equipment (i.e., tablets, mounts, cables, and server equipment)	x	x	x									
Phase 2: Installing the tablets on snowplows, training the drivers, and setting the system's server			x	x								
Phase 3: Maintaining the Snowplow Operations Management System				x	x	x	x	x				
Phase 4: Collecting the data acquisition equipment from snowplows to be installed for the next winter season								x	x			

CHAPTER 7. ON-DEMAND ROAD CONDITIONS IMAGES

7.1 Introduction

Transportation operations managers need to know the state of highways' assets to make informed decisions regarding their maintenance and rehabilitation (Haas et al., 2005). Traditionally, highway agencies manually collect road conditions data by visual inspection (Azari, 2021). Manual recording of road conditions information, such as countywide signage inventory, abandoned traffic control devices, bridge decks, or any highway asset, especially during snowstorms, could be time-consuming for highway agencies (Graybeal et al., 2002). Also, the manual reporting process may produce inaccurate information due to personal judgments and human errors (Skorokhod, 2018). Therefore, transportation agencies may not be able to respond to road conditions issues quickly through a manual reporting process (Taneja et al., 2011).

The developed functionality of the system, explained in chapter 2, collects and transfers road conditions images at predetermined time intervals (e.g., 10 minutes) without any interaction from the user— which may result in missing out specific road conditions issues if they are not at the exact time when the application records data. Since some of the particular road conditions issues (e.g., abandoned traffic control devices, damaged traffic signs, dead animals on the road, etc.) may not be at the time intervals when the system automatically collects road conditions images, it is of interest to develop a feature in the system that facilitates providing on-demand images of road conditions upon request from users when needed for analysis in real-time.

The objective of this chapter is to develop a feature in the system that enables the operations and maintenance staff to collect road conditions images when needed for analysis in real-time. The collected images are further processed and visualized on an ArcGIS map-based interface. These new functionalities enable TxDOT maintenance and operations staff, either on roads or from the office, to collect on-demand images from road conditions.

The developed ArcGIS map-based interface, visualizing field staff's collected on-demand road conditions images, is accessible through a password-protected web page similar to the system explained in chapter 5. The URL address for the on-demand road conditions image webpage is https://axb9294.uta.cloud/OnDemandPicture/login.php. Section 7.2 describes how a user interacts with this system. Further details about the developed system have been presented in the following sections.

7.2 Developing On-Demand Road Conditions Image Collection Feature

The following section elaborates how a custom application, running on tablets, was developed to collect and transfer geotagged images of road conditions associated with comments made by field staff. It also explains how the research team developed an approach to enable the operations and maintenance staff in the office to request road conditions images at any desired time when the application is running on tablets.

7.2.1 Developing a Custom Android Application to Collect On-Demand Road Conditions Images

The research team developed a custom Android application using Java, the official language for Android development. Figure 7.1 shows the data flow from the Android application, running on a tablet device, to the map-based interface.

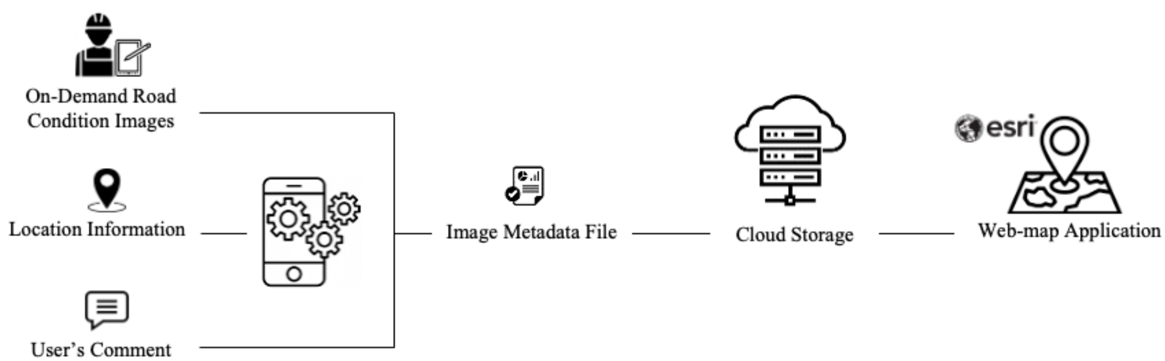


Figure 7.1 Data flow from the Android application to the ArcGIS map-based application

To develop the Android application, the research team utilized the capabilities of Java Application Programming Interfaces (APIs) to execute various tasks, such as capturing images, determining locations, adding user's comments, constructing metadata files, and uploading the file to cloud space. Figure 7.2 illustrates the function modeling methodology used to develop the application, which runs on Android tablets.

