COLORADO
Department of Transportation

Applied Research and Innovation Branch

Benefit-Cost Analysis of CDOT Fixed Automated Spray Technology (FAST) Systems

Anburaj Muthumani, David Veneziano, Jiang Huang and Xianming Shi

Report No. CDOT-2014-11
October 2014

The contents of this report reflect the views of the author(s), who is (are) responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Colorado Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CDOT-2014 - 11		

4. Title and Subtitle	5. Report Date
Benefit-Cost Analysis of CDOT Fixed Automated Spray Technology (FAST) Systems	
	6. Performing Organization Code
7. Author(s) Anburaj Muthumani, David Veneziano, Jiang Huang and Xianming Shi	8. Performing Organization Report No. CDOT-2014-11
9. Performing Organization Name and Address Western Transportation Institute P.O. Box 174250 Bozeman, MT 59717-4250	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Colorado Department of Transportation - Research 4201 E. Arkansas Ave. Denver, CO 80222	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the US Department of Transportation, Federal Highway Administration

16. Abstract

The Western Transportation Institute (WTI) conducted research on behalf of the Colorado Department of Transportation (CDOT) to study the cost effectiveness of existing CDOT FAST systems. Both the national survey and the CDOT survey confirm the need for significant maintenance activities to ensure successful operation of FAST systems. Safety analysis of CDOT FAST system reveals a reduction in the number of annual crashes on multilane rural highways by 2 percent, urban interstates by 16 to 70 percent, rural interstates by 31 to 57 percent and interchange ramps between interstates by 19 to 40 percent. Overall, CDOT FAST systems included in the analysis have reduced crash severities at many sites resulting in potential safety benefits of $196,428 per winter season during the "after deployment" study period. Further, a benefit-cost excel sheet was developed based on the estimated crash reductions observed for each of the different roadway types.

Implementation

The study found that FAST systems have demonstrated the potential to reduce the number of crashes and reduce the cost of winter maintenance activities, if sited at appropriate locations (e.g., high-traffic-volume ice-prone ramps). However, improved installation techniques and involvement of maintenance crews during FAST installation are necessary to further increase the cost-effectiveness of a FAST system deployment. Extra effort will be made in sharing the information gained from this research study by focusing on CDOT personnel involved in planning, design, construction, operation and maintenance of FAST systems.

17. Keywords	18. Distribution Statement
Fixed automated spray technology, winter road maintenance, cost benefits, safety analysis, snow and ice control	This document is available on CDOT's website http://www.coloradodot.info/programs/research/pdfs

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

BENEFIT-COST ANALYSIS OF CDOT FIXED AUTOMATED SPRAY TECHNOLOGY (FAST) SYSTEMS

Final Report

CDOT - Study No. 42.50

Submitted to the Colorado Department of Transportation

by

Anburaj Muthumani, M.S.
Research Associate
Western Transportation Institute
Montana State University
Bozeman, Montana

David Veneziano, Ph.D.
Research Scientist II
Western Transportation Institute
Montana State University
Bozeman, Montana

Jiang Huang, M.S.
Research Associate
Western Transportation Institute
Montana State University
Bozeman, Montana

Xianming Shi, Ph.D., P.E.
Senior Research Scientist, Western Transportation Institute
Research Professor, Civil Engineering
Montana State University
Bozeman, Montana

A Report on Research Sponsored by
Colorado Department of Transportation - Research
4201 E. Arkansas Ave.
Denver, CO 80222

October 2014

ACKNOWLEDGEMENTS

The authors wish to thank the CDOT Applied Research and Innovation Branch for funding this research and David Reeves for overseeing the project. Authors also acknowledge the guidance and valuable support provided by the CDOT panel members Phillip Anderle, Roberto DeDios, David Wieder, Masoud Ghaeli, Stephen Henry, Aziz Khan, Mark Mueller, Skip Outcalt, Steve Pineiro, Andrew Pott, David Swenka, Matt Rickard, Matt Greer and Richard Griffin. Further, they would like to thank Todd Anselman, Thomas Aguilar, Mark Carrillo, Kenneth Quintana, Ronald Morin, Wayne Lupton and Allen E. Roys for their support during the field site visits. The professionals who responded to the surveys in this study are sincerely acknowledged. Special thanks are due to Carla Little for her editorial assistance for this report.

EXECUTIVE SUMMARY

The Western Transportation Institute (WTI) conducted research on behalf of the Colorado Department of Transportation (CDOT) on the effectiveness of Fixed Automated Spray Technology (FAST) systems. FAST systems have emerged as an important way to supplement mobile winter maintenance operations by enabling winter maintenance personnel to treat selected locations before snow and ice problems arise. However, some CDOT regional maintenance personnel have concerns regarding the performance, cost-effectiveness, and safety effects of the technology; whereas others have a favorable view toward FAST based on historical performance and observed benefits. In this context, this study was conducted to determine the cost-effectiveness of all the existing CDOT FAST systems. Components of the study included a literature review, a national survey, a CDOT survey, a safety analysis, and a benefit cost analysis.

<u>Literature review</u>

The literature review revealed that the FAST system uses complex technologies, and implementation challenges are often site-specific. Difficulties can be expected during operations, particularly in areas related to software, activation processes, and pumping systems. Also, researchers emphasize the growing need to focus on low-cost systems and high-reliability sensors to maximize the benefits of FAST system.

<u>National survey</u>

Twenty-five respondents participated in an online survey to document the use of currently available systems, and to highlight the successes and lessons learned from FAST practitioners.

- The survey revealed that almost every installed FAST system (reported in this survey) needed significant maintenance activities for its successful operation. In one case, a FAST system failed to operate even after repeated maintenance activity.
- Initial cost of a FAST system is significantly higher than the annual operating and maintenance costs. However, respondents believe that payback period could be as short as one year for a properly functioning FAST system.
- The benefits of using FAST perceived by the agencies include: reduction on winter related accidents, savings on material use and labor, and reduction of negative environmental impacts.

<u>CDOT survey</u>

Within CDOT, WTI conducted an online survey of CDOT personnel who use FAST systems, and a field trip to observe selected sites that use the technology.

- Inconsistency in proper functioning of FAST systems among various CDOT regions is mostly due to the poor design, poor quality of installation and lack of maintenance practices for some cases.
- FAST systems in Colorado faced frequent mechanical, electrical and software issues.

- Involving maintenance crew in every aspect of design and installation of FAST systems could help reduce the maintenance issues.
- Location selection is an important factor for the success of a FAST system. Further, FAST systems may not be of benefit for some types of bridges (e.g., straight and short-span bridges that are less than 40 feet).
- In addition to the improved installation technique, continued success of the FAST system heavily relies on timely maintenance activities.

Safety analysis

The research team employed accident prediction models to estimate the number of crashes before and after FAST deployment, in order to better quantify the impacts that the systems had on crashes.

- The safety analysis of CDOT's FAST system revealed an estimated reduction in the number of annual crashes on multilane rural highways by 2 percent, urban interstates by 16 to 70 percent, rural interstates by 31 to 57 percent and interchange ramps between interstates by 19 to 40 percent.
- CDOT FAST systems have reduced crash severities at many sites, resulting in potential safety benefits of $196,428 per winter season during the "after deployment" study period.
- FAST may be better applied on higher traffic roads when the intent is largely to prevent or reduce crashes. If maintenance concerns are paramount, then FAST installations may provide an advantage on a two-lane road.

Benefit-cost analysis

Finally, a benefit-cost excel sheet was developed based on the estimated crash reductions observed for each of the different roadway types. The benefit-cost excel sheet used crash reduction rates of 10 percent for two-lane rural locations, 2 percent for multilane rural freeway locations, 16 percent for urban interstate locations, 31 percent for rural interstate locations and 40 percent for interchange ramp locations.

IMPLEMENTATION

The study using a model and traffic accident history found that FAST systems have demonstrated the potential to reduce the number of crashes and reduce the cost of winter maintenance activities, if sited at appropriate locations (e.g., high-traffic-volume ice-prone ramps). However, improved installation techniques and involvement of maintenance crews during FAST installation are necessary to further increase the cost-effectiveness of a FAST system deployment.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

AADT – Annual average Daily Traffic

AASHTO – American Association of State Highway and Transportation Officials

ADT – Average Daily Traffic

ARWIS - Advanced Road Weather Information System

$CaCl_2$ - Calcium Chloride

CMA - Calcium Magnesium Acetate

CMAK - a mixture of CMA and KAc

CMFs - Crash Modification Factors

CPI - Consumer Price Index

DOT –Department of Transportation

EB - Empirical Bayes

ESS - Environmental Sensor System

FAST – Fixed Automated Spray Technology

HSM - Highway Safety Manual

KAc - Potassium Acetate

$MgCl_2$ - Magnesium Chloride

NaCl - Sodium Chloride

PDO - Property Damage Only

RPU - Remote Processing Unit

RTM - Regression-to-Mean

RWIS - Road Weather Information Systems

SH – State Highway

SPF - Safety Performance Functions

INTRODUCTION

Anti-icing is the application of chemical freezing-point depressants on the roadways in advance of or during deteriorating weather conditions, aimed to prevent black ice formation and to prevent or weaken the bond between ice and the road surface. Recent study has revealed that anti-icing works by not only depressing the freezing point of the solution on pavement but also physically weakening the ice on pavement (Klein-Paste and Wåhlin, 2013). Compared with traditional methods for snow and ice control (e.g., deicing and sanding), anti-icing (if applied appropriately) can lead to decreased applications of chemicals and abrasives, decreased maintenance costs, improved level of service, and lower accident rates (O'Keefe and Shi, 2006).

In the last two decades or so, anti-icing has been gradually accepted and adopted by North American highway agencies as a proactive approach to addressing winter driving safety. Anti-icing can be performed through many different methods, through either fixed asset or mobile asset technologies. Mobile asset anti-icing technology is widely accepted and practiced by many agencies to combat severe winter roadway conditions and maintain a high level of service. This type of technology generally uses tanker-equipped trucks with specialized spray equipment to deliver a liquid (sometimes solid) agent onto the roadway pavement based on the analysis of weather forecast. Fixed Automated Spray Technology or FAST systems are designed as a fixed asset technology for anti-icing operations at specific target areas such as bridges, tunnels, ramps and other elevated roadways (Hanson et al., 2013). This technology is a permanent installation of a pump, tank nozzles, and a controller, with the application of anti-icing chemicals on a predetermined area. The system can be initiated by manual activation, or by automation based on detected highway conditions. FAST systems, if coupled with road weather information systems (RWIS), reliable weather forecasts and performance metrics, make the anti-icing program complete and promote the paradigm shift from being reactive to proactive in fighting winter storms at key locations.

FAST technologies remotely sense the potential of frost or ice formation on pavement in light of atmospheric and pavement data from RWIS or an Environmental Sensor System (ESS), and apply chemical freezing-point depressant in a timely manner. There are sensitive structures and critical segments of the roadway network that need to be free of snow and ice in a timely manner, before the winter maintenance vehicles can travel to the site and treat them. During the winter season, accidents often occur on bridge decks or shaded areas where the surface temperature tends to be lower than the adjacent areas and to create potentially hazardous driving conditions, such as frequent frost and black ice (Friar and Decker, 1999, Barrett and Pigman, 2001). With conventional mobile operations, it is difficult and costly to maintain levels of service and traffic safety for locations far from the winter maintenance sheds (Christillin et al., 1998), or for areas that experience a high traffic volume. In contrast, FAST is a technological solution designed to provide quick, effective service delivery to such high-risk locations prone to icy conditions and/or with high traffic volumes, while reducing the amount of labor and materials needed through timely prevention of ice formation/bonding or snow packing. FAST systems are ideal where stretches of highway: (1) are very remote and application of material by truck would take several hours, (2) have very high traffic volumes and traffic congestion creates a significant barrier to winter maintenance, or (3) are prone to icing or accidents, such as bridges, off ramps, and intersections (Bell et al., 2006). The benefits of FAST may include: quick response time, enhanced roadway safety, reduced chemical use, reduced corrosion and negative environmental impacts, and reduced traveler delay and stress. A conceptual study for the Minnesota Department of Transportation (MnDOT) indicated that eliminating even one accident per year would provide a benefit-cost ratio greater than 1 for two automated systems installed at bridge locations (Keranen, 1998). Another study indicated a benefit/cost ratio of 2.36 for a proposed FAST installation on a section of I-90 in Washington State, assuming a 60 percent reduction in snow and ice-related accidents (Stowe, 2001).

In this context, this work synthesizes information with a focus on the benefit-cost analysis of Colorado Department of Transportation (CDOT) FAST systems. The information in the study is presented in the following sections:

- Literature review and documents pertaining to the state-of-the-practice of FAST systems.
- National survey to examine the user experience of FAST systems.
- Field survey to examine the FAST systems operated by CDOT.
- Safety analysis of CDOT FAST systems.
- Benefit-cost analysis sheet for CDOT's specific use.
- Best management practice guide.

1. LITERATURE REVIEW

Description of FAST system

FAST systems were originally developed in Europe, with two early systems installed in Germany and Switzerland, and have been used in Europe more extensively than in North America (Hanson et al., 2013). Since the mid-1980s, hundreds of automated anti-icing systems have been used throughout Europe as an established tool to battle snow and ice conditions on highways, bridges, and airports. In North America, FAST is a relatively new technology that has gained popularity since the late 1990s (SICOP, 2004). FAST systems aim to deliver the anti-icing chemical to key locations in a controlled manner, using pumps, piping, valves and nozzles or discs (Waldman, 2004, Beach and Waldman, 2005). Ideally, the application should be fully automated, using the pre-programmed logic and real-time input from a number of atmospheric and pavement sensors on site. When the sensors detect ice presence or an imminent frost or icing event, the nozzles will be automatically triggered to spray the anti-icing chemical at a pre-determined rate and pattern. Figure 1 shows a FAST system in operation on a bridge.

Figure 1: A FAST system in action

While the concept is intuitive, its implementation is complex as the FAST system “integrates sensing technology, fluid mechanics, data processing, and communications technology with the concrete and asphalt of a highway facility” (Bell et al., 2006). To reduce the level of sophistication and facilitate the implementation of FAST, systems with less automation are often deployed in the U.S., particularly those with the capabilities of automatic detection and remote activation. Such systems sacrifice some of the FAST benefits for better system reliability. For instance, the fully automated FAST system may be able to treat short-lived frost events, whereas the remotely activated FAST system cannot. In addition, the fully automated system can improve the level of service at the installation site even when the winter maintenance personnel are not available.

A complete FAST system includes a spray subsystem that delivers the anti-icing chemical onto the road surface and a control subsystem that triggers the spraying action. The spray subsystem consists of the following:

- Reservoirs to store an appropriate amount of anti-icing chemical in accessible areas. Anti-icing chemicals range from potassium acetate, calcium magnesium acetate, sodium chloride, calcium chloride and magnesium chloride, to other products (SICOP, 2004), generally in liquid form.
- A set of pumps to deliver the chemical through the piping of the hydraulic system, which connects the nozzles to the reservoirs through valves. A pump station is often installed by the side of the FAST installation site (e.g., a bridge deck) to house the valves, filters, and reservoir level sensors. Other sensitive equipment used to manage the FAST system’s power and communications and an interface that monitors the proper functioning of the system are also installed in the pump station, which is accessible only to authorized personnel.

- A series of valves that deliver the chemical to various point locations.
- A set of devices that spray the chemical onto the road surface in an appropriate manner. They are flush nozzles, or spray nozzles, mounted on a barrier, curb, parapet, or bridge rail, or spray discs embedded in the pavement.

The control subsystem consists of the following:

- RWIS or atmospheric and pavement sensors on-site for early frost or ice warning. If they work properly, these sensors enable the FAST system to be fully automated and thus provide truly proactive treatment of the road surface in a timely manner. Pavement sensors usually collect data to detect snow, frost and ice presence; temperature of pavement surface and subsurface; pavement condition (dry, moist, or wet); chemical concentration of moisture on roadway; and freezing-point temperature of the moisture. Passive sensors such as infrared road surface temperature sensors have been useful in predicting freezing-point temperatures; however, their accuracy has not been very satisfactory. Active sensors offer more accurate measurements as they collect a sample of liquid that is on the roadway. They often use a Peltier cell to cool and warm any moisture or liquid on top of them to determine its freezing point (Pyde, 2005), by measuring the amount of energy released when the mixture melts.
- A remote processing unit (RPU) that is able to collect data from road condition sensors and atmospheric weather sensors, then process, store, and transmit the data to the computer monitor. The historical data are recorded to compare with the real time data for later performance review. It should trigger the spray system with an appropriate spray program based on observations from the detection sensors (Bell et al., 2006). Maintenance personnel at the headquarters or shed level can also use a modem or network to access real-time data at the RPU and monitor the conditions. The RPU should allow maintenance personnel to choose from different spray configurations (i.e. rate, mix, and time) based on the observations or sensor readings, and offer the capability to remotely activate, stop or modify the configurations.
- A FAST data server to store the data at a physical location different from the RPU, to avoid potential disruption or security breaches to the control of the FAST system. The server dials out to the FAST site on a regular interval to retrieve and archive data. These data can be accessed from the server via dial up or network connections and can be viewed with proprietary vendor software (Pinet et al., 2001).
- A software application to display the FAST data in graphic and tabular formats and to manage users and their privileges.
- Electronic control and triggering devices. For automated activation, when the atmospheric and pavement conditions meet the pre-determined parameters, the logic module triggers or stops the sprayers accordingly. When not in the automated mode, the

activation signal for the FAST system can be sent remotely via a cellular phone call, a text message, or a command from a maintenance employee's computer via dial-up/broadband connection or wireless digital communication systems. While rarely used, another manual activation option is a push-button at the installation site.

Planning and Design of FAST System

Location Selection

FAST is not a cost-effective solution for the entire road network, but rather for key locations where it can derive the maximum benefits. Selection of the proper site is crucial to the success of any FAST system installation. The site should have unique characteristics such as high winter accident statistics, a remote location away from the regular maintenance route, or very high traffic volumes (CERF, 2005). A report summarizing the experience of the Kentucky Transportation Cabinet recommended that the FAST system be used in the following areas and/or conditions: (1) crash-prone areas, (2) isolated structures that require the deicing truck to travel an unreasonable distance to treat, (3) remote areas that are difficult to reach in bad weather, or (4) bridges over water which may be more susceptible to freezing moisture (Barrett and Pigman, 2001). In a CDOT report, it was indicated that FAST system would be more efficient if the winter maintenance vehicle would take two or three hours to reach the location and apply ice control chemicals (Bell et al., 2006). A methodology and a decision support tool were developed for the Nebraska Department of Roads to prioritize candidate bridge deck FAST installations, which considered accident history, bridge alignment, weather, traffic, and bridge distance from maintenance yard, among others (Khattak et al., 2003). Such an approach supported by in-depth data analysis is highly recommended before investment in FAST systems, as it illustrates the conditions and constraints defining the need and viability to install and maintain a FAST system at a given location. In principle, FAST systems should be deployed at locations that are remote, feature high traffic density and significant congestion, or feature considerable safety risk during wintery weather (Ye et al., 2013).

In-House vs. Vendor

Before making the investment, the agency should consider various options for implementing FAST. For instance, the New York City DOT successfully designed and built their FAST systems in-house (Ward, 2002). The Utah DOT designed and installed a home-built FAST system on the Northbound I-215 at Knudsen's Corner (Stewart, 2004). However, most DOTs have used a contractor to deploy their FAST systems, in which case performance and quality should be considered the most important criteria for the contractor selection.

Considerations in System Design

FAST is not an "off-the-shelf" system that can be purchased and installed right away at any given site. It requires customized design of the installation after studying the site requirements and conditions (CERF, 2005), such as the specific spray logic. Feasibility studies are necessary to identify and address technical design and systems issues; structural and aesthetic concerns; and costs and warrants for the FAST installation (Pinet et al., 2001). Infrastructure needs should be considered before FAST installation, such as utilities to the site and communications between on-site sensors and the maintenance headquarters (Stewart, 2004).

A study by Bell et al. (2006) recommended the following features to be part of each FAST installation: full RWIS instrumentation; full automatic detection and activation; active and passive roadway sensors; data recording for atmospheric and road surface conditions as well as system functions; manual activation (on-site or remote) or automatic activation; and alarm notification for system activation and system functions (e.g., leaks, pump failure, activation failure, low chemical level). Other desirable features include multiple firing and time cycles, ability to adjust firing sequences and chemical volume, and compatibility with the National Transportation Communications for ITS Protocol (NTCIP) (Bell et al., 2006). Several potential considerations were identified during research on the A2 Jubilee Way Bridge FAST system installed in United Kingdom in 2009 and operated in 2010-2011 winter season, and should be taken into account during feasibility studies. These considerations include the high capital cost; local unique specific design; the consistent power supply; and monthly, pre-season and post-season maintenance to ensure safe operation (Plumb, 2011).

Detailed specifications must be established for components of the FAST system that are prone to failure, such as storage reservoirs; pumps; pipes, valves and other delivery system components; nozzles; and triggering mechanism and associated components (Bell et al., 2006). A sufficient storage reservoir for chemicals must be provided on site, and during the fall, chemical levels may be low as a result of activations to address early morning frost (Pinet et al., 2001). Another consideration with respect to storage of chemicals is the location of the tanks, which should facilitate their replenishment during wintery weather. Placing multiple sensors in the traffic lanes along the roadway might provide more reliable data on pavement conditions.

Information technology staff should be involved in the early stage of the contracting process. The FAST system should be designed with an open architecture to facilitate the integration of additional sensors in the future. The vendor should fully describe the FAST system decision logic, programs and default variables to the agency, and licenses for proprietary user interface software must be flexible enough to allow for access by the full range and number of potential users (Pinet et al., 2001). The system data server should permit full access to atmospheric, pavement and FAST data and for data mining by the system administrators (Pinet et al., 2001).

The type and quality of the anti-icing chemical used for the FAST system can significantly affect its performance (CERF, 2005), and FAST chemical selection should consider potential interaction with the chemical applied on the adjacent roadway segment. For instance, magnesium chloride may react with potassium acetate and form a precipitate (Stewart, 2004, Shi et al., 2011) that may lead to slippery conditions. The chemicals used should be verified to be non-corrosive to the reservoirs, pipes, valves, and nozzles. Moreover, from a quality point of view, the liquid chemicals should be free of foreign matter or particulates so as to prevent clogging of filters, screens or nozzles. Despite the fact that the system contains strainers to prevent some objects entering the pipe work, crystallization may occur from some anti-icing solutions which can cause blockages. Finally, the procurement contract for anti-icing chemicals should take into account the holding capacity of the FAST system reservoirs (Stewart, 2004). Potassium acetate has been used to avoid problems with corrosion. However, based on the experiences of using other chemicals, corrosion can be reduced by preventive maintenance practices and applying protective coatings. The selection of chemicals should be primarily based on its ability to perform over its effective temperature range. (Interview with users/vendors - User experience, (Bell et al., 2006))

It should be noted that there are two distinct hydraulic system design philosophies for FAST systems. The first design (referred to as Type I), more common in North America, utilizes a pump located in a pump house to deliver the fluid to the nozzles some distance away. The delivery pressure needs to be rather high to overcome the hydraulic head loss in the delivery lines. In these systems the flow is metered by the size of the nozzle orifice. The reliability of these systems becomes more problematic as the nozzles get farther away from the pump. In the second design (referred to as Type II), common in European systems, the pump at the pump house is used to fill a small pressurized vessel (tank) located in close proximity to each individual nozzle. When the signal to activate is given, a valve on the small pressure vessel is opened and the liquid is discharged through the spray head. This reduces the effect of the head loss, delivering a fixed amount for each activation.

