User Manual for Veteran's Glass City Skyway Bridge Monitoring System

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16. Abstract

The Veterans' Glass City Skyway Bridge is a large cable stayed bridge in Toledo, Ohio owned and operated by the Ohio Department of Transportation. The bridge superstructure and, particularly, the stay cables have been subject to periodic icing events. An icing event monitoring system was designed and installed on the bridge to enable the bridge operators to mitigate the potential hazards associated with ice falling onto the bridge deck from the stays. The monitoring system collects regional weather data and integrates it with data from a weather station on the bridge and icing sensors mounted on the stays. The monitoring system displays information on ice accumulation and potential shedding for the operators on a compact dashboard.

This user manual was provided to ODOT when the monitoring system was transitioned to ODOT from the universities conducting the research, testing in the laboratory and field, and development after a trial operation period covering two winters. It contains operation and maintenance instructions for the hardware and software that constitute the monitoring system.

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Chapter 1:   Icing Background

Section 1.1:   Bridge Background

The Veteran's Glass City Skyway (VGCS), formerly known as the Maumee River Crossing is a large cable-stayed bridge on Interstate 280 that crosses over the Maumee River in Toledo, Ohio. The VGCS is owned by the Ohio Department of Transportation and was considered the single most expensive project ever undertaken by ODOT (Wikipedia, 2013). The construction began in 2002 and the bridge was opened for service in June 2007. The entire project consists of 8,800 feet of approaches and main span. The main span is approximately 1,225-feet in length, consists of a single pylon that rises approximately 270 feet above the bridge deck, and has a single plane of stays, seen in Figure 1 below. The VGCS, which is an important connector for multimodal transportation and economic development, carries three lanes of traffic and has thousands of vehicles crossing daily.

Figure 1.1: Veteran's Glass City Skyway

The VGCS has several novel features: the cradle system for the stays, the stainless steel stay sheathes, and the illuminated glass in the pylon. The VGCS is one of two installations of a new cradle system (Figure 1.1). This particular system eliminates the need for cable anchorage in the pylon by carrying stays from one side of the bridge deck to the other. This allows the tower to be more slender than what is possible with a conventional anchorage arrangement. The pylon is illuminated with internal LED lighting that is infinitely variable, an example of one lighting schemes can be seen in Figure 1.2 below. This makes the pylon visible for miles at night and the pylon can be lit to reflect local events or the time of the year.

Figure 1.2: Veteran' Glass City Skyway's Illuminated Glass Pylon (ODOT, 2010)

Under some winter conditions, ice forms on the stay cables of the VGCS. Ice accumulation can exceed a 1/2 inch and may persist for several days on the stays. Ice then sheds in semi-cylindrical sheets from the cable sheaths. Shedding of an individual stay can occur in less than a minute. Ice shedding is triggered by a combination of rising temperatures and solar radiation. The sheets may fall over two hundred and fifty feet to the roadway. Due to their aerodynamic shape, they can glide or be blown across several lanes of traffic. In some instances, large ice sheets have crossed all the lanes of traffic and fallen in the river. The potential of falling sheets typically requires lane or bridge closure for the duration of the ice persistence. Lane closures result in the inconvenience to the traveling public as well as loss to economic activities. Falling ice is a safety hazard to motorists and determining ice presence remotely is problematic. Currently, ice presence is determined manually, putting ODOT personnel in harm's way.

Figure 1.3 and Figure 1.4 show ice accumulation on the stays and pylon of VGCS in the 2011 icing event.

Figure 1.3: Ice Accumulation on the East Side of VGCS (Baker, 2007)

Figure 1.4: Ice on the Pylon and the VGCS Glass

Figure 1.5, which was captured during 2011 ice fall event, shows a large piece of ice, circled in red, falling into the third lane of traffic while vehicles are still travelling over the bridge (Belknap, 2011).

Figure 1.5: Large Piece of Ice Almost Hitting a Car

Section 1.2:   Weather History, Modeling and Analysis

Section 1.2.1:   Introduction

A brief look into the causes of ice storms as well as the history of icing events that have occurred on the VGCS will be presented in this chapter in order to provide a better understanding of icing events, nature of ice accretion and ice shedding, and what happens during ice storms. Since the VGCS was opened for service in June of 2007, there have been five major icing events that have occurred. Jones' report describes the first four icing events and the weather conditions which preceded them (Jones, 2010). The last icing event, which occurred in February 2011, was directly observed by the research team. Since February 2011, there have been minor icing events that the Dashboard has collected data on. These minor icing events will also be discussed. The weather history and the observed icing behavior described in this chapter serves as the basis for the ice accretion and shedding algorithms in the Dashboard.

Section 1.2.2:   Description of the basic weather that gives rise to an ice storm

Freezing rain has been the cause of four of the five icing events on VGCS. A prolonged freezing rain event requires a layer of cold (below-freezing) air at ground level, warmer air aloft, a high pressure system to hold the cold air in the place, and precipitation. The duration of a freezing rain event depends on how long the high pressure stays in the place and variations in the thickness of the cold air layer at that location. For a major icing event in Toledo, typically, the warm air aloft comes from the Gulf of Mexico and the cold air originates in Canada.   Liquid precipitation in the warm air layer (that may have fallen from the clouds above as snow) supercools as it falls through the cold air layer at the surface. If that layer is not too thick the supercooled drops remain liquid. These freezing rain drops are likely to freeze when they impact a cold surface, primarily because of convective and evaporative cooling, with some contribution from supercooling. If the surface cold air layer is thicker the drops might freeze as they fall, forming ice pellets. These particles of ice accumulate on the ground, but are likely to bounce or slide off the bridge stays. On the cold side of a freezing rain event the precipitation is likely to be falling as snow, and on the warm side the precipitation is plain rain. As an event like this evolves, the precipitation type at one location may change between rain, freezing rain, ice pellets, and snow, sometimes with different types of precipitation occurring at the same time.
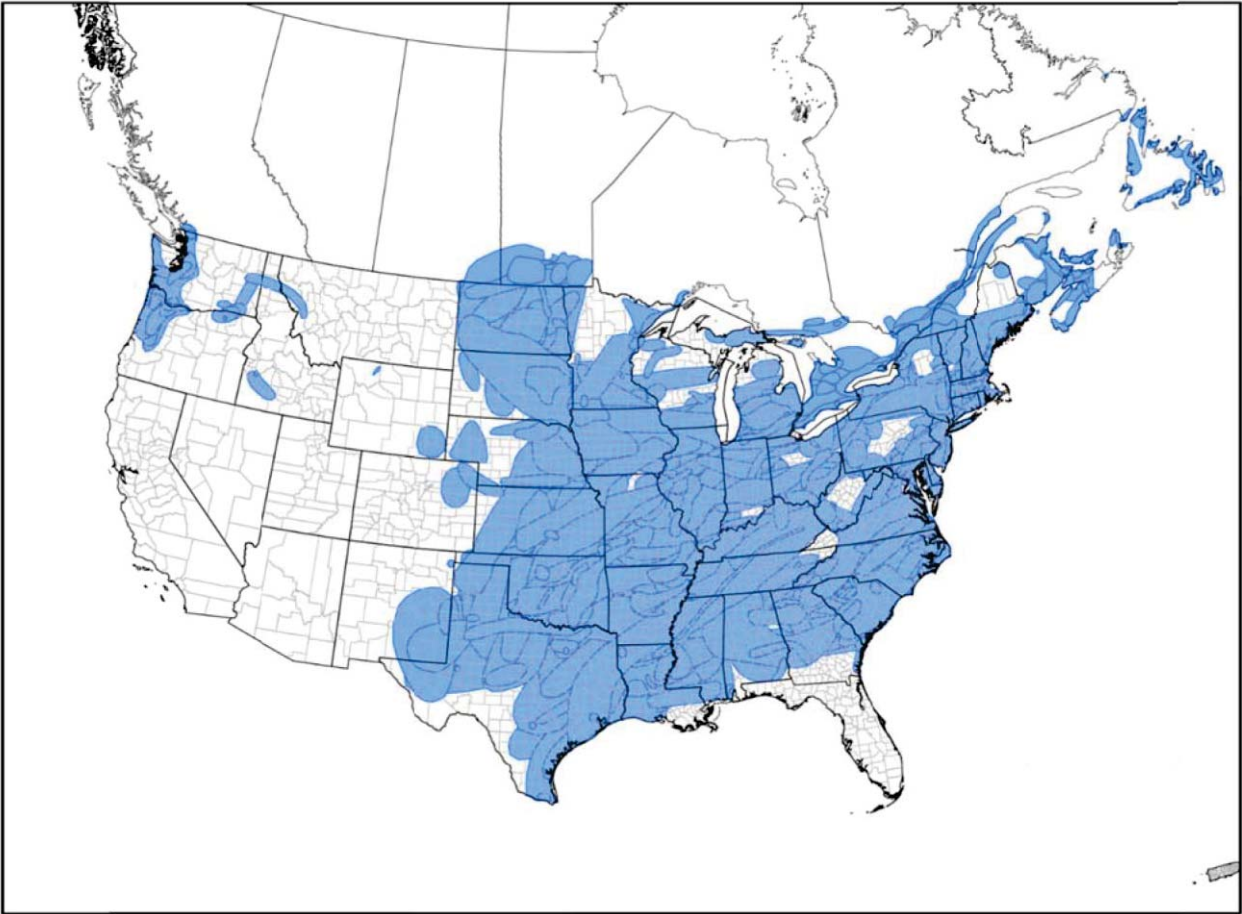
Figure 1.6: Damaging ice storm footprint map, 1946-2014 in the lower 48 states and portions of the lower tier of Canada.

Section 1.2.3:   VGCS Weather History

Five icing events have occurred on the VGCS. Kathleen Jones, CRREL expert and research team member, has prepared a report that describes the first four icing events as well as the conditions which caused them (Jones, 2010). The last event, which occurred in February 2011, was documented by the University of Toledo graduate students. The icing events and basic features are listed in Table 1-1 and

Table 1-2

Table 1-1: Ice Accumulation Weather Conditions

Ice Event	Precipitation Event
December 2007	Freezing rain and Fog
March 2008	Snow, rain, and fog
December 2008	Snow and fog; freezing rain and fog
January 2009	Freezing rain and fog
February 2011	Freezing rain, clear

Table 1-2: Ice Falling Weather Conditions

Ice Event	Ice Fall Weather
December 2007	Rain with temperature above freezing
March 2008	Sun with temperature above freezing
December 2008	Rain, gusty winds and temperatures above freezing
January 2009	Gusty winds, temperature above freezing
February 2011	Light wind, overcast, and temperature above freezing

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It is also possible for wet snow to accumulate on the stays and cause an ice event. This wet snow, that includes both snowflakes and liquid water can accumulate on the stays. That means that an icing event can begin with the air temperature above freezing.

Icing on the cables of VGCS may also occur in supercooled clouds or fog. The Liquid water content of the fog is inversely proportional to visibility. Fog droplets, with typical diameters of a few 10s of microns, have essentially zero terminal velocity, so move only when they are carried by the wind. Therefore, in cloud icing is likely to be significant only in a thick fog and high winds.

To have a better understanding of icing events, nature of ice accretion and shedding, as well as what happens during ice storms, a brief summary and lessons learned from past icing events on the VGCS is presented below. Jones report describes the first four icing events and weather conditions that preceded them. The last icing event, February 2011, was captured and documented by the University of Toledo graduate students.

December 2007: The data from Toledo Express Airport and Metcalf Field indicated freezing rain and fog occurred on December 9 - 10, which is believed to have caused ice accretion on the stays. Rainfall with temperatures above freezing triggered the ice shedding from stays, which took place on December 12. Ice shedding resulted in the closure of two out of three lanes of traffic as well as damaged vehicles. (Jones, 2010)

March 2008: Weather data revealed that a snow and rain mixture with temperatures falling below freezing, concurrent with a fog, caused ice formation on the stays on the evening of March 27. The shedding of ice occurred in the afternoon of March 28. Clear skies and air temperatures above freezing on March 28 were considered to be the shedding triggers. During the ice fall event, the center and left lanes in both directions had to be closed and at least one vehicle was damaged (Jones, 2010)

December 2008: On December 17, ice was first observed on the stays. Data gathered from Toledo Express Airport, Metcalf Field, and Toledo Blade indicated that freezing rain, snow, and fog were the conditions that caused ice accretion on the stays. On December 24, ice shedding occurred with temperatures above freezing and gusty winds. It should be noted that ice persisted on the stays for 7 days. Throughout this event, the left and center lanes were closed for 5 days, starting on December 19.

January 2009: Ice first was observed on January 3 and shedding occurred on January 13. The data from airport weather stations showed that freezing rain accompanied by fog caused ice accretion on the stays. Temperature rising above freezing and gusty winds on January 13 triggered the ice shedding from the stays. Note, the left lanes were closed until January 21, 2009. This could be due persistence of ice on the stays after the initial shedding event, which then melted over the next week (Jones, 2010).

February 2011: This icing event was observed and recorded from the time of ice accretion, which started on the evening of February 20, to the time in which ice shedding occurred, which began on the morning of February 24. This event will be given as a day by day account in order to provide a clear and better understanding of icing on the VGCS. Researchers were on the bridge regularly throughout the event to capture photographs and video as well as properly document the behaviors between the accreted ice and the VGCS stay sheath. A detailed description of this event is in Belknap, 2011. Photos and video from this event are permanently archived by ODOT Research.

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The forecast for the night of February 20 was freezing rain, followed by a drop in temperature. On a local television station's weather website (Storm Tracker 11, 2011), the forecasters predicted snow changing to freezing rain. The update for the overnight was scattered rain or freezing rain with additional ice accumulation. With low temperatures and precipitation, the conditions were conducive to ice accumulation.

The ice dashboard was monitored that night by the research team. RWIS Station 582016, located on the bridge, was tracked watching both the readouts from the dashboard and the cameras on the stays. At 9 pm, the dashboard ticker was reporting Y3, indicating that the conditions had been conducive to ice accumulation for 6 hours and visual observation should be made to ascertain if ice had accumulated. At 10:29 PM, a researcher and the ODOT shift supervisor visited the bridge and confirmed the presence of ice. With this confirmation, the dashboard was put on alert status. Figure 1.7 shows a screenshot of the ice dashboard on February 21. The "Record of the last 48 hours" at the bottom of the dashboard shows the progression of conditions from "clear" to "alert".
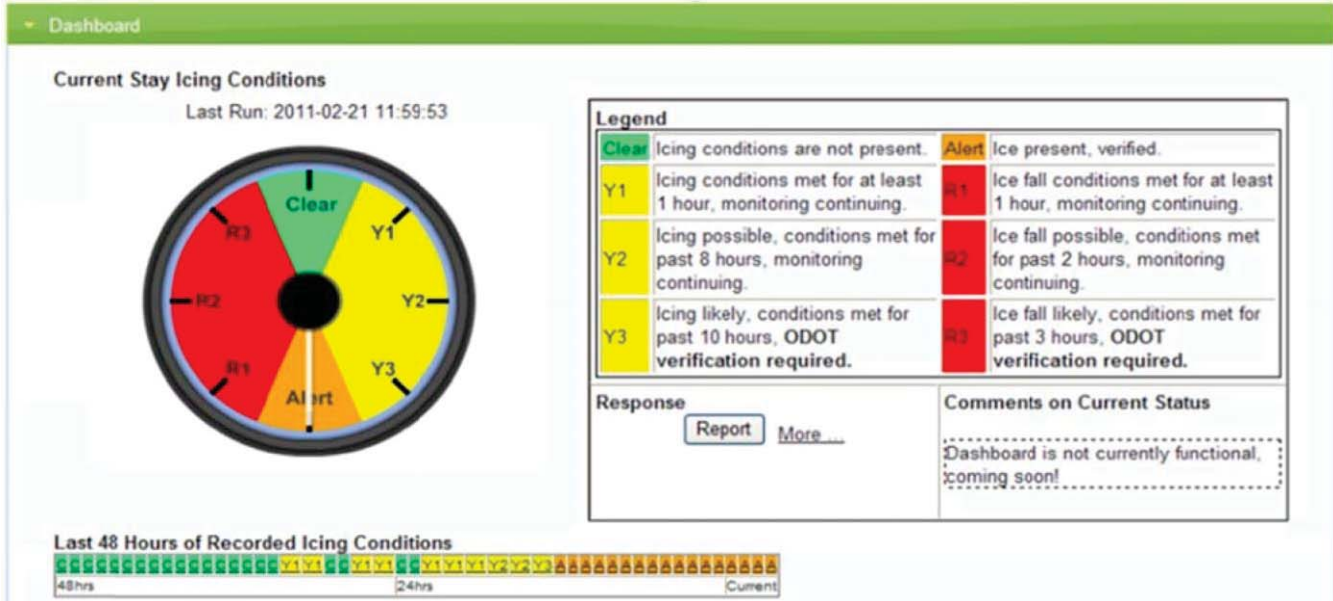
Figure 1.7: Dashboard readout for February 21, 2011

Also, at 9 pm, ODOT personnel and researchers observed ice on the stays. At 10:30pm, the ODOT shift supervisor and the researchers returned to the bridge to observe the stays. At that time, the air temperature was 30° F and the precipitation was cold blowing rain and the prevailing wind was from the east. Rain droplets were of average size and liquid water was clinging to or blowing off the stays. On the stay checked, the ice was 1/4 inch thick on top of the stay, about ½ inch thick on the east side of the stay, there were small icicles and the ice was about 1/2 in thick on the bottom of the stay, and on the west side the stay was bare except for occasional frozen rivulets. Clear ice was accumulating. Clear ice with few air bubbles deposited by freezing rain or freezing drizzle is referred to as glaze ice. This is opposed to white rime ice with more air bubbles which results from super-cooled fog or cloud drops carried by the wind (Ryerson, 2011). There was no sign of melting - rain was running down and blowing off the icicles.

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The deck outside the parapet was covered with slushy ice. The parapet had crusty wet ice. Inside of the parapets on the median was an accumulation of wet ice that was 1/2 to 1 inch thick. The ice covered the eastern face of the cable. There was little to no ice on the western face. The conditions on the stays appeared uniform as far up the stay as visible. Figure 1.8 shows an overview of the ice accumulation and Figure 1.9 shows a close up of the ice accumulating on the east face of the stay. Figure 1.10 is a schematic of the distribution of the accumulated ice.

Figure 1.8: Overview of ice accreting on stay at 10:29 PM Sunday evening
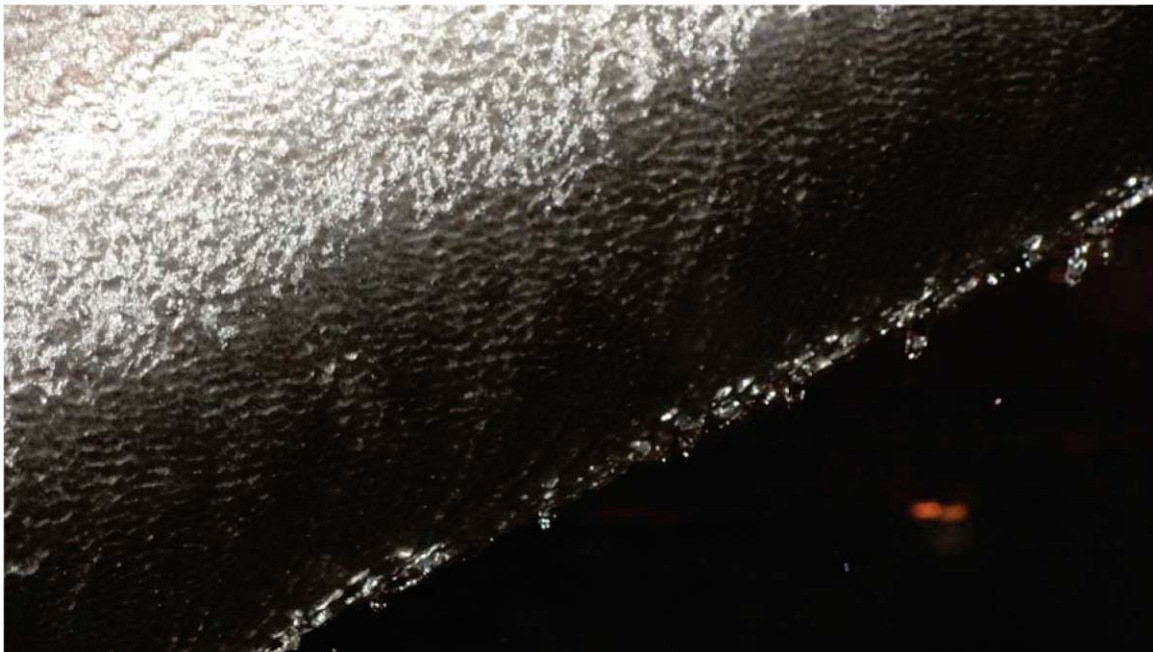
Figure 1.9: Close up of ice accreting on stay at 10:29 PM Sunday evening
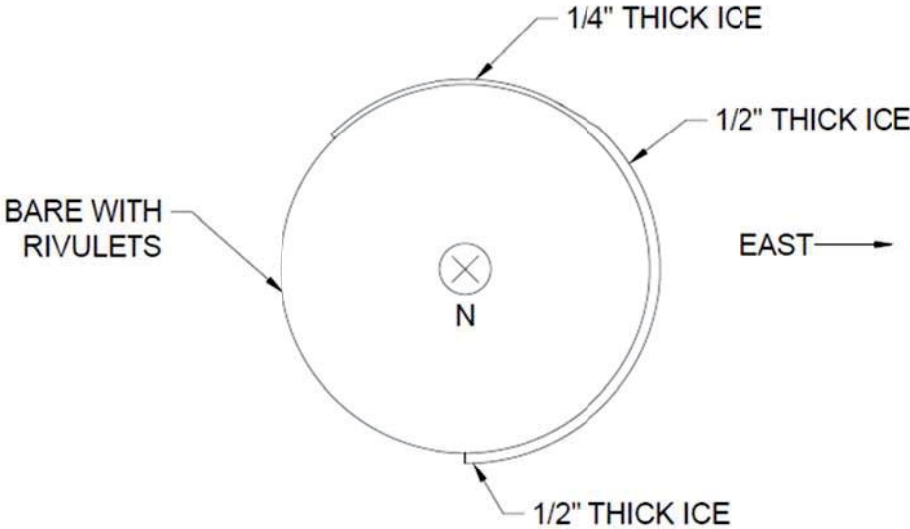
Figure 1.10: Stay cable diagram with ice accumulation

Table 1-3 compares the I-280 bridge RWIS station weather reading with the ice dashboard and Toledo Metcalf Field weather reading.

Table 1-3: Weather Conditions for February 20, 2011 (Kumpf et. al, Weather Underground, 2011)

20/Feb/2011		5-6 pm	6-7 pm	7-8 pm	8-9 pm	9-10 pm	10-11 pm
RWIS	**Temp**	30° F	30° F	30° F	30° F	30° F	30° F
	Precip	None	Rain	Rain	Rain	Rain	Rain
	Surface	Wet	Wet	Wet	Wet	Wet	Wet
	Surface Temp	30° F	30° F	30° F	30° F	30° F	30° F
Dashboard	**Icing Conditions**	Clear	Y1	Y2	Y3	Alert	Alert
Toledo Metcalf	**Temp**	27° F	28° F	28° F	28° F	26° F	28° F

On February 21, 2011, Storm Tracker 11 (2011) recapped that 1/4" to 1/2" of ice accumulated Sunday. They called for an additional mix of snow, freezing rain, and sleet for the morning and 3-5 inches of snow in the evening. The wintery mix and snow fell throughout the day and accumulated on the stays. A layer of snow was between the ice already on the stay and the new accumulation in some areas. ODOT placed barrels out at the inside shoulder. This allows the barrels to be quickly reconfigured to close lanes.

The research team stopped a total of four times, three times on main span and once on the back span. They chipped a hole in the ice to measure thickness at the main span near stay 6, which was inspected from the median. The ice on the east side was roughly ½ inch thick with closely spaced icicles on the bottom. Then the team looked for any variation in conditions along the length of the bridge, however,

they appeared to be consistent when viewed near stay 14 from the north bound side. Near stay 10 visual inspection from inside the truck on from the south bound side it was seen that below the damper collar the ice appeared very thin or even possibly bare spots and above the damper collar ice appeared thicker with pronounced frozen rivulets. The team stopped one time on the back span near stay 8 where conditions were seen that roughly matched what was observed near stay 10.

The wind was from the east as it had been throughout the storm. Generally, on the east side, the ice appeared to be thicker than on the west side. The ODOT supervisor felt the coating on the east side was thicker than he had seen before. On the west side, there were some spots that appeared to have a very thin coat below the damper collar. Above the damper collar, ice was thicker and the frozen rivulets appeared more pronounced than on the east side.

The ice above the collar appeared uniform as high as it could be seen on both the east and west sides of the stay. However, it is impossible to discern anything more than gross icing further up than about mid-height.

On February 22, 2011, the temperature started at 15° F and climbed to 21° F by midafternoon then dropped to the teens again at sundown (Weather Underground, 2011). Although the air temperature was below 32° F, the sun was out and the solar radiation was 575 Watts/m^2 at 1:35 pm. At this time, the researchers observed liquid water under the ice on the stays and ice fall due to solar radiation seemed imminent. However, the ice did not fall when due to the solar radiation and the liquid water refroze at the end of the day.

The research team noted that water was dripping from the icicles on the bottom of the stays. There was ice covered snow in many spots along the stays. The ice cover was uniform from the bottom up to the pylon, as observed with binoculars. Cracking in the ice was observed on stay 4 and there was significant cracking of the ice at bottom of the sleeve. There was ice on the east face of the pylon glass, but there was not any ice on the west face of the pylon glass. ODOT moved the orange barrels out closing the inside lane.

Figure 1.11 and Figure 1.12 portray the ice accumulation on the stays for February 22. The eastern face was coated and the western face was bare except for frozen rivulets.

Figure 1.11: Ice Accumulation up east side of stay February 22, 2011

Figure 1.12: Frozen Rivulets and bare metal on the west side of stays February 22, 2011

On February 23, 2001, the Weather Underground (2011) archived the outside temperature starting at 19°F in the early morning and rising through the day to 28° F in the late evening. No precipitation occurred and there was an overcast sky the entire day.
Wind speed reached 9 mph mostly South to Southwest (Weather Underground, 2011).

The research team continued to monitor the conditions on the bridge. Temperature readings and pictures were taken at intervals on the stays. Liquid water was seen under the ice again even though

there was an overcast sky and the ambient temperatures in the mid-20's. As the team checked later in the day, the ice was breaking off easily and liquid water was observed under the ice.

The temperature in the interstice, gap between the ice accumulation and stay sheath, was measured throughout the day. A Fluke 561 Infrared Thermometer was used to measure surface temperatures and the temperatures in the interstice. The interstice temperature was measured with a type K contact thermocouple. The lead of the contact thermocouple is approximately 0.1 inch in diameter and during the day it would slide easily into the interstice. Sometimes the lead could slide in as far as 6-10 inches with little resistance. Figure 1.13 shows a measurement being taken. In Figure 1.14, the indicated temperature of the stay surface, measured with the infrared thermometer, is 27.0 °F. Because of the high emissivity of the brushed stainless steel surface, it is likely that the temperature of the stay surface is overestimated. In laboratory trials with reflective surfaces, the infrared thermometer consistently read higher than the actual temperature. The temperature indicated in the interstice, measured by the contact thermocouple, was
32 °F. The lead for the contact thermocouple can be seen inserted into the interstice. Table 1-4 shows the variation in the temperature in the throughout the day.

Figure 1.13: Thermocouple reading between ice and stay February 23, 2011

Figure 1.14: Thermocouple reading between the ice and stay February 24, 2011

Table 1-4: Interstice Temperature February 23

Time	Interstice Temperature	Air Temperature	Stay	Note
8:15 am	24 ºF	21 ºF	20B	No visible liquid water
8:50 am	24 ºF	21.9 ºF	N/A	No visible liquid water
9:20 am	24 ºF	21.9 ºF	20B	
9:30 am	28 ºF	21.9 ºF	15B	
9:45 am	26 ºF	21.9 ºF	11B	Liquid water under ice
12:15 pm	30 ºF	24.1 ºF	19B	Liquid water under ice. Large pieces of ice broke free easily.
1:00 pm	31 ºF	24.1 ºF	20B	
1:00 pm	32 ºF	24.1 ºF	19B	
1:15 pm	35 ºF	24.1 ºF	18B	Liquid water under ice. Sheets break free easily.
2:55 pm	32 ºF	25 ºF	20B	Liquid water that had bled from under the ice refroze on the stay.
3:57 pm	32 ºF	27 ºF	20B	
5:23 pm	31 ºF	27 ºF	19B	Liquid water under ice. Sheets break free easily.

Even though the day was overcast, the UV radiation penetrated the clouds and passed through the clear glaze ice. It then warmed the surface of the sheath under the ice. The resulting infrared radiation could not escape the interstice, which resulted in a significant increase in the temperature within the

interstice. Due to this dramatic temperature increase in the interstice, a patch of ice was able to be removed easily. Figure 1.15 portrays the fragility of the ice when the interstice temperature is significantly increased. Note the liquid water on the surface of the stay. The contact thermocouple indicated temperature in the interstice was 36 °F. This seems a bit unreasonable because the water in the gap was in close contact with the overlaying ice. However, water moving under the ice was sometimes visible and would run out from under the ice in small streams.

Figure 1.15: Cracking in ice from chipping away ice, February 23, 2011

At 5:23 pm stay 19B was examined closely and it was observed that there was liquid water under most of the ice. Figure 1.16 shows the extent of the layer of water. Only the small section of ice at the bottom of the stay was frozen solidly to the sheath. Ice this precariously attached could easily be dislodged. All the research observations were made at ground level, so it is possible that the ice layer further up the stay was materially different. Figure 1.17and Figure 1.18 are schematics of the ice buildup and liquid water observed at different stays and times.

