Safety Effects of Fixed Automated Spray Technology Systems

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Fixed automated spray technology (FAST) has emerged as a solution to provide quick, effective service delivery to high-risk locations prone to icy conditions or with high traffic volumes. The Colorado Department of Transportation has installed and used FAST on bridges since 1998, with 32 units currently installed on bridges around the state. There is some concern regarding the effectiveness of FAST in reducing accidents during winter weather. Previous studies of FAST have considered the changes to crash occurrence following deployment, but these studies were basic and compared seasonal figures or rates without accounting for site conditions. To address this shortcoming, an observational before–after study with the empirical Bayes technique was used to determine the effect of FAST systems on crash frequencies. The results revealed that at sites where crashes were reduced, FAST systems contributed to an annual reduction of 2% on multilane rural highways, 16% to 70% on urban Interstates, 31% to 57% on rural Interstates, and 19% to 40% on interchange ramps between Interstates. However, at some sites, safety deteriorated with an increase in crashes. Although the precise causes of such increases are not completely clear, they may have been the result of increased traffic, systems not being maintained properly, or systems applying fluids in improper amounts or at the wrong time. On the basis of the collective results, high-traffic, high-crash severity locations are most suitable for FAST deployment.

A recent review has revealed a consistent pattern in existing studies, that is, adverse winter weather increases crash frequencies on highways, reduces traffic speed, and lessens the chance of fatal crashes (*1*). During the winter, accidents often occur on bridge decks or shaded areas where the surface temperature tends to be lower than the adjacent areas and creates potentially hazardous driving conditions, such as frequent frost and black ice (*2, 3*). Fixed automated spray technology (FAST) has emerged as a solution to provide quick, effective service delivery to such high-risk locations prone to icy conditions or with high traffic volumes. FAST systems are designed as a fixed technology for anti-icing at target areas such as bridges, tunnels, ramps, and other elevated roadways (*4*). The challenges associated with the installation and operation of FAST systems are often site-specific (*5*). This technology is a permanent installation of a pump, tank nozzles, and a controller for the application of anti-icing chemicals manually or automatically.

The Colorado Department of Transportation (DOT) has installed and used FAST on bridges since 1998, with 32 units currently installed on bridges around the state. In areas where FAST has been deployed for several years, there is a favorable view of the system. However, there is some concern about how effective the system is in reducing accidents during winter weather events. The Colorado DOT's experience mirrors that of other agencies in North America and Europe, which have generated different views of effectiveness. Consequently, many transportation agencies still consider FAST as an evolving technology.

As one of the main objectives of FAST systems is to provide a safer driving surface through timelier chemical applications, it was necessary to determine whether safety improvements had been achieved through Colorado's deployments. Consequently, this work aimed to determine what changes had occurred in vehicle crash rates at the different FAST sites throughout Colorado. The objective of the study was to determine whether crashes had decreased in a statistical sense after different FAST deployments compared with the years before the deployments. Such an evaluation would provide a clearer picture of whether FAST systems had produced a positive impact on safety at each site.

LITERATURE REVIEW

Although FAST systems have been deployed around the world for a few decades, observations of crash reductions are somewhat limited. Gladbach discussed a FAST system that was installed in 1984 along a 3.7-mi (6 km), topographically and climatically challenging road section between Hagen and Lüdenscheid in Germany (*6*). Safety benefits were assessed by comparing the annual number of crashes caused by winter conditions (e.g., snow and icy patches) in two 7-year periods before and after installation. The number of crashes was reduced by 58% and traffic congestion was also reduced (*6*).

A FAST system was installed in Dover, United Kingdom, and operated for the 2010–2011 winter period. The system was located on Jubilee Way Bridge and designed to operate automatically or manually (*7*). No winter-related crash reduction data were reported, since the number of incidents on Jubilee Way was not sufficient to consider statistically following installation of the system.

The effectiveness of a FAST system installed on an interchange overpass on I-215 in Salt Lake City, Utah, was analyzed for the 1997–1998 winter season. Comparing the 1997–1998 winter season data with the five previous winters, a 64% reduction in snow and ice-related accidents was reported on the northbound lanes (*2*).

The first FAST system in Canada was installed along a 550-ft (168-m) interchange ramp with an average daily traffic of 3,000 vehicles in Ontario. No winter weather–related accidents had occurred since the FAST installation (as of 2001) (*8*).

