Investigating Safety Effectiveness of Wyoming Snow Fence Installations Along a Rural Mountainous Freeway

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Drifting and blowing snow is a problematic and dangerous aspect of Interstate travel in the state of Wyoming. The control of snow and the maintenance of roadways is an essential and significant task for many state and local agencies. Many significant factors—such as vehicle control, surface conditions, and visibility—can be affected by hazardous winter weather. In areas such as the inspected 19-mi section of Interstate 80, snow fences have become a common and practical method of mitigating the problems caused by large quantities of snow near or on the traveled way. Wyoming deals with a high rate of adverse weather–related crashes during the winter season. Naive before–after analyses of snow fence installations have historically indicated a slight decrease in such crashes. In this study, the safety effectiveness of snow fence installations was investigated; more rigorous quantitative-based approaches were used and included a before–after analysis with empirical Bayes—in which Wyoming-specific safety performance functions were used—and odds ratio analyses. Crash modification factors were estimated for various crash types and severity levels. The results from this study indicate that the installation of snow fences contributes to a significant increase in the safety effectiveness of Interstate use during the winter. Specifically, it was found that during adverse weather conditions, snow fences decreased total crashes and fatal and injury crashes by about 25% and 62%, respectively.

Drifting and blowing snow is a problematic and dangerous aspect of roadway travel in the state of Wyoming. The maintenance and control of drifted snow can be a large component of winter maintenance costs for state or local agencies; drifting can also create dangerous situations by affecting vehicle control, road surfaces, and driver expectations (*1*). In notably affected areas, snow fences have become an efficient and practical method for mitigating the problems caused by large quantities of snow and ice near or on the traveled way (*2*).

Inclement weather events—such as fog, ground blizzards, and strong wind—affect roadways by modifying pavement conditions, vehicle performance, visibility, and driver behavior (*3–8*). Adverse weather conditions can result in a sudden reduction in visibility on roadways and increase the risk of crashes. According to the Fatality Analysis Reporting System, inclement rain, snow, and fog or smoke resulted in 5,897 fatal crashes between 2005 and 2014. FHWA reported that weather contributed to over 22% of all crashes between 2005 and 2014. In Canada and the United Kingdom, such crashes account for approximately 30% and 20%, respectively, of all crashes (*9, 10*). The financial burden of weather-related crashes in the United States is approximately $42 billion (*11*).

Several studies have concluded that vision obstruction can increase the number of crashes by 100% or more (*12, 13*); other studies have found more moderate (but still statistically significant) increases (*14, 15*). A sudden reduction in visibility was found to increase the severity of crashes and, typically, increase the number of vehicles involved in a crash. Shankar et al. reported that the crash rates increased at locations with many rainy days per month, a high maximum rainfall, and a high maximum snowfall (*4*). Ahmed et al. reported that a 1-in. increase in precipitation elevated the risk of a crash by 169% (*16*). Koetse and Rietveld stated that precipitation generally increased the frequency of crashes but decreased the severity of crashes (*17*). Jones et al. mentioned that the risk of crashes increased in adverse weather conditions (*3*). Donnell and Mason stated that wet roadway surface conditions increased the severity of crashes (*7*). The literature shows a variation of crash risk estimates; however, the general trend is that adverse weather and road conditions can easily elevate the risk of crashes.

Wyoming has a high number of winter weather–related crashes, particularly within the Wyoming Department of Transportation (DOT) District 1 (southeastern Wyoming). Past data show that up to 25% of the crashes on Interstate 80 occurred in areas without snow fences; a mere 11% of crashes occurred in areas protected by fences (*2*). Snow fences not only provide a simple, practical solution but also have proved to be highly economically advantageous when compared with other snow mitigation techniques and practices (notably, machine removal) (*2*).

This study investigated the safety effectiveness of snow fence installations through a comparison of crash data before and after the installation of fences between mileposts (MPs) 325 and 344 on Interstate 80 (Route ML80) in southeastern Wyoming. Odds ratios, naive before–after analysis, and before–after analysis with empirical Bayes that utilized a negative binomial (NB) Wyoming-specific safety performance function (SPF) were used.