Figure 1.16: Section where ice was chipped away to take temperature readings February 23, 2011
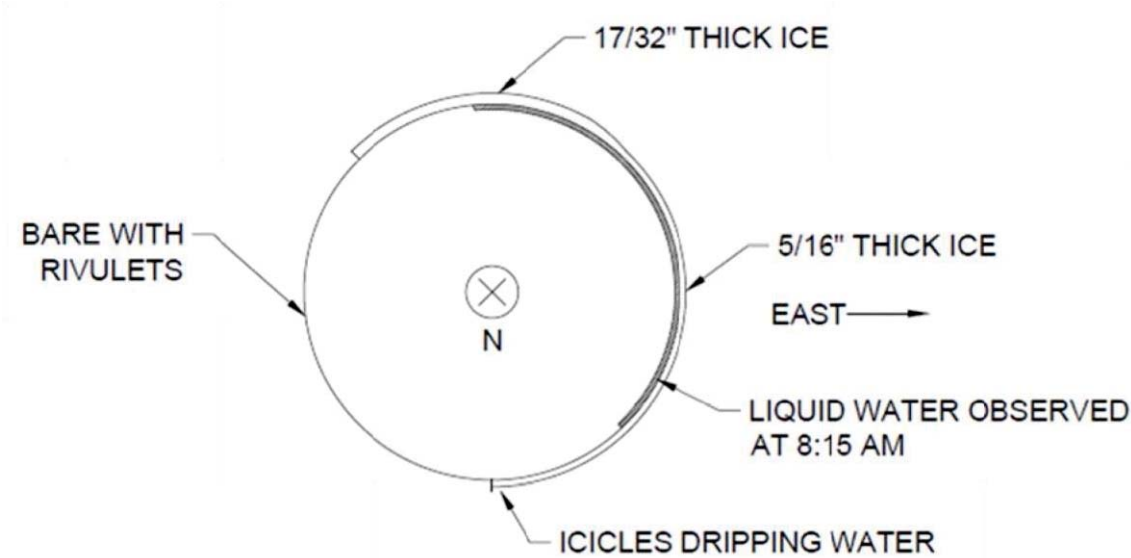
Figure 1.17: Ice thickness measurements on back stay 19 February 23, 2011
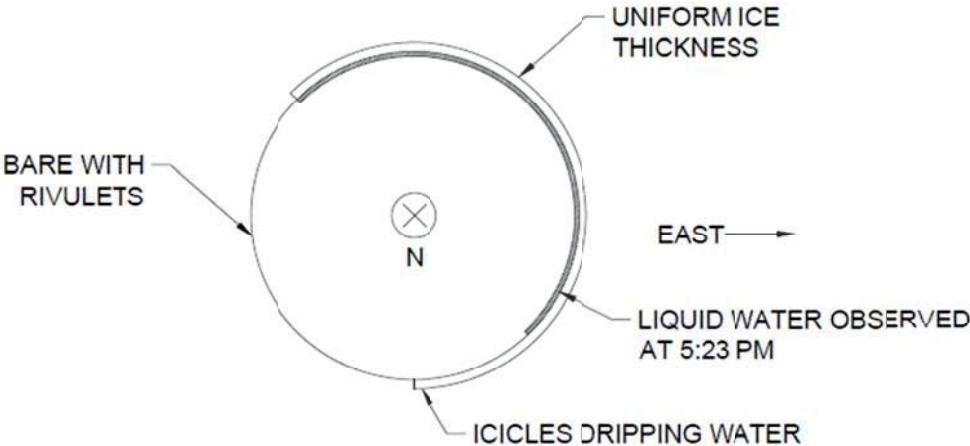
Figure 1.18: Ice thickness measurements on back stay 19 February 23, 2011

On February 24, 2011 at 5am, a senior researcher was on the bridge making observations. The research team met on the bridge around 8am. Cameras were given to two junior researchers to capture the ice fall event. At 8:40am, the ice fall event began. The ice fell in large chunks, at random intervals and from random stays. Weather conditions during the shedding event were temperatures above freezing (32° F), overcast sky, and light wind.

Traffic was stopped at 9:30am because pieces were falling close to vehicles in the outer lane as well as off the bridge and into the Maumee River. The video footage showing the actual lane closure is MOV04201 with the last semi-truck driving over the bridge at 5:28, film time. The ice continued to fall until 11am. By this time, 80-90% of the ice had already fallen. Some ice remained on the pylon glass as well as on the stays close to the pylon. Temperature at the time of the ice fall was above freezing (32° F), overcast, and light wind. The south bound lanes were opened before 11:30 am; the north bound lanes remained closed for several hours because of the ice on the pylon.

Table 1-5 compares the I-280 bridge RWIS with the ice dashboard and Toledo Metcalf Field weather readings. Figure 1.19 show ice accumulation on the pylon glazing at the very top. Figure 1.20 show the bridge deck after a majority of the ice had fallen off.

Table 1-5: Weather conditions for February 24, 2011 (Kumpf et. al, Weather Underground , 2011)

24/Feb/2011		6-7 am	7-8 am	8-9 am	9-10 am	10-11 am
RWIS 280 Bridge	**Temp**	33° F	33° F	34° F	34° F	34° F
	Precip	None	None	None	None	None
	Surface	Wet	Wet	Wet	Wet	Wet
	Surface Temp	33° F	33° F	34° F	34° F	34° F
Dashboard	**Icing Conditions**	R1	R2	R3	R3	R3
Toledo Metcalf	**Temp**	33° F	33° F	34° F	34° F	34° F

Figure 1.19: Ice accumulation on pylon glazing February 24, 2011

Figure 1.20: Ice on bridge deck after 80-90% had shed, February 24, 2011

In summary, ice shed from the stay cables was confirmed. Videos from the ice fall event documented the size and fall pattern of the ice. Large rectangular pieces of ice from stays 20B-16B and 20A-16A, roughly, had pieces making it to the north bound outer lane of traffic and even completely off the bridge.

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When the ice started accumulating on the stays Sunday night, barrels were set out one lane of traffic. As the days went by and the ice was predicted to fall, the barrels were moved out so that only one of three lanes of traffic could cross the bridge in the northbound direction and leaving two of the three lanes of traffic open in the southbound direction. This was decided because the ice had accreted most heavily on the eastern side of the stays and the typical wind direction throughout the persistence and shedding period was coming from the west. On Thursday February 24th, after about a half hour of ice falling, ODOT closed the lane behind stay 20B on the north bound side. Vehicles were routed off the bridge that could turn around. Cars could turn around. Semis's could not. Once 80-90% of the ice was down, the trucks remaining on the bridge were instructed to cross with caution. Once all the vehicles were off the bridge was closed until all the ice had fallen. The last ice to fall fell from the pylon glass in the early afternoon.

Figure 1.21 shows the weather for the week of February 20, 2011. Figure 1.22, Figure 1.23, and Figure 1.24 graph the solar radiation for February 22, 23, and 24, 2011, respectively.
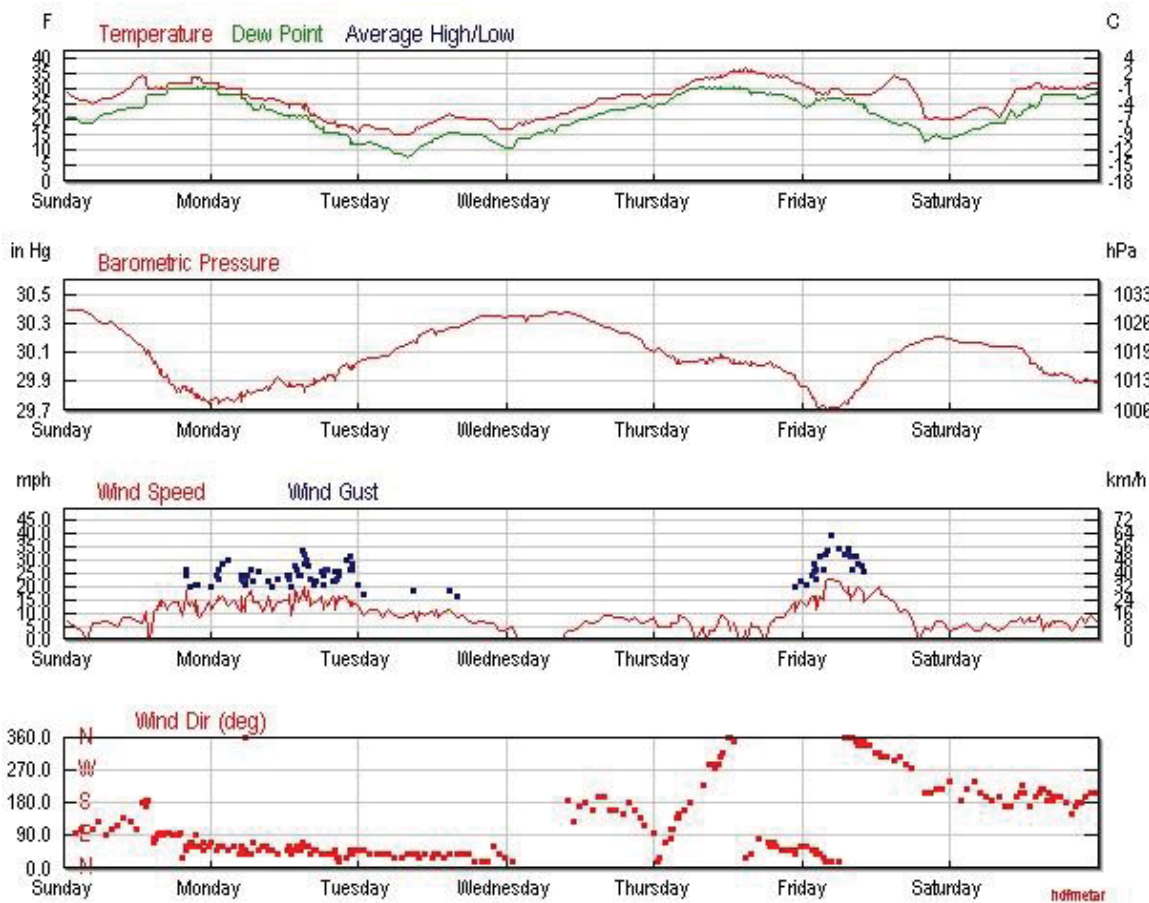
Figure 1.21: Weather Summary for the week of February 20, 2011 (Weather Underground, 2011)
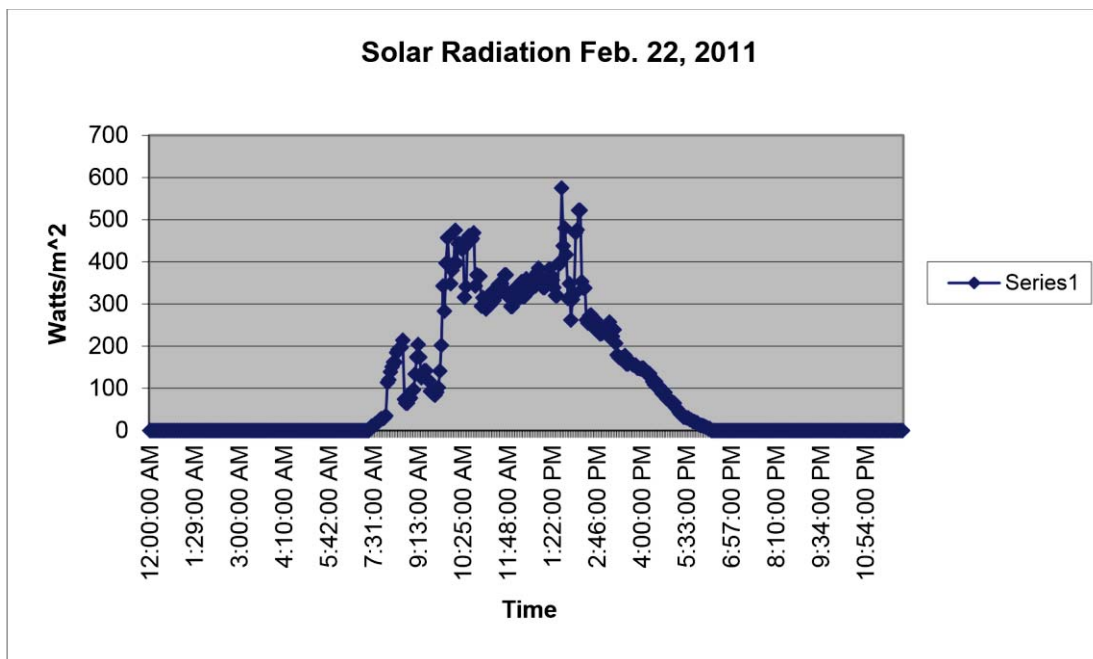
Figure 1.22: Solar radiation counts February 22, 2011
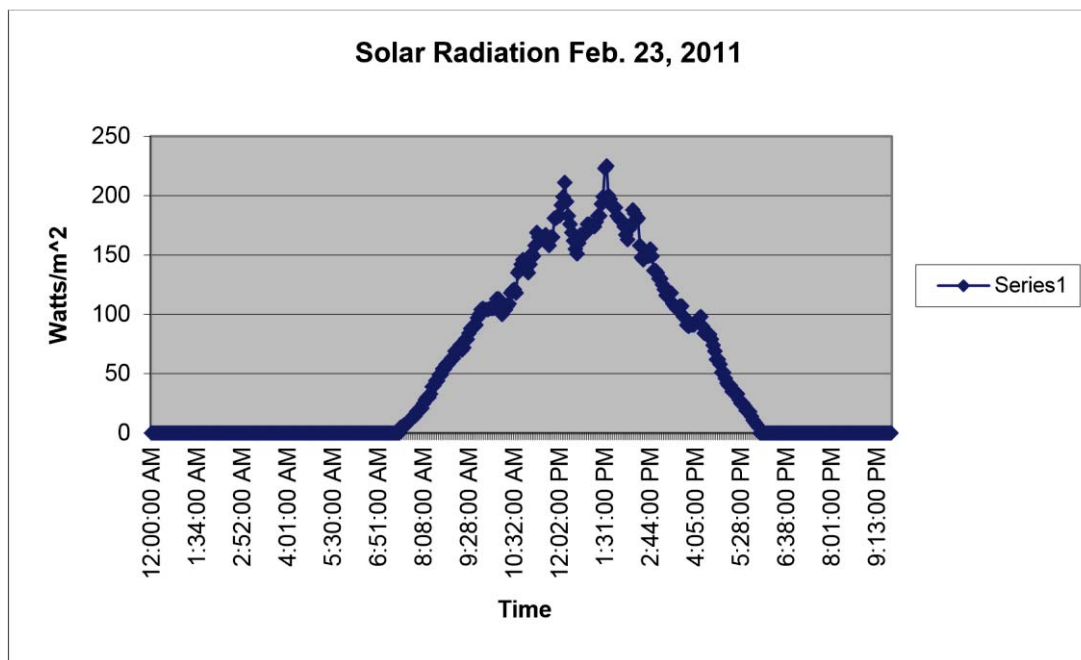
Figure 1.23: Solar radiation counts February 23, 2011
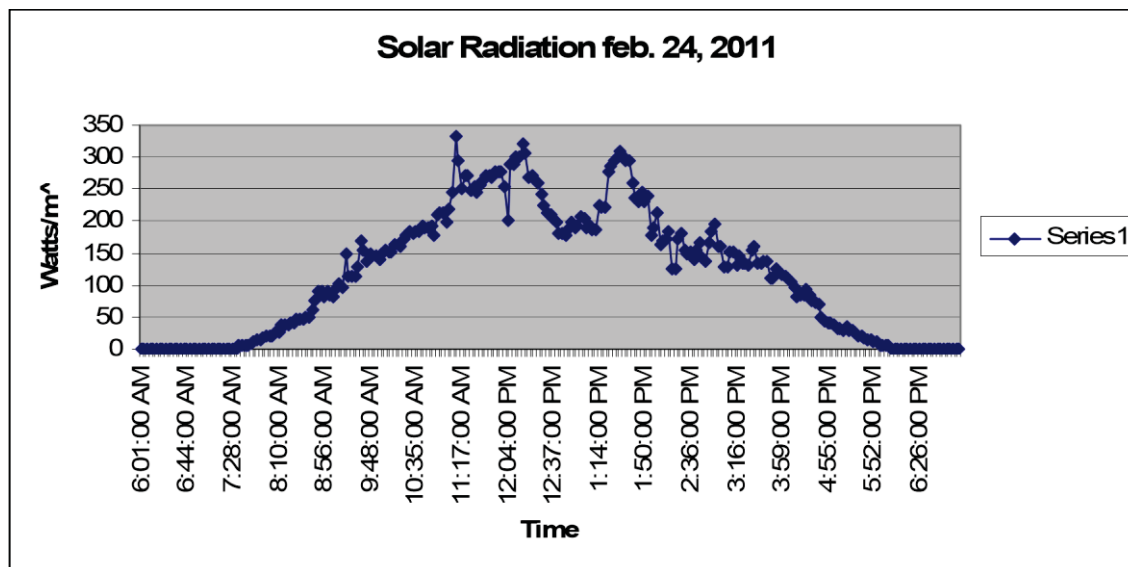
Figure 1.24: Solar radiation counts February 24, 2011

Section 1.2.4: Lessons Learned from Previous Icing Events

There are several lessons to be learned from the five previous icing events. The first is how ice is accretes onto the stay sheaths. In all five events, accretion occurred in conditions where freezing rain and/or snow were present. These events are typically, followed by a sharp temperature drop and accompanied by fog. Additionally, it has been noted that in some events there is minimal precipitation, yet significant amounts of ice still accumulates, therefore it is possible that some of the ice that is accreted onto the stay sheaths comes from supercooled drizzle or cloud droplets (Jones, 2010).

Another lesson to be learned is how the ice sheds off of the stay sheaths. In four of the five events, shedding which cleared the ice off the stays occurred when the air temperature warmed to above freezing and was accompanied by gusty winds, clear skies or sunshine, and rain. The exception was the January 2009 event. Then ice shed intermittently and partially. Although, this was true for the last major icing event, which was the only to be directly observed and documented, it was learned that the temperature doesn't necessarily need to be above freezing in order for shedding to occur. This is due to a greenhouse effect in the interstice between the ice layer and sheath surface. It was observed that considerable water flowed under the ice layer at temperatures in the mid-20's. This effect caused ice to be removed easily, thus, displaying the possibility that shedding could potentially occur at temperatures below freezing (32 $^\circ$F).

The ice detector has proven to be sensitive and accurate for ice accretion.

Section 1.2.5: Analysis

The common weather conditions prior to the previous ice events on the bridge led to the development of criteria to use when checking for icing event conditions.

Weather conditions (for at least 6 hours) that would likely cause Ice Accumulation:

1. Precipitation with air temperature at the bridge below 32° F, or

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2. Fog with air temperature at the bridge below 32º F, or

3. Snow with air temperature at the bridge above 32º F. Weather conditions that would likely cause Ice Fall:

    1. Air temperature above 32º F (warm air), or

    2. Clear sky during daylight (solar radiation).

In order to automate the process of predicting ice fall events, an algorithm was developed based upon the above criteria to evaluate weather data. The weather data collected consists of RWIS measurements and METAR data from the local airports. Taking these criteria and the available data into account, a specific set of criteria was developed for Ice Accumulation and Ice Fall (Table 1-6 and Table 1-7).

Table 1-6: Ice Accumulation Criteria

Source	Condition	Description
METAR or RWIS	Freezing Rain	(Air Temp. <= 32º F & Precipitation type is Rain) OR (Precipitation type is Freezing Rain)
METAR	Freezing Fog	Air Temp. <= 32º F & Precipitation type is Fog
METAR or RWIS	Wet Snow	Air Temp. > 32º F & Precipitation type is Snow

Table 1-7: Ice Fall Criteria

Source	Condition	Description
METAR	Warm Air	Air Temp. >= 32º F
METAR or RWIS	Clear	Sky Condition type is Clear

The data sources used, including the secondary sources used for redundancy, are:

METAR Data Sources

1. http://www.wunderground.com/history/airport/KTOL/2011/05/13/DailyHistory.html ?format=1

2. http://www.wunderground.com/history/airport/KTDZ/2011/05/13/DailyHistory.html ?format=1

RWIS Data Source

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1. ftp://ftp.dot.state.oh.us/pub/doit/ssi_rwis/

2. http://www.buckeyetraffic.org/reporting/RWIS/results.aspx

The RWIS stations report only four precipitation types (Rain, Snow, Fog, None/Other) while the METAR stations report more than 30 types, many of which are similar and could be grouped into the four RWIS types.   A similar grouping is applied to the METAR data for the Ice Fall criteria. The only available metric for sky cover is from the METAR data. This metric had several values, four of which are used to classify the sky cover as "Clear", with all other values grouped as "Not Clear".

Several assumptions guided the design of the dashboard. The assumptions below are based on Kathleen Jones' report (Jones 2010a), discussions with research team members Kathleen Jones and Jeff Baker and Mike Madry, ODOT Northwood Outpost, concerning the icing events on the VGCS. The assumptions are rough guidelines.
There will be exceptions to the assumptions.

Assumptions:

*   Ice accumulates in a discrete time period and does not fall during that period.

*   The original threshold of concern for radial ice accumulation was ¼". This was later reduced to 1/8".

*   It takes a long event (roughly 12 hours or more) for ice to accumulate.

*   If the sky is overcast and the temperature is less then 32°F, the stay sheath temperature after the icing event remains below freezing. (Note: On Tuesday February 23, 2011 this assumption was revealed to be flawed.)

*   Ice can accumulate on the stays from fog or precipitation other than freezing rain, e.g., wet snow accumulations can lead to ice accumulation on the stays.

*   Air temperature can be used as a reasonable approximation for stay sheath temperature.

*   Wind by itself does not trigger an ice fall.

Previously accumulated ice falls when either of these conditions occur

*   The stay sheath temperature rises above freezing.

*   If the sky is clear, sunlight could trigger the ice fall at temperatures below freezing.

Section 1.2.6:   Summary

This chapter described the weather that gives rise to ice storms, the VGCS's weather history including previous icing events, lessons learned from those previous icing events, and accretion and shedding algorithms.

The weather system most often associated with major icing is warm air from the Gulf of Mexico overriding cold air from Canada. This leads to liquid water falling on a cold surface. However, other conditions and weather systems have also lead to ice accretion. Historically, roughly two icing events

occur each year. The last major icing event on the VGCS was in 2011. Once the ice accretes, it persists until shedding conditions occur.

Temperatures above 32 and/or solar radiation cause ice fall. The ice fall in four of the five previous events was accompanied by temperatures rising above 32. If the solar radiation level is high enough, ice can shed. In February of 2011, copious amounts of water flowing beneath the ice were observed when the outside temperature was several degrees below freezing. This layer of water below the ice is a precursor to ice shedding. There is a greenhouse effect that occurs when the solar radiation passes through the ice and heat is trapped between the sheath and the ice. Ice accretion and shedding do not occur simultaneously.

The findings from the weather study and observation include:

- The VGCS is not a special icing structure which accretes ice at a rate different from the surrounding structures. The hazard arises because the aerodynamic ice sheets from the stays can fall on vehicles crossing the bridge.
- Ice can come directly from precipitation or supercooled drizzle or fog.

Chapter 2:   Dashboard

Section 2.1:   HOW IT WORKS

Section 2.1.1:   Objectives

The primary objective of this project was to leverage existing weather data from sources available on the web and to use the sensors installed in the bridge to develop a virtual instrument. This virtual instrument allows weather researchers, infrastructure researchers, and transportation personnel all to monitor for potential icing events from any Internet connected device. Listed below is the list of tasks for the dashboard:

- Add weather data to existing VGCS web interface and database for possible use in algorithms below.
- Add stay-mounted camera views to existing VGCS weather interface.
- Develop a "check engine" light (e.g., green (no ice), yellow (ice, but no shedding), red (ice with possibility of shedding) that responds to the algorithm and sends out corresponding alerts to a list of ODOT's choice.
- Develop a reporting function that will allow ODOT to:
  - o Verify that alerts are responded to
  - o Declare an icing event
  - o Capture time stamp and observation notes/comments
- Develop database of ground truth field data collected during actual icing events to compare against Dashboard performance.
- Develop export function for historical data archived on the VGCS weather website.

To accomplish this, a dashboard was developed which included the virtual instrument to deliver the right information based on the task list mentioned above. The dashboard also provides a rich toolset for more detailed monitoring and assessment based on regular collection and storage of weather data from multiple sources. In addition the dashboard provides a way to interact with all data collected by location on a map and plotting the different types of measurements over time. A complete section on the features of the dashboard is provided in this document.

This manual is now divided into four main sections:

1. **Data Classification:** This section explains:

   - The conditions for Ice accumulation and Ice shedding
   - The data sources used for this project
   - A complete list of the weather parameters that can be read by each data source
   - List of weather parameters used to determine Ice accumulation/ Ice shedding

2. **Ice Accumulation/Fall Determination Algorithm:** This section explains:

   - The algorithm used to determine whether Ice accumulation or Ice shedding conditions occurred

3. **Persistence Algorithm:** This section explains:

   - The algorithm used to determine current icing status using the past data. Henceforth, the action of the algorithm, is explained, when the Ice accumulation and Ice shedding conditions persist for a long time

4. **Front End Implementation:** This section explains:

   - The front-end design for the user
   - The features of the dashboard, In detail

Section 2.1.2:   Data Classification

Section 2.1.2.1:   Data Sources

The data sources used in this algorithm are primarily from three sources and listed below:

Meteorological Terminal Aviation Routine (METAR): METAR is a format for reporting weather information. A METAR weather report is predominantly used by pilots in fulfillment of a part of a pre-flight weather briefing, and by meteorologists, who use aggregated METAR information to assist in weather forecasting. METAR typically come from *airports* or permanent weather observation stations. Reports are generated once an hour, but if conditions change significantly, a report known as a SPECI may be issued several times in an hour. A typical METAR contain data for the temperature, dew point, wind speed and direction, cloud cover and heights, visibility, barometric pressure, precipitation amount, lightning, and other information.

The algorithm is using METAR data from two airports Table 2-1 namely Toledo Express Airport (KTOL), and Toledo Metcalf (KTDZ).A map around the VGCS bridge Figure 2.1 is shown that justifies the choice of the airports chosen for the algorithm. Here's listed the links to the METAR data including the second sources for redundancy and reliability:

METAR Data Sources

1. http://www.wunderground.com/history/airport/KTOL/2011/05/13/DailyHistory.html?format=1

2. http://www.wunderground.com/history/airport/KTDZ/2011/05/13/DailyHistory.html?format=1
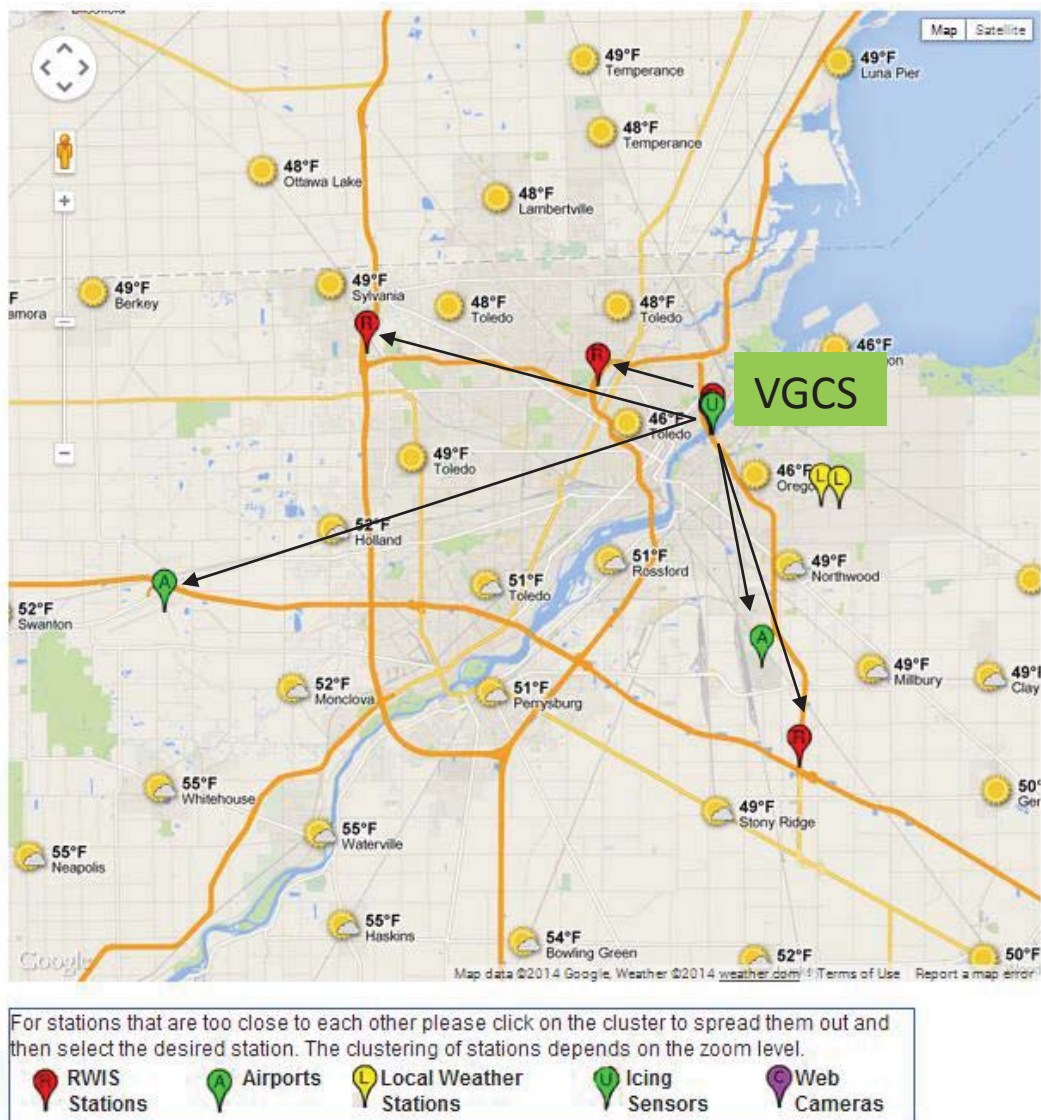
Figure 2.1: Map showing Distances of Weather Stations from VGCS

A sample METAR data screenshot for KTOL airport Figure 2.2 is shown below:

Figure 2.2: METAR Data Screenshot

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Road Weather Information System (RWIS): RWIS can be defined as a combination of technologies that uses historic and current climatologically data to develop road and weather information (for example, now casts and forecasts) to aid in roadway-related decision making. A typical RWIS contain data for the air temperature, dew point temperature, surface temperature, relative humidity, wind speed and direction, and precipitation type.

