Speed Impacts of an Icy Curve Warning System

David Veneziano Ph.D.
Western Transportation Institute
Montana State University
P.O. Box 174250
Bozeman, MT 59717-4250
Phone: (406) 994-6320, Fax: (406) 994-1697
Email: david.veneziano@coe.montana.edu

Zhirui Ye Ph.D. *
Western Transportation Institute
Montana State University
P.O. Box 174250
Bozeman, MT 59717-4250
Phone: (406) 994-7909, Fax: (406) 994-1697
Email: jared.ye@coe.montana.edu

Ian Turnbull P.E.
California Department of Transportation - District 2
1657 Riverside Drive
Redding, CA 96001
Phone: (530) 225-3320, Fax: (530) 225-3299
Email: ian_turnbull@dot.ca.gov

* Corresponding author

6,181 words
5 tables and figures = 1,250 words
7,431 words total

ABSTRACT

Weather has significant safety impacts on the roadway system. 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. To this end, the California Department of Transportation (Caltrans) has deployed an Icy Curve Warning System (ICWS) on a five-mile segment of State Route 36 in Lassen County. This section of roadway has a history as a high-crash location with fatal crashes, the vast majority of which occurred during icy pavement.

The objective of this study was to evaluate operational effects of the ICWS, specifically on speeds during various conditions. The results of statistical analysis found that mean speeds were significantly different by greater than 5 mph when the system was on versus off in general, as well as when examined by day and night. Mean speeds were significantly reduced by greater than 5 mph during wet weather (during day and night). The real interest of the evaluation was the system's impacts on reducing speeds during conditions when ice was present but unexpected (called clear, cold and not dry in this work). Statistical analysis found that mean speed reductions were significant by greater than 3 mph (but less than 5 mph) when the system was on both during the day and at night. Consequently, the ICWS appears to reduce speeds by approximately 3 mph in conditions where icy roads are unexpected.

INTRODUCTION

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. This section of roadway has a history as a high-crash location involved with multiple fatal crashes. Speeding has been a major cause of collisions that occurred in this roadway segment. The vast majority of these accidents have occurred when the pavement is icy, despite static signage that Caltrans has installed to increase motorist awareness.

Based on the crash history along the identified roadway segment, Caltrans deployed an Icy Curve Warning System (ICWS) to reduce ice-related accidents. 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 the ICWS is shown in Figure 1.

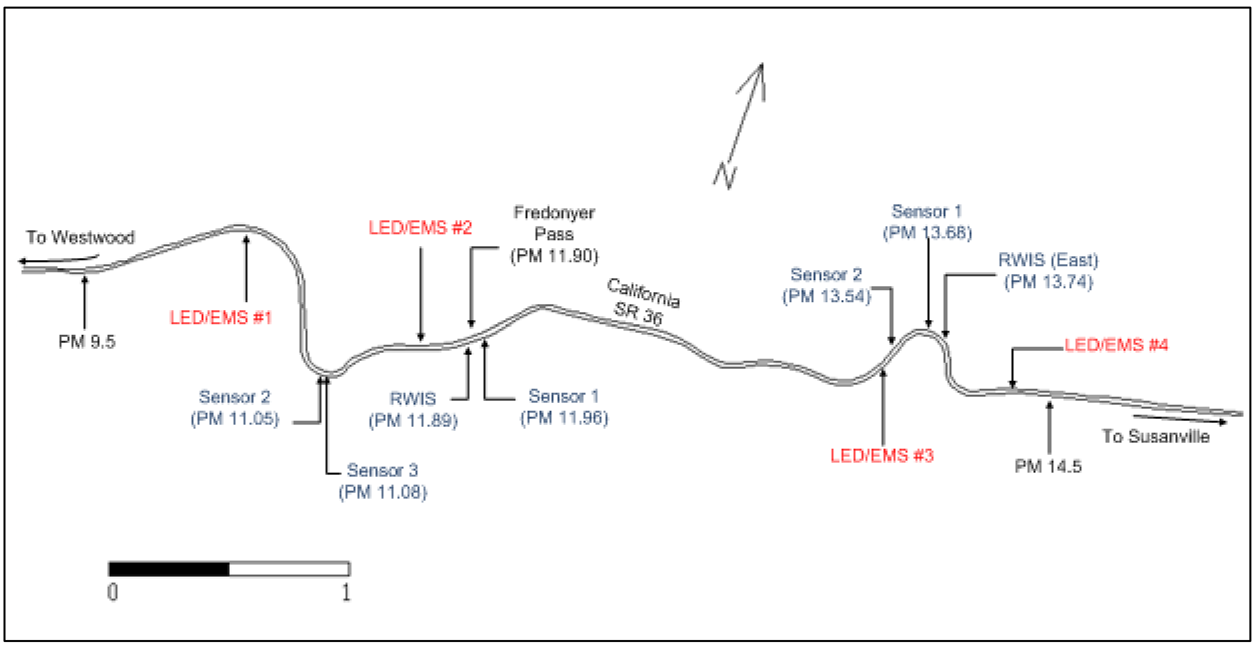

Figure 1 Schematic of the Fredonyer Pass ICWS

The five-mile highway section starts at Post Mile (PM) 9.5 and ends at PM 14.5 (Note: Post Mile is a term used by Caltrans for distance measurements from west and south to east and north starting at each county border.). Two Extinguishable Message Signs (EMS) are used in each direction of travel to warn motorists of icy conditions through a message stating "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 Environmental Sensor Station (ESS) 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 ESS 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 ESS sensors. The complete system was considered operational and reliable beginning with the winter season of 2008-2009.

The objective of this study was to evaluate operational effects of the ICWS. In addition to a better understanding of the impacts of ICWS on vehicle speeds, 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.

LITERATURE REVIEW

In evaluating the performance of the Fredonyer Pass ICWS, the effectiveness of similar systems deployed by other transportation agencies that sought to provide dynamic weather-based warnings to travelers via message signs was of interest. While many of these systems did not focus on warnings related to icy roadway conditions, their impacts on vehicle speeds were still of interest. Note that the focus of this review is on systems that employ message signs (variable message signs, dynamic message signs, etc.) to advise drivers of adverse weather/conditions. The exception to this is the Butte Creek Ice Warning System in Oregon, which was of interest given its focus on icy conditions.

In 2005, the Oregon Department of Transportation deployed an ice warning system along a segment of Oregon Highway 140 (1). The system (referred to as the Butte Creek Ice Warning System) employed an ESS and two static warning signs, located at mileposts 41.7 and 21.7, which read “Watch For Ice When Lights Flash Next 20 Miles”. These static signs were equipped with beacons which flashed when threshold conditions measured by the ESS were met. Threshold conditions included the presence of a combination of pavement temperature, humidity and wet pavement status.

An analysis of the system completed in 2009 examined its impact on vehicle speeds. To measure the changes on speeds that the system had, data were collected between September 13, 2007 and April 20, 2008. Data were collected at two locations; one at a point between the ice warning signs (a Wavetronix SmartSensor HD radar, milepost 35) and one outside the zone (an automatic traffic recorder site, milepost 16). In total, 19,838 hourly average speeds were collected. A full factorial analysis using a three way analysis of variance (ANOVA) was employed to account for directional, site (within or outside the ice-warning system segment) and beacon status factors. Results found that overall speeds were significantly lower when the beacons were flashing within the ice-warning system segment. Within the ice-warning segment, mean speeds fell by 9.5 miles per hour (mph) overall (eastbound fell by 10.4 mph and westbound by 8.4 mph). Speeds at the ATR sites were also observed to fall by approximately 1 mph, which were determined to be significant. Overall speeds were also significantly lower as measured in the ice warning segment compared to those of the ATR site. This was found to be the case regardless of the direction of travel and the system status (on/off). Additionally, when packed snow conditions were observed, average speeds at the ESS site were 43.4 mph compared to 52.6 mph at the ATR site, which was statistically significant. However, despite these findings, the researchers noted that it could not be conclusively determined from the data collected whether the beacons caused drivers to slow down or if poor road conditions caused motorists to drive more cautiously.

An ice warning system was installed in 2001 by the Wyoming Department of Transportation (WYDOT) to address a curved bridge prone to icing in Nugget Canyon(2). The basic system included an in-pavement sensor used in conjunction with atmospheric sensors, and in-field software to interpret the sensor data. Based on conditions, the system would determine if ice or frost was present and activate flashing beacons on an ice warning sign. As part of the deployment WYDOT installed traffic counters to record vehicle volumes, classifications, and speed at the site. It was found that motorist speeds dropped 5 to 10 miles per hour when the signs were on, and anecdotally there were no fatal crashes since the system was installed (as of 2005).

The Idaho Transportation Department deployed a storm warning system along Interstate 84 on the border of Utah and Idaho in 1993. It contained sensors to measure traffic, visibility, roadway, and weather data near the Cotterell, Idaho port-of-entry (3). The system included four Variable Message Signs (VMS) that provided information to motorists: two were used to provide direct information to the motorist while the others were used primarily by maintenance staff to close the interstate in severe weather. During the evaluation period, the system employed additional automatic traffic counters that recorded the lane number, time, speed, and length of each vehicle passing the sensor site. The effects of the VMS were found by comparing the results of data collected before and after VMS activation. The evaluation found that during periods of low visibility, when all other conditions were ideal, the signs did not have an apparent effect on driver speed, although only limited data were available for such conditions. When the signs were operational during periods of high winds and other extreme weather conditions, drivers in both directions reduced their speeds by 20 mph (3).

The Utah Department of Transportation installed VMSs in a fog prone area of Interstate 215 in Salt Lake City to reduce the risk of accidents during fog and other severe weather by advising drivers of the appropriate speed for real-time conditions (4). Sensors along the roadside continually evaluated visibility; the signs used a weighted algorithm to process visibility data and display messages that reflected the conditions. The mean speeds collected after the VMS signs were installed were found to be higher than the before installation period by 8 mph. When the speed information and standard deviation results were combined, results suggested that the slower drivers sped up. Standard deviation decreased from the before and after period by 22 percent. Overall, the researchers felt that the VMS helped in defining safe speed for drivers who would otherwise rely on their own judgment to gauge safe speeds.

Finally, the Finland Road Administration installed 36 variable speed limit signs along a 12-km long experimental section of Inter-Urban highway E18 beginning in 1992, as well as five variable message signs with the capability of displaying text messages, temperature, and three different sign legends: slippery road, general warning, and road construction (5). Two road weather stations recorded standard meteorological data and road surface conditions via imbedded sensors in the roadway, with conditions classified into three bins: good, moderate, and poor. A road running perpendicular to the experimental road served as a control road and was used to determine the effects of weather on traffic data. The system was evaluated using an analysis of the speed data from the experimental and control road. The effects of VMS were found by subtracting the effects of adverse road conditions from the total effects found from the experimental road. The researchers found that the mean effect of lowering the speed limit on the experimental test section from 60 mph to 50 mph was 2.11 mph due to the VMS system. When the symbol for slippery road was presented, the decrease in mean speed was 1.5 mph; under these conditions the decrease in mean speed on the control road was 6.03 mph. Through a separate analysis, it was found that the mean speed changes caused by the system were not sufficient to make the system socio-economically acceptable (6).