A FAST system installed on a bridge on Interstate 68 in Allegany County, Maryland, in the 1998–1999 winter season reduced accidents

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on the bridge by approximately 40% and led to estimated cost savings of $16,000 in avoided mobile operations (*9*).

Johnson evaluated a FAST system deployed on a 2,000-ft (609-m) long, Interstate 35W bridge over the Mississippi River, in Minnesota, in 1999 (*10*). Comparing the 2000–2001 winter season data with the climatologically similar 1996–1997 winter season, a 68% reduction in winter-related accidents was reported, at least part of which was attributable to the FAST system. Another benefit included reduced traffic congestion associated with winter crashes.

The North Dakota DOT has installed two FAST systems since 2002 at I-29 Buxton Bridge (near Buxton, North Dakota) and I-94 Red River Bridge between Fargo and Moorhead, North Dakota (*11*). Significant crash reductions were observed at both locations after the FAST systems were installed, with a 66% reduction at the Buxton Bridge location and a 50% reduction at the Red River Bridge location.

The Pennsylvania DOT installed three FAST systems in Warren, Westmoreland, and Allegheny Counties (*12*). On the Warren County Bridge, 25 crashes were reported in the 2 years before installation of the system and no crashes occurred following installation (the exact time period of observation after implementation was not reported).

As this literature review indicates, previous studies and evaluations of FAST systems have considered the changes in crash occurrence following deployment. However, these evaluations have been basic and compared seasonal figures or rates without accounting for site conditions such as traffic, geometry, and so forth, with any reductions in crashes following deployment expressed as percentage of reductions. Although these results provide a sense of the impact that the FAST system may have had, the studies did not consider the influence that the overall characteristics of the site had in contributing to or reducing crashes. To address the shortcomings of previous studies, the work discussed here employed a more rigorous approach to analysis. The study used accident prediction models to estimate the number of crashes before and after FAST deployment to identify the impacts that FAST systems had. That approach and results are outlined in the following text.

STUDY DATA

To generate more reliable results, the study employed a longer period of before and after crash data during data analysis. 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. The Colorado DOT database provided at least 2 years of before data for the systems, but more typically 5+ years, depending on the duration of the deployment. All available years of after data were obtained.

The crash data obtained from the Colorado DOT's crash database, which is maintained by the Safety and Traffic Engineering branch, included date and time, milepost, weather conditions, type of accident, and related details. The total number of crashes at each site varied over time, as shown in Table 1. At most locations, winter-related crashes (snow or icy weather conditions) were a small portion of the overall crashes that occurred at each site. The traffic volumes at each location varied significantly, which accounts for higher crash numbers on urban interstates as opposed to rural two-lane roads.

Geometric and traffic data for each site came from the Colorado DOT database records. In addition, the Colorado's DOT videolog data were accessed online to verify site conditions and characteristics. Finally, the Colorado DOT's Traffic Data Explorer database provided annual average daily traffic (AADT) information for the various study years for each site. Some sites saw extensive changes before and after a FAST system was deployed. Such changes were identified via the videolog data and through examination of Google Earth aerial imagery.

Construction records were also requested from the Colorado DOT to determine other changes that may have occurred at each site. Construction records were not readily available during the course of the research, so it is unknown what other improvements (e.g., chip seals) may have been made that affected safety. Consequently, changes in crashes discussed in later sections may not be entirely attributable to the FAST system present at a respective site, although evaluation of videolog and aerial imagery largely indicated no major changes occurred at many sites. The analysis focused on 21 FAST sites, by excluding sites with obvious changes.

Although winter weather is an important aspect when considering a system such as FAST, historical weather records were not used as part of the overall analysis because the approach that was employed considered crash data from throughout the year rather than only seasonal data. The use of annual crash data was necessitated by the models available for examining the different facility types with FAST deployments, which estimated annual crashes. Ideally, seasonal (winter) models would have been employed; however, the development of such models is data and resource intensive and was beyond the scope of the work performed. Therefore, the analysis assumed 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.

METHODOLOGY 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 whether the system positively or negatively affected 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 impact, the effects of the system on crash frequencies were investigated.

The safety effects of the FAST deployments were evaluated through an observational before–after study (*13, 14*), which was used to determine the change in safety as reflected in crash counts:

$$\delta = \pi - \lambda \quad \text{or} \quad \theta = \frac{\lambda}{\pi} \tag{1}$$

where

δ = crash reduction (or increase),
θ = index of safety effectiveness,
π = predicted number of crashes in the after period without the FAST system, and
λ = number of reported or observed crashes in the after period with the FAST system present.

In vehicle crash analysis, before–after studies can be grouped into three types: simple (naïve) before–after study, before–after study with control groups (the comparison group method), and before–after study with the empirical Bayes (EB) technique. The selection of the study type is usually governed by the availability of data, such as crash records and traffic, and whether the analyst has access to entities that are part of the reference group (comparison sites). The

TABLE 1 Crash History Before and After Deployment for Colorado FAST Sites

Site	Range of Mileposts	Deployment Year	Number of Before Crashes (winter related)	Before Period (years)	Number of After Crashes (winter related)	After Period (years)
Two-Lane Rural Roads						
SH-67 (NB, SB)	47.05–47.28	2003	2 (0)	5.5	3 (1)	10
US-34 (EB, WB)	68.73–68.77	2002	0 (0)	5.5	0 (0)	11
US-34 (EB, WB)	70.54–70.58	2002	0 (0)	5.5	0 (0)	11
US-34 (EB, WB)	75.68–75.72	2002	1 (0)	5.5	3 (0)	11
Multilane Rural Roads						
SH-119 (EB, WB)	61.95–62.00	2009	6 (3)	5.5	5 (4)	4
Urban Interstates						
I-25 (NB, SB)	147.39–147.52	1998	33 (8)	5.5	40 (13)	15
I-25 (NB, SB)	139.75–139.88	2003	27 (2)	5.5	33 (7)	10
I-25 (NB, SB)	238.09–238.14	2007	12 (2)	5.5	10 (0)	5
I-25 (NB, SB)	231.10–231.13	2004	17 (2)	5.5	12 (4)	8
I-25 (NB, SB)	233.08–233.11	2004	22 (1)	5.5	20 (4)	8
I-25 (NB, SB)	241.11–241.18	2010	2 (0)	5.5	0 (0)	3
I-25 (NB, SB)	242.15–242.18	2010	2 (2)	5.5	1 (0)	3
Rural Interstates[a]						
I-70 (EB, WB)	216.23–216.28	2004	1 (0)	5.5	4 (1)	9
I-25 (NB, SB)	172.2–172.22	2004	14 (5)	4.5	5 (1)	6.5
I-25 (NB, SB)	171.80–171.82	2004	15 (5)	4.5	13 (5)	6.5
I-25 (NB, SB)	172.01–172.02	2004	0 (0)	4.5	3 (3)	6.5
I-70 (EB, WB)	171.20–171.29	2004	34 (22)	5.5	59 (43)	9
I-70 (WB)	124.74–124.85	2004	10 (7)	5.5	16 (10)	9
Interchange Ramp Structures						
Ramp from EB I-270 to EB I-76	na	2010	5 (1)	2	13 (3)	3
Ramp from SB I-25 to EB I-225	na	2010	54 (17)	5.5	38 (9)	3
Ramp from WB I-225 to SB I-25	na	2010	24 (6)	5.5	29 (6)	3
Other Routes						
SH-52[b,c]	11.09–11.16	2000	0 (0)	5.5	46 (2)	13
SH-66[b]	42.86–42.93	2010	3 (0)	5.5	2 (0)	3
SH-83[d]	65.30–65.44	2011	10 (7)	5.5	16 (10)	2
SH-160[e]	173.93–173.96	2002	na	na	0 (0)	11.5
SH-160[f]	174.16–174.19	2002	na	na	1 (1)	11.5

NOTE: NB = northbound; SB = southbound; EB = eastbound; WB = westbound; na = not applicable.
[a]I-25 sites at Mileposts 171 and 172 were deactivated in 2011, which explains the reduced after-period data.
[b]SH-52 and SH-66 overpass sites underwent significant changes in the number of lanes and traffic control before and after deployment.
[c]Before data for SH-160 were not available, because changes in alignment precluded a direct comparison of the same crash data by milepost.
[d]SH-83 was an at-grade intersection in the before period and a grade-separated overpass in the after period.
[e]SH-160 was a two-lane road skirting an outcrop during the before period and a tunnel exit in the after period following tunnel construction.
[f]SH-52 data from the before period indicated no crashes, which may be attributed to the site being more rural at the time.

selection can also be influenced by the amount of available data (or sample size). The EB method was employed in this work because it has been shown to have better performance than the naïve and comparison group methods (*13*) in addressing problems associated with these approaches (e.g., regression-to-mean) 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 used effectively in many traffic safety evaluations over time (*15–25*).