The algorithm is using RWIS data from four weather stations Table 2-1 namely: 140-I-475 @ US-23 Split - Lucas Co., 141-I-75 @ I-475 Split - SLM 4.9 Lucas, 142-I-280 @ VGCS, and 150-I-280 @ Libbey Road. A map around the VGCS Bridge [Figure 2.1]is shown that justifies the choice of the RWIS weather stations chosen for the algorithm. Here's listed the links to the RWIS data including the second sources for redundancy and reliability:

RWIS Data Source

1. ftp://ftp.dot.state.oh.us/pub/doit/ssi_rwis/
2. http://www.buckeyetraffic.org/reporting/RWIS/results.aspx

A sample RWIS data screenshot for the 142-I-280 @ VGCS [Figure 2.3]is shown below:

142 - I-280 @ Veterans Glass City Skyway (VGCS) (582016)	Status	Air Temp	Sfc Temp	Sub Temp	Dew Temp	Wind	Precip	Traffic	Updated
Sensor [A]: Atmospheric	-	51.8	-	-	51.3	7.5 / NE	-	-	5/8/2011 4:50:16 AM
Sensor [0]: NB I-280 Driving Lane	Dry	-	49.8	-	-	-	-	2 / 32.9	5/8/2011 4:50:16 AM
Sensor [2]: NB I-280 Passing Lane	Dry	-	49.8	-	-	-	-	2 / 32.9	5/8/2011 4:50:16 AM
Sensor [3]: SB I-280 Passing Lane	Dry	-	49.8	-	-	-	-	1 / 52.8	5/8/2011 4:50:16 AM
Sensor [4]: SB I-280 Center Lane	Dry	-	49.8	-	-	-	-	7 / 59.0	5/8/2011 4:50:16 AM

Figure 2.3 RWIS Data Screenshot

Table 2-1 shows the list of all the six weather stations including RWIS and Airport.

Weather Station	Station Type
140-IR 475 @ US 23 Split	RWIS
141-IR 75 @ SLM 4.9 475 Split	RWIS
142-I-280 @ VGCS	RWIS
150-I-280 @ Libbey Road	RWIS
Toledo Express Airport	Airport
Metcalf Field Airport	Airport

Table 2-1 Lists of Six Weather Stations

Bridge sensors: In summer 2013 a few sensors were installed on the bridge to add more voters to the dashboard algorithm. These new sensors are used along with the thermistors which were installed earlier in the algorithm. The bridge sensors comprise of Geokon Thermistors, LWS-L Dielectric Leaf Wetness Sensor, Goodrich Ice Detector Manual, MetOne Rain Tipping Gage and the sunshine BF5 sensor.

For more information on programming the loggers for these sensors, their circuit connections and their specifications please refer to Appendices A,B and C respectively of the document "Continued Weather Monitoring System for the Veterans' Glass City Skyway".

Section 2.1.2.2:   Ice Accumulation/Fall Conditions

Based on extensive analysis of the past icing events' weather conditions (K.F. Jones 2010), it was determined that certain weather properties were common and persistent during each of the ice events. These properties led to the development of the first three criteria to use when evaluating for icing event conditions. The last three rules were added after the sensors were exhaustively tested and then installed on the bridge.

Criteria that would likely cause **Ice Accumulation**:

1. Precipitation with air temperature at the bridge below 32° F.

2. Fog with air temperature at the bridge below 32° F.

3. Snow with air temperature at the bridge above 32° F.

4. Wet surface and stay temperature below 32° F.

5. Precipitation recorded by rain bucket and stay temperature below 32° F.

6. Ice recorded by the Ice detector or Cumulative Ice threshold is exceeded.

In order to automate the process of determining ice events, an algorithm was developed based upon the above criteria and was used when evaluating weather data. The weather data collected consisted of RWIS measurements and METAR data, as explained in the previous section. Since these two weather stations records variety of precipitation types in different weather conditions, let's first go through the complete list Table 2-2 of the precipitation types that METAR and RWIS measure and then try to classify the precipitation types that can be used for the ice accumulation determination.

It can be seen that there are 30+ precipitation types measured by METAR data and couple of them can be used to determine criteria 1, 2 and 3 as shown in the below table. On the contrary, RWIS measures only 'Rain' and 'Snow' for conditions 1 and 3 respectively.

METAR Precipitation Types	RWIS precipitation Types
CRITERIA 1 AND 2 Fog Mist Rain Light Rain Heavy Rain Thunderstorm Heavy Thunderstorms Light Thunderstorms Thunderstorms and Rain Ice Pellets	**CRITERIA 1** Rain

Light Ice Pellets Light Freezing Fog Light Freezing Rain Light Freezing Drizzle	
CRITERIA 3 Snow Light Snow Heavy Snow Blowing Snow Ice Pellets Light Ice Pellets Light Freezing Fog Light Freezing Rain Light Freezing Drizzle	**CRITERIA 3** Snow
Clear Haze Partly Cloudy Scattered Clouds Unknown Overcast Mostly Cloudy	Other None

Table 2-2 Lists of Prec. Types for Ice Accumulation

Taking these criteria and the data being collected into account, a specific set of criteria was developed for Ice Accumulation shown in Table 2-3.

Source	Condition	Description
RWIS	Freezing Rain	Atmospheric Temp. <= 32º F & Precipitation type is Rain
RWIS	Wet Snow	Atmospheric Temp. > 32º F & Precipitation type is Snow
METAR	Freezing Rain	(Atmospheric Temp. <= 32º F & Precipitation type is Rain) OR (All precipitation types listed under criteria 1 in the Table 2-2)
METAR	Freezing Fog	(Atmospheric Temp. <= 32º F & Precipitation type is Fog) OR (All precipitation types listed under criteria 2 in the Table 2-2)
METAR	Wet Snow	(Atmospheric Temp. > 32º F & Precipitation type is Snow) OR (All precipitation types listed under criteria 3 in the Table 2-2)

Table 2-3 Ice Accumulation Criteria

Similar to the Ice accumulation criteria, the study by K F Jones, close observation on the past icing events and testing of the sensors installed at the bridge led to criteria for Ice fall, which are listed below.

Criteria that would likely cause **Ice Fall:**

1. Air Temperature above 32º F (warm air).
2. Clear sky during daylight (solar radiation).
3. Stay Temperature above 32º F.

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4. Solar radiation sensor reports Sunshine.

Again since the two weather stations, METAR and RWIS, records variety of precipitation types in different weather conditions, we first need to check the complete list of the precipitation types in Table 2-4 that they measure and then try to classify the ones that can be used for ice fall determination.

RWIS precipitation Types	METAR Precipitation Types
Rain	Fog
	Mist
	Rain
	Light Rain
	Heavy Rain
	Thunderstorm
	Heavy Thunderstorms
	Light Thunderstorms
	Thunderstorms and Rain
	Ice Pellets
	Light Ice Pellets
	Light Freezing Fog
	Light Freezing Rain
	Light Freezing Drizzle
Snow	Snow
	Light Snow
	Heavy Snow
	Blowing Snow
Other	Unknown
None	Overcast
	Mostly Cloudy
	CRITERIA 2
	Clear
	Haze
	Partly Cloudy
	Scattered Clouds

Table 2-4 Lists of Prec. Types for Ice Fall

Source	Condition	Description
RWIS	Warm Air	Atmospheric Temp. >= 32° F
METAR	Warm Air	Atmospheric Temp. >= 32° F
METAR	Clear	(Sky Condition type is Clear) OR (All precipitation types listed under criteria 2 in the table 4)

Table 2-5 Ice Fall Criteria

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Based on the two ice fall criteria previously mentioned and the available precipitation types reported, the only metric for sky cover available was from the METAR data. This metric had several values, four of which are used to classify the sky cover as clear whereas all other values are evaluated as sky cover not clear. Taking these criteria and the data being collected into account, a specific set of criteria was developed for Ice Fall shown in Table 2-5.

The table below summarizes different checks need to be done according to the algorithm and checks actually being doing in the dashboard.

Type of station	Ice accumulation check	Ice fall check
RWIS	☒ Temperature less than 32°F and precipitation type: rain ☒ Wet snow with temperature greater than 32°F ☐ Fog with the temperature less than 32°F ☐ Wet surface and stay temperature below 32° F. ☐ Precipitation recorded by rain bucket and stay temperature below 32° F. ☐ Ice recorded by the Ice detector or Cumulative Ice threshold is exceeded.	☒ Temperature greater than or equal to 32°F ☐ Clear sky ☐ Stay Temperature above 32° F ☐ Solar radiation sensor reports Sunshine
Airports	☒ Temperature less than 32°F and precipitation type: rain ☒ Wet snow with temperature greater than 32°F ☒ Fog with the temperature less than 32°F ☐ Wet surface and stay temperature below 32° F. ☐ Precipitation recorded by rain bucket and stay temperature below 32° F. ☐ Ice recorded by the Ice detector or Cumulative Ice threshold is exceeded.	☒ Temperature greater than or equal to 32°F ☒ Clear sky / Scattered Clouds / Partly Cloudy during day time (8am to 6pm) ☐ Stay Temperature above 32° F ☐ Solar radiation sensor reports Sunshine
Bridge Sensors	☐ Temperature less than 32°F and precipitation type: rain ☐ Wet snow with temperature greater than 32°F ☐ Fog with the temperature less than 32°F ☒ Wet surface and stay temperature below 32° F. ☒ Precipitation recorded by rain bucket and stay temperature below 32° F. ☒ Ice recorded by the Ice detector or Cumulative Ice threshold is exceeded.	☐ Temperature greater than or equal to 32°F ☐ Clear sky / Scattered Clouds / Partly Cloudy during day time (8am to 6pm) ☒ Stay Temperature above 32° F ☒ Solar radiation sensor reports Sunshine

Legends

☒ - Conditions checked in dashboard

☐ - Conditions not checked in dashboard

Once the data sources and the criteria are decided, we need to use them to determine the Ice Accumulation or Ice Fall occurrences.

Section 2.1.3: Ice Accumulation/Fall Determination

The determination of ice conditions at each of the measurement locations can be done automatically and used to further evaluate the likelihood of an icing event.

First it must be noted that each of the weather stations has its own data collection time, which is shown in Table 2-6. This has a considerable significance on the time between which the algorithm is run. Since METAR data is important in both the Ice accumulation and Ice Fall determination and its update time is 1 hour, the algorithm cannot be run for less than one-hour time difference to avoid checking same records for consecutive algorithm run. That's why the least count between two runs in this algorithm is one hour.

Source	Update Time
RWIS	10 minutes
METAR	1 hour
Bridge Sensors	10 minutes

Table 2-6 Data Collection Time

Sensors in any environment can occasionally misread the actual measurement so for all the weather station (RWIS, METAR and Bridge Sensors), we evaluate all the records for the last hour but even if only a certain percentage of the total records from the last hour meet any (or combination) of the three ice accumulation criteria, then the station has met the icing criteria as a whole for the last hour. For RWIS 80% of the data must meet the criteria whereas in the case of the Airports and the Bridge sensors 50% of the data is enough. This is then used to find the likelihood of ice accumulation by multiplying the condition of each weather station (0 for not met, 1 for met) by the station weight [Table 2-7] and summing each result. If the total weight calculated, as above, is greater than a set threshold [Table 2-7], we consider that icing conditions has met for the last hour.

The pictorial representation of the algorithm for determination of Ice accumulation is shown in [Figure 2.4]:
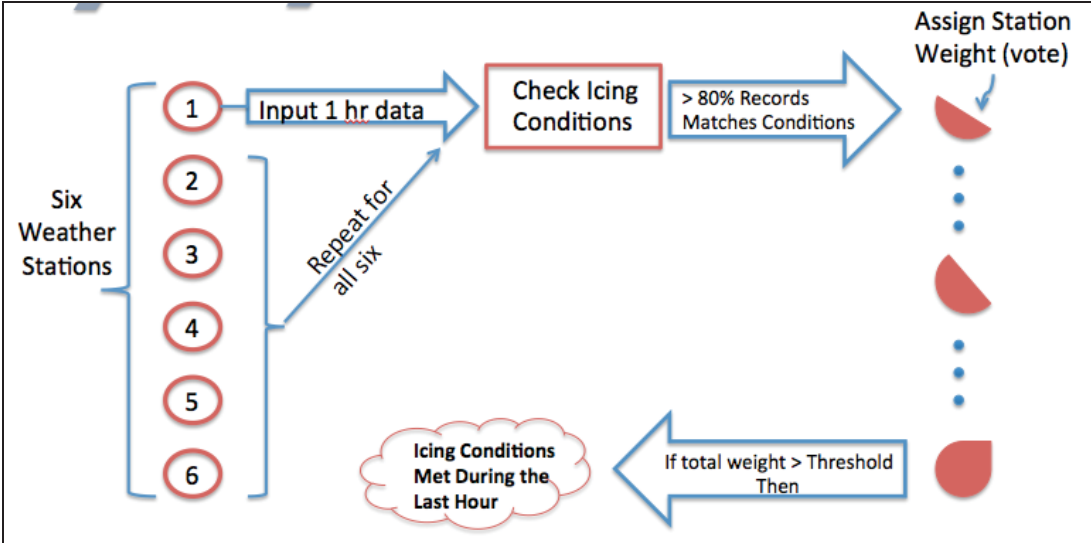
Figure 2.4 Pictorial representation of icing algorithm

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Below are the mathematical equations representing the algorithm shown above.

(1) $\sum_{1}^{n}(s_i * w_i) = WL$

(2) $if\ WL \geq TH; Icing\ possible$

Here, s_i = Station condition (0 or 1), value is 1 if 80% of the records meet ice accumulation conditions in the last hour, otherwise 0.
w_i = Station weight
n = number of stations
WL = Likelihood
TH = Threshold, 0.3 in this case

The station weights are based on two parameters listed below:

- Station's geographic location relative to the VGCS Bridge - As seen in Figure 2.5, the weather stations distances from the VGCS Bridge influences weight, so the weather station on the bridge has the highest weight

- Amount of useful weather information that could be retrieved – As it is clear from Table 2-2, the METAR data offers more – for the ice accumulation determination, it has been also given high weights in spite of its larger distance from the VGCS Bridge.

- The sensors installed on the bridge are very reliable and they reflect the actual conditions on the bridge.

Table 2-7 shows the weights taken for the weather stations, which depends upon the two parameters listed above.

Weather Station	Station Type	Weight
140-IR 475 @ US 23 Split	RWIS	0.1
141-IR 75 @ SLM 4.9 475 Split	RWIS	0.1
142-I-280 @ VGCS	RWIS	0.3
150-I-280 @ Libbey Road	RWIS	0.1
Toledo Express Airport	Airport	0.3
Metcalf Field Airport	Airport	0.3
Leaf Wetness	Bridge Sensors	0.1
Ice detector	Bridge Sensors	0.3
Rain bucket	Bridge Sensors	0.3
Thermistors	Bridge Sensors	0.3
Solar sensor	Bridge Sensors	0.3
Threshold Value: 0.3		

Table 2-7: Default weights of different weather stations

Figure 2.5 shows a map that justifies providing high weights to the weather station located near to the VGCS Bridge.
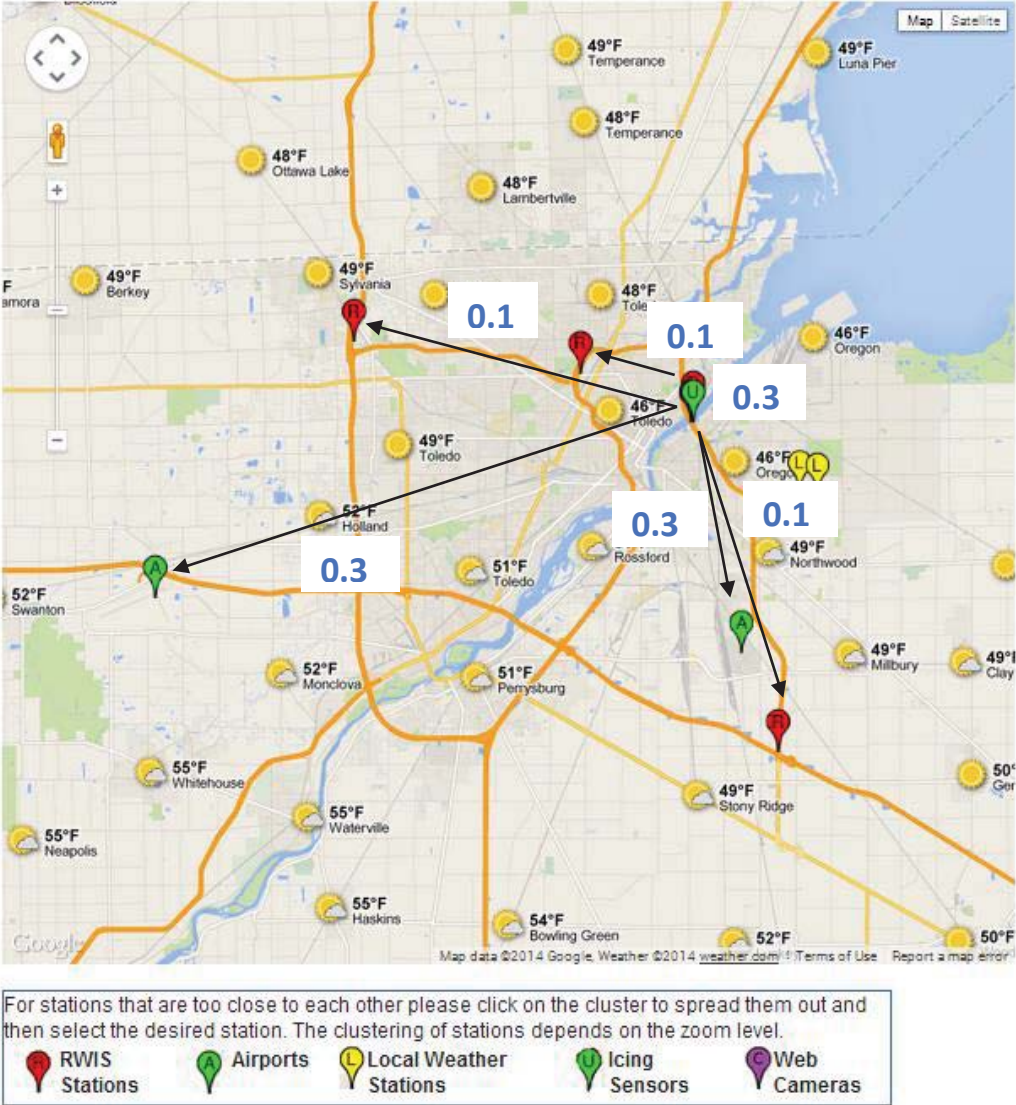
Figure 2.5 Map showing default weights of different weather station

Ice Fall - the process where ice sheds pieces of ice that are potentially dangerous - requires ice accumulation to exist first and to a certain degree.

Once it ice has accumulated to the degree of concern, the ice fall determination is then evaluated from the data collected at each weather station. The same check for the percentage of the last hour of Weather data from the stations is used to determine the station's overall condition. Since the ice fall check is significantly more critical and occurs at a faster rate, any indication of clear sky or sunlight has a high weight. This makes the weight of the airport's METAR sky cover measure as high as the temperature reading of the weather station on the bridge. From here, just like the ice accumulation, each weather station's condition assessment result (0 or 1) is multiplied by the station weights and each result is summed Figure 2.5. Again if the total is greater than the threshold, ice fall is considered possible during at this point in time.

Section 2.1.4:   Persistence Algorithm

The determination of possible ice conditions ("yes"=1 or "no" = 0) happens each data collection cycle as discussed in the previous section. However, ice event conditions that lead to ice shedding, specifically dangerous ice shedding, have historically been preempted by persistent ice accumulation over a period of hours. To determine if ice event conditions persist and to what extent required the development of a set of states and corresponding conditions for transition between states. The resulting states were also driven by the need to have a dial or speedometer style gauge on the dashboard where each state is a position on it with the current state marked by a pointer as in a car. Transitioning between states is limited by the maximum measurement rate of the available date sources to get all pertinent measurements necessary for decision making. Specifically in this case the METAR data from the airport is updated once per hour, which limits the rate of determination and state transition to once per hour.

Section 2.1.4.1:   Ice Accumulation

Before continuing with the states transition algorithm, let's get introduced to few terminologies, which we will be using often.

Different states used in the Ice accumulation process:

C: 'Clear'–No Ice present
Y1: 'Yellow 1'–Icing possible
Y2: 'Yellow 2'–Icing likely
Y3: 'Yellow 3'–Icing highly likely
A: 'Alert'–Ice confirmed

To start, the initial state is set to "Clear" or C (also associated with green) and stays at this state until the first resulting ice accumulation likelihood of 0.3 or greater. Once this happens, the state moves to the Y1 state. The next evaluation cycle first determines the likelihood based on the last hour of measurements and if less than the threshold, the state moves back to C. If it is above the threshold, then it evaluates the likelihood of the last 8 hours of data and if 6 of the last 8 hours of results are above the threshold, the state moves to Y2, otherwise the state remains at Y1. At the next cycle, if we are at state Y2, a similar process is used, but instead checks for 8 of the last 10 hours of likelihood results above the threshold. If this is not the case then the Y2 evaluation is checked in order to remain at Y2 and if this is also not met the state moves to Y1. When the check for 8 of the last 10 hours of likelihood is met, the state moves to Y3 and email and text message alerts are sent to officials that ice accumulation is highly likely and visual confirmation is required. The emails and text messages indicates that not only do we need visual confirmation, but also that the response can be submitted through the web site and is required for the ice fall evaluation processing to start. If there is no response after 2 hours, another email and text message is sent but the state remains at Y3 unless a response is received.

If at any time a response is received indicating ice is present, the state moves to 'A' regardless of the current state.

Figure 2.6 shows the flow chart of the algorithm explained above. Also the pictorial representation of each state transition in the ice accumulation process is shown in [Appendix C].
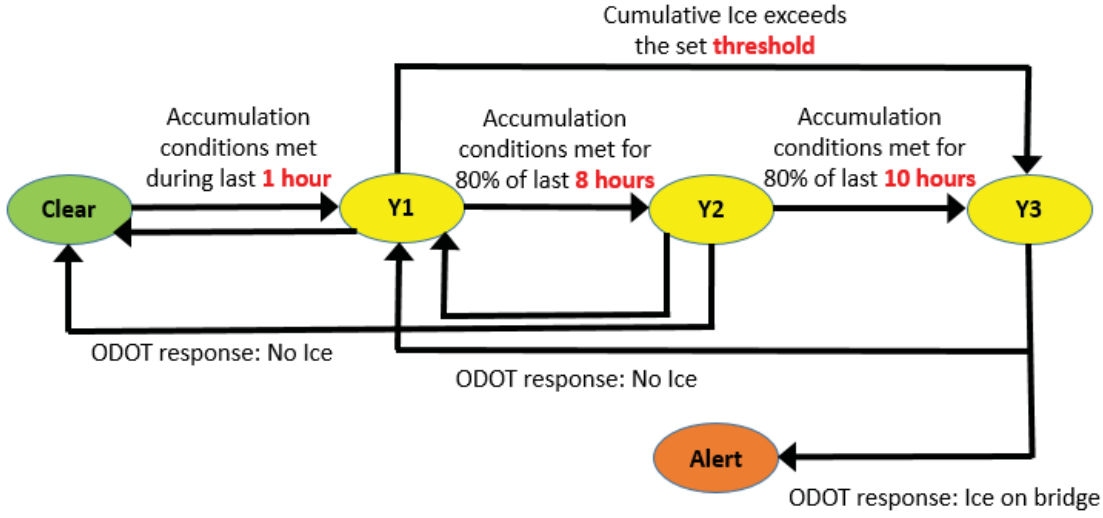
Figure 2.6: Ice Accumulation States Algorithm

Section 2.1.4.2:   Ice Presence

Different states used in the Ice presence process:

C: 'Clear' – No Ice present
Y1: 'Yellow 1' – Icing possible
A: 'Alert' – Ice confirmed

After Y3 state has reached, it will wait for a response from ODOT and continue sending mails and messages every two hours. Upon receiving this response, the state will either move back to Y1 or forward to A ("Alert" also associated with orange).

Figure 2.6 shows the flow chart of the algorithm explained above. Also the pictorial representation of each state transition in the ice presence process is shown in [Appendix C].

From here, we move to the Ice Fall check.

Section 2.1.4.3:   Ice Fall

Different states used in the Ice Fall process:

R1: 'Red 1' – Ice Fall possible
R2: 'Red 2' – Ice Fall likely
R3: 'Red 3' – Ice Fall highly likely
A: 'Alert' – Ice confirmed
C: 'Clear' – No Ice present

From the alert 'A' state ice fall determinations are evaluated, but as previously mentioned, this check is significantly more time critical so each state transition is evaluated based on the last hour's worth of data. So if the current state is A and the evaluation result is that ice fall conditions from the last hour of data are met then the state moves to R1. On the next cycle the last hour of data is evaluated and if ice

fall conditions are met, then the state moves to R2; otherwise we move back to A. Again on the next cycle if the ice fall conditions are met then the state moves to R3; otherwise, the state moves back to R1. Once at the R3 state the evaluation will only result in staying at R3 because a response is required after visual inspection. Also, because of the criticality of the ice fall detection, all transitions between R1, R2, or R3 states send email and text messages to the officials. The message when R3 state is reached has the addition of the response requirement after visual inspection. Similar to the ice accumulation check the dashboard will send mails and text messages every alternate hour if a response is not received. If at any point during the ice fall evaluation process a response is received indicating no ice presence then the state moves back to C.

Figure 2.7 shows the flow chart of the algorithm explained above. Also the pictorial representation of each state transition in the ice presence process is shown in [Appendix C].
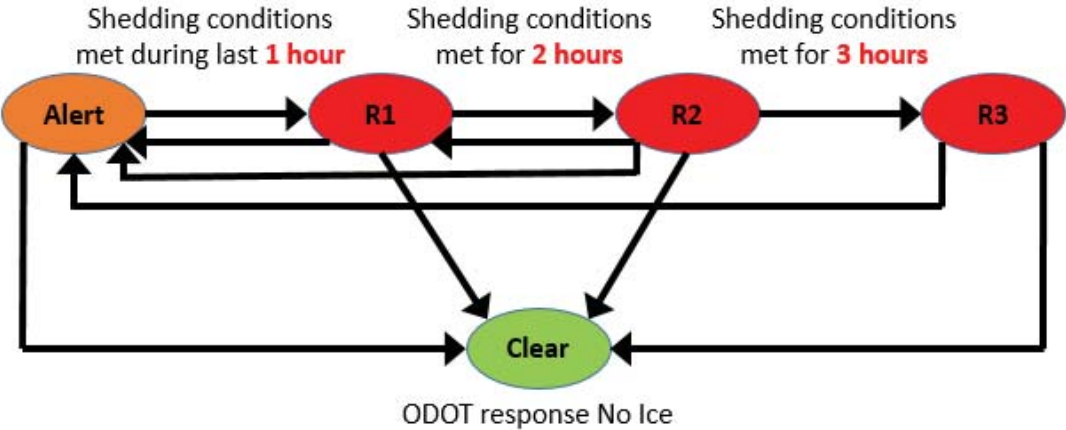
Figure 2.7: Ice Fall States Algorithm

Section 2.1.5:   Front End Implementation

The implementation of the algorithm and the dashboard was divided into three parts in order to integrate data from and manage connectivity between separate systems. The first part was to automate the collection and data warehousing of weather data from RWIS, METAR stations and the bridge sensors. These processes needed to be stable and robust so we have a reliable set of weather measurements from all the necessary sources. This system was not required for development of the next part, but having the necessary data stored locally inherently increases performance, reliability and robustness. From the developed algorithm and all the necessary conditions, software was developed to carry out the automated evaluation process and scheduled to run once per hour as previously mentioned. Finally a set of web pages were developed which is called the dashboard (http://ucii.ceas.uc.edu/public/index.php/Skyway/weather).
It can also be accessed through the following link (http://portal.dot.us/Districts/D02/Pages/VGCS.aspx)

Below listed are few of the dashboard's important features:

Section 2.1.5.1:   Dashboard Main Panel

The main panel of the dashboard contains the icing speedometer showing all the states including {G, Y1, Y2, Y3, O, R1, R2, and R3}.The main panel also includes the reporting function for ODOT, which can be used to report icing status after visual inspection. The ticker on the main panel shows icing conditions of the last 48 hours. Figure 2.8 is a screen shot of the web site showing the dashboard main panel.
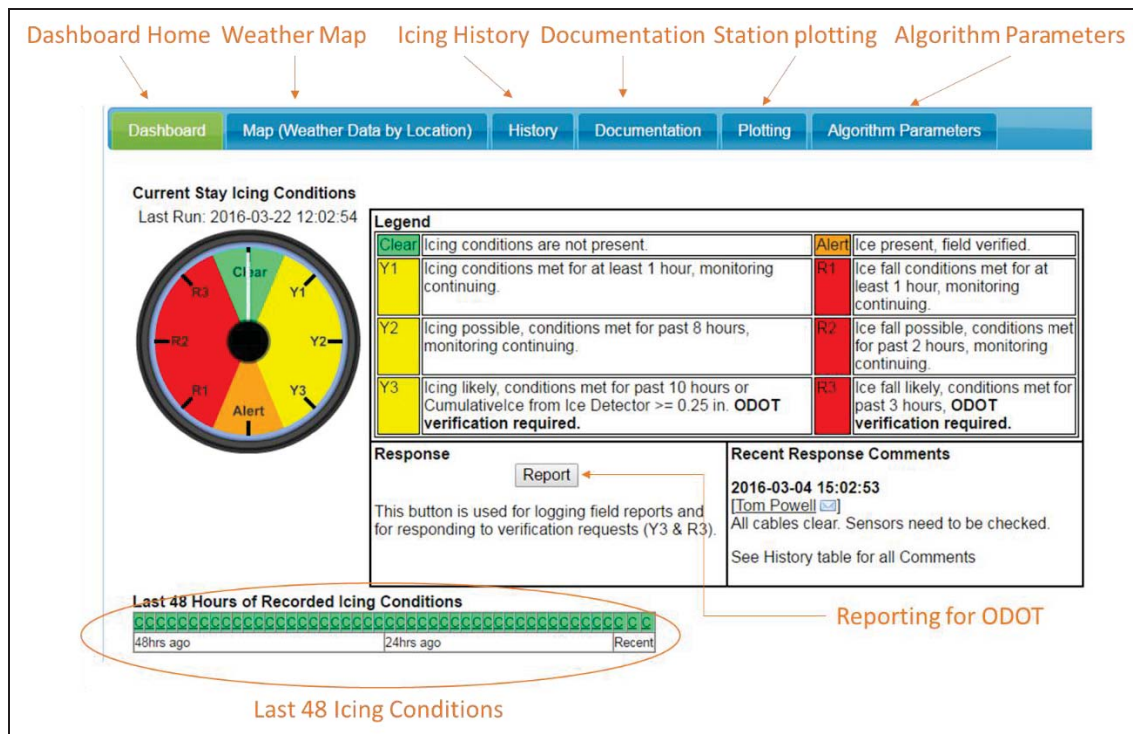
Figure 2.8: Dashboard Main Panel

Section 2.1.5.2:   Weather Map

Dashboard includes an interactive map of the weather stations where current sensor readings are shown and where historical readings can be plotted on a timeline. There are also cameras installed on the bridge that can be seen from this interactive map. Complete feature of the weather map can be seen in [*Appendix D*].

