

FINAL REPORT

**A BRIDGE DECK ANTI-ICING SYSTEM IN VIRGINIA:
LESSONS LEARNED FROM A PILOT STUDY**

**Daniel S. Roosevelt, P.E.
Research Scientist**

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ABSTRACT

The need for this project originated with the Virginia Department of Transportation's (VDOT) plans to widen and replace a number of bridges along Route I-95. Many of the bridge decks in the new facilities will be in the shade, which will increase the probability that maintenance crews will have to respond to icy conditions. Various anti-icing technologies have shown promise, but most still require personnel to travel to the site of icing problems to treat them. Fixed automatic spray technology (FAST) is an exception. FAST is the application of a liquid chemical freezing-point depressant using an in-place, mechanical, spray system.

The purpose of this study was to evaluate the automatic anti-icing spray technology for bridge decks and become familiar with the construction, maintenance, and operations issues involved with such systems. The study evaluates a number of design options for delivery of a liquid chemical to the deck to determine the effectiveness of the options. For the purposes of this report, effectiveness is defined in terms of timeliness of operation, appropriateness of response, achievement of desired results, and a benefit-cost ratio greater than 1.

The report recommends that VDOT consider FAST an option for initial delivery of deicing chemicals to road and bridge travel lanes and develop criteria for prioritizing FAST installations that consider savings for reduced accidents and congestion. Recommendations are also made for nozzle and surface sensor design and location based on lessons learned from the pilot project.

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A BRIDGE DECK ANTI-ICING SYSTEM IN VIRGINIA: LESSONS LEARNED FROM A PILOT STUDY

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INTRODUCTION

Virginia experiences numerous freeze-thaw weather cycles during a winter season. These cycles occur daily, as overnight atmospheric temperatures drop below freezing and daytime temperatures rise above freezing. Because of their increased exposure to air, the surface temperature of bridge decks usually tracks air temperature more closely than do the adjacent roadway pavements. When precipitation occurs, this condition often leads to icing of bridge decks while the adjacent roadway remains wet. To combat this safety problem, maintenance crews treat bridge decks with chemicals and abrasives when icing occurs. This strategy, known as deicing, is rapidly being replaced by a technology known as anti-icing.

Anti-icing is defined as the practice of preventing the formation or development of bonded snow and ice by timely applications of a chemical freezing point depressant. Anti-icing is not a substitute for mechanical removal (e.g., plowing) when snow accumulates. Whether anti-icing or deicing is used, the purpose of the application of chemicals to pavements during snow removal operations is to keep the snow-pavement bond from forming, not to melt snow.

Various anti-icing technologies have shown promise, but most still require personnel to travel to the site of icing problems to treat them. Fixed automatic spray technology (FAST) is an exception. FAST is the application of a liquid chemical freezing-point depressant using an in-place, mechanical, spray system.

The need for this study reported herein originated with the Virginia Department of Transportation's (VDOT) plans to widen and replace a number of bridges along Route 95 through its Richmond District and the construction of the Route 95–Springfield Interchange in Northern Virginia. The new facilities will have many bridge decks in the shade, which will increase the probability that maintenance crews will have to respond to icy conditions. In the interest of providing motorists with the safest driving conditions possible on Virginia's highways and bridges during icy weather, VDOT is evaluating the effectiveness and practicality of FAST systems on bridge decks.

When this project started in 1997, the use of FAST on bridges in the United States was a new and untested technology. The original fixed anti-icing spray systems were manually activated, usually by telephone from a remote location. Usually the decision to activate the system was based on a review of atmospheric and road surface conditions at the site as collected by a road weather information system (RWIS) station. This project was among the first to try

automatic operation. For this reason, VDOT set two operational goals for the project. The first was to determine the effectiveness of the technology, and the second was to become familiar with FAST through the installation and operation of a system. Assuming the technology showed promise, a third goal was to develop a prototype performance specification for use in Virginia.

Since 1997, conditions have changed. FAST systems in use in Europe for more than 20 years began to appear in the U.S. market and a number of state departments of transportation (DOTs) undertook FAST projects that duplicated our effort. As a result, FAST has rapidly moved from cutting edge technology to common practice. Due primarily to the lack of snow and icing conditions in Virginia during the project life, other states have had better opportunities to gather data and assess their findings. For this reason, the third goal was dropped and the purpose of the project modified.

PURPOSE AND SCOPE

The purpose of the study was to evaluate an automatic anti-icing spray system for bridge decks. The plan was to test and evaluate a number of design options for delivery of a liquid chemical to the deck. The goals of this project were:

1. Determine the effectiveness of the options.
2. Become familiar with the construction, maintenance and operations issues involved with such a system.

Effectiveness was defined in terms of timeliness of operation, appropriateness of response, achievement of desired results, and a benefit-cost ratio greater than 1.

The primary purpose of spraying chemicals on a bridge deck during winter storms is to prevent formation of ice on the deck and maintain friction, thereby preventing traffic accidents from occurring. This is not a substitute for plowing when snow accumulates. With this function in mind, the objectives of this project were to provide answers to the following questions:

1. Is the selected system activating properly and early enough during each storm?
2. Does the system provide chemical uniformly to the entire deck and the approach slabs, and how does traffic influence this coverage?
3. Is the system providing a sufficient amount of chemical?
4. How effective is the anti-icing system and is the system effective only under a limited range of weather conditions?
5. Have accidents occurred on the deck when icy conditions were reported in its general area?

6. Are problems encountered during construction that are related to the design and installation of the anti-icing system?
7. What are the actual costs of operating and maintaining the system?
8. What routine maintenance is required?
9. Is the system cost-effective?

It was not the focus of this study to evaluate a the product of a single vendor, although the study was limited to one vendor's system, which was installed on one bridge and operated during two winter seasons.

METHODOLOGY

The study objectives were approached by conducting four tasks:

1. Select a system and a site to conduct the project.
2. Conduct a literature review of the system.
3. Develop a plan to collect data to determine the system's effectiveness and associated construction, operation, and maintenance issues.
4. Conduct the analysis required to determine the answers to the questions enumerated.

Selection of System and Site

The initial phase of this study involved selecting an anti-icing spray system most suitable for a bridge site. An informal panel consisting of VDOT's Northern Virginia District's Structure and Bridge Engineer, representatives from VDOT's Asset Management Division, representatives from the Virginia Transportation Research Council, and representatives of the Federal Highway Administration met to discuss the project in December 1997.

Time constraints due to the design schedule for the Route 95 and Springfield Bypass bridges dictated that the pilot test system be operational for the 1998/99 winter season. In December 1997, a system manufactured by Odin Systems International, Inc. (Odin) was the only system available in the United States that had progressed beyond the experimental stage. The decision was made to select and pilot test the deck anti-icing spray system manufactured by Odin.

Due to the time constraints, a bridge scheduled for deck surface replacement in 1998 was chosen for the pilot test installation. The bridge is located on the ramp from Route 7 eastbound to I-66 westbound in Fairfax County, Virginia. It is situated in an urban area where frost

conditions during the winter season are prevalent, although this was not a primary consideration in choosing this location. The bridge deck is 30 ft wide but functions as a single-lane one-way roadway. The travel lane is marked with edgelines and measures 16 ft wide. The installation is located on a vertical and horizontal curve with the high point of the vertical occurring on the bridge.

The reconstruction of the bridge deck began in the fall of 1998. The contractor removed the top 1 in of the deck by grinding, patched the remaining concrete, and replaced the riding surface with 1.5 in of latex concrete. Although the surface was removed, conduits were placed to serve the in-deck nozzles and sensors. The conduits were placed in grooves to ensure the conduits had a minimum 1.5-in cover when the riding surface was replaced. The reconstruction project was completed in January 1999.