Installation and Warranties

A traffic control plan should be submitted by the contractor before the FAST installation (Stewart, 2004). The construction process should be carefully inspected, particularly when the nozzles or discs are cored into the bridge or roadway surface. In the FAST installation contract, it is advantageous to require a 30-day “burn-in” period during the winter months and to include an extended warranty. A long term relationship with vendors is needed to ensure the FAST system functions as intended. The installation of a FAST system is an ongoing commitment, not a one-time event. There are significant challenges in achieving fully automated operation of a FAST installation, and there should be significant work in the deployment phase to achieve full functionality (Bell et al., 2006). It is suggested to avoid winter installation of FAST (Lo and Bielkiewicz, 2013).

Operation and Maintenance

The experience of several agencies has provided valuable information regarding successful operations and maintenance requirements of FAST systems. To be cost-effective, the spray operations should not be activated under certain inclement road weather conditions, such as when snow has accumulated, when temperatures are below the effective range of the chemical, or when a large volume of freezing rain is occurring (Roosevelt, 2004). In moderate to heavy snowfall (greater than 2 inches [5 cm] of accumulation), instead of the FAST system, a plowing operation by vehicles becomes essential to ensure roadway safety (CERF, 2005). The Province of Alberta, Canada has suggested to monitor seasonal liquid changeovers in the system, check for consistent spray coverage (over-spraying or under-spraying), and check for leaks to ensure proper and effective operation (Lo and Bielkiewicz, 2013).

Previous studies have documented preventative maintenance requirements for FAST, and these cover before-season, during-season, and after-season inspection and services needed for the FAST system to work properly (Barrett and Pigman, 2001, Roosevelt, 2004). For manually activated systems, which are less complex and more affordable, agencies should have staff with expertise utilizing RWIS and anti-icing practices regularly monitor site conditions (Bell et al., 2006). For systems operated in a semi-automatic mode (remote activation) based on video monitoring of the site, a high-quality video camera and sufficient transmission rate for its data transmission are key to successful operations. For the fully automated systems, the upper edge of elevated bridges should be cleared of snow. Otherwise, on sunny days the snow may melt and run across the structure and trigger unexpected sprays (Pinet et al., 2001).

Additionally, in North America there might not be the supply of readily available parts, particularly if the system is imported from Europe. In such cases, the use of different languages in manuals and software code can create issues during maintenance and repair of the system. The training should be suitable to address a variety of levels of expertise and is required on an ongoing basis (Pinet et al., 2001). In addition, it is important to seek technical support from the vendor and perform the maintenance activities according to the manufacturer's recommendations. The agency should work with the vendor to optimize the operational parameters such as spray pattern, angle, and pressure and to ensure proper spray area coverage for wheel paths, and to optimize the use of chemical and customize it for agency or local preferences (Pinet et al., 2001). On balance, North American transportation agencies consider FAST to be an evolving technology (Ye et al., 2013).

FAST System Evaluation and Case Studies

Much research has been conducted to evaluate the costs and benefits of utilizing FAST systems. Fixed Automated Spray Technology systems are now in use in more than 20 states in the U.S., Canada and some European countries. In general, the costs to operate and maintain the FAST systems are relatively small compared to the installation costs. On-going costs include those related to labor, anti-icing chemicals, utilities, communications, scheduled and periodic cleaning of check valves, routine maintenance, repairs/replacement and system modifications. A FAST system installed on a bridge on Interstate 215 in Utah in 2003 was fully automated by both on-location active and passive sensors or by meteorological conditions. The system used 18 valves to spray potassium acetate onto the bridge via deck-mounted spray discs. The total cost for installation was $250,000. Traffic control costs amounted to $7,000. First full year operations used 1,500 gallons of potassium acetate, costing approximately $4,500 (Stewart, 2004). For a demonstration FAST system installed in Ontario, Canada covering a total of 21,100 ft^2 (1,960 m^2) of bridge and its approach area, the actual construction cost and the annual operating cost (excluding maintenance of the spray system, pumps and systems) were $300,000 and $15,000, or $14.20/$ft^2$ and $0.70/$ft^2$, respectively (Pinet et al., 2001). For later deployment of FAST systems in Ontario, however, the bid price of the basic spray systems ranged from $90/$ft^2$ to $370/$ft^2$ for two-lane structures, and a cost of $93,000 was estimated for the Advanced Road Weather Information System (ARWIS) station associated with each FAST installation.

Currently there is a lack of evaluation for the cost-effectiveness or environmental-friendliness of FAST relative to mobile operations or anti-icing pavement technologies. Furthermore, the anticipated benefits from FAST systems are site-specific and are a function of winter weather severity, traffic density, accident history, and distance from maintenance yard, among other factors. The following sections present case studies of FAST systems that were installed in Europe or North America, and the associated benefits, costs and reliability that were analyzed in some of the studies.

European Experience

It is interesting to note that FAST has been considered a proven technology in Europe and the systems deployed did not report any problems with the automated activation, in contrast with the user experience across North America (SICOP, 2004, Bell et al., 2006). A couple of studies have documented positive results of FAST deployments in Europe. The largest FAST system in Europe was developed on an 8.15 km stretch of the A9 Lausanne bypass in Switzerland. A detailed economic analysis of the FAST system indicated a benefit cost ratio of 1.45. Similar results were found in Germany, where a FAST system that has been installed since 1983 revealed a benefit cost ratio of 1.9 (Bell et al., 2006).

A FAST system (with Type I hydraulic system design) was installed in 1984 along a 3.7-mile (6 km) long, topographically and climatically challenging road section between Hagen and Lüdenscheid in Germany. The benefits regarding road safety were assessed by considering the annual number of accidents due to winter conditions (e.g. snow and icy patches) in two seven-year periods before and after the system installation. The number of accidents was reduced by 58 percent and traffic congestion was also reduced, leading to an estimated benefit-cost ratio of 1.9 (Gladbach, 1993). An analysis by the German Federal Highway Research Institute indicated a similar benefit-cost ratio for the various FAST systems deployed on the German Federal road system (Moritz, 1998).

Another FAST system (with Type II hydraulic system design) was installed along a 5-mile (8-km) long road segment of a six-lane highway in Switzerland that had an average daily traffic (ADT) volume of 70,000 vehicles per day (vpd). The salt brine was stored in four main (3,170-gallon or 12,000-L) and eight intermediate (528-gallon or 2,000-L) tanks. The system could be either manually triggered, or automatically activated when the ice detection system of twelve active sensors detected ice or gave advanced warning of ice formation. A pre-installation analysis indicated a benefit-cost ratio of 1.45, considering capital, interest and depreciation costs, material costs, and savings due to accident reduction and avoided mobile maintenance operations.(Zambelli, 1998)

Table 1: Calculation of agency cost for European and North American countries (Plumb, 2011)

System	**Stage**	**Cost per lane mile ($)**
FAST system Project data average from a number of systems in Europe and North America	Installation of FAST system	1,452,499
	Recurring operation	27,858
	Asset maintenance	7,085 per year plus 80,837at 5 years
	Salvage/residual value	241,546
FAST system Northern France	Installation of FAST system	1,460,551
A2 Jubilee Way Bridge FAST System	Installation of FAST system	1,216,023
	Annual operating costs	20,403

A more recent FAST system, weather station and associated works were installed along Jubilee Way, Dover during 2009 and operated for the 2010-2011 winter period in the United Kingdom. The FAST system is located on Jubilee Way Bridge and designed to operate automatically or manually, with surface sensors constantly monitoring the road surface temperature and surface friction. The cost benefit analysis has shown a system costs comparison among the average costs of a number of existing systems in Europe and North America, a FAST system in Northern France, and the A2 Jubilee Way Bridge FAST system (Wint et al., 2008). Table 1 provided more detailed information on the comparison. The study indicated that Jubilee Way FAST system cost was comparable with the cost figures of FAST systems set up in North America and Europe. No winter related crash reduction data were reported, since the number of incidents on Jubilee Way was not sufficient to statistically consider incident reduction following installation of the FAST system. The system has been both effective and reliable; a site visit has identified pressure failure rather than automatic system checks. Regular visits and the installation of a camera to give warning of such problems were recommended. The authors concluded that a comprehensive feasibility study should be conducted to identify and address technical design and system issues, structural and aesthetic considerations, cost and justification. An investigation into the effects of different types of anti-icing liquid and/or different concentrations to demonstrate system functionality utilizing these liquids is recommended prior to adoption (Plumb, 2011). Table 2 provides the summary of European Experience on FAST Implementation.

Table 2: Summary of European Experience on FAST Implementation

Study /Country	**Winter Season Studied**	**Location /Chemicals**	**System Description with Hydraulic Type**	**Benefits and Costs /B-C Ratio**
Gladbach (1993) /Germany	1984 (Two seven-year periods before/after installation)	3.7-mile (6 km) long topographically and climatically challenging road section between Hagen and Lüdenscheid /NA	Type I	Accidents reduced by 58%, traffic congestion reduced. /1.9(similar ratio for German FAST)
Zambelli (1998) /Switzerland	1997	a 5-mile (8-km) long with a six-lane highway ADT: 70,000 /salt brine	Type II/ both manual and automatic mode	Reduced capital, interest, depreciation costs and material costs Accident reduction, avoided mobile maintenance operations /1.45 with interest costs included(or 1.98 without)

Plumb (2011) /United Kingdom	2010-2011	A2 Jubilee Way Bridge, Dover. /Potassium acetate (magnesium chloride or sodium chloride).	Automated and manually operated: remotely via radio, telephone or via secured internet site. Non-invasive pavement sensors and the associated activation system constantly monitor weather parameters	Benefits will be realized on particularly busy, strategically sensitive or vulnerable roads that are hard to access or maintain Installation cost: S725, 082 and the annual operating costs: $12,166 /No b-c ratio computed

North American Experience

The effectiveness of a parapet-mounted, "home-built" FAST system (with Type I hydraulic system design) installed on an interchange/overpass on I-215 in Salt Lake City, Utah was analyzed for the 1997-98 winter season. The system applied approximately 60 gallons/lane-mile/spray event of liquid magnesium chloride to the northbound lanes of the freeway bridge deck. Comparing the 1997-98 winter season data with the five previous winters, a 64 percent reduction in snow and ice-related accidents was reported on the northbound lanes (Friar and Decker, 1999), at least part of which was attributable to the FAST system. No operational issues were reported with this FAST system.

The Virginia DOT (Roosevelt, 2004) conducted a pilot FAST installation (with Type I hydraulic system design) on a 30-ft (9.1-m) wide bridge on a roadway in Fairfax County in 1998. The nozzles were placed in three configurations: parapet-mounted, in-deck lane-mounted and in-deck centerline-mounted to spray magnesium chloride brine. The environmental sensor station for the installation, provided and installed by the Virginia DOT, was unable to determine the chemical concentration on the structure; therefore, the system failed to accurately determine the freezing-point temperature of the bridge surface. As such, the automated triggering mechanism could not work appropriately. No benefit-cost analysis could be performed for this study due to the lack of data. However, the FAST system was able to uniformly spray chemicals over the bridge with the assistance of traffic and was considered an effective option for initial delivery of anti-icing chemicals. It was suggested to place nozzles in the traffic lane(s) to maximize the spray coverage on the surface and to place multiple active sensors in the traffic lanes to improve the accuracy of measuring surface temperature, surface conditions and freezing-point temperature.

The first FAST system in Canada (with Type I hydraulic system design) was installed along a 550-ft (168-m) interchange ramp with an ADT of 3,000 vehicles per day (vpd) in Ontario. The sensors in place detected the roadway and atmospheric conditions and either sounded an alarm so that the maintenance personnel manually triggered the sprayers, or the spray operations were activated automatically. No winter weather-related accidents had occurred since the FAST installation (Pinet et al., 2001). It also resulted in benefits to the environment by the elimination of road chloride salt use. Chemical costs for the potassium acetate, however, were approximately twice as much as anticipated ($12,000 vs. $5,000-7,000 per year), partly due to unnecessary spray. The estimated benefit-cost ratio is 1.13 and the investment was recovered in the first year of operation. Table 3 demonstrates the benefit-cost comparison associated with the system.

Table 3: Benefit Cost Demonstration, 401/416 Ramp, Prescott, ON (Pinet et al., 2001)

Costs		**Benefits**	
Design, Construction, Commissioning	$300,000	Collision Avoidance	$165,600
Operating	$30,000	Reduced Corrosion	$10,666
		Reduced Travel Delays	$198,072
Total Costs	$330,000	Total Benefits	$374,338

A study conducted by Barrett and Pigman (2001) evaluated a FAST system (with Type I hydraulic system design) installed on a bridge on southbound Interstate 75 at the north interchange to Corbin, Kentucky in October 1997. The system was remotely activated by the winter maintenance personnel through a dial-up connection, based on a combination of the RWIS information and visual observations from a video camera. The eleven parapet-mounted/bridge rail-mounted spray nozzles per side treated the two travel lanes and the approach plate with liquid calcium chloride at the rate of 8 gallons (30 liters) per application along the 600-ft (183-m) segment. After four winter seasons, the system had minimal problems associated with it, worked efficiently as expected and prevented the formation of icy conditions on the bridge deck. There was no noticeable driver reaction to the spraying as it occurred. However, the study found that system was not as effective as anticipated since the location was neither prone to freezing conditions nor remote from maintenance sheds. The study highlights the need for selecting appropriate locations such as crash prone areas, isolated structures or remote structures and bridges that are prone to freezing conditions to achieve the anticipated benefits (Barrett and Pigman, 2001).

A FAST system (Type I hydraulic system design) was installed on a bridge on Interstate 68 in Allegany County, Maryland in the 1998-99 winter season to spray CMAK (a mixture of calcium magnesium acetate and potassium acetate sold by Cryotech). Initially the system experienced problems such as plugged nozzles and pipelines, loose fittings and software issues. The problems were fixed and system improvements were made, including a low level warning on the storage tank and the deployment of a wide angle camera monitoring both eastbound and westbound bridge decks simultaneously. The Maryland DOT considered the system a major success, as it reduced accidents on the bridge by approximately 40 percent and led to estimated cost savings of $16,000 due to avoided mobile operations (Lipnick, 2001).

The installation, operations and safety benefits of a FAST system (with Type I hydraulic system design) deployed on a 2,000-ft (609-m) long, six-lane wide Interstate 35W bridge over the Mississippi River, Minnesota was analyzed by MnDOT in 1999 (Johnson, 2001). The system included eight parapet-mounted nozzles and 68 flush-mounted disc spray nozzles, as well as 38 valve units each controlling the chemical flow of two nozzles. Potassium acetate was the anti-icing chemical stored in a 3,100-gallon (11,734-L) tank. Comparing the 2000-2001 winter season data with the climatologically similar 1996-1997 winter season, a 68 percent reduction in winter-related accidents was reported, at least part of which was attributable to the FAST system. The other benefits include reduced traffic congestion associated with winter crashes, improved productivity by lowering material costs and enhancing winter maintenance operations. For the $538,300 FAST installation, a benefit/cost ratio of 3.4 was estimated based on the cost savings assigned to reduced crashes and delays. The automatic triggering mechanism worked appropriately and adequately activated the system. The report also detailed operational problems encountered with the system, such as nozzles blocked by snow, a failed in-line filter (50 gallon spill of ice control chemical, but the problem was resolved by a redesign of the line filter), software issues (difficulty in accessing data and modifying operational parameters), insufficient size of the storage tank, a malfunctioning Environmental Sensing Station (ESS) that had to be replaced, and chemical reaction of the potassium acetate with galvanized metals. The chemical used in the system (potassium acetate, specifically the Cryotech CF7 product) performed well, and worked in low temperatures. The chemical has a potential for hydrogen gas build up: thus, it is critical that the pump house be properly vented. The traffic flow was not significantly impacted by the spraying. The system was activated 501 times, dispensing more than 17,000 gallons of potassium acetate during the winter 2000/2001.

The New York City DOT developed two in-house FAST systems (with Type I hydraulic system design) and installed them on the Brooklyn Bridge, which has an ADT of 148,000 vpd (Ward, 2002). Bridge sections treated with Potassium Acetate by FAST achieved a higher level of service than sections treated with conventional spray trucks. A variable message sign (VMS) was used to alert motorists about spray operations, and then the 50 barrier-mounted nozzles were triggered remotely when maintenance personnel decided to initiate anti-icing based on television and radio weather forecasts. The total reliance on broadcast media or the operation managers' judgment was not adequate for effective decision-making. The benefits of FAST system are optimally realized when activated with integration of a Road Weather Information System (RWIS). The study also indicated that the FAST systems should not eliminate the need for plowing technology for heavy snow events.

The North Dakota (ND) DOT has installed two FAST systems (with Type I hydraulic system design) since 2002 at I-29 Buxton Bridge (near Buxton, ND) and I-94 Red River Bridge between Fargo, ND, and Moorhead, ND (Birst and Smadi, 2009). The ND DOT district staff considered the two FAST systems to be very effective in treating the bridge structures, especially for frost conditions. Both systems were found to operate as expected in terms of spraying at the appropriate time, applying the proper amount of chemical agent and achieving the proper system pressure. The reliability of the systems was estimated to be 95 percent (communication problems did occur). Moreover, significant crash reductions were observed at both locations after the FAST systems were installed, with a 66 percent reduction at the Buxton Bridge location and a 50 percent reduction at the Red River Bridge location. Correspondingly, the benefit-cost ratios at these two locations are 4.3 (with 20 year period, net benefits of $1,257,869) and 1.3 (with 20 year period, net benefits of $675,184), respectively.

The Pennsylvania DOT installed three FAST systems (with Type II hydraulic system design) in Warren, Westmorelane, and Allegheny Counties (Penn DOT, 2005). Preliminary evaluation results indicated that the systems performed well functionally. On the Warren County Bridge, 25 crashes were reported in the two years before installation of the system and no crashes have occurred since installation (the exact time period of observation after implementation was not reported). Table 4 summarizes the implementation and evaluation results of the above mentioned FAST system.

In addition to these systems, FAST has been successfully implemented in some other states such as Wisconsin, Colorado, Washington, Nebraska, and Iowa (Bell et al., 2006). At the time of this report, transportation agencies in the states/provinces of Alaska (Zhang et al., 2009), Missouri (MoDOT, 2010), and Alberta (Osburn, 2010) were planning or installing FAST systems; Nevada DOT was planning to install 4 separate FAST systems on four structures (in 2012). Finally, other systems similar to FAST have been recently developed for preventing snow, ice, and frost from bonding to road surface. Two examples are the ESI-Spray Mini Systems (EnviroTech Services, Inc.) and the FreezeFree Automated Anti Icing System (Energy Absorption Systems, Inc.).

Table 4: Summary of North America Experience on FAST Implementation

Study	**System Description and Location**	**Findings (benefits, costs, problems, impacts)**
Friar and Decker (1999)	• Parapet-mounted, “home-built” system • Installed on an interchange/overpass on I-215 in Salt Lake City, Utah in 1997-1998 • Type I hydraulic system design	• 64 percent reduction in snow and ice-related accidents

Stewart (2004)	• Knudsen's Corner Bridge, on I-215, Utah • Fully automated on North bound and South bound structures • Using active and passive pavement sensor technology	• No weather related crash on the structure after the installation • No definitive benefit-cost evaluation were provided
Keranen (1998)	• Three remotely-activated systems in Minnesota • Type II hydraulic system design	• 82 percent reduction in winter-related accidents
Pinet et al. (2001)	• Canada's first FAST system • Installed along a 550-ft long and 37-ft wide Highway 401/416 interchange ramp near Prescott Ontario, Canada in 2000 • Average Annual Daily Traffic of 3000 vehicles • Automatically activated or manually activated (sounding an alarm to notify maintenance personnel) • Type I hydraulic system design	• Benefits included: collision avoidance(100% reduction since installation), reduced corrosion and travel delays • MTO ceased the use of chloride salt after installation of FAST and the savings on repairs to the structure due to corrosion are estimated to be $10,669 per year • The FAST system coverage is 1963 m^2 with actual construction cost of $300,000 and annual operating cost of $15,000 • Chemical costs doubled partly due to unnecessary automatically spray operations • Benefit-cost ratio is estimated at 1.13
Barrett and Pigman (2001)	• Installed on a bridge on southbound of I-75 at the north interchange to Corbin, Kentucky in 1997 • Remotely and manually activated by maintenance personnel • Type I hydraulic system design	• Worked efficiently • System location was not perfect, which affected system effectiveness • The system had minimal problems after four seasons of use
Lipnick (2001)	• Installed on a bridge on I-68, over Street Road, in Allegany County, Maryland • Type I hydraulic system design	• Maryland DOT considered the system a major success • Reduced accidents on the bridge by approximately 40 percent

		• Cost savings of $16,000 due to avoided mobile operations
Johnson (2001)	• Installed on a six-lane wide I-35W bridge over the Mississippi River in Minnesota • Fully automated with an ESS • Type I hydraulic system design	• 68 percent reduction in winter-related accidents • A benefit-cost ratio of 3.4 • Various problems with the system operation
Ward (2002)	• Installed on the south-roadway of the Brooklyn Bridge in NYC (Two in-house systems) • Manually activated • Type I hydraulic system design	• Timely and rapid spray applications of potassium acetate were safe and effective • Integration of a RWIS and plowing equipment are necessary tools for effective anti-icing
Roosevelt (2004)	• Installed on a bridge in Fairfax County, Virginia in 1998 • Type I hydraulic system design	• Able to uniformly spray chemicals over the bridge with the assistance of traffic • System was not effective due to the limitation of capabilities of environmental sensors
Birst and Smadi (2009)	• Two systems installed at I-29 Buxton Bridge (near Buxton, ND) and I-94 Red River Bridge between Fargo, ND, and Moorhead, ND • Type I hydraulic system design	• Very effective in treating the bridge structures, especially for frost conditions • Reliability of the systems was estimated to be 95 percent • 66 percent reduction at the Buxton Bridge location and a 50 percent reduction at the Red River Bridge location
Penn DOT (2005)	• Three FAST system in Warren, Westmorelane, and Allegheny Counties • Type II hydraulic system design	• Performed well functionally • On the Warren County Bridge, 25 crashes were reported in the two years before installation of the system and no crashes have occurred since installation
Hanson et al. (2013)	• Installed on I-80 over Anderson Creek Road and Anderson Creek in Clearfield County, Pennsylvania in 2002	• Safety benefits include: reduction of crashes from an average of 2.63 crashes per year to 0.63 crashes per year on the bridge (there were 21

	• The twin structures are at the low point of a valley • Installed due to high traffic crashes and persistent icing conditions	crashes from 1995-2002 and there were 5 crashes from 2003 to 2010)

Conclusion

The literature review revealed considerable knowledge of and experience with FAST systems. FAST has emerged as an important way to supplement mobile winter maintenance operations by enabling winter maintenance personnel to treat selected locations before snow and ice problems arise. Documented experience with FAST systems in North America and Europe has revealed a mixed picture. On the one hand, several studies have indicated reductions in mobile operations costs and significant reductions in crash frequency, resulting in favorable benefit-cost ratios. On the other hand, there have been a variety of problems related to activation, system maintenance and training. Recently the application of FAST systems has increased in North America.