Section 2.1.5.3:   History

This tool allows for more detailed information on the past evaluations, responses submitted, and any additional notes available. This section also provides the tool to check a short summary of the weather data between two dates. Complete feature of the History section of the Dashboard can be seen in [*Appendix E*].
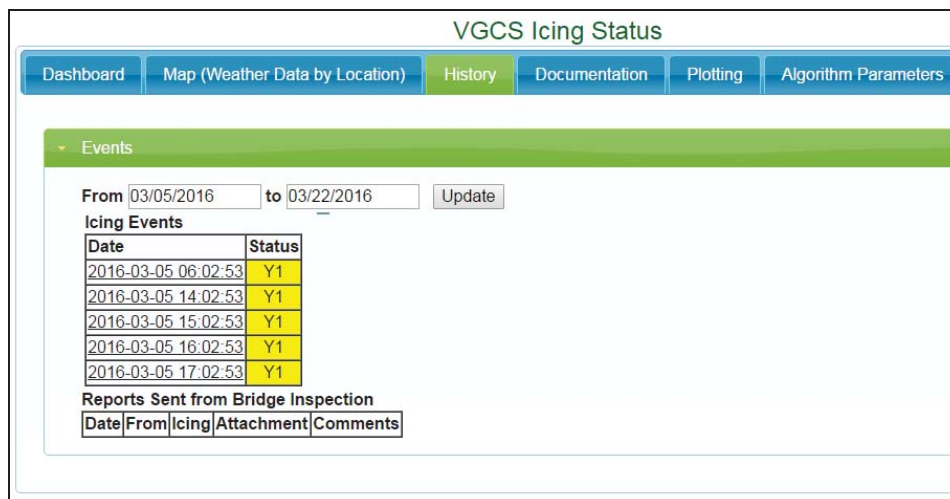
Figure 2.9: Dashboard History Section

Section 2.1.5.4:   Documentation

All of the project documentation has been included and listed in this section for reference as well as how the dashboard operates and how to use the web site.
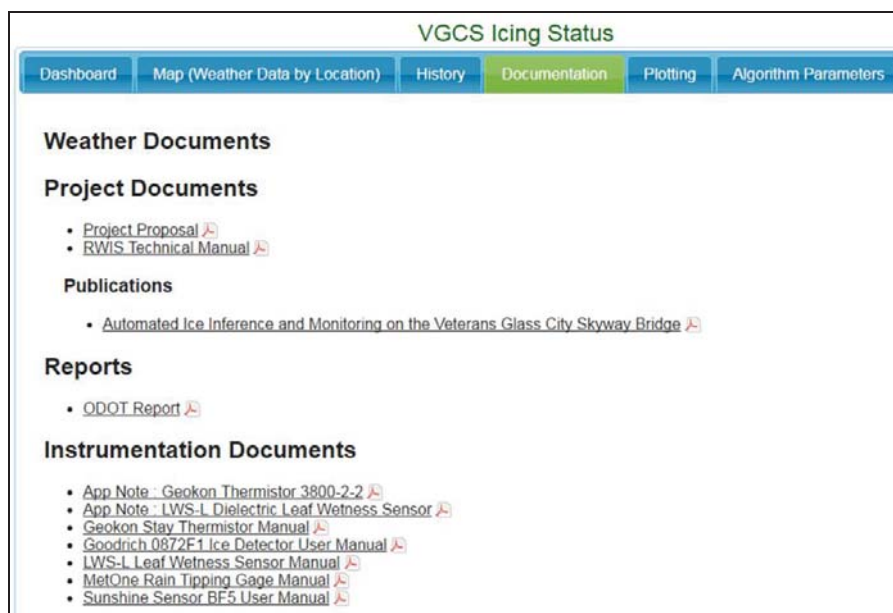
Figure 2.10: Dashboard Documentation Section

Section 2.1.5.5:   Plotting

All of the data collected and used in the dashboard algorithm can be plotted as graphs in this section. The section contains tools to plot archived data for the Stay thermistors, Local bridge sensors, RWIS sensors, State sensors and Laser Thickness Sensors. Complete feature of the Plotting section of the Dashboard can be seen in [*Appendix F*].
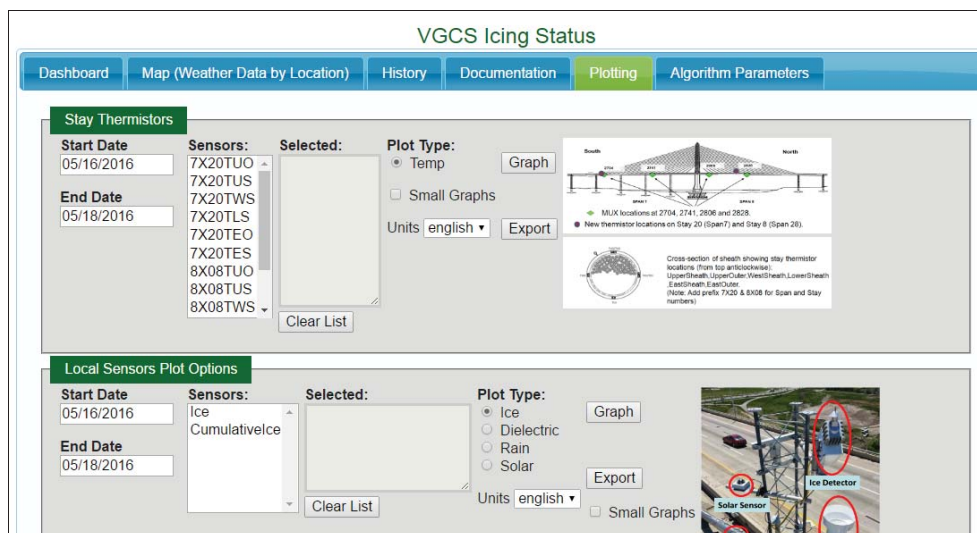
Figure 2.11: Dashboard Plotting Section

Section 2.1.5.6:   Algorithm Parameters

The purpose of the Algorithm Parameters tab is to provide a platform to dynamically make changes without having to go through the algorithm code. The tab has options to add, delete and modify details on the fly. Complete feature of the Algorithm Parameters section of the Dashboard can be seen in [*Appendix G*].
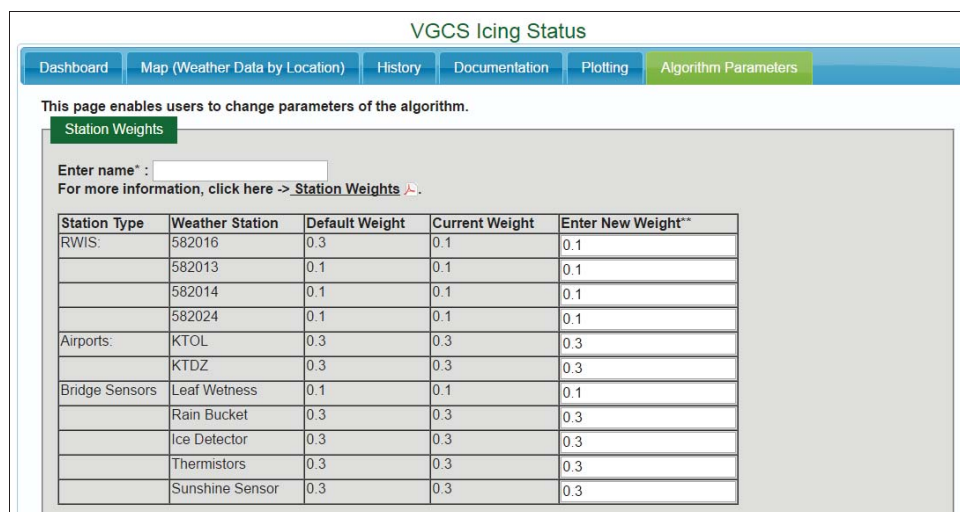
Figure 2.12: Dashboard Algorithm Parameters Section

Section 2.1.6:   Example: Stepping through an event

This section will explain how the dashboard will act when an event occurs. To see this let us consider the events on Feb 26-27, 2013.

At 12:00 hrs on the 26th the Dashboard started alarming for Ice accumulation, at state Y1 based on the data received from the RWIS station 582016 and the KTDZ airport. Over the next few hours the system continued to see conditions for Ice accumulation, staying at Y1 till 16:00 hrs.

Figure 2.13: Speedo at Y1

Between 16:00 hrs and 17:00 hrs reports from physical inspection confirmed that accumulations up to 0.25 inches were measured on the site. This was reported using the "Report" button to the right of the speedometer on the dashboard.

Figure 2.14: Reporting

At 17:00 hrs the temperatures started rising and the dashboard started reporting Ice shedding alerts, the speedo showing R1.

Figure 2.15: Speedo at R1

Over the next few hours the dashboard continued to alarm as conditions for Ice shedding persisted. The speedo was on R2 at 20:00 hrs and on R3 at 21:00 hrs and 22:00 hrs. After visual inspections after 22:00 hrs there was confirmation that no ice was present at the site and the reports were filed using the

Report button on the site. The event on the 26th ended with this report and the dashboard stayed clear till there were conditions seen on the next day.

On the 27th, the conditions remained clear until the KTOL airport started reporting conditions causing accumulation at 11:00 hrs. The other airport KTDZ joined in soon to report similar conditions and the speedo stayed on Y1 till 15:00 hrs. Since the conditions for accumulation were met for the sixth consecutive hour speedo moved to Y2 at 16:00 hrs. It stayed on Y2 at 17:00 hrs but died down to clear at 18:00 hrs since accumulation conditions were not met. At 20:00 hrs the speedo again moved to Y1 with favourable conditions occurring again, followed by the dashboard moving to Y2 at 21:00 hrs (since accumulation conditions were met for 6 of the last 8 hours. The dashboard then went to Y3 at 22:00 hours, after 8 hours of accumulation conditions reported in the last 10 hours. At this point a physical inspection was required to move from Y3 to Alert if Ice was present or to back down if there was no ice present on the site. Since the report filed confirmed that there was no or minimal ice on the bridge the speedo backed down to Y1 at 00:00hrs on the 28th.

Section 2.2:   HOW TO EDIT PARAMETERS

This section will explain the Algorithm Parameters tab of the website. The tab has four parts to it which can be modified by users to make crucial changes to the algorithm without having to know how to change and where to change the actual lines of code.

Anyone who has access to the website can use this section to make changes to the algorithm. In order to make any changes on the algorithm parameters tab, the user must enter name. The changes made to the parameters will be in effect at the top of the following hour. The previous states and the current state will not change.

Section 2.2.1:   Station Weights

The table shows the weather stations, their recommended default weights, the current weight that is being used in the algorithms and the text box to enter the new weights. The user can click on update to reflect the changes and the click on the History button to see the historical changes made to this section.

Figure 2.16: Station Weights Section

Station Weights FAQ:

1. What is the ideal value for station weights?

Stations are assigned weights between 0 and 0.3. Stations that are more reliable and whose conditions reflect the conditions on the bridge and those that are located geographically closer to the bridge are assigned a high weight of 0.3. The other stations are assigned a weight of 0.1. Assigning 0.3 to a station would mean that the station can trigger an alarm by itself. Setting the weight lower to 0.2 or 0.1, for example, would mean that during icing conditions it will need other voters to contribute to raising an alert. So if one wants to make a station alert by itself then it should be set to 0.3, otherwise setting a lower weight is recommended.

2. How to change the station weights?

In the Station Weights section of the Algorithm Parameters tab, the first 2 column of weights indicate the default and current weights of all the stations. The new weights column will show the same weights as the current weights, please change the weights of the station(s) as required and click on Update. Note that the station weights must be a number in the range 0 to 0.3.

3. When should one change station weights?

If a particular station is not reflecting the weather conditions correctly and is causing false alerts then the weight of that station can be lowered. If it is found that a station has been reporting conditions that are very similar to the conditions on the bridge but it is not able to alert by itself then the weight of that station can be increased.

Section 2.2.2:   Email List

The table shows the list of names and email addresses of the users who are on the email list when alarms are issued. The user can add a new name and email address to the existing list and also delete an email address from the list if need be. The user can click on update to reflect the changes and the click on the History button to see the historical changes made to this section.

Figure 2.17: Email List Section

Email List FAQ:

1. How to add emails?

Please enter a valid email address in the textbox without any spaces. An error message will come up if the email address entered doesn't have a '@' character.

2. How to delete emails?

Each email address in the list will be assigned a unique number (ID) which can be looked up in the table. To delete an email address from the recipients list, enter its corresponding ID in the textbox and click update. Note that only one address can be removed at a time.

3. Can addition and deletion be done at the same time?

Yes, one email address can be added while the other is deleted in the same update.

4. What does the history section show?

The history section shows a record of every time a change is made to the recipient list. It will show the new list of recipients every time an email address is added or deleted. To find out the list of recipients at any particular time please look at the most recent record before that time.

Section 2.2.3:   Alarm Thresholds

The table shows the list of sensors and their recommended default thresholds, the current thresholds that is being used in the algorithms and the text box to enter the new thresholds. The user can click on update to reflect the changes and the click on the History button to see the historical changes made to this section.

Figure 2.18: Alarm Thresholds Section

Alarm Thresholds FAQ:

1.   What are the ideal alarm threshold values?

The default thresholds that is shown in the table are the ideal values for alarm thresholds. For more detailed information on the limits of each sensor refer to the results from Lab experiments conducted at UC and UT which were published in the report. For all the sensors reducing the threshold will make them more sensitive.

2.   How to change the alarm thresholds?

In the Alarm Thresholds section of the Algorithm Parameters tab, the first 2 columns of thresholds indicate the default and current thresholds for all the sensors. The new thresholds column will show the same values as the current thresholds, please change the thresholds of the sensor(s) as required. Please enter a numerical value greater than or equal to zero in the appropriate text boxes and click on update.

3. How does Cumulative Ice affect the algorithm?

Cumulative Ice threshold governs the transition from Y1 to Y3 directly, therefore changing the threshold of Cumulative Ice will decide when state Y3 will be reached. If it is set to a lower value the dashboard will jump to the Y3 state faster. Note that the Cumulative Ice's real function will kick in only when the heater in the Ice detector works (at 0.15 inches). So setting the Cumulative Ice to a threshold less than 0.15 inches is not recommended.

Section 2.2.4: Rules – Transition Times

The table shows the list of Rules Transition types and their recommended default transition times, the current transition times that is being used in the algorithms and the text box to enter the new transition times. The user can click on update to reflect the changes and the click on the History button to see the historical changes made to this section.

Figure 2.19: Transition Times Section

Rules – Transition Times FAQ:

1. What are the ideal alarm threshold values?

Over the years it has been found that for significant ice to build up on the stays it takes about 8 to 10 hours. The default values have been set based on this observation. Note that, in case of a

faster buildup of ice, one can bypass the wait time and move to the Alert state by reporting on the dashboard page.

Since shedding is usually a faster process than accumulation the shedding times are set to 1, 2 and 3 hours respectively.

2. How to change the transition times?

In the Transition Times section of the Algorithm Parameters tab, the first 2 columns of times indicate the default and current transition times. The new times column will show the same values as the current times, please change the times of the state(s) as required. Please enter a numerical value greater than zero in the appropriate text boxes and click on update. Not that the accumulation times and shedding times must be in ascending order, otherwise an error message will show up. Also note that the minimum values will be 1, 2 and 3 hours for both accumulation and shedding times.

3. Why is there an 80% of the time rule for transitions from Y1 to Y2 and Y2 to Y3?

If the dashboard has to move from Y1 to Y2 state then conditions for Icing must be satisfied for 'X' consecutive hours. But the probability of having 'X' consecutive hours is very less and we will miss events if X is a big number. Say if 'X' is 8 hours, probability of 8 hours consecutive hours of icing conditions is less. However if the conditions are true for 7 of the last 8 hours then it is good enough to move from one state to another. The 80% rule has been incorporated to implement this functionality. Note that since hours has to be a whole number the 80% value is rounded to the next higher whole number.

4. Why changing times for transitions Y1 -> Y3 and Y3 ->A not allowed on the website?

Transition from Y1 to Y3 depends on the Cumulative Ice threshold, it is not a function of time. The dashboard will move from Y1 to Y3 if the Cumulative Ice exceed the set threshold. The transition from Y3 to A is also not a function of time. Manual inspection/confirmation is required and a report has to be submitted on the website to move to the Alert state. The dashboard will stay at Y3 until a report has been submitted.

Chapter 3:   Maintenance

Section 3.1:   Hardware Components:

Below is the list of all the sensors and information such as Contact information, Cost, Life expectancy and Maintenance.

Section 3.1.1:   Geokon stay thermistor

Figure 3.1: Geokon stay thermistor

Contact information:

Geokon Incorporated,

48 Spencer Street, Lebanon, New Hampshire, 03766 · USA

Telephone: 1 (603) 448-1562, Fax: 1 (603) 448-3216

E-mail : info@geokon.com, Website: www.geokon.com

Cost:

Life expectancy: 13 months of warranty.

Regular maintenance: None required.

Section 3.1.2:   Ice detector
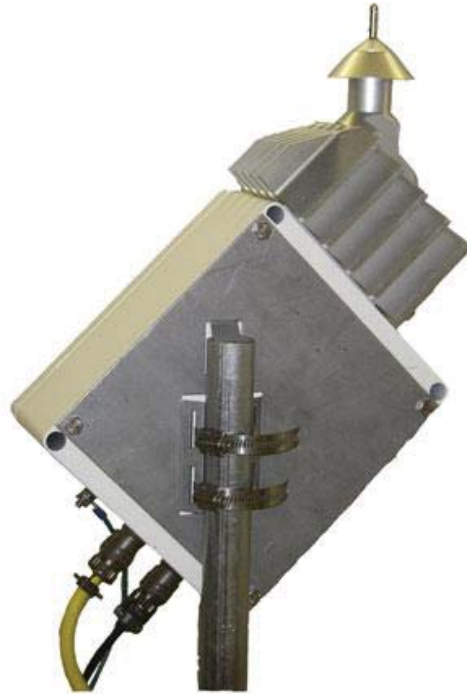
Figure 3.2: Ice detector

Contact information:

Campbell Scientific, Inc.

815 West 1800 North, Logan, UT 84321-1784 USA

Phone : 1-435-227-9120

E-mail : info@campbellsci.com, Website: www.campbellsci.com

Cost:

Life expectancy: 12 months of warranty.

Regular maintenance: None required.

Section 3.1.3:   Leaf Wetness Sensor
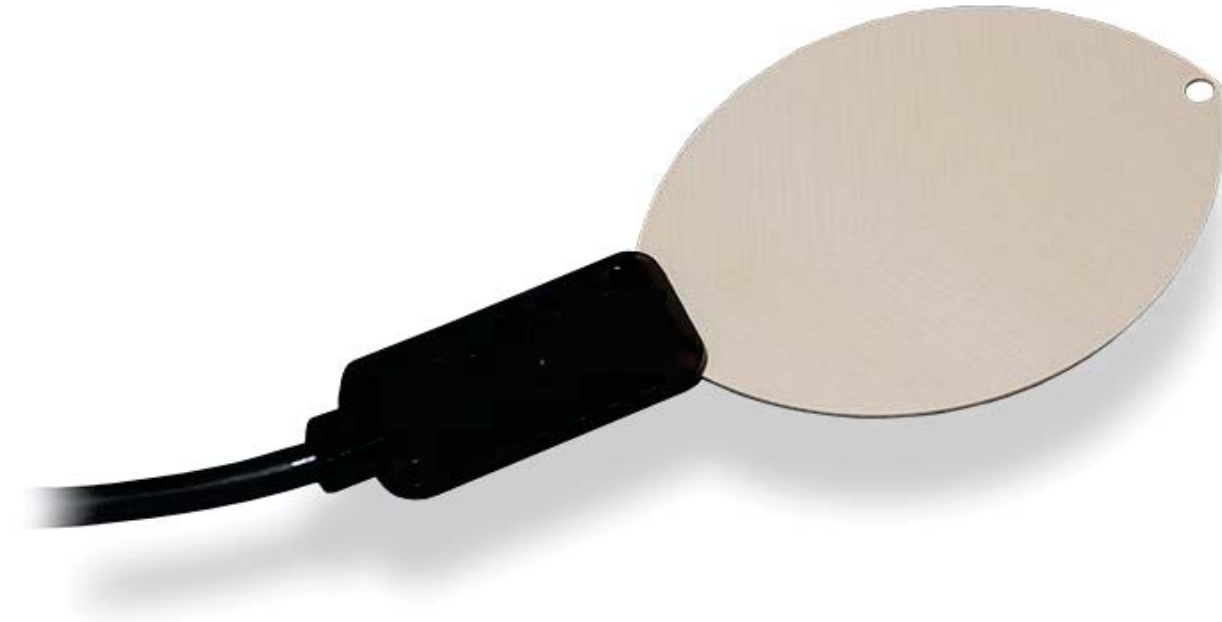
Figure 3.3: Leaf Wetness Sensor (LWS)

Contact information:

Campbell Scientific, Inc.

815 West 1800 North, Logan, UT 84321-1784 USA

Phone : 1-435-227-9120

E-mail : info@campbellsci.com, Website: www.campbellsci.com

Cost:

Life expectancy: 12 months of warranty.

Regular maintenance: None required.

Section 3.1.4:   Rain bucket

Figure 3.4: Rain bucket

Contact information:

Campbell Scientific, Inc.

815 West 1800 North, Logan, UT 84321-1784 USA

Phone : 1-435-227-9120

E-mail : info@campbellsci.com, Website: www.campbellsci.com

Cost: Product discontinued; replaced by: 52202-L,CS700H-L.

Life expectancy: 12 months of warranty.

Regular maintenance: Cleaning the bucket once every 6 months, emptying any leaves/feathers that might have fallen into the bucket is recommended.

Section 3.1.5: Solar sensor

Figure 3.5: Solar sensor

Contact information:

Dynamax Inc

10808 Fallstone Suite #350, Houston Texas 77099, USA

Tel: +1 281 564 5100 , Fax: +1 281 564 5200

E-mail : admin@dynamax.com, Website: www.delta-t.co.uk

Cost:

Life expectancy: 12 months of warranty.

Regular maintenance: None required.

Section 3.1.6:   CR 1000

Figure 3.6: CR 1000 Data Acquisition System.

Contact information:

Campbell Scientific, Inc.

815 West 1800 North, Logan, UT 84321-1784 USA

Phone : 1-435-227-9120

E-mail : info@campbellsci.com, Website: www.campbellsci.com

Cost:

Life expectancy: 36 moths of warranty.

Regular maintenance: None required.

Section 3.2: Troubleshooting bad dashboard information:

The dashboard might display bad information due to two reasons.

1. Bad information from weather sources: If one or more weather sources report bad or wrong information it might lead to false alarms being triggered by the dashboard algorithm. To avoid this the station weight of the faulty station(s) should be reduced or set to zero until the station's data is deemed reliable.

2. Bad/Wrong computation by the dashboard algorithm: This is highly unlikely to occur, but in such an event the last hour status of the dashboard must be set to "Clear" or "G" in the database. The 'current_status' field in the 'VGCSIcingStatus' table must be updated to "G". During the next run the dashboard will correct itself, if it fails again then this must be repeated until the dashboard returns to normal working condition. Such bad computations can occur when the time changes from Standard times to Daylight savings and vice-versa. The dashboard has been programmed to handle this automatically, but if the stations fail to adjust this issue can arise.

Section 3.3: Communication, hardware, software and any other IT requirements

Section 3.3.1: INTRODUCTION TO VGCS WEBSITE

The website is developed by UCII (University of Cincinnati Infrastructure Institute) for the purpose of real time monitoring of weather conditions on the Veterans' Glass City Skyway Bridge in Toledo, OH. The website consists of a dashboard that displays data interpretations from the bridge in the form of alarms, maps and plots.

Section 3.3.2: WEB SERVER DETAILS

A Web Server is a computer system or software that, using the client/server model and the World Wide Web's Hypertext Transfer Protocol (HTTP), handles and processes requests. It serves the files that form Web pages to web users.

Section 3.3.2.1: Location of Web Server:

The web server for VGCS is D02VGCS02 and is located at ODOT District 02 Office.

Section 3.3.2.2: Specifications:

The D02VGCS02 server runs on:

- Operating System: Windows Server 2008

- HTTP Server: Apache HTTP Server 2.4

- PHP: PHP v5.5

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Section 3.3.2.3: Server Setup:

The steps to setup the Webserver at D02VGCS02 are the following:

1. Download and Install XAMPP v3.2.1 , MySQL v5.6, PHP v5.2.

2. Using the XAMPP Control Panel, you can control the Apache and MySQL servers.

3. Modify/Add/Set the following parameters in the *'httpd.conf'* file located in *C:\xampp\apache\conf\httpd.conf*.

   o Listen 80

   o ServerAdmin postmaster@localhost

   o ServerName localhost:80

   o <Directory/>

      Allow override none

      Require all denied

      </Directory>

   o Document Root "C:/xampp/htdocs"

   o <Directory "C:/xampp/htdocs">

      Options Indexes FollowSymLinks Includes ExecCGI

      Allow override all

      Require all granted

      </Directory>

   o <Directory "C:/xampp/cgi-bin">

      Allow override all

      Options none

      Require all granted

      </Directory>

   o AcceptFilter http none

4. Modify/Add/Set the following parameters in the 'php.ini' file located in C:\xampp\php\php.ini.

   o memory_limit = 128M

   o error_reporting = E_ERROR

o   post_max_size = 8M

o   upload_max_filesize = 128M

o   Uncomment the following :

- extension = php_gd2.dll

- extension = php_mysql.dll

- extension = php_mysqli.dll

- extension = php_pdo_mysql.dll

- extension = php_pdo_sqlite.dll

5. Add the following FIREWALL setting to the webserver :

o   Inbound Rules:

- Rule Name :'Ping'

- Enabled, Protocol : ICMP v4

- Local port: any, Remote port: any

- Allowed Users/Computers: Any

o   Outbound Rules:

- Rule Name: 'MySql'

- Enabled, Protocol : TCP

- Local port: All, Remote port: any

- Allowed Users/Computers: Any

6. Add all the website files into C:\xampp\htdocs and under respective folders as shown in the Files and Folders Structure below.

Section 3.3.3:   WEBSITE DETAILS

Section 3.3.3.1:   DEVELOPER'S MANUAL

The website runs on XAMPP which is a free and open source cross-platform web server solution stack package consisting of Apache HTTP Server, MySql Server and interpreters for scripts written in PHP. The structure of the website is based on the Zend Framework which is an open source, object oriented web application framework for PHP 5. Zend Framework provides an advanced Model-View-Controller (MVC) implementation that is used to establish a basic structure for the website. MVC or Model-View-Controller is a software architecture pattern for implementing websites. It divides a given software

application into three interconnected parts, so as to abstract the background functionalities from the end user view.

The Veterans' Glass City Skyway website also follows the above MVC concept.
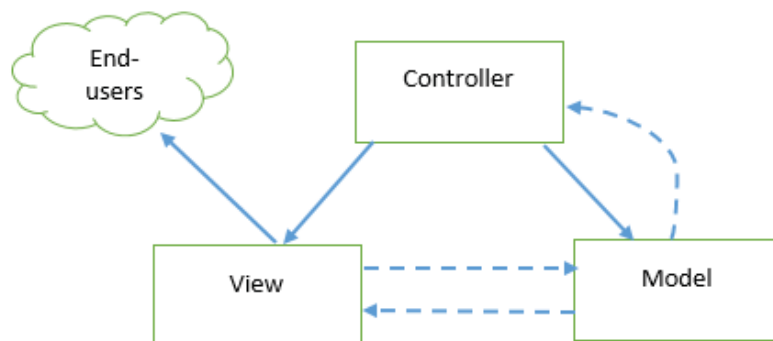
Figure 3.7: Basic Flow Diagram of code control

Model - This part of the website defines the basic functionality behind a set of abstractions. Data access routines and business logic can be defined in the model.

The files that belong to this category are the main functional files for Documents page, Pictures page, Reports page, Database query model etc,.

View - Views define exactly what is presented to the user. Usually controllers pass data to each view to render in some format. Views will often collect data from the user, as well. This is where the HTML pages for the website is located like the weather dashboard tab, map, history, documents, pictures, plotting tab layout and user interface.

Controller - Controllers bind the whole pattern together. They manipulate models, decide which view to display based on the user's request and other factors, pass along the data that each view will need, or hand off control to another controller entirely. The VGCS website uses the Skyway controller which decides the systematic flow of control within the different website files.

Section 3.3.3.2:   FILES AND FOLDER STRUCTURE

There are numerous files and folders for the website.

The main folders structure is as below:

Applications

- Config
  - application.ini
  - PHPDocConfig.ini
- Controllers
  - ErrorController.php
  - IndexController.php
  - SkywayController.php
  - UserController.php
- Layouts
  - Functions
    - functions.php
  - Scripts
    - filemanage.phtml
    - layout.phtml
- Models
  - Database.php
  - Documents.php
  - Panel.php
  - Pictures.php
  - Reports.php
- Views
  - Helpers
    - LoginRedirect.php
  - Scripts
  - Error
    - error.phtml
  - Index
    - index.phtml
  - User
    - form.phtml
  - Skyway
    - documents.phtml
    - history.phtml
    - index.phtml
    - mainreports.phtml
    - managefiles.phtml
    - managegroups.phtml
    - newgroup.phtml
    - pictures.phtml
    - respond.phtml
    - upload.phtml
    - weather.phtml

Library

- jpgraph3
  - jpgraph source files
- Zend
  - Framework Folders and Files

Public

- CSS
  - all css files for the website
- Documents
  - Skyway
    - all documents related to VGCS
- Images
  - Skyway
    - images pertaining to VGCS webpages
- js
  - Javascript extensions, libraries and api files needed for the webpages

Other files

- Plotter.php
  - consists of all the plotting functions
- Weather.php
  - consists of all the dashboard functions and manipulations

Section 3.3.4: Database Server

Section 3.3.4.1: Server details

The database is hosted by a server that runs on Windows 7 operating system. The server is a virtual machine and serves as the database as well as the Loggernet server. MySQL database version 5.6 is installed and is set a static IP.