Design of the FAST System

The FAST system is composed of an anti-icing fluid reservoir, a pump, and a network of spray nozzles capable of dispersing liquid anti-icing agent on the bridge deck. A programmable logic controller (PLC), which is part of the Odin system, provides the sequencing and duration of spray in each spray nozzle.

The liquid used with this system is magnesium chloride. Magnesium chloride was chosen primarily because it can be used at lower temperatures than can sodium chloride. Sodium chloride is effective to about 15°F, whereas magnesium chloride is effective to near 0°F, which is below the minimum temperature usually experienced in this area.

VDOT directed that three nozzle-mounting schemes be employed on this project: parapet mounted, in-deck lane edge mounted, and in-deck centerline mounted. Odin designed the size, type, and spacing of the nozzles and related conduits. An environmental sensor station (ESS), provided and installed by VDOT, was used to monitor conditions and automatically activate the PLC. Eight surface sensors were installed to monitor the surface conditions. Three of the sensors supplied data for the algorithm developed to activate the system. The other five sensors were used only in the evaluation study. Figure 1 shows the layout of spray nozzles and monitoring sensors. Figure 2 shows the control algorithm. The algorithm was programmed to activate the system under the following set of conditions:

1. deck temperature is 0°C (32°F) or below *AND*
2. deck is wet and/or precipitation has occurred within 1 hour *AND*
3. deck temperature is at or below the freezing point threshold of the brine as calculated by ZENO *AND*
4. deck temperature is in the effective temperature range of the chemical, which is 0°C (32°F) to -15°C (5°F) for magnesium chloride *AND*
5. time since the last FAST application exceeds 20 minutes.

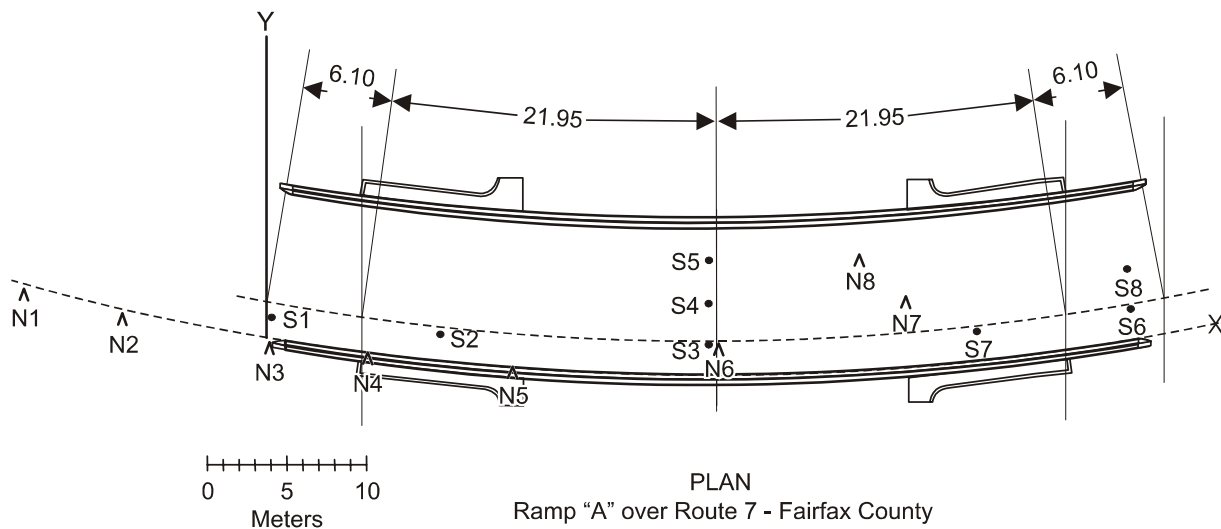


Figure 1. Layout of spray nozzles and monitoring sensors.

The spray system was designed with three activation options: (1) manually, by telephone, (2) manually by toggle switch at the site, and (3) automatically, based on sensor information gathered and processed on site. The two manual options involve activation of the FAST system using direct contact with the PLC. Automatic activation was accomplished through the VDOT algorithm programmed into the ESS data logger/controller.

Design of the Automatic Activation System

The design, implementation, and testing of an automatic activation system was performed by VDOT. At the time of purchase of the FAST system, Odin indicated they were developing an algorithm to operate the system automatically but had not completed that task. VDOT made the decision to develop its own algorithm that would detect the need for application of chemical and direct the PLC to operate.

An ESS manufactured by Coastal Environmental Systems was installed to monitor atmospheric and surface conditions. A ZENO 3200 electronic data logger and processor (ZENO) was used to collect, monitor and analyze the data. Analysis was based on the VDOT-developed algorithm, which was programmed into the ZENO. Based on the analysis, the ZENO directed the PLC to operate. The ZENO features 16-bit resolution and 16 analog and 15 digital channel inputs. The computerized control system uses the following inputs:

- relative humidity
- precipitation (heated tipping bucket)
- moisture on deck surface
- temperature of deck surface
- chemical presence on deck surface.

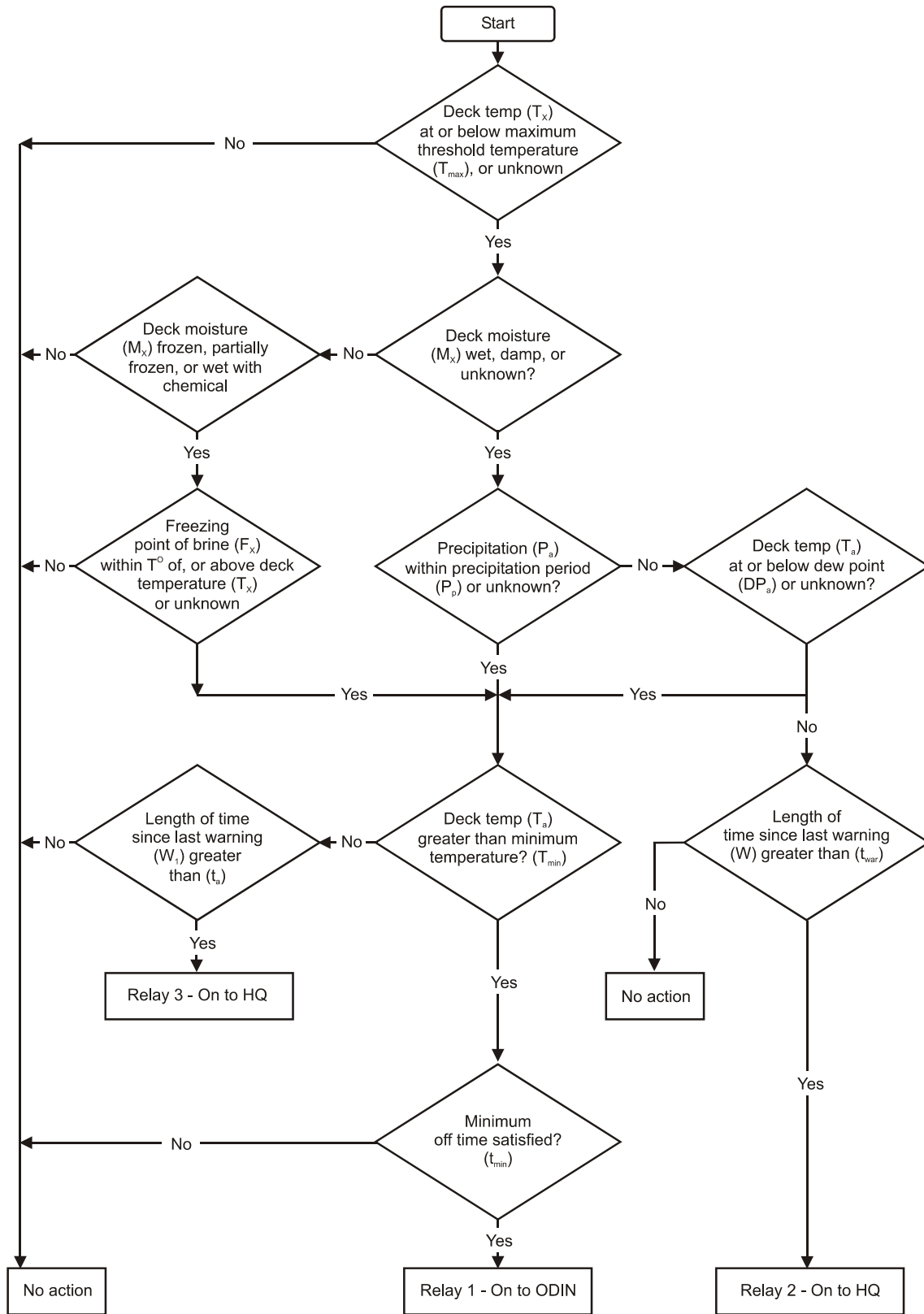


Figure 2. Control algorithm.

Atmospheric and road surface sensors were used to collect data for the atmospheric and surface weather conditions. Eight sensors, embedded in the concrete deck and bridge approach slabs, monitor the road surface conditions. They measure the surface temperature, surface condition (e.g., wet, dry), and brine concentration. The algorithm that automatically operates the spray system initially used data from sensors 1, 4, and 7, as shown in Figure 2.

The type of surface sensor is defined as passive. It measures the temperature of the sensor casing, which is representative of the material it is placed in (e.g., bridge deck), and the conductivity of any liquid or solid compound existing between electrodes located at the surface of the sensor. From this information, the data logger/computer calculates the condition (e.g., wet, ice) of the brine. To do this accurately the brine measured must be known.

Odin designated the locations of sensors 1, 4, and 7, since they affected the automatic operation of the system. Each sensor monitors one of the spraying schemes, which allows independent operation of the three nozzle layout schemes or operation as a single system.

Atmospheric conditions are monitored with sensors for ambient air temperature and relative humidity (Coastal, part 1112), wind speed and direction (Coastal, part 1104), quantity of precipitation (Coastal, part 1069), and solar radiation (Coastal, part 1114). Data from the weather station are collected and processed by ZENO.

Literature Search

A literature search was conducted using the TRANSPORT database, via Silver Platter, for all relevant studies completed by or started since 1988. Because this technology is in its early development in the United States, considerable written information has not yet reached the TRANSPORT database. Personal contacts by the researcher with others working with this technology and papers presented at national meetings were also used.

Data Collection Plan

System Effectiveness

To evaluate nozzle and sensor location options and evaluate the timeliness and appropriateness of automatic activation of FAST systems, data from the surface and atmospheric sensors were collected each minute and archived. The 41 data points collected each minute are listed in the Appendix.

In addition to the three surface sensors used in the activation process, five surface sensors were placed at locations to monitor the spread of the sprayed chemical. Sensor 2 was placed at the location along the edge of the travel lane where the bridge deck is at its highest elevation. Sensors 3, 5 and 6 monitor locations along the edge of the travel lane. Sensor 8 monitors a location along the centerline of the marked travel lane. Sensors 3 and 5 are placed at the furthest point in the downstream flow of traffic from the parapet spray nozzles before the first in-deck

spray nozzle would affect them. Sensors 6 and 8 are placed at the furthest point on the bridge in the downstream flow of traffic from the last nozzle.

A surveillance camera was installed near the bridge at a point where five of the nozzles and most of the bridge deck can be viewed. Figure 3 is a typical view recorded during a snowstorm. Automatic operation of the spray system is permanently recorded on a time-lapse VCR unit. During the first winter season, the VCR was programmed to start video recording 30 sec prior to a spray sequence and continue recording for 20 min. After the first year, the video recorder was modified to record snapshots of the site every 6 minutes in addition to recording when activation occurred. An infrared illuminator is in place adjacent to the camera to illuminate the deck for video recording at night.



Figure 3. Typical view recorded during a snowstorm.

System Construction, Operation, and Maintenance Issues

Cost and the construction process were documented. This included costs for installation, operation, and maintenance of the FAST system and the ESS equipment. Visual inspections of the FAST system and the bridge were made periodically to evaluate the effect of the system on the structure and the durability of the system.

RESULTS

Literature Search

FAST has a long history of use in Europe. Beginning in 1977, systems similar to that used by VDOT were retrofitted to bridges. Initially, the spray nozzles were placed on the

shoulder and trenching for the supply piping did not involve cutting of the pavement. In the early 1990s, a system developed by Boschung Mecatronics (Boschung) was installed on a bridge over the Dortmund-Ems Canal, in Germany. The installation used in-deck spray nozzles. Use of the system is reported to have reduced accidents by more than 50% and reduced the consumption of deicing chemicals. (“Danger,” 1994).

The most impressive project of this nature constructed to date is in the Canton of Vaud, near Lausanne, Switzerland. The canton installed a Boschung in-surface system on a 6-km section of roadway coincident with a roadway improvement project between 1995 and 1997. The roadway was widened from four lanes to six lanes, and porous pavement and sound walls were installed to dampen traffic noise. The section has a history of black ice formation, which the porous pavement was anticipated to aggravate. The section is three lanes in each direction, includes six bridges, and averaged 70,000 vehicles per day in 1997. The location varies in elevation from 495 to 695 m.

The Lausanne system is similar in layout to the VDOT system, but on a larger scale. Approximately 800 spray nozzles are located along the centerline between the outside lane and middle lane of the roadway in each direction and spaced about every 15 m. The spray from each nozzle covers a three-lane width of roadway. Eight 2,000-L tanks, spaced along the route, provide deicing fluid for the nozzles. Four 12,000-L tanks at a central location restock the intermediate tanks as necessary via underground pipes. Solenoid valves control the order and length of time each nozzle sprays. Twelve icing detectors located at points along the route monitor pavement condition. The detectors are active sensors, which freeze small samples of the liquid on the sensor to determine the liquid’s freezing point. The system can be operated automatically or manually.

The system has been operational since the beginning of 1998 (Michel Zambelli, Canton of Vaud, personal communication). The construction cost was approximately \$6.1 million (\$4.674,000 for the roadway, \$1,425,000 for the bridges). The system is designed to prevent ice, not to eliminate snow; in the case of light snows, the need to plow has decreased. Regarding the effect on overall maintenance expenses, it is too early to draw conclusions. Although no objective data were available concerning the operation of the system, the winter of 1998/99 was colder and involved more snow than normal. The system was viewed as contributing to improved driving conditions.

Kuemmel (1998) reported on the review by the 1998 NCHRP Scanning Review of European Winter Service Technology Team of the Lausanne system and some German installations. Information on the adequacy of the automatic system operation is not detailed, but European studies referenced in his report support a cost benefit and environmental benefit of such systems. The report recommends in-pavement systems be funded experimentally in the United States to document further the benefits and cost of such installations.

Bridge anti-icing research and development in the United States dates from 1995. At that time, the National Cooperative Highway Research Program (NCHRP) funded IDEA Program Project 27, Automated Bridge Deck Anti- and Deicing System. This project funded an experimental system on a Utah DOT (UDOT) bridge on I-215, near Salt Lake City. Friar (1999)

reported a comparison of accident data for a test and control before and after installation of the system that indicated a 64% reduction in accidents for the test location. The analysis covered one winter of operation and used accident data from 5 years prior to the installation through the test period. $MgCl_2$ was used as the deicing chemical and was applied at a rate of 95 L/lane-km (40 gal/lane-mile).

Since 1996, DOTs in Colorado (CoDOT), Kansas (KsDOT), Kentucky (KyDOT), Maryland (MdDOT), Minnesota (MnDOT), New York (NYSDOT), North Carolina (NCDOT), Pennsylvania (PennDOT), Wisconsin (WisDOT), and Washington State (WSDOT) have sponsored experimental bridge anti-icing projects (Cogburn, 2000). Only MnDOT, UDOT, and WSDOT have reported results that are in the literature.

Keranen (2000) reported on MnDOT's experience with fixed spray systems. MnDOT has placed three systems of the same relative size as VDOT's pilot system. None of the sites operated automatically, but they could be operated remotely by telephone. Accident experience at the three sites dropped from 22 snow-related accidents in the 18 to 24 months before the systems were installed to four snow-related accidents in a similar period after installation. This resulted in a positive benefit/cost ratio for each location.

In 1999, MnDOT installed a bridge anti-icing system on the I-35 bridge over the Mississippi River near downtown Minneapolis. The bridge is approximately 2,000 ft long and is six lanes wide. The location is prone to surface ice formation in winter due to its location downwind from a power plant that produces moisture laden smoke, exhaust from congestion-slowed traffic and its proximity to the river below. The system serves 76 spray nozzles and includes a state-of-the-art pump storage house, an ESS attached to the structure. The system can operate automatically, and conditions can be monitored remotely. The system includes all the features VDOT requested for the pilot test site, but on a larger scale. Because of the length of the system, small pressure storage tanks were required at points along the system. This system contract was awarded to Boschung for \$538,300. An evaluation report (Johnson, 2001) issued after the first winter of operation indicates the automatic operation program appropriately and adequately activated the system. The evaluation compared non-dry weather crashes and congestion delay for similar winters before and after installation of the system. A benefit-cost analysis that assigned costs to crashes and congestion delay indicated a benefit/cost ratio for the system of 3.4.

Stowe (2001) reported on WSDOT plans to install a FAST system on a section of road 0.60 mi long. The system is estimated to cost \$599,500 for design and construction. Annual maintenance is estimated at \$32,800. He reported on WSDOT's procedure for determining the benefit/cost ratio of an existing site. He reviewed accident data for the site for a 3-year period to determine the number of accidents that occurred under winter conditions. Then, assuming a bridge anti-icing system would have prevented 80% of the accidents, he assigned a cost to each accident based upon severity. (Stowe reported that there is no history in Washington of the resultant rate of collision reduction accountable to an automatic anti-icing system; therefore, a mid-range resultant factor of 0.40 was initially used based on the assumption that most snow or ice accidents [60%] would be eliminated but not wet roadway accidents. According to Stowe, information from maintenance managers at PennDOT, who have observed systems in place,

indicates that accident reduction due to automatic anti-icing systems was closer to 100%. Given that information, further consideration was warranted. Allowing for wet pavement accidents and the possibility of ice-related accidents during a refreeze or heavy snow conditions, a higher resultant factor of 0.20 was used. Thus, it was presumed that 80% of the snow and ice-related accidents would be eliminated.) Using this process, he determined the benefit/cost ratio of 2.36.

Maxwell (1999) reported on WisDOT's installation of a pilot bridge anti-icing system, similar in most respects to that installed by VDOT. The system has in-deck and parapet nozzles and can be operated manually or automatically. Mechanically, the system installed has operated adequately. The in-deck nozzles produced 100% coverage of the traveled surface. Motorist reaction to the nozzle operation was carefully observed, and no adverse reaction was observed. At the time of the report, insufficient incidents had occurred to assess the appropriateness and accuracy of the automatic operation algorithm.

Barrett (2001) reported on the Kentucky Transportation Cabinet's installation of a pilot bridge anti-icing system, similar to that installed by VDOT. They operate their system only in the manual mode. The report discusses a number of problems encountered during construction, which were equipment related. At the time of the report the system had not been in place long enough to note significant maintenance or operational problems.

The Ontario Ministry of Transportation has a FAST demonstration site on the northbound Route 416/401-interchange structure. The system was installed in response to a documented high winter accident frequency. The system has been in service since the winter of 2000/01. A report (Pinet, 2001) describes the design, installation, operation, and preventive maintenance activities and contains many lessons learned from the project. The report indicates the Ministry is very pleased with the FAST installation in terms of its success since winter weather-related accidents have not occurred since it has been in operation. Chemical costs, however, were about double that anticipated (\$12,000 vs. \$5,000 to \$7,000 anticipated), and automatic operation occurred at some times when chemicals were not needed.

A number of other agencies operate FAST systems, but no written reports on system performance were available. A list of systems in the United States and Canada, with contacts for additional information, is available at www.sicop.net.

System Effectiveness

System effectiveness has been defined as timeliness of operation, appropriateness of response, achievement of desired results, and a benefit/cost ratio greater than 1.

Timeliness of Operation

Timeliness of operation depends on the accuracy of the data used in the algorithm; namely surface temperature, surface condition (e.g., wet, dry), and freezing point of the brine.

Surface sensor location on the deck and its relationship to the nozzles appear to be important. An investigation of this relationship was made.

Data were collected over two winter seasons. Data collection dates were February 15 to March 31, 1999 (season 1), and December 15 to March 31, 2000 (season 2). Observation of the video record indicated that traffic did not follow the lane marking. During season 1, sensors 1, 4, and 7 were used to activate the spray system, but they were not all located in areas used by traffic. Sensors 4, 5, and 8 were in the actual travel lane. During season 2, the activation sensors were changed to 4 and 8 to coordinate the activation sensors with locations where traffic was running.

Surface Temperature Data

The surface temperature data for all eight sensors were compared minute by minute for all days collected during season 1. A difference in temperature recorded by the sensors at any given time ranged from approximately 0.5°C to over 15°C. Figure 4 indicates the range of the difference for each day from February 16 to March 31, 1999.

The bridge where the sensors are located is oriented in a generally WSW/ENE direction. The parapet and vegetation shade the deck. In the morning, there is a 1 hr 40 min period between the time the first sensor (5) is exposed to direct sunlight and the time the last sensors (1, 2, 3) are exposed. In the evening, this period of change is approximately 50 min.

At night, the maximum difference in surface sensor readings was in the range of 1 to 2 degrees C. Some of this difference was due to sensors being located in the bridge deck and in the approach slab. Sensors 1, 6, and 8 are located in concrete approach slabs that are in contact with the ground. The ground slows the heating and cooling of the approach slabs as the air temperature falls and rises above the ground temperature.

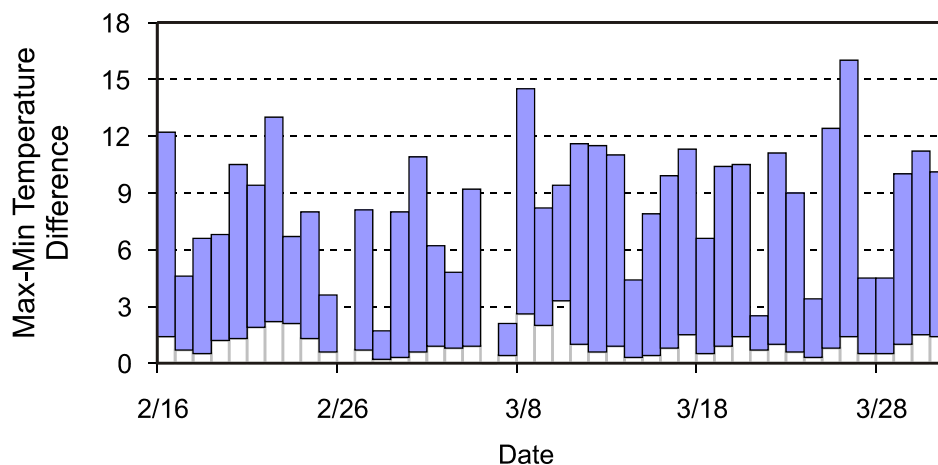


Figure 4. Range of the difference for each day from February 16 to March 31, 1999.

Some of the difference in the sensor readings is due to sensor error. There is no accepted method of calibrating surface sensors in the field, and subsurface or ground temperatures were not collected. To estimate surface temperature, sensor error readings for all eight sensors were compared over a 5-day period between 9 P.M. and 6 A.M. on two occasions. These hours were chosen to minimize the effect of solar heating and to allow the rate of change of air, ground, and surface temperature to stabilize. The statistical analysis of the data is provided in Table 1.

Figure 4 and Table 1 imply that solar heating strongly influences road surface and bridge deck temperature and that location of the surface temperature sensor is important. To improve the accuracy of surface temperature measurement, multiple sensors should be used and should be placed in the traffic lanes.

Table 1. Statistical Analysis of Pavement Temperature Data

	2/16 to 2/20, 1999	3/26 to 3/30, 1999
Data Points	2054	2374
Average difference max to min	1.65°C	1.66°C
Standard Deviation	0.37°C	0.59°C

Surface Condition Data

Surface condition in this case refers to the presence of moisture. The two states are “not dry” or “dry.” The surface sensors sense this directly by passing a current between two electrodes. If fluid is present, the current flows and the sensor reports “not dry.” No current flow results in a report of “dry.” Based on surface temperature and resistance, which are measured at the same time, the “not dry” condition is further refined to “wet,” “ice,” etc.

The surface condition data for the eight surface sensors were reviewed for season 1. The readings were classed as “consistent” when all sensors read dry or not dry at a given time. The readings were classed as “not consistent” if dry and not dry readings were recorded among the eight sensors at any given minute.

Figure 5 indicates the percentage of time each day during season 1 when consistent and inconsistent readings were recorded for all sensors. Figure 6 indicates these same data for sensors used to activate the system. Figure 7 indicates these same data for the sensors located in the travel lane. A block above the data for a specific date indicates dates when measurable precipitation was recorded.

The mean percentage of inconsistent readings and the standard deviation were calculated for groups containing all sensors, the operational sensors, and the travel way sensors over all days in season 1. The same percentage was also calculated for the same groups of sensors, but only for those days when precipitation was present and for days when the some percentage of inconsistent activity was recorded. The number of days, each of which was considered a sample; the mean; and the standard deviation for each analysis are shown in Table 2.

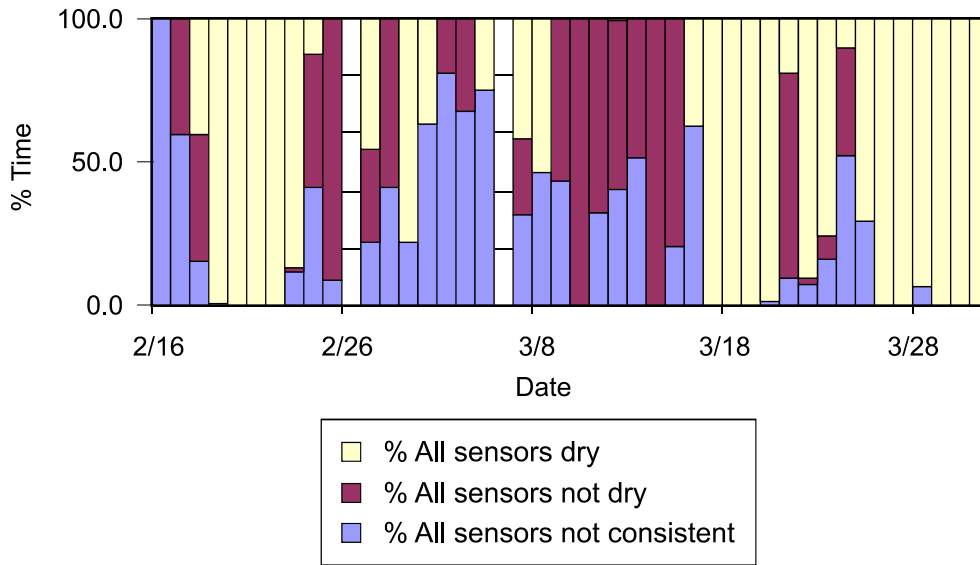


Figure 5. Percentage of time each day during season 1 when consistent and inconsistent readings were recorded for all sensors.

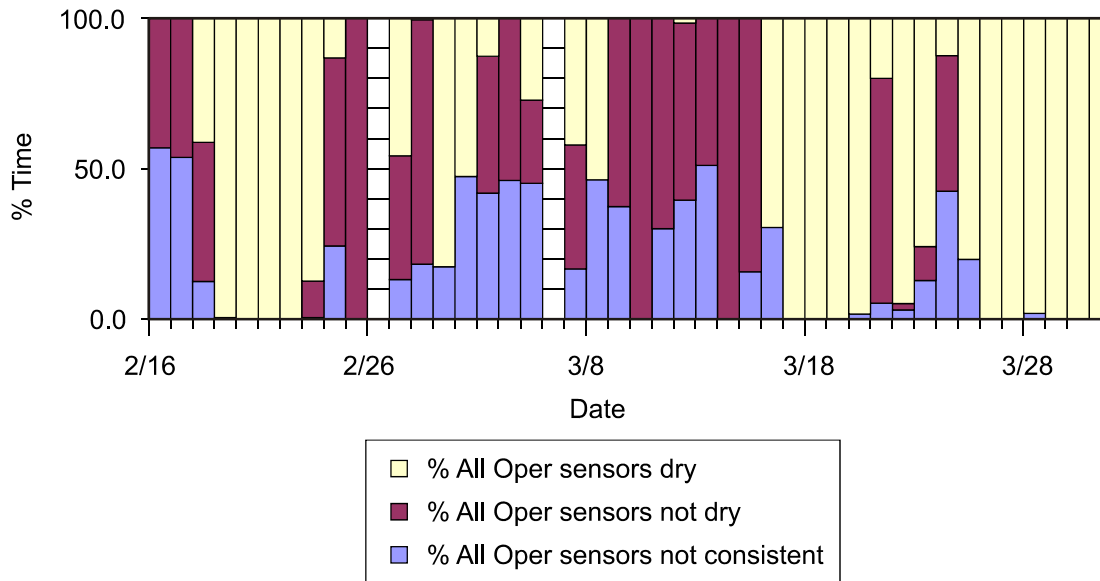


Figure 6. Percentage of time each day during season 1 when consistent and inconsistent readings were recorded for sensors used to activate the system.

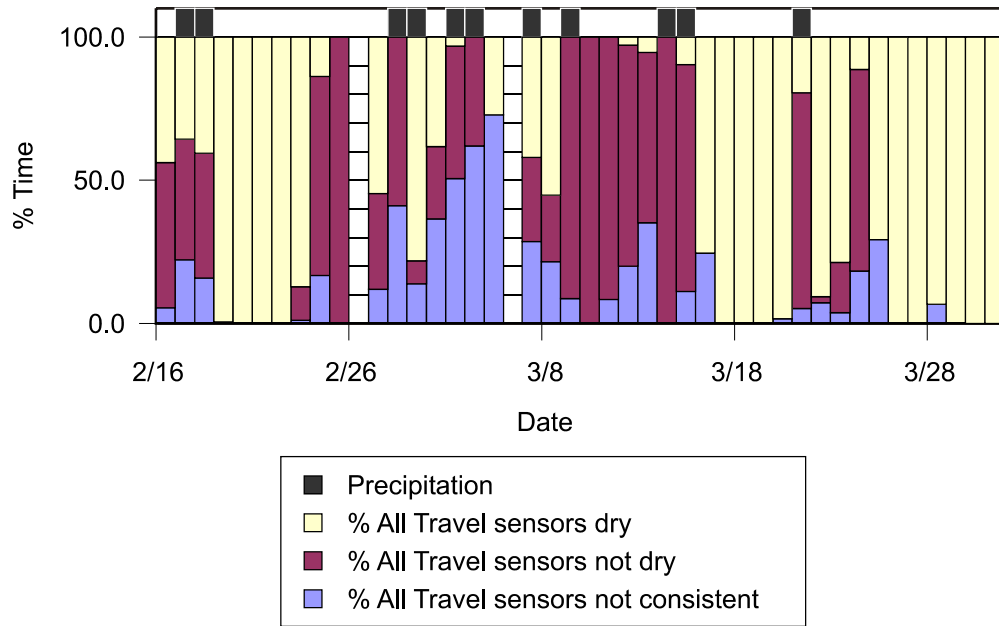


Figure 7. Percentage of time each day during season 1 when consistent and inconsistent readings were recorded for sensors located in the travel lane.

Table 2. Mean and Standard Deviation of Inconsistent Surface Condition Sample Readings for Season 1

	All Days Season 1			Precipitation Days Season 1			Inconsistent Days Season 1		
	Days (samples)	Mean	Std Dev	Days (samples)	Mean	Std Dev	Days (samples)	Mean	Std Dev
All sensors	42	25.3	27.5	10	32.5	24.5	28	34.3	23.4
Operational sensors	42	17.4	19.4	10	21.9	17.0	28	26.2	18.4
Travel way sensors	42	13.8	18.0	10	19.7	16.1	28	21.3	18.6

Measuring Chemical Concentration and Brine Freezing Point

Comparison of the surface temperature and the calculated freezing point of the fluid sensed is one of the parameters for operation of the spray systems. The chemical concentration sensor measures the electrical resistance of the brine and calculates the freezing point of the brine. As with the surface temperature sensor, there is no accepted method of calibration or testing for the sensor; therefore a comparison of calculated brine freezing point data, collected every minute, and video of the bridge surface were used to verify the accuracy of the brine freezing point calculation. Discounting, for the moment, that “inconclusive” is an option, there are four possible outcomes for this comparison:

		Video indicates ice/snow bonded to surface	
		No	Yes
Sensor data indicate ice	No	Correct	Type II error
	Yes	Type I error	Correct

During both years of the study, video was recorded whenever the system sprayed. This allowed comparison of all options except the Type II error. During the second year, when video was also captured every 6 minutes, the Type II error condition could also be confirmed.

During year 2, video was recorded for two periods totaling just over 14 days. Review of the video indicated that at no time did the deck need to be treated by the spray system although the surface sensors used in the algorithm calculated the presence of ice 1,496 times. Table 3 indicates the outcomes for year 2 at times when both video and sensor data were available.

Table 3. Surface Condition as Indicated by Surface Sensor Data and Visual Observations

		Video indicates ice/snow bonded to surface	
		No	Yes
Sensor data indicate ice	No	18070	0
	Yes	1496	0

The 1,496 Type I errors occurred during 11 separate time periods (events). None of those events was accompanied by precipitation. The communications link between the detection system and the operating system was inoperable during most of this period; therefore, the spray system did not operate when directed to do so. Only once did the system operate as directed, resulting in follow-on notifications of ice. In addition, the surface sensors were calibrated to measure the conductivity of sodium chloride brine. Since the spray system used magnesium chloride brine, this created inaccurate measurements of chemical concentration and brine freezing point when magnesium chloride brine was present.

Three events involving precipitation occurred during the two periods of video recordation. The first precipitation event began on January 25 at 3:25 A.M., and accumulation ended around 1 P.M. Total accumulation recorded by the ESS was 5.35 mm (0.21 in) of water, which would equate to approximately 2 to 2.5 in of snow. The video indicated a higher accumulation. From the video, the appearance was that the travel lane was plowed around 6:30 A.M., at which time chemicals were probably applied. From the start of the storm to the time when the deck was plowed, all sensors read, “wet, temperature below freezing.” No spray event

was called for, and none occurred. The video shows the traffic tracking through the snow, and the indication is that residual chemical had kept a bond from forming. From the first plowing, and probable chemical application by the snowplow vehicle, to the end of the storm, all sensors read: “wet, temperature below freezing.” Conditions after the initial plowing and each subsequent plowing indicated that a bond breaker existed between the surface and the snow. The system appeared to operate correctly.

The second precipitation event began on January 30 at approximately 11:45 A.M. and ended around 6:30 P.M. Total accumulation recorded by the ESS was 8.64 mm (0.34 in) of water. Surface temperatures during this period ranged from -1°C to -2°C . The precipitation began as rain, and total accumulation of snow was estimated from the video to be approximately 2 in. From the video, the appearance was that the travel lane was plowed around 1:55 P.M., at which time chemicals were probably applied. From the start of the storm to the time when the deck was plowed, all sensors read “chemical wet.” No spray event was called for, and none occurred. The video showed the traffic tracking through the snow, and the indication was that residual chemical had kept a bond from forming. From the first plowing, and probable chemical application by the snowplow, to the end of the storm, all sensors read, “wet, temperature below freezing.” Conditions after the initial plowing and each subsequent plowing indicated that a bond breaker existed between the surface and the snow. The system appeared to operate correctly.

The third precipitation event occurred on February 18 at approximately 4:20 A.M. and continued beyond the video recording, which ended at 10:03 A.M. Total accumulation recorded by the ESS at 10 A.M. was 1.02 mm (0.04 in) of water. Surface temperatures during this period ranged from -1.3°C to 1.6°C . The precipitation began as snow, and total accumulation of snow was estimated from the video to be less than a half-inch. From the video, the appearance was that the surface temperature rose above 0°C around 7 A.M., as the snow cover near the traffic lane disappeared. From the start of the storm to the time when the deck temperature rose above 0°C , all sensors read, “wet, temperature below freezing.” No spray event was called for, and none occurred. The video showed the traffic tracking through the snow, and the indication was that residual chemical had kept a bond from forming. The system appeared to operate correctly.

The system activated on three occasions during the periods of video-recording:

1. On January 27 at 6:31 A.M., sensor 8 changed from sensing “wet, temperature below freezing” to “ice,” triggering the system. The video confirmed the event. This was the only time during the period of video recording that the system activated based on the algorithm. Since the video indicated the application was not needed, the event was counted as a Type I error. Within minutes of the application, both operational sensors changed from “ice” to “wet, temperature below freezing.”
2. On January 28 at 7:51 A.M., the data record indicated 17.7 L were sprayed, but the video did not confirm a spray event. The sensor data did not indicate a need for operation. This conflict between the video and data record for flow is unexplained. The incident was counted as a Type I error.

3. On February 18 at 9:07 A.M., the data recorder malfunctioned and automatically reset. This appears to have erroneously triggered the system, causing a spray event. The malfunction was considered beyond the control of the system and was not counted as a Type I error.

On an event basis, Table 4 shows a comparison of surface condition by sensor data and visual observation.

Table 4. Action Needed as Indicated by Surface Sensor Data and Visual Observations

		Video indicates ice/snow bonded to surface	
		No	Yes
Sensor data indicate ice	No	3	N/A
	Yes	11	N/A

During the periods covered by the video, the non-operational surface sensors calculated “ice” 3,166 times when the operational sensors did not indicate ice. These icing events lasted from a minimum of 11 minutes (the minimum time between sensor updates) to over 17 hours. If the sensors had been part of the operational algorithm, the system would have operated on 19 occasions.

Surface sensor 1 never indicated icing conditions during the period. It was the only surface sensor that received chemical brine directly from a spray nozzle. This direct application of brine to the sensor appeared to have contaminated or desensitized it, making it ineffective as an indicator of surface condition.

Surface sensor 2, located at the highest point on the surface, had the highest incidence of “ice” detection. This is logical since traffic did not pass over the sensor and brine from the spray system was not dragged to that location.

These findings have weighed heavily on the video observations as correct. Although the scene is lighted, conditions at night are difficult to gauge. Comparisons of video of the surface during daylight hours, before and after nighttime observations, and action of the traffic have been used to draw some conclusions as to the true surface condition. Since the sensors monitored only a small area of the surface, the possibility is strong that the condition detected by the sensor and the prevailing condition of the surface differ.

System Construction, Operation, and Maintenance Issues

System Planning, Design, and Construction Cost

Because the bridge anti-icing system used in this study was purchased from a single source, the system was included in the bridge repair proposal as a lump sum pay item. Payment was full compensation for providing, furnishing, and installing the bridge anti-icing system complete in place, including pump house, storage tank, and all piping lines and nozzles; traffic control; bridge access; site restoration with necessary incidental labor; and coordination as specified. The cost was \$30,000.

The ESS and software used to monitor conditions at the site and automatically direct the system to operate were a sole source purchase. The equipment purchased was a processing unit (RPU), NEMA enclosure, power supply, wind sensor, relative humidity and air temperature sensor, precipitation sensor (tipping bucket), solar radiation sensor, 10 surface sensors, a 10-m tower, and operating software. Cost for the equipment was \$17,400.

Installation of the RWIS equipment was accomplished by VDOT forces, assisted by the bridge contractor and the anti-icing subcontractor. This work also included installation of a warning sign in advance of the first spray nozzle. Cost for that work is estimated at \$13,000.

The surveillance camera, time-lapse VCR unit, and infrared illuminator cost approximately \$2,500.

Annual Operating Cost

No information was kept on the quantity of chemical used, so annual operating costs are unavailable. In theory, the cost to operate the system is low, especially if the reduction/elimination of trips to the site to apply chemicals manually is considered. The pilot system is set to apply 10 L of liquid magnesium chloride each time it operates. At \$0.18/L, the average price for magnesium chloride in the area, this amounts to about \$1.81 per application. Electricity is needed to operate the spray system and the RWIS station that collects data for the automatic operation algorithm, but that cost was considered too small to consider.

The bridge chosen for this pilot test was not a high-priority location for emergency response. No data on emergency response costs were available, making verification of the savings for emergency response difficult to determine. A trip to the site solely for the purpose of treating the deck with chemicals or abrasives can easily require an hour or more of operator and vehicle time plus the cost of the chemical. At current rates for VDOT operator and dump trucks, this amounts to about \$33.00 per trip. Chemical applied by this manual response would be a small volume for the area covered by the spray system. At the cost of \$0.03/kg for salt, the chemical used would cost about \$0.25 per application.

MnDOT published information on their experience with automated bridge anti-icing systems that supports the idea that operations costs are relatively low. They estimate annual operational costs between \$1,000 and \$1,500.

Annual Maintenance Cost

The recommended maintenance procedures were not followed during the life of the study, and an inspection made in September 2003 indicated no preventive maintenance was done on the system after the study was completed. The storage tank and the system lines have never been drained. This has resulted in corrosion of the connections in the supply system. The pump in the pump house has surface pitting and corrosion from chemical. A number of the sensors casings have “melted.” The result is the sensor contacts are covered with the casing material and do not function. The casing material was soft and could be penetrated with a fingernail. The system is not currently functioning.

The recommended annual maintenance for the spray system consists of draining the system and storage tank at the end of the winter season, rinsing the system with water and preventive maintenance to the system pump. On a system this size, a small crew at an estimated cost of \$450 to \$500 can easily accomplish these tasks in 1 day. The RWIS station also requires preventive maintenance. This is also estimated to take 1 day to complete, at a cost of \$500. The MnDOT report supports these costs with estimates in the range of \$270 to \$340 for maintenance of the spray system.

Projected Service Life of Spray System

The system has not been in place long enough to document service life, and the lack of proper preventive maintenance makes data from this facility unreliable as a guide. Although automated operation is a relatively new feature, fixed anti-icing systems have been in existence since the late 1970s. Most liquids used for anti-icing involve chlorides that are highly corrosive to metals. This corrosive action and the wearing of moving parts are the two major influences on the life of the system

The parts in direct contact with the chemical are of a material resistant to chemical corrosion, although UV rays affect them. However, external piping can be protected from the direct rays of the sun should not deteriorate.

On short bridges, the system involves only two moving parts, which are the pump that propels the anti-icing liquid and the solenoid valves that control the amount of liquid delivered to each nozzle. A reasonable life for the pump is 5 years. Inexpensive solenoids are available that last for 50,000 cycles, which should last the life of the system.

The wiring that supplies electricity to the pump, solenoid, and RWIS station is particularly susceptible to chloride corrosion. Under normal circumstances, the wiring should not come in contact with the deicing chemical. Precautions to protect the wiring from contact

with the chlorides, a strict preventive maintenance program for the brine system, and rapid cleanup of any spills should allow the system to last the life of the bridge.

Keranen estimated a 12-year service life for the systems MnDOT installed. He anticipates pump replacement and computer hardware replacement in the fifth and tenth year at a cost of approximately \$3,500 each time.

Projected Service Life of the Bridge

The installation PVC tubing in bridge decks and/or the attachment of utilities to the bridge is not a new or unique situation. A bridge anti-icing system is light, and the additional weight can easily be absorbed in the design of the structure. The operation of the anti-icing system appears to place no unusual structural stress on the structure and if constructed properly should not subject the structure to unusual chemical effects. The usual operation of the system is as a supplement to the normal anti-icing and deicing program used for the structure. Proper preventive maintenance procedures, as would be planned for any bridge subjected to deicing chemicals, should result in no reduction to the service life of the bridge.

Effect on Construction and Maintenance of the Deck

Construction Record

Installation of the spray system and the RWIS surface sensors were part of a deck surface repair project. The contract required milling of the top 1 in of the existing deck and replacement with 1.5 in of latex hydraulic cement concrete. This was done in two phases of one-half the width of the bridge times the full length. After the milling operation in each phase, grooves were cut in the exposed surface and 1-in (id) PVC pipe was placed to serve as in-deck raceways for the liquid chemical supply lines and the cables for the surface sensors. Project specifications called for the top of the PVC pipes to be lower than the adjacent exposed surface.

A 4-in PVC conduit was placed from the pump house, underground to the end of the south end of the bridge and along the outside of the east parapet wall. This conduit was a raceway for the spray system lines. A separate 4-in PVC conduit paralleled the raceway for the spray system lines to approximately the midpoint of the span and carried the cables that connected the sensors to the ZENO. Along the east parapet of the north span of the bridge, a single 4-in PVC raceway carried the liquid supply lines and the sensor cables. Electrical wiring to operate the solenoid valves used these same raceways.

After the latex concrete surface was placed, holes were drilled in the surface at the locations of the in-deck nozzles and sensors. The flexible supply line for the spray system was threaded through the PVC raceways and the nozzles were attached. The sensor and cable are a single unit that was installed by inserting the cable through the raceway pipe from the sensor location to the ZENO. The runs of cable were 100 to 200 ft long. A VDOT specification EP-5

epoxy was used to bond the nozzles and sensors with the deck and to seal the opening created in the surface.

A 10 by 10 ft pump house was constructed on a concrete foundation to house the 500-gal chemical supply tank, pump, electrical supply box, and system operating equipment. The equipment used to collect video data, telephone equipment needed to communicate with the PLC, and ZENO were also located in this building.

The construction schedule for this project resulted in a January installation of the spray system lines, nozzles, and sensors. Temperatures during the period were often below freezing and never more than a few degrees above freezing. The slope of the deck resulted in water collecting in the in-deck raceways, which froze. This required the raceways to be heated at times to facilitate the installation of the spray lines and sensor cables. The EP-5 epoxy required a minimum 40°F for use. While the air temperature reached this level, the bridge deck had to be heated adjacent to the sensors to bring the deck surface to this temperature.

Each in-deck nozzle was served by its own in-deck raceway, but two and sometimes three cables to the surface sensors were placed in a single in-deck raceway. This increased the difficulty with the installation of the sensors and resulted in the elimination of one monitoring sensor when the cable could not be installed in the raceway provided due to the lack of a raceway cross section.

Integrity of Concrete

The installation of the bridge anti-icing system was coordinated with a deck repair project. The deck repair project was initiated because surface cracking was exposing the deck's reinforcing steel to water. The placement of latex cement concrete was expected to seal the deck and return the surface to an "as new" condition.

A visual inspection of the deck in spring 2000 detected cracks at locations over the in-deck raceways installed to carry the spray system lines and the sensor cable. No investigation of the cause was pursued, but from their location, a safe assumption is that the effect was due to the proximity of the in-deck raceway. No other problems were detected with the surface or the openings created by the installation of the nozzles and the surface sensors.

A visual inspection of the deck in September 2003 did not detect any cracks in the deck but did detect problems with the surface sensors. The cracks over the raceways had closed to a point where they were no longer visible to the naked eye. The epoxy around the nozzle locations appeared sound, but a number of the surface sensors had deteriorated. The compound that holds the sensors, commonly known as the "hockey puck" because it is that size and shape, had melted, covering the contacts. The compound was soft and could be penetrated with a fingernail.

DISCUSSION

This study attempted to answer nine questions. The answers as supported by the findings are as follows:

1. Is the selected system activating properly and early enough during each storm?

The system should be considered as two subsystems, sensing and spray, that work together to form the whole. The surface sensors, part of the sensing subsystem, never properly measured the chemical brine concentration due to improper settings at the factory. Where the brine concentration was a factor, the sensing subsystem did not direct spray subsystem to activate. During season 1, the system did activate on a number of occasions where the video record indicates snow was present and prior to action by a chemical spreading truck. Overall, the sensing subsystem did not properly measure conditions present or activation the spray subsystem appropriately.

2. Does the system provide chemical uniformly to the entire deck and the approach slabs, and how does traffic influence this coverage? The spray subsystem does not provide a uniform coverage to the entire deck, but this may not be necessary. The chemical placed on the surface does not move during snow events except as traffic tracks it to new locations. This phenomenon occurs when chemical is placed by other means. Emphasis should be placed on maximizing the amount of chemical placed in areas where the traffic runs. If this is done, the spray subsystem will provide uniform coverage of trafficked areas.

3. Is the system providing a sufficient amount of chemical? According to the data collected, the application rate was twice that recommended based on the square feet of surface. Since chemical was spread only on locations traversed by traffic, the amount in the traffic lanes should have been more than sufficient. The video supported the finding that the areas traversed by traffic were properly treated, and the bond between the surface and the snow was reduced in those areas.

4. How effective is the anti-icing system and is the system effective only under a limited range of weather conditions? On a few occasions, the system delivered an effective volume of chemical at the appropriate time. The literature indicates that sensing subsystems exist that include algorithms to operate automatically and that activate appropriately a high percentage of the time. The range of weather conditions when a FAST system is effective is similar to that of other deicing and anti-icing methods. Activation of the spray subsystem is not recommended when snow has accumulated, when temperatures are below the effective range of the chemical, or when a large volume of freezing rain is occurring.

5. Have accidents occurred on the deck when icy conditions were reported in its general area? Accident data in the vicinity of the bridge were reviewed covering a 2-year period before and after installation of the system. No accidents of any kind were reported over that 4-year period.

6. Are problems encountered during construction that are related to the design and installation of the anti-icing system? The attempt to place conduit in the bridge deck as part of a

bridge surface rehabilitation caused problems that affected both the bridge deck rehabilitation and installation of the FAST system.

7. *What are the actual costs of operating and maintaining the system?* Operational costs were not documented and are not available. System maintenance was not continued after the pilot test period, and the system has fallen into disrepair. The current state of the system supports the need and value of a scheduled preventative maintenance program.

8. *What routine maintenance is required?* Based on the current condition of the system and the weather sensors, routine maintenance is relatively simple. Draining of the supply lines and tank at the end of the season, flushing of the system with water, and general pump maintenance appear to be all that is necessary for the physical system. The surface sensor deterioration appears to be a product defect, not found with most sensors. The sensors on this site are exposed to conditions that are typical for ESS surface sensors. This sensor deterioration is not typically seen at other sites and is therefore not considered a FAST system routine maintenance issue.

9. *Is the system cost-effective?* This question cannot be answered based on this project site alone. The limitations of time and availability precipitated picking a site that had low traffic volumes and a record of no crashes. Since reduction of costs due to crashes and congestion delay is the major benefit of FAST systems, a benefit-cost ratio greater than 1 was never possible.

CONCLUSIONS

- The assumption that FAST is an anti-icing system, not a snow removal system, was reinforced. As such, the effectiveness is dependent on surface temperature, the amount of chemical dispensed, and the timing of application. FAST must be supplemented with plowing and coordination of subsequent applications of chemicals after the initial application.
- Although FAST can be designed to place chemical anywhere, only chemical placed at locations where traffic travels is effective as a bond breaker.
- The temperature of the surface can vary significantly at any given time and is influenced by solar radiation.
- The condition of the surface (e.g., wet, dry, ice) can vary between locations at any given time.
- Based on the literature review, active sensors produce a more accurate brine freezing point determination over a wide range of chemicals than do passive sensors.
- Preventive maintenance of the system is essential to maintaining the life of the system.

RECOMMENDATIONS

- Consider FAST as an effective option for initial delivery of deicing chemicals to road and bridge travel lanes.
- Develop benefit/cost criteria for prioritizing FAST installations that consider savings for reduced accidents and congestion.
- Place nozzles in the travel lane(s) to maximize the amount of chemical sprayed on the surface.
- Measure surface temperature, surface condition (e.g., wet, dry, ice), and freezing temperature at point(s) where traffic travels. Use monitor multiple locations where feasible.
- Use active sensor(s) to determine the brine freezing point.
- Develop detailed preventive maintenance guidelines for FAST systems and follow them.

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APPENDIX

SENSOR DATA AND UNITS

The ZENO records data once per minute for atmospheric sensors, surface sensors, and the flow rate sensor on the system pump. Each recording results in a line of data, which is date and time stamped for a total of 41 data points per line (excluding the date/time stamp). Atmospheric sensor data and the pump flow sensor data are polled and updated each minute. The ZENO requires more than a minute to poll each surface sensor and polls sequentially. Therefore, each of the eight surface sensors updates once every 11 minutes. Intermediate lines of data for each surface sensor repeat the last update for that sensor. The sensor data collected were as follows:

	Measurement	Units of Measure	Precision	Range
	<i>Atmospheric Sensors</i> (Collected once per minute)			
	Wind speed	Miles per hour	0.1 mph	0 to 134
	Wind direction	Degrees from north	1 degree**	0 to 360°
	Wind gusts	Miles per hour	0.1 mph	0 to 134 mph
	Air temperature	°Fahrenheit	0.1°F	-40 to +176°F
	Dew point	°Fahrenheit	0.1°F	
	Relative humidity	Percent	1 %	0 to 100%
	Precipitation	Inches	0.01 in	N/A
	Solar radiation	Lumens/minute	80μA per 1000 Wm ⁻²	
	<i>Deicer chemical flow rate</i> (Collected once per minute)			
		Gallons per minute	0.1 gal	
	<i>Surface Sensors (8 total)</i> (Collected once every 11 minutes)			
	Surface temperature	°F	0.1 °F	-112 to +176°F
	Surface condition	Condition*	Calculated	N/A
	% Saturation	Percent	1%	0 to 100%
	Freezing temperature	°F	1°F	-5 to +32°F

*Surface conditions reported: Dry; Wet; Wet, temperature below freezing; Ice; Dew; Frost.

**Threshold reading at 2.2 mph.