Installing a FAST system is complex and the challenges are often site-specific. Difficulties can be expected during operations, particularly in areas related to software, activation processes, and pumping systems. However, the evaluations cited show that FAST systems can be cost-beneficial if their locations are carefully chosen and if the systems are supported with reliable environmental sensors. In the researchers' opinion, the selection of FAST systems should focus on low-cost, high-reliability sensors (such as those for air temperature, pavement temperature, relative humidity, dew point, and surface salinity), instead of relying on ice-presence or friction detection sensors. Although there are a number of studies that reported on the successes and failures of FAST design, planning, installation, operation and maintenance, very few studies have involved a formal benefit-cost analysis of FAST systems due to the lack of experience and lack of well-documented data. As more FAST systems are installed to reduce weather-related traffic accidents and to maintain a high level of service on winter roadways, more studies on benefit-cost analysis supported by relevant data are recommended to help agencies maximize their return on investment.

2. SURVEY RESULTS

National Survey

The purpose of this survey was to document the state of practice of FAST systems currently available and used by road maintenance agencies nationally, and to highlight the successes and lessons learned from FAST practitioners. The online survey consisted of 23 questions and was designed to seek information regarding general experience during planning, construction, maintenance and operations of FAST systems, user acceptance, perceived or documented costs and benefits, and so on. Respondents were notified about the survey via the Snow and Ice List Serve where it was posted for one month. The List Serve is operated under the Snow and Ice Pooled Fund Cooperative Program (http://www.sicop.net/), which has hundreds of subscribers including state and local DOT professionals, researchers, and private sector specialists in highway winter maintenance issues.

Respondents from a total of 25 FAST agencies and vendors participated in the survey, with two agencies from Canada and one vendor from the United Kingdom, and the rest from the U.S. representing agencies from 12 different states (Alaska, Illinois, Kansas, Kentucky, Montana, New Hampshire, New York, North Dakota, Pennsylvania, Maine, Wyoming and Wisconsin), and one vendor from California.

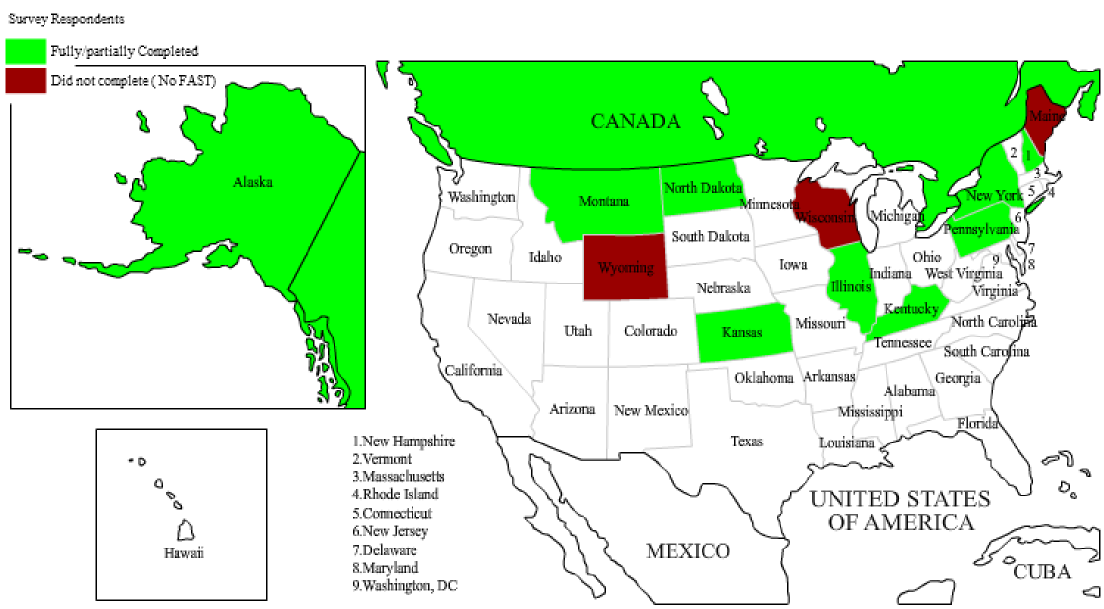

Figure 2: Survey respondents in North America

The Wyoming DOT and Maine DOT users stated that they do not have FAST systems installed in their regions. In particular, the Wyoming DOT did not install any FAST systems as their bridge program was not in favor of placing extra chlorides on the bridge deck. Additionally, the Wisconsin DOT decommissioned the FAST system due to the lack of maintenance support from the vendor (Boschung), so this specific survey was not completed. In some cases, participants did not answer all of the questions, often due to the lack of available data or experience. As a result, the summaries of some questions have information provided by fewer than 25 respondents. Figure 2 shows the distribution of the survey respondents in North America.

Reasons for Use, Extent of Deployment and General Description of FAST System

Respondents listed numerous reasons for using FAST systems, most of which can be grouped into four major categories: safety concerns, material savings, crash reduction and environmental concerns. In addition, the Illinois (IL) DOT uses FAST to reduce chloride use on the bridge and protect bridge components from chloride corrosion. The North Dakota (ND) DOT uses FAST to reduce maintenance activities in rural areas. The respondent from the U.K. also stated that the major reason for using FAST is to prevent ice formation condition on an economically important export route, which must stay open during snow events. Agency staff from Ontario mentioned testing a micro FAST system, which is a patent strip anti-icing spray system developed by Boschung America. In this system, deicing chemicals are applied to various types of road surface through a fine, invisible and dense stream by the control of the ice early warning system. The major features of micro FAST include: self-contained pumping cabinet, supply tank, micro FAST strips cover up to ½ mile (2 lane), and optional atmospheric and pavement sensors for full automation. According to the manufacturer, the major advantages of micro FAST systems over a traditional fast system are low cost, minimum maintenance and easy installation/operation. Micro-FAST has been installed in four states: Pennsylvania (2005), Vermont/New Hampshire (2006), Montana (2006) and Alaska (2006) (Boschung America, 2013).

The agency from Pennsylvania DOT has deployed 14 full scale FAST systems with the 15th one pending. Ontario, Canada has deployed eight FAST systems and is currently testing one Micro FAST system. The agency from Alberta (Canada) has started full FAST deployment on two bridges. The rest of the agencies have a couple of FAST systems installed and in operation, while New York State (NYS DOT) Region 6, Kentucky DOT, Kansas DOT and IL DOT have each removed one FAST system for various reasons.

Most FAST systems were installed on bridges with only a few placed on interstate ramps. There are seven FAST systems that are fully auto-triggered, while five use both auto and manual triggering systems. For the hydraulic system type, there are eight agencies using the type I system only, including IL DOT, Alaska DOT Central Region, Montana DOT (MT DOT), KY DOT, New Hampshire DOT (NH DOT), KS DOT, Pennsylvania DOT (Penn DOT) and one vendor from the United Kingdom. North Dakota and the Province of Ontario have both types as their hydraulic system. In contrast, there are only three agencies using the type II hydraulic system (Alberta Canada, Ontario Canada and NYS DOT Region 6). Ontario is using primarily type II Boschung systems and Alberta also installed two type II Boschung systems. Based on the survey results, the type I hydraulic system is more common than the type II hydraulic system for the surveyed agencies.

When asked if their FAST experience was a success or failure, six agencies reported their FAST as a major success (ND DOT, NH DOT, Penn DOT, MT DOT, United Kingdom, Ontario Canada, and Alberta Canada). The ND DOT and Alberta Canada reported their experience as a success after addressing some issues (damage to the pavement surface from the installation requiring frequent repairs reported by Alberta agency). However, there were four agencies that reported failures: NYS DOT, KY Transportation Cabinet, KS DOT, and IL DOT. The NYS DOT stated their FAST failure was due to the fact that system maintenance was complex and currently beyond the capabilities of DOT staff. The Kentucky Transportation Cabinet stated that their FAST was experimental and was removed due to the poor location that was chosen. The IL DOT has one FAST system that had problems with the chemical applied (potassium acetate), and high cost and maintenance were other reasons for the system's removal. The Kansas DOT removed one FAST after trials on various occasions, because the advantages never outweighed the disadvantages.

The responding agencies cited the following selection criteria for the use of FAST systems:

- Past accident history and maintenance concerns (MT DOT and Alaska DOT Central Region)
- Safety problems and high risk due to icing conditions, high traffic volumes, priority routes, and economically sensitive location (Alberta Canada)
- Specialized locations that pose unique hazards either due to road conditions/geometry or response time limitations (Ontario Canada)
- Potential trouble areas, identified based on the judgment of senior maintenance management staff (NYS DOT Region 6)
- Importance of the road to the U.K. economy (U.K.)
- A high traffic count and to avoid regular maintenance that may lead to lane closure (NH DOT)

Chemicals Used for FAST and Related Issues

Liquid chemicals that can be used by FAST systems include, but are not limited to: Calcium Chloride ($CaCl_2$), Magnesium Chloride ($MgCl_2$), Potassium Acetate (KAc), Sodium Chloride (NaCl), Calcium Magnesium Acetate (CMA), and CMA/KAc blend (CMAK). Potassium acetate is the most commonly used chemical in FAST systems according to the responses of this survey (11 out of 14). FAST systems from eight state agencies, two Canada provinces and one United Kingdom agency have used potassium acetate, and these agencies listed the following advantages: non-corrosiveness, reasonable cost, extremely low freezing temperature and environmental friendliness. Table 5 shows the agencies surveyed and the chemical of choice. A vendor from California stated that potassium acetate was by far the best chemical for a FAST system; the other chemicals were either corrosive, expensive, or had limited temperature range use. A researcher from Alberta, Canada also mentioned the problems of using potassium acetate, as it is still corrosive to non-stainless steel components inside junction boxes. It may also have an effect on concrete, but this issue still requires further assessment.

With regard to other chemicals, the Ontario Ministry of Transportation (Canada) suggested that even if other products were available they should be researched and considered with the design of the FAST system. For example, when a sprayer did not work well, all the chemicals became expensive. The Pennsylvania DOT is the only agency that used sodium chloride for its FAST system. The KS DOT is the agency that used Calibur M1000 and Apex Meltdown, and staff members believe that the two chosen chemicals are much more cost-effective than CMA, but also too expensive when the sprayer didn't work well.

Table 5: Chemicals Used for FAST Systems of Surveyed Agencies

Agency	**Chemical(s) Used in FAST System(s)**	**Comments**
Montana DOT	$CaCl_2$, $MgCl_2$, and Potassium Acetate	$CaCl_2$-Concern for compatibility with $MgCl_2$ used on adjacent road segments. $MgCl_2$: worked fine. Potassium Acetate: worked fine, cost was high compared to $MgCl_2$.
North Dakota DOT	Potassium Acetate	Studies have shown it is related to causing ACR (alkali-carbonate reaction) in concrete bridges, but it is environmentally friendly over waters and is capable of extremely low freeze points.
CA(Vendor/Manufacture)	$CaCl_2$, CMA, $MgCl_2$ NaCl, Potassium Acetate	$CaCl_2$, CMA, $MgCl_2$ and NaCl are all corrosive. Potassium Acetate is the best chemical for FAST system
Alaska, Central Region	Potassium Acetate	Performs very well. Some corrosion on non-stainless parts
NYS DOT, Region 6	Potassium Acetate	Price escalated sharply after the first year of operation.

UK(Vendor/Manufacturer)	Potassium Acetate	It's widely available, works effectively in the climatic conditions experienced.
Kansas DOT	CMA, $MgCl_2$, Calibur M1000, Apex Meltdown.	CMA-Worked well, but expensive, especially when spray system leaked or sprayed inappropriately MgCl2-much more cost-effective than CMA, but also too expensive when sprayer didn't work well Other - Calibur M1000, Apex Meltdown, much more cost-effective than CMA, but also too expensive when sprayer didn't work well
Pennsylvania DOT	NaCl	NaCl - Salt Brine Only NaCl - Solar Salt
New Hampshire DOT	Potassium Acetate	Potassium Acetate used. No issues to date.
North Dakota DOT	Potassium Acetate	Potassium Acetate - Studies have shown that Potassium Acetate is related to causing ACR in concrete bridges. But it is environmentally friendly over waters. It is capable of extremely low freeze points.
Kentucky Transportation Cabinet	$CaCl_2$	$CaCl_2$ - Vandalism
IL DOT	Potassium Acetate	Problems occurred with maintenance and costs are significant
Ontario Canada	Potassium Acetate	An environmentally friendly anti-icing product. The use of this product on the bridge may actually extend the life of the structure and potentially reduce rehabilitation costs as a secondary benefit.
Alberta, Canada	Potassium Acetate	Corrosive to non-stainless steel components inside junction boxes, may have had effect on concrete, still requires assessment.

Conditions that Increase Effectiveness and System Limitations

The agencies agreed that the FAST system was most effective when the targeted area had frost, ice formation and light snow (< 1 inch). The Alaska Central Region staff reported that the system worked most effectively when the temperature was between mid-20s to 32 degrees Fahrenheit. The NH DOT used FAST effectively during night hours when freezing conditions could occur. The agency from the United Kingdom stated that FAST allowed repeated treatment over a short period, which would not be possible with a vehicle based treatment. The KS DOT stated that when there were falling temperatures with precipitation, active sensors could anticipate freezing point in time to activate sprayers.

The survey agencies cited several system limitations, including: high wind (ND DOT: >15mph, KS DOT, and Ontario Canada); extreme low temperatures (KS DOT and ND DOT: <12F); extreme snow falls (FAST is not for snow clearing) (Ontario Canada); rapidly falling temperatures (KS DOT); lack of precipitation (Kentucky Transportation Cabinet); and low traffic volumes (NYS DOT: rely on tire tracking to spread potassium acetate). One agency stated that competing winter maintenance activities (salting/sanding) tend to interfere with FAST operations, which has made the use of FAST more complex and less effective.

Other limitations to FAST systems were attributed to their mechanical and technological complexity, which requires a lot of maintenance to remain operational. Examples include plugged nozzles (Montana/Alaska), unsupported software (Montana), unreliable frost detection algorithms (IL DOT), and inaccurate sensors (IL DOT) not supported; IL DOT: frost detection algorithms were not reliable and sensors were not accurate enough).

The number of FAST activations per winter season varied depending on winter road conditions. However, one respondent indicated that the low number of activations does not reflect the importance of the system.

Activation Features and Challenges

The survey asked which features or technologies were used to activate the FAST system. Ten agencies reported that they use RWIS in the activation of FAST (ND DOT, NYS DOT, MT DOT, NH DOT, KS DOT, Penn DOT, IL DOT, Alberta Canada, Ontario Canada and United Kingdom). In most cases, the RWIS was used without any major problems and functioned well. Surface sensors have been reported to experience damage due to traffic wear and snow plows (Alaska). Ontario, Canada has used surface sensors with minor issues. The NYS DOT had sensor failures. No surveyed agency has used infrared sensors. The Pennsylvania DOT has reported activation problems with plumbing leakage in the conduit raceway. The detailed responses are presented as follows.

Automatic Detection (RWIS): The IL DOT had false alerts of RWIS in activation. The KS DOT used RWIS in activation, but it was not reliable. Staff favored the idea of using active sensors instead of passive ones for the mix of chloride deicers, but poor algorithms or poor sensors made appropriate treatments an unattainable goal. The PA DOT system was generally set to spray automatically at 34 degrees Fahrenheit and newer FAST systems can be controlled manually by traffic centers; to optimize the system effectiveness, staff also recommended setting the trigger temperature to fit the temperature profile of the bridge. In the southern part of England, the two FAST systems were triggered from a combination of grip readings and snow level readings. A vendor from California has pointed out that the most important measure for activating FAST is a grip reading, which uses less chemical and always treats slick problems. There were two agencies that reported no problems with RWIS (NYS DOT and Ontario, Canada).

Surface Sensors: Some agencies have reported sensor damage due to traffic wear, snow plows or epoxy failure. The KS DOT has used passive and active sensors but has never achieved reliable activation. Two agencies had no problems noted (Alberta, Canada).

Infrared Sensors: No surveyed agency has used infrared sensors.

Alarm Message: Five agencies used alarm messages, while one used messages for maintenance alarms. Alberta, Canada reported that the alarm message used in a complex system was not as satisfactory as it was when used in a single system.

Data Recording: One agency responded that the SSI software used at FAST sites was capable of data history (North Dakota). Another agency responded that the PC in the District Office displayed history (NH DOT).

Other Activation Features: Manual activation by cell phone (KS DOT) and manual operation and web activation from the controller software were possible (vendor from United Kingdom).

Problems with Operations, Maintenance and Reliability

Maintenance is a critical component of using these systems effectively, and according to one respondent, regular maintenance resolves most problems (Alaska). Typical maintenance requirements included regular service on system hardware to ensure the system is operating correctly, such as checking for leaks, pressure loss, and plugged nozzles. Ontario's MTO suggested regular checks on FAST once a month and more frequently (weekly, or as determined by the regional representatives) during the winter maintenance period. FAST had a high reported reliability of over 75% as indicated by three agencies (ND DOT 95%, Alaska Central Region

85%, Penn DOT 75%). Problems with operation and maintenance did occur regularly. The major problems reported were air leakage, sensor failure, plugged nozzles and communication problems. The following operation and maintenance problems were identified by the surveyed agencies.

- FAST system needs to be flushed and changed over to fire water during the summer. (NYS DOT Region 6, MT DOT, ND DOT, NH DOT, and Alberta Canada)
- Lack of initial training and staff turnover, issue on cleaning (ND DOT and MT DOT)
- Periodic sensor problems (Alaska)
- Leakage air in the system, remote activation has communication problems: high level of data usage on the 3g network. (UK)
- Leakage problem once in a year. (NH DOT District 2)
- The reliability is declining due to the age of most of our systems and the need to upgrade system.
- Some reliability issues have occurred; a good maintenance agreement with 24 hour response time is paramount for success. (Penn DOT District 11-0)
- North Saskatchewan River Bridge (NSRB) - there was one road sensor failure that required replacement; otherwise was reliable. Athabasca River Bridge (ARB) - there were some communication problems, the system over sprayed but no conclusions as to why. (Alberta, Canada).
- In a fully automatic FAST system, it is important to follow the suppliers' recommended maintenance protocol that can typically be found in their respective manuals. (Ontario MTO, Canada)

Problems with maintenance of each major system component

RWIS – Pavement sensors issue (IL); active sensors did not make the system fire at the right times (KS); during operational months, maintenance is an issue: access to the equipment requires a full closure on bridge. (UK, Vendor)

Pumping/Storage – Issue with air getting into the system (UK, vendor); major failure (KY DOT); various leaks (Penn DOT); component failure (NH DOT); Mice and other outdoor life (IL DOT); filter change on hydraulic manifold (Alberta, Canada).

Controller – False alerts and software issues, but improved (IL DOT), No problems for other agencies.

Chemical Distribution/Spray System – Small leaks where the hoses connect due to differential pressure caused by the location on steep slope (UK, Vendor); spray heads are clogged (NYS DOT); nozzle clogging is big issue (ND DOT); nozzle clogging (Penn DOT);

periodic leaks (NH DOT), initial leaks (IL DOT); pressurized manifold makes leak, prevention and early identification are critical (KS DOT); maintenance on nozzle to prevent dirt accumulation (Alberta, Canada).

Features that are critical/important or most problematic and innovations for future use

Critical/important: non-invasive sensors that measure grip for best results (CA vendor); regular and good quality maintenance (UK vendor); training, ongoing support for repair parts and software upgrades (MT); controls/configurations that determine the amount and frequency of treatments (NH); proactive responses (Alberta, Canada).

Most problematic: valves (CA vendor); sensors and nozzles (Alaska); maintaining same pressure throughout the system (UK vendor); corrosion, leaking valve boxes, maintenance (Ontario, Canada); nozzle plugging (MT, ND, NH, Alaska, Alberta, Canada); leaks in supply tubing (NH); conduits for hydraulic lines (fit ups) on the bridge caused significant pavement cracking, nozzles failed frequently, causes may be inadequate sealant epoxy, bridge heavy traffic, vibration, conduits and nozzle installation method (Alberta, Canada)

Innovations for future use: buy maintenance program from vendor along with the system (CA vendor); more durable nozzle (Alaska); PC based triggering system rather than simple relays (UK vendor); Micro FAST (Ontario, Canada); non-intrusive sensors and nozzles (Alberta, Canada).

Costs and Evaluations

FAST system is relatively expensive. Its implementation needs to be weighed against the costs of winter maintenance activities related to the structure or target area. Mobilization of maintenance equipment to treat frosted bridge decks carries an associated cost. The use of a FAST system is intended to reduce the need for such mobilizations. Rather than replacing winter maintenance activities, it is intended to enhance activities. More experience and additional data with the use of FAST systems will help review the cost-benefit ratios associated with FAST (Ontario, Canada). FAST system's initial costs include: design, construction, project management and commissioning of the RWIS system, the spray system and the chemical storage facilities. Annual operating and maintenance costs include: chemical costs, monthly monitoring/reporting, site inspections, maintenance and utility costs. The variable costs (chemicals and utilities) will depend on the severity and nature of winter. No formal evaluation was conducted for most of the surveyed agencies, except for the ND DOT and the KY DOT. The Alberta Ministry of Transportation indicated a planned benefit-cost study next year, in which safety records would be used to assess the benefits of using FAST. Table 6 has summarized the initial costs and annual operating costs associated with FAST systems for surveyed agencies.