The steps to setup the Database server at D02VGCS01 are the following:

1. Download and Install XAMPP v3.2.1 , MySQL v5.6, PHP v5.2.

2. Using the XAMPP Control Panel, you can control the Apache and MySQL servers.

3. Modify/Add/Set the following parameters in the 'my.ini' file located in "C:\xampp\mysql\bin\my.ini".

- port = 3306

1. Create a schema named 'vgcs'. Create a user 'skyway' with password '1234'. This user must have permissions to read and write, not just from the localhost but from any computer with any IP. (This is to enable people making reports on the website and make changes to the algorithm parameters from any computer.)

2. Add the following FIREWALL setting to the webserver :

   o Inbound Rules:

     - Rule Name :'Ping'

     - Enabled, Protocol : ICMP v4

     - Local port: any, Remote port: any

     - Allowed Users/Computers: Any

     - Rule Name: 'MySql'

     - Enabled, Protocol : TCP

     - Local port: 3306, Remote port: any

     - Allowed Users/Computers: Any

The data collection scripts and the website codes are written to work with the above mentioned database credentials. The scripts and the website will fail to function if these credentials are not strictly followed.

Section 3.3.4.2: Tables and Views

The table below shows the list of tables and the purpose of each table briefly.

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Table name	Purpose
GlassSkyway	Save data for Thermistors, Historic data of strain gages
METAR	Save data for both Airports
RWISatmos	Save data for all the RWIS stations
VGCS_CumulativeIce	Save data for calculated Cumulative Ice
VGCS_IceDetector	Save data for Ice Detector
VGCS_LeafSensor	Save data for Leaf Sensor
VGCS_SolarSensor	Save data for Solar sensor
VGCS_RainBucket	Save data for Rain Bucket
VGCSIcing	Save reports made on the website.
VGCSIcingCodes	Stores codes for display on History page.
VGCSIcingStationHealth	Save the station health status for every hour.
VGCSIcingStatus	Save Status, Accumulation/Shedding flags, report flags, mail status etc., for every hour.
VGCS_AlarmThresholds	Save alarm thresholds of sensors.
VGCS_EmailList	Save names and email IDs of recipients.
VGCS_EmailHistory	Record any changes made to Email list.
VGCS_StationWeights	Save station voting weights.
VGCS_TransitionTimes	Save algorithm state transition times.
VGCS_UT_ThicknessSensor	Save data for Laser thickness sensor.
VGCS_UT_StateSensor	Save data for State sensor.
Users	Save user login credentials.

The table below lists the views and the purpose of each.

View	Parent Table (s)	Purpose
GlassSkyway_ThermistorsNew	GlassSkyway	Choose only thermistors from the parent table, convert temperatures to Fahrenheit scale and round to one decimal place.
RWISatmosEST	RWISatmos	Convert time to EST/EDT from GMT/GDT and change temperature to Celsius scale.
RWISatmosESTF	RWISatmos	Convert time to EST/EDT from GMT/GDT.
VGCS_AllSensorsNew	VGCS_SloarSensor, VGCS_IceDetector, VGCS_RainBucket, VGCS_CumulativeIce, VGCS_LeafSensor	Combine all data from Icing sensors on the bridge to one View, for plotting purposes.
VGCS_UT_StateSensor_View	VGCS_UT_StateSensor	Filter out of range data from the sensor output, convert temperatures to Fahrenheit scale and round to one decimal place.
VGCS_UT_ThicknessSensor_View	VGCS_UT_ThicknessSensor	Filter out of range data from the sensor output and convert thickness to inches.

Section 3.3.5: Logger Net Server

Section 3.3.5.1: Logger Net server set up

The database is hosted by a server that runs on Windows 7 operating system. The server is a virtual machine and serves as the Logger Net server as well as the database server.

Section 3.3.5.1.1: Software Installed

The Logger Net software package, published by Campbell Scientific Inc., is installed. This is to facilitate connection to the loggers and to collect data from them. Logger Net is also used as a task master to schedule collection and processing scripts. The version of Logger Net installed is 4.2.1.

The data collection and processing is done by executables developed using python. These are scheduled to run at specified time intervals using the Logger Net task manager.

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For ease of working the MySQL workbench 6.2 is also installed on the server to access the database if need be. Though this is not necessary for the functioning of the server it is useful to check database connections and to run a few queries if and when required.

The server must have access to internet, to be able to pull weather data from Airports. It must also be able to access ODOT's ftp site. The executables must be granted permissions to send emails through the 'DOT.D02.VGCSIcing@dot.ohio.gov' email account.

Section 3.3.5.1.2:   Scripts

The python scripts that are scheduled to run for data collection and processing are stored in the directory C:\data\scripts\processing\icing\dist. The list of scripts and the function of each is described in the table below.

Function	.exe file	Location	Task master	Scheduling
Collect data from airports	pullMETAR.exe	C:\data\scripts\processing\icing\dist\METAR\dist	METAR	Base Time : 12:01:00AM Interval : 30 min
Collect data from RWIS stations	ftpRWIS.exe	C:\data\scripts\processing\icing\dist	RWIS	Base Time : 12:01:01AM Interval : 15 min
Collect data from all Bridge stations	VGCS_ALL_SENSORS.exe	C:\data\scripts\processing\icing\dist	VGCS_ALL_SENSORS	Base Time : 12:01:01AM Interval : 10 min
Calculate Cumulative Ice	VGCS_Cumulative_Ice.exe	C:\data\scripts\processing\icing\dist	VGCS_CumulativeIce	Base Time : 12:02:00AM Interval : 10 min
Icing Algorithm	VGCSIcingnewBDread.exe	C:\data\scripts\processing\icing\dist	Dashboard	Base Time : 12:03:00AM Interval : 1 hr
Collect State sensor data	VGCS_UT_SENSORS.exe	C:\data\scripts\processing\icing\dist	VGCS_UT_Sensors	Base Time : 12:01:00AM Interval : 10 min
Collect Laser thickness sensor data	VGCS_UT_LaserThickess.exe	C:\test	VGCS_UT_Laser Thickness	Base Time : 12:06:00AM Interval : 15 min
Status check program	StatusCheck.exe	C:\data\scripts\processing\icing\dist	Status Check	Base Time : 07:00:00AM Interval : 1 day

Function	.exe file	Location	Task master	Scheduling
Copy UT Optical Sensor data out to ODOT FTP Scheduling: Base	.exe File: OPSensFTP.exe	C:\test	Optical Sensor	Base Time : 12:05:00AM Interval : 15 min

There are separate collection scripts for every type of station/connection, one each for airports, RWIS stations and the bridge sensors. The two other scripts are processing scripts which does processing and alarming of the data collected by the other scripts.

Section 3.3.5.2:   Connection to sensors

The connection to the sensors/loggers are set up using the Setup program in LoggerNet. Loggers are accessed through IP ports as shown in the figure above. The scheduling of data collection and the files to be collected are set up as shown in the figure below.

The IPs of the Loggers are listed in the table below.

Sensor/Logger	IP address
Stay Thermistors	10.227.141.120:6783
Ice detector	10.227.141.121:6783
Leaf wetness sensor	10.227.141.122:6783
Solar sensor	10.227.141.123:6783
Rain bucket	10.227.141.124:6783
UT State sensor	10.227.141.125:6783

Section 3.3.5.3:   Data Collection

The data from airports (METAR), RWIS stations and the bridge sensors are collected from three different collection scripts. These scripts were programmed based on the source and the type of data available.

All these scripts will work only if the database is set up on the same server as the LoggerNet server and is located at 127.0.0.1 with the correct schema, user name, password and tables set up as described in the database server details section.

Section 3.3.5.3.1:   METAR data collection

The source of the data is from wunderground.com. The data for stations KTOL and KTDZ are collected from the following links.

KTOL – *http://www.wunderground.com/history/airport/ KTOL/YYYY/MM/DD /DailyHistory.html?format=1*

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KTDZ – *http://www.wunderground.com/history/airport/ KTDZ/YYYY/MM/DD /DailyHistory.html?format=1*

These stations report once every hour under normal conditions. If there are significant weather changes in the middle of the hour there are additional reports. The collection scripts check for new data twice

Section 3.3.5.3.2: RWIS data collection

The source of the data is from ODOT's ftp site. The text file from the ftp site contains data from all the RWIS stations in Ohio. The data from four stations – 582013, 582014, 582016, 582024 that are close to the bridge are saved to the database.

FTP url - *ftp.dot.state.oh.us*

Username – "anonymous"

Password – "ucii-download"

File - /pub/doit/ssi_rwis/SSIExpAtmos582.txt

RWIS stations get updated 4-6 times every hour. The frequency of reported has varied over the years and also varies for each station.

Section 3.3.5.3.3: Bridge sensors data collection

The 'dat' files that carry information of the sensors are retrieved from the loggers by Logger Net. There are five different 'dat' files, one each for the ice detector, solar sensor, leaf wetness sensor, rain bucket and the thermistors. All the sensors are scheduled to record measurements every 10 minutes. Their 'dat' files are retrieved every 10 minutes and saved to the database.

Section 3.3.5.3.4: Cumulative Ice calculation

This script is to calculate the Cumulative Ice variable from the Ice detector. This will read the values from the VGCS_IceDetector table in the database and calculate the new variable Cumulative Ice based on the Ice accumulated and the working of the heater in the Ice detector. The results are stored in the VGCS_CumulativeIce table. This program is run every time a new record from the Ice detector is available.

Section 3.3.5.3.5: Icing Algorithm

The Icing algorithm script runs at the top of each hour. It reads the last one hour's data from all stations from the database for processing. Based on a set of rules the conditions from the previous hour are analyzed and depending on previous hour's icing status the current hour's icing status is decided. The results are then stored in the database.

Chapter 4:   User Manual for UT Ice Presence and State Sensor

Section 4.1:   Introduction

This technical manual provides operation information for the UT Ice Presence and State Sensor. This sensor was designed to detect water beneath an ice layer on the Veterans' Glass City Skyway cable stay sheaths. This layer of water means that ice shedding may be imminent. The sensor can detect ice or water presence or absence on the bridge stay. If there is water present it indicates the state (water or liquid). If no water is present, it indicates the stay is clear. It is a resistance-based sensor which uses the change of the electrical conductivity between ice, water, and air and the stay temperature at the same location to determine the medium that covers the sensing element. The sensor consists of two parts, i.e., a sensing element bonded to the stay sheath which includes the sensing terminal and thermocouple, and a signal condition elements which includes the fixed resistance mounted in the control cabinet where it will is connected to the data logger and power supply.

Details of the design and field and laboratory testing are in Byanjankar (2016) and Abdelaal (2016)

Section 4.2:   Theory of operation

The sensor consists of five main elements: (1) power source with voltage of 2500 – 5000 millivolts DC (E0). (2) Two electrodes with an open space between them which acts as variable resistance (RV). The resistance depends on the medium in the open space. (3) A fixed resistor (RF) which functions as a reference for the differential voltage that will be measured. (4) Two open ends where the data acquisition system (DAQ) is connected. (5) A surface thermocouple with self-adhesive backing between the two electrodes that measures the temperature at the point where the sensor is installed. Figure 4.1 shows a circuit diagram of the sensor.

The main objective of the sensor is to measure the differential voltage between the two electrodes which are separated by a gap. The medium in the gap performs as a variable resistor. The state of the medium changes the differential voltage reading. The temperature measurement facilitates accurate differentiation between water and ice.
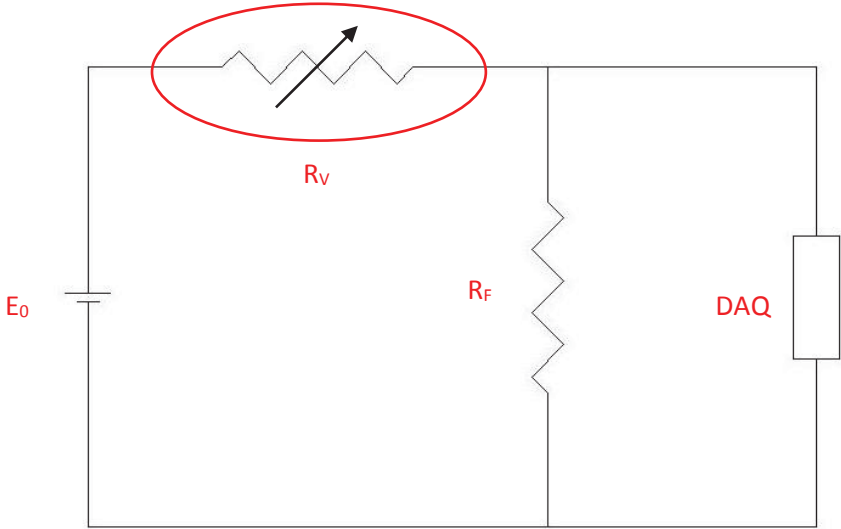
Figure 4.1Circuit Diagram for UT Ice Presence and State Sensor

Section 4.3:   Sensor installation and wiring

Section 4.3.1:   Installation

The sensor was designed to be flat, small, compact, and robust. It can adhere directly to the surface of the stay. It was installed on Omega SA1 series type K-thermocouple (Omega 2016) which has a self-adhesive backing which sticks to the surface of the stay. Figure 4.2 shows AutoCAD drawing for the top part of the sensor while Figure 4.3 shows one of the sensors installed on the bridge stays.

Figure 4.2 AutoCAD drawing for the Ice state and Presence Sensor Sensing Element and Connector.

Figure 4.3 UT Ice state and presence senor installed on VGCS stay

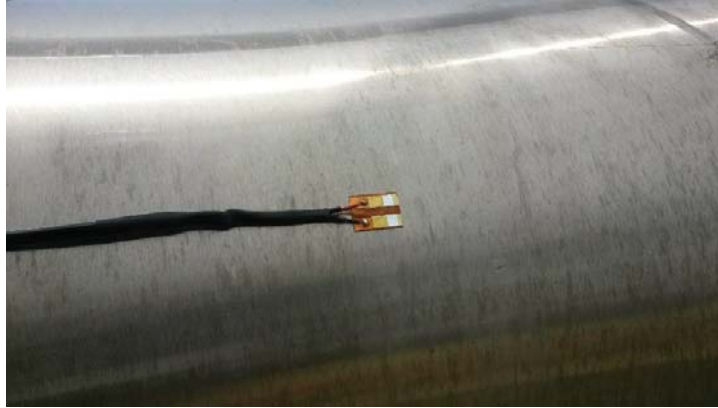## Section 4.3.2:   Power Source and Data Collection

The electrodes and thermocouple are designed to be connected to the DAQ This provides power for the electrodes and thermocouple and collects the output. The DAQ mounts in the control cabinet near the stays and has a reference cold junction thermocouple for the thermocouple mounted on the stays. For better accuracy, a thermistor was used as a reference cold junction since the thermocouple inside the DAQ might be affected by heat generated by the electronics which differ from the situation where the measurement is conducted.

Section 4.3.3:   Wiring of Electrodes

There are four wires required to be connected which are described as follows:

Red: Positive Excitation of 2500 millivolt to 5000 millivolt DC.

Black: Ground.

White: Positive signal.

Blue: Negative signal.

Section 4.3.4:   Wiring of Thermocouple

There are two wires required to be connected to the thermocouple and the thermocouple should use the cold junction thermocouple in the DAQ or utilize an outer thermistor.

Section 4.4:   Data Acquisition System and Software

This sensor is compatible with any data acquisition system that can provide voltage and temperature reading. It was tested with MicroStrain, National Instrument and Campbell Scientific DAQs. Since the DAQ used for installation on the bridge was Campbell Scientific, it will be described in detail. The DAQ system on the bridge includes four devices: 1) Battery (PS100), 2) Data logger (CR10x), 3) Multiplexer (AM16/32), and 4) Network Link Interface (NL201) which connected the system to a network where the data were sent to the receiving computer. Loggernet software, a product provided by Campbell Scientific, was utilized for collecting data at user specified interval at the receiving server computer.

The Data Logger needs to be programmed prior to any measurement. The language that is used depends on the logger. For the CR10x, Edlog language was used, while for the CR1000 CRBasic language

was used. The program includes the algorithm for converting the voltage and temperature readings into state output. The initial parameters for the algorithm are: voltage less than 17 mVolt – the state is dry; voltage between 17 mV and 1700 mVolt and the temperature is 32degF or below – the state is ice; and for the same voltage range with temperature above 32 deg F or voltage greater than 1700 mV – the state is wet. This algorithm is based on 2500 mVolt excitation. It is possible to fine tune the senor to detect slush, but since the object is to detect the layer of water beneath the ice, there is no need to, Appendix H includes the Edlog Program used for the CR10x Logger to read one state sensor, while Appendix I includes CRBasic program used for CR1000 since it was utilized for some indoor experiments.

As part of the outdoor experiments, a monitoring system was designed and built at the University of Toledo to display the data from the sensors, including the UT Ice Presence and State sensor, and plot them. Figure 4.4 is a screenshot for the state sensor result on the UT monitoring system. More details can be found at Abdelaal, 2016.

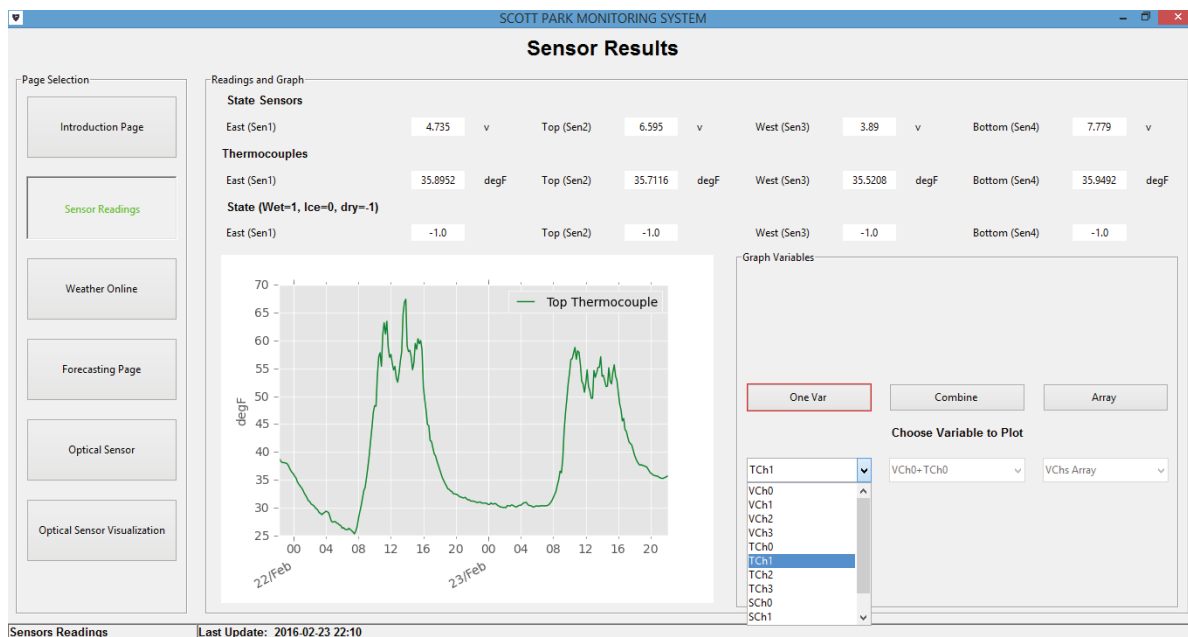**Figure 4.4 Screenshot for the State sensor page for UT Monitoring System.**

Section 4.5:   Data Output

There are three outputs from the sensor: voltage, temperature, and state. The state is calculated from an algorithm based on the voltage and temperature reading. The user will be able to read the state from looking at the state graph. Figure 4.5 and Figure 4.6 show sample outputs from the sensor.
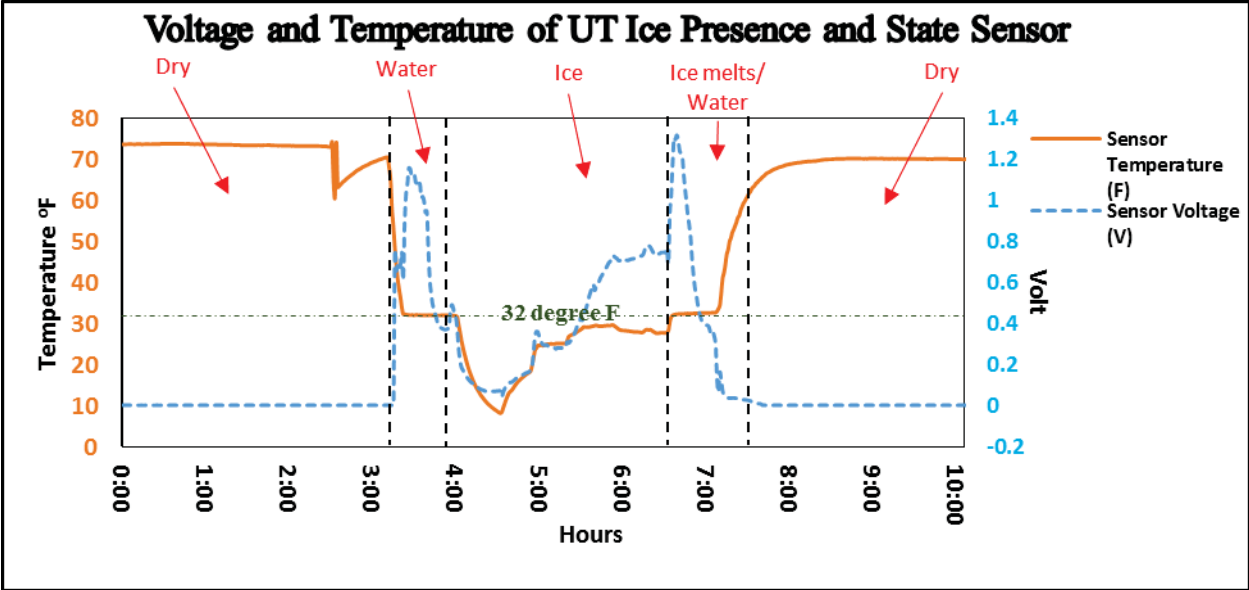
Figure 4.5 Voltage and Temperature readings of the sensor.
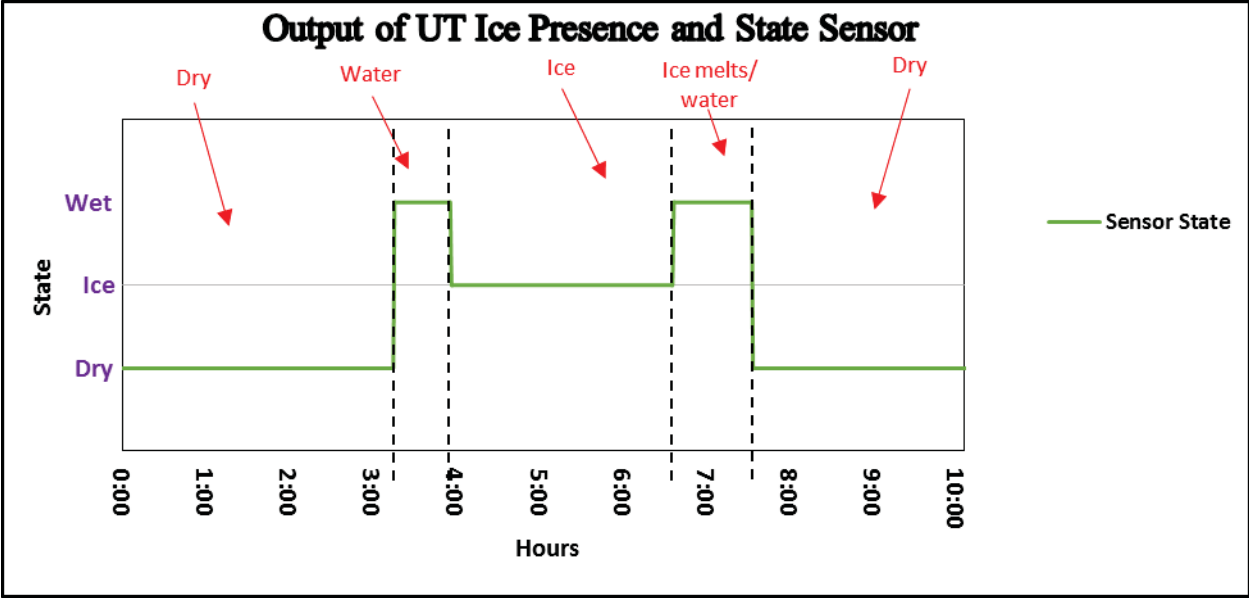
Figure 4.6 State output of the sensor.

Section 4.6: Specifications

Power: 2500 mVDC to 5000 mVDC

Output: 0 to 2500 mVDC when excitation is 2500 mV DC

Operating temperature: -30 $^\circ$C to 55 $^\circ$C

Dimensions of the sensing pad: 25 mm x 19mm x 0.6 mm

Accuracy: Detecting water beneath the ice layer 100% in laboratory trials, No ice of sufficient thickness collected during the field trials on the bridge. Detecting ice or water on the stay surface 90 -98%

Section 4.7: Life expectancy

The life expectancy of Presence and State Sensor is greater than five years. They have been field and laboratory tested and none have failed.

Section 4.8: Source and Replacement Parts

This sensor is custom built and is not commercially available.

Section 4.9: References

Abdelaal, Ahmed 2016, "Atmospheric Icing on Bridge Stays", Ph.D. Dissertation, University of Toledo, December.

Byanjankar, Manil, "Testing of New Ice Presence and State Sensor on Above Deck Structure of a Bridge", MS Thesis University of Toledo, August.

Omega 2016, Surface Thermocouple with Self-Adhesive Backing, http://www.omega.com/pptst/SA1.htm

Chapter 5: Operation Manual for UT Optical thickness Sensor

Section 5.1: Introduction

This technical manual provides operation information for the UT Optical Thickness Sensor. The aim of this sensor is to measure the thickness of ice, snow, or any object covering the bridge stays. The sensor consists of three components: IP camera, laser with line configuration, and optical filter match with the wave length of the laser. The IP camera is a camera with its own internet address that is configured to automatically move images over the internet. Three software programs were generated utilizing Python language for capturing images, calibration process, and to visually and computationally measure the thickness. The programs are named "Take Image", "Calibration" and "Optical Sensor" respectively.

Details of the design and field and laboratory testing are in Byanjankar (2016) and Abdelaal (2016)

Section 5.2: Theory of operation

This sensor is based on image processing where the camera is used in capturing image indicating the position of the laser line on the stay. Before conducting any measurement, a calibration procedure must be carried out which involves the comparison of two images, namely the "base image" and the "known thickness image". The base image represents the image of the laser line on the bare stay, while the known thickness image represents image of the laser line on an object of known thickness on the stay. The calibration process will be performed using the calibration software which will result in a scale for the number of pixels per unit length. This scale will be used in determining the thickness through the images in the Optical Sensor software where the images are obtained using the IP camera. The base image and the known thickness image are captured through Take Image software which will be discussed in a later section.

Section 5.3: Installation

The optical filter should be installed in front of the camera lens. The filter should pass the wave length of the laser which is used. For safety reasons, the fan angle of the laser should be selected so that the laser beam will not be projected out off of the stay. The larger the fan angle, the wider the laser line will be. The camera lens should be directed to the laser line where the angle between the camera lens and the position of the laser line should not be less than 20 degrees, and the maximum angle should not exceed 80 degrees. The larger the angle of inclination, the greater the scale will be, which will lead to higher resolution results. Figure 5.1 shows the sensor installation on the bridge

Figure 5.1 UT Optical Sensor Installation on VGCS Bridge.

Section 5.4:   Programs

Three programs were created for the Optical Thickness Sensor:

Take Image: which is used in taking fixed images such as the base image and the known thickness image

Calibration: which was designed for inputting the system configuration, such, as laser type, known thickness length, radius of the stay, and image properties, in addition to conducting the calibration process.

Optical thickness sensor: displays the thickness visually in two different ways which are called the "replicated grid" and the "cylindrical grid", in addition to displaying the measurements that are conducted at different angles and plots them with respect to time for the past 48 hours. The replicated grid is a 2D planar representation of the ice thickness on the stay. While the cylindrical grid displays the ice thickness on a cylindrical grid similar to the stay surface.

Each one of these programs will be described in detail in the following section.

Section 5.4.1:   Take Image v 1.1

This program is used in taking still image from the IP camera. The program was coded using Python software, then it was turned into executable files. The user will need to install the software in any directory through the windows installer. The Take Image executable in the file directory is shown in

Figure **5.2**. In the same directory, a .dat file called "CameraURL.dat" should be created, which include the url for the camera that is used. The url for the camera on the bridge will be in the following format: http://192.168.1.108 /video1.jpg?1?user=Admin&pwd=1234, where 192.168.1.108 represents the IP address of the camera, user=Admin represents the user name, and pwd=1234 represents the password of the camera. A shortcut for the program will be created on the desktop. By double clicking on the software, the image will be captured which will be named " originali" beside time stamp such as "Originali20160602140650" which is in the format of "yyyymmddhhMMss" where yyyy is year, mm is month, dd is day, hh is hour, MM minute, and ss is second. A screenshot of the Take Image exe file and the image taken in the file directory is shown in

Figure 5.3 and Figure 5.4

Figure 5.2 Windows installer for Take Image software.

Figure 5.3 Screenshot for the exe file generated.

Figure 5.4 Screenshot for the Image taken.

Section 5.4.2:   Calibration v 1.2

Similar to the Take Image program, the Calibration program was coded using Python and the program was converted to an executable file which can be installed using the windows installer which is shown in Figure 5.5. After installation in C drive or in a selected directory, a shortcut of the desktop will be generated as shown in Figure 5.6.

Figure 5.5 Windows installer for Calibration software

Double clicking the shortcut icon or the exe file in the directory of installation will start the calibration process. The Photo Configuration page will be opened as shown in Figure 5.7 which includes three sub frames, i.e., Laser Type frame, Lengths frame, and Image Setup frame.

Figure 5.6 Shortcut for the Calibration software.

Figure 5.7 Photo Configuration Page of the Calibration program.