As the literature review indicates, previous ice and weather warning systems have examined system performance, but their results are not readily transferable to the ICWS discussed here. These studies have examined speed trends at a point location for a system targeted at a multiple mile length corridor (Butte Creek), focused on descriptive performance trends as opposed to statistical significance testing for a spot treatment (Wyoming), examined systems to address visibility rather than ice (Idaho, Utah), or focused on an idealized roadway segment as opposed to one with challenging geometrics (Finland). Consequently, there was a need for research that examined the impacts of an ice warning system applied to address site specific safety issues along a roadway with complex geometrics (curves and grades).

STUDY DATA

Continuous (24/7) speed data were collected and provided by Caltrans from each of the ICWS sign locations near the beginning of each set of curves. Data were available for the time periods of March 12, 2009 – April 15, 2009, October 1 2009 – March 31, 2010, and October 1, 2010 – April 15, 2011. Note that the data collection units first became active in March, 2009, which is why limited data were available from the initial period. Speed data were measured by radar units mounted to each of the ICWS EMS signs and aimed at the lanes of approaching traffic. Limitations in power availability at locations past these signs prevented the collection of data through each set of curves. Similarly, the use of tube counters was precluded in collecting speeds because of weather concerns (tubes being torn by maintenance equipment during storms). Data were recorded with a timestamp in a comma delimited file to a memory unit at each location and downloaded approximately once per month by Caltrans staff. The speed recorded by the system was the highest of a series measured for each approaching vehicle. Only vehicle speeds were collected; the system was not equipped to collect vehicle type/classification.

While the data from these locations represented vehicle speeds prior to entering each curve, the nature of the system (signs only displaying a message when the system is on) made it likely that most local motorists would already be slowing down after seeing an ice warning message displayed from an advanced distance. Consequently, the collected speed data represents the initial behaviors of motorists as they begin to enter each curve. If slower vehicle speeds were observed prior to entering the curves when the system was turned on, it would be reasonable to conclude that vehicles may be traveling slower throughout the length of the curve. Note that one limitation to this evaluation is that speed data were not available from the center of each curve, where vehicles, in theory, should be traveling slowest when an ice warning was posted.

Prior to beginning the statistical analysis, minor data cleanup was required. This included correction of timestamp errors, identification and removal of erroneous data (ex. continuous readings of the same speeds over a long period of time) and determination of missing periods of data (caused by brief power outages). The large sample sizes collected throughout each season at all locations were deemed sufficient to minimize the impacts of short headways and missing data on the analysis (with the exception of the March-April 2009 period in some cases).

METHODOLOGY

The two-sample t-test (unequal variance) was employed to perform the statistical comparisons of vehicle speeds between the different system conditions/states. An explanation of the t-test can be found in many statistical textbooks and is commonly known and understood, so it will not be presented here. Speed thresholds of zero miles per hour (mph), 3 mph and 5 mph were evaluated by this work. The hypotheses being tested for the zero mph condition were:

H_0: $\mu_1 = \mu_2$, indicating that the mean speeds between non-icy and icy conditions are not significantly different.

H_1: $\mu_1 \neq \mu_2$, indicating that the mean speeds are significantly different (ideally, the icy speeds being lower).

When examining whether mean speeds have changed by a significant value, for example 3 mph, similar hypotheses were employed:

H_0: $\mu_1 - \mu_2 \geq 3$ indicating that the difference between mean speeds of more than 3 mph was significant (ideally, the icy speeds being lower).

H_1: $\mu_1 - \mu_2 < 3$, indicating that the mean speeds between non-icy and icy conditions were not significantly different from one another at 3 mph.

To ensure the soundness of the conclusions drawn from the statistical tests, levels of significance corresponding to 0.025 and .05 were employed in evaluating the null hypothesis for the one- and two-tailed tests, respectively. A two-tailed test was employed for evaluating the hypotheses related to changes in speeds greater or less than 0 mph, while one-tailed tests were employed to evaluate the hypotheses that speed reductions when the system was operating were significantly greater than 3 mph and 5 mph. The critical value for these confidence levels was 1.96 (given large sample sizes). Based on the results of hypothesis testing, if vehicles showed statistically significant reductions in speeds between different conditions, this would indicate that the system is meeting the objective of warning motorists to slow down.

The evaluations performed during this work examined a number of conditions related to the system state, lighting conditions, weather conditions, and the presence of chain control on the route. The initial comparison examined on the system state, where the signage was either on or off. Following this high-level examination, speed differences were examined by the system state during the day and night. Thirdly, the system is intended to address specific roadway conditions (ex. ice formation during clear, cold and dry days), and the next evaluation focused on the different weather aspects, categorized by system state and time of day (day versus night). Finally, speeds under different levels of chain control during the day and night were examined. A general summary of the different evaluation scenarios and notes pertaining to them is presented in Table 1. Note that for brevity, only the results of the weather evaluations are presented in this work, as these summarize the true impact of the system on meeting the objective of providing ice warning to drivers when it may not be expected.

Table 1 Scenarios evaluated by the research

Evaluation Scenarios	Notes
On versus off	Comparison of speeds when system was on versus off only
Day versus night	Comparison of speeds when the system was on versus off during the day and night
Weather	Comparison of speeds when the system was on versus off during different weather conditions (wet, clear, cold and dry, etc.), categorized by day and night
Chain control	Comparison of speeds when the system was on versus off under different levels of chain control, categorized by day and night

RESULTS

System On Versus Off

The highest level of speed data comparison performed by this work examined whether vehicle speeds were significantly different when the ICWS was on versus when it was off. Aside from the March-April 2009 period (due to small sample sizes), mean speeds were found to be significantly different by greater than 5 mph when the system was on versus off. The mean speeds observed when the system was off ranged between 53 mph and 57 mph, depending on the site, while mean speeds when the system was on ranged between 45 mph and 50 mph. Given that only the general state of the system was examined in this initial evaluation, the results generated were expected.

Day Versus Night

In order to better understand the impacts of the ICWS under different conditions, mean speeds were evaluated between day and night for times when the system was on versus off. This analysis was performed to determine whether a significant change in speeds occurred when the system was on versus off during the day and night. In order to determine day versus night conditions, sunrise and sunset times for Susanville, California (approximately 10 miles east) were obtained for each day of data from http://www.sunrisesunset.com/. While this approach did not account for dusk and dawn periods where some limited daylight existed, it did serve to approximate light versus dark conditions. Given the extensive sample sizes of data available, this approximation was acceptable.

The statistical analyses found significant differences in mean speeds during both the day and night when the system was on versus off. With the exception of the first analysis period (March-April, 2009), these differences were significant by greater than 5 mph during both the day and night, suggesting that motorists tended to lower their speed when the ICWS signs were activated considerably. Observed mean speed reductions ranged between 5.19 mph and 8.66 mph during the day and 5.72 mph and 8.30 mph during the night. Of course, the inclusion of all data from the times when the signage was on did not present a completely clear picture of whether the system is warning motorists of ice during unexpected (e.g. clear, cold and not dry, or icy) conditions. One would expect motorists to drive significantly more slowly when bad weather conditions are present, which may be contributing to the significant speed reductions observed in this portion of the analysis. To truly understand whether the system is addressing motorist speeds in conditions where ice may not be expected (clear, cold and not dry) but is present, examination of speed data by system state, time of day and weather conditions in combination is necessary. This is presented in the next section.

Weather Conditions

One of the primary objectives of the Fredonyer Pass ICWS was to address crashes/speeding which occur during clear, cold and dry (i.e. no atmospheric precipitation) conditions. Such conditions consist of a clear, sunny day or evening with low or moderately low temperatures (slightly above freezing or lower) with no atmospheric precipitation. A driver was likely to travel at a higher speed in these conditions, as they do not expect to encounter an icy roadway. However, in the curve sections where the ICWS has been deployed, icy conditions may be present even at times expected to be clear, cold and seemingly dry. In detecting such conditions and providing drivers with a warning of the presence of ice ahead, one would expect to observe significantly different (lower) vehicle speeds compared to times when then system was off. If this was indeed the case, it may be concluded that the ICWS is likely performing its intended purpose.

To identify the different weather conditions at the site, ESS data were obtained from the Fredonyer Summit Pass station that also provides data used by the ICWS. These data were obtained via records maintained by WeatherShare (http://www.weathershare.org/). Two types of data were obtained, pavement surface temperature and condition (ex. wetness) data, as well as general weather data. All readings obtained for these elements had a timestamp associated with them, allowing conditions at that specific time to be matched with individual speed readings. Two lookup tables were set up in Excel and populated with the ESS data; one contained precipitation data, while the second contained surface temperature data. As the ICWS directly employs information regarding surface wetness, this element was not included as a lookup variable. Each individual speed record was matched to the weather conditions in the lookup tables that were present at the same time. Each of the different conditions variables associated with the individual speed reading were then classified by their respective scenario (see Table 2), which included wet, clear, cold and dry, and clear, cold and not dry, for both day and night. Note that Table 2 does not include wet conditions where precipitation was detected either during the day or night and for which the ICWS may or may not have been active; these scenarios were still evaluated however. In some cases, historical weather data were not available for a specific time period and was classified as “N/A”. Such data were eliminated from analysis, as it was not possible to definitively know what conditions were at that time. The elimination of these observations was not detrimental to the statistical analysis, given the large sample sizes available for each condition scenarios.

Table 2 Various weather scenarios identified for analysis

Time of Day	**Conditions**	
	Clear, Cold, and Dry	**Clear, Cold, but not Dry**
Daytime	• No precipitation • Surface Temp < 32F • Surface Status = Dry • ICWS is OFF	• No Precipitation • Surface Temp < 32F • ICWS is ON
Nighttime	• No precipitation • Surface Temp < 32F • Surface Status = Dry • ICWS is OFF	• No Precipitation • Surface Temp < 32F • ICWS is ON

Table 3 presents the results of the t-tests performed on mean speeds under precipitation conditions at each sign location. These conditions represent some of the weather events which were observed, namely snow. While the mean speeds of the initial March-April 2009 period saw varying significance (with significant speed changes greater than 5 mph observed only at Signs 3 and 4), the results of the two longer analysis periods were significant in all cases. From the fall of 2009 onward, mean speeds were significantly lower when the system was on by greater than 5 mph. In fact, the lowest difference in mean speeds observed during wet conditions was a drop of 6.20 mph when the system was on during daylight (Sign 4, 2009-2010). During the day, mean speeds during wet weather fell between 6.20 mph and 10.73 mph when the system was on. At night, mean speeds during wet weather fell between 10.34 mph and 16.14 mph when the system was on.