Table 6: Initial costs and annual operating costs for the respondents' FAST systems

FAST Agency Surveyed	FAST Description	Initial Costs	Annual Operating Costs
Alaska DOT Central Region	Has been in service for 7 years, 4 lanes, the only FAST in this region	$1.3 million for/ installation of plumbing and pumping systems	$30,000-$40,000/chemical and component replacements
New York State DOT Region 6	Full scale demonstration at two locations 2007-2009	$1 million+	$25000-$50000/ material and sensor replacements
Montana DOT	Pilot study 8-9 years of operation, <500 feet length	$600,000 for initial construction including material and maintenance costs	N/A
North Dakota DOT	Red River Bridge-7 years of operation (1300 feet and 3 lanes)	$650,000 Red River Bridge not including the ESS costs	$1000/maintenance $1162/utilities $9471/chemicals
	Buxton Bridge-11 years of operation (370 feet and 4 lanes)	168,000 Buxton Bridge not including the ESS costs	$2000/maintenance $2955/utilities $66,703/chemicals
New Hampshire DOT	30 feet curb to curb wide and 2 lane bridge	$200,000-$250,000 without labor and equipment	$25,000 - $50,000/liquid anti-icer cost, repair costs of $500 annually
Kansas DOT	12 years of operation, 200 feet and 2 lanes	$200,000	High maintenance cost and high cost of inappropriate spray
Ontario, Canada	Demonstration, installed in 2000 (Coverage is 21,250 ft^2) AADT=3000)	$300,000 or $153/$m^2$ /design, construction and commissioning	$30,000

Alberta, Canada	NSRB (2 lanes, one direction, AADT=43,000) Boschung system (Switzerland)	$2.1 million/NSRB (2 lanes, 400 m long)	$100,000 - $300,000/ $90 - $140 per lane per meter per season
	ARB (5 lanes, one direction, AADT=60,000) two spray subsystems, Boschung system (Switzerland)	$4.0 million/ARB (5 lanes 470 m long)	

Benefits, Lessons Learned, and Improvement on New FAST Systems

The benefits of using FAST listed by the agencies include: winter road related accident reduction, labor and material savings, and immediate roadway treatment (enhanced response time). Ontario MTO has indicated that although the FAST systems are far more expensive to implement than traditional mobile anti-icing and deicing technology, the benefits are indirect and can be listed as: collision avoidance, reduced liability, environmental benefits, and reduced corrosion and travel delays. The surveyed practitioners listed the following lessons learned.

- Every possible issue to eliminate future problems should be considered and addressed in the installation stage (Ontario, Canada).
- Maintenance (NYS DOT, region 6)
- Operator buy-in, staff cross-training (MT DOT)
- More appropriate location (Kentucky Transportation Cabinet)
- Older pavements will crack and rut, with more failure and early replacement if overlay required, not as good as new surface (NH DOT)
- For bridge deicing, systems were expensive and frost events are challenging to detect (IL DOT).
- Hydraulic tubing should be installed in the final surface after paving (surface cut method), metal conduits are damaging to the pavement, and embedded nozzles also cause pavement deterioration (Alberta Ministry of Transportation, Canada)

Some agencies showed interest in using a new FAST system or improving its features. The ND DOT and Ontario MTO were interested in the Micro FAST technology. The U.K. vendor would add a camera for improved effectiveness and wind sensor to allow wind speed to be taken into account in the decision making process. The MT DOT had a new FAST system in the planning stage.

CDOT Survey

In order to assess the FAST systems in the state of Colorado, two types of survey were conducted: an online survey and a field survey.

The online survey was conducted to provide insight on all of the FAST systems that are installed in Colorado for snow and ice control. The online survey consisted of 19 questions (APPENDIX B) that focused primarily on performance, maintenance problems and benefit-cost of using FAST systems. The survey was provided to the CDOT regional staff via an online link. The researchers received feedback from CDOT FAST users representing Regions 2, 3, 4 and 5. A total of six CDOT staff members completed the online survey to the best of their knowledge.

Most of the respondents in Colorado installed the FAST system in selected locations as a region-wide deployment program, except for one user who reported using a FAST system for a pilot test. Generally, all the respondents used the FAST system to address the issue of icing on the bridge decks and to prevent accidents. However, some users installed the FAST system in mountain areas, tunnel approaches and to reduce chemical usage and sand build up on the bridges.

$MgCl_2$ or APEX (enhanced $MgCl_2$) was the most common anti-icing chemical used for the FAST system, except in some cases where sodium chloride was used. No problems with chemical use were reported by the respondents.

Reliability and high maintenance were common issues with the FAST system. Frequent electrical and mechanical issues make the system unreliable at times; also, it needs routine maintenance such as replacing nozzles and sensors. Corrosion problems, electrical problems, valve problems and clogging in hose/nozzles are the common maintenance issues encountered while operating a FAST system.

In general, the FAST system could be of significant use to address icing issues on various superstructures. However, one respondent believes that improper spraying of chemicals by a FAST system could worsen the icing conditions. The triggering mechanism in a FAST system should be set for an appropriate temperature range (16 – 34^{o}F) to prevent the spraying of chemicals at extreme cold temperatures (to prevent re-freeze).

None of the respondents have a formal evaluation procedure (such as a benefit-cost analysis) to evaluate the benefits or document the paybacks of their FAST system. Further, responding users believed that the FAST system should be improved to make it more reliable and to achieve better data tracking. Some of the planned improvements by the agencies include: investigating non-invasive sensors, adding new installations, upgrading of all sites to ESI sites, and redesigning the current FAST system. Interestingly, one respondent is planning to remove the FAST system if it fails again after performing an upgrade and maintenance.

From the online survey, it can be noted that responding users realize the benefits of properly functioning FAST systems. However, frequent maintenance issues of different components of the system make it unreliable at times. Some users of the FAST system complain about electrical issues while others complain about clogging of spray nozzles and so on. This could be due to the difference in installation techniques and maintenance practices among different regions in Colorado.

To further investigate the use of FAST systems in Colorado, a field survey was conducted. The main aim of the field survey was to identify the differences in installation techniques and maintenance practices between a properly functioning and a problematic FAST system. The field survey consisted of site visits to observe existing FAST systems and interview the maintenance crews. In locations where there were multiple FAST systems with similar design and operational features, only one FAST system was included for the field survey.

The field survey mainly focused on answering the following questions.

- Where the FAST system should be installed?
- What should be considered during FAST installation?
- What are the advantages and disadvantages of various components of the FAST system?
- How can various components of the FAST system be improved for future FAST installations?

The following section provides a summary of the field survey, based on the interviews with maintenance crew members and the in-depth field investigation by researchers.

Location Selection

At times, FAST systems can be very expensive to install and maintain. Therefore, it is important to select a suitable location to install the system to achieve the most benefits. During the site visit, CDOT staff provided several reasons for their decision on where to install FAST systems.

Overall, CDOT staff considered or suggested the following key locations for installing FAST systems:

- Long-span bridges with slope and curves
- Short-span (less than 50 feet) bridges ending with an intersection and/or traffic signal
- Tunnel exits on a sharp horizontal curve slippery road conditions;
- Remote bridges that require unreasonable time to treat with deicer; and

- High priority roads and bridges.

CDOT staff members also noted that a FAST system may not be of significant use for straight and short-span bridges that are less than 40 feet.

From the site interview, most participants selected ‘bridges’ as their first choice to install FAST systems, based on the fact that ice can form on bridges at a faster pace relative to pavements. However, in-depth analysis and on-site interviews suggest that short-span bridges (span length less than 50 feet) located in a straight lane with high traffic volume do not necessarily need a FAST system (Figure 3a). This is due to the fact that incoming traffic can bring brine/abrasive with their tires, which “treats” most of the bridge surface. However, a FAST system can be beneficial to short-span bridges, if there is an intersection and/or traffic signal at the end of the bridge (Figure 3b).

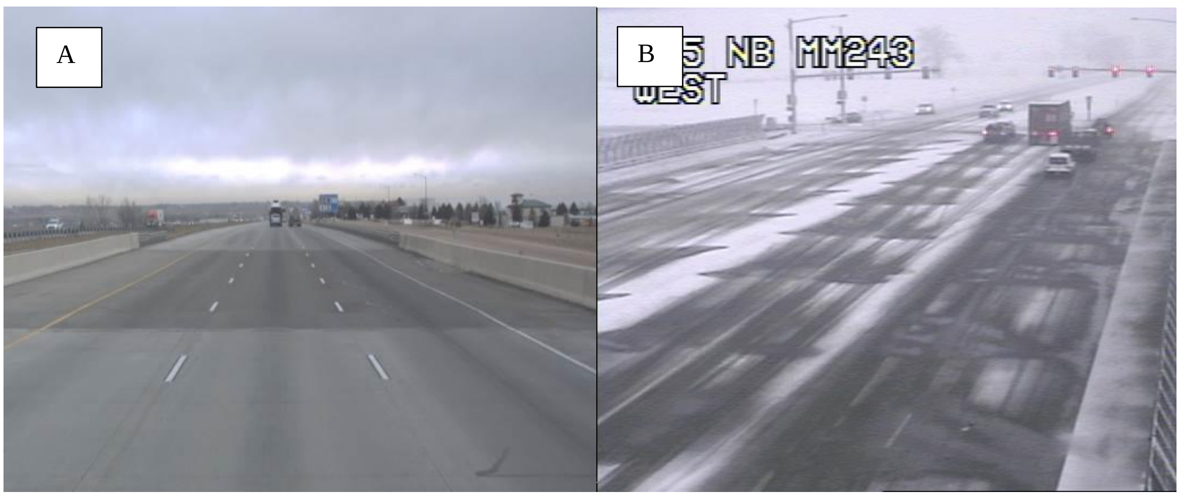

Figure 3: Bridge selection for FAST system
a) Short-span bridge on a straight lane that does not require FAST system;
b) Traffic signal at the end of the bridge and FAST system in operation

Among types of bridges, respondents prefer to install FAST systems on long-span bridges that have steep cross slopes and sharp horizontal curves (Figure 4). In addition, respondents suggest accident prone areas as another location to install FAST system. A tunnel exit could be an example of an accident prone zone. During slippery road conditions, drivers tend to drive slowly while they approach a tunnel. Once they hit the tunnel, drivers tend to increase their speed due to better road conditions inside the tunnel. However, when they exit from the tunnel, drivers tend to maintain the same speed without realizing the slippery road conditions outside the tunnel. Vehicles exiting tunnels at relatively high speed (during slippery conditions outside tunnels) are more prone to accidents, especially if the exit from the tunnel is a bridge located on a sharp horizontal curve (Figure 5). The FAST system in the ‘Hanging Lake Tunnel’ on I-70 was primarily installed due to slippery conditions at the west bound tunnel exit which transitions to a sharp horizontal curve.

Figure 4: Long-span bridge with steep cross slope and sharp horizontal curve

Figure 5: Tunnel exit with a bridge located on a sharp horizontal curve

Further, CDOT personnel also suggest installing FAST systems on remote structures/bridges that are difficult to reach in bad weather conditions or where trucks would need to travel an unreasonable distance to treat a single bridge. Respondents believe that a functioning FAST system on remote structures/bridges will allow the maintenance crews to concentrate on other roadways instead of taking care of a single bridge. FAST systems installed on bridges that intersect the 'Big Thompson River' are good examples of remote places where the system could be effective. In addition, respondents suggest high priority roads, bridges and flyovers that connect the airport and major intersections as other locations to install FAST systems.

Respondents prefer these high priority structures/bridges to be treated in a timely manner to prevent any formation of ice. The FAST system on the bridge on Pena Blvd, Denver (inbound) was primarily installed due to the high traffic volume and because it is a primary access route to the airport.

<u>System Installation</u>

FAST systems do not have a manual to follow for installation. It is therefore necessary for the maintenance crew and the vendor to work together to analyze the location requirements and select an appropriate installation technique.

In general, installation technique varies based on the selected location and requirements of the customers. FAST systems in Colorado used various installation techniques within and between regions of the state. During site interviews, maintenance staff emphasized that the success or failure of FAST system is highly dependent on the installation technique.

Respondents highlight the importance of involving maintenance crews for a successful FAST system installation. This is due to the fact that maintenance crews tend to have a better knowledge of the locations that are selected for FAST system. For example, the information from a maintenance crew about the ease in accessibility to various areas within the bridge could be helpful in selecting a location to install valve systems. Installing a valve system in an appropriate location may well help the maintenance crew to perform a maintenance operation without access difficulty. One of the major issues encountered by maintenance crews is their difficulty to access and perform maintenance activities on the broken components (spray nozzles, valves, storage tanks, controllers etc.). For instance, micro strips (the outlets to spray deicers) located on the center of a two lane road (Figure 6) are difficult to access and maintain, because it requires a complete lane closure. A FAST system in Colorado that has micro strips on a center lane is not currently operated due to the need for high traffic control to perform maintenance activities.

In another case, a deicer storage tank was difficult to access during a heavy snow storm (Figure 7). The FAST system in this location was not operated for a few weeks, because a truck could not reach the storage tank and fill the deicer. These examples illustrate the need for involving both the vendor and CDOT maintenance staff during the installation phase of FAST system. The inputs from the maintenance crew will provide guidance in selecting the locations to install various components of the FAST system. Respondents also insist that efforts to cut costs during installation will only come back as high maintenance costs in the future. Further, continued success of the system is dependent on the proper maintenance of the system.

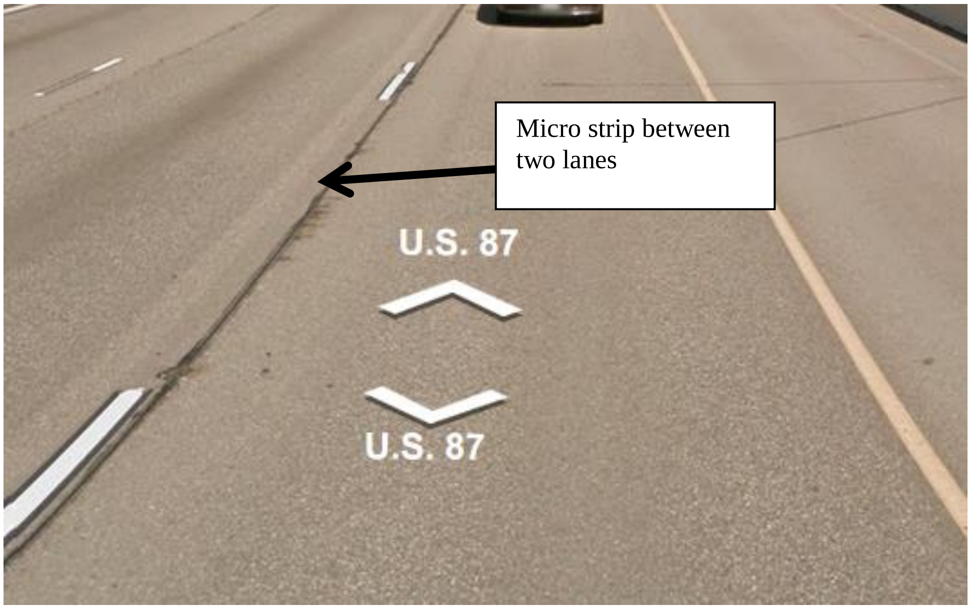

Figure 6: Micro strips on the center of two-lane road

Figure 7: Storage tank difficult to access during heavy snow storm

Considerations in FAST Design

Spray nozzles

The spray nozzle is a very important part of a FAST system. Maintenance crews expressed their concern about the clogged nozzles, which prevent the system from functioning. Selecting proper locations to mount spray nozzles may help to reduce the clogging problem. Typically, spray nozzles are mounted on three locations of the bridge structure such as:

- Bridge shoulder (letter A of Figure 8)
- Side rail or side wall (letter B of Figure 8)
- Between two lanes (letter C of Figure 8)

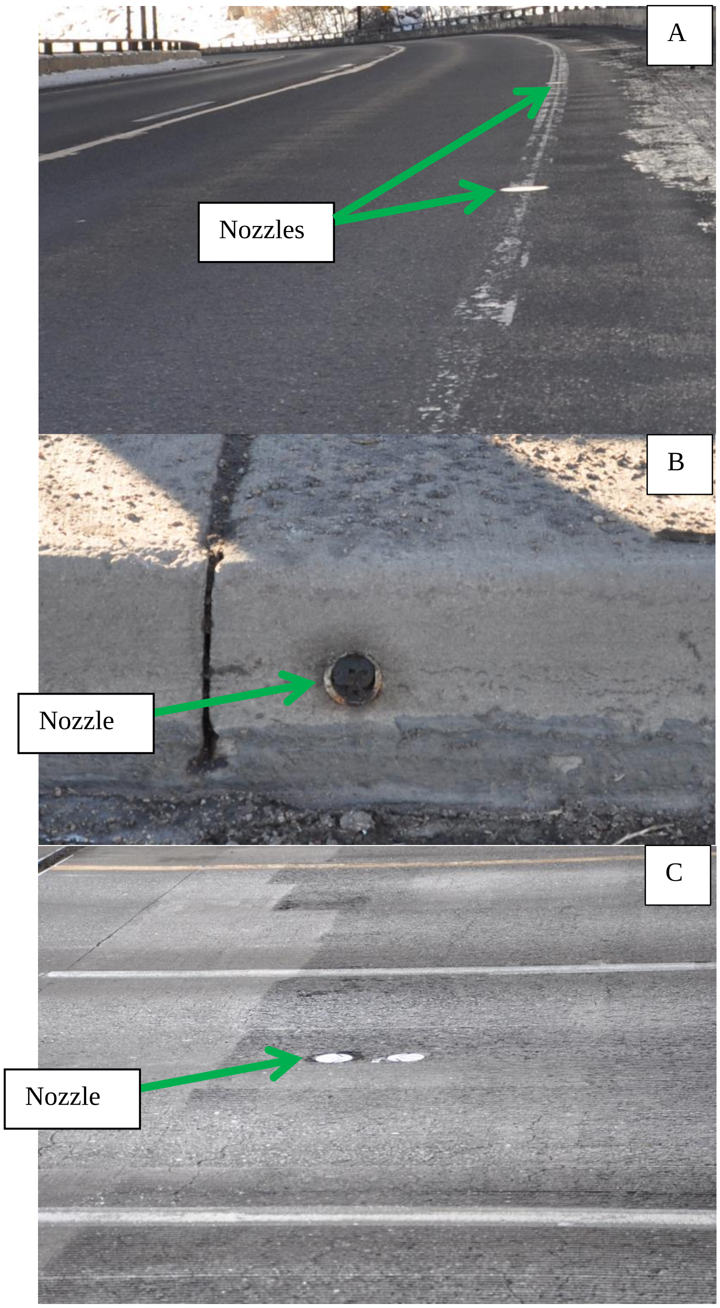

Figure 8: Various locations to mount spray nozzles
A) Bridge shoulder B) side rail or side wall C) between two lanes

From the interview responses, mounting on the side rail or side wall was the most preferable choice because of: 1) easy access to nozzles; 2) no clogging from abrasives; and 3) less damage to nozzles. However, in some scenarios mounting on the shoulder is unavoidable. In particular, a bridge that has four or more lanes needs spray nozzles mounted on the shoulder or between lanes so that deicers can reach all lanes. Also, if the side rail or side walls are far away from the lanes, then nozzles may have to be mounted on the shoulder or between lanes. However, placing the spray nozzle on the travel lane is not recommended because spray nozzles could be damaged by traffic, snow plows etc., and performing any maintenance activity on the sprays nozzles requires lane closure."

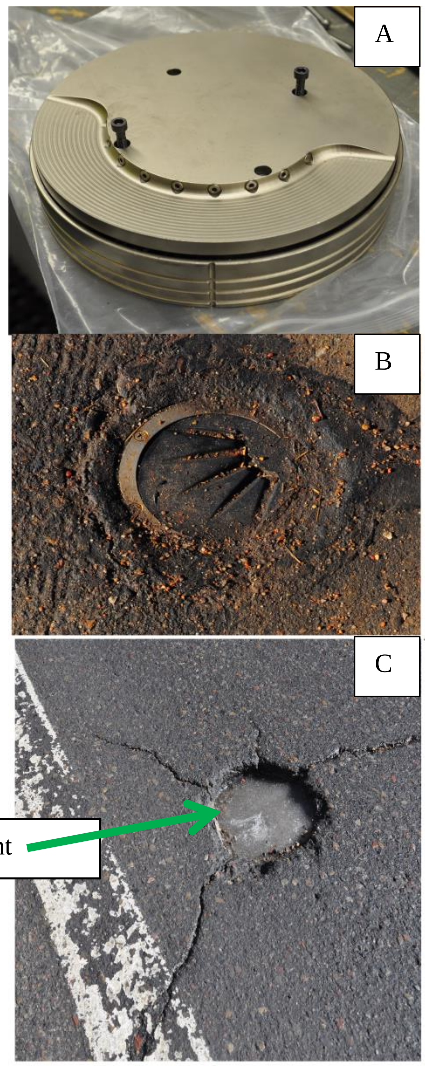

Figure 9: Spray nozzles used for mounting in the pavement
A) Stainless steel nozzle B) Rubber and stainless steel nozzle C) Buried nozzle in asphalt pavement

Respondents prefer plastic nozzles (if mounted on the side rail/wall) to nullify the corrosion factor. Conversely, the mounting height of the nozzles from the lane surface should be decided such that the deicer does nott shoot very high at the running vehicle, and also so that the plowing trucks do not block and damage the nozzles. In the case of nozzles mounted inside the pavement

(Shoulder and between lanes), respondents suggest various considerations in nozzle design and mounting. Letters A and B of Figure 9 show the two types of spray nozzles used in Colorado. Respondents do not recommend mounting nozzles in asphalt pavement and they prefer it in concrete pavement. Spray nozzles mounted in the asphalt pavement could get buried (as shown in letter C of Figure 9) due to the melting of asphalt pavement during warm weather. Respondents also suggest installing side rail near the shoulder of asphalt pavement if side rails are not already in place. Respondents also suggest having strong and thick outer walls for nozzles to withstand stress induced by the vehicle. Furthermore, the pattern of nozzles should be designed in such a way that it is sufficient to provide chemical coverage to the whole structure. Finally, the nozzle design should be improved for easy removal from its location (in pavement or side walls/rails) to perform any maintenance activities.

Valves and piping system

Valves are another important part of the FAST system; they open automatically to shoot deicers at the prescribed settings. In the CDOT regions visited, the agencies use two types of valves: motorized ball valves and solenoid valves. The selection of solenoid valves versus motorized ball valves should consider the advantages and disadvantages of each type, as shown as in Table 7.

Table 7: Solenoid versus motorized ball valves

Valve Type	Advantages	Disadvantages
Solenoid	• Small in size • No need for big valve boxes • Water can enter in valve box	• Corrodes more with chloride products • With use of chloride products, expected service life is 3-5 years
Motorized ball	• More resistant to chloride products • Longer service life	• Bigger in size • Need big valve boxes • Water cannot enter the valve box

However, most respondents in Colorado recommend changing from solenoid valves to motorized ball valves. Respondents said that solenoid valves do not hold up to the $MgCl_2$, and the best life expectancy of the solenoid valves is between 3 and 5 years. Further, location of valves should be carefully selected to ensure easy access, which will make it easy to perform maintenance activities without traffic control. If needed, small structures can be constructed to mount valves boxes or enclosures.

The respondents also suggest not using brass components in the pipe lines due to corrosion issues. They prefer using stainless steel, polypropylene, nylon 12, rubber hose and schedule 80 PVC for the piping materials..

