SAFETY AND ROAD CLOSURE BENEFITS ANALYSIS OF USING VARIABLE SPEED LIMIT (VSL) SYSTEMS ON RURAL FREEWAY

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ABSTRACT

The purpose of this research was to analyze safety and road closure benefits resulting from the implementation of Variable Speed Limit (VSL) systems on rural interstates where adverse winter conditions cause high crash rates and frequent road closures. The VSL system provides variable, regulatory speed limits to drivers based on real-time traffic, weather, and roadway conditions. In order to isolate the effects of the VSL system from the effects of mild versus severe winters, it was necessary to perform weather-based safety and road closure analyses. Crashes and road closures for the winter seasons (October 15 to April 15) from 2007 to 2012 and on four VSL corridors along Interstate-80 in the state of Wyoming were analyzed. Negative Binomial (NB) modeling technique was found to be a best regression technique to model the frequency of crash occurrence and road closures separately considering explanatory variables related to weather and the use of the VSL system. The results from the analyses show a significant reduction in winter crashes and road closures due to the use of the VSL systems. A benefit-cost analysis was performed to determine the effectiveness of VSL system in terms of monetary value considering reduced freight truck delay and crash costs.

Keywords: Weather, Benefits Analysis, Variable Speed Limit, Negative Binomial

INTRODUCTION

In order to improve the safety and operational efficiency along roadway corridors where a significant number of crashes and road closures occur due to adverse weather events, previous research suggests that Variable Speed Limit (VSL) systems could be a method to reduce crashes and improve efficiency (*(1), (2)*). Variable Speed Limit (VSL) systems are a way of managing traffic using Intelligent Transportation Systems (ITS). Unlike the traditional static speed limit signs, VSLs are speed limit signs with the capability of changing the regulatory speed limits according to real time variables such as traffic conditions or weather. VSL systems are typically installed for congestion management in urban areas, for managing adverse weather conditions in rural areas, and to manage work zone areas *((3), (4),* and *(5))*. Congestion-related VSL systems are deployed when large traffic volumes cause reoccurring congestion problems. On the other hand, weather-related VSL systems are used when weather events (fog, ice, rain) reduce roadway safety and increase delay. In the state of Wyoming, four weather-related VSL systems have been deployed on Interstate 80 along the southern part of the state. The first variable speed limit corridor in Wyoming was installed in February of 2009 along a section of Interstate 80 known as Elk Mountain between the towns of Rawlins and Laramie in the southeastern part of the state. Since that time, three additional variable speed limit corridors have been installed along I-80 to cover 143 miles of the 400 miles of I-80 in the state (FIGURE 1). The mileposts and the date of initial VSL system implementation for the four VSL corridors are shown in TABLE 1. The Wyoming Department of Transportation (WYDOT) has also implemented a non-interstate VSL system on Wyoming State Route 28 but that corridor is not included in this research since it was only recently installed and is on a roadway type very different from the other four interstate VSL systems.

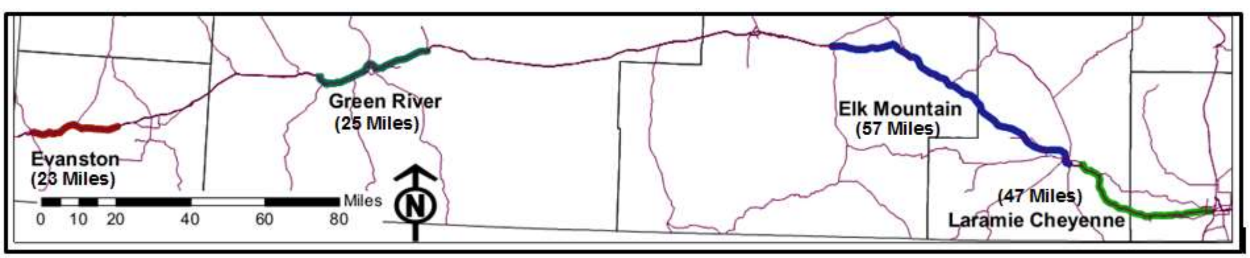

FIGURE 1 Map of Wyoming Variable Speed Limit Corridors

TABLE 1 VSL Implementation Dates

	Beg. MP	End MP	Length ,miles (km)	VSL Implementation
Laramie Cheyenne	315	357	42 (67.6)	Feb 2009
Elk Mountain	234	291	57 (91.7)	Feb 2011
Green River-Rock Springs	87	112	25 (40.2)	Oct 2011
Evanston-Lyman	6	29	23 (37)	Oct 2011