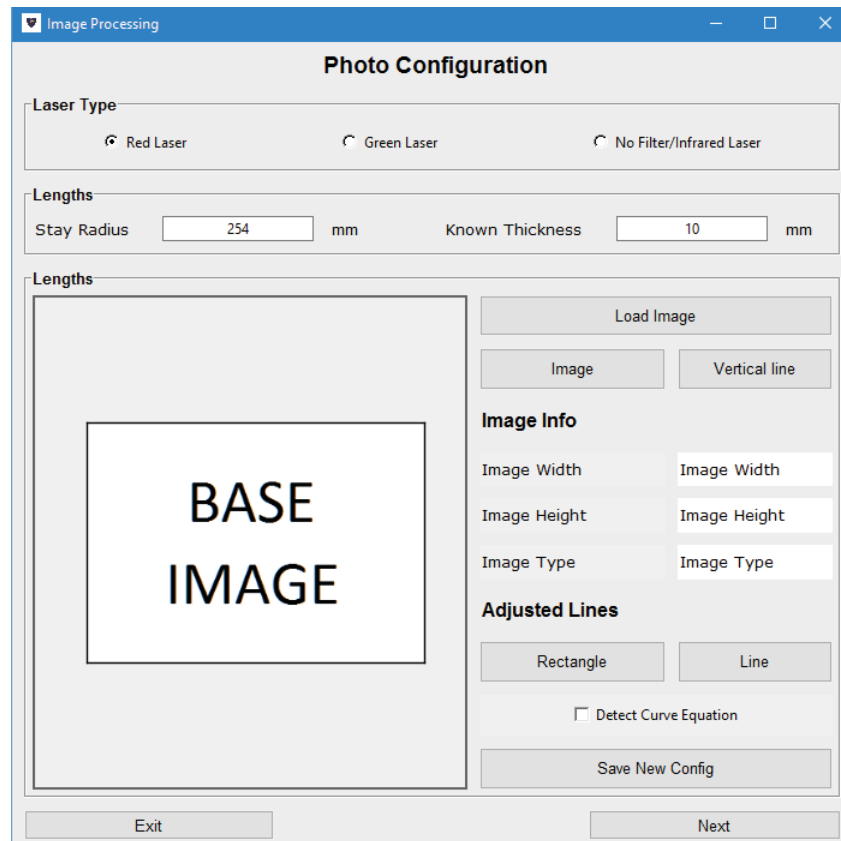The Laser Type frame allows user to select the type of laser that is used, whether it is Red, Green, or Infrared. Each one of these choices changes the algorithm inside the software based on the laser type. The Lengths frame has two text boxes where the user will input the radius of the stay and the thickness of the object used in calibration default values shown in the figure.

Finally, the Image Setup frame is used in analyzing the image that will be uploaded by the user. The user can upload the image by clicking on "Load image" button which will open browsing options. Once the image is selected, it will be shown in the left hand frame in the base image box and the image information (width, height, and type) will be displayed. "Image" button will display the image, while "Vertical line" button will draw line on the highest point of the laser line.

The "adjusted line" are lines that allow user to interact with images for better calibration results. The "Rectangle" button allows user to draw rectangle inside the image where the user will enclose the area that the laser line exists, which will create a curve following the laser line projection on the stay. The "Line" button allows the user to change the vertical line position if the user sees that the original vertical line is not on the position of the highest laser point. Before saving the new configuration, the "Detect Curve Equation" check box needs to be checked, then the "Save New Config" button will be clicked. The Base Image is the image that is used for configuration. Then, the "Next" button will be clicked to move to the Main Calibration page.

The Calibration Process page has three frames, i.e., Base Photo, Known Thickness Photo, and Calibration Photo as shown in Figure 5.8.
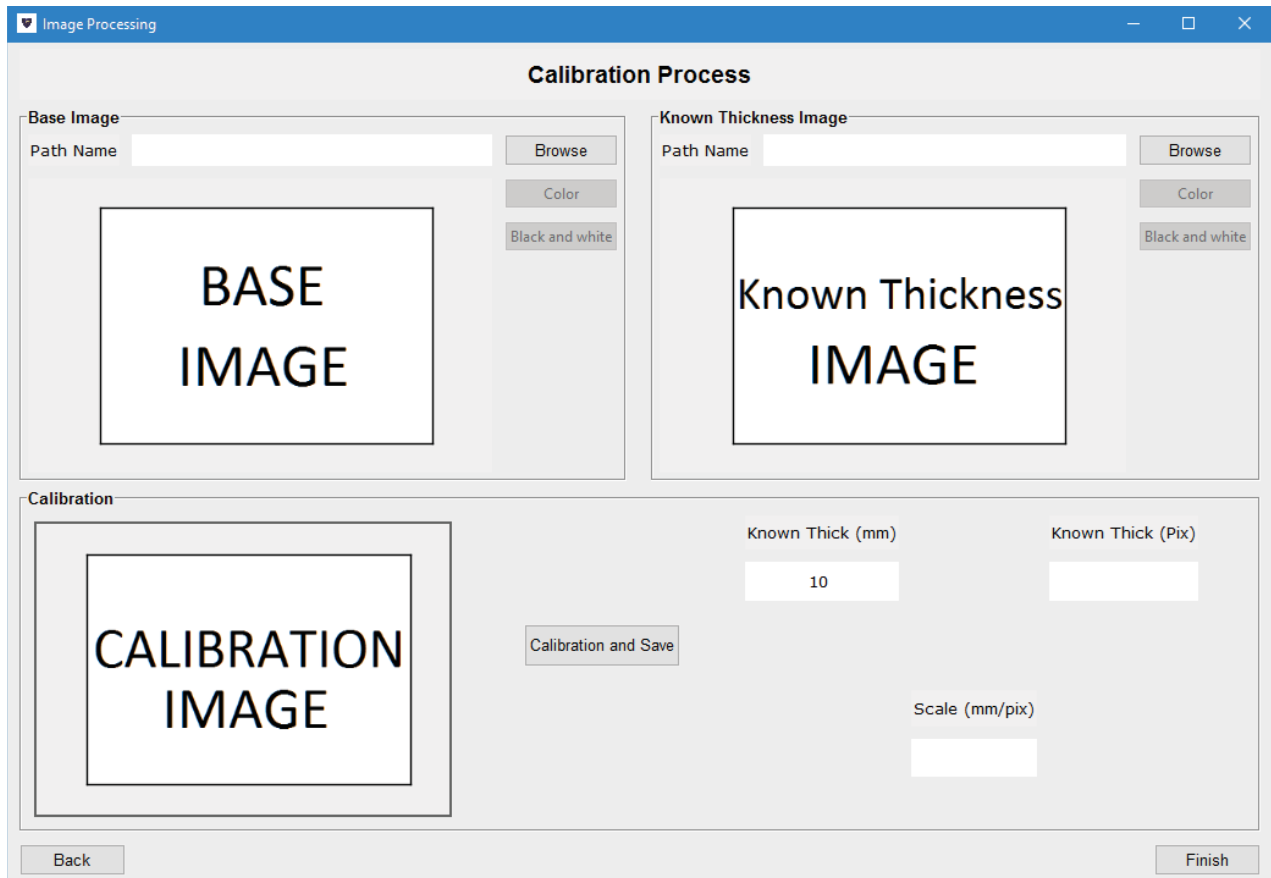
Figure 5.8 Screenshot of the Calibration Process Page

In order to conduct the calibration calculations, the user will need to select a base image through the "Browse" button in the base image frame and, similarly, select the known thickness image using the "Browse" button in the known thickness image frame. In both frames, the user can display the image in 3D color or in 2D black and white to ensure that the laser line appears clearly in the image without noise. Then, the user will click "Calibration and Save" button to perform the calibration process and save the result. Finally, click the "Finish" button to close the program, or click the "Back" button to return to the previous page to start the calibration process from the beginning.

This process will result in a folder called Configuration which contains calibration files, base image and known thickness image properties, and setup files. This folder will be copied to the directory where the Optical Sensor software is installed.

Section 5.4.3:   Optical Sensor v 1.2

Similarly, the Optical sensor program was coded using Python and was converted to executable file that can be installed to the computer using windows installer as shown in Figure 5.9. The installer can be installed in directory on the C drive, or according to the user's choice. The installation will result in a shortcut on the Desktop as shown in Figure 5.10 . As mentioned in the calibration section, the Configuration folder will be copied to the directory of the Optical Sensor software.

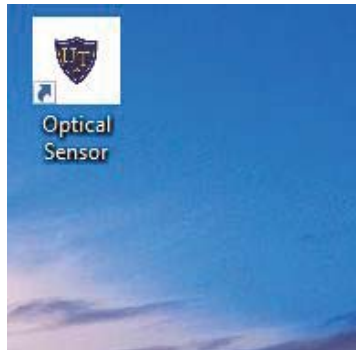**Figure 5.9 Windows installer for Optical Sensor software**

Figure 5.10 Shortcut for the Optical Sensor software as it appears on the desktop.

When starting the software by double clicking on the shortcut or the exe file in the installation directory, a login page will be initiated which will request the user to enter username and password as shown in Figure 5.11. The username for this software is: VGCS and the password is: skyway and both Username and Password are case sensitive.
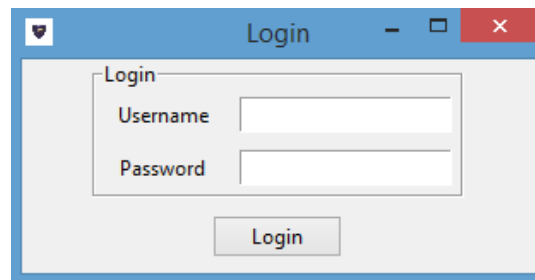
Figure 5.11 Login page to Optical sensor software.

Then, the Settings page will be displayed asking the user for the camera URL which is the IP camera address. The original collection interval was set to 10 minutes. A screenshot of the setting page is shown in Figure 5.12.
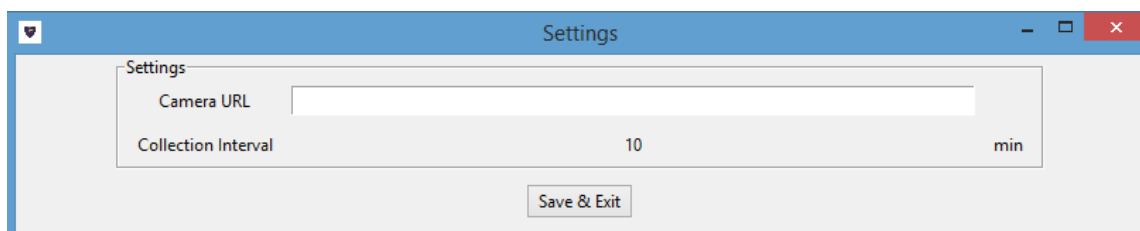
Figure 5.12 Settings page of the Optical Sensor software.

Once the user clicks the "Save & Exit" button on the Settings page, the Start page will appear. The Start page has four tabs on the left hand side as shown in

Figure **5.13** which shows the introduction page to the software. The second two buttons show the cylindrical grid and the replicated grid as shown in

Figure 5.14 and the last button shows the computed results of the thickness at different angle if available in addition to plotting them versus time for the last 48 hours as shown in

Figure 5.15. The user can choose to plot the thickness and any angle by using the drop down list beside the plotting figure.

Results will be saved in the "Result" folder with time stamp of the day in which measurement was conducted in the following format "Resultyyyymmdd". Three sub folders will exist inside the timestamp folder, i.e., a folder for the original image captured by the camera called "Original", a folder for the cylindrical grid image called "Cyl Grid", and a folder for the replicated grid images called "Rep Grid". In each of these three folders, images with timestamp for each reading are saved with the format "yyyymmddhhMM". In addition, an "Optical Thickness Result.dat" file is created inside the result folder including all the computed thickness measurements performed. The storage that is required for saving the result is approximately 1.5 to 2.0 Gigabytes per month. If the computer will not have enough space. it is recommended to back up the data onto an external hard drive.
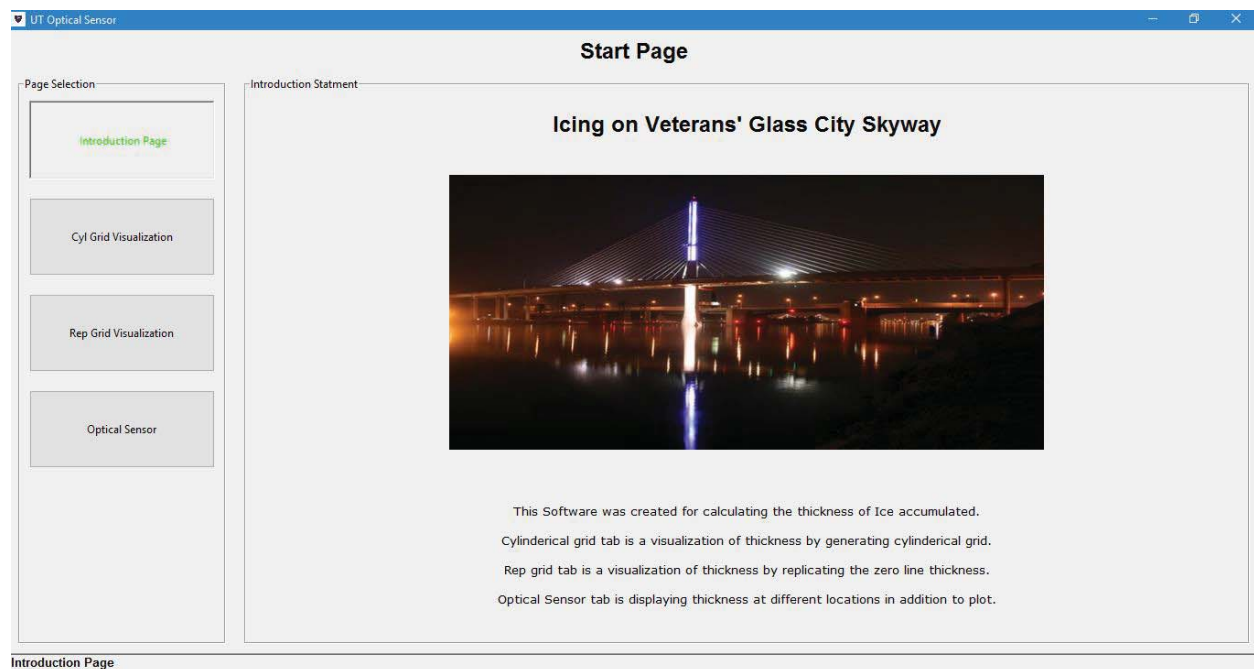

Figure 5.13 Start page for the Python Optical sensor software.
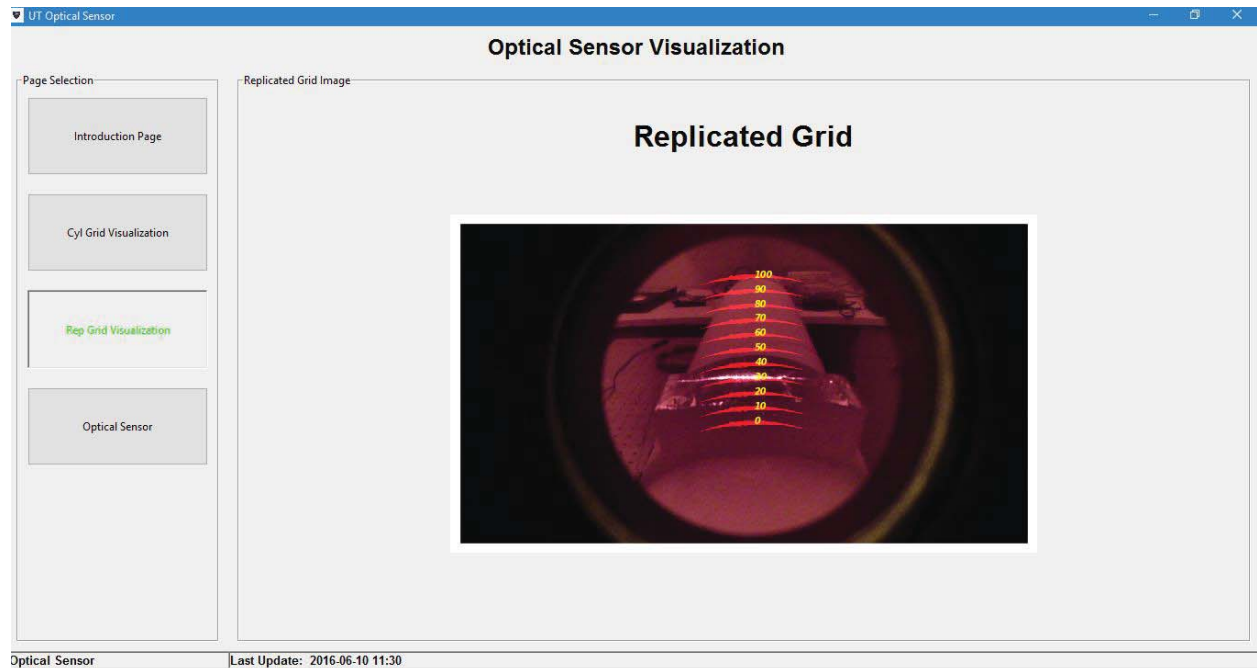
Figure 5.14 Replicated Grid page to the Python Optical sensor software.
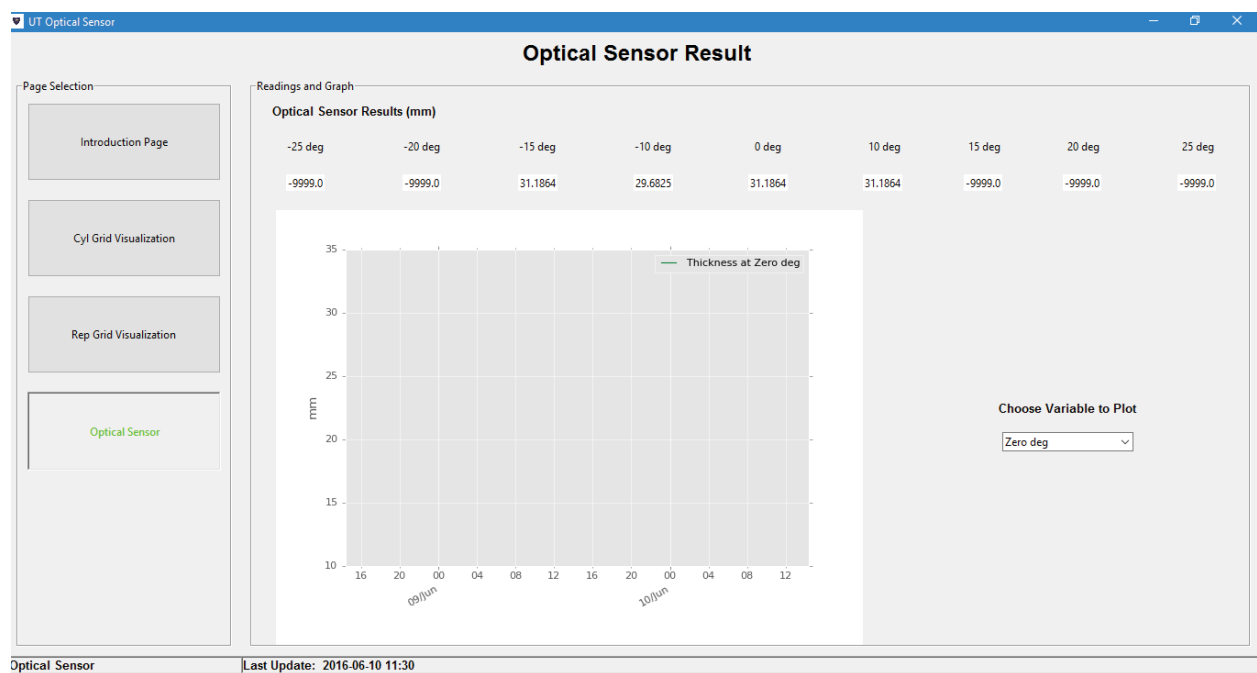
Figure 5.15 Optical Sensor Result page of the Python Optical sensor software.

Section 5.5:   Operation Summary

The steps of utilizing the UT Optical Thickness Sensor can be summarized as follows:

1- Base image and known thickness image should be obtained in the field by using the "Take Image" software. This requires a visit to the bridge.

2- The calibration process should be conducted through the "Calibration" software:

   a. Laser type is selected.

   b. Lengths are entered by the user.

   c. Base image is selected. If the camera and the laser are in installed in a way that the laser is perpendicular to the stay and camera are centered in the middle of the stay, then go to calibration. However, in the general case, use the adjusted rectangle to detect the laser line and generate the curve equation to be used in the cylinder grid, then save the new configuration and go to calibration.

   d. In the calibration window, select the base image and the known thickness image, then click the "Calibration and Save" button, then finish.

3- Copy the configuration file to the Optical Sensor software directory.

4- Run the "Optical Sensor" software:

   a. Enter the user name and password and press Login.

   b. Enter Camera URL and press Save and Exit.

   c. The software will start and run collect data at 10 minute intervals.

   d. Results will be saved in the result folder

   e. Close the program when finished.

Section 5.6:   Life expectancy

The life expectancy of Optical Sensor will be depend on the laser and camera life time. The laser that will be used should be designed to work in harsh conditions where it will be powered through power supply for continuous operation or to data logger for intermittent operation. Also, the camera that is used should be IP outdoor camera.

Section 5.7:   Source and Replacement Parts

This sensor is custom built and is not commercially available.

Section 5.8:   Recalibration

The camera should be recalibrated at least annually.

Section 5.9:   Initial User Name and Password

The username for the Optical Sensor program is "VGCS" and the password is "skyway" and both Username and Password are case sensitive. The Take Image and Calibration programs do not require a username or password.

Section 5.10:   Potential Hazards

Care should be taken that the laser light falls only on the stay. There is a hazard if a person looks into the laser beam.

Section 5.11:   References

Abdelaal, Ahmed 2016, "Atmospheric Icing on Bridge Stays", Ph.D. Dissertation, University of Toledo, December.

Byanjankar, Manil, "Testing of New Ice Presence and State Sensor on Above Deck Structure of a Bridge", MS Thesis University of Toledo, August.

Appendix A: System Architecture

The diagrams below show how the system is setup to collect and archive data, how the data is processed and how it is displayed to the users. It also shows the languages and tools used to accomplish these objectives.
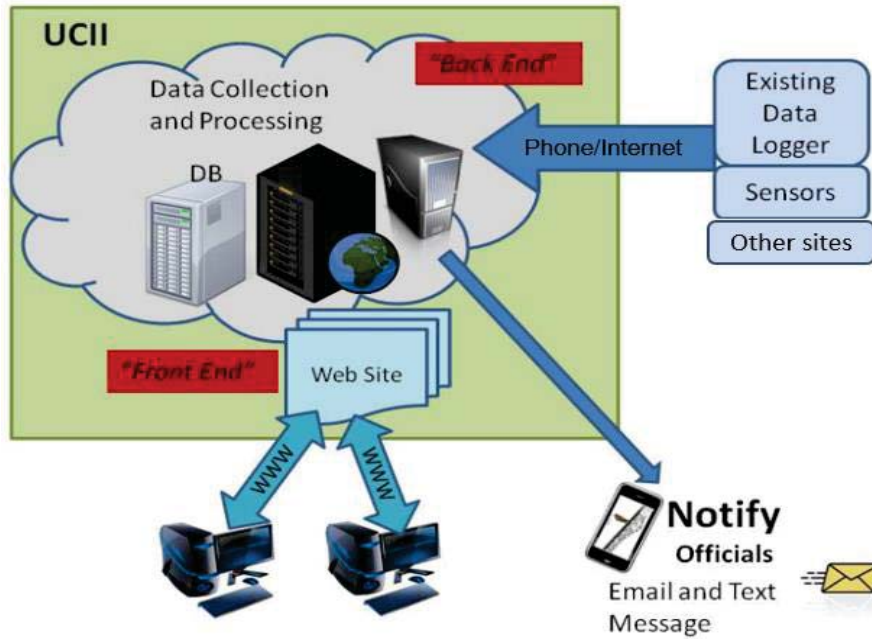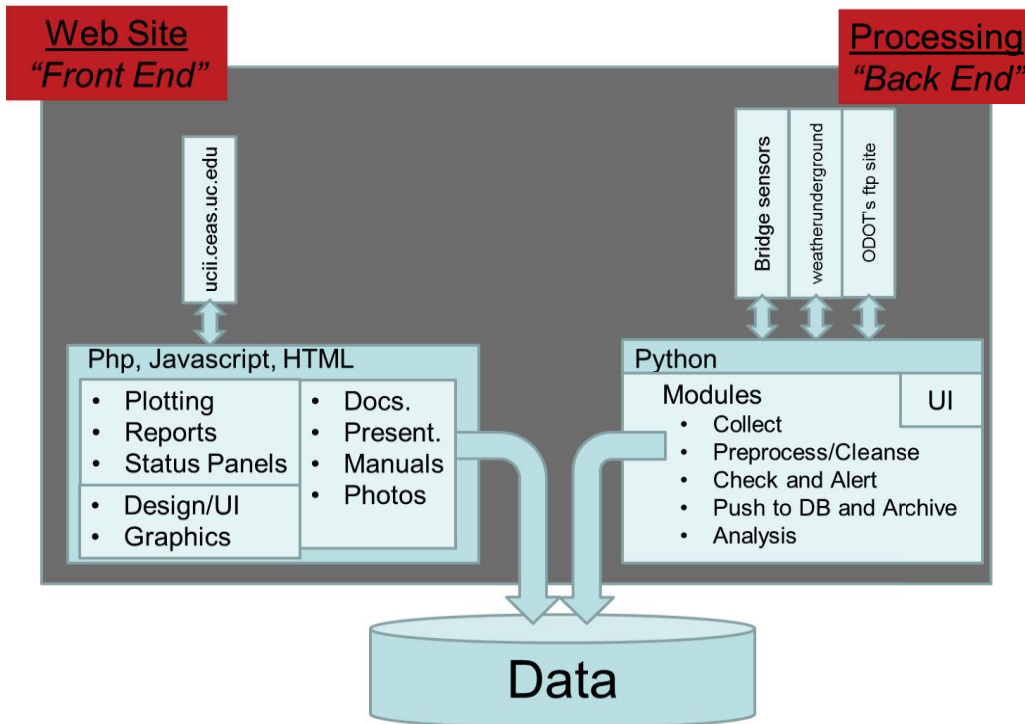

Figure A. 1: System Overview

Data from these stations are processed and stored in multiple tables in the database and their definitions and formats are explained in Section 2.3 on Data Collection and Storage which comes under Chapter 2 in the document "Continued Weather Monitoring System for the Veterans' Glass City Skyway".

Appendix B: Freezing Rain

Freezing rain is the name given to rain that falls when surface temperatures are below freezing. The raindrops become super cooled while passing through a sub-freezing layer of air, just above the surface, and then freeze upon impact with any object they encounter. The resulting ice can accumulate to a thickness of several centimeters. The METAR code for freezing rain is FZRA.

Freezing rain intensity is quantified by the equivalent radial thickness of the ice contained in the rain, i.e. the thickness of ice on a horizontal cylinder with its axis perpendicular to the wind direction. It was shown that for very less number of freezing rain occurrences (around 20%), the equivalent ice thickness in the rain was greater than 0.5cm. Therefore it is useful to study the number of freezing rain events occurring in the year along with the corresponding air/dew point temperature, wind speed and precipitation. A freezing rain event requires cold air below, warm air aloft, a high to hold the cold air in place, and precipitation of liquid water. The length of the icing event depends on how long the high pressure persists at a particular site.

Appendix C: Pictorial Representation of State Transition Algorithm

Ice event conditions that lead to ice shedding have historically been preempted by persistent ice accumulation over a period of hours. To determine if ice event conditions persist and to what extent required the development of a set of states and corresponding conditions for transition between states. The resulting states were also driven by the need to have a dial or speedometer style gauge on the dashboard where each state is a position on it. Figure C. 1 shows the dial when the conditions are pertinent to 'no ice' i.e. clear.
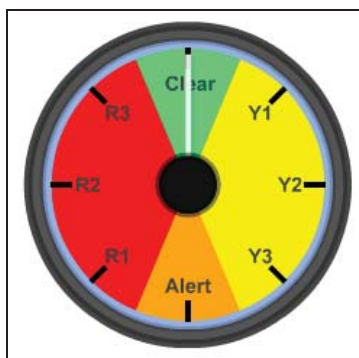

Figure C. 1: Dial for Ice States

The different states on the dial {C, Y1, Y2, Y3, A, R1, R2, R3}, shows different icing status, yellow(s) being the conditions when ice accumulation criteria are satisfied and red(s) being the conditions when ice fall

criteria are satisfied. C – No Ice, and A – Ice confirmed. Transitioning between states occur due to the current and the past weather conditions, the algorithm for which is explained below in three stages namely ice accumulation, ice presence, and ice fall.

Ice Accumulation

Transitions possible from the state 'Clear'

At start, the state is at 'C', i.e. no ice. From 'C', the states may go either to 'A' (if ODOT reports presence of ice) or Y1 (if the icing criteria are satisfied for the last hour). These two actions are done priority wise, the priority of 'A' being higher than that of 'Y1'. 'Y1' means icing is possible but the time for which ice accumulation criteria are met is very small. The state transition diagram is shown in the Figure C. 2.