Fluid tank, fluid pump and storage facility

The maintenance crews strongly recommend having a fluid tank that can store enough chemicals so that it does not need to be refilled too often. In particular, they prefer a fluid tank with a minimum capacity of 1,000 gallons. However, storage capacity is directly relation to the size of the bridge, application rate per cycle and the environment. Respondents also suggest having aboveground storage facilities for a fluid reservoir, a fluid pump and associated components (letter A of Figure 10), instead of an underground vault (letter B of Figure 10). This preference is mainly due to difficulty in accessibility and high moisture (which damages the system components and reduces life time) in underground storage units. Finally, storage units must be secured from vandalism or any other related issues.

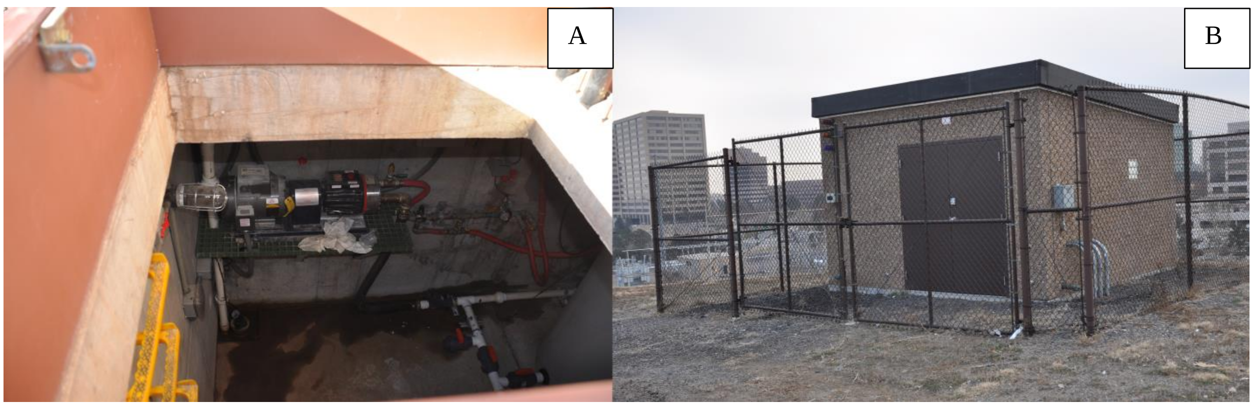

Figure 10: Storage facility for fluid tank, fluid pump and its associated components A) Under the ground B) Above the ground

For a fluid pump, there is no real concern about the pump's capacity (typically 220 psi) to pressurize the pipe lines and shoot the chemicals from the nozzles. However, respondents expressed concern about the malfunctioning of the fluid pump due to electrical issues. Respondents suggest periodic maintenance to mitigate this problem.

Triggering mechanism and associated systems

The triggering mechanism is another important component for the successful operation of a FAST system. All the respondents prefer a fully automated system that can be triggered by a computer from web-based PC software.

The input for the trigger mechanism is provided by the pavement sensors. Respondents prefer using non-invasive sensor technology (For example: Vaisala sensors) instead of in-pavement sensors (sensors mounted in the pavement). This is due to the fact that in-pavement sensors can be easily damaged by the traffic and snow plows. Further, in-pavement sensors can be potentially damaged while performing maintenance operations (e.g., milling of the surface or resurfacing) on the bridge structure. In addition, FAST systems that use non-invasive sensors mounted on a pole should be installed at an appropriate location. Respondents emphasize locating the non-invasive sensors on the center of a bridge instead of on the entry or exit of a bridge as shown in Figure 11. The middle span area of a bridge behind the rail provides a better representation of the actual prevailing conditions on the bridge.

Figure 11: Non-invasive sensors mounted on a pole

Water leakage into the electrical systems is another area of concern expressed by respondents (Figure 12). In some cases, rats were seen inside the control boxes. Respondents suggest that the electrical components should be sealed by a watertight enclosure. Further, maintenance crews expressed their concern about the inability to perform a repair of an electrical system due to the unavailability of parts in local stores. This emphasizes the need to use standard parts that can be purchased from the local area.

Figure 12: Water leakage in an electrical wiring of a FAST system

Conclusion

The survey results have documented extensive knowledge of the FAST systems used nationally and internally within the Colorado DOT. The positive and negative issues encountered with various systems were addressed by the participating agencies, as described in the survey results. All FAST systems discussed by respondents were installed and implemented with problems or issues. Most of the systems performed with success once the problems or issues were addressed. However, some systems did not function well even after years of repair and replacement and were removed as failures. One respondent reported one system failure due to the inappropriate selection of location and recurring maintenance issues. A number of operation and maintenance issues are expected throughout the process of design, planning, installation and implementation. Early detection of problems and proactive maintenance are critical in improving FAST system effectiveness.

The benefits of using FAST identified by the agencies include: reduction of winter related accidents, savings on material use and labor, and avoidance or reduction of negative environmental impacts. The survey results are consistent with the findings obtained from the literature review. The initial costs of FAST construction and installation were significantly higher than the operating and maintenance costs, but the benefits can be offset as early as the first year after installation. Survey results have disclosed cost-benefit information associated with the FAST systems surveyed, which may be of great value for future FAST installations and implementation. However, there is a lack of evaluation for the cost-effectiveness or environmental friendliness of FAST systems relative to mobile operations or anti-icing pavement technologies.

Location selection is an important factor for the success of a FAST system. It can be beneficial to have a FAST system at locations such as accident prone areas, long-span bridges, tunnel exits, remote bridges and high priority roads. Short-span bridges do not require a FAST system (unless there is an intersection or traffic signal after exiting the bridge). Further, it is necessary to involve both the maintenance crew and the vendor at each stage of the installation to minimize potential problems.

In addition, future improvements in system design, hardware, software, and installation techniques may help enhance the reliability of FAST systems. To improve the user acceptance of FAST technology, the key is to integrate cost-effective technologies that reliably detect relevant changes in pavement surface conditions. Some advances in the use of roadside sensor technologies for road condition monitoring (Greenfield, 2008, Kutila et al., 2009, AADI, 2011) have been seen in recent years. As such, FAST systems may become a valuable tool for transportation agencies engaged in winter operations, as they can complement or reduce the number of mobile winter applications and the amount of materials required. By proactively addressing icing problems, FAST systems can help reduce the number of crashes and traffic delays occurring during winter conditions. However, these systems are appropriate only at a highly localized level and are best viewed as a supplement to mobile winter maintenance operations.

Inconsistency in proper functioning of FAST systems among various CDOT regions is mostly due to the poor design, poor quality of installation technique, and insufficient maintenance in some cases.

4. SAFETY ANALYSIS OF CDOT FAST SYSTEMS

One of the objectives of FAST systems is to provide a safer driving surface through timelier chemical applications. Consequently, one of the tasks of this work was to determine what changes had occurred in vehicle crash rates at the different FAST sites throughout the state. Specifically, it was of interest to determine whether crashes had decreased in a statistical sense in the years after different FAST deployment compared to the years before deployment. Such an evaluation would provide a clearer picture of whether FAST systems had produced a positive impact on safety at each site.

As the literature review has indicated, previous studies and evaluations of FAST systems have considered the changes to crash occurrence following deployment. However, these evaluations have been largely simplistic and typically compared seasonal crash figures without accounting for site conditions such as traffic, geometry and so forth. Rather, crash figures before and after deployments were compared, with any reduced numbers of crashes following deployment expressed as percent reductions. While this provides a sense of the impact that the FAST system may have had, it does not consider the influence that the overall characteristics of the site have in contributing to or reducing crashes.

In order to address the shortcomings of previous studies, the work discussed here employed a more rigorous approach to analysis, employing accident prediction models to estimate the number of crashes before and after FAST deployment to better identify the impacts that the systems had on crashes. That approach is outlined in the following text.

Study data

In conducting safety evaluations such as those presented here, it was important to decide what constitutes the before and after period of the study. In order to generate more reliable results, it is better to employ a longer period of before and after crash data in the analysis process. Depending on the specific study, a period can vary, but typically ranges from at least 3 to 5 years for the before period and a similar duration or longer for the after period following an improvement or deployment. For this work, a before period of 5 years was employed, while the period after the installation of the FAST system ranged from 2 to 15 years in duration. Colorado has an excellent crash record database, which was able to provide 5 years of before period data for all sites. This included one location which required data as far back as 1993.

Crash data were obtained from CDOT's crash database maintained by the Safety & Traffic Engineering Branch. Crash information included date and time, milepost, weather condition, type of accident, and related details. The total numbers of crashes at each FAST site varied over time, as shown in Table 8. At most locations, winter-related crashes (coded in the database as being snowy or icy weather conditions) are a small portion of the overall crashes that occurred at each site over the respective time period. The traffic volumes at each location varied significantly, which accounts for higher crash numbers on urban interstates as opposed to rural two-lane roads.

Table 8: Crash history before and after deployment for Colorado FAST sites

Site	Mileposts	Before Crashes (Winter-Related)	Before Period (years)	After Crashes (Winter-Related)	After Period (years)
Two-Lane Rural Roads					
SH67 (NB, SB)	47.05 - 47.28	2 (0)	5.5	3 (1)	10
U.S. 34 (EB, WB)	68.73-68.77	0 (0)	5.5	0 (0)	11
U.S. 34 (EB, WB)	70.54-70.58	0 (0)	5.5	0 (0)	11
U.S. 34 (EB, WB)	75.68-75.72	1 (0)	5.5	3 (0)	11
Multi-lane Rural Roads					
SH 119 (EB, WB)	61.95 - 62.00	6 (3)	5.5	5 (4)	4
Urban Interstates					
I-25 (NB, SB)	147.39 - 147.52	33 (8)	5.5	40 (13)	15
I-25 (NB, SB)	139.75 - 139.88	27 (2)	5.5	33 (7)	10
I-25 (NB, SB)	238.09 - 238.14	12 (2)	5.5	10 (0)	5
I-25 (NB, SB)	231.10 - 231.13	17 (2)	5.5	12 (4)	8
I-25 (NB, SB)	233.08 - 233.11	22 (1)	5.5	20 (4)	8
I-25 (NB, SB)	241.11 - 241.18	2 (0)	5.5	0 (0)	3
I-25 (NB, SB)	242.15 - 242.18	2 (2)	5.5	1 (0)	3
Rural Interstates					
I-70 (EB, WB)	216.23 - 216.28	1 (0)	5.5	4 (1)	9
I-25 (NB, SB)	172.2- 172.22	14 (5)	4.5	5 (1)	6.5
I-25 (NB, SB)	171.80 - 171.82	15 (5)	4.5	13 (5)	6.5
I-25 (NB, SB)	172.01 - 172.02	0 (0)	4.5	3 (3)	6.5
I-70 (EB, WB)	171.20 - 171.29	34 (22)	5.5	59 (43)	9
I-70 (WB)	124.74 - 124.85	10 (7)	5.5	16 (10)	9
Interchange Ramp Structures					
Ramp from EB I270 to EB I 76		5 (1)	2	13 (3)	3
Ramp from SB I25 to EB I225		54 (17)	5.5	38 (9)	3
Ramp from WB I225 to SB I25		24 (6)	5.5	29 (6)	3
Other Routes*					
SH52	11.09 - 11.16	0 (0)	5.5	46 (2)	13
SH66	42.86 - 42.93	3 (0)	5.5	2 (0)	3
SH83	65.30 - 65.44	10 (7)	5.5	16 (10)	2
SH 160	173.93 - 173.96	N/A	-	0 (0)	11.5
SH 160	174.16 - 174.19	N/A	-	1 (1)	11.5

*Notes:

1. The overpasses that comprise the SH 52 and SH 66 sites underwent significant changes in the period before and after FAST deployment in terms of number of lanes and traffic control.
2. The SH 83 site was an at-grade intersection in the before period and a grade separated overpass in the after period.

3. The SH 169 locations consisted of a two-lane road skirting an outcrop during the before period and tunnel exits in the after period following tunnel construction.
4. SH 52 crash data from the period before FAST deployment indicates no crashes, which may be attributed to the site being more rural in terms of development at the time.
5. Before period data for SH 169 has not been provided as changes in alignment precluded a direct comparison of the same crash data by milepost.

Geometric and traffic data for each site came from records available from CDOT's MapView and Traffic Data Explorer websites. MapView is an online Geographic Information System (GIS) which provided geometric data for each site such as number of lanes, pavement widths, shoulder types, median widths and so forth. MapView also serves as a portal to CDOT's Windshield website, which serves as a viewer for the state's videolog data. This videolog data offered a supplemental source of information, allowing the researchers to view each study location and verify conditions and characteristics identified through MapView. The Traffic Data Explorer website provided Annual Average Daily Traffic (AADT) information for the various study years associated with each FAST site.

As the notes in Table 8 indicate, some sites saw extensive changes before and after a respective FAST system were deployed. Such changes were identified via the videolog data from the state, as well as through examination of Google Earth aerial imagery over time. Construction records were also requested from CDOT to determine other changes that may have occurred at each site. The identification of such changes, which might include safety-related improvements, was necessary to establish what portion of any reduction or increase of crashes might be attributable to the FAST system versus other changes. However, construction records were not readily available during the course of the research. Consequently, the changes in crashes discussed in later sections may not be entirely attributable to the FAST system present at a respective site.

As a result of the changes and differences at the five locations noted in Table 8's notes, it was not possible to perform a statistical evaluation of crashes for these FAST systems. This was due to the different characteristics of the roadways at each site between the before and after periods, which precluded a comparison of the same facility in terms of alignment, number of lanes, and traffic control. Despite the inability to examine these five sites in detail, 21 FAST sites remained available for the before and after analysis.

While winter weather is an important aspect when considering a system such as FAST, historical weather records (e.g., storm occurrence) were not necessary as part of the overall analysis. This is because the approach employed, which is detailed in the following sections, considered crash data from throughout the year rather than only seasonal data. The analysis considers that the deployment of a FAST system at each site was the only major change that occurred. As a result, any improvement or deterioration in safety at the site from the entire after period would be tied to the introduction of FAST at a particular location.

Methodologies and data analysis

The purpose of the safety analysis was to investigate crash history before and after the deployment of FAST at different sites and determine if the system positively or negatively affected traffic safety by reducing crashes. The impact of the FAST system on traffic safety would be during winter months (October through March). In light of this, the effects of the system on accident frequencies were investigated.

The safety effects of the FAST deployments can be evaluated through an observational before-after study (Hauer, 1997, AASHTO, 2010), which is used to determine the change in safety in terms of crash counts:

$$\boldsymbol{\delta} = \boldsymbol{\pi} - \boldsymbol{\lambda} \text{ or } \boldsymbol{\theta} = \boldsymbol{\lambda}/\boldsymbol{\pi} \tag{1}$$

Where:

δ = crash reduction (or increase);

θ = index of safety effectiveness;

π = the predicted number of crashes in the after period without the FAST system; and

λ = the number of reported/observed crashes in the after period with the FAST system present.

In vehicle crash analysis, before-after studies can be grouped into three types: the simple (naïve) before-after study, the before-after study with control groups (the Comparison Group (C-G) method), and the before-after study using the Empirical Bayes (EB) technique. The selection of the study type is usually governed by the availability of the data, such as crash records and traffic flow, and whether the transportation safety analyst has access to entities that are part of the reference group (comparison sites). The selection can also be influenced by the amount of available data (or sample size). The EB method is employed in this work, as it has been shown to have better performance than both the naïve and the C-G methods (Hauer, 1997) in addressing problems associated with these approaches (e.g., regression-to-mean (RTM)), and appropriate selection of a before period. Regression to the mean is of particular concern, as it is the potential for a high or low number of crashes to occur during any given year, but over time, and for such crashes to hover around a mean annual figure. The EB technique has been effectively used in numerous traffic safety evaluations over the past decade (Persaud et al., 2001, Persaud et al., 2003, Bauer et al., 2004, Persaud et al., 2004, Miller et al., 2006, Hadayeghi et al., 2007, Patel et al., 2007, Gross et al., 2008, Srinivasan et al., 2008, Ye et al., 2011, Ye et al., 2012).

Observational before-after study using empirical Bayes approach

In the EB before-after procedure, an important task is to estimate the number of crashes in the after period had the safety treatment (π) not been implemented. In this case, the estimation being made is for the case where the FAST was not deployed. To do this, the Safety Performance Functions (SPF) from the current edition of the Highway Safety Manual (HSM) (AASHTO, 2010), as well as other SPFs developed for future editions of the HSM (Bonneson et al., 2012a, Bonneson et al., 2012b) were used. These SPFs included rural two-lane, two-way roadway segments; rural, multilane highways; urban and rural freeways/interstates; and interchange ramps. The forms of these SPFs are presented in the following equations. The SPFs were used to predict average crash frequency for base conditions (e.g., 12-feet lane width, 6-feet shoulder width, no horizontal or vertical curves):

- Two-lane rural roads

$$N_{spf} = AADT * L * 10^{-6} * e^{(312)} \tag{2}$$

where:

N_{spf} = predicted total crash frequency for roadway segment base conditions;

$AADT$ = annual average daily traffic (vehicles per day); and

L = length of roadway segment (miles).

- Multilane rural highways

$$N_{spfrd} = e^{(a+b*\ln(AADT)+\ln(L)} \tag{3}$$

where:

N_{spfrd} = predicted total crash frequency for divided roadway, segment base conditions;

a, b = regression coefficients, provided by HSM.

$AADT$ = annual average daily traffic (vehicles per day); and

L = length of roadway segment (miles).

- Multilane urban and rural freeways/interstates

$$N_{spf,fs,n,[mv\ or\ sv],[z\ or\ pdo]} = L * \ e^{(a+b*\ln[c*AADT])} \tag{4}$$

where:

$N_{sp,f,s,n,\ [mv\ or\ sv],[z\ or\ pdo]}$ = predicted average multiple-vehicle (mv) or single vehicle (sv) crash frequency of a freeway segment with base conditions, n lanes, and severity (fatal and injury or property damage only) (crashes/yr);

L = effective length of roadway segment (miles) *a, b, c* = regression coefficients, provided by the reference document (Bonneson et al., 2012b); and

AADT = annual average daily traffic (vehicles per day).

- Interchange ramps

$$N_{spf,w,x,y,z,[mv\ or\ sv],[z\ or\ pdo]} = L * e^{(a+b*\ln[c*AADT])} \quad (5)$$

where:

$N_{spf,w,x,y,z}$ = predicted average crash frequency determined for base conditions of the SPF developed for site type w, cross section or control type x, crash type y (multi or single vehicle), and severity z (fatal and injury or property damage only) (crashes/yr);

L = effective length of roadway segment (miles)

a, b, ,c, d = regression coefficients, provided by the reference (Bonneson et al., 2012b); and

AADT = annual average daily traffic (vehicles per day).

As indicated, the different SPFs were employed for predicting crash frequency for roadway segment base conditions. Crash Modification Factors (CMFs) must be applied to account for the effect of site-specific geometric design features. The HSM and the additional references provide various CMFs for this purpose specific to the rural two-lane, two-way roadway segments, rural multi-lane highway segments, urban and rural freeway segments and interchange ramp segments. Based on the existing geometrics present at the various FAST sites, different CMFs were applied to account for lane widths, shoulder types and widths, presence of horizontal curvature, barrier presence and so forth. In some cases, the specific feature present matched the default conditions of the particular SPF being used. In such cases, the default value for the CMF of 1.0 was used. When a particular feature was not present at a site, such as the presence of rumble strips, the CMF value was also equal to 1.0. CMFs are easy to calculate based on the reference tables and equations provided in the HSM and the future HSM chapters referenced.

In typical safety analysis using the HSM approach, a series of roadway segments along a continuous route would be evaluated. However, in the case of this work, each FAST site represents a short segment (typically a bridge deck) of roadway. Each site was unique in terms of its specific features, traffic and so forth and had to be evaluated individually, as opposed to combining all sites together as would normally be the case. Consequently, only the short segments where the FAST system was present were evaluated. While it is possible that the FAST system may contribute to improving safety for a brief portion of roadway beyond its location, the extent of this contribution is not known and was not established as part of this work. Only the immediate segment of roadway which was treated by the FAST system was examined.

As stated previously, the EB technique was used to estimate the expected crash frequency by combining the predictive model estimate, generated through the calculations of the various SPFs, with observed crash frequency. The expected crash frequency for an individual roadway segment is computed by:

$$N_{expected} = w * N_{predicted} + (1 - w) * N_{observed} \quad (6)$$

$$w = \frac{1}{1 + k * (\sum_{all\ study\ years} N_{predicted})} \quad (7)$$

where:

$N_{expected}$ = estimate of expected average crash frequency for the study period;

$N_{predicted}$ = predicted model estimate of average crash frequency for the study period;

$N_{observed}$ = observed crash frequency at the site for the study period; and

w = weighted adjustment to be placed on the predictive model estimate.

Results

Based on the analysis results, the general effect of the FAST on accident frequency can be calculated. Instead of calculating the index of effectiveness (θ) presented in Equation 1, an approximate, unbiased estimate of θ for each site was determined by the approach developed by Hauer (1997):

$$\boldsymbol{\theta = \frac{\lambda/\pi}{1 + Var(\pi)/\pi^2}}$$

The variance of θ was calculated by:

$$Var(\theta) = \frac{\theta^2 * (\frac{Var(\lambda)}{\lambda^2} + \frac{Var(\pi)}{\pi^2})}{(1 + \frac{Var(\pi)}{\pi^2})}$$

The value of θ, presented along with other data in Table 9, indicates that the deployment of FAST at a particular site reduced or increased the number of crashes by a given percentage during the after period for the study section. For example, on urban interstates, values of θ ranged from 0.30 to 0.84 (disregarding the 0.00 value), suggesting that the introduction of FAST at these sites reduced crashes between 16 and 70 percent. Of course, the introduction of FAST alone likely did not contribute entirely to this reduction; however, in the absence of any information indicating other safety improvements were made at the sites, it can be concluded that FAST played a role in reducing crashes on an annual basis. This is one limitation of the HSM method, as the SPFs employed can only be used for annual crash prediction. Hence, the percent reduction of annual crashes is based on the assumption that there were no changes in crashes during the summer seasons of the study period, which of course is not the case, particularly on highly trafficked corridors.

The results of the observational before-after study using the EB technique are presented in Table 9. While the following paragraphs will discuss FAST deployments by facility type, some general observations are in order. As the table indicates, the number of expected crashes at each FAST site following deployment varied greatly. This is due, in part, to factors such as different (higher) traffic levels, facility types and so forth varying between sites. In some cases, the number of crashes observed in the after period was lower than the expected number, indicating that the FAST system likely contributed to improving safety. At other sites, slightly more crashes were observed compared to the expected number, making it unclear whether the FAST system had any impact on safety. Finally, in at least four cases, the number of observed crashes at a site greatly exceeded the estimated number of crashes expected. While it is clear that the addition of FAST at such sites did not lead to an obvious improvement in safety, it is also likely that it did not lead to a deterioration of safety to the extent observed. Rather, other factors could have contributed to the lack of an observed improvement in safety, such as a reduction in police enforcement in the area or other contributors.