SNOW FENCE DESIGN

The calculation and design work behind snow fences is relatively straightforward. Compared to many other current roadway safety technologies and practices, snow fences have a relatively simple

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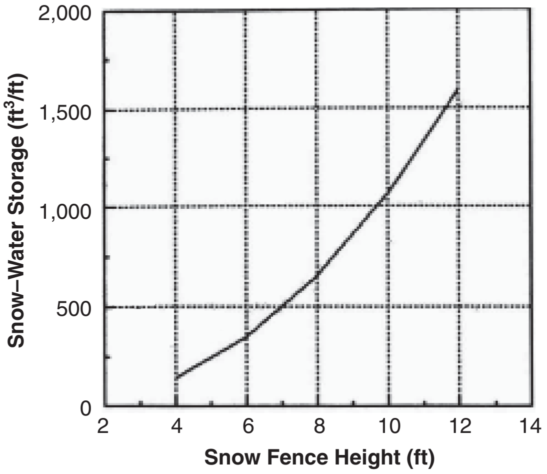

FIGURE 1 Simple relationship between fence height and storage capacity (*18*).

process of design and implementation. Additionally, because snow fence design is not a new practice, the design recommendations and practices have been significantly refined and simplified.

Snow fence performance, measured by the amount of material retained, is primarily a function of geometry. Specifically, the performance is a function of, primarily, fence porosity and height and, secondarily, of length, angle, inclination, material, and topography (*2*). Figure 1, provided by a Montana report, shows the relationship between fence height and water storage (when water and snow are used interchangeably, there is generally a 1:10 snow–water ratio) (*18*).

Although it is essential to understand this relationship, it still must be realized that additional snow fence characteristics, such as the inclination angle, can also greatly affect storage capabilities. The most significant of these characteristics is porosity. Porosity is defined as the ratio or percentage of open area to the total frontal area, excluding the bottom gap (*2*). Figure 2 displays storage geometry as a function of the fence height, but for varying porosity values (*2*). Additionally, storage quantities and densities are crucial in maintaining the targeted or desired snow storage, so that the purpose of the fence can be efficiently achieved. Figure 3 displays the relationship between snow density and snow depth.

The Wyoming DOT uses snow fences made primarily from wood, with steel reinforcement and fastening, referred to as "anchor clips." Standard plans for snow fence construction call for 12-ft panels of fence, with a maximum gap of 1 in. between each, as well as a typical offset height of 1.5 ft. A typically inclined fence would have a brace angle of 62° (measured from the ground on the interior of the fence) and a front panel angle of 75° (also measured on the interior of the fence). Also, according to the Wyoming DOT Winter Research Department, the agency now focuses on two structural fence sizes: 10 and 12 ft.

WEATHER DATA

In 2007, the Wyoming DOT installed numerous snow fences along Interstate 80. In this study, an investigation was conducted on an area stretching from MP 325 to MP 344 that includes very high-density snow fence installations. This particular stretch of roadway is part of one that is notoriously hazardous during the winter weather season and adverse weather conditions. The hazardousness of this stretch is at least partially attributable to the elevation and geographic characteristics of the area. The roadway elevation in this section reaches a high point of approximately 8,880 ft (2,707 m). This elevation, combined with precipitation rates seen during the primary snow accumulation season, creates an area in which roadway conditions can be highly affected by adverse weather conditions. Figure 4 demonstrates how an increase in elevation affects the length of the snow accumulation season in Wyoming.

According to the Wyoming State Climate Office, this area has approximately 12 to 18 days of snow annually that exceed 5 in. per day, with a maximum 24-h snowfall of 23 to 26 in. (*19*). Additionally, this area can receive anywhere from 63 to 140 in. of snowfall for an entire year (*19*).

To better understand the weather in this area, forecasted data were developed for three adjacent 12-km (7.46-mi) sections that covered the investigated roadway segment. From these data, weather patterns over winter seasons (October 15 through April 15) could be analyzed. See Table 1 for a brief overview of the weather data gathered during the winter season for the study location. The mobile and blowing snow rates found in Table 1 are not given as velocities, but rather as a total depth in millimeters per hour.