OBSERVATIONAL BEFORE–AFTER STUDY WITH EB 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 estimation, the safety performance functions (SPF) from the current edition of the *Highway Safety Manual* (HSM) (*14*), as well as other SPFs developed for future editions of the HSM were used (*26, 27*). These SPFs included rural two-lane, two-way roadway segments; rural, multilane highways; urban and rural freeways and 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-ft lane width, 6-ft shoulder width, no horizontal or vertical curves):

1. Two-lane rural roads:

$$N_{\text{spf}} = \text{AADT} * L * 365 * 10^{-6} * e^{(-0.312)} \tag{2}$$

where

N_{spf} = predicted total crash frequency for roadway segment base conditions,
AADT = annual average daily traffic [vehicles per day (vpd)], and
L = length of roadway segment (mi).

2. Multilane rural highways:

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

where N_{spfrd} is the predicted total crash frequency for divided roadway, segment base conditions; and *a* and *b* are regression coefficients, provided by HSM.

3. Multilane urban and rural freeways and Interstates:

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

where $N_{\text{spf,fs},n,[\text{mv or sv}],[z \text{ or pdo}]}$ is the predicted average multiple-vehicle (mv) or single-vehicle (sv) crash frequency of a freeway segment (fs) with base conditions, number of lanes (*n*), and severity (fatal and injury or property damage only (PDO)) (crashes per year); and *a, b,* and *c* are regression coefficients, provided by the reference document (*26*).

4. Interchange ramps:

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

where $N_{\text{spf},w,x,y,z}$ is the 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* (multiple or single vehicle), and severity *z* (fatal and injury or property damage only) (crashes per year); and *a*, *b*, *c*, and *d* are regression coefficients, provided by the reference document (*26*).

Crash modification factors (CMFs) must be applied to account for the effect of site-specific geometric design features that may differ from SPF base conditions. The HSM and the additional references provide CMFs for this purpose specific for respective roadway types. On the basis of existing geometrics present at the 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 was 1.0. When a particular feature was not present at a site, the CMF value was also 1.0. CMFs are easy to calculate based on the reference tables and equations provided in the HSM and future HSM chapters.

In typical analysis with 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 represented a short segment (typically a bridge deck) of roadway. Each site was unique if its specific features, traffic, and so forth had to be evaluated individually, as opposed to combining all sites together as would normally be the case. Consequently, only the short segments where a system was present were evaluated. Although 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 that was treated by the FAST system was examined.

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

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

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

where

N_{expected} = estimate of expected average crash frequency for the study period,
$N_{\text{predicted}}$ = predicted model estimate of average crash frequency for the study period,
N_{observed} = observed crash frequency at the site for the study period,
w = weighted adjustment to be placed on the predictive model estimate, and
k = overdispersion parameter.

RESULTS

On the basis of the analysis results, the general effect of the FAST systems 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 (*13*):

$$\theta = \frac{\frac{\lambda}{\pi}}{1 + \frac{\text{var}(\pi)}{\pi^2}} \tag{8}$$

The variance of θ was calculated by

$$\text{var}(\theta) = \frac{\theta^2 * \left(\frac{\text{var}(\lambda)}{\lambda^2} + \frac{\text{var}(\pi)}{\pi^2} \right)}{\left(1 + \frac{\text{var}(\pi)}{\pi^2} \right)} \tag{9}$$

Table 2 presents the values of θ, along with other data. The table indicates that the deployment at a particular site reduced or increased the number of crashes by a given percentage during the after period. Values of 0.0 typically result from cases where zero crashes were observed in the after period, which would suggest that a treatment was completely effective in reducing crashes. When zero crashes were observed during the before and after periods,

TABLE 2 EB Analysis Results for Colorado FAST Sites

Site	Range of Mileposts	Segment Length (mi)	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 Predicted Crashes (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
Multilane Rural Roads										
SH-119	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

the site is effectively removed from consideration, as no change occurred. Care must be taken in the type of evaluation presented here, where zero before or after period crash figures (particularly over short highway segments) do not necessarily mean that the treatment was completely responsible for reducing crashes. In such cases, the results should be viewed with caution.

Values below 1.0 indicate safety improvements, while values greater than 1.0 indicate safety reductions. For example, on urban interstates, θ values ranged from 0.30 to 0.84, suggesting that the introduction of FAST at these sites reduced crashes between 16% and 70%. 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 entirely the case, particularly on highly trafficked corridors.

The results of the before–after study are presented in Table 2. Some general observations on these results are in order. The number of expected crashes at each site following deployment varied greatly. This was in part because of factors such as different (higher) traffic levels, facility types, and so forth. In some cases, the number of crashes observed in the after period was lower than the expected number, indicating that the system likely contributed to improving safety. At other sites, slightly more crashes were observed relative 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 exceeded the estimated number of crashes expected. While it is clear that the addition of FAST at such sites did not lead to a safety improvement, it is also likely that it did not entirely contribute to a deterioration in safety. Rather, other factors could have contributed to the lack of an improvement, such as a reduction in police enforcement in the area.

FAST deployments on two-lane rural roads produced mixed results as measured by θ. At the SH-67 site and the US-34 site at Milepost 75.68–75.72, crashes slightly increased in the after period relative to the predicted number. The θ value for these sites indicates that an increase of 33% to 57% in annual crashes following deployment could be expected. This figure should be considered with caution, given the low number of crashes observed during the before and after periods, as well as the short length of the sites. The findings may be explained by evidence from past research that suggests that applying chemicals at the wrong time can lead to worsened surface conditions through refreeze (*28–30*). Unfortunately, operational records from the FAST sites were not available from the Colorado DOT, so the timing and rate of application could not be established to confirm whether this situation was the case for these sites (such an evaluation would represent an entire research effort in itself). The remaining two US-34 sites produced θ values of 0.00, which was the result of zero crashes being observed during the before and after periods. Therefore, the calculations used to establish θ produced the zero value (essentially removing these sites from consideration) and it is unclear what role FAST may have played in reducing or preventing crashes. 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 θ value for the site was 0.98, indicating that crashes fell by 2% following deployment. This is a low percentage of a crash reduction, making it unclear whether FAST systems would reduce or maintain current crash numbers at comparable locations. Still, based on the results, it is reasonable to conclude that the FAST system did not contribute to a deterioration of safety.

Urban Interstate sites showed the most positive results, with θ values ranging from 0.30 to 0.84, indicating that crashes following FAST deployment fell by 16% to 70% 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. This is especially true given that the sites were all located along routes with high traffic volume where there was an increased probability for crashes.

Rural Interstate sites produced mixed results. Sites on I-70 at milepost 216.20–216.28 and I-25 at Milepost 172.20–172.23 showed improvements in safety, with θ values of 0.43 and 0.69, respectively, or annual crash reductions between 31% and 57%. Remaining sites showed safety deterioration, as evidenced by high numbers of observed crashes versus the numbers expected following deployment and high θ values. The reasons for these trends were not clear, although a few pieces of supplementary evidence are offered. Interviews with the Colorado DOT's maintenance staff indicated that the I-25 sites at Mileposts 171.80–171.82 and 172.01–172.02 were part of a series of systems deployed together and deactivated in 2010 because of maintenance issues. This information suggests that these sites may not have been operating reliably during some storms, although normal maintenance efforts (plowing, etc.) continued. In such a case, it is possible that the supplemental treatments provided by the FAST systems would have contributed to enhanced safety if the systems were working. For these sites, as well as on I-70 at Milepost 171.20–171.30, AADT also increased during the after period, which correspondingly increased vehicle exposure and the opportunity for a crash to occur. The I-70 site at Milepost 124.99–125.47 was located immediately at the exit of a tunnel. Although FAST may have improved pavement conditions at the location, it is possible that drivers exiting the tunnel still encountered unexpected conditions leading to crash occurrence. It is also possible for all the sites that experienced deteriorated safety that the timing or rate of application was incorrect and produced a worse driving surface. Again, operational records were not available to determine this.

FAST sites on interchange ramps, specifically on ramps between Interstates, showed generally positive results. It was found that θ values of 0.60 and 0.81 were produced by two sites, translating into annual crash reductions between 19% and 40%. One ramp showed a significant increase in crashes and a corresponding index of effectiveness value of 2.49 (a 149% increase in crashes). Supplemental evidence suggests that the system did not necessarily contribute to that deterioration. Referring to Table 1, approximately 20% of crashes on this ramp occurred during winter weather conditions before and after deployment, suggesting that the FAST system had a neutral impact on safety. Once again, it is also possible that the timing or rate of treatment application was incorrect and produced a worse driving surface, and operational records were not available to determine this.

Additional sites 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 was of interest to examine some aspects of these sites to determine the impact FAST systems. Information for these additional sites is presented in Table 3. In general, the total number of crashes following FAST deployment was relatively low, aside from the SH-52 site. This finding was in part due to the long period of data available following FAST deployment, moderate traffic volume, and the character of the location itself (signalized diamond interchange). A low number of winter weather–related crashes were also observed at each site post-deployment, although the number was still high at some locations relative to the total number of crashes that had occurred. To facilitate a meaningful comparison among sites, crash rates were determined for the after period.

As Table 3 illustrates, the sites produced different winter weather crash rates. SH-160 and SH-66 each produced rates of 0.00, attributable to there being no winter weather crashes following deployment. This does not mean that the FAST systems eliminated winter crashes, although it is likely that the systems helped in preventing crashes. The second SH-160 site produced a crash rate of 0.09, which was reasonable over the 11 winter seasons following deployment. Similarly, the SH-83 and SH-52 sites produced low crash rates. The rate of 0.50 for the SH-83 site is a bit higher than for the 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, crashes at each location following deployment were

TABLE 3 Crash Trends for Additional Colorado FAST Sites

Route	Range of Mileposts	Segment Length (mi)	Years	Total Crashes	Winter Weather Crashes	Winter Weather Crash Rate (per million vehicle mi)
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

low. Only at one SH 160 site did winter crashes make up the majority of crashes following deployment. Although it is not clear to what extent the FAST system at each location contributed to safety improvements, it is clear that FAST did not negatively impact safety.

DISCUSSION OF RESULTS

Construction and other work zone activities on this study roadway segment could affect traffic safety. Although the Colorado's DOT records were not available, examination of aerial imagery indicated that only a few sites experienced changes that could impact safety. This finding 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. This possibility must be kept in mind when interpreting the results of this work.

Across the country, many types of systems have been deployed to reduce weather-related accidents. However, as noted in the HSM (*14*), knowledge regarding the quantitative effects of systems on reducing weather-related accidents is limited. No accident modification factors have been developed for weather-related treatments. Consequently, the results from this study are useful in understanding the safety effects of FAST systems. Although the ages of the deployments varied, the results from the overall evaluation provide an understanding of the safety effects and benefits of FAST systems on different highway types.

CONCLUSIONS

This study analyzed the safety effects of the FAST systems deployed on various types of highways in Colorado. An observational before–after study with the 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%, urban Interstates by 16% to 70%, rural Interstates by 31% to 57%, and interchange ramps between Interstates by 19% to 40%. These values correspond to accident modification factors 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.

Aside from these improvements, safety deteriorated at seven FAST sites following deployment in spite of normal maintenance operations (such as plowing) continuing. In some cases, information from maintenance staff indicated that the FAST systems were deactivated after operating unreliably, although normal winter maintenance efforts (plowing, etc.) continued. In addition, AADT increased during the after period at four of the seven sites, which correspondingly increased vehicle exposure and the opportunity for a crash to occur. Finally, deteriorated safety may be explained by evidence from past research that suggests that applying chemicals at the wrong time can lead to refreeze (*28–30*). It is possible that this situation occurred at all of these sites, with chemicals applied by the FAST systems at the wrong time leading to worsened surface conditions. Operational records from the FAST sites were not available, so the timing and rate of application could not be established to confirm whether this was the case for these sites.

When one chooses future deployment locations in light of safety, several points should be considered. It is unclear whether 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. Instead, it may be better to apply FAST on roads with more traffic to prevent or reduce crashes. If maintenance concerns are paramount (e.g., need for shorter response time), then FAST installations may provide an advantage on a two-lane road.

On rural multilane divided highways, the deployment of FAST appears to have produced a small improvement in safety. Urban Interstate applications of FAST systems produced the most positive results, with crash reductions between 16% and 70%. Although 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 deployments, given that the benefits of the system reach the largest number of vehicles.

Rural Interstate deployments showed effectiveness in reducing crashes in some cases, but also increases in crashes at other locations. Some of these increases were at sites that were later decommissioned, which may indicate that maintenance problems limited the effectiveness of the system.

Finally, deployments on interchange ramps between Interstates produced encouraging results. However, future deployments on interchange ramps should be limited to ramps that serve high traffic volumes, as was the case with the systems evaluated in this work.

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