The deployment of FAST on two-lane rural roads produced mixed results for the four sites examined, as measured by the index of effectiveness. At the SH 67 site and the U.S. 34 site at milepost 75.68-75.72, crashes slightly increased in the after period compared to the expected number that had been predicted. The index of effectiveness for these sites indicates an increase in annual crashes following deployment of 33 to 57 percent could be expected when a FAST is deployed. This figure should be considered with caution given the low number of crashes observed during both the before and after period, as well as the short length of the deployment site itself. The remaining two U.S. 34 sites produced an index of effectiveness of 0.00, which was the result of zero crashes being observed at each of these sites during both the before and after periods. Due to this lack of observed crashes, the calculations used to establish the index of effectiveness produce the zero value, and it is unclear what role FAST may have played in reducing or preventing crashes at the sites. However, it is reasonable to conclude that the deployment of FAST at these locations did not deteriorate safety.

Only one multilane rural (divided) highway hosted a FAST deployment. The index of effectiveness for the site was 0.98, indicating that crashes fell by 2 percent following FAST deployment. Relatively speaking, this is a low percentage in terms of a crash reduction, which makes it unclear whether FAST systems would reduce or maintain current crash numbers at comparable locations if installed. Still, based on the results from this site, it is reasonable to conclude that the FAST system did not contribute to a deterioration of safety.

Table 9: EB Analysis Results for Colorado FAST Sites

Site	Milepost	Segment Length (mile)	Before Period (years)	Observed Crashes During Before Period	EB Estimated Crashes During Before Period	After Period (years)	Observed Crashes During After Period (λ)	EB Estimated Crashes During After Period (π)	Variance of (π)	Unbiased Estimate of Index of Effectiveness (θ)
Two-Lane Rural Roads										
SH 67	47.05 - 47.28	0.23	6	2	0.98	10	3	1.58	0.51	1.57
US 34	68.73 - 68.78	0.05	6	0	0.15	11	0	0.31	0.22	0.00
US 34	70.54 - 70.58	0.04	6	0	0.12	11	0	0.25	0.17	0.00
US 34	75.68 - 75.72	0.04	6	1	0.77	11	3	1.61	1.05	1.33
Multi-lane Rural Roads										
SH119	61.95 - 62.01	0.06	6	6	6.27	4	5	4.06	4.06	0.98
Urban Interstates										
I-25	238.10 - 238.14	0.04	6	12	5.23	15	10	11.56	4.18	0.84
I-25	231.10 - 231.13	0.03	6	17	5.83	10	12	39.54	13.43	0.30
I-25	233.08 - 233.11	0.03	6	22	7.83	5	20	44.83	15.84	0.44
I-25	241.11 - 241.18	0.07	6	2	2.39	8	0	2.94	1.04	0.00
I-25	242.15 - 242.18	0.03	6	2	1.70	8	1	1.77	0.72	0.46
I-25	147.39 - 147.52	0.13	6	33	31.49	3	40	93.73	65.06	0.42
I-25	139.75 - 139.88	0.13	6	27	17.77	3	33	42.21	20.50	0.77
Rural Interstates										
I-70	216.20 - 216.28	0.06	6	4	2.98	9	1	1.98	0.69	0.43
I-25	172.20 - 172.23	0.03	5	14	7.09	7	5	6.75	3.04	0.69
I-25	171.80 - 171.82	0.02	5	15	8.55	7	13	10.62	5.64	1.17
I-25	172.01 - 172.02	0.01	5	1	0.46	7	2	0.57	0.16	2.34
I-70	171.20 - 171.30	0.20	6	34	21.80	9	59	23.33	9.89	2.48
I-70 (WB)	124.99 - 125.47	0.48	6	10	6.85	9	16	5.64	2.28	2.65
Interchange Ramps										
I-270/I-76	EB to EB	0.40	2	5	1.09	3	13	1.64	0.11	2.49
I-25/I-225	SB to EB	0.30	6	54	4.82	3	38	3.39	2.05	0.60
I-225/I-25	WB to SB	0.10	6	24	2.09	3	29	1.46	1.06	0.81

Urban interstate FAST sites showed the most positive results in terms of the index of effectiveness values produced. Values ranging from 0.30 to 0.84 were produced, indicating that crashes following FAST deployment fell by 16 to 70 percent annually. While the FAST deployments were likely only one contributor along with other unidentified factors in improving safety at these sites, it is encouraging that safety improved at all sites following deployment. This is especially true given that the sites were all located along high traffic volume routes where there is an increased probability for crashes to occur.

Rural interstate sites produced mixed results, unlike their urban counterparts. Sites on I-70 at milepost 216.20-216.28 and I-25 at milepost 172.20-172.23 showed improvements to safety, with index of effectiveness values of 0.43 and 0.69 respectively. These translated into annual crash reductions of between 31 and 57 percent. However, remaining sites showed deterioration in safety as evidenced by high numbers of observed crashes versus the numbers expected following deployment, as well as correspondingly high index of effectiveness values. The reasons for the trends present at these sites are not entirely clear, although a few thoughts may be offered. The I-25 sites at milepost 171.80-171.82 and milepost 172.01-172.02 were part of a series of three FAST systems deployed together and deactivated in 2010. Maintenance issues were the cause of the deactivation, which suggests that these sites did not operate reliably and may not have been operating during some storms. This could in part explain why crashes did not decrease following deployment. The I-70 site at milepost 124.99-125.47 (westbound direction only) was located immediately at the exit of a tunnel. While FAST may have improved general pavement conditions at the location, the general nature of the site itself may be the contributing factor to crashes. It is possible that drivers exiting the tunnel encounter conditions that they do not expect, regardless of weather, leading to crash occurrence. No conditions at the I-70 milepost 171.20-171.30 site were evident to explain the increase in crash occurrence following FAST deployment.

FAST sites located on interchange ramps, specifically on ramps between interstates, showed generally positive results. It was found that index of effectiveness values of 0.60 and 0.81 were produced by two sites, translating into annual crash reductions between 19 and 40 percent. However, one ramp showed a significant increase in crashes and a corresponding index of effectiveness value of 2.49 (an increase in crashes of 149 percent). At this site, it is evident that safety did not improve following FAST deployment, although supplementary evidence suggests that the system did not necessarily contribute to that deterioration. In referring to Table 8, approximately 20 percent of crashes on this ramp occurred during winter weather conditions both before and after deployment. This offers at least some indication that the FAST system at this site had a neutral impact on safety.

As indicated in earlier text, additional sites also had FAST deployments that could not be evaluated by the EB method because of dramatic changes to the roadway environment. In some cases, this precluded comparison of even before versus after numbers of observed crashes, as entirely new roadway alignments were employed. Still, it is of interest to examine at least some aspects of these sites to determine what impact FAST systems may have had. Information for these additional sites is presented in

Table **10**. In general, the total number of crashes following FAST deployment was relatively low, aside from the SH 52 site. This was in part due to the long period of data available following FAST deployment (12.5 years), the moderate volume of traffic on the segment and the character of the location itself, which was an overpass for a diamond interchange, with the intersection of each ramp signalized. A low number of winter-weather related crashes were also observed at each site post-deployment, although this low number was still high at some locations when compared to the total number of crashes that had occurred. In order to facilitate a meaningful comparison among sites, crash rates were determined for the after period at sites where a statistical evaluation could not be performed.

As

Table **10** illustrates, the sites produced different winter weather crash rates, all of which were quite low. SH 160 and SH 66 each produced rates of 0.00, attributable to there being no winter weather crashes following FAST deployment. This does not mean that the FAST systems eliminated winter crashes, although it is likely that the systems helped in reducing crashes. The second SH 160 site produced a crash rate of 0.09, which is quite reasonable over the 11 winter seasons that occurred following deployment. Similarly, the SH 83 and SH 52 sites performed well, each with low crash rates. The rate of 0.50 for the SH 83 site is a bit higher than other sites, but this is primarily attributable to the short duration of the after deployment period.

When looking at the raw crash figures for winter weather crashes at each site, winter weather crashes at each location following deployment are quite low. Only at one SH 160 site did winter weather crashes make up the majority of crashes following deployment. However, this one crash over an 11.5 year period can still be considered good. While it is not clear to what extent the FAST sites at each location contributed to safety improvements, it is clear that the deployments did not negatively impact safety.

Table 10: Crash Trends for Additional Colorado FAST Sites

Site	Milepost	Segment Length	Years of Data	No. of Total Crashes	No. of Winter Weather Crashes	Winter Weather Crash Rate
SH 160	173.93 - 173.96	0.03	11.5	0	0	0.00
SH 160	174.16 - 174.19	0.03	11.5	1	1	0.09
SH 83	65.30 - 65.44	0.14	2	4	1	0.50
SH 52	11.10 - 11.16	0.16	13	46	2	0.15

SH 66	42.86 - 42.82	0.06	3	2	0	0.00

So far, the evaluation has focused on the effect of the system on crash frequency and has not investigated its effect on crash severity nor winter weather crash rates at specific sites where apparent reductions in such crashes occurred (see Table 8). Thus, further analysis was conducted to investigate the crash rates by severity level for winter weather crashes, as described below.

Crash severity analysis

Based on Table 8 data, some sites saw reductions in winter weather (i.e. snow and ice) crashes following FAST deployment, although the overall number of annual crashes may have risen. Since the EB analysis considers the entire crash history for a year rather than seasonally, it was also possible that some sites with an index of effectiveness above 1.0 may have seen reductions in winter weather crashes. As a result, it is of interest to examine how winter weather crash rates by severity may have changed. Sites in Table 8 were selected where at least winter weather crash had occurred following FAST deployment. Sites with zero crashes during the before and after period were not considered, as these could be considered locations where safety had not changed during the winter months. Information on the different crash severities for each site is presented in Table 11.

The crash rates at selected sites (crashes per winter season) for different severity levels are presented in Table 12. The crash rates in the before period were adjusted by multiplying the factor ($\frac{\text{AADT}_{\text{after}}}{\text{AADT}_{\text{before}}}$) to compare with those in the after period. The collective annual costs associated with each of these crash severities at the site level are also presented. CDOT uses the average economic cost values established by the National Safety Council (National Safety Council, 2012). The costs per fatal crash, nonfatal disabling injury crash, and property damage only (PDO) crash are \$1,410,000, \$78,900, and \$8,900 respectively in 2012. The Consumer Price Index (CPI) inflation between 2012 and 2013 (the last year of crash data employed) is 1.01, according to the Bureau of Labor Statistics (Bureau of Labor Statistics). When applied to Table 12, the total safety benefits of deployment per winter season can be obtained for each site. The safety benefit can be calculated by the following equation:

$$SB = \sum_{i=1}^{3}(Crash_{before}^{i} - Crash_{after}^{i}) * Cost_i \quad (8)$$

where:

SB = safety benefit (\$);

$Crash_{before}^{i}$ = crash rate for crash type *i* (PDO, injury, and fatal) during before period;

$Crash_{after}^{i}$ = crash rate for crash type *i* (PDO, injury, and fatal) during after period; and

$Cost_i$ = cost per crash for crash type *i* (PDO, injury, and fatal).

Table 11: Breakdown of winter weather crash severities by type at select FAST sites

Site	Milepost	Segment Length	Before					After				
			Period (Years)	AADT	Fatal Crashes	Injury Crashes	PDO Crashes	Period (Years)	After AADT	Fatal Crashes	Injury Crashes	PDO Crashes
SH 119 (EB, WB)	61.95 - 62.01	0.06	5.5	38000	0	1	2	4	34000	0	0	4
I-25 (NB, SB)	147.39 - 147.52	0.13	5.5	92000	0	5	3	15	99000	0	1	12
I-25 (NB, SB)	139.75 - 139.88	0.13	5.5	68000	0	0	2	10	80000	0	0	7
I-25 (NB, SB)	238.10 - 238.14	0.04	5.5	38000	0	0	2	5	70000	0	0	0
I-25 (NB, SB)	231.10 - 231.13	0.03	5.5	38000	0	2	0	8	97000	0	1	3
I-25 (NB, SB)	233.08 - 233.11	0.03	5.5	38000	0	0	1	8	85000	0	0	4
I-25 (NB, SB)	242.15 - 242.18	0.03	5.5	38000	0	0	2	3	70000	0	0	0
I-25 (NB, SB)	172.20 - 172.23	0.03	4.5	55000	0	0	5	6.5	61000	0	0	1
I-25 (NB, SB)	171.80 - 171.82	0.02	4.5	55000	0	1	4	6.5	61000	0	0	5
I-70 (EB, WB)	172.01 - 172.02	0.01	5.5	55000	0	7	15	9	61000	0	8	35
I-70 (WB)	124.74 - 124.85	0.20	5.5	34000	0	0	7	9	35000	0	1	9
EB I270 to EB I 76	Ramp	0.40	2	4700	0	0	1	3	4700	0	0	3
SB I25 to EB I225	Ramp	0.30	5.5	24500	0	0	17	3	26000	0	0	9
I225 to SB I25	Ramp	0.10	5.5	32500	0	0	6	3	34000	0	0	6

The results show that the crash rate for PDO crashes, which are generally the most common type of crash, ranged from 0.33 – 3.02 in the before period to 0.00 – 3.89 in the after period. In some cases, PDO rates increased for a site, while in others they fell. Sites where rises were observed can be explained largely by corresponding drops in injury crash rates at the same location following deployment. While a FAST system may not have entirely eliminated crashes, their severity and corresponding costs were reduced. Fortunately, no site experienced a fatal crash during winter weather, as reflected in the crash rate figures. Overall, it appears that the FAST systems have reduced crash severities. This analysis, however, is similar to the naïve before-after study as it does not take regression to the mean (RTM) into account. However, the generally long before and after periods do provide a fair picture regarding the overall winter weather crash trends at each site.

When looking at the estimated crash savings through changes to crash rates and severities, it can be concluded that the results produced following FAST system deployment are mixed. Some sites, particularly high traffic volume interstates produced significant annual crash cost savings. Many sites produced a marginal savings on the order of a few thousand dollars. Remaining sites saw an increased crash costs, primarily because crashes had not necessarily been eliminated, but rather, reduced in severity. For most sites, these costs were low, not exceeding $7,800. When the total crash cost savings (or increased costs) produced by each system are summed, the 14 FAST systems examined here produced a savings of $196,428.39 annually. This figure rises to $217,993.84 when sites that have experienced increased costs are not considered.

While cost savings have been achieved, many of these were found to occur on higher traffic volume routes. Interchange ramps experienced increased costs or only minimal crash savings. When one considers the average cost of a FAST system is over $250,000, the crash savings produced by most sites in Table 12 can take anywhere from three and a half to over 40 years to recover. And this recovery only takes into account the initial cost of the system, not the annual maintenance, repair/replacement parts, brine materials, and other costs that are incurred. As a result, it appears that high traffic and high crash severity locations are most suitable for FAST deployment.

Table 12: Ice-related crash rates by severity level

Route	Milepost	Study Period	Crash Rate (Weather-related crashes per winter season)				Costs	Savings
			Total	PDO	Injury	Fatality		
SH 119 (EB, WB)	61.95 - 62.01	Before	0.49	0.33	0.16	0.00	$15,888	**6,899.41**
		After	1.00	1.00	0.00	0.00	$8,989	
I-25 (NB, SB)	147.39 - 147.52	Before	1.57	0.59	0.98	0.00	$83,233	**70,728.98**
		After	0.87	0.80	0.07	0.00	$12,504	
I-25 (NB, SB)	139.75 - 139.88	Before	0.43	0.43	0.00	0.00	$3,846	**(2,446.74)**
		After	0.70	0.70	0.00	0.00	$6,292	
I-25 (NB, SB)	238.10 - 238.14	Before	0.67	0.67	0.00	0.00	$6,021	**6,021.34**
		After	0.00	0.00	0.00	0.00	$0	
I-25 (NB, SB)	231.10 - 231.13	Before	0.93	0.00	0.93	0.00	$73,970	**60,637.69**
		After	0.50	0.38	0.13	0.00	$13,332	
I-25 (NB, SB)	233.08 - 233.11	Before	0.41	0.41	0.00	0.00	$3,656	**(838.69)**
		After	0.50	0.50	0.00	0.00	$4,495	
I-25 (NB, SB)	242.15 - 242.18	Before	0.67	0.67	0.00	0.00	$6,021	**6,021.34**
		After	0.00	0.00	0.00	0.00	$0	
I-25 (NB, SB)	172.20 - 172.23	Before	1.23	1.23	0.00	0.00	$11,077	**9,694.43**
		After	0.15	0.15	0.00	0.00	$1,383	
I-25 (NB, SB)	171.80 - 171.82	Before	1.23	0.99	0.25	0.00	$28,502	**21,587.79**
		After	0.77	0.77	0.00	0.00	$6,915	
I-70 (EB, WB)	172.01 - 172.02	Before	4.44	3.02	1.41	0.00	$139,676	**33,884.60**
		After	4.78	3.89	0.89	0.00	$105,792	
I-70 (WB)	124.74 - 124.85	Before	1.31	1.31	0.00	0.00	$11,777	**(6,066.30)**
		After	1.11	1.00	0.11	0.00	$17,843	
EB I270 to EB I 76	Ramp	Before	0.50	0.50	0.00	0.00	$4,495	**(4,494.50)**
		After	1.00	1.00	0.00	0.00	$8,989	
SB I25 to EB I225	Ramp	Before	3.28	3.28	0.00	0.00	$29,485	**2,518.25**
		After	3.00	3.00	0.00	0.00	$26,967	
I225 to SB I25	Ramp	Before	1.14	1.14	0.00	0.00	$10,259	**(7,719.23)**
		After	2.00	2.00	0.00	0.00	$17,978	

Discussion

Construction and other work zone activities on this study roadway segment could affect traffic safety. While CDOT records were not available, examination of aerial imagery indicated that only a few sites, which were identified in prior sections, experienced changes that could impact safety. However, this does not mean that other safety-related treatments, such as chip seals, did not occur at the remaining study locations, which would have a positive impact on safety beyond that provided by a FAST system. This must be kept in mind when interpreting the results of this chapter.

Across the country, many types of systems have been deployed to reduce weather-related accidents. However, as noted in the HSM (AASHTO, 2010), knowledge regarding the quantitative effects of systems on reducing weather-related accidents is limited. No Accident Modification Factors (AMFs) have been developed for weather issue treatments. Consequently, the results from this study are useful to provide a better understanding of safety effects of FAST systems. While the ages of the various deployments examined varied, the results from the overall evaluation provide an understanding of the safety effects and benefits of FAST systems on different highway types.

Conclusion

This chapter presented analysis and results of the safety effects of the FAST systems deployed at different locations for various types of highways. An observational before-after study with EB technique was used to determine the effect of FAST systems on crash frequencies. The results revealed that the deployment of FAST systems contributed to a reduction in the number of annual crashes on multilane rural highways by 2 percent, urban interstates by 16 to 70 percent, rural interstates by 31 to 57 percent and interchange ramps between interstates by 19 to 40 percent. These correspond to AMFs of 0.98 for rural multilane highways, 0.30 to 0.84 for urban interstates, 0.43 to 0.69 for rural interstates and 0.60 to 0.81 for interchange ramps. Furthermore, a crash rate method was used to investigate the effect of different FAST deployments on crash severities, with a focus on winter weather-related accidents. The results showed that the use of FAST systems has reduced crash severities at many sites. As a result, the systems examined have potentially provided safety benefits of $196,428 per winter season during the "after deployment" study period. This figure does not account for sites where no winter weather crashes had occurred during the before and after periods, as crash rates could not be established for them.

When choosing future deployment locations in light of safety, a number of points should be considered. It is unclear if FAST systems deployed on rural two-lane roads have any significant effect on improving safety. Some of the results from this work indicate that safety may have deteriorated, although these sites experienced low crash numbers and the occurrence of even one winter weather crash could give the appearance of deteriorated safety after installation. In light of this, FAST may be better applied on higher traffic roads when the intent is largely to prevent or reduce crashes. If maintenance concerns are paramount (e.g., need for quicker response time), then FAST installations may provide an advantage on a two-lane road.

On rural multilane divided highways, the deployment of a FAST system appears to have produced a small improvement in safety and would likely produce a comparable result when applied in similar locations. Urban interstate applications of FAST systems produced the most positive results, with crash reductions of between 16 and 70 percent observed. While the FAST systems alone did not account for these reductions, they likely played a large role. Consequently, it can be concluded that high volume urban interstates are likely the best sites for FAST deployments, given that the benefits of the system reach the largest number of vehicles.

Rural interstate FAST deployments showed effectiveness in reducing crashes in some cases, but also increases (some large) in crashes at other locations. Some of these increases were at sites that were later decommissioned, which may indicate that maintenance problems during the course of the deployment itself limited the effectiveness of the system. However, given the time and distances required to perform maintenance at rural interstate sites, FAST systems may provide safety benefits, if they are maintained in a suitable operating condition throughout the winter season.

Finally, FAST deployments on interchange ramps between interstates produced encouraging results, with crash reductions found for two of three locations. However, future deployments on interchange ramps should be limited to those that serve high traffic volumes, as was the case with the systems evaluated in this work.

5. DEVELOPMENT OF BENEFIT-COST TOOL

One of the goals of FAST systems is to provide a safe driving surface in locations that are particularly susceptible to snow and ice such as bridge decks. Correspondingly, one of the primary benefits of such systems is a reduction in crashes at such sites. However, other benefits are also accrued from FAST systems, such as maintenance savings from reduced call-outs for a maintenance vehicle to travel to and from a specific location to address a localized snow or ice issue. Reduced travel delays due to crashes are another benefit, albeit hard to quantify in the case of a short segment covered by a FAST system. The maintenance benefit is more likely to occur for rural locations than urban ones, where travel from a local maintenance garage to the site can represent a significant amount of time, labor, and fuel use.

The following sections discuss these three components of the benefits produced by FAST systems. This is followed by an overview of a framework for conducting a benefit-cost analysis for individual FAST sites. Note that hard data such as the exact cost of the FAST system at each site and the number of call-outs to treat a specific site were not available from CDOT records, so a conclusive benefit-cost analysis could not be performed for each site. Rather, a general benefit-cost analysis has been performed to provide a sense of the prospective impact that could be produced by FAST systems.

Safety Benefits

A reduction in the number and severity of crashes is one of the primary benefits of a FAST system. In light of this, the dollar value associated with these reductions represents the safety benefit accrued by deployment of FAST at a respective site. A prior discussion in this report provided an analysis of the specific crash reduction savings (or increased costs, a disbenefit) achieved by specific fast sites based on crash rates before and after FAST deployments. This section discusses how a general calculation of the prospective crash reduction savings can be calculated in the future for an existing FAST site or proposed sites.

The approach used in calculating the crash reduction benefit of FAST relies on the estimated percentage crash reductions observed for each of the different roadway types that had existing deployments. For the purposes of being conservative, higher values of potential reductions as determined by the index of effectiveness for each type of site are recommended here. For two-lane rural roads, the index of effectiveness values did not yield a specific percentage of decrease in crashes (in two cases, an increase was observed). However, for the purpose of evaluating sites in the future, a conservative value for a crash reduction of 10 percent may be assumed. For rural multi-lane freeways, a reduction of 2 percent should be used, based on the index of effectiveness. Urban interstate applications should use a reduction of 16 percent, while rural interstates should employ a value of 31 percent. Finally, interchange ramps should employ a crash reduction value of 40 percent. In all cases, an analyst may employ more conservative values if desired.

Similarly, if additional research and evaluation results become available in the future, crash reduction percentages from that work should be considered and incorporated as appropriate.

In determining the savings achieved by a reduction of crashes attributable to the FAST system, historical crash data is necessary. This data may consist of any duration of time, although at least one year is preferable. Crash data should be separated into fatal, injury and property damage only categories. The number of crashes divided by the selected period of time yields an annual crash rate, which is then multiplied by the selected percentage crash reduction observed by FAST systems for a specific highway type. The resulting figure is then multiplied by CDOT's average economic cost values for crashes. Recall that these costs per fatal crash, nonfatal disabling injury crash injury and property damage only (PDO) crash are $1,410,000, $78,900, and $8,900 respectively in 2012 dollars. The resulting calculations represent the financial savings achieved through the FAST system in reducing crashes at a particular site.

Maintenance Benefits

The second benefit which can be calculated for a FAST site is the potential savings in maintenance that are achieved by reducing the need for maintenance vehicles to travel to a specific site to apply chemical treatments. While it is likely that other maintenance operations would be performed while traveling to and from such sites, there may also be cases where a site is particularly prone to ice and snow remaining on the roadway while remaining pavement on the route is bare and/or wet. In such cases, a trip to and from the specific FAST site represents a significant expense in terms of time and labor. The use of FAST at such a site eliminates, or at least reduces, the number of trips (referred to as call-outs here) to perform maintenance.

To establish the value of the maintenance benefit, it is first necessary to establish how many maintenance activities or call-outs there are on an annual basis, specifically to address conditions at a particular site (this could be an average). While maintenance may have been performed enroute to or from that site, the specific reason for a maintenance vehicle being out in such a case is to treat the site itself. The number of call-outs to the FAST site before deployment is multiplied by the loaded labor cost associated with a plow operator and the total time in hours required to travel to and from the site. Travel time is calculated as the total distance to the site multiplied by 2 (to account for returning to the maintenance garage) and divided by an average maintenance vehicle travel time of 25 miles per hour. A similar calculation is made for the number of callouts (if any) that have been made annually following FAST deployment. The difference between these two dollar amounts represents the savings (ideally, assuming callouts have not risen following FAST deployment) that has been achieved through the use of FAST.

Delay Reduction Benefits

Given that the FAST systems deployed in Colorado cover a relatively short distance of highway (typically measured in tenths of a mile), it is difficult to establish what, if any, collective travel time improvements they provide over the course of a winter season when snow and ice may be present. In other words, the use of a FAST system to provide an improved pavement surface over a short distance of highway is difficult to measure in comparison to other adjacent segments of roadway. This is because drivers are not going to travel at a higher speed through the section of road treated by the FAST and then slow down when they exit that section. Similarly, the travel time savings produced by a FAST system accrued from a reduction in delay related to vehicle crashes is difficult to estimate. As the result of a crash, it is likely that a certain number of vehicles will encounter a delay as they are forced to slow (or stop) when passing by the crash site. Consequently, when crashes are reduced or eliminated at a site, it stands to reason that a portion of vehicles passing that site will not encounter a travel delay as they would have in the absence of the FAST system.

Establishing the delay savings associated with an estimated crash reduction is difficult however, as it relies on many assumptions. These include the hourly traffic volume passing the site at the time of a crash, the average time required to clear a crash of a given severity, the approximate speed that passing traffic will slow down to after a crash, the average value of time associated with each vehicle, and so forth. Given that many of the FAST sites deployed in Colorado are located along lower volume roads, the delay savings resulting from a reduction in crashes would be relatively small, likely on the order of a few thousand dollars. In light of the numerous assumptions that would need to be made in order to establish the delay savings accrued from a reduction in crashes, such a calculation is not proposed nor incorporated into this work. However, it may be employed if a sound methodology is developed in the future, incorporating observed figures associated with the various categories of assumptions listed above.

Benefit-Cost Analysis

Provided that the information necessary to calculate the benefits at FAST sites is available along with information on initial (installation and equipment) and annual (maintenance, materials, etc.) costs, it would be possible to calculate a benefit-cost ratio. Unfortunately, information such as the number of call-outs for maintenance operations, as well as initial and annual costs associated with the FAST systems is not readily available for the sites discussed in this report, and so a formal benefit-cost analysis for each site cannot be performed. However, spreadsheets have been created as part of this work that can perform such calculations for each of the facility types examined when such information becomes available. As a result, a discussion of benefit-cost analysis is presented in the following paragraphs.

When a financial value can be assigned to most of the costs and benefits of a piece of equipment, a practice or an operation, it becomes possible to compute a benefit-cost ratio. Benefit-cost ratios greater than 1.0 are generally desired. Given that winter maintenance items such as FAST systems entail long service lives that incorporate present and future (e.g., recurring materials and maintenance) costs and benefits, there is a need to bring the values of all future costs and benefits accrued to a present value. A discount rate is employed to accomplish this. The discount rate is an opportunity cost value, or alternatively stated, the time value of money, which indicates how much money could be worth if invested in alternative ways.

Different approaches may be used to select a discount rate. For example, one could use the Consumer Price Index (CPI) or the Office of Management and Budget's guidance on discount rates. Fortunately, CDOT uses its own specific approach to calculate discount rates, making the process straightforward. CDOT uses an approach, discussed by Harris (2009) to set discount rates based on the 10 year moving average of 30 year Treasury bond interest rates (Harris, 2009). Based on that approach, the discount rate in use at the time (2008) was 3.3 percent. For the purposes of developing the benefit-cost analysis spreadsheets that accompany this work, that value has been used as a placeholder, although this figure should be updated with whatever current one is in use by CDOT.

Using the project life and a selected discount rate, the values of costs and benefits are converted to a present value by the following: present value = initial costs + present value of the annualized cost PV(A), where

$$PV(A) = \frac{A}{i} * \left[1 - \frac{1}{(1+i)^n}\right] \quad (8)$$

Where
A = present value of annualized cost
i = the discount rate, and
n = number of years

Once present values are available for costs and benefits, it is possible to calculate the benefit-cost ratio. This is calculated by dividing present value benefits by present value costs. The benefit-cost ratio is calculated for the total costs and benefits that have been accrued by the system.

In conducting a benefit-cost analysis on a system such as FAST, the primary benefits that will be achieved are reductions in crashes. The values of crashes, particularly fatal and injury crashes, have higher dollar values associated with them. When reductions in these types of crashes, even small reductions occur on an annual basis, significant financial savings are achieved. Financial savings stemming from maintenance can also be significant, particularly for locations where extensive travel time to and from an isolated location is necessary when performing a spot treatment. However, these savings will typically be much smaller than those achieved by crash reductions.

The costs associated with FAST systems can be extensive, both in terms of initial installation costs and the recurring costs that occur annually to maintain and inspect the system, charge it with treatment fluid, and so forth. Unfortunately, there is not a clear picture of what the initial cost of many FAST systems has been, as installations have been made in conjunction with bridge projects. In the process, the costs associated with the systems have been combined with other aspects of a project. Maintenance and material cost data is also sporadic at this time. Consequently, records pertaining to these aspects of FAST systems will be necessary before a meaningful benefit-costs calculation can be made for many sites.

As part of this overall project, spreadsheets have been developed that can calculate the benefit-cost ratio for FAST sites in Colorado. These spreadsheets employ the general approaches to establishing the value of benefits discussed in earlier sections, as well as lump sum data for initial and annual costs of the system at a particular site. Requisite data for each aspect of the analysis should be entered into the particular spreadsheet for the facility type being evaluated. Spreadsheets have been developed for two-lane rural roads, multi-lane rural highways, urban and rural interstates and interchange ramps. Other types of sites, such as two-lane road tunnel exits, would be considered under their respective roadway type (ex. two-lane, freeway, interstate). Note that when using the spreadsheets to examine a specific site historically, the number of years for the life of the system should match the number of years of crash data being considered. Similarly, unless the system was removed at the end of that analysis period, no salvage value should be entered.

6. BEST MANAGEMENT PRACTICES GUIDE

Location Selection for FAST Installation

- High risk areas prone to icing conditions.
- Specialized locations that pose unique hazards either due to road conditions/geometry or response time limitations.
- Long-span bridges, tunnel approaches and exits.
- High priority routes (such as economically sensitive locations).
- FAST may not be necessary for all bridges, especially for straight and short-span bridges (span length less than 50 feet).

System Design and Installation

- Vendor should consider modifying the design of FAST components (such as spray nozzles) based on the specific site and the requirements of maintenance crew.
- Involve maintenance crew during every aspect of installation and location selection for various FAST components.
- All the parts used in the FAST systems should be standard (off the shelf) parts that can be purchased from local stores.

Spray Nozzles

- Mounting the spray nozzles on the side rail or side wall should be the preferred option due to easy access and less damage from traffic.
- Spray nozzles can be mounted on the shoulder if the chemicals cannot reach all the lanes due to multiple lanes (4 or more lanes), or if the side rail/side wall is too far away from the lanes.
- For asphalt pavement, an outer wall should be constructed around the spray nozzle. If needed, a side rail can be installed to mount spray nozzles.
- Mounting spray nozzles between lanes should be avoided due to the potential of damage due to traffic, and the need to conduct a complete lane closure to perform maintenance activities.
- Spray nozzles should be made of plastic with a thick stainless steel outer wall.
- The pattern of spray nozzles should be designed such that the chemical spray covers the whole structure.

Valves and Piping System

- Motorized ball valves should be used instead of solenoid valves.
- Valves boxes should be sealed by a water tight enclosure.
- No brass components in the piping system.

- Piping materials could be of stainless steel, polypropylene, nylon 12, rubber hose and schedule 80 PVC.

Fluid tank, fluid pump and storage facility

- It is preferred to have two fluid tanks with a transfer pump between them.
- Access to chemical refilling trucks should be made easy (especially during heavy snow storm events).
- Capacity of fluid pumps should be selected based on the spray area of each nozzle.
- Storage facility should be kept above the ground (no underground vault) and sealed by water tight enclosure.
- Storage facility must be secured from the entry of rodents, insects and other foreign objects.
- Storage facility must be secured from vandalism or any other related issues.

Triggering mechanism and associated systems

- A fully automated system is preferred which can be triggered by a computer from web based PC software.
- Non-invasive sensors should be considered over in-pavement sensors.
- Non-invasive sensors mounted on the pole which triggers the spray of chemicals should be located on the middle span area of the FAST structure behind the rail.
- The triggering mechanism in the FAST system should be set for an appropriate temperature range (16 – 34^{o}F) to prevent the spraying of chemicals at extreme cold temperatures (to prevent re-freeze).
- Electrical components should be sealed from water and rodents.
- All the electrical components should be made of standard parts that can be purchased from local stores.

Finally, a record should be kept on the maintenance issues experienced by each FAST system and the approach used by the maintenance crew to resolve them.

CONCLUSION

FAST has emerged as an important way to supplement mobile winter maintenance operations by enabling winter maintenance personnel to treat selected conditions before snow and ice problems arise. The literature review revealed that a FAST system is complex to install and operate, and the challenges are often site-specific. Difficulties are expected during operations, particularly in areas related to software, activation processes, and pumping systems. Also, researchers emphasize the growing need to focus on using high reliability sensors to maximize the benefits of FAST systems. Furthermore, very few studies have been performed to study the benefit-cost analysis of FAST systems due to the lack of experience and related data tracking.

The key conclusions from this study include:

<u>National survey</u>

- The national survey revealed that almost every installed FAST system (that was discussed by respondents) needed a significant maintenance activity for its successful operation. In some cases, FAST systems failed to operate even after repeated maintenance activity.
- The initial cost of the FAST system is significantly higher than the annual operating and maintenance costs. However, respondents believe that the payback period could be as short as one year for a properly functioning FAST system.
- The benefits of using FAST perceived by the agencies include: reduction on winter related accidents, savings on material use and labor, and reduction of negative environmental impacts.

<u>CDOT survey</u>

- Improper functioning of some FAST systems in Colorado is due to the poor design, poor quality of installation, and insufficient maintenance.
- FAST systems in Colorado faced frequent mechanical, electrical and software issues.
- Involving maintenance crew in every aspect of design and installation of a FAST system can help reduce the maintenance issues.
- Location selection is an important factor for the success of a FAST system. Furthermore, FAST system may not be of benefit for bridges.
- In addition to the improved installation technique, continued success of the FAST system heavily relies on timely maintenance activities.

Safety analysis

- A safety analysis of CDOT FAST systems revealed a reduction in the number of annual crashes on multilane rural highways by 2 percent, urban interstates by 16 to 70 percent, rural interstates by 31 to 57 percent and interchange ramps between interstates by 19 to 40 percent.
- CDOT FAST systems have reduced crash severities at many sites, resulting in potential safety benefits of $196,428 per winter season during the "after deployment" study period.
- FAST may be better applied on higher traffic roads when the intent is largely to prevent or reduce crashes. If maintenance concerns are paramount, then FAST installations may provide an advantage on a two-lane road.

Finally, a benefit-cost excel sheet was developed based on the estimated crash reductions observed for each of the different roadway types. The developed benefit-cost excel sheet used crash reduction rates of 10 percent for two-lane rural locations, 2 percent for multilane rural freeway locations, 16 percent for urban interstate locations, 31 percent for rural interstate locations and 40 percent for interchange ramp locations.

RECOMMENDATIONS AND FUTURE RESEARCH

This study aimed to examine the cost effectiveness of existing CDOT FAST systems. One of the key findings from this study is that FAST systems have shown the potential to reduce the number of crashes. The safety analysis was based on the observational before-after crash data with Empirical Bayes (EB) technique. However, the study assumed that there were no construction/safety improvements aside from the FAST systems at the sites examined. While some sites were excluded from the statistical evaluation because other changes were detected through examination of aerial photos, it is possible that minor improvements, such as chip seals, could also have been made at sites and affected safety.

However, future work should consider a more focused evaluation. Such an analysis would consider only the winter months and require the development of a specific Safety Performance Function (SPF) for different roadway types. The development of such SPFs can be quite costly, which is why such an approach was not employed in this work.

In consideration of future deployment of FAST systems, a small research study can be conducted to find the cost-effectiveness of a FAST system for a selected location. In addition, a detailed examination can be done to find the suitable location and installation technique for each FAST component before the deployment of a FAST system.

REFERENCES

AADI (2011). "Road condition sensor 3565." Aanderaa Data Instruments (AADI). http://www.aadi.no/Aanderaa/Document%20Library/1/Data%20Sheets/Road%20Condition%20Sensor.pdf.

AASHTO (2010). "Highway Safety Manual. 1st edition." Washington, DC, 2010.

Barrett, M. L. and J. G. Pigman (2001). "Evaluation of automated bridge deck anti-icing system."

Bauer, K. M., D. W. Harwood, W. E. Hughes and K. R. Richard (2004). "Safety effects of narrow lanes and shoulder-use lanes to increase capacity of urban freeways." Transportation Research Record: Journal of the Transportation Research Board 1897(1): 71-80.

Beach, M. E. and J. R. Waldman (2005). Anti-icing spray assembly. U.S. Patent No. US 6,955,304.

Bell, G. T., W. A. Nixon and R. D. Stowe (2006). A synthesis to improve the design and construction of Colorado's bridge anti-icing systems.

Birst, S. and M. Smadi (2009). "Evaluation of North Dakota's fixed automated spray technology systems."

Bonneson, J., S. Geedipally, M. Pratt and D. Lord (2012a). "Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges." National Cooperative Highway Research Program Transportation Research Board of the National Academies, Washington, D.C., May 2012. 776 p.

Bonneson, J., M. Pratt, S. Geedipally, D. Lord, T. Neuman and J. Moller (2012b). "Enhanced Interchange Safety Analysis Tool: User Manual." National Cooperative Highway Research Program Transportation Research Board of the National Academies, Washington, D.C., May 2012. 142 p.

Bureau of Labor Statistics "CPI Inflation Calculator." Available at: http://www.bls.gov/data/inflation_calculator.htm.

CERF (2005). "Evaluation of the FreezeFree Anti-Icing System." Final Report by the Civil Engineering Research Foundation, Prepared for the U.S. Federal Highway Administration.

Christillin, M., C. Ardemagni and G. Trombella (1998). The Buthier Viaduct-a Different Approach to Road Network Maintenance in winter. Xth PIARC International Winter Road Congress.

Friar, S. and R. Decker (1999). "Evaluation of a fixed anti-icing spray system." Journal of the Transportation Research Board 1672(1): 34-41.

Gladbach, B. (1993). "Efficacy and economic efficiency of thawing agents spray systems (final report)." Translated from the Original German Text.

Greenfield, T. (2008). "Laser road surface sensor camera evaluation project." Aurora Program.

Gross, F., R. Jagannathan, C. Lyon and K. Eccles (2008). "Safety Effectiveness of" Stop Ahead" Pavement Markings." Transportation Research Record: Journal of the Transportation Research Board 2056(1): 25-33.

Hadayeghi, A., B. Malone, J. Suggett and J. Reid (2007). "Identification of intersections with promise for red light camera safety improvement: application of generalized estimating equations and Empirical Bayes." Transportation Research Record: Journal of the Transportation Research Board 2019(1): 181-188.

Hanson, R., R. Klashinsky, B. Comm, E. Kenneth Day and B. Eric Cottone (2013). "Evaluating Automated Anti-Icing Technology to Reduce Traffic Collisions." Paper prepared for presentation at the Better, Faster, Safer Road Maintenance Session of the 2013 Conference of the Transportation Association of Canada Winnipeg, Manitoba.

Harris, S. (2009). "Colorado Department of Transportation's Current Procedure for Life Cycle Cost Analysis and Discount Rate Calculations." No. CDOT-2009-2. 2009.

Hauer, E. (1997). Observational Before/After Studies in Road Safety. Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety.

Johnson, C. (2001). I-35W and Mississippi River Bridge Anti-Icing Project Operational Evaluation Report.

Keranen, P. (1998). Automated bridge deicers for increased safety and decreased salt use in Minnesota. Xth PIARC International Winter Road Congress.

Khattak, A. J., G. Pesti and V. Kannan (2003). Guidelines for prioritizing bridge deck anti-icing system installations. Phase I and Phase II Report.

Klein-Paste, A. and J. Wåhlin (2013). "Wet pavement anti-icing—A physical mechanism." Cold Regions Science and Technology 96: 1-7.

Kutila, M., M. Jokela, B. Roessler and J. Weingart (2009). Utilization of optical road surface condition detection around intersections. Advanced Microsystems for Automotive Applications 2009, Springer: 109-127.

Lipnick, M. (2001). "Automated bridge anti-icing system interstate 68 over street road Allegany County, Maryland." The Winter Materials and Technologies Evaluation Team, State Highway Administration, Maryland Department of Transportation.

Lo, A. and B. Bielkiewicz (2013). "Application of Fixed Automated Spray Technology (FAST) in Winter Bridge Maintenance." IMSA conference April 16-18, 2013 http://www.westernprairie.imsasafety.org/canadian/PDF/Fixed%20Automated%20Spray%20Technology%20(FAST).pdf (Last accessed on Nov, 2013).

Miller, J. S., R. Khandelwal and N. J. Garber (2006). "Safety impacts of photo-red enforcement at suburban signalized intersections: an Empirical Bayes approach." Transportation Research Record: Journal of the Transportation Research Board 1969(1): 27-34.

MoDOT (2010). "Request for proposals: Fixed automated spray technology services." D8PP-10052. MoDOT, Jefferson City, MO.

Moritz, K. (1998). Effectivity and economy of de-icing agent spraying systems. Xth PIARC International Winter Road Congress.

National Safety Council (2012). "Estimating the Costs of Unintentional Injuries. ." National Safety Council, Itasca, Illinois, 2012. http://www.nsc.org/news_resources/injury_and_death_statistics/Pages/EstimatingtheCostsofUnintentionalInjuries.aspx

O'Keefe, K. and X. Shi (2006). Anti-icing and pre-wetting: improved methods for winter highway maintenance in North America. Proceedings of the Transportation Research Board Annual Meeting.

Osburn, C. (2010). "A FAST way to make highway safer." Alberta Construction Maganize, June 2010.

Patel, R. B., F. M. Council and M. S. Griffith (2007). "Estimating safety benefits of shoulder rumble strips on two-lane rural highways in Minnesota: empirical Bayes observational before-and-after study." Transportation Research Record: Journal of the Transportation Research Board 2019(1): 205-211.

Penn DOT (2005). "Automated anti-icing bridge systems." PennDOT Research IIB-05-10. Bureau of Planning and Research, PennDOT.

Persaud, B., H. McGee, C. Lyon and D. Lord (2003). "Development of a procedure for estimating expected safety effects of a contemplated traffic signal installation." Transportation Research Record: Journal of the Transportation Research Board 1840(1): 96-103.

Persaud, B., R. Retting, P. Garder and D. Lord (2001). "Observational before-after study of the safety effect of US roundabout conversions using the empirical Bayes method." Transportation Research Record: Journal of the Transportation Research Board(1751): 1-8.

Persaud, B. N., R. A. Retting and C. A. Lyon (2004). "Crash reduction following installation of centerline rumble strips on rural two-lane roads." Accident Analysis & Prevention 36(6): 1073-1079.

Pinet, M., T. Comfort and M. Griff (2001). Anti-icing on structures using fixed automated spray technology (FAST). Annual Conference of the Transportation Association of Canada, Halifax, Nova Scotia.

Plumb, C. (2011). "Severe Weather Policy Support Fixed Automated Spray Technology (FAST) evaluation " Highways ConsultancyGroup - Highways Research Group. Task Reference: [357 (1308) MOTT].

Pyde, D. (2005). "One fleet for 1 bridge." Roads & Bridges magazine 43(4).

Roosevelt, D. S. (2004). A bridge deck anti-icing system in Virginia: lessons learned from a pilot study.

Shi, X., L. Fay and S. Mumma (2011). "Laboratory investigation into interactions among chemicals used for snow and ice control." Journal of Testing and Evaluation 39(6): 1205-1212.

SICOP (2004). "Fixed, Automated Anti-icing Spraying Systems." Snow and Ice Pooled Fund Cooperative Program http://www.sicop.net/FAST%20Project.pdf(Retrieved on July 10, 2006).

Srinivasan, R., F. Council, C. Lyon, F. Gross, N. Lefler and B. Persaud (2008). "Safety effectiveness of selected treatments at urban signalized intersections." Transportation Research Record: Journal of the Transportation Research Board 2056(1): 70-76.

Stewart, R. (2004). "Fixed Automated Spray Technology (FAST) on Knudsen's Corner Interim Report." Utah Department of Transportation Research Division, Report No. UT-04.03.

Stowe, R. (2001). A benefit/cost analysis of intelligent transportation system applications for winter maintenance. Transportation Research Board 80th Annual Meeting.

Waldman, J. R. (2004). State-of-the-art fixed automated spray technology. Sixth International Symposium on Snow Removal and Ice Control Technology.

Ward, B. (2002). Evaluation of a fixed anti-icing spray technology (FAST) system. Proceedings of the 81st Annual Meeting of the Transportation Research Board, Washington, DC.

Wint, J., A. Naja and Y. Huang (2008). "Alternative precautionary spreading on slip roads." HCG/HRG. Task 418. Highways Agency.

Ye, Z., D. Veneziano and D. Lord (2011). "Safety impact of gateway monuments." Accident Analysis & Prevention 43(1): 290-300.

Ye, Z., D. Veneziano and I. Turnbull (2012). "Safety effects of icy-curve warning systems." Transportation Research Record: Journal of the Transportation Research Board 2318(1): 83-89.

Ye, Z., J. Wu, N. E. Ferradi and X. Shi (2013). "Anti-icing for key highway locations: fixed automated spray technology." Canadian Journal of Civil Engineering 40(1): 11-18.

Zambelli, M. (1998). Implantation of a Steady Plant for Automatically Spraying Chemical De-icer on the Lausanne Bypass. Xth PIARC International Winter Road Congress.

Zhang, J., D. Das and R. Peterson (2009). "Selection of effective and efficient snow removal and ice control technologies for cold-region bridges." Journal of Civil, Environmental, and Architectural Engineering 3(1): 1-14.

Appendix A: NATIONAL SURVEY

Fixed Automated Spray Technology (FAST) System: State of the Practice Survey

CONTACT INFORMATION

1. Please provide your contact information

Name: ______________________
Title: _______________________
Agency (Region):______________
Email Address:________________
Phone Number:_______________
City or County:________________
State and Zip Code: ____________
Country (if not US):_____________

2. Please indicate the group that you belong to

☐Dot winter maintenance manager (headquarter level)
☐DOT winter maintenance supervisor (district level)
☐County winter maintenance manager
☐City winter maintenance manager
☐Contractor
☐Researcher
☐Vendor/Manufacturer
☐Other (please specify)__________________________

PLANNING/DESIGN/CONTRACTING

3. Please list reasons that your agency uses FAST system(s) and specific problems your agency expected to solve. Were the problems solved or expectations met?

____

4. What is the extent of your agency's deployment of FAST system (s)? (Feasibility testing, demonstration/pilot test, regional deployment, full-scale deployment; and approximate number of systems)

____

5. Please describe your FAST systems in details. Email Me Documents

Years of Operation ______________________________

Type of Location ________________________________
Length/Number of Lanes Covered ___________________
Activation Type (manually/automated/both) ___________
Hydraulic System Type (I or II) **___________________
Success/Failure ___________________________________

(* Types of locations may include bridges, intersections, remote locations, non-structure roadways, high accident locations, high traffic locations, or other)

(** type I hydraulic system utilizes a pump located in a pump house to deliver the fluid to the nozzles some distance away and is more common in North America; in type II hydraulic system, the pump at the pump house is used to fill a small pressurized vessel (tank) located in close proximity to each individual nozzle. When the signal to activate is given, a valve on the small pressure vessel is opened and the liquid content is discharged through the spray head. It is more common in European systems.)

6. Please list criteria for selecting sites/locations of FAST installations. If you have documented files, would you share with CDOT? Email Me Documents
____

MATERIAL USE

7. Please indicate anti-icing chemicals used for FAST and the problems occurred (corrosion, reaction with other chemicals, freezing under extreme cold, etc.) or any lessons learned.

Calcium Chloride____
Calcium Magnesium Acetate____
Magnesium Chloride____
Sodium Chloride____
Potassium Acetate____
Other____

SYSTEM ACTIVATION AND MONITORING

8. Please indicate features that are used in the FAST activation process, and the problems occurred in system activations.

Automatic Detection (RWIS) ________________
Surface Sensors___________________________
Infrared Sensors__________________________
Alarm Message____________________________
Data Recording____________________________
Other____________________________________

OPERATIONS

9. Under which conditions your FAST system(s) was most effective?
____

10. Please list any limitations in using your FAST system(s)? (High wind, extreme low temperature etc.)

____

11. Please estimate average number of times your FAST system(s) sprayed deicer in a winter season.

____

12. Is there any problem with the operations of your FAST? How reliable was your FAST (in estimated %)? Please describe how you resolve the problem(s), if there is any.

____

____

13. How often is your FAST system(s) maintained?
☐Monthly
☐Pre-season
☐Post-season
☐Other
Please specify_____________

14. Are there any preventive maintenance requirements for the FAST system?
If it is Manually Activated FAST ______________________________________
If it is Fully Automated FAST ____
If it is Semi-automatic FAST ____

15. Do you have defined and documented system maintenance procedures? <u>Email Me Documents</u>
☐No
☐Yes
If yes, would you share with CDOT?________

16. Please describe the problems with maintenance of each major FAST system component.
RWIS ____
Pumping/Storage System ____
Controller ____
Chemical Distribution/Spray System ___________________________________
Other (Please Specify) ____

COSTS/BENEFITS AND EVALUATION

17. What are the initial costs (capital or implementation) of using FAST? Or Email Me Documents
Cost or Range ____
Types of Costs Incurred _______________________________

18. What are the costs and activities for operations and maintenance with FAST?
Estimated Cost or Range ____
Type of Costs Incurred ____
Maintenance Needs ____

19. Under which conditions your FAST system(s) was most effective? Please share your success stories and/or lessons learned.

____

20. Have you conducted any formal evaluation of the benefits of FAST (e.g. Benefit-cost analysis, customer surveys)? If so, would you share with CDOT?

____

FUTURE RECOMMENDATIONS

21. Please list any features of your FAST that are
Critical/Important _________________________
Most Problematic _________________________
Innovation(s) for the future use _______________

22. What are the benefits of using FAST successfully based on your experience? If it doesn't work properly, what are the lessons you learned?
Benefits ____
Lessons Learned ____

23. Do you plan to use a new system or improve any system features that would be most beneficial over the 5 to 10 years?
☐No
☐Yes
If yes, please explain in the box below.

Appendix B: CDOT SURVEY

Fixed Automated Spray Technology (FAST) System: Survey of CDOT Practices

CONTACT INFORMATION

1. Please provide your contact information

Name: ______________________
Title: ________________________
Agency (Region):______________
Email Address:________________
Phone Number:_______________

2. Please indicate the group that you belong to

☐CDOT winter maintenance manager (headquarter level)
☐CDOT winter maintenance supervisor (district level)
☐County winter maintenance manager
☐City winter maintenance manager
☐Other (please specify)__________________________

EXTENT

3. Please select the FAST system(s) your agency is currently using.

- ☐ Region 1 Structure Number F-13-P Highway I20 Milepoint 216.139
- ☐ Region 1 Structure Number H-17-AH Highway I25 Milepoint 172.21
- ☐ Region 1 Structure Number H-17-CH Highway I25 Milepoint 171.82
- ☐ Region 1 Structure Number H-17-CI Highway I25 Milepoint 171.82
- ☐ Region 1 Structure Number H-17-CQ Highway I25 Milepoint 172.01
- ☐ Region 2 Structure Number I-17-DU Highway I25 Milepoint 147.389
- ☐ Region 2 Structure Number I-17-FJ Highway I25 Milepoint 139.84
- ☐ Region 2 Structure Number I-17-NN Highway I25 Milepoint 147.389
- ☐ Region 2 Structure NumberJ-16-C Highway SH67 Milepoint 47
- ☐ Region 3 Structure Number F-11-AD Highway I70 Milepoint 171.1
- ☐ Region 3 Structure Number F-08-AM Highway I70 Milepoint 125.01
- ☐ Region 4 Structure Number C-15-O Highway US34 Milepoint 68.75
- ☐ Region 4 Structure Number C-15-U Highway US34 Milepoint 70.58

☐ Region 4 Structure Number C-15-Y Highway US34 Milepoint 75.69
☐ Region 4 Structure Number D-16-CG Highway SH119 Milepoint 62.006
☐ Region 4 Structure Number D-16-DR Highway SH119 Milepoint 62.006
☐ Region 4 Structure Number D-17-AP Highway SH52 Milepoint 235.15
☐ Region 4 Structure Number D-17-CR Highway I25 Milepoint 233.11
☐ Region 4 Structure Number D-17-CT Highway I25 Milepoint 233.11
☐ Region 4 Structure Number D-17-DM Highway I25 Milepoint 231.09
☐ Region 4 Structure Number D-17-DN Highway I25 Milepoint 231.09
☐ Region 4 Structure Number D-17-DW Highway I25 Milepoint 238.12
☐ Region 4 Structure Number D-17-EA Highway I25 Milepoint 238.12
☐ Region 4 Structure Number D-17-EP Highway SH66 Milepoint 42.73
☐ Region 4 Structure Number D-17-EQ Highway I25 Milepoint 241.12
☐ Region 4 Structure Number D-17-ER Highway I25 Milepoint 241.12
☐ Region 4 Structure Number D-17-ES Highway I25 Milepoint 242.15
☐ Region 4 Structure Number D-17-ET Highway I25 Milepoint 242.15
☐ Region 5 Structure Number TUNNEL TUNNEL ENDS WOLF CREEK PASS TUNNEL
☐ Region 6 Structure Number E-17-QK Highway 76
☐ Region 6 Structure Number F-17-OD/ F-17-FW Highway I-25/I-225 Milepoint 0.00
☐ Region 6 Structure Number F-17-QU Highway SH 88 Milepoint 21.734

4. Out of all the FAST system(s) you have chosen, please provide details regarding the FAST structure number, the type of locations, type of activation (auto, manual, both), full length/number of lanes covered and the hydraulic system type it belongs to (type I or type II).

FAST structure number________________________________
Type of Location * ______________________________
Type of Activation (auto, manual, both)______________
Full Length/Number of Lanes Covered ______________
Hydraulic System Type (I or II) **__________________

(* Types of locations may include bridges, intersections, remote locations, non-structure roadways, high accident locations, high traffic locations, or other)

(** type I hydraulic system utilizes a pump located in a pump house to deliver the fluid to the nozzles some distance away and is more common in North America; in type II hydraulic system, the pump at the pump house is used to fill a small pressurized vessel (tank) located in close proximity to each individual nozzle. When the signal to activate is given, a valve on the small pressure vessel is opened and the liquid content is discharged through the spray head. It is more common in European systems.)

5. What is the extent of your agency's deployment of FAST system(s)? (Feasibility testing, demonstration/pilot test, regional deployment, full-scale deployment; and approximate number of systems)

____

PLANNING

6. Please provide reasons that your agency use FAST in the winter maintenance program (Specific problems that were expected to be solved, and outcomes or benefits that were envisioned).

____

7. Were the problems solved or expectations met after the FAST system(s) were installed?

____

MATERIAL USE

8. Please indicate anti-icing chemicals used for FAST and the problems occurred (corrosion, reaction with other chemicals, freezing under extreme cold, etc.) or any lessons learned.

Calcium Chloride____
Calcium Magnesium Acetate____
Magnesium Chloride____
Sodium Chloride____
Potassium Acetate____
Other____

9. Please list the problems in using anti-icing chemicals for your FAST system (corrosion, reaction with other chemicals, freezing under extreme cold, etc.) and any lessons learned.

____
_____

OPERATIONS

10. Which features are available and used in the activation process for your system? And are there any problems in system activations?

Automatic Detection (RWIS) _____________
Surface Sensors_______________________
Infrared Sensors______________________

Alarm Message___________________________
Data Recording___________________________
Other__________________________________

11. Please list the types of data from RWIS that are necessary to properly operate your FAST system.

____

12. Please list any limitations in using your FAST system(s)? (High wind, extreme low temperature etc.)

____

13. Is there any problem with the operations of your FAST? How reliable was your FAST (in estimated %)? Please describe how you resolve the problem(s), if there is any.

____
____

COSTS/BENEFITS AND EVALUATION

14. What are the initial costs (capital or implementation) of using FAST? Or
Cost or Range _______________________________________
Types of Costs Incurred _______________________________

15. What are the costs and activities for operations and maintenance with FAST?
Estimated Cost or Range ____
Type of Costs Incurred ____
Maintenance Needs ____

16. Under which conditions your FAST system(s) was most effective? Please share your success stories and/or lessons learned.

____

17. Do you have any formal evaluation of the benefits of FAST (e.g. Benefit-cost analysis, customer surveys)? If so, would you share with CDOT?

____

FUTURE RECOMMENDATIONS

18. What type of innovation(s) in FAST could be most beneficial to your agency over the next five to ten years?

____
___

19. Do you plan to use a new system or improve any system features that would be most beneficial over the 5 to 10 years?

□No
□Yes
If yes, please explain in the box below.

Appendix C: CDOT SURVEY RESPONSES

Responses from CDOT FAST surveyed agencies

1. What is the extent of your agency's deployment of FAST system(s)? (Feasibility testing, demonstration/pilot test, regional deployment, full-scale deployment; and approximate number of systems)

- regional deployment as deemed appropriate for location
- 2 systems mainly for a pilot test. Have not been dependable.
- Full blown growth for Region 4
- Unknown
- regional deployment 4 systems
- Regional Deployment, Region 5 has only one system. We are looking to install two more in the next year or so.

2. Please provide reasons that your agency uses FAST in the winter maintenance program (Specific problems that were expected to be solved, and outcomes or benefits that were envisioned).

- protect flyovers from freezing, prevent accidents
- Locations used are bridge structure's that are built in curves. These areas are also mountain areas along the I-70 corridor.
- Improving LOS on structures. Reducing material usage and waste.
- To mitigate slippery conditions on bridges, to regulate the use of chlorides on the bridges, to mitigate sand build up on bridges and to use the system to alert personnel of changing conditions on the bridge.
- Upon construction it was decided to use FAST because of the length of the bridge.
- Advance application of liquid deicer to bridge deck. Envisioned benefit reduce hazard of icing of bridge deck.
- The vision was to keep the tunnel approaches and the lanes through the tunnel wet. The system has not worked nor have we been able to understand why. We are looking at redesigning the system
- These systems were installed primarily to augment snow removal operations and reduce accidents

3. Were the problems solved or expectations met after the FAST system(s) were installed?

- Not really, the systems have not been reliable. Then parts became an issue to replace, had to do an upgrade just to be able to get parts.
- To my knowledge, when systems are properly maintained they work very well, and accomplish the goals of improved LOS and materials savings.
- Yes.
- No. We have had mechanical/electrical issues with the system from the beginning.
- At times, the systems is very high maintenance and very unreliable. If the systems were to work properly it be a great benefit.
- These systems are not reliable and are extremely cost prohibitive.

4. Please indicate the types of anti-icing chemicals you have used for FAST.

- Magnesium Chloride
- Magnesium Chloride
- Cold Temperature Modified Magnesium Chloride
- Magnesium Chloride
- Sodium Chloride
  Other (please specify) - APEX
- Magnesium Chloride

5. Please list any limitations in using your FAST system(s)? (High wind, extreme low temperature, etc.)

- None to my knowledge
- None
- None
- When system under applies it creates icing issues.
- Low Temps
-

6. Is there any problem with the maintenance or operations of your FAST? How reliable was your FAST (in estimated %)? Please describe how you resolve the problem(s), if there is any.

- Please talk to the field personnel
- In Region 4 the systems work great
- We have to have the system worked on every year. Mechanical and electrical issues occur yearly. The system has never operated a full winter season.
- System requires a large amount of maintenance and is about 35% reliable. We currently use a contractor to supply the needed repairs and our employees supply routine maintenance.
- Not reliable at all.
- These systems have been down approximately 80% of the time have put over $150,000 combined into both systems

7. Under which conditions was your FAST system(s) most effective? Please share your success stories and/or lessons learned.

- All winter precipitation conditions
- None
- Warmer temperatures 25 degrees and rising.

8. Do you have any formal evaluation of the benefits of FAST (e.g. benefit-cost analysis, customer surveys)? If so, could you provide us with a copy of the findings?

- None replied

9. What type of innovation(s) in FAST could be most beneficial to your agency over the next five to ten years?

- Reliability and better data tracking.
- None

10. Do you plan to use a new system or improve any system features that would be most beneficial over the 5 to 10 years?

- Yes. Investigating non-invasive sensors
- Yes. New installs and upgrade all sites to ESI sites
- No
- No.
- Yes. We will redesign the current system.
- Yes. Currently in the process for the final time to upgrade and fix systems for operation. If they fail this time they will be removed.

Appendix D: EXAMPLE OF BENEFIT-COST SPREAD SHEET FOR CDOT FAST SYSTEMS.

Below is an example of benefit-cost worksheet for FAST systems on two-lane rural roads.

Benefit-Cost Worksheet for FAST in Two-Lane Rural Locations

Location:	Route	________		MP	________	to	MP	________

Crash Reduction Benefit

Crash Type	Total Number of Crashes	Years of Crash Data	Annual Crash Rate	Observed Crash Reduction	Estimated Annual Crash Reduction	CDOT Crash Cost	Annual Crash Savings
Fatal			#DIV/0!	0.10	#DIV/0!	$1,410,000	#DIV/0!
Injury			#DIV/0!	0.10	#DIV/0!	$78,900	#DIV/0!
PDO			#DIV/0!	0.10	#DIV/0!	$8,900	#DIV/0!
				Total Annual Crash Savings:			#DIV/0!

Maintenance Benefit

Number of Site-specific Call-outs Per Season Before FAST	Distance from Maintenance Yard to Site (mi)	Travel Speed (mph)	Loaded Labor Cost (/hr)	Annual Site-specific Call-out Cost Per Season without FAST	Number of Site-specific Call-outs Per Season After FAST	Annual Site-specific Call-out Cost Per Season with FAST	Savings From Reduced Call-outs
		25		$0.00		$0.00	$0.00
					Total Annual Savings:		$0.00

Initial site cost (installation,. Labor, etc.)	
Maintenance and Operations cost (annual)	
Salvage value	
Expected life of system	
Interest Rate (decimal)	0.033
Present Value of Benefits	**#DIV/0!**
Present Value of Maintenance and Operations Costs	**$0.00**
Present Value of Salvage	**$0.00**
Present Value of Costs	**$0.00**
Benefit/Cost Ratio	**#DIV/0!**

Appendix E: CDOT MAINTENANCE ACTIVITIES (REGION 4)

Pump Vault or Building

- Inspection shall include cleanliness and or general house keeping
- Infestation of vermin
- General condition, pertaining to structural integrity
- Presence of excessive moisture or water intrusion
- Vandalism or other damage

Fluid Pumps

- Pressure pumps shall be checked for leakage, bearing and seal water. Proper operation and performance within specifications. Where applicable oil levels shall be checked for proper level and contamination.
- Sump pumps shall be checked for float operation and to make sure foreign debris is not in the sump pit.
- Transfer pumps, if present, to load or unload tanks shall be checked for proper operation and condition.

Pressure gauges

- Verify operating pressures
- Visual inspection of gauges for operation and condition

Over pressure or relief valves

- Check for proper operation
- Check for leaks
- Make sure there is fluid going back into tank while operating the pump
- Inspect that locking nut is secure and tight

Flow meters, if present

- Verify proper operation
- Calibrate if required

Pressure Transducers

- Verify operation and calibration against gauges if present

Piping

- All piping shall be inspected for leaks
- All piping and connection shall be inspected for general condition

Pressure piping manifolds

- Pressure piping shall be inspected for leakage, wear or aging of any kind

Filters and or strainers

- All filters and strainers shall be inspected for debris and contaminants

- Any contaminants found must be reported and source of contamination determined

Spray Heads
- Shall be inspected to check spray patterns and pressure
- Shall be checked for damage
- Shall be checked to ensure they are secure and sealed around pavement edges

Fluid Reservoirs
- Shall be checked for leakage
- Inspection shall include visual inspection for contamination
- Inspection lids shall be checked to make sure rodents, insects, other foreign objects are not able to enter the reservoirs
- Tank level either floats or ultra-sonic sensors shall be checked for proper operation and accuracy

Motorized or Solenoid valves
- Valves shall be operated to verify activation and proper operation
- Valves shall be inspected for leakage
- Where possible electrical amp draw and resistance should be checked for proper specifications

Valve Boxes or enclosures
- Shall be checked for physical damage and cause of damage
- Shall be checked for leaks or seeping fluid
- Open boxes and checks for rodents and damage

Power or Main Breaker panels
- Inspect to ensure all breakers are in good shape
- Inspect to ensure all breakers are properly marked as to what they protect
- Correct Voltage to system is verified

Conduits – Electrical
- All conduits shall be inspected for breakage, water tightness and general condition

Electrical wiring
- Visual inspection for corrosion or damage of any kind
- Verify proper voltages leading from power supplies
- Look for any insulation damage or evidence of overheating

Electrical motors that drive pumps
- Amperage draw on all motors shall be checked to make sure motors are not getting worn and pumps they drive are in proper operating condition and within specifications.

Readings shall be noted and recorded. Previous inspection reports should be checked if available to verify age or aging of motors by increasing amperage draw.

Control Cabinets

- Cabinets shall be inspected for infestations of rodents
- Controllers shall be inspected for operation and all fuses and/or breakers checked
- Moisture present or any evidence of moisture shall be noted and investigated

Activation Controls

- All forms of activation shall be checked for proper operation. This includes push button, remote radio controls, phone, internet and sensors (embedded and/or noninvasive) if present

Sensors

- Verify that sensors are working correctly
- Calibrate sensors if required
- Check for loose wiring or cables
- Clean lenses and check to ensure that the sensor hardware is tight

Camera

- Verify that camera is aimed correctly
- Clean lenses and check to ensure that the camera hardware is tight
- Verify infrared is working if so equipped

Internet communications

- If applicable, internet activation, data logging and communication shall be checked

Phone lines

- Phone, DSL, fiber or wireless communication shall be checked to verify proper working condition

Season Commissioning

- Perform component check inspection
- Test for proper operation and activation of system
- Ensure water is purged from tanks and lines and that the system will perform as intended

End of Season De-commissioning

- Perform component check inspection
- Shut down system and drain back chemicals
- Flush with water
- Configure to spray water weekly during the night

Miscellaneous work

- Clean and purge tanks
- Clean and purge system lines
- Clean and purge entire system

Monitoring of system throughout the year

Monitor the system weekly via web page during non-storm events

- Review the site weekly to ensure that all information is up to date and accurate

Storm events

- Review the system during storm events to ensure that all items are functional
- Document that the system is functioning correctly