In addition to the adverse weather conditions in this area, the composition of traffic along this roadway tends to be heavily commercially based (approximately 46%). In adverse weather conditions, commercial motor vehicles have shown increased susceptibility to crashes of a higher severity (*20*). The U.S. DOT and the FMCSA have found that, in the event of snow, commercial motor vehicles can experience approximately 2.67 times the fatal weather-related crashes of all vehicles (*20*). This high percentage of commercial traffic—combined with the snowfall rates, adverse weather conditions, and high Interstate travel speeds [a 75-mph posted speed; variable speed limit systems were initially implemented in Wyoming in

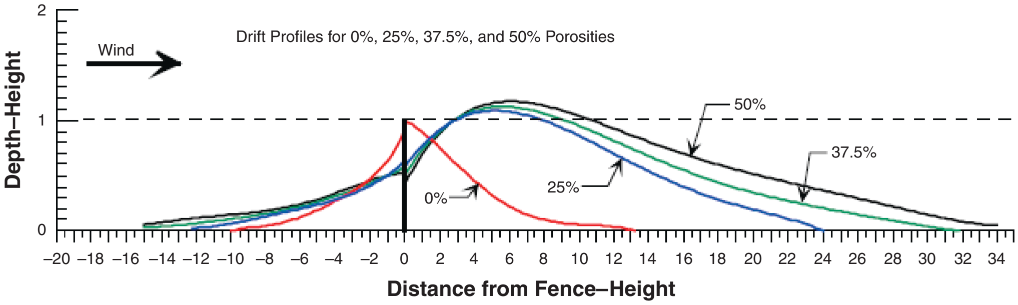

FIGURE 2 Storage capabilities at various porosities (*2*).

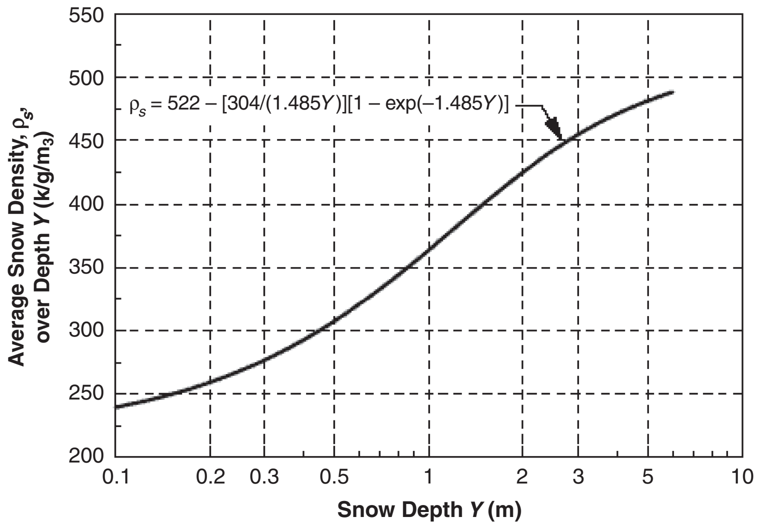

FIGURE 3 Snow density change with depth (*2*).