Table 3 Mean speed evaluation results: wet conditions

March 12, 2009 - April 15, 2009

	Site	Condition	Sample Size	Mean	Δ mph	t stat Δ of 0 mph @ 0.05 (1.96)	t stat Δ of 3 mph @ 0.025 (1.96)	t stat Δ of 5 mph @ 0.025 (1.96)
Precipitation	**Sign 1**	Off-Night	579	57.02				
		On-Night	135	56.58	0.44	0.75	-4.48	-7.97
		Off-Day	8630	56.64				
		On-Day	491	56.17	0.47	**2.33**	-12.64	-22.63
	Sign 2	Off-Night	357	55.37				
		On-Night	59	50.44	4.93	**5.07 (1)**	1.98 (2)	-0.07 (2)
		Off-Day	8949	57.20				
		On-Day	491	56.17	1.03	**5.06**	-9.64	-19.45
	Sign 3	Off-Night	727	55.14				
		On-Night	12	39.33	15.81	**7.58 (3)**	**6.14 (4)**	**5.18 (4)**
		Off-Day	10143	55.65				
		On-Day	140	46.29	9.36	**17.85 (5)**	**12.13 (6)**	**8.31 (6)**
	Sign 4	Off-Night	440	56.64				
		On-Night	6	39.33	17.31	**10.02 (2)**	**8.28 (7)**	**7.12 (7)**
		Off-Day	9006	58.52				
		On-Day	77	53.92	4.60	**5.14 (1)**	1.79 (2)	-0.44 (2)

October 1, 2009 - March 31, 2010

	Site	Condition	Sample Size	Mean	Δ mph	t stat Δ of 0 mph @ 0.05 (1.96)	t stat Δ of 3 mph @ 0.025 (1.96)	t stat Δ of 5 mph @ 0.025 (1.96)
Precipitation	**Sign 1**	Off-Night	12071	55.88				
		On-Night	3859	43.94	11.94	**93.37**	**69.90**	**54.26**
		Off-Day	48312	55.99				
		On-Day	12543	49.34	6.65	**93.08**	**51.10**	**23.12**
	Sign 2	Off-Night	15678	55.51				
		On-Night	2448	39.37	16.14	**100.11**	**81.51**	**69.11**
		Off-Day	49411	56.31				
		On-Day	7896	46.93	9.38	**80.25**	**54.57**	**37.41**
	Sign 3	Off-Night	22451	54.07				
		On-Night	2606	40.41	13.66	**88.94**	**69.41**	**56.38**
		Off-Day	68115	54.64				
		On-Day	14813	46.69	7.95	**119.54**	**74.41**	**44.31**
	Sign 4	Off-Night	28154	56.87				
		On-Night	4097	46.53	10.34	**75.02**	**53.27**	**38.77**
		Off-Day	66621	58.01				
		On-Day	11590	51.81	6.20	**78.18**	**40.36**	**15.15**

BOLD indicates significance

Table 3 cont'd Mean speed evaluation results: wet conditions

	Site	Condition	Sample Size	Mean	Δ mph	t stat Δ of 0 mph @ 0.05 (1.96)	t stat Δ of 3 mph @ 0.025 (1.96)	t stat Δ of 5 mph @ 0.025 (1.96)
Precipitation		Off-Night	7894	54.69				
		On-Night	4368	43.48	11.21	**80.17**	**58.71**	**44.40**
		Off-Day	50023	55.49				
	Sign 1	On-Day	10457	47.78	7.71	**95.59**	**58.40**	**33.61**
		Off-Night	11132	55.34				
		On-Night	3020	39.90	15.44	**101.97**	**82.15**	**68.94**
		Off-Day	51741	55.68				
	Sign 2	On-Day	7462	44.95	10.73	**93.87**	**67.61**	**50.11**
		Off-Night	10664	53.44				
		On-Night	2621	39.96	13.48	**85.54**	**66.51**	**53.82**
		Off-Day	40995	54.00				
	Sign 3	On-Day	7072	44.90	9.10	**92.99**	**62.34**	**41.91**
		Off-Night	22262	56.78				
		On-Night	4649	45.51	11.27	**84.48**	**61.99**	**46.99**
		Off-Day	63477	57.25				
	Sign 4	On-Day	9279	49.55	7.70	**83.69**	**51.08**	**29.33**

BOLD indicates significance
(1) Critical value = 1.98
(2) Critical value = 2.57
(3) Critical value = 2.20
(4) Critical value = 2.77
(5) Critical value = 1.97
(6) Critical value = 2.44
(7) Critical value = 3.18

The highest speed differences observed were during nighttime hours. This was not surprising, as one would expect that motorists would slow down more significantly during the night when visibility is lower and even further hampered by precipitation. Aside from the March-April 2009 period, all mean speed reductions observed were greater than 10 mph during night hours when the ICWS was on. Daytime speed reductions when the ICWS was on did not exceed 10 mph, with the exception of the October 2010 – April 2011 period at Sign 2. Of course, all of these speed reductions occurred during inclement conditions when motorists could be reasonably expected to slow down. Consequently, the reduced speeds observed may only be partly attributable to the ICWS.

In order to understand the true impact the ICWS may have on speeds, an examination of speed behaviors when inclement conditions are not present but ice has formed was necessary. These are the conditions where a motorist will not expect to encounter ice and where, if the warning posted by the ICWS was heeded, speeds for the on versus off system state should be significantly different. If the system was meeting its objective of effectively warning motorists to slow down at the target curves, significant drops in vehicle speeds should be observed in this portion of the analysis.

Examining the differences in speeds between clear, cold and dry versus clear, cold and not dry (i.e. icy) conditions at 0 mph provided varying results. Significant changes in mean speeds were observed between the on and off system states in almost all cases (the exceptions being three cases in the March-April 2009 period which included small sample sizes). As one would expect, larger differences in mean speeds were observed during nighttime periods, ranging from 2.76 mph to 6.36 mph. Daytime mean speeds also fell when the system was on, dropping by 2.91 mph to 6.80 mph (excluding the March-April 2009 period where small sample sizes yielded varying results).

Table 4 Mean speed evaluation results: clear, cold and dry/not dry conditions

March 12, 2009 - April 15, 2009								
Site	**Time**	**Condition**	**Sample Size**	**Mean**	**Δ mph**	**t stat Δ of 0 mph @ 0.05 (1.96)**	**t stat Δ of 3 mph @ 0.025 (1.96)**	**t stat Δ of 5 mph @ 0.025 (1.96)**
	Day	Clear, cold and dry / OFF	858	56.53				
	Day	Clear, cold and not dry / ON	312	55.72	0.81	**2.81**	-7.67	-14.67
	Night	Clear, cold and dry / OFF	46	59.08				
Sign 1	Night	Clear, cold and not dry / ON	82	57.17	1.91	1.56 (1)	-0.88 (2)	-2.52 (2)
	Day	Clear, cold and dry / OFF	982	57.55				
	Day	Clear, cold and not dry / ON	187	52.48	5.07	**8.83**	**3.60**	0.12
	Night	Clear, cold and dry / OFF	37	55.27				
Sign 2	Night	Clear, cold and not dry / ON	28	47.17	8.10	**3.98 (3)**	2.50 (4)	1.52 (4)
	Day	Clear, cold and dry / OFF	731	55.40				
	Day	Clear, cold and not dry / ON	40	44.37	11.03	**11.86 (3)**	**8.63 (4)**	**6.48 (4)**
	Night	Clear, cold and dry / OFF	12	55.41				
Sign 3	Night	Clear, cold and not dry / ON	86	51.45	3.96	-0.41 (5)	-1.62 (6)	-2.43 (6)
	Day	Clear, cold and dry / OFF	661	58.45				
	Day	Clear, cold and not dry / ON	32	51.91	6.54	**4.93 (7)**	**2.67 (4)**	1.16 (4)
	Night	Clear, cold and dry / OFF	5	46.60				
Sign 4	Night	Clear, cold and not dry / ON	29	52.96	-6.36	-1.49 (1)	-2.2 (8)	-2.67 (8)

BOLD indicates significance

In most cases, mean speed differences of greater than 3 mph but less than 5 mph were observed during clear, cold and not dry conditions. The exceptions to these findings were the Sign 2 location during the day (2009-2010 period) and Sign 1 during the day and night (2010-2011 period). In the first instance, a mean speed reduction of over 3 mph was observed, but statistical testing indicated this drop was not significant. In the second instance, mean speed changes of less than 3 mph were observed, resulting in non-significant statistical results. It was encouraging to note that statistically significant changes in mean speeds were greater than 3 mph at some sign locations, as this indicates that motorists were likely changing their speed behaviors when the ICWS was active. In other words, the system was achieving its intended results; lower vehicle speeds under conditions where ice may not normally be expected.

Table 4 cont'd Mean speed evaluation results: clear, cold and dry/not dry conditions

Site	Time	Condition	Sample Size	Mean	Δ mph	t stat Δ of 0 mph @ 0.05 (1.96)	t stat Δ of 3 mph @ 0.025 (1.96)	t stat Δ of 5 mph @ 0.025 (1.96)
	Day	Clear, cold and dry / OFF	2143	54.96				
	Day	Clear, cold and not dry / ON	20089	51.58	3.38	**25.98**	**2.90**	-12.48
	Night	Clear, cold and dry / OFF	2493	55.26				
Sign 1	Night	Clear, cold and not dry / ON	15138	50.84	4.42	**33.66**	**10.78**	-4.46
	Day	Clear, cold and dry / OFF	1915	53.09				
	Day	Clear, cold and not dry / ON	11075	49.71	3.38	**13.47**	1.52	-6.44
	Night	Clear, cold and dry / OFF	2173	54.55				
Sign 2	Night	Clear, cold and not dry / ON	7904	49.38	5.17	**26.19**	**11.01**	0.88
	Day	Clear, cold and dry / OFF	2018	52.49				
	Day	Clear, cold and not dry / ON	11156	45.69	6.80	**46.00**	**25.71**	**12.19**
	Night	Clear, cold and dry / OFF	4602	53.65				
Sign 3	Night	Clear, cold and not dry / ON	11409	47.29	6.36	**56.92**	**30.12**	**12.25**
	Day	Clear, cold and dry / OFF	1972	57.11				
	Day	Clear, cold and not dry / ON	7245	51.78	5.33	**34.83**	**15.23**	**2.17**
	Night	Clear, cold and dry / OFF	5997	57.11				
Sign 4	Night	Clear, cold and not dry / ON	15537	52.28	4.83	**56.21**	**21.32**	-1.93
October 1, 2010 - April 15, 2011								
Site	**Time**	**Condition**	**Sample Size**	**Mean**	**Δ mph**	**t stat Δ of 0 mph @ 0.05 (1.96)**	**t stat Δ of 3 mph @ 0.025 (1.96)**	**t stat Δ of 5 mph @ 0.025 (1.96)**
	Day	Clear, cold and dry / OFF	2927	54.50				
	Day	Clear, cold and not dry / ON	22122	51.59	2.91	**25.34**	-0.79	-18.22
	Night	Clear, cold and dry / OFF	2847	53.62				
Sign 1	Night	Clear, cold and not dry / ON	14076	50.86	2.76	**21.15**	-1.89	-17.26
	Day	Clear, cold and dry / OFF	2403	55.28				
	Day	Clear, cold and not dry / ON	16675	50.18	5.10	**31.46**	**12.95**	0.62
	Night	Clear, cold and dry / OFF	3402	54.90				
Sign 2	Night	Clear, cold and not dry / ON	14548	48.32	6.58	**44.39**	**24.14**	**10.64**
	Day	Clear, cold and dry / OFF	5533	52.49				
	Day	Clear, cold and not dry / ON	12813	46.93	5.56	**55.74**	**25.64**	**5.57**
	Night	Clear, cold and dry / OFF	3995	50.93				
Sign 3	Night	Clear, cold and not dry / ON	11224	47.08	3.85	**31.16**	**6.89**	-9.28
	Day	Clear, cold and dry / OFF	5668	56.82				
	Day	Clear, cold and not dry / ON	10507	52.40	4.42	**44.25**	**14.19**	-5.83
	Night	Clear, cold and dry / OFF	6169	55.64				
Sign 4	Night	Clear, cold and not dry / ON	14157	52.00	3.64	**37.86**	**6.67**	-14.11

BOLD indicates significance
(1) Critical value = 1.98
(2) Critical value = 2.44
(3) Critical value = 2.02
(4) Critical value = 2.57
(5) Critical value = 2.14
(6) Critical value = 2.77
(7) Critical value = 2.03
(8) Critical value = 3.18

Finally, in examining mean speed changes greater than 5 mph, it was found that in only limited instances did statistically significant reductions occur. These included Sign 3 during the day and night (2009-2010 period), Sign 4 during the night (2009-2010 period), Sign 2 during the night (2010-2011 period), and Sign 3 during the day (2010-2011 period). Each of these locations resulted in large t-statistics and were the result of large changes in observed mean speeds overall (ranging from 5.56 to 6.80 mph). In general, the lack of significance in speed changes greater than 5 mph at most sign locations was the result of the lack of such notable drops in mean speeds for many observation periods and sites. This is evidenced by the negative and near zero values computed in many instances. This finding was expected, as large changes in speed (i.e. 5 mph or greater) on a clear and cold day even with ice present and the system providing warning, could not entirely be expected from drivers until they have entered a curve. Without speed data from the center of the curves targeted by the ICWS, it remains unknown whether larger drops in mean speeds in excess of 5 mph were produced by the system. Given that mean speed reductions of at least 3 mph were observed at the majority of sign locations, it is reasonable to speculate that speed drops within the targeted curves may indeed approach or exceed 5 mph. In such instances, particularly on clear, cold and icy days, the ICWS would indeed be achieving its intended purpose, as such an observable reduction should translate into reduced crashes over time.

Chain Control

Chain control data were acquired from Caltrans maintenance records for a brief period pertaining to the crash analysis (July 1, 2008 – December 31, 2009). Given this range of data, the analysis and results presented here are exploratory in nature, covering March through December of 2009 rather than a comprehensive review of all available data (i.e. 2009, 2010 and 2011). They provide a general sense of the speed trends that may be observed when chain control is in effect, both when the ICWS is on as well as off. For brevity, an in-depth discussion of the results for individual chain control levels is not presented here; rather, a summary of the key findings is presented.

When examining different levels of chain control versus the system state and time of day, it was found that the greatest impact of the ICWS is when R-1 chain control is in effect. R-1 requires chains on all commercial vehicles (trucks or buses), while all other vehicles (cars, pick-ups, vans, etc.) must have either snow tread tires or chains on the drive axle. The results indicated that significant speed changes greater than 0 mph were observed when the ICWS was on at all sites, with the exception of Signs 1 and 2 at night. These speed differences were also greater than 5 mph at all signs, with the exception of Sign 3 at night, where the mean speed difference was greater than 0 mph and less than 3 mph. These results were encouraging, as any additional speed reductions that might be achieved in addition to those produced by chain control are a benefit. The impact of the ICWS under Watch (static sign warning of ice) and R-1M (chains required on all single-axle drive vehicles towing trailers) conditions were limited and varied by the specific sign and time of day. While some statistically significant speed reductions were observed, these were cursory and generally less than 3 mph.

DISCUSSION

In considering the results observed in this study, two items should be considered. First, the speed data was collected at sign locations where the posted speed limit was 55 mph, while the posted speed limit in each curve was 40 mph. In examining mean speeds during clear, cold and dry conditions, it is evident that drivers were traveling close to the posted speed limit. During clear, cold and not dry (icy) conditions, mean speeds were significantly lower than the posted speed limit. However, all observed mean speeds were higher than the 40 mph speed limit of the curves. What the results indicate is that vehicle speeds between clear, cold and dry versus clear cold and not dry conditions are significantly different, and the only real difference that could prompt this change is the ICWS being on and presenting its message, as the general weather conditions are identical, with the only exception being the presence of moisture in some form on the roadway. Again, whether the mean speed changes observed in advance of the curves translate into adequate reductions within the curves remains to be examined; however, it is encouraging that the signs appear to be affecting driver behavior.

Second, when examining the different mean speeds at each sign, one must bear in mind the geometrics present at the site. Signs 1 and 4 (eastbound and westbound, respectively) are located at the end of long, level tangents, which may contribute to higher speeds approaching the curves. Signs 2 and 3 (westbound and eastbound, respectively) are also located on tangents, and are also on downgrades, which are likely to impact speeds in different ways (some vehicles may travel faster or slower, depending on driver comfort). At all sites, sight distances are not a significant concern. Each sign is located in advance of the curves (1000+ feet). However, all of these items may act in a combined manner to influence the observed vehicle speeds under different conditions. Again, it is important to note however, that the observed changes in speeds when conditions are essentially equal save for roadway moisture indicates that the signage appears to have some impact.

CONCLUSIONS

The results of the statistical analysis, specifically the analyses performed on clear, cold and dry/not dry data, suggest that vehicle speeds are lower when the ICWS is on. Mean speeds were significantly different by greater than 5 mph when the system was on versus off. Of course, this collective analysis told little about the performance of the system under different conditions, namely during the day and night, as well as during different weather conditions. When day and night speed data were examined, it was once again found that mean speeds significantly differed by greater than 5 mph when the system was on versus off. Observed reductions ranged between 5.19 mph and 8.66 mph during the day and 5.72 mph and 8.30 mph during the night.

When general wet weather conditions were evaluated, mean speeds were significantly different by greater than 5 mph. During the day, mean speeds during wet weather fell between 6.20 mph and 10.73 mph when the system was on. At night, mean speeds during wet weather fell between 10.34 mph and 16.14 mph when the system was on. Of course, such large changes in vehicle speeds were expected during inclement weather, when visibility and the potential of reduced pavement friction combined to lead motorists to drive more slowly.

The real interest in evaluating the Fredonyer ICWS was to determine its impacts on reducing speeds during conditions when ice was present but would be unexpected. Such conditions, called clear, cold and not dry, were times when snow melting or general water/ice pooling from the wet and cold environment of the curve locations may produce runoff across the roadway in the target curve and result in ice formation. Statistical analysis found that mean speed differences were significant by greater than 3 mph when the system was on both during the day and at night. However, only a limited number of speeds were significantly different by greater than 5 mph. Consequently, it appears that the ICWS is prompting motorists to reduce their speeds by approximately 3 mph in conditions where icy roads are not necessarily expected. While this does not indicate that speeds have been reduced throughout the targeted curves, it suggests that drivers are reacting to the ICWS messages and are likely continuing to lower their speed when past the signs. In a separate safety analysis, it was found that crashes fell by 18 percent following the deployment of the ICWS, suggesting that the speed reductions observed here were more just drivers reacting to poor conditions but rather, taking into account the messages presented by the signage. Whether this reduction translates into long-term safety benefits (e.g. continued reductions in crashes in the curves of interest), remains to be seen. As the speed readings employed in this evaluation were collected at sign locations in advance of the curves targeted by the ICWS, the true changes in speeds throughout the course of the curve remains unknown. It is possible that the observed changes in mean speeds reported here are translating into even more significant reductions by motorists as they enter and traverse each curve.

When examining different levels of chain control versus the system state and time of day, it appears that the greatest impact of the ICWS is when R-1 chain control is in effect. Under R-1 chain control, mean speeds at almost all sign locations fell by greater than 5 mph when the ICWS was on, a statistically significant change.

Future evaluations of this and similar systems should focus on speed changes throughout the course of targeted curves. While this work provides a general sense of driver reactions to the ICWS message prior to curves, it remains unknown whether, and to what extent, drivers slow down while passing through the targeted curves. In addition, the speed data collected by radar during the course of this project were aggregate and did not classify vehicles by their type. While this was not viewed to be a problem in this analysis, given the large sample sizes of data examined, it would provide interesting information related to the speed behaviors of specific vehicle types when the system was on versus off.

DISCLAIMER

The contents of this report 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.

ACKNOWLEDGEMENTS

The authors wish to thank the California Department of Transportation (Caltrans) and the University Transportation Centers Program of the Office of Research, Development and Technology, Research & Innovative Technology Administration at the U.S. Department of Transportation for funding this research. They also thank Gerry Reyes and Ken Beals of Caltrans for their assistance in obtaining the various data used in support of this work. The authors thank the Highway Safety Information System (HSIS) for providing part of crash data employed here. Finally, they thank Sean Campbell, Ed Lamkin, and Clint Burkenpas of Caltrans and Shyam Sharma of the Oregon Department of Transportation for their input to this work.

REFERENCES

1. Lindgren, R. and S. St. Clair. *Butte Creek Ice Warning System*. Oregon Department of Transportation Research Report, Oregon Institute of Technology, August 2009.
2. Telephone conversation with Tom Easley, Wyoming Department of Transportation on October 20, 2005.
3. Kyte, M., Shannon, P. and Kitchener, F., *Idaho Storm Warning System Operational Test-Final Report*, Report No. IVH9316 (601), National Institute for Advanced Transportation Technology, University of Idaho, December 2000.
4. Perrin, J. and Coleman B., *Adverse Visibility Information System Evaluation (ADVISE): Interstate 215 Fog Warning System*, UDOT Report No. UT-02.12, Civil and Environmental Engineering Department, University of Utah, June 2003.
5. Rama, P., “Effects of Weather Controlled Variable Speed Limits and Warning Signs on Driver Behavior,” *Transportation Research Record 1689*, Transportation Research Board, National Research Council, Washington [DC] (1999), pp. 53-59.
6. Lahesmaa, J. *The Socio-Economic Profitability of the Kotka-Hamina Weather-Controlled Road*. Report 36. Finnish Road Administration, Helsinki, 1997.