BACKGROUND

This section summarizes previous research relevant to the benefit-cost analysis of implementing VSL systems on roadway corridors where weather plays an important role in the safety and frequency of road closures. In Europe and United States, significant research has been performed to evaluate the effectiveness of VSL system in terms of improving safety *((5), (6),* and *(7)*. But VSL systems can also help roadway operations by reducing the frequency and duration of road closures. For example, on Interstate-80 in Wyoming every winter there are on average 20 weather-related road closures. Every weather-related closure lasts on average 8 hours and has estimated impacts due to freight truck delays of $12 million *(8)*. This research is the first attempt to quantify the benefits of variable speed limits that considers reduction of road closures along with safety benefits.

Researchers have utilized different approaches to find the relationship with crash occurrences to geometric characteristics, weather variables, traffic related explanatory variables using statistical models such as Multiple Linear Regression, Poisson Regression, Zero-Inflated Poisson (ZIP) Regression, Negative Binomial (NB) regression, Zero-Inflated Negative Binomial (ZINB) Regression. In 1986, Jovanis and Chang studied why Multiple Linear Regression is not appropriate for modeling crash occurrence since accident frequency data did not fit well with the basic assumptions underlying the model *(11)*. The major assumption with linear regression models is that the frequency distribution of observations must be normally distributed. Most crash frequency data violates this assumption. It was also observed that crash frequency data possess special characteristics such as count data, and overdispersion. In 1993, Miaou studied on the performance evaluation of Poisson and Negative Binomial regression models in modeling the relationship between truck accidents and geometric design of road sections *(12)*. This research recommended that the Poisson regression or ZIP model could be the initial model for establishing relationship because of the count data aspect of crash frequencies. But in most crash data, the mean value of accident frequencies is lower than the variance, which is termed as overdispersion. If overdispersion is present in crash frequency data, NB or ZINB would be the appropriate models since it accounts for overdispersion. In most accident data, crash frequencies show significant overdispersion and exhibit excess zeroes. In this case the ZINB regression model appears to be the best model.

In Finland, a road weather information system with VSL signs was tested by Finish National Road Administration to reduce crash rate *(7)*. It was found that new VSL system helped to reduce the vehicle speed by 0.4 to 1.4 percent and reduce the annual crash rate by 8 to 25 percent. Based on the benefit-cost analysis, it was estimated that the $1.4million investment saves nearly $234,500 annually in reduced crash costs resulting in an estimated benefit-cost ratio of 1.1 indicated that the project is socio-economically beneficial. Based on several studies from United States and Europe as reported by the USDOT's ITS benefits database, the effectiveness of VSL system in terms of crash reduction, it was found that VSL system can reduce crash potential by 8 to 30 percent *(13)*.

In Wyoming, WYDOT implemented a VSL system along the Elk Mountain corridor in February 2009 with the goal of improving traffic safety and reducing road closures and duration of an average road closure. A research was conducted to evaluate the effectiveness of this system in 2010. It was found that the crash rate was the lowest of the last 10 years period *(5)*. Even though, it was too early at the time of that report to make final conclusions about whether the VSL system was helping to improve safety and reduce road closures and duration.

The objective of this research was to evaluate benefits-cost of the implementation of VSL system on rural freeway in winter. This research is specifically aimed at evaluating benefits from reducing crash frequency and road closures, and costs from implementation and maintenance of VSL system. Statistical modeling techniques were conducted to determine whether or not the VSL system is effective in reducing crashes and road closures. Wyoming crash cost and delay cost by truck was used to calculate benefits.

DATA DESCRIPTION

Data from multiple sources were used in modeling safety and road closures in this research including crash data, