Safety Effects of Icy Curve Warning Systems

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ABSTRACT

The California Department of Transportation (Caltrans) deployed an Icy Curve Warning System (ICWS) on a five-mile section of State Route (SR) 36 in Lassen County over Fredonyer Pass. This section of roadway had a history as a high-crash location, with multiple fatal crashes. The vast majority of these accidents occurred when the pavement was icy, despite static signage that Caltrans had installed to increase motorist awareness.

This study presents the results of research that investigated safety effects of the ICWS. An observational before-after study method with Empirical Bayes technique was used to determine the effect the ICWS on crash frequencies. The results showed that the ICWS reduced annual crashes by 18%. Moreover, analysis of ice-related accidents during winter seasons found that the ICWS had reduced crash severities on this roadway section. Based on these results, a benefit analysis revealed that the ICWS provided an estimated monetary benefit of $1.7 million dollars per winter season to motorists through reduced crashes. The study results are anticipated to contribute to a better understanding of safety effects of ice (or icy curve) warning systems and increase the knowledge base of weather-specific treatments and their associated effects.

INTRODUCTION

Weather has significant safety impacts on the roadway system. More than 1.5 million weather-related crashes occur in the United States every year, resulting in 690,000 injuries and 7,400 fatalities (*1*). Slippery conditions, especially icy pavements, can significantly reduce the coefficient of friction between automobile tires and road surfaces, and impair the ability of drivers to operate their vehicles safely. Improving traffic safety under icy conditions is of importance to many state transportation departments.

Static ice warning signs (i.e. fixed metal signs) have been widely used by states with the intent to reduce ice-related accidents. In 1998, a national survey found that only nine states did not use ice warning signs (*2*). Carson and Mannering (*3*) conducted a study to evaluate the effectiveness of static ice warning signs in Washington State. It was found that such signs did not have a statistically significant impact on the frequency or severity of vehicular accidents that involved ice. This could have been primarily due to two facts. First, ice formation is a complex process that is both time and location dependent (*3*). It can form in localized areas (e.g., bridges, shaded areas), which makes it unpredictable and historical climatic data are of minimal use in the prediction of localized icing without the presence of pavement sensors. Second, many ice-warning signs were posted at inappropriate locations where ice was rarely present, desensitizing drivers to the potential danger. The study suggested that there was a need for standardized sign-placement procedures to reduce the frequency and severity of ice-related accidents (*3*).

Limited studies were identified on the safety effects of ice warning systems that use road and weather sensors to gather information and predict the formation of ice. Conceptually, ice warning systems should be more effective than static ice warning signs as they are installed at problematic areas (where ice formation is known to be recurring) and are able to detect or predict ice formation in localized areas. An ice warning system was deployed in 2005 along a 20-mile corridor of Oregon Highway 140 to actively warn motorists of potentially icy driving conditions (*4*). The system consists consisted of a Road Weather Information System (RWIS) near the summit of the Lake of the Woods Pass. The RWIS is linked to two static signs with flashing beacons that were activated when icy conditions were present. The flashing beacons are activated when threshold conditions at the RWIS site are met (generally a combination of pavement temperature, humidity and indication of wet pavement status) (*4*). Crash data including two winter seasons prior to system installation and three seasons after the installation were used to evaluate safety effects of this system. A naive (simple) before-after study method which only examined the number of crashes per winter season was used to evaluate safety effects of the system. Results revealed that there was no apparent reduction in crashes since the installation of the warning system.

The California Department of Transportation (Caltrans) has deployed an Icy Curve Warning System (ICWS) on a five-mile segment of State Route (SR) 36 in Lassen County. This section of roadway has a history as a high-crash location involved with multiple fatal crashes. The vast majority of these accidents have occurred when the pavement is icy, despite static signage that Caltrans has installed to increase motorist awareness. The objective of this study is to evaluate safety effects of the ICWS. In addition to a better understanding of the impacts of ICWS on traffic safety, it is anticipated that the findings of this study will provide useful information for the deployment of similar systems in the future, either by Caltrans or other state transportation departments.

BACKGROUND

Safety is a critical component of the Caltrans' vision to have "the safest, best managed, seamless transportation system in the world." Consequently, one of Caltrans' ongoing activities is to identify and remedy safety challenges in its infrastructure. This is especially pressing for locations where there have been an above-average number of crashes with injuries and fatalities. One such location identified by Caltrans District 2, located in northeastern California, is a five-mile segment of SR 36 in Lassen County over Fredonyer Pass.

Based on the crash history along the identified roadway segment, Caltrans deployed an ICWS to reduce ice-related accidents. Advances in technology have permitted Caltrans to employ an improved method for warning motorists. The technology consists of using pavement sensors to detect icy conditions, in combination with dynamically activated signage, to provide motorists with real-time warning when icy conditions are present. This system is collectively known as the Fredonyer Pass ICWS, and consists of two identical but separate warning systems: Fredonyer Summit ICWS and Fredonyer East ICWS. The schematic of Fredonyer Pass ICWS is shown in Figure 1.

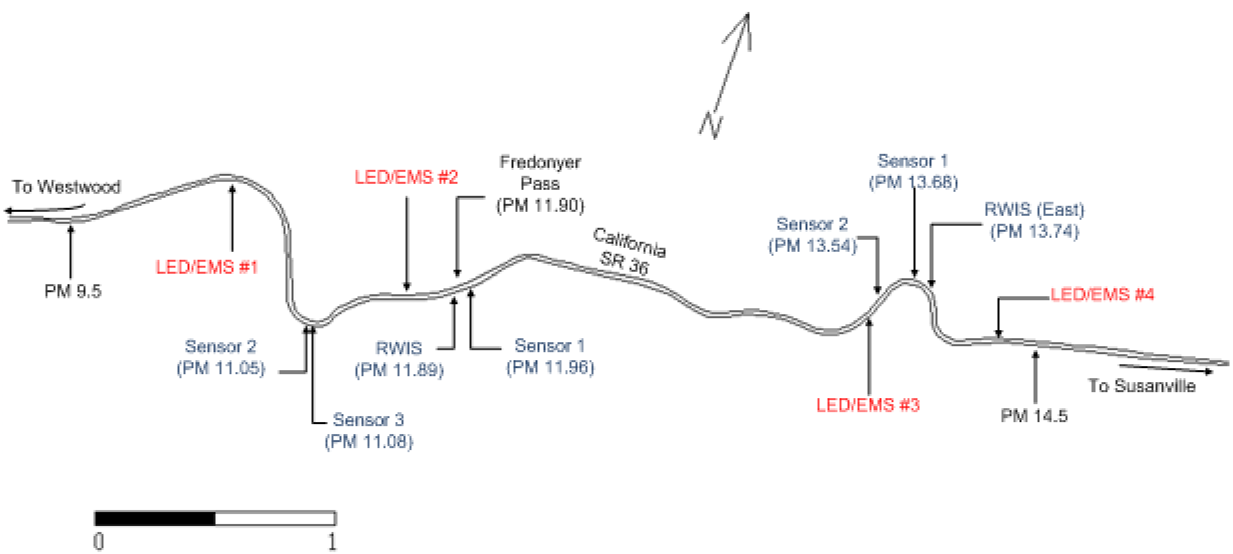

Figure 1 Schematic of the Fredonyer Pass ICWS

The five-mile highway section starts at Post Mile (PM) 9.5 and ends at PM 14.5. Two Extinguishable Message Signs (EMS) are used in each direction of travel to warn motorists of icy conditions. The EMS' are similar to Changeable Message Signs (CMS), with only a fixed set of messages which read "Icy Curves Ahead" when icy conditions are detected. Three ice detection sensors were installed for the Fredonyer Summit system. Sensor 1 is located just east of the RWIS location, basically at the top of the grade. Sensors 2 and 3 are located in a curve that tends to stay wet much more than Sensor 1 due to the trees present on both sides of the road. On the Fredonyer East system, two ice sensors were deployed. Sensor 1 is just west of the RWIS location and is in a clear zone. Sensor 2 is about 740 feet west of Sensor 1 and is in a location shaded by trees. For each system, the two EMS will be activated if ice is detected or predicted by one of the ice and RWIS sensors.