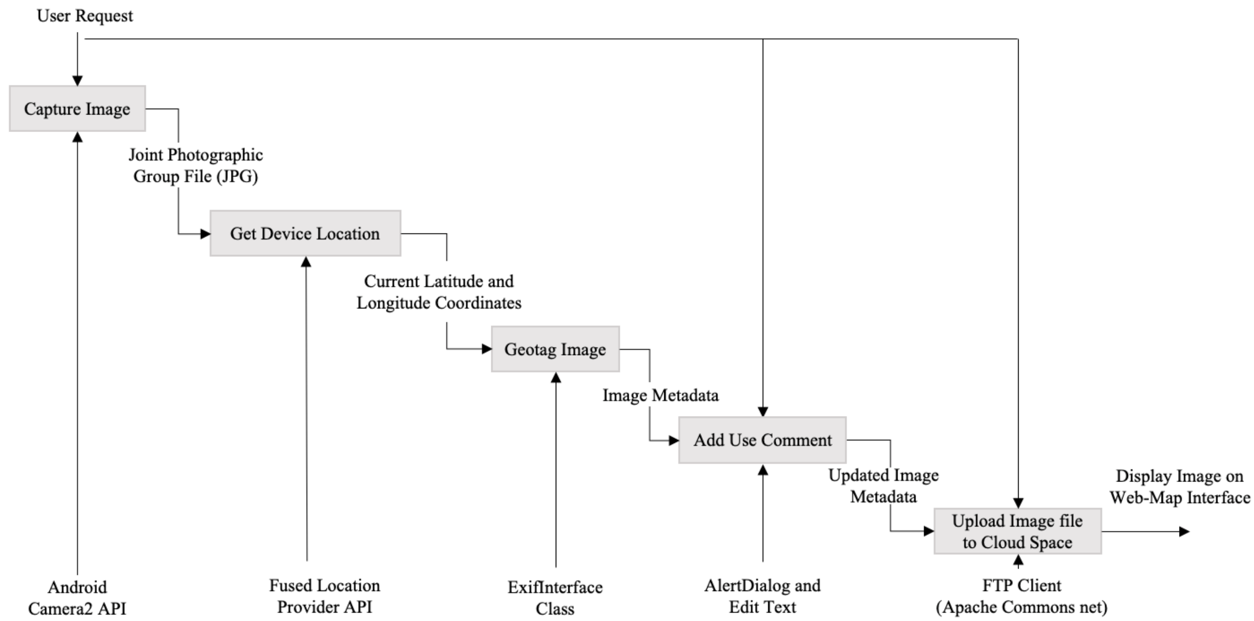


Figure 7.2 Function modeling methodology to develop the Android application to collect on-demand images

Capturing Image

The developed custom application utilizes the built-in tablet's camera device to capture images using the "android.hardware.camera2" package. The "android.hardware.camera2" package uses the tablet's camera device as a pipeline, which accepts input requests from the application to capture a single frame and outputs a metadata packet for each frame (Android developers, 2020b).

To capture a single image, first, the application constructs a CaptureRequest, which defines all the capture parameters a camera device needs to capture it. Once the request is set up, it will be handed to the active capture session with a set of output surfaces. Each surface is pre-configured with an appropriate size and format to match the sizes and formats available from the camera device. After processing the request, the camera device produces a TotalCaptureResult object, which includes the image file and information about the state of the camera device at the time of capture, and the final settings used. Lastly, A preview of the captured image is displayed on the TextureView target surface. Appropriate permissions, including "access to the camera" and "write to external storage," were granted in the application manifest file to access the camera and the device's storage space.

Determining Location

In this Android application, the "Fused Location Provider" combines different signals (i.e., GPS and cell tower) to determine the device's location information. The "fused location provider" is one of the location APIs in Google Play services that manages the underlying location technology and provides a simple API that optimizes the device's use of battery power (Android developers, 2020c). To add the Fused Location Provider to the application's development project, the Google Play Service is downloaded and added to the library of the project. Once the Location Service client is created, the application can determine the last known location of the tablet by the "getLastLocation" Java method. This method returns the current latitude and longitude of the device's location. Appropriate permissions, including access to" fine location" and "coarse location," were granted in the Android manifest file to access the device's location services.