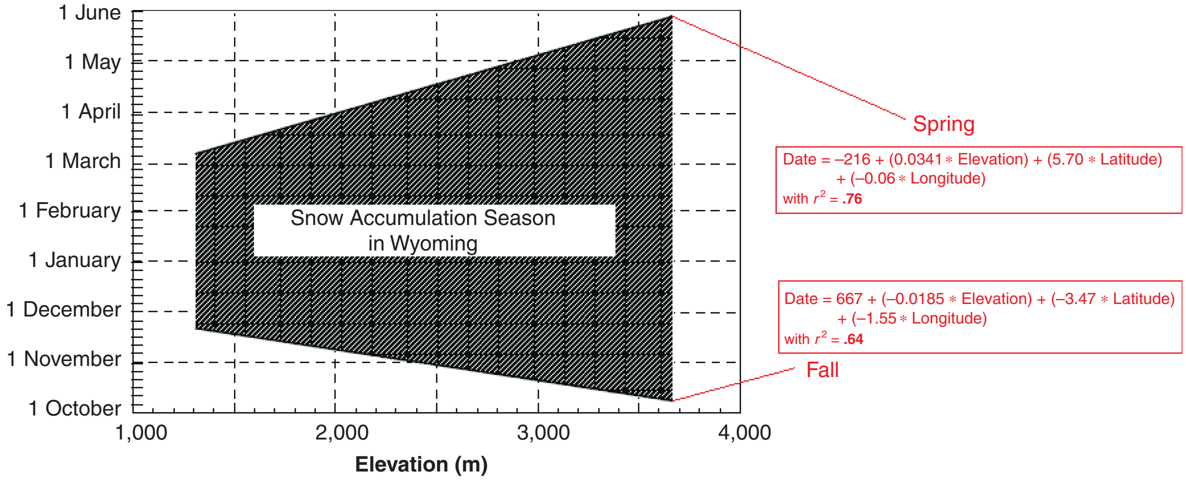

FIGURE 4 Effect of elevation on the snow accumulation season in Wyoming (*2*).

TABLE 1 Weather Data from Study Location

Winter Season	Average 2.5-m Wind Speed (m/s)	Average Mobile Snow Rate (mm/h)	Average Blowing Snow Rate (mm/h)	Total Snowfall (mm)	Average Air Temp (°C)
2004–2007	6.013	0.196	0.104	300.6	–0.478
2007–2010	6.272	0.231	0.144	332.6	–1.423
Increase or decrease	↑ 4.37%	↑ 17.9%	↑ 38.5%	↑ 10.6%	↓ 0.945°C

2009 (*21*)]—creates a roadway environment that, during the snowfall season, can be extremely problematic in terms of roadway condition and safety.

CRASH DATA COLLECTION

To properly understand the effect that the snow fence installations have had on the roadway and its users, crash data were collected. The crash data were acquired from the Critical Analysis Reporting Environment crash database software. This desktop software is updated and maintained by the Wyoming DOT and allows for the acquisition of crash data through various analysis methods and criteria (*22*). MP limitations were applied and, from there, the data were trimmed to only display and analyze data from the winter season (October 15 through April 15).

CRASH DATA ANALYSIS

Odds Ratio

To understand the distribution of crash types, the odds ratios for total crashes and for fatal and injury (F+I) crashes were estimated (*23*). Odds ratio analysis and the ratio of the odds ratio analyses were used to further understand and analyze the frequency of the crashes. Additionally, performing this analysis on F+I crashes would better help to understand the frequency of higher-severity crashes. The total and F+I crashes were categorized into all winter season crashes and target crashes (all adverse weather crashes during the winter season). See Table 2 for the odds ratio of the total and F+I crashes with regard to snow fence presence.

The odds ratio (OR) was found with Equation 1 (*23*):

$$\mathrm{OR} = \frac{\left(\dfrac{\pi_{11}}{\pi_{12}}\right)}{\left(\dfrac{\pi_{21}}{\pi_{22}}\right)} \qquad (1)$$

where

π_{11} = target crashes before implementation,
π_{12} = all crashes before implementation,
π_{21} = target crashes postimplementation, and
π_{22} = all crashes postimplementation.

To understand the significance of the odds ratio, the confidence intervals for a 95% confidence level were utilized, in addition to the standard error. These values were found with Equations 2 and 3 (*23*):

$$\text{confidence interval} = e^{\ln(\mathrm{OR}) \pm z_{0.05} * \sqrt{\mathrm{SE}}} \qquad (2)$$

$$\mathrm{SE} = \frac{1}{\pi_{11}} + \frac{1}{\pi_{12}} + \frac{1}{\pi_{21}} + \frac{1}{\pi_{22}} \qquad (3)$$

where $z_{0.05} = 1.96$.

As can be seen in Table 2, the odds ratio for total crashes was found to be 0.72; this result indicated that a smaller portion of crashes during adverse weather was experienced before the installation of snow fences. The confidence intervals for the total crashes odds ratio were found to be 0.57 to 0.88; this result indicated that there was no statistically significant effect on total crashes during the winter season as a result of snow fences being installed.

The odds ratio for the F+I crashes was found to be 0.77. This value indicates, similar to the total crash odds ratio, that a higher portion of the F+I crashes during adverse weather conditions came after the installation of the snow fences. The confidence interval for the F+I crashes was found to be 0.52 to 1.14; this finding indicates that there was no statistically significant effect on F+I crashes during the winter season as a result of snow fence installation.

The ratio of the odds ratios for total crashes (0.72) and F+I crashes (0.77) is 1.07. This ratio is promising as it indicates that there has been less of an increase in F+I crashes since the installation of snow fences when compared to the total crashes.

Naive Before–After Analysis

To properly quantify the safety effectiveness of the snow fence installations in the study area, the first step was to perform a naive before–after study that used the gathered crash data to find values for crash modification factors that would indicate the safety effectiveness of the snow fences.

Because the snow fences along the selected segments were installed in 2007, the analysis was performed from October 2003 to April 2011; this time span allowed for eight full winter seasons of crash data to be analyzed (four before and four after). Figure 5 displays the crash type frequencies on Interstate 80 between MP 325 and MP 344 for all weather conditions during winter months.

For the 8-year investigation period, there were 953 total crashes; just under 48% of these crashes occurred after the installation of snow fences. Of the total crashes that occurred during all weather types, 31% were F+I crashes before the installation of snow fences and 23% were F+I crashes after the installation: a 31.41% decrease in F+I crashes. Additionally, there was a 2.94% increase in property damage only (PDO) crashes after the installation of snow fences.

To further understand the effect of the snow fence installations on crash frequency and severity, adverse winter weather conditions were taken into consideration. In the case of the data gathered from the Critical Analysis Reporting Environment crash database, any accident within the previously discussed time frame and study area that

TABLE 2 Contingency Table with Odds Ratio for Total and F+I Crashes

	Total				F+I			
Status of Snow Fence Installation	Crashes	Target Crashes	Odds (%)	Odds Ratio	Crashes	Target Crashes	Odds (%)	Odds Ratio
Before installation	496	268	54	0.72	156	87	56	0.77
After installation	457	342	75	0.72	107	78	73	0.77

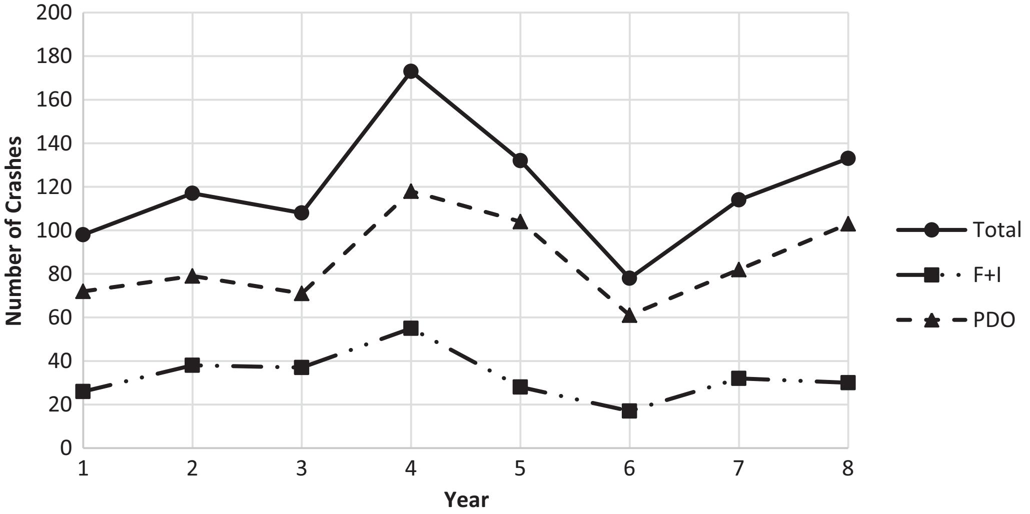

FIGURE 5 Crashes during winter months: all weather (PDO = property damage only).

had an indicated weather condition of “blowing snow,” “snowing,” or “blizzard” was considered an adverse weather crash in this study. See Figure 6 for the crash type frequencies of adverse weather crashes during the winter season.

The crashes that occurred under adverse weather conditions during winter months were expected to be more representative of the true effect of the snow fences. There was a 10.34% decrease seen in F+I crashes that occurred in adverse weather, but a 45.86% increase in PDO crashes and a 27.61% increase in total crashes. These results do not seem reliable, as they suggest a significant increase in total and PDO crashes after snow fence installation.

The year-to-year variability in crashes during the winter months is evident. This variability is to be expected because crashes are rare and random events. Additionally, this segment of the roadway operates at relatively low volumes [5,855 to 6,830 annual average daily traffic (AADT) over the investigation period] for an Interstate freeway.

Before–After Analysis with Empirical Bayes

To more accurately interpret the obtained crash data, simple SPFs were calibrated for rural Interstate freeways in Wyoming during the winter months (*24*). For this study, the simple SPFs were calibrated with AADT data. Although full SPFs are preferable to simple SPFs, it is unrealistic to expect all transportation agencies to have site-specific full SPFs, given that they require higher traffic volumes, unique roadway attributes, and season-specific information. These simple SPFs, calibrated from AADT data and segment lengths, were used as part of an NB model to evaluate safety effectiveness (*25*). One of the main advantages of a before–after study with empirical Bayes is that it accurately reflects anticipated changes in crash frequencies in the before and after periods that may be attributable to regression to the mean bias (*25*). Additionally, this method will account for the influences of traffic volumes and time trends on safety.

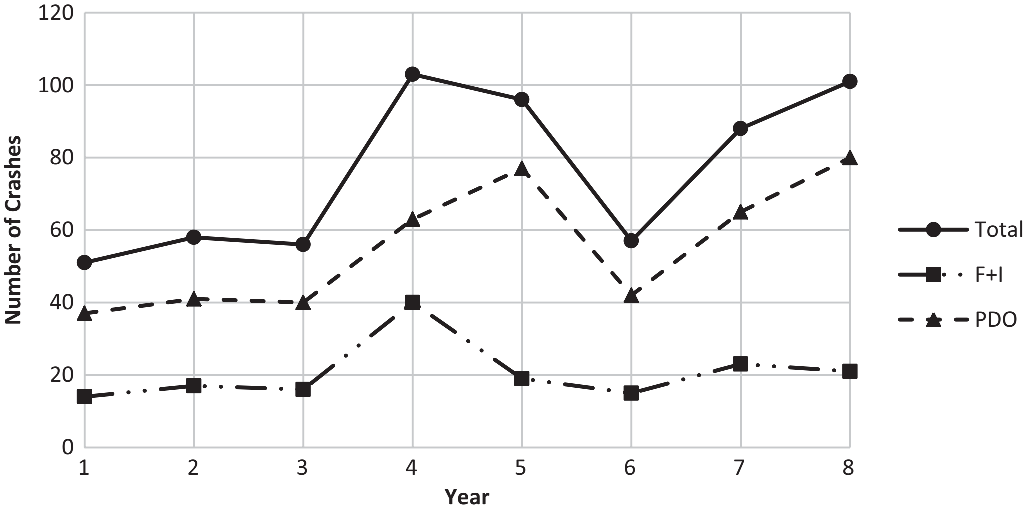

FIGURE 6 Crashes during winter months: adverse weather.

The estimate of expected crashes (E) at the investigation location is based on a weighted average of information from treatment and reference sites and is given in Equation 4:

$$\hat{E}_i = (\gamma_i \times y_i \times n) + (1 - \gamma_i)\eta_i \qquad (4)$$

where

i = index corresponding to the respective section of investigation area,
γ = weight factor,
y = expected crashes estimated from SPF,
n = number of years in period, and
η = observed number of crashes at treatment site during "before" period.

The weight factor is estimated from the overdispersion parameter of the NB relationship and is shown in Equation 5:

$$\gamma_i = \frac{1}{1 + k \times y_i \times n} \qquad (5)$$

where k is the overdispersion parameter from the NB relationship.

The regression model (SPF) is used to provide an estimate of crash occurrences within the given segment. The model uses an NB regression model to estimate crashes; therefore, the NB model is used to fit the SPF through the use of traffic data. Equation 6 represents the form of a typical SPF:

$$y_i = e^{(\beta_0+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_n x_n)} \qquad (6)$$

where β_1 represents regression parameters and x_1 and x_2 are the logarithmic values of AADT and segment length.

See Table 3 for the developed simple SPFs, corresponding to Equation 6, for Wyoming Interstate freeways during the winter months.

The standard deviation (σ) for the expected crashes (E) is given by Equation 7:

$$\hat{\sigma}_i = \sqrt{(1 - \gamma_i) \times \hat{E}_i} \qquad (7)$$

After this step, the changes in traffic volumes must be accounted for. To adjust for the AADT seen during the before and after periods, Equation 8 is utilized:

$$\rho_{\text{AADT}} = \frac{\text{AADT}_A^{\beta}}{\text{AADT}_B^{\beta}} \qquad (8)$$

where

ρ_{AADT} = AADT adjustment,
AADT_A = AADT in after period,
AADT_B = AADT in before period, and
β = regression coefficient of AADT from SPF (seen in Equation 6).

TABLE 3 Wyoming-Specific SPFs for Interstate Freeways During Winter Months

Crash Type	Intercept Estimate	log(AADT) Estimate	Dispersion (k)
F+I	−8.2786	2.1192	0.1501
PDO	−11.3416	3.1278	0.2512
Total	−12.7676	3.5971	0.3857

Similar to adjusting for AADT, the time interval of the study must be adjusted. However, in equal time periods, such as the ones in this study, this adjustment factor (ρ_{time}) will have no impact (=1).

The final estimated number of crashes at the treatment location in the after period, adjusted for traffic volume changes and time period differences, is given by Equation 9:

$$\hat{\pi}_i = \hat{E}_i \times \rho_{\text{AADT}} \times \rho_{\text{time}} \qquad (9)$$

The index of effectiveness of the countermeasure ($\hat{\theta}_i$) can be found with Equation 10:

$$\hat{\theta}_i = \frac{\left(\dfrac{\hat{\lambda}_i}{\hat{\pi}_i}\right)}{1 + \left(\dfrac{\hat{\sigma}_i^2}{\hat{\pi}_i^2}\right)} \qquad (10)$$

where $\hat{\lambda}_i$ is the observed crashes during the after period.

The percent reduction in crashes ($\hat{\tau}_i$) of each type is given by Equation 11:

$$\hat{\tau}_i = \left(1 - \hat{\theta}_i\right) \times 100\% \qquad (11)$$

The crash modification factor of the countermeasure averaged over all sites is given by Equation 12:

$$\hat{\theta} = \frac{\left(\dfrac{\sum_{i=1}^{m} \hat{\lambda}_i}{\sum_{i=1}^{m} \hat{\pi}_i}\right)}{1 + \left(\dfrac{\text{var}\left(\sum_{i=1}^{m} \hat{\pi}_i\right)}{\left(\sum_{i=1}^{m} \hat{\pi}_i\right)^2}\right)} \qquad (12)$$

where m is the total number of treated sites.

The variance of estimated crashes during the after period, based on time and AADT ratios, is given by Equation 13 and enables the standard deviation of the overall safety effectiveness to be estimated, as shown in Equation 14 (*25*).

$$\text{var}\left(\sum_{i=1}^{k} \hat{\pi}_i\right) = \sum_{i=1}^{k} \rho_{\text{AADT}}^2 \times \rho_{\text{time}}^2 \times \text{var}\left(\hat{E}_i\right) \qquad (13)$$

$$\hat{\sigma} = \sqrt{\frac{\hat{\theta}^2 \left[\left(\dfrac{\text{var}\left(\sum_{i=1}^{k} \hat{\pi}_i\right)}{\left(\sum_{i=1}^{k} \hat{\pi}_i\right)^2}\right) + \left(\dfrac{\text{var}\left(\sum_{i=1}^{k} \hat{\lambda}_i\right)}{\left(\sum_{i=1}^{k} \hat{\lambda}_i\right)^2}\right)\right]}{\left[1 + \left(\dfrac{\text{var}\left(\sum_{i=1}^{k} \hat{\pi}_i\right)}{\left(\sum_{i=1}^{k} \hat{\pi}_i\right)^2}\right)\right]^2}} \qquad (14)$$