Installation, calibration and testing of the system began in the summer of 2002 and concluded in the summer of 2008. A significant period of this time was spent testing and validating the system to ensure that the various weather and roadway conditions were properly accounted for by the system. Consequently, the ICWS was not considered fully operational and reliable until the winter season of 2008-2009. As a result of this period, where different components of the system were present but the entire system was not fully operational, only accident data from the summer of 2008 onward was considered to be a part of the "after" period in this work. It was viewed that this data reflected the true operational nature of the system and its impacts on safety following deployment.

Table 1 shows the geometrics of the five-mile highway section. This section is divided into seven segments based on the total number of lanes present and speed limit. A passing lane is present in the eastbound (EB) direction between PM 9.50 and PM 12.27; another passing lane is present in the westbound (WB) direction between PM 11.76 and PM 14.50. The shoulder type of the whole highway section is gravel/cinders. Speed limits are lower within the two major curves where the ICWS' were deployed.

Table 1 Geometrics of the Highway Section

Seg. No.	PM (Begin)	PM (End)	Seg. Length	Lane Width	Total Lanes	No. of Lanes (EB)	No. of Lanes (WB)	Should Width	Speed Limit
1	9.50	10.35	0.85	13	3	2	1	5	55
2	10.35	11.26	0.91	13	3	2	1	5	40
3	11.26	11.76	0.50	13	3	2	1	5	55
4	11.76	12.27	0.51	13	4	2	2	5	55
5	12.27	13.43	1.16	13	3	1	2	5	55
6	13.43	14.10	0.67	13	3	1	2	5	40
7	14.10	14.50	0.40	13	2	1	1	5	55

STUDY DATA

Study Period

As mentioned previously, there was a time period that the system was present but did not represent its final operational/deployment configuration. Hence, for safety evaluation presented here, it was important to decide what constituted the before and after period of the study. For this work, the before study period consisted of the time before the deployment of original ICWS. Since the system was not fully operational between the fall of 2002 and the spring of 2008, this time period was not included in the "after" deployment period. Consequently, 4.5 years of the before period (January 1, 1998 – June 30, 2002) and 1.5 years of the after period data (July 1, 2008 – December 31, 2009) were chosen for safety evaluation. (Note that crash data in 2010 were not available during this study due to lags in Caltrans' crash reporting database.)

Crash data were obtained from Caltrans's Traffic Accident Surveillance and Analysis System (TASAS) database and the Highway Safety Information System (HSIS) for the study period. Crash information included date and time, post mile, road surface condition, type of accident, etc., as summarized in Table 2. The total numbers of crashes were 56 and 18 for the before and after periods, respectively. Two fatal crashes occurred during the before period, on December 3, 1998 and March 7, 2002. The crash records show that both fatal crashes were under icy conditions. Moreover, among the total 74 crashes, 54 (73%) were involved with icy road conditions. It was found that all of the ice-related accidents happened during winter seasons (from October to March in the following year). Annual Average Daily Traffic (AADT) data were also gathered for the seven study years. Small variations in AADT were identified during the study period (Table 2).

Table 2 Summary of Crash and Traffic Data

Period	Year	No of Months	Crashes (ice-related)	PDO (ice-related)	Injury (ice-related)	Fatality (ice-related)	AADT
Before	1998	12	17	8 (5)	8 (5)	1 (1)	2850
	1999	12	9 (6)	9 (6)	0	0	2850
	2000	12	14 (10)	11 (9)	3 (1)	0	2850
	2001	12	8 (5)	5 (3)	3 (2)	0	2900
	2002	6	7 (6)	3 (2)	4 (3)	1 (1)	2950
After	2008	6	3 (3)	1 (1)	2 (2)	0	2850
	2009	12	9 (7)	7 (5)	2 (2)	0	2850

Note: PDO – Property Damage Only

Weather is another parameter that needed to be considered for this study. However, the RWIS and ice sensors that could provide site-specific information were installed after the before period; consequently, site-specific weather information was only available for the after period. To address the weather data gap in the before period, National Weather Service (NWS) stations close to the study location were sought. Unfortunately, no appropriate NWS station was identified which could provide data for this work. Two nearby NWS stations were deactivated in the 1950's. Other stations only had weather information available which corresponded to the after period. Hence, it was assumed that there was no significant climate change during the study period. Actually, this assumption is supported by a Caltrans's recent study (*5*), which found that although changes have occurred over time (1972 through 2008) in terms of precipitation received by county, these changes have not been significant.

METHODOLOGIES, DATA ANALYSIS, AND RESULTS

The purpose of this research was to investigate crash history before and after the deployment of the ICWS and determine if the system positively/negatively affected traffic safety. The impact of the ICWS on traffic safety can be twofold if it was effective. First, it may reduce the number of ice-related accidents as motorists drive more cautiously on icy pavements. Second, the system may help reduce the severity of accidents, again through reduced vehicle speeds. In light of this, the effects of the ICWS on ice-accident frequencies and severities were investigated.

Safety effects of the ICWS can be evaluated through an observational before-after study (*6*, *7*), which is used to determine the change in safety in terms of crash counts:

$$\boldsymbol{\delta = \pi - \lambda} \text{ or } \boldsymbol{\theta = \lambda / \pi} \quad (1)$$

Where:

δ = crash reduction (or increase);

θ = index of safety effectiveness;

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

λ = the number of reported crashes in the after period with the ICWS present.

Before-after studies can be grouped into three types: the simple (naïve) before-after study, the before-after study with control groups (the Comparison Group (C-G) method), and the before-after study using the Empirical Bayes (EB) technique. The selection of the study type is usually governed by the availability of the data, such as crashes and traffic flow, and whether the transportation safety analyst has access to entities that are part of the reference group. The selection can also be influenced by the amount of available data (or sample size). The EB method was employed in this work, as it has been shown to have better performance than both the naïve and the C-G methods (*6*) in addressing problems associated with these approaches (e.g., regression-to-mean (RTM), which is the potential for a high or low number of crashes to occur during any given year, but over time, for such crashes to hover around a mean annual figure), and appropriate selection of a before period. This technique has been effectively used in numerous traffic safety evaluations (*8*, *9*, *10*, *11*, *12*, *13*, *14*, *15*, *16*, *17*).

Observational Before-After Study with Empirical Bayes

In the EB before-after procedure, an important task is to estimate the number of crashes in the after period without the safety treatment (π), or in this case, had the ICWS not been present. As data from a reference group were not available, the Safety Performance Function (SPF) for rural two-lane, two-way roadway segments provided in the Highway Safety Manual (HSM) (*7*) was used, as denoted in Equation 2. The SPF was used to predict average crash frequency for base conditions (e.g., 12-feet lane width, 6-feet shoulder width, no horizontal or vertical curves).

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

where:

N_{spf} = predicted total crash frequency for roadway segment base conditions;
$AADT$ = annual average daily traffic (vehicles per day); and
L = length of roadway segment (miles)

Equation 2 is employed for predicting crash frequency for roadway segment base conditions. Crash Modification Factors (CMFs) must be applied to account for the effect of site-specific geometric design features. The HSM provides 12 CMFs for this purpose. Based on the existing geometrics of the Fredonyer Pass highway section, 6 CMFs need to be used. These CMFs included shoulder width and type, horizontal curves (length, radius, and presence or absence of spiral transitions), horizontal curves (superelevation), grades, passing lanes, and roadside design. The other 6 CMFs, including lane width, driveway density, and lighting were equal to 1.0. Most CMFs are easy to calculate based on the reference tables or equations provided in the HSM. The CMF for horizontal curves (length, radius, and spiral transitions) is worth noting, as the calculation of this CMF is more complex. This CMF is calculated by:

$$CMF_{hc} = \frac{(1.55*L_c)+\frac{80.2}{R}-(0.012*S)}{(1.55*L_c)} \tag{3}$$

where:

CMF_{hc} = crash modification factor for the effect of horizontal alignment on total crashes;
L_c = length of horizontal curve (miles) which includes spiral transitions, if present;

R = radius of curvature (feet); and
S = 1 if spiral curve is present, 0 if not present, and 0.5 if present at one but not both ends of the horizontal curve.

For the five-mile roadway section in this study, 15 horizontal curves were identified with varying radii and lengths. There were no spiral curves on this roadway section. Some of the circular curves were connected by short tangent segments (e.g., around 200 feet). In such cases, these curves were treated as a horizontal curve set. For each individual curve, the value of L_c used in Equation 3 is the total length of the compound curve set and R is the radius of the individual curve. The CMF for the consecutive curve set is the aggregated effect of individual curves: $CMF_{hcj} = \prod_{i=1}^{n} CMF_{ij}$, given n individual curves in the *j*th horizontal curve set. Based on the total number of lanes, speed limit and presence of horizontal curves, the whole roadway section was divided into 15 roadway segments (including 3 horizontal curve sets), based on the presence of curves, number of lanes, and speed limit. Table 3 shows segment numbers running from west to east and associated segment lengths. Note that those tangent segments having the same geometrics (number of lanes) and speed limit were combined as a longer segment for simplicity. Actually, this combination has statistical benefits, based on the value of the overdispersion parameter associated with Equation 2 determined by $k = 0.236/L$. As indicated in the HSM (*7*), the closer the value k is to zero, the more statistically reliable the SPF. Combing those tangent segments with same geometrics could improve the reliability of the predictive model.

The EB technique was used to estimate the expected crash frequency by combining the predictive model estimate with observed crash frequency. The expected crash frequency for an individual roadway segment is computed by:

$$N_{expected} = w * N_{predicted} + (1 - w) * N_{observed} \quad (4)$$

$$w = \frac{1}{1 + k * (\sum_{all\ study\ years} N_{predicted})} \quad (5)$$

where:

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

The results of the observational before-after study using the EB technique are presented in Table 3. The expected number of crashes was 14.08, with a standard deviation of 2.81 crashes. In the analysis, the weighted average *AADTs* was used for both before and after periods since there were small variations among the study years. As a result, the weighted average *AADTs* were 2,873 and 2,850 vehicles per day for the before and after periods, respectively.

Table 3 EB Analysis Results

Seg. No	Type of Seg.	Seg. Length (mile)	Observed Crashes during the Before Period	EB Estimated Crashes during the Before Period	Observed Crashes during the After Period (λ)	EB Estimated Crashes during the After Period (π)	Variance of π
1	Tangent	0.61	4	3.10	0	1.02	0.48
2	Horizontal Curve Set	1.05	6	5.07	0	1.68	0.81
3	Horizontal Curve	0.27	5	3.39	2	1.12	0.62
4	Horizontal Curve	0.21	2	1.46	0	0.48	0.24
5	Horizontal Curve	0.11	1	0.78	1	0.26	0.14
6	Tangent	0.35	0	0.64	0	0.21	0.09
7	Horizontal Curve	0.16	2	1.45	0	0.48	0.26
8	Tangent	0.55	5	3.44	1	1.14	0.53
9	Horizontal Curve	0.12	3	1.99	2	0.66	0.37
10	Horizontal Curve	0.11	6	4.33	1	1.43	0.96
11	Horizontal Curve Set	0.46	1	1.53	2	0.51	0.26
12	Horizontal Curve	0.14	8	5.54	1	1.83	1.18
13	Horizontal Curve Set	0.44	9	6.74	1	2.23	1.38
14	Tangent	0.24	3	2.18	0	0.72	0.39
15	Horizontal Curve	0.16	1	0.96	1	0.32	0.18
	Total	5.00	56	42.59	12	14.08	7.90

The results show that the EB estimated crashes during the before period were 42.59, which is lower than the observed crashes (56). This could have been due to RTM effect, more severe weather during the before period, and/or other confounding factors. The numbers of crashes that were not ice-related were 18 in the before period and only 2 in the after period. Most of the crashes which occurred between April and September were under dry pavement conditions. The crash rate of non ice-related accidents in the before period was higher than that in the after period. Thus, the crash rate in the before period might be higher than the normal rate and cause the RTM effect.

Based on the analysis results, the effect of the ICWS on accident frequency can be calculated. The index of effectiveness (θ) is calculated by $\theta = \lambda/\pi$ (Equation 1). However, as mentioned by Hauer (*6*), even if the expected values of accident counts are known, the estimate of θ is still biased, as there is a term of $1/\pi$ in the equation. For this reason, an approximate, unbiased estimate of θ was determined by (*6*):

$$\boldsymbol{\theta = \frac{\lambda/\pi}{1+Var(\pi)/\pi^2} = \frac{12/14.08}{1+7.9/14.08^2} = 0.82}$$

Interested readers are referred to Chapter 6 of the book by Hauer (*6*) for the derivation of the unbiased equation. The variance of θ was calculated by:

$$Var(\theta) = \frac{\theta^2 * (\frac{Var(\lambda)}{\lambda^2} + \frac{Var(\pi)}{\pi^2})}{(1+\frac{Var(\pi)}{\pi^2})} = 0.08$$

The value of θ indicates that the deployment of the Fredonyer Pass ICWS reduced the number of crashes by 18% during the after period for the five-mile roadway section. It is noted that the crash reduction factor (θ =0.82) applies to annual crashes, not only ice-related accidents during the winter season. This is one limitation of the HSM method, as the safety performance function in Equation 2 is only used for annual crash prediction. Hence, the 18% reduction annual crash is based on the assumption that there were no changes in crashes during the summer seasons of the study period when the system was off. It also is reasonable to conclude that the majority of reduced crashes can be attributed to the presence of the ICWS, as Caltrans records indicated that no other geometric or safety improvements were made to the roadway environment during the study period. While manned chain control was also used along the study route during the before and after period, the proportion of time such policies were in effect compared to the continuous presence and operation of the ICWS were minimal. Consequently, while manned chain control also contributes to the overall safety in the study area, its safety effect was assumed to remain the same during the before and after periods, and the continuous operation of the ICWS is believed to be a greater contributor to the estimated safety improvement.

So far, the evaluation has focused on the effect of the system on crash frequency and has not investigated its effect on crash severity. The HSM (*7*) does not provide SPFs for crash severity levels, but it does provide information about the default distribution for crash severity levels on rural two-lane, two-way roadway segments. The default distribution was developed based on data collected in Washington State. The proportions for severity levels and collision types may vary with jurisdictions, let alone a specific site that experienced high crashes. Thus, further analysis was conducted to investigate the crash rates for severity level, as described below.

Effect on Crash Severities

Based on the crash data provided in Table 1, the crash rates (ice-related crashes per winter season) for severity levels were calculated (Table 4). The crash rates in the before period were adjusted by $\frac{AADT_{after}}{AADT_{before}} = 0.99$ to compare with those in the after period. The results show that the crash rate for PDO crashes was reduced from 5.51 to 4.00 crashes per winter season. The crash rate for Injury crashes increased from 2.42 to 2.67 crashes per season, although it was actually reduced when looking at both injured and fatal rates together. Overall, it appears that the ICWS has reduced crash severities. This analysis, however, is similar to the naïve before-after study as it does not take RTM into account. The 4.5-year before period provides a reasonable duration for evaluation, but it would be better to have a longer duration of data (e.g., 3 years) for the after period.

Table 4 Ice-related Crash Rates by Severity Levels

Study Period	Total	Crash Rate (ice-related crashes per winter season)			
		PDO	Injury	Fatality	Fatality + Injury (F+I)
Before	8.38	5.51	2.42	0.44	2.86
After	6.67	4.00	2.67	0	2.67

Note: assume an AADT of 2,850 vehicles per year.