Adding User's Comment

After the image is captured and the location is determined, the application allows the user to comment on the image using the "AlertDialog" feature in Android development. The user can also skip this step and upload the image without any comments. If the user opts to add a comment about the image, an "EditText" pop-up window accepts the comment from the user. "EditText" is a user interface element in Android development that allows entering and modifying texts and numbers to the application as an input (Android developers, 2020e). By having all the required information about the image (e.g., device's location, time, and user's comment), the application combines all the data into one image metadata file to be transferred to the cloud space to be further processed and visualized on the map-based interface.

Constructing Image Metadata File

Metadata describes information about data. Specifically, image metadata is the information embedded into an image file and includes details about the image itself and information about its creation. The image metadata allows information to be transferred together with an image in a way that can be understood by software, hardware, and humans, regardless of the format. While the "android.hardware.camera2" package generates some metadata by default (e.g., time, camera model, image size, etc.), other metadata shall be added manually (i.e., location information and user's comment). The Android "ExifInterface" class adds the required information (i.e., location information and user comment) to the image metadata in this application. The "ExifInterface" class allows reading and writing Exchangeable Image File (EXIF) tags into a JPEG file or a RAW image file (Android developers, 2020d). Table 7.1 provides examples of metadata created by the custom Android application for a sample test image.

Table 7.1 Example metadata created by the application

Property	Value
Camera Make	Samsung
Camera Model	SM-T295
Image Width	1920
Image Height	1080
Orientation	Rotate 90 CW
Date and Time	2021:06:10 15:52 PM
GPS Latitude	32.732814
GPSLatitudeRef	North
GPSLongitude	97.113237
GPSLongitudeRef	West
User's Comment	"Test Image"

Uploading Image Metadata File to Cloud Space

The application uses the "File Transfer Protocol (FTP)" method to upload the image metadata to cloud space. FTP is a secure network protocol to transfer data between a host device (i.e., tablet) and a remote server (i.e., cloud space). The application implements the "Apache Commons Net" library to establish an FTP connection. The Apache Commons Net library contains a collection of network utilities and protocol implementations, including FTP, to set up the connection between host device and server (Apache Software Foundation, 2020). In this application, the host device is the tablet, and the server is "The University of Texas at Arlington (UTA)" cloud space, where the images are stored to be further processed and visualized on the map-based interface. The appropriate permissions, including access to "network state" and "internet," were granted in the Android manifest file to set up an FTP connection within the application.

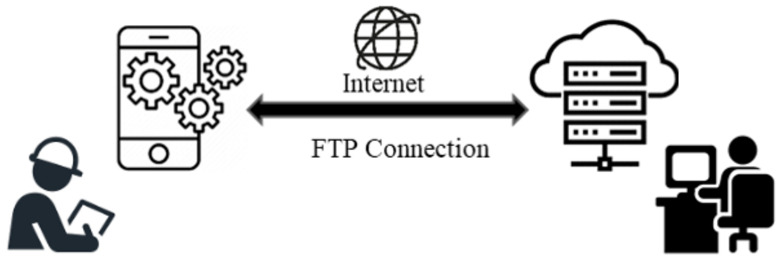


Figure 7.3 Uploading image metadata to cloud space

The User Interface of the On-Demand Image Collection Application

Data collection using the developed application is simple for the field staff. The user could capture an image by pressing the "Capture" button at the bottom of the tablet screen. When the button is pressed, the application captures the image, and a preview of the captured image will be displayed to be confirmed. Upon confirming the image preview, the user will be asked to add a comment to the image using a pop-up EditText window. The user can also skip adding a comment to the image. Lastly, by pressing the "Done" button, the image metadata file is constructed and uploaded to the cloud space, where it can be further processed and visualized on the map-based interface. Figure 7.4 illustrates the user interface of the developed Android application.

Figure 7.4 The user interface of the Android application to collect on-demand road conditions images

Use Cases

A use case is a set of possible sequences of interactions between a user and a system and indicates the system's action in response to a user's action. Table 7.2 presents the use case for the developed Android application to collect road conditions images upon users' demand.

Table 7.2 Use Case for the developed Android application to provide on-demand road conditions images

Actor: User	System: On-Demand Image Collection Application
	0. The tablet's main screen displays a list of the installed applications on the tablet.
1. The user presses the "on-demand image collection application" icon available on the main screen of the tablet	2. The tablet launches the application and displays the camera view for the user.
3. The user presses the "Capture" button.	4. The application captures the image and displays a preview of the image for the user's confirmation.
5. The user presses the "Done" button	6. The image metadata is constructed.
7. The user presses the "Skip" button	8. The image metadata is sent to the cloud space without any comments from the user
9. The user types the comment in the text bar and presses "Done."	10. The user's comment will be added to the constructed image metadata, and the updated file will be uploaded to the cloud space.