Figure C. 2: State Transition from 'Clear'

Transitions possible from the state 'Yellow 1'

From 'Y1', the states may go either to 'A' (if ODOT reports presence of ice) or Y2 (if the icing criteria are satisfied for at least 6 of last 8 hours) or 'C' (if none of the above two conditions are satisfied and also icing criteria did not meet during the last hour). 'Y2 ' means icing is likely to happen. The state transition diagram is shown in the Figure C. 3.
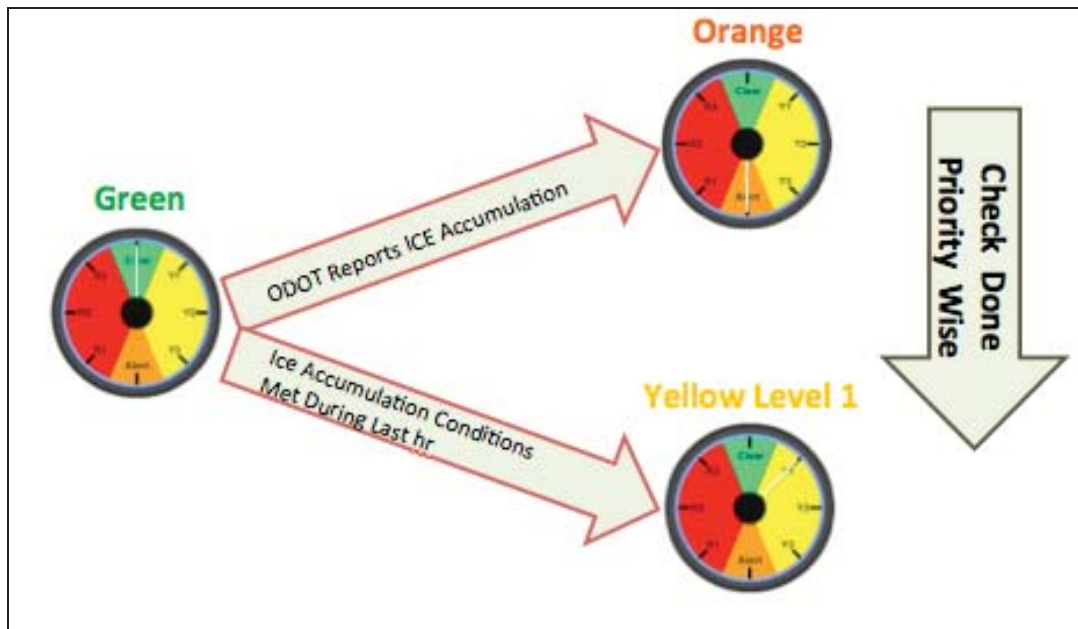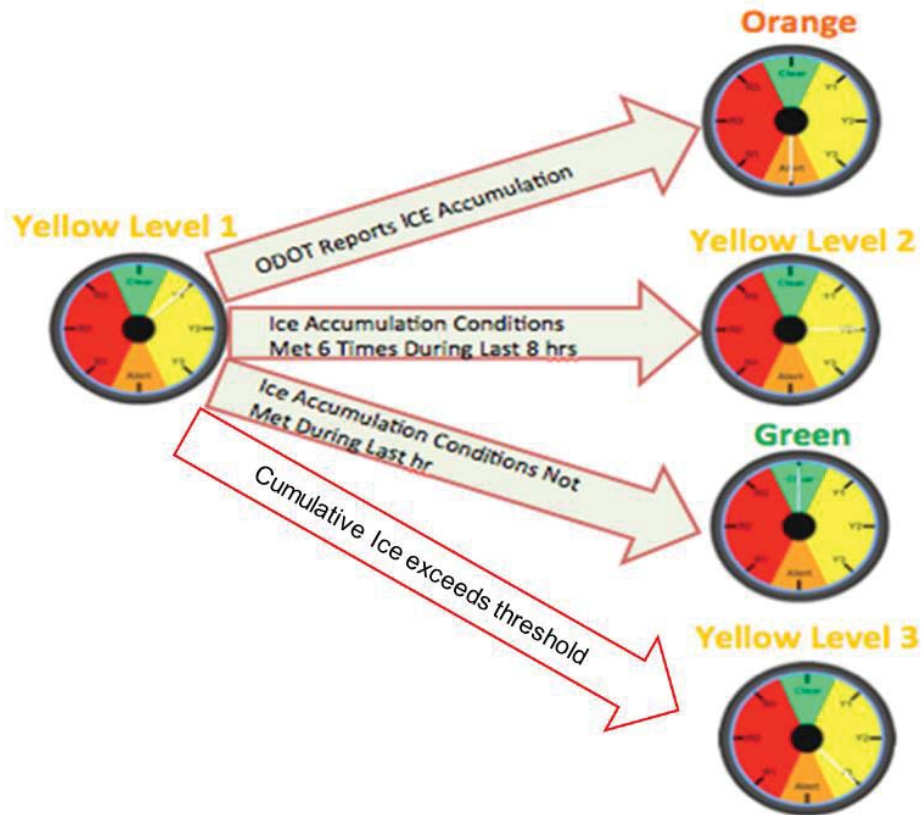
Figure C. 3: State Transition from 'Yellow 1'

Transitions possible from the state 'Yellow 2'

From 'Y2', the states may go either to 'A' (if ODOT reports presence of ice) or 'Y3' (if the icing criteria are satisfied for at least 8 of last 10 hours) or 'Y1' (if none of the above two conditions are satisfied and also icing criteria did not satisfy for Y2 state). 'Y3' means icing is very likely to happen and now a visual check must be done to confirm the presence of ice. The state transition diagram is shown in the Figure C. 4.
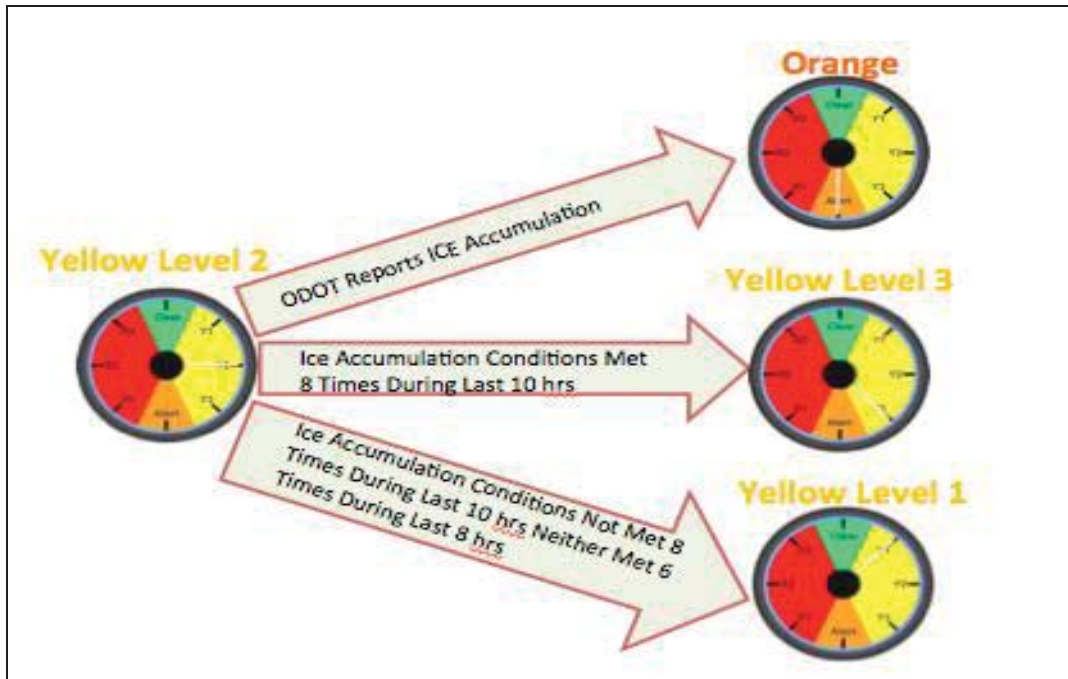
Figure C. 4: State Transitions from Yellow 2

Once Y3 state has been reached, the algorithm will take the following actions:

- No further transition until ODOT response is received.
- Send mail and text message to ODOT officials.
- Will keep sending alerts (mails/text) to ODOT until a response is received.
- ODOT is needed to sign onto the dashboard and provide response on actual icing condition at the bridge.

After the Y3 state is reached, the algorithm will wait for a response for ice presence. This led the algorithm to move to the next stage of the icing event process.

Ice Presence

At Y3, further states are determined by the response. If the response received says 'there is ice present on the stays', the state will move to 'A', which means ice is confirmed. If the response says 'there is no ice present on the stays', the state will move to 'Y1'. The state transition diagram is shown in the Figure C. 5.

There are two reasons behind why upon receiving a negative response, the state will move to Y1 and not C.

- Ice may present on the stays but it might not be enough to cause ice fall hazard. In that case, the response received may be negative but a smarter move is to assign Y1 as the new state in action to the response.
- In case of a mistake in submitting the response, assigning Y1 will take lesser time than 'C' to go to Y3 state, which is desirable.

95
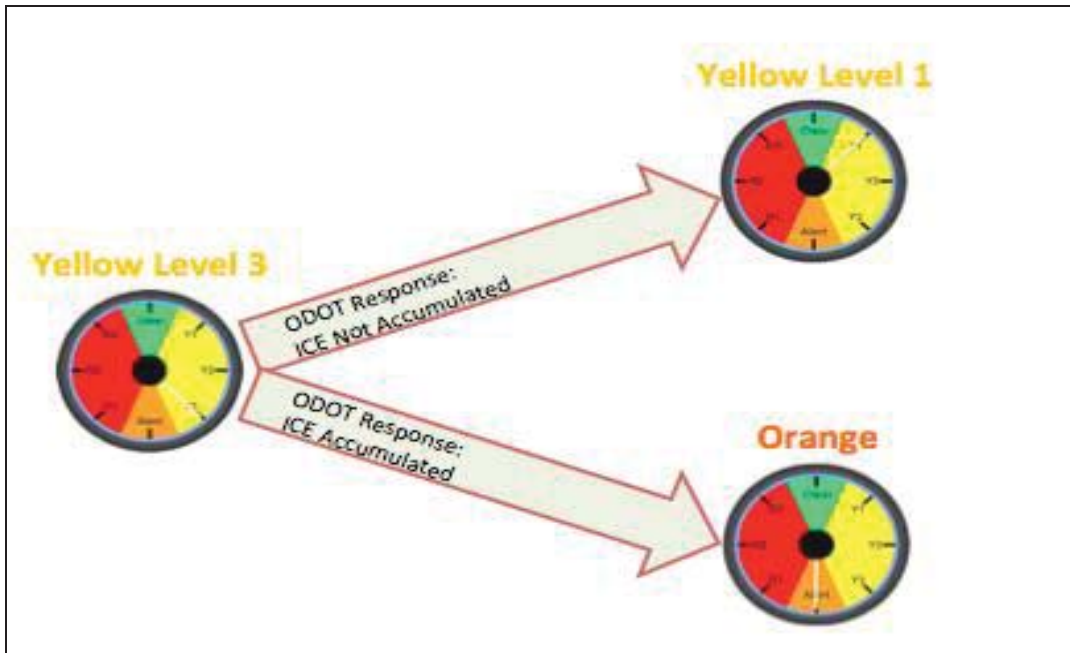
Figure C. 5: State Transition from Yellow 3

From here, we move to the last stage of the ice events, i.e. state transition algorithm for the Ice Fall process.

Ice Fall

Transitions possible from the state 'Alert'

From 'A', the states may go either to 'C' (if ODOT reports that there is no ice on the stays) or 'R1' (if the ice fall criteria are satisfied for the last hour). These two actions are done priority wise, the priority of 'C' being higher than that of 'R1'. 'R1' means ice fall is possible. The state transition diagram is shown in the Figure C. 6. Since the ice fall process is faster and more critical than the ice accumulation process, an alerting system is implemented at every state change. Therefore, if the ice fall criteria are met during the last hour, the state will be changed from A to R1, and also e-mails and text messages are sent to the ODOT officials notifying about the weather and the states.
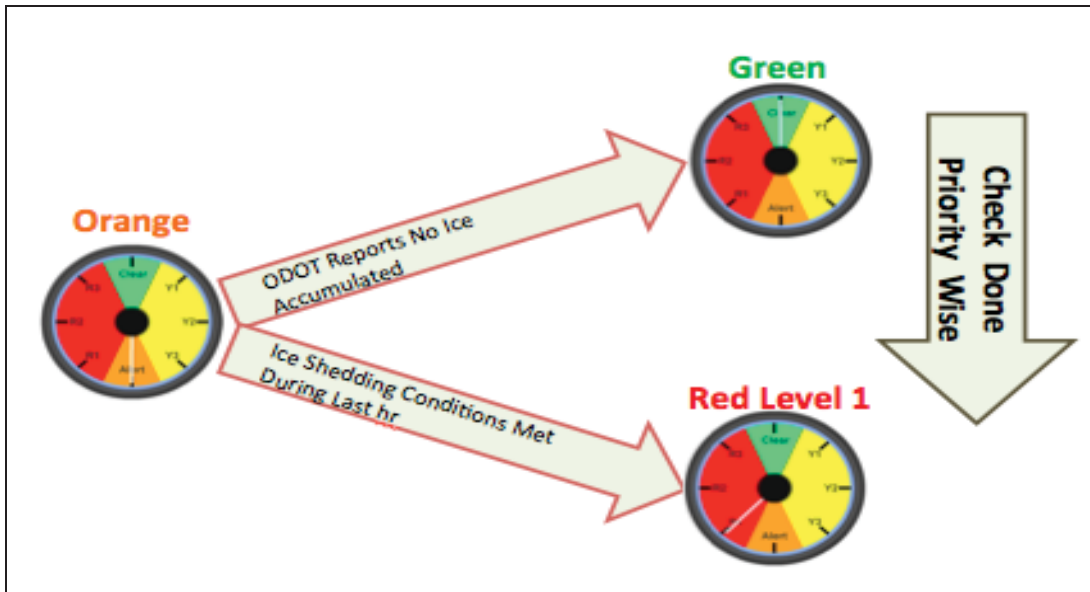
Figure C. 6: State Transition from Alert

Transitions possible from the state 'Red 1'

From 'R1', the states may go either to 'C' (if ODOT reports no presence of ice) or 'R2' (if the ice fall criteria are satisfied for the last hour) or 'A' (if none of the above two conditions are satisfied). 'R2' means ice fall is likely to happen. The state transition diagram is shown in the Figure C. 7.

Figure C. 7: State Transition from Red 1

From 'R2', the states may go either to 'C' (if ODOT reports no presence of ice) or 'R3' (if the ice fall criteria are satisfied for the last hour) or 'R1' (if none of the above two conditions are satisfied). 'R3' means ice fall is very likely to happen. The state transition diagram is shown in the Figure C. 8.
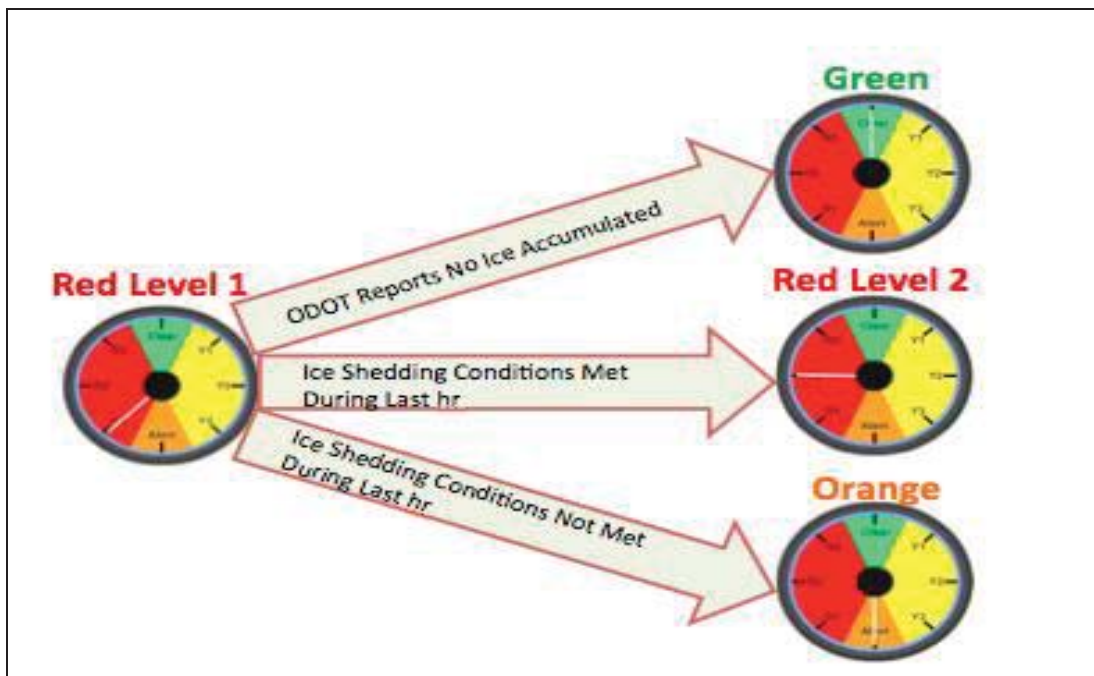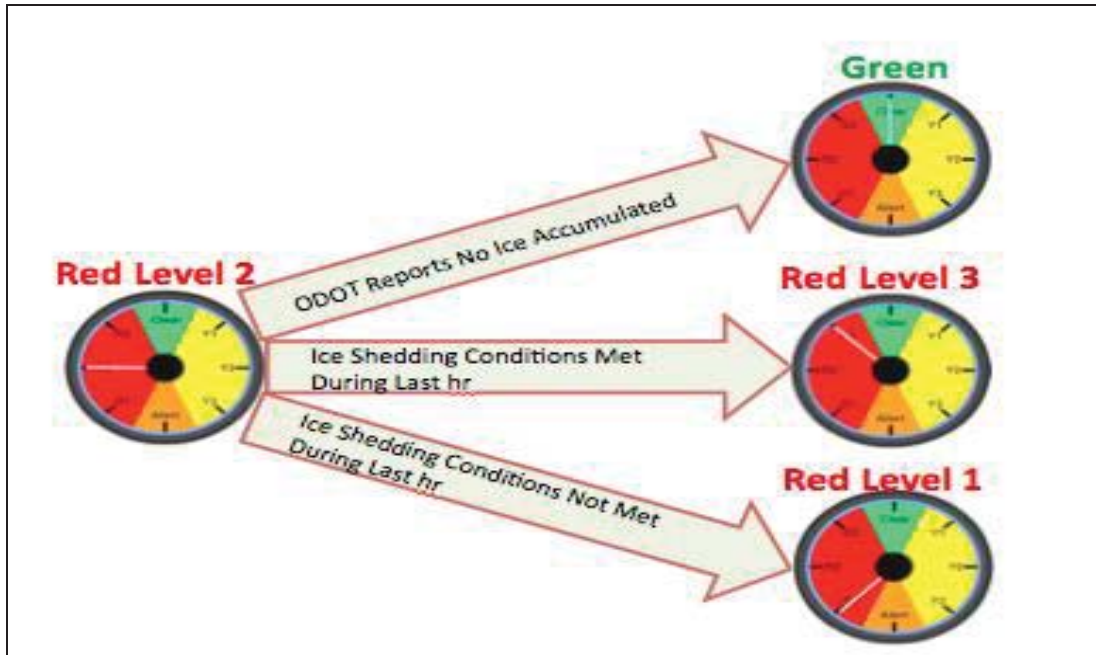

Figure C. 8: State Transition from Red 2

Once R3 state has been reached, the algorithm will take the following actions:

- No further transition until ODOT response is received.
- Send mail and text message to ODOT officials.
- Will keep sending alerts (mails/text) to ODOT until a response is received.
- ODOT is needed to sign onto the dashboard and provide response on actual icing condition at the bridge.

As shown in [Figure C. 9], after the R3 state is reached, the algorithm will wait for a response. If the response received is "no ice present on the stays", the state will change to 'C' and if the response received is "ice present on the stays", the state will change to 'A'.
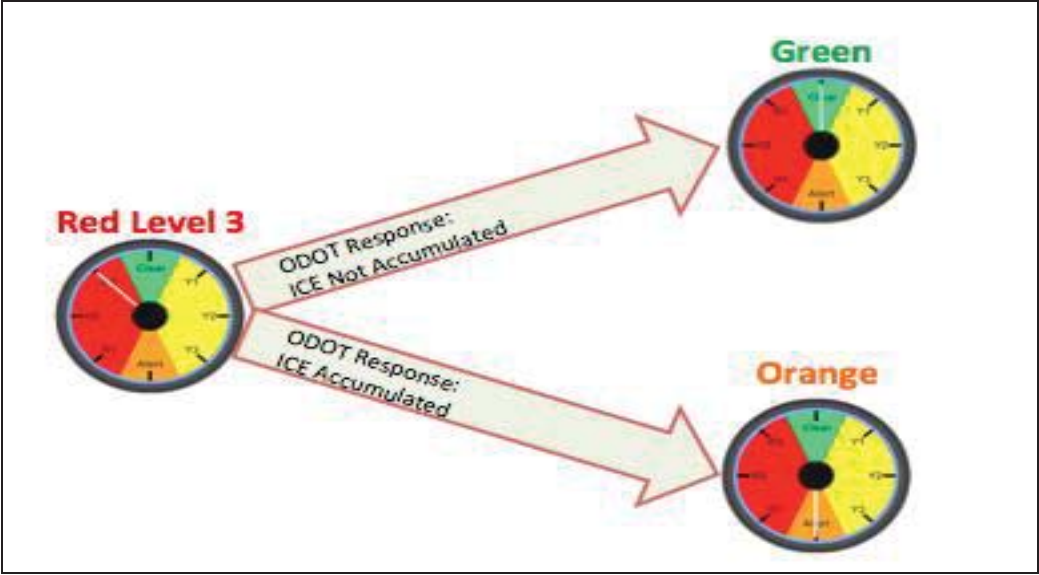
Figure C. 9: State transition from Red 3

This completes the complete cycle of all the states used in the algorithm.

Appendix D: Weather Map Documentation

Google Maps: A brief on API

Google Maps is a free web mapping service provided by Google, which offers street level maps for pedestrians, cars, and public transportation. It has an extendable API (Application Programming Interface) that can be used to develop custom Google Maps based applications. The Google map on the dashboard is used as an interface to provide the details about the various sites being monitored for determining the icing conditions at VGCS. It also contains the location of various sites, their past/current weather conditions along with a few reference links.

Structure of Weather Map

This document will walk through the working of the Google map on the dashboard. Once the accordion labeled "Map (Weather Data by Location)" on the dashboard is clicked, a Google map will open which has ten markers on it. Attached below is a screenshot of the map with all the markers labeled.
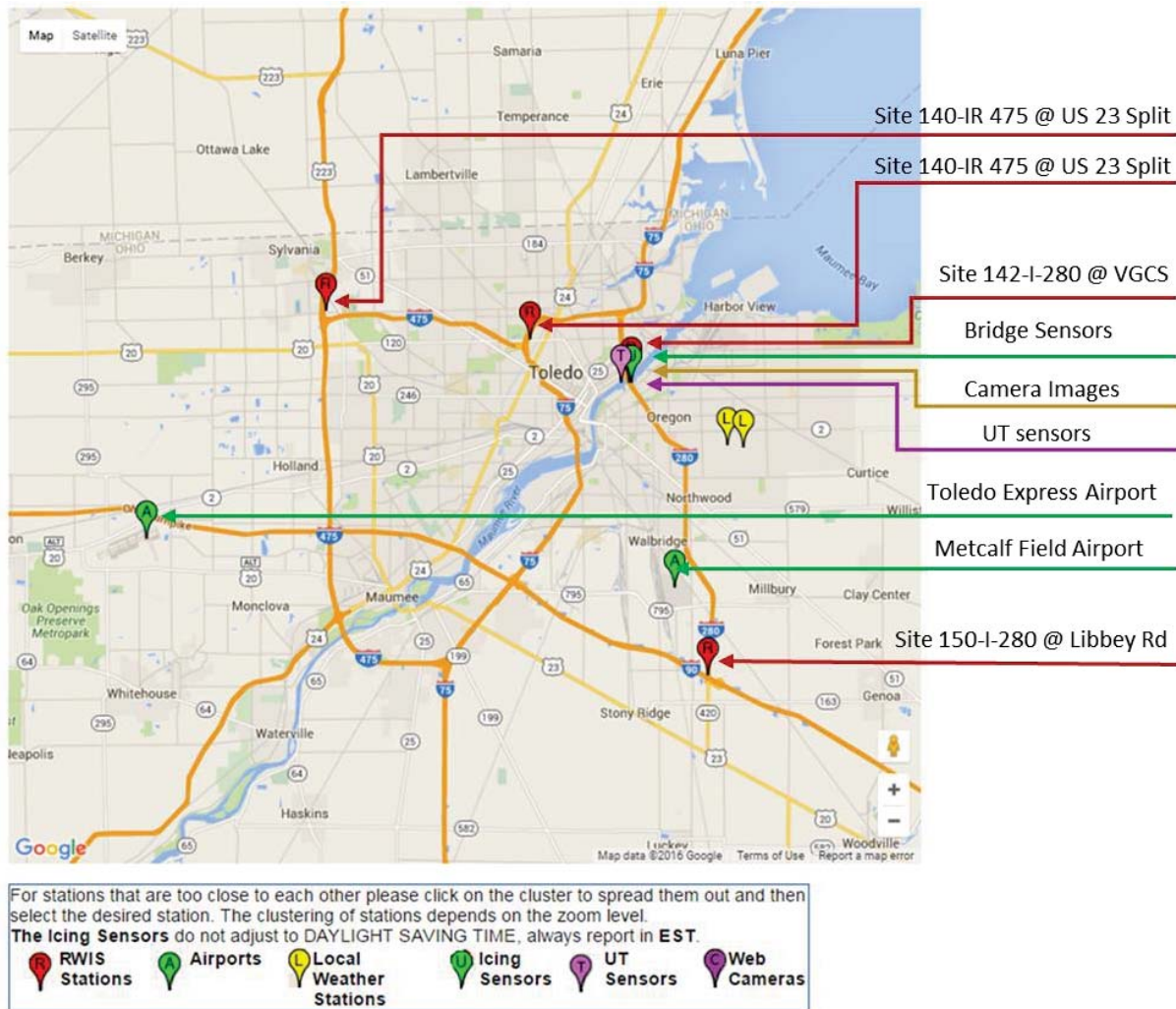
Figure D. 1: Weather Map

- There are two green markers written 'A' on it. These are the two Airports namely KTOL (Toledo Express Airport) and KTDZ (Metcalf Field Airport) whose weather data are being monitored by the dashboard.
- There are four red markers written 'R' on it. These are the four RWIS stations namely Site 140-IR 475 @ US 23 Split, Site 141-IR 75 @ SLM 4.9 475 Split, Site 142-I-280 @ Veterans Glass City Skyway, and Site 150-I-280 @ Libbey Rd whose weather data are being monitored by the dashboard.
- There are three yellow markers written 'L' on it. These are the local weather stations near to the VGCS Bridge. They are: East Toledo, Oregon. These are not considered in the algorithm.
- The pink marker is the link to the live cameras installed on VGCS.

RWIS Stations

Red markers on the map represent RWIS stations. On clicking them, an information box will be popped up that contains the weather station information, station id, current weather conditions and last 48

hours graphs to atmospheric and surface weather readings. Attached is the screenshot for the same for Site-140.

Figure D. 2: Typical RWIS Measurement

Clicking the "Buckeye Traffic Readings" link on the information window opens up a new window having the weather reading from http://www.buckeyetraffic.org/
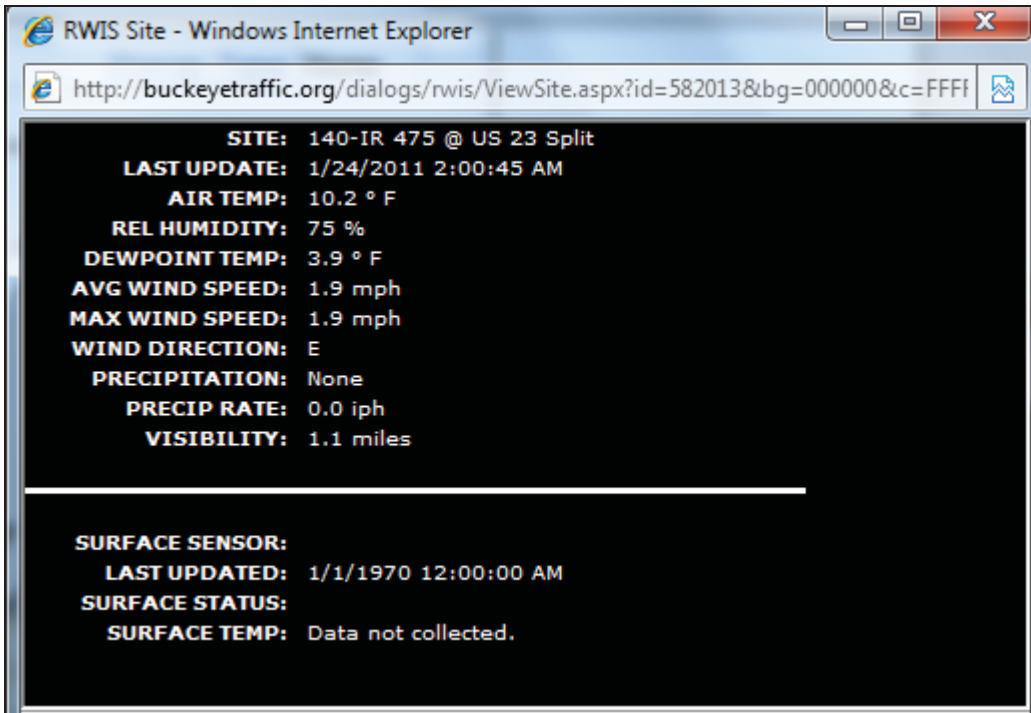
Figure D. 3: Buckeye Traffic Reading

Clicking all other links on the information window opens up a new window having the last 48 hours weather readings. Below is an example for last 48 hours plot for the parameter 'Air Temperature'. The 'Export' button will export the Air Temperature data for the last 48 hours into the excel sheet.
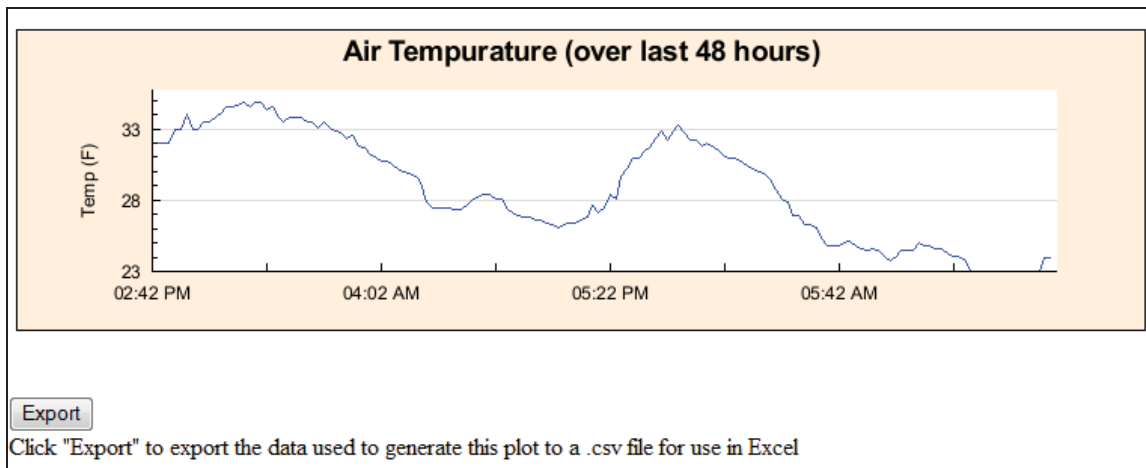
Figure D. 4: Air Temperature Plot

There are 185 RWIS stations in Ohio, out of which four stations were chosen to determine the Icing conditions of VGCS Bridge as they were the nearest to the bridge.