While additional data are necessary to draw more certain conclusions, it appears that the ICWS has provided benefits for motorists in terms of the improvement of traffic safety. The Federal Highway Administration (FHWA) provides information on motor vehicle accident costs by severity level based on the KABCO (K—fatal, A—incapacitating injury, B—evident injury, C—possible injury, and O—PDO) scale (*18*). The costs per fatal crash (K), evident injury (B), and PDO (O) are $2,600,000, $36,000, and $2,000 respectively in 1994. If these values are applied to Table 4, the total safety benefits of deployment the ICWS per winter season can be obtained. The safety benefit can be calculated by the following equation:

$$SB = \sum_{i=1}^{3}(Crash_{before}^{i} - Crash_{after}^{i}) * Cost_i \tag{6}$$

where:

SB = safety benefit ($);

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

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

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

A brief calculation found that the monetary safety benefit of the ICWS is approximately $1.7M per winter season (present value). The Consumer Price Index (CPI) inflation between 1994 and 2011 is 1.49, according to the Bureau of Labor Statistics (*19*).

DISCUSSION

Construction and other work zone activities on this study roadway segment could affect traffic safety. According to Caltrans' records, there was only one construction activity (extending and replacing existing culverts) that occurred between PM 6.7 and PM 10.4, starting on December 8, 2009 and continuing for a brief period. No vehicle crashes were identified within/around the construction work zone during this time. Hence, the safety evaluation of the ICWS was not influenced by construction activities.

Compared with ice warning signs and the Woods Pass ice warning system (*3*, *4*), the Fredonyer Pass ICWS appears to have produced greater effects on traffic safety. Bear in mind that the Oregon study employed a basic safety evaluation, as the focus of that project was an evaluation of vehicle speed and motorist survey data. This may be due in part to the technologies used in this case. In the ICWS, RWIS and ice sensors were deployed at several locations where ice was prone to developing, which could not only increased the accuracy of ice detection, but also reduced false alarm rates. Malfunction of a sensor did not significantly impact system performance. As a result, system reliability was improved. Moreover, the EMS signs of the ICWS were placed close to the curves where ice conditions were historically of concern. When the EMS were activated, motorists were likely to encounter ice within a short period. This was likely to increase motorists' confidence in the system. In the Woods Pass study (*4*), evidence showed that there were many days when the road conditions were dry and clear at the beacon sites, drivers traveled several miles before encountering ice. Thus, the design approach of the Fredonyer Pass system is also critical to the success of such ITS systems.

Across the country, many types of ITS have been deployed to reduce weather-related accidents. However, as noted in the HSM (*7*), knowledge regarding the quantitative effects of ITS on reducing weather-related accidents is limited. No Accident Modification Factors (AMFs) have been developed for weather issue treatments. Consequently, the results from this study are useful to have a better understanding of safety effects of ice (or icy curve) warning systems. While still a relatively recent deployment, the initial results from the Fredonyer Pass ICWS provide an understanding of the safety effects and benefits of ITS for addressing site-specific weather issues on rural highways.

CONCLUSION

This study presented the results of research that investigated safety effects of ICWS. An observational before-after study with EB technique was used to determine the effect of ICWS on crash frequencies. The results revealed that the deployment of the ICWS reduced the number of annual crashes by 18%, which corresponds to an AMF of 0.82. Furthermore, a crash rate method was used to investigate the effect of the ICWS on crash severities, with a focus on ice-related accidents. The results showed that the use of ICWS have reduced crash severities. As a result, the system has potentially provided safety benefits of $1.7 million dollars per winter season during the "after deployment" study period. It is anticipated that the study results will be useful for a better understanding of safety effects of ice (or icy curve) warning systems and the increase of knowledge base about weather-related treatments and their associated effects.

DISCLAIMER

The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data herein. The contents do not necessarily reflect the official views or policies of the State of California, the California Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. This report is not intended to replace existing Caltrans mandatory or advisory standards, nor the exercise of engineering judgment by licensed professionals.

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