7.2.2 Developing an Add-on for the Web-Map Application to Allow Requesting for Road Conditions Data

This section explains how the research team developed an approach to enable the operations and maintenance staff in office to request road conditions images when the tablets are working in the snowplows. The snowplow Android application, developed in chapter 2, provides road conditions images at predetermined time intervals (e.g., every 10 minutes). However, this may not be sufficient to determine the road conditions — especially during severe winter storms. Therefore, the research team developed a new add-on for the developed web-map application, explained in chapter 5, to allow the operations and maintenance staff in office to request road conditions images between the time intervals of the automatic image collection if needed. The new add-on is created using the capabilities of JavaScript, CSS, and PHP programming languages and is added to the web page discussed in chapter 4, where the map-based interface is accessible. The users could ask for road conditions images from each snowplow by clicking the "Request" button and choosing the "Snowplow ID" from the drop-down list. Selecting the snowplow ID and submitting the request will send a signal text to the cloud associated with the selected snowplow ID. Additionally, the snowplow application reads the signals in the cloud at predetermined intervals (e.g., every minute) and captures a new image of the road conditions each time a signal is available. Figure 7.5 illustrates the new add-on in the web-map interface.

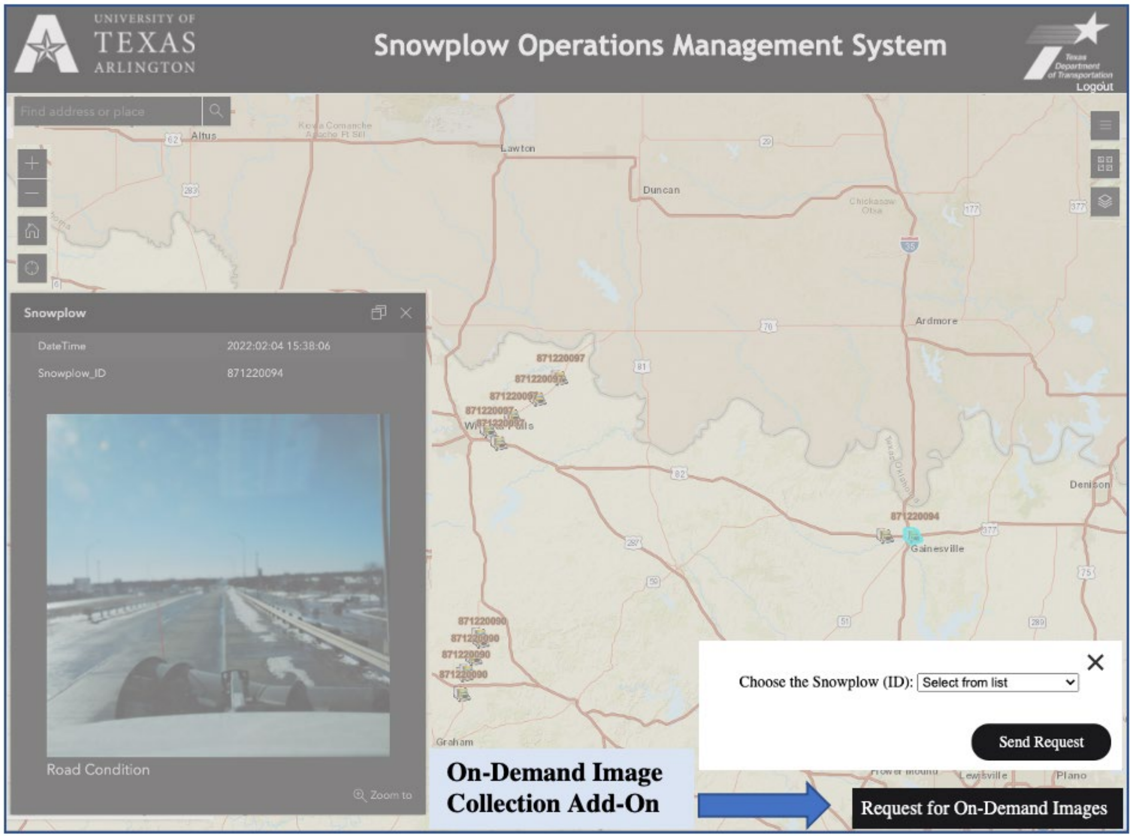


Figure 7.5 Developed add-on for the web-map interface to allow requests for road conditions images