TABLE 4 Before–After Analysis Results

	Naive (All Weather)		Naive (Adverse Weather)		EB (All Weather)		EB (Adverse Weather)	
Crash Type	CMF (Safety Effectiveness)	Standard Error	CMF (Safety Effectiveness)	Standard Error	CMF (Safety Effectiveness)	Standard Error	CMF (Safety Effectiveness)	Standard Error
F+I	0.69	0.64	0.9	0.61	0.41	0.047	0.38	0.051
	(31.41%)	64.11%	**(10.34%)**	61.17%	**(59.09%)**	4.75%	**(61.98%)**	5.15%
PDO	1.03	0.71	1.46	0.78	0.77	0.056	0.94[a]	0.08
	(–2.94%)	70.55%	(–45.86%)	78.32%	**(23.21%)**	5.57%	(5.98%)[a]	7.99%
Total	0.92	0.85	1.28	0.86	0.75	0.047	0.84	0.063
	(7.86%)	85.34%	(–27.61%)	85.98%	**(25.3%)**	4.72%	**(15.67%)**	6.33%

NOTE: EB = empirical Bayes; CMF = crash modification factor; bold indicates significant crash reduction.
[a] Indicates statistical insignificance.

Finally, the standard error allows the statistical significance of the estimated safety effectiveness to be determined, as seen in Equation 15:

$$\text{abs}\left(\frac{\text{safety effectiveness}}{\text{SE}(\text{safety effectiveness})}\right) > 1.96 \qquad (15)$$

If the ratio found with Equation 15 exceeds 1.96, it can be concluded that the snow fence effect is significant at the 95% confidence level.

Like the naive before–after analysis, the time period included eight winter seasons, from October 2003 to April 2011. The division of the investigated area (MP 325 to MP 344) by AADT data made available by WYDOT resulted in six segments of varying lengths.

The process outlined through Equations 4 to 15, combined with the AADT data and resulting segmentation, allowed the safety effectiveness and corresponding statistical significance to be determined for each crash type during all weather conditions, as well as during adverse weather conditions. See Table 4 for these results as well as the safety effectiveness from the naive study.

DISCUSSION AND CONCLUSIONS

Overall, snow fence design seems to be an extremely under-investigated engineering implementation. Snow fences act as an extremely economic method of snow management. This makes them increasingly significant for transportation agencies whose funding may not allow for additional spending on auxiliary activities (such as snow removal). It has been historically proved that snow fence installation can be, on average, up to 100 times cheaper than traditional snow plowing (*2*). This figure is primarily, but not solely, derived from a Wyoming study that showed that snow fences had resulted in a design and construction cost of approximately 3 cents per ton of snow stored, compared with the transportation and relocation of snow, which cost an average of $3 per ton of snow transported (*2*).

The historical effects of snow fences on roadway travel have indicated positive results, but in-depth analysis of snow fences' quantitative safety effectiveness helps to understand and explain the effects. Throughout this study, crashes were evaluated primarily as total, PDO, and F+I to help better understand the effect that the snow fences have on both crash frequency and severity. Crashes were categorized into those that occurred during any weather conditions within the winter weather season and those that occurred only during adverse weather conditions within the winter weather season (October 15 to April 15).

The naive before–after analysis showed signs that snow fence installations were positively affecting the frequency of F+I crashes (a 31.41% decrease in all weather conditions; a 10.34% decrease in adverse weather), but the results for PDO and total crashes indicated decreased safety effectiveness during winter months after the installation of snow fences.

These results were refined through the empirical Bayes method and the calibration of Wyoming-specific SPFs, and it became evident that the safety effectiveness related to the different crash types (and their associated standard errors) was adjusted and better developed when changes in time and traffic volumes were considered. The empirical Bayes method showed that all types of crashes, regardless of weather conditions, were reduced by the presence of snow fences during the winter months. Most significantly, there was a 59.09% decrease in F+I crashes during all weather conditions and a 61.98% decrease during adverse weather conditions. In addition, PDO crashes displayed a decrease of 23.21% in all weather conditions and a 5.98% decrease in adverse weather conditions, and total crashes displayed a decrease of 25.3% in all weather conditions and a 15.67% decrease in adverse weather conditions as a result of snow fence presence. These values reflect extremely well on the safety effectiveness of the snow fence installations and provide assurance that crashes that result from inclement winter weather conditions and their effects have been significantly reduced in frequency and severity. These results are especially encouraging when combined with the findings (based on an investigation of data for wind speed, mobile snow, blowing snow, total snowfall, and air temperature) that winter weather conditions at this location have worsened.

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All results and opinions in this paper are those of the authors.

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