- Site 140-IR 475 @ US 23 Split – This weather station is 11.3 miles from the Veteran Skyway Bridge.

- Site 141-IR 75 @ SLM 4.9 475 Split – This weather station is 5.2 miles from the Veteran Skyway Bridge.
- Site 142-I-280 @ Veterans Glass City Skyway – This weather station is 0 miles from the Veteran Skyway Bridge.
- Site 150-I-280 @ Libbey Rd – This weather station is 10.1 miles from the Veteran Skyway Bridge.

* All the distances are aerial distance.

Data Source

The weather information for all these four RWIS stations is taken from ODOT ftp site ftp.dot.state.oh.us and the data is getting updated every 10 minutes. Current weather conditions and the details of sensor installed at these RWIS sites which are recording atmospheric and surface weather readings can be seen at: http://www.ohgo.com/Dashboard/toledo

Also the location of these RWIS sites can be seen at the same link.

Airports

Green markers on the map represent nearby airports. On clicking them, an information box will be popped up that contains the current METAR report, plots of last 24 hours METAR reports and WIKI references to METAR & PIREP.

The two nearest airports are chosen to determine the Icing conditions of VGCS Bridge:

- Toledo Express Airport – This airport is 9.1 miles from the Veteran Skyway Bridge.
- Metcalf Field Airport – This airport is 6.2 miles from the Veteran Skyway Bridge.

* All the distances are aerial distance.

Attached is the screenshot for the same for the airport 'KTOL'.
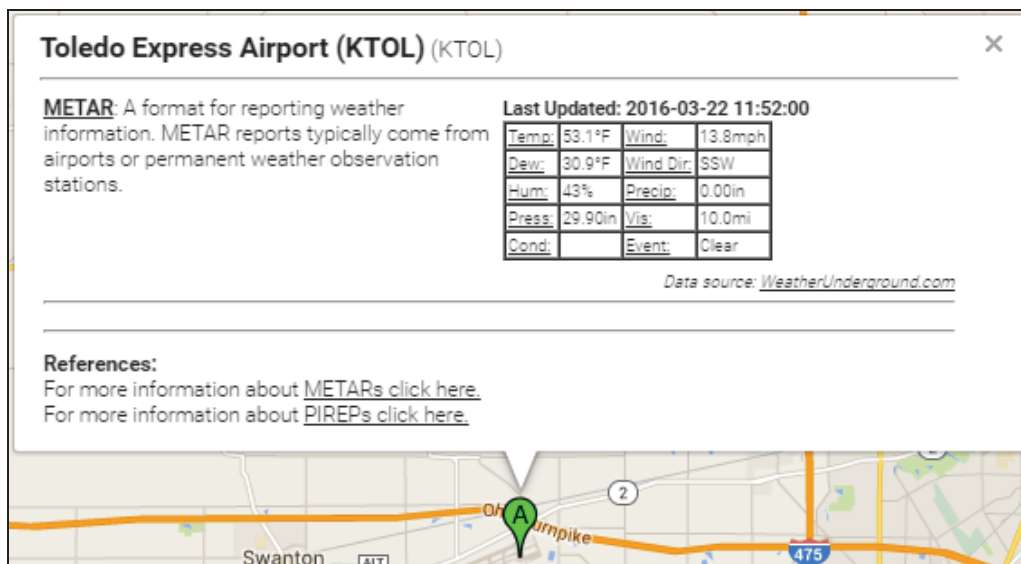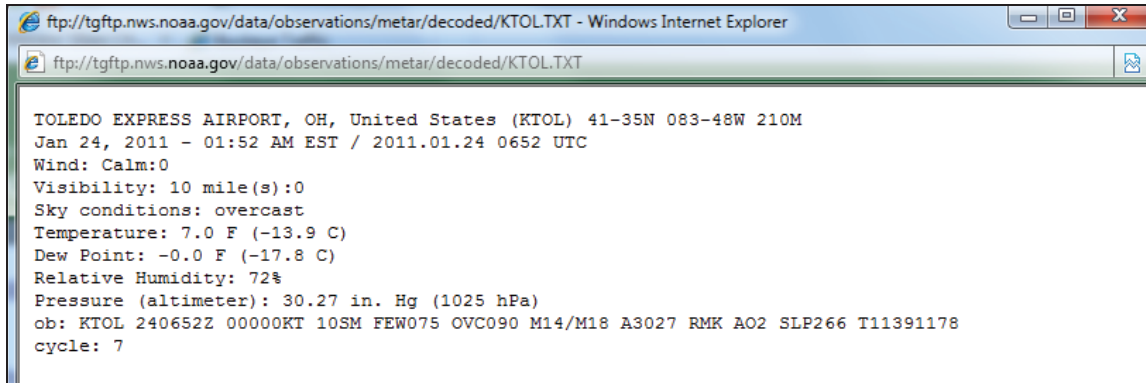
Figure D. 5: Typical Airport Reading

Clicking the "METAR" link on the information window opens up a new window having the current METAR reading from: ftp://tgftp.nws.noaa.gov/data/observations/metar/decoded/KTOL.TXT

Data Source

METAR: Specially encoded weather observation report, which is predominantly used by meteorologists to assist in weather forecasting. METAR reports are typically generated once an hour. METAR data information in the dashboard is taken from the link:

http://www.wunderground.com/history/airport/KTOL/2011/05/13/DailyHistory.html?format=1

http://www.wunderground.com/history/airport/KTDZ/2011/05/13/DailyHistory.html?format=1

Local Weather Stations

Yellow markers on the map represent nearby weather stations. On clicking them, an information box will be popped up that contains the weather information at the local station. Attached below is the screenshot for the local weather station: East Toledo.
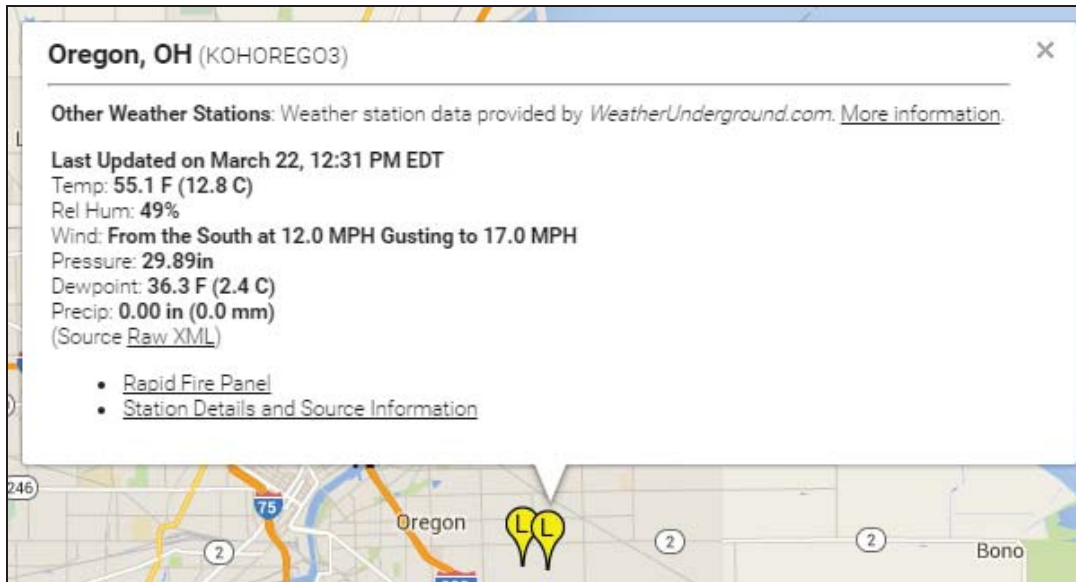
Figure D. 6: Local Weather Reading

Clicking the "Rapid Fire Panel" link opens up a new window having the weather information from: https://www.wunderground.com/weatherstation/

Clicking the "More information" link opens up a new window having the weather information from: http://www.wunderground.com/weatherstation

Figure D. 7: History Section for Local Station

Data Source

The data source of all the local weather station is:

http://www.wunderground.com/weatherstation/

The weather data from this link is updated generally every 10 minutes but it's varies.

Live Camera

Pink markers on the map represent link to the four live cameras installed at the Veteran Skyway Bridge. Clicking on any will get the live view with the images getting refreshed every five seconds. Attached is the screenshot for the same. The sources of these images can be found at

http://cmhimg01.dot.state.oh.us/images/I-280SApproachVGCS-North-Large.jpg

http://cmhimg01.dot.state.oh.us/images/I-280NApproachVGCS-North-Large.jpg

http://cmhimg01.dot.state.oh.us/images/I-280VGCS-Icing-Large.jpg
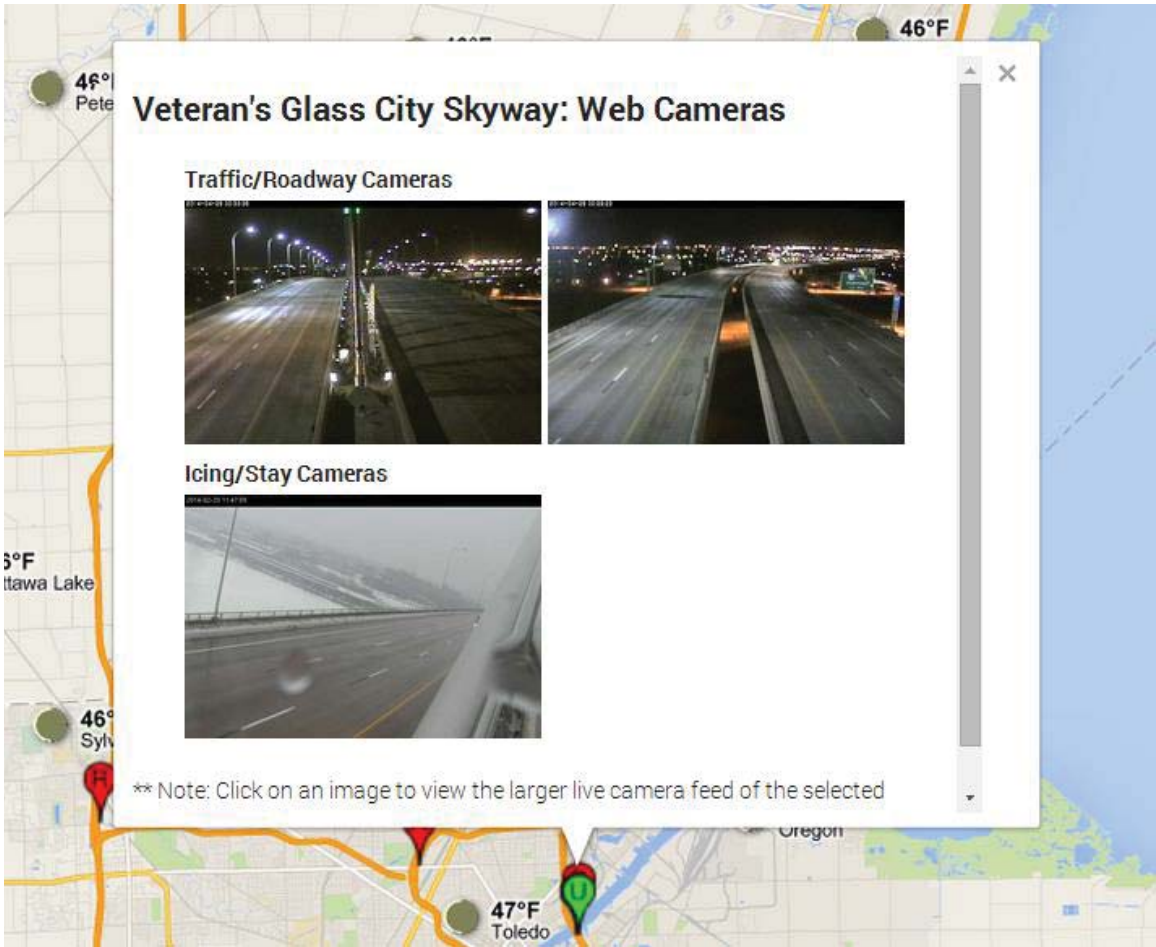
Figure D. 8: Live Camera Screenshot

Appendix E: Dashboard 'History' Section

The History section of the Dashboard provides many additional features that are useful for the users for analyzing and reporting purposes. This appendix provides a detailed explanation of the same. Figure E. 1 shows the main panel of the history section of the dashboard.
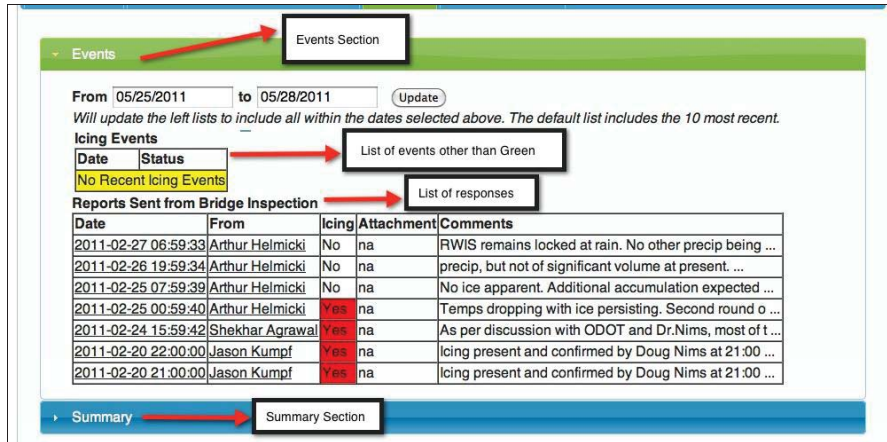
Figure E. 1: Dashboard History Main Panel

The main functionalities of this section of the dashboard include:

List of events (status other than green) between dates selected by the user

User can select two dates between which the statuses need to be displayed. As shown in Figure E. 2, two dates are selected i.e. 03/11/2011 and 05/28/2011, and a click on update button will display all the events occurred between these dates. Also clicking on any event will provide the cause of the event.
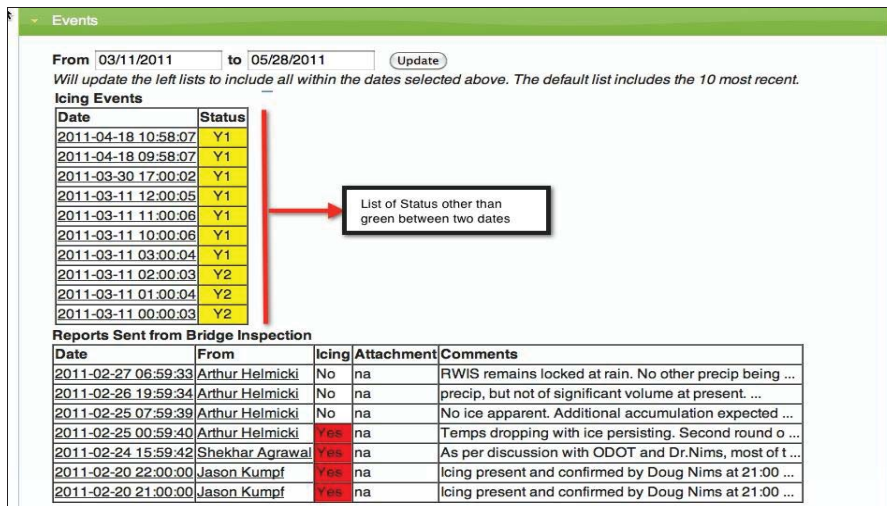
Figure E. 2: History Section - Events List

List of responses received by dashboard

All the responses received by the dashboard over the time are displayed in this section. This also includes the name of the person who posted the comment. Given below is a screenshot.

Figure E. 3: History Section - List of Responses

Appendix F: Plotting

This section will explain the different parts on the Plotting tab.

Each part of this tab consists of:
Start Date and End Date - which is to denote the date range for which the user wants to plot the data
Sensors – consists of a list of sensors available to plot under this category.
Selected – displays the selected sensors from the available list.
Plot Type – allows the user to change the type of plot they wish to see.
Graph and Export buttons – which help the user to graph the data and export the data as a csv file respectively.

Stay Thermistor:
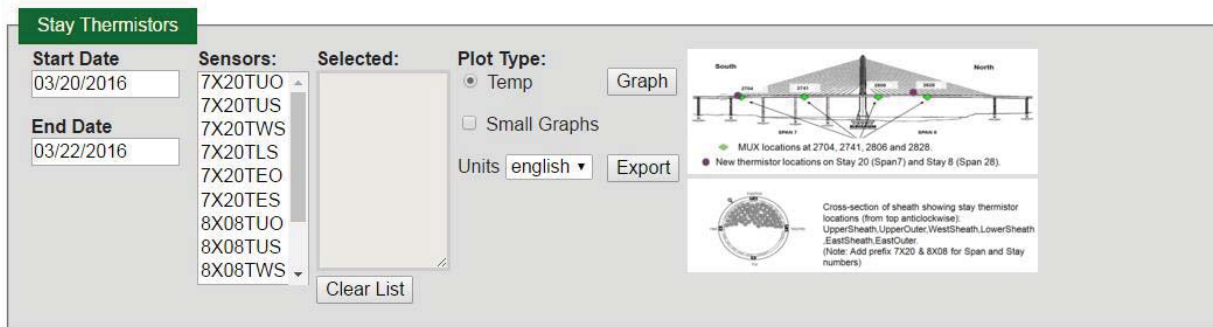
Figure F. 1: Stay Thermistor Plotting

Local Bridge Sensors:
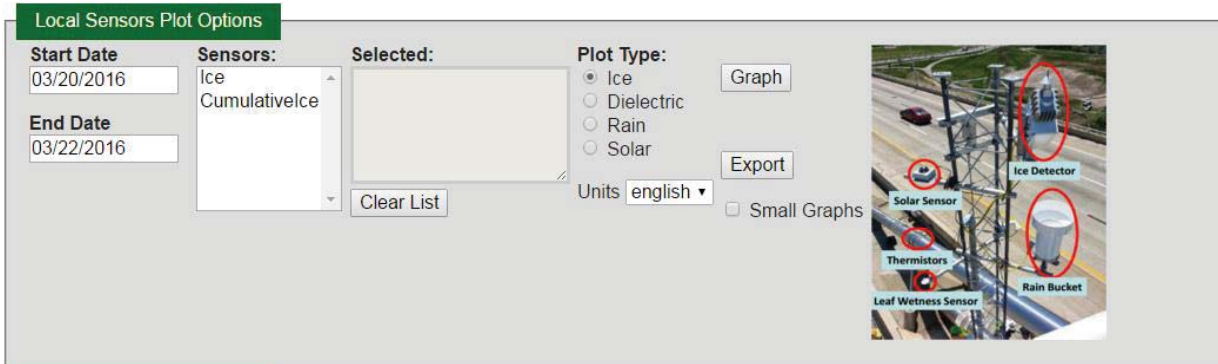
Figure F. 2: Local Bridge Sensor Plotting

RWIS:

Figure F. 3: RWIS Plotting

METAR:

Figure F. 4: METAR Plotting

UT Sensor – State Sensor:
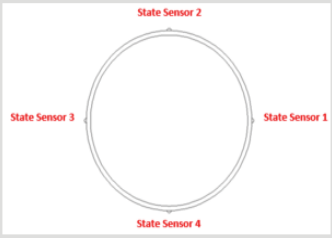
Figure F. 5: State Sensor Plotting

UT Sensor – Laser Thickness Sensor:
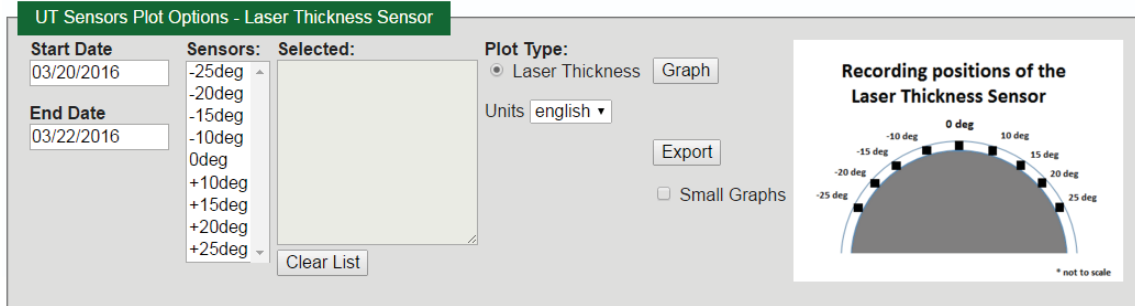
Figure F. 6: Laser Thickness Sensor Plotting

Appendix G: RWIS precipitation classification

Precipitation reports from the RWIS stations is under the Pc_Type column of the report table. The format of reporting was modified last in October 2015 and the following classification is valid for the data since then. The field Pc_Type reports the type of precipitation in numerical values. The tables below show what each of the reports mean and the classification of these into three categories for the purpose of the dashboard.

Pc_Type code	Precipitation/ Condition
1	Light
2	Unknown
3	None
4	Rain
5	Snow
6	Frozen
-1	Error

Table G- 1: RWIS Precipitation Reports

Categories	New Classification
Rain	4, 6
Snow	5, 6
None/Other	1, 2, 3, -1, Any other code

Table G- 2: RWIS Precipitation Classification

Appendix H: EdLog Program for CR10x

;{CR10X-TD}
;
*Table 1 Program
 01: 600   Execution Interval (seconds)

;;
;;;;;;;;;;;;;;;;;;;;;;;;;;READ BATTARY VOLTAGE;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;

1: Batt Voltage (P10)
 1: 1   Loc [BattVolt   ]

;;
;;;;;;;;;READ INTERNAL TEMPERATURE AS A COMPENSATION FOR THERMOCOUPLE;;;;;;;;
;;;
2: Internal Temperature (P17)
 1: 2   Loc [InternalTemp   ]

;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;ACTIVATE MULTIPLEXER;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;
3: Do (P86)
 1: 42   Set Port 2 High

;;
;;
;;
;;;STATE SENSOR 1;;;
;;
;;
;;

;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;DELAY;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;
;4: Excitation with Delay (P22)
; 1: 1   Ex Channel
; 2: 0   Delay W/Ex (0.01 sec units)
; 3: 1   Delay After Ex (0.01 sec units)
; 4: 0   mV Excitation

   ;;
   ;;;;;;;;;;;;;;;;;;;;;;;CLOCK PULSE FOR VOLTAGE READING;;;;;;;;;;;;;;;;;;;;
   ;;
4: Do (P86)
 1: 71   Pulse Port 1

;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;DELAY;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;

5: Excitation with Delay (P22)
 1: 1   Ex Channel
 2: 0   Delay W/Ex (0.01 sec units)
 3: 1   Delay After Ex (0.01 sec units)
 4: 0   mV Excitation

  ;;
  ;;;;;;;;;;;;;;;;;;;;EXCITE AND READ DIFFERENTIAL VOLTAGE;;;;;;;;;;;;;;;;;;;;
  ;;

6: Ex-Del-Diff (P8)
 1: 1   Reps
 2: 25   2500 mV 60 Hz Rejection Range (Delay must be zero)
 3: 1   DIFF Channel
 4: 1   Excite all reps w/Exchan 1
 5: 100   Delay (0.01 sec units)
 6: 2500   mV Excitation
 7: 3   Loc [Volt1   ]
 8: 1.0   Multiplier
 9: 0.0   Offset

  ;;
  ;;;;;;;;;;;;;;;;;;;IF THE VALUE IS NEGATIVE, TAKE THE VALUE ZERO;;;;;;;;;;;;;;;;;;
  ;;

7: If (X<=>F) (P89)
 1: 3   X Loc [Volt1   ]
 2: 4   <
 3: 0.0   F
 4: 30   Then Do

   8: Z=F x 10^n (P30)
    1: 0.0   F
    2: 00   n, Exponent of 10
    3: 3   Z Loc [Volt1   ]

9: End (P95)

  ;;
  ;;;;;;;;;;;;;;;;;;;;;;;;CLOCK PULSE FOR TEMPERATURE READING;;;;;;;;;;;;;;;;;;;;;
  ;;

10: Do (P86)
 1: 71   Pulse Port 1

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;DELAY;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```
11: Excitation with Delay (P22)
 1: 1   Ex Channel
 2: 0   Delay W/Ex (0.01 sec units)
 3: 1   Delay After Ex (0.01 sec units)
 4: 0   mV Excitation


```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;THERMOCOUPLE READING;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```
12: Thermocouple Temp (DIFF) (P14)
 1: 1   Reps
 2: 21   2.5 mV 60 Hz Rejection Range
 3: 1   DIFF Channel
 4: 3   Type K (Chromel-Alumel)
 5: 2   Ref Temp (Deg. C) Loc [InternalTemp   ]
 6: 4   Loc [Temp1   ]
 7: 1.0   Multiplier
 8: 0.0   Offset


```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;STATE SENSOR READING;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;-1= AIR,,,,,,0=ICE,,,,,,1=WATER;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;IF VOLT>1800 STATE=WATER (1) ;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```
13: If (X<=>F) (P89)
 1: 3   X Loc [Volt1   ]
 2: 3   >=
 3: 1700   F
 4: 30   Then Do
     14: Z=F x 10^n (P30)
     1: 1   F
     2: 0   n, Exponent of 10
     3: 5   Z Loc [State1   ]


```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;IF VOLT<17 STATE=AIR(-1) ;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```
15: Else (P94)

     16: If (X<=>F) (P89)
     1: 3   X Loc [Volt1   ]

```
     2: 4       <
     3: 17      F
     4: 30      Then Do

       17:  Z=F x 10^n (P30)
        1: -1      F
        2: 00      n, Exponent of 10
        3: 5       Z Loc [ State1    ]


   ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
   ;;;;;;;;IF 1700>VOLT>15, IF TEMP>=0.0 STATE=WATER(1), ELSE STATE=ICE(0);;;;;;;;;
   ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
    18:  Else (P94)

       19:  If (X<=>F) (P89)
        1: 4       X Loc [ Temp1     ]
        2: 3       >=
        3: 0.0     F
        4: 30      Then Do

          20:  Z=F x 10^n (P30)
           1: 1       F
           2: 00      n, Exponent of 10
           3: 5       Z Loc [ State1    ]

       21:  Else (P94)

          22:  Z=F x 10^n (P30)
           1: 0       F
           2: 0       n, Exponent of 10
           3: 5       Z Loc [ State1    ]

       23:  End (P95)

    24:  End (P95)

 25:  End (P95)
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;


;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;DEACTIVATE MULTIPLEXER;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
92:  Do (P86)
 1: 52     Set Port 2 Low


;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```

;;;;;;;;;;;;;;;;;;;;;;;;;WARITE THE DATA TO TABLE;;;;;;;;;;;;;;;;;;;;;;
;;;
93: Data Table (P84)^30282
 1: 0.0   Seconds into Interval
 2: 600   Seconds Interval
 3: 0.0   (0 = auto allocate, -x = redirect to inloc x)
 4: UTStateSensor   Table Name

;;;
;;;;;;;;;;;;;;;;MEASURE THE SAMPLED DATA TO SAVE TO INPUT LOCATION;;;;;;;;;;;;;;
;;;

94: Sample (P70)
 1: 05   Reps
 2: 1   Loc [BattVolt   ]

*Table 2 Program
 02: 0.0   Execution Interval (seconds)

*Table 3 Subroutines

End Program

-Input Locations-
1 BattVolt
2 InternalTemp
3 Volt1
4 Temp1
5 State1
6 Volt2
7 Temp2
8 State2
9 Volt3
10 Temp3
11 State3
12 Volt4
13 Temp4
14 State4

Appendix I: CR1000 Program for CR1000

```
'CR1000 Series Datalogger
'To create a different opening program template, type in new
'instructions and select Template | Save as Default Template
'date:
'program author:

'Declare Public Variables
'Example:
Public PTemp, batt_volt

'Declare Other Variables
'Example:
'Dim Counter
Public Temp1 As Float
Public V10 As Float
Public V1 As Float
Public S1 As Float


'Declare Constants
'Example:
'CONST PI = 3.141592654

'Define Data Tables.
DataTable (Ahmed,True,-1) 'Set table size to # of records, or -1 to autoallocate.
        Minimum (1,batt_volt,FP2,0,False)
        Sample (1,PTemp,FP2)
  'SENSOR ONE'
        Sample(1,V1,Float)
        Sample(1,Temp1,Float)
        Sample(1,S1,Float)

EndTable

'Define Subroutines
'Sub
        'EnterSub instructions here
'EndSub

'Main Program
BeginProg
  'SCAN INTERVAL
        Scan (60,Sec,0,0)
          'TEMPERATURE OF THE DATA LOGGER'
```

```
                PanelTemp (PTemp,_60Hz)
                'READ THE
                Battery (batt_volt)

''''''''''''''''''''''''''''''''''''''''''''''''''''
'''''''''''''''''''''''SENSOR ONE'''''''''''''''''''''
  ''''''''''''''''''''''''''''''''''''''''''''''''''''
 'Excite - delay 1 second - differential measurement:
   ExciteV(Vx1,2500,0)
   Delay(0,10,mSec)
   VoltDiff(V10,1,mv2500,1,True,0,_60Hz,1.0,0)

   'IF THE VOLTAGE READING LESS THAN ZERO PRINT ZERO TO THE FILE'
   If V10<0 Then
     V1=0
   Else
     V1=V10
   EndIf

'Temperature
   TCDiff(Temp1,1,mV2_5,2,TypeK,PTemp,True,0,_60Hz,1.0,0)

 'State
   If V1>1700 Then
     S1=1
   ElseIf V1<17 Then
     S1=-1
   ElseIf 17<V1 AND V1<1700 Then
     If Temp1>0 Then
      S1=1
     ElseIf Temp1<0
      S1=0
     EndIf

   EndIf

 'Enter other measurement instructions
   'Call Output Tables
   'Example:
   CallTable Ahmed

 'Delay(0,15,Sec)
 'ExciteV(Vx2,2500,0)
 'Delay(0,30,Sec)
   NextScan

EndProg
```