7.3 Results

The research team set up a pilot test with one (1) tablet in the TxDOT Wichita Falls district to collect on-demand road conditions images when needed. With the help of TxDOT Wichita Fall district staff, the research team tested the developed application and collected several on-demand road conditions images— which were further visualized on the ArcGIS map-based interface. Figure 7.6 shows a screenshot of the map-based interface displaying an on-demand road conditions image in Throckmorton County on November 11, 2021, at 1:54 PM. Furthermore, Figure 7.7 illustrates examples of the collected on-demand road conditions images during the testing period.

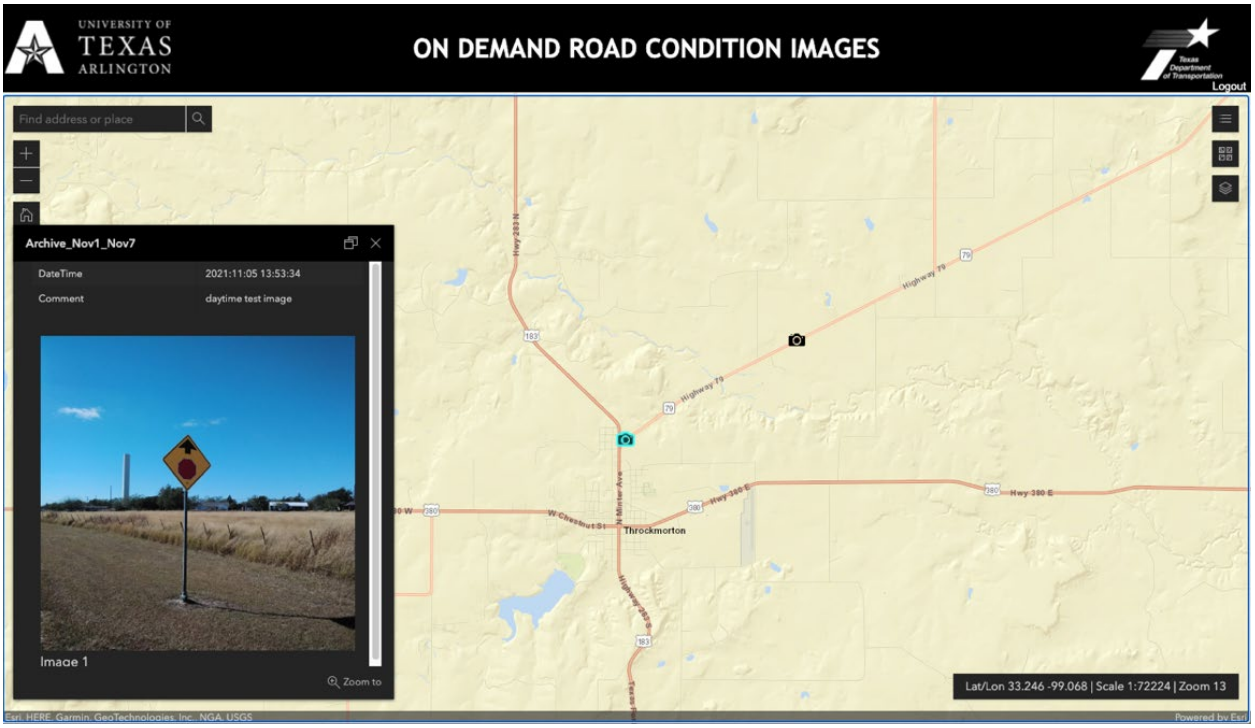


Figure 7.6 Example screenshot of the map-based interface showing on-demand road conditions images in Throckmorton County, Wichita Falls district (November 11, 2021)

Figure 7.7 Examples of collected on-demand road conditions images in Wichita Falls district

(a) Throckmorton County, 11/05/2021, 1:53 PM; (b) Throckmorton County, 11/05/2021, 1:51 PM; (c) Wichita County, 11/05/2021, 12:52 PM; (d) Wichita County, 11/05/2021, 12:47 PM

The developed custom application for collecting on-demand road conditions images and the developed add-on for the web-map application enable maintenance and operations transportation managers to monitor the state of the roads during winter storms and the routine asset inspections along the highways when needed. The developed feature, explained in this chapter, is expected to facilitate providing road conditions images for monitoring the state of the roads to users either on the road or in the office upon their request.

