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Benefits and Costs of Snow Fences on Wyoming Interstate 80

RONALD D. TABLER AND RICHARD P. FURNISH

Snow-fence protection along a 100-km section of Wyoming Interstate 80 has gradually been increased from none to 50 percent since 1970. This presents a unique opportunity to identify effects of the snow fences on snow-removal expenditures, accident frequency, and road closure. This information is needed for economic analyses to determine the feasibility of future snow-control projects. The study indicated that snow-removal costs were reduced by more than one-third as a result of the effective elimination of snowdrifts. Accidents during blowing snow conditions decreased in proportion to the length of highway protected, with a 70 percent reduction at the current level of fencing. There is some indication of a comparable reduction in wind-related accidents. These effects reflect the improved visibility and road-surface conditions observed in the areas protected by snow fences. The fences have had no significant effect on the length of time the highway is closed to traffic, and it is hypothesized that protection might have to approach 100 percent before such an effect could be expected. Fence construction costs can be amortized within 10 years through reduced winter maintenance costs and property damage. Effectiveness of the snow fences is attributed primarily to adequate snow-storage capacity and the use of tall (3.78-m) fences.

On October 3, 1970, a 124-km section of Interstate 80 (I-80) between Laramie and Walcott Junction, Wyoming, was opened to traffic. This new road was in a different location from US-30, which it replaced; by following the old Overland Trail along the foot of the Medicine Bow Mountains, the new route was about 27 km shorter. Because the new highway was in a sparsely populated region up to 30 km from US-30, there was little beforehand knowledge of weather conditions, and highway engineers thought it necessary to gain a winter's experience before building snow fences.

The first winter, large drifts formed on the highway and snow-removal expenditures were excessive in comparison with those on US-30. Frequent ground blizzards caused poor visibility that required the highway to be closed to traffic for a total of 8.4 days. Several factors contributed to more severe snow problems on the new route than had been experienced on US-30. About two-thirds of the old route was immediately downwind of the Union Pacific Railroad, which was well protected with snow fences that also provided protection for US-30, although this was not generally appreciated at the time. The new route is also much closer to the Medicine Bow Mountains, which resulted in more snowfall and stronger winds.

As a result of the first winter's experience, highway engineers gave high priority to construction of snow fences to reduce drifts forming in the road cuts. The first snow-fence construction began in the summer of 1971 and continued into the summer of 1972. By the end of the second winter, it was apparent that fences would alleviate drift formation on the road, but, in addition, dramatic improvements in visibility and road-surface conditions were also evident (1). As a result, additional snow fences have been constructed over subsequent years; the last ones were completed in the summer of 1979. The gradual addition of snow fences along this highway provides a unique opportunity to evaluate their effectiveness in relation to accidents, snow-removal expenditures, and days of road closure. Although there are many published references to the effectiveness of snow fences in qualitative terms, we are not aware of any quantitative evaluation comparable to that provided by this 11-year study.

PHYSICAL AND CLIMATIC CHARACTERISTICS

The section of this highway with the greatest winter weather problems is that between Miles 235 and 295, where the road is closest to the mountains, and this 96.6-km segment comprises the study section. General road orientation is southeast-northwest, and mean elevation over the study section is about 2250 m (Figure 1).

Typically, the first snow falls after mid-September and the last in mid-May. During the study, only 0.8 percent of the ground blizzard accidents were in September and May combined, which led us to choose October 1 to April 30 as the period for the accident analyses. More than 95 percent of the precipitation over this period is snow.

Mean monthly precipitation, wind speed, and air temperature for the study period (1970-1981) are shown in Table 1. Mean water-equivalent precipitation from October 1 to April 30 is 31.1 cm. Snowfall in October and April usually melts within a few days. Most drifting is between November 1 and March 31; precipitation averages 19.8 cm for this period.

Westerly winds are dominant and strongest. Maximum wind gusts up to 45 m/s were recorded in three years of the study. Although major snowstorms are often associated with easterly winds, these are of relatively short duration and are not so strong as the prevailing westerlies. More than 95 percent of the annual snow transport is from the west, and all the snow fences are on the west side of the highway. Because of the strong, persistent winds and long periods of below-freezing temperatures, most of the snowfall is relocated by the wind.

The highway passes through uncultivated rangeland vegetated with low-growing grass and sagebrush 10-45 cm in height; there are only a few isolated groves of trees and taller shrubs. The upwind "fetch"

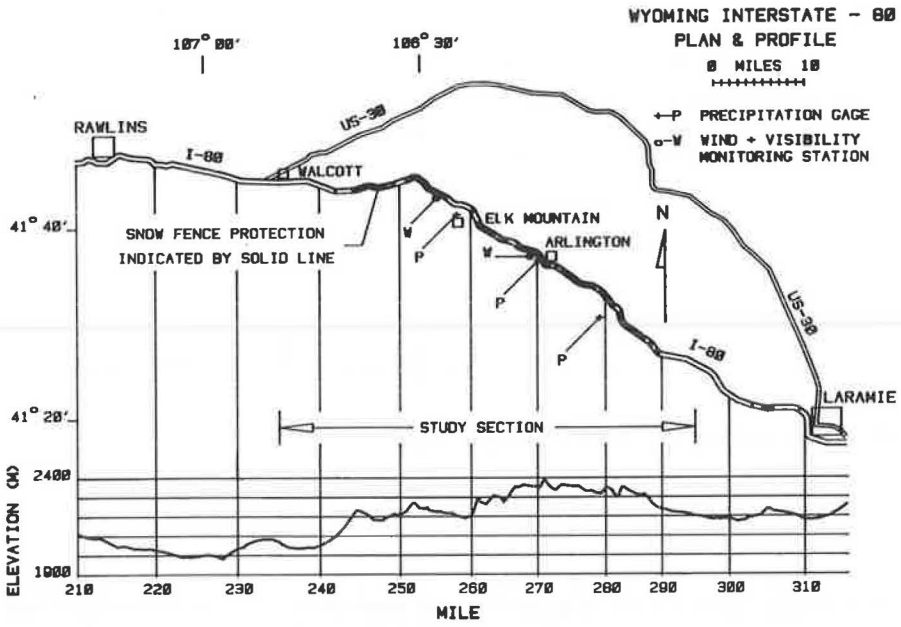


Figure 1. Location map and profile of I-80 between Laramie and Walcott, Wyoming.

Table 1. Climatological characteristics of I-80 study section.

Characteristic	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	Total
Wind speed (m/s)								
Mile 255[a]	4.9	7.0	9.3	7.9	8.3	6.6	5.4	
Mile 270[b]	6.0	8.2	10.0	9.5	9.4	8.0	6.7	
Air temperature (°C)[c]	6.7	–0.6	–3.4	–5.9	–3.4	–0.9	3.3	
Precipitation (cm)[d]								
Mile 261	3.5	3.1	3.0	3.0	2.4	3.6	5.2	23.7
Mile 270	5.9	4.4	4.9	4.9	3.5	5.8	8.1	37.6
Mile 282	4.3	4.2	4.2	4.0	2.7	5.6	6.8	32.0
Mean	4.6	3.9	4.0	4.0	2.9	5.0	6.7	31.1

[a]Location, Mile 255; elevation, 2225 m. Means are for January 1975 to April 1981; 7.3 m measurement height [from Martner (2)].
[b]Location, Mile 270; elevation, 2400 m. Means are for February 1974 to April 1981; 8.2 m measurement height [from Martner (2)].
[c]Location, Mile 261; elevation, 2217 m. Means for 1971 to 1981 from Elk Mountain station (Climatological Data for Wyoming from National Oceanic and Atmospheric Administration).
[d]Means for 1971 to 1981 from gages operated by the Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. Elevations are as follows :Mile 261, 2210 m; Mile 270, 2364 m; Mile 282, 2358 m.

distance contributing blowing snow to the highway ranges from 200 m to 7000 m; a typical value is 3000 m. Total annual snow transport, as measured in the snow-fence drifts, has ranged from a maximum of 195 water-equivalent m^3/m of width transverse to the wind over the 1978-1979 winter to a low of 22 m^3/m for the 1980-1981 winter.

SNOW-FENCE SYSTEM

The snow fences between Laramie and Walcott were built in five stages, starting in 1971 (Table 2). Of the 53 km of snow fence in the total system, 70 percent is 3.78 m in height, 5 percent is 3.17 m, 24 percent is 2.44 m, and 1 percent is 1.83 m. About 98 percent of the snow fences are within the study section, providing protection for 49 km, or 51 percent, of this section of highway. Total construction cost, including that outside the study section, has been $1 910 000, or about $38 200/km of protected highway.

Fences built in the first contract protected road cuts where large drifts formed on the roadway during the first winter. Half of the second contract was to improve visibility in a 4-km section of the highway; the other half was to eliminate smaller drifts not severe enough to have been included in the first contract as well as drifts at interchanges and grade separations. Subsequent contracts have concentrated on locations with unusually high accident frequency and locations where drifts encroach on the traffic lanes only during the heaviest snowfall years.

The snow fences are of a standard design adopted by the Wyoming State Highway Department in 1971 and have been described in a previous publication (3). The structures consist of horizontal boards 15 cm wide separated by 15-cm spaces, a bottom gap of approximately one-tenth of the fence height, and a 15° inclination downwind (Figure 2). Net porosity (open area) of the structure, excluding the bottom gap, is about 48 percent.

Studies of the geometry of the snowdrifts formed by these fences indicate that their storage capacity equals or exceeds that of other designs (4). Combined cross-sectional area of the windward and leeward equilibrium drifts is $21.9H^2$, and water-equivalent capacity in cubic meters per meter is about $7.8H^{2.18}$, where H is total vertical fence height in meters. Maximum length of the lee drift when the fence is full is about 30H.

Placement criteria for the fences have been revised from those reported previously (3) as more information has become available concerning the drift geometry. Current specifications include a minimum distance of 30H from the right-of-way, a

Table 2. Snow-fence contracts between Miles 235 and 295, Wyoming I-80.

Contract	Construction Date	Location (Mile)	Fence Height (m) 1.83 Length (m)	1.83 Price ($/m)	2.44 Length (m)	2.44 Price ($/m)	3.17 Length (m)	3.17 Price ($/m)	3.78 Length (m)	3.78 Price ($/m)	Road Protection (m)
1	1971-1972	246-280	419	17.23	2 589	20.51	2643	24.61	12 728	26.84	12 746
2	1973	246-285	0	–	2 165	22.97	0	–	12 504	29.53	14 489
3	1974-1975	244-256	0	–	1 741	33.63	0	–	2 507	55.61	5 757
4	1977-1978	242-279	0	–	3 706	29.20	0	–	5 413	46.75	9 494
5[a]	1979	281-289	0	–	1 589	31.17	0	–	3 852	50.86	6 708
Total			419		11 790		2643		37 004		49 194

[a]Values for fifth contract do not include 927 m of 2.44-m fence built outside study section.

Figure 2. Standard 3.78-m snow fence used on I-80 (Mile 254.2, Feb. 18, 1972).

35-40H spacing between tandem rows, a minimum length of 30H to minimize "end effect," orientation perpendicular to the prevailing wind, a 10H extension of fences beyond the length of road to be protected, and placement of fences on hills or at the upwind edge of depressions to increase storage capacity.

Fence systems at each site are designed to have sufficient capacity to store all the anticipated snow transport over an average winter by using the method described by Tabler (5). At most locations, one row of 3.78-m fence is adequate. Because the storage capacity of the new fence design was uncertain when the first contract was engineered, those fence systems were overdesigned to such an extent that they have not filled completely over the 10 years they have been in place.

DATA AND ANALYSES

Accident Data

Accident data were compiled by computer by the Highway Safety Branch of the Wyoming State Highway Department from standard reports filed by the Wyoming Highway Patrol and motorists. The Wyoming state standard categories of weather conditions used for this analysis were as follows:

1. Snow: snowfall without appreciable blowing snow;
2. Ground blizzard: conditions with blowing and drifting snow sufficient to reduce visibility (the term "ground blizzard" is not strictly correct because there may or may not be concurrent precipitation; under conditions of moderate to severe blowing snow, it is difficult to tell whether or not it is snowing);
3. Wind: wind speed averaging about 10 m/s or more without precipitation or appreciable blowing snow; and
4. Other: a category that includes rain, fog, dust, and clear-weather conditions.

These categories include all road-surface conditions and are not necessarily related to the cause of the accidents.

Number of vehicles traveling the study section was measured by a permanent traffic counter, allowing accidents to be expressed per million vehicle kilometers.

Weather Data

To account for annual variations in snowfall, accidents and duration of road closure were normalized with respect to precipitation. A National Oceanic and Atmospheric Administration (NOAA) cooperative observer weather station is located in the town of Elk Mountain, but this station alone is not representative of the entire study section. The usefulness of the NOAA gage is also limited because the location has been moved several times during the study period, none of the sites has been sufficiently protected from the wind, no wind shield has been used, and there are periods of missing data. Unfortunately, the gage was not in operation during the 1970-1971 winter when the highway was first opened to traffic.

For these reasons, recording precipitation gages have been maintained at three locations along the highway since September 1971 (Figure 1). These gages are equipped with wind shields and are also located in small openings in groves of trees to reduce undermeasurement caused by wind. We believe that these sites furnish exceptionally accurate precipitation measurements and provide a reasonable estimate for precipitation along the study section.

A linear regression was used to estimate precipitation for the 1970-1971 winter by using the mean values from these gages with the mean of NOAA weather stations at Leo, Rawlins, and Laramie for the winters of 1971-1972 through 1980-1981. This analysis provided an estimate having a 0.95 confidence interval of ±11 percent of the estimated mean.

In addition to the precipitation-gage network, the Wyoming State Highway Department also operates weather-condition monitoring stations (Figure 1) by using instrumentation developed by Schmidt (6). Wind-speed and visual-range data are transmitted

from these locations to the district maintenance office in Laramie, where they are recorded on strip charts and analyzed by an on-line computer (7). These stations are the source of the wind data in Table 1 and are also used for the traffic operations decisions discussed later in this paper.

Snow- and Ice-Removal Expenditures

Maintenance for the highway in the study section is provided by several crews, which makes precise calculations impossible. Crews at Laramie provide winter maintenance from Mile 280.5 to 295, and it is not possible to isolate those expenditures on the study section. Consequently, snow- and ice-removal data used in this report are for Miles 235-280.5, which is served by maintenance crews stationed at Arlington and Elk Mountain; the length of highway protected by fencing for the analysis of snow- and ice-removal costs is different from that used for the accident analysis.

Snow- and ice-removal expenditures were difficult to retrieve and suffer from several deficiencies. Although the maintenance station at Elk Mountain was in operation by September 1970, the Arlington station was not built until July 1971. Much of the snow-removal work the first winter was done by crews stationed at Laramie and Rawlins, which makes it difficult to separate expenses incurred on the study section. Charges for special heavy equipment to clear the larger drifts were identifiable, however, and constitute most of the expenditures for the study section during calendar year 1971. Maintenance crews from Laramie and Rawlins have continued to help the Arlington and Elk Mountain crews on special occasions, and these expenses cannot be identified from accounting records.

Calendar-year accounting was used until June 1973, which makes it impossible to separate expenses by the winter in which they were incurred. Fiscal-year accounting was instituted in 1973, and records were computerized by fiscal year 1977. The 1975-1976 winter was the only one for which maintenance costs could not be retrieved for this study.

To account for the effects of inflation over the analysis period, snow-removal expenditures for the Arlington-Elk Mountain maintenance sections were expressed in relation to expenditures for the remainder of Wyoming I-80 (about 550 km). This ratio is essentially independent of inflation and should partly adjust for annual variations in snowfall.

Snow-Fence Protection

Snow-fence protection was measured on aerial photographs as the road length between lines parallel to the prevailing winter wind direction drawn from the ends of the fences. Wind directions are known for all fence locations from preconstruction studies that measured orientation of snowdrifts shown on aerial photographs. No adjustment was made for the poorer efficiency near the ends of the snow fences (3,4).

RESULTS

Snow- and Ice-Removal Expenditures

Snow- and ice-removal expenditures and snow-fence protection are shown in Table 3 and Figure 3. For the reasons discussed previously, costs for the study section in the first half of the 1970-1971 winter are unknown, and the calendar-year accounting combines the last half of 1970-1971 with the first half of the 1971-1972 winter, by which time more than half of the first contract had been installed. Despite this complication and the fact that an appreciable portion of the costs on the study section are not included, snow- and ice-removal costs in calendar year 1971 were about 50 percent higher than the average over succeeding years. For calendar year 1972 through fiscal year 1981, the ratio of expenditures on the study section to those on the rest of I-80 was 0.31 ± 0.10, with a 0.999 confidence interval. There is little doubt that the decrease from the calendar year 1971 value of 0.48 was caused by the snow fences built under the first contract, which comprised 35 percent of the total system.

There is no significant further decrease in costs as additional fences were built, but this is to be expected because the first contract protected all sites where snowdrifts formed in traffic lanes the first winter; subsequent contracts have been primarily to improve visibility and protect structures.

The data suggest that the fences reduced snow- and ice-removal costs by at least a third and, considering the conservative nature of the 1971 data, the actual reduction was probably closer to 50 percent. Visual observations over the study period, as documented by photographs such as Figures 4-6, support the conclusion that the fence systems have eliminated drifts on the traffic lanes, even in years of record precipitation.

Road Closures

The most common reason for closing the highway to traffic is poor visibility caused by blowing snow. Occasionally, however, closure is necessitated by intense snowfall that accumulates faster than plows can remove it or because of an excessive number of accidents.

Road-closure data for 1970-1981 are included in Table 4. As shown in Figure 7, the fences had no apparent effect on the amount of time the highway had to be closed to traffic. The variability in closure time suggests that normalizing this variable with respect to total precipitation does not account for all the yearly differences in weather conditions, but, in addition, closure decisions are often largely subjective, which in itself contributes to the year-to-year variability.

A reasonable explanation for the apparent failure of the fences to reduce closure time is that poor visibility in even a short section of unfenced highway could necessitate closure of the road, which suggests that fence protection might have to approach 100 percent before a reduction in closure time could be expected.

Accidents

Accidents by categories, snow-fence protection, and supporting data for 1970-1981 are shown in Table 4. As shown in Figure 8, snow accidents were independent of the degree of fence protection, and this was also true for "other" accidents. This is to be expected, by definition of these weather-condition categories. In Figure 6, accident frequency for the first two categories is expressed per centimeter of precipitation from October 1 to April 30.

Ground blizzard accidents, however, have been reduced significantly (Figure 8). Although there is some suggestion of a convex curvilinear relationship, the residual variance is reduced very little by any transcendental transformation, and it is difficult to justify a particular model on theoretical grounds. The curve might be expected to level out at some accident frequency greater than zero as 100 percent protection was approached, but there is no indication that such a plateau has been reached

Table 3. Expenditures for snow and ice removal, Miles 235-280.5, Wyoming I-80.

Period	Snow-Fence Protection (%)	Expenditure ($)		
		Mile 235-Mile 280.5	Remainder of I-80	Ratio
Jan. 1-Dec. 30, 1970	0	–	–	–
Jan. 1-Dec. 30, 1971	4.54	235 800	489 485	0.482
Jan. 1-Dec. 30, 1972	12.82	104 147	393 177	0.265
Jan. 1-June 30, 1973	16.55	137 055	360 613	0.380
1973-1974 winter	32.34	175 442	604 979	0.290
1974-1975 winter (to Feb. 1)	36.71	53 710	219 634	0.245
1975-1976 winter	40.20	–	–	–
1976-1977 winter	40.20	118 729	294 597	0.403
1977-1978 winter	44.04	227 184	623 397	0.364
1978-1979 winter	53.17	297 777	856 804	0.348
1979-1980 winter	53.17	345 580	1 141 134	0.303
1980-1981 winter	53.17	137 240	574 315	0.239

Figure 3. Expenditures for snow and ice removal (Miles 235-280.5 to remainder of I-80) versus snow-fence protection.

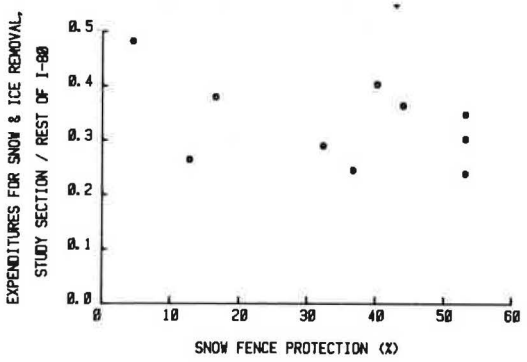


Figure 4. Snow accumulation at Mile 269.5 on Feb. 19, 1971, before installation of snow fences.

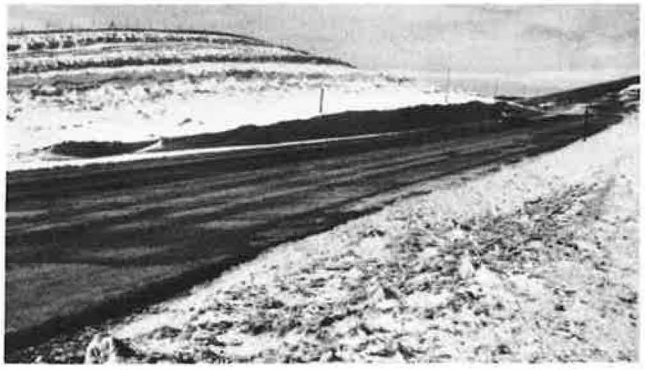
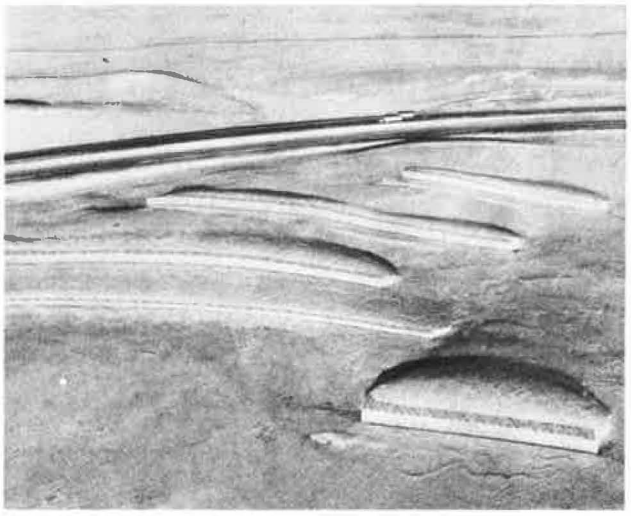


Figure 5. Snow accumulation at Mile 269.5 on Feb. 1, 1972, after installation of snow fences.

Figure 6. Aerial view of system protecting cut at Mile 269.5 on Feb. 11, 1972.



with the current level of fence protection. The data provide little justification for choosing a curvilinear model, which leads us to fit the following linear regression:

$$G/P = 0.0281 - 0.000\,39X, X \leq 51 \quad (R^2 = 0.62; SE = 0.001\,65) \quad (1)$$

where

- G = number of ground blizzard accidents per million vehicle kilometers,
- P = precipitation from October 1 to April 30 (cm), and
- X = fence protection in percentage of total study section length.

This regression indicates that ground blizzard accidents have been reduced about 70 percent with the current level (51 percent) of fence protection. Expressing the accident frequency in terms of precipitation improves the correlation, but the regression between X and G alone also shows a significant decrease in ground blizzard accidents.

Another test that does not require normalization with respect to precipitation is the ratio of ground

Table 4. Road-closure data, Oct. 1 to April 30, 1970-1981, Wyoming I-80, Miles 235-295.

Winter	Snow-Fence Protection (%)	Total Vehicles	Precipitation (cm)	Time Closed (days)	Accidents[a]					Valuation per Accident ($)
					Total	Snow	Ground Blizzard	Wind	Other	
1970-1971	0	683 020	32.3 ± 3.6	8.4	148 (110)	32 (18)	55 (48)	27 (20)	34 (24)	1301
1971-1972	7.54	662 655	28.4	6.2	128 (57)	12 (4)	41 (27)	54 (21)	21 (5)	1683
1972-1973	13.20	527 043	45.9	14.8	187 (101)	28 (18)	62 (36)	40 (19)	57 (28)	1180
1973-1974	28.21	554 560	32.8	7.8	132 (70)	17 (9)	36 (25)	52 (24)	27 (12)	1639
1974-1975	31.52	666 669	28.4	5.3	94 (52)	20 (25)	25 (3)	28 (12)	21 (12)	1763
1975-1976	34.17	708 192	30.6	4.4	140 (66)	20 (10)	52 (28)	38 (12)	30 (16)	1236
1976-1977	34.17	818 456	22.6	1.5	84 (59)	20 (20)	13 (11)	7 (7)	44 (21)	1711
1977-1978	37.08	857 638	25.4	4.8	133 (82)	23 (10)	27 (14)	36 (22)	47 (36)	1846
1978-1979	44.00	941 716	35.0	9.4	145 (85)	24 (10)	49 (32)	30 (19)	42 (24)	2930
1979-1980	50.95	779 443	41.4	15.6	163 (88)	33 (16)	29 (26)	43 (15)	58 (31)	2994
1980-1981	50.95	920 676	18.8	0.7	61 (53)	20 (16)	2 (4)	7 (5)	32 (28)	3041

[a]Injuries plus fatalities are shown in parentheses.

Figure 7. Days of road closure per centimeter of precipitation Oct. 1 to April 30 versus percentage of highway protected by snow fence.

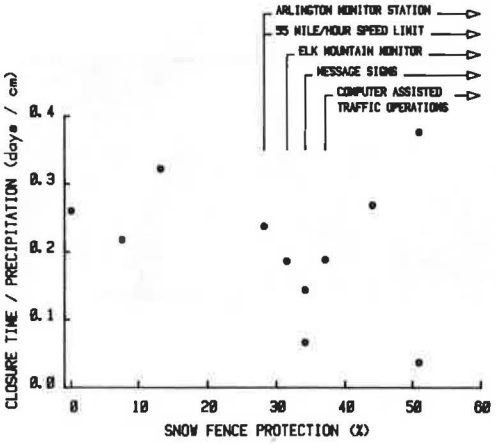
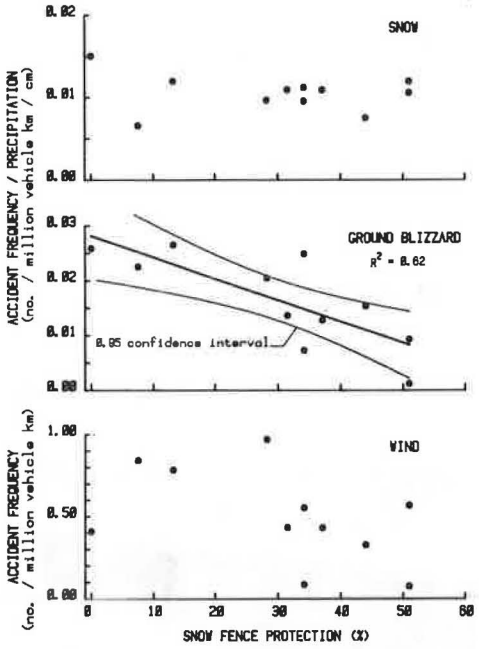


Figure 8. Snow, ground blizzard, and wind accidents in relation to percentage of highway protected by snow fence.



blizzard accidents to "other" (O) accidents. A linear regression fitted to these data is given as follows:

$$G/O = 1.8134 - 0.0254X, X \leq 51 \ (R^2 = 0.49) \quad (2)$$

This relationship also suggests a 70 percent reduction in ground blizzard accidents with the current level of fence protection.

The reduction in this category of accidents is to be expected, considering the dramatic improvement in visibility observed in the areas protected by snow fences (Figures 9-11). There is also a general improvement in road-surface conditions downwind of the fences (Figure 12) caused by a reduction in snow transport across the road, which reduces heat loss and slush accumulation during periods of sunshine with air temperature above -5°C. A dark road surface provides much better delineation than a snow- or ice-covered surface under conditions of reduced visibility. All these effects contribute to the reduction in ground blizzard accidents.

It should be noted that precipitation over the 1972-1973 winter (13 percent protection) was the highest since records were begun in 1906 at Elk Mountain, and the 1978-1979 winter was the fifth highest on record.

Were it not for the anomalous value for the 1970-1971 winter, there would also be a significant reduction in the frequency of wind accidents over the study period. The relatively low number of accidents in this category over the first winter may be due to the fact that before the first fences were installed there was reduced opportunity for wind accidents because of the prevalence of blowing snow. If it were reasonable to exclude the 1970-1971 data for this reason, the linear regression relating the frequency of wind accidents (W) to fence protection would be as follows:

$$W = 0.9656 - 0.0137X, 0 < X \leq 51 \ (R^2 = 0.43) \quad (3)$$

If this effect were real, it could reflect the improvement in road-surface conditions that contribute to wind accidents. There is also some evidence that wind speeds on the roadway are significantly reduced downwind of the snow fences. In March 1979, Tabler measured wind profiles (in the first 10 m above the ground) upwind and downwind of a 3.78-m snow fence nearly filled to capacity with snow. On the highway at 190 m (50H) downwind of the fence, mean horizontal wind speed up to the 3.4-m height averaged about 14 percent less than that of the wind measured simultaneously at 134 m upwind of the fence (ambient 10-m wind averaged 20 m/s). This would

Figure 9. Aerial view of two rows of 3.78-m snow fence showing effect of fences on visibility (Mile 263, Feb. 11, 1972).

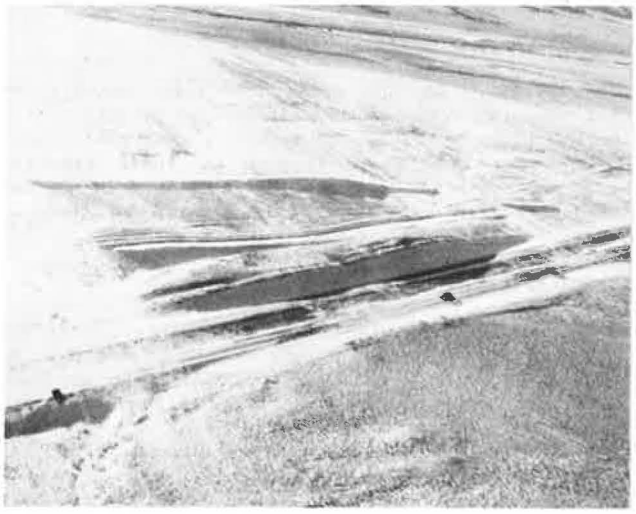


Figure 10. Visibility 70 m outside area protected by two rows of 3.78-m snow fence (Mile 262, Feb. 15, 1972).

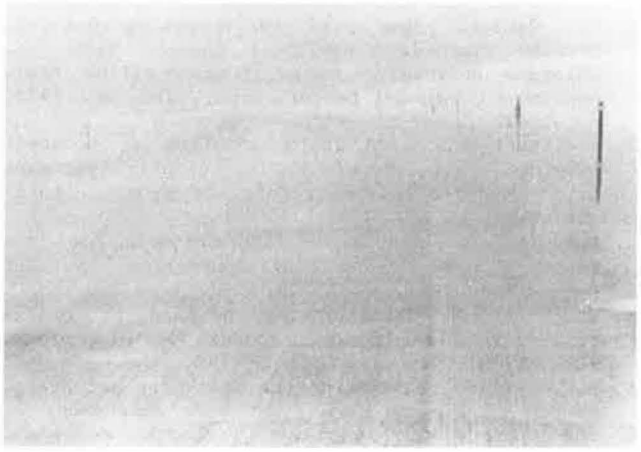
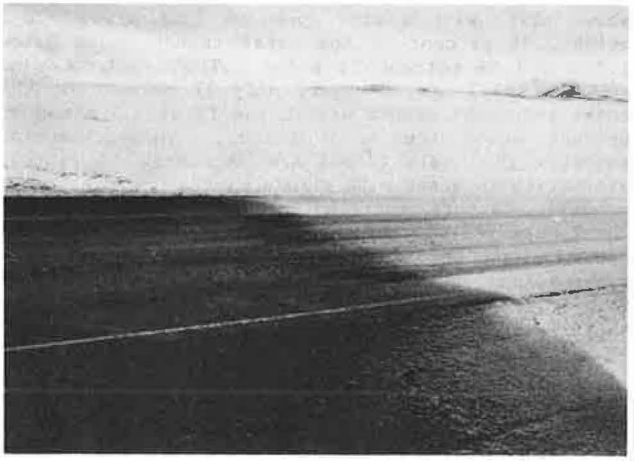


Figure 11. Visibility of same area as in Figure 10 inside area protected by two rows of 3.78-m snow fence.

Figure 12. Effect of single row of 3.78-m snow fence on road-surface conditions; end corner of fence extending left near center; most of fence hidden behind lee drift (Mile 247.6, March 22, 1973).



imply a reduction of about 25 percent in wind load on a standard tractor-trailer combination. The reduction in wind speed may be even greater before a fence fills with snow, but these data are not yet available.

DISCUSSION AND CONCLUSIONS

Representativeness of Study Period

Average winter precipitation from 1970 to 1981 at our Elk Mountain gage (23.7 cm) was comparable with that from 1906 to 1969 published for the NOAA station at Elk Mountain (21.5 cm). Precipitation over the 1972-1973 winter (39.8 cm) exceeded the previous maximum (36.3 cm) recorded over the winter of 1916-1917. Precipitation in 1979-1980 was the fifth highest on record. We conclude that the study period included winters as severe as any in the last 75 years and was representative of long-term precipitation to be expected over the study section.

Effect of Other Safety Measures

The snow fences have not been the only step taken to improve highway safety on this section of I-80. The first weather-monitoring station (as described previously) was installed in January 1974, and a second was in operation by January 1975. Since the on-line computer for analysis of these data was installed during the 1977-1978 winter, standardized criteria have been available to the maintenance foremen who make decisions relative to road closure.

In March 1976, overhead variable-message signs were installed at Laramie and Walcott, where traffic can be stopped or rerouted as conditions require. Optional automatic computer control of these signs was available for the 1978-1979 winter. A motorist information low-power radio system was also in operation from 1976 to 1978.

All these measures could contribute to the reduction in accidents, but two pieces of evidence suggest that the effect was due largely to the snow fences. First, the efficacy of these other measures should be reflected in the frequency of snow accidents, which was shown to be independent of fence protection. The absence of any significant decrease in snow-accident frequency over the 1970-1981 period suggests that the snow fences were primarily responsible for the reduction in the ground blizzard and wind accidents. Second, the downward trend in

ground blizzard accidents was evident prior to the institution of these other measures, although the other safety aids may contribute to the more marked reduction evident in the last five years.

The 55-mile/h (89-km/h) speed limit went into effect on March 4, 1974. This would not be expected to influence the snow or ground blizzard categories but could have some effect on the frequency of wind and other accidents when road-surface conditions were conducive to high-speed driving.

Factors Contributing to Fence Effectiveness

Improved visibility and more favorable road-surface conditions in areas protected by snow fences are considered to be the primary reasons for accident reduction on the study section. In turn, these favorable effects are only possible because of the adequate design of the fence systems. A primary requirement for these effects to be realized is that the fence systems have sufficient capacity to store all snow transported over a winter with average precipitation.

Although most of the snow transport is within the first meter above the ground, a significant portion is carried at greater heights; the vertical distribution of blowing snow becomes more uniform as wind speed increases. Our analysis of Antarctic data (8) shows that, with a wind speed of 11.6 m/s at 10-m height, 95 percent of the total transport is below 1.2 m and 99 percent is below 3.7 m. With a wind speed of 22.3 m/s, however, only 77 percent of the total transport occurs within the first 1.2 m and 95 percent below the 3.7-m height. This reasoning suggests that tall fences are necessary to improve visibility in areas with strong winds.

Other factors contributing to effectiveness of the fences include the structural design itself, the use of long fences without holes or gaps in the systems, and optimum fence placement.

Amortization of Fence Construction Costs

If snow- and ice-removal costs are assumed to be reduced by one-third, the total savings in the last five years (when costs are most accurately known) is $563 000. This suggests that the cost of fence construction is easily amortized over their anticipated physical life (≥25 years) by the savings in expenditures for winter maintenance.

For a winter with average precipitation and current traffic levels, 23 ground blizzard accidents are expected with the current level of fence protection (51 percent) compared with 77 without fencing (Equation 1). The average property-damage valuation per accident has been about $3000 over the last three years. If the entire fence system were rebuilt at 1979 contract prices, then construction cost could be amortized in about 15 years by the reduced accident damage alone. The average number of injuries plus fatalities per ground blizzard accident has been 0.65, which implies that over the average winter, 35 injuries are also prevented. This represents a further economic benefit as well as a humanitarian one. Inclusion of the possible reduction in wind accidents would further shorten the repayment period.

CONCLUSION

The experience on this section of I-80 demonstrates that properly designed snow fences can significantly improve highway safety and reduce winter maintenance costs. For conditions similar to those reported here, it appears that construction costs of an extensive system can be amortized in less than 10 years.

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This paper is dedicated to the maintenance personnel and patrolmen on the Arlington-Elk Mountain section, who have served the public with unexcelled dedication and self-sacrifice.

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