CHAPTER 8. THE PILOT DISTRICT FEEDBACK

The research team conducted a follow-up interview with the pilot district (Wichita Falls district) to solicit their feedback during the implementation period. Interview questions were designed to evaluate the system's performance from a practical standpoint. In order to gain insight into the district's experience, the research team interviewed the district's Maintenance Administer, who had supervised the implementation process in the pilot district. The following is a summary of the interview.

- How did the information provided by the system, including the road conditions snapshots, road weather forecasts, and on-demand images, benefit you?

  It allowed supervisors in the office to have a bird's-eye view of road conditions and to know about the locations of specific issues on the roads to analyze them in real-time. This information facilitated decision-making on allocating resources, including the equipment, material, and manpower during the winter operations. It also helped to oversee the actual progress in field.

- How easy or difficult was it for drivers to install the equipment in the snowplows and learn to use the system?

  The process of installing the equipment was very easy. Even operators with minimum experience working with technological devices had no problem installing the equipment and operating the tablets.

- Do you believe that operating the system distracted snowplow drivers from their primary duties?

  We did not receive any reports from drivers that they were distracted while the tablets were running in the trucks.

- Do you suggest using the system for other districts in TxDOT?

  Yes, for sure. We also like to install it on other maintenance vehicles besides snowplows.

- Did maintaining the system hardware add a burden to your regular duties of supervising snowplow operations?

We did not find it difficult to distribute the hardware at the beginning of the winter season and then collect them at the end of the season.

- We welcome any additional comments or suggestions you have about using the system.

  I found the system to perform as expected. One thing that should be considered during the equipment's installation is the place of the tablets. They should be placed in a location where the snow will not accumulate in front of them during winter storms, so that, they could capture clear snapshots of roads.

CHAPTER 9. SUMMARY AND CONCLUSION

In this project, a Snowplow Operations Management System was developed to collect and visualize road conditions information that facilitates snowplow operations management decisions. Spatial data entities, such as real-time road conditions images, weather information from national weather services, and estimated road surface temperatures were collected and temporarily stored in a geodatabase to be visualized in an ArcGIS map-based interface.

To collect road conditions images, the research team developed an approach to turn tablets into snowplow operations management devices to automatically collect road condition images at predetermined time intervals (i.e., every 10 minutes) when snowplows are moving at a speed of 5 mph or more. The collected images were transferred and temporarily stored at the University of Texas at Arlington cloud space to be processed and visualized in a map-based interface. The research team also created a feature in the system that facilitates collecting on-demand road conditions images upon requests from TxDOT staff when needed.

Moreover, certain weather information that facilitates snowplow operations decisions, such as ambient temperatures, snowfall accumulation forecast, ice accumulation forecasts, and warnings, watches and advisories were identified from national weather services and integrated into the map-based interface to be displayed along with snowplow locations and road conditions images.

In addition, the research team estimated road surface temperatures along roads by developing sets of statistical models which allowed estimating the road surface temperatures using available forecasts weather data from the national weather service. From extensive data collection and statistical data analysis on actual road surface temperatures and ambient weather data during the winter season of 2021-22, the research team concluded that the ambient temperature, relative humidity, wind speed, average temperature of the previous day, and road surface condition are correlated with the road surface temperature. The estimated road surface temperatures were visualized along roads for up to five (5) days.

Furthermore, a map-based interface was developed to facilitate the visualization of the collected spatial data. The map-based interface was created using the ArcGIS platform. The spatial data entities are published in the University of Texas at Arlington (UTA) ArcGIS online account, and the published data entities are displayed in the map-based interface. This map-based interface is accessible through a password-protected web page that is only accessible for TxDOT and UTA staff.

The research team set up a pilot test for this system in the TxDOT Wichita Falls district and provided the related road conditions information to the district's transportation managers through interactive maps for 2020-21 and 2021-22 winter seasons. By providing real-time images of road conditions, this implementation project helped transportation managers monitor road conditions visually and make well-informed decisions during the snowstorms. In addition, access to certain weather information from observing systems and forecast providers, along with information about road surface temperatures provided helpful information to the district's transportation managers about possible locations of low road surface temperatures and potential ice and snow hazards on roads. This information could improve decision-making for deploying snowplows to administer anti-icing and snow-removal measures on roads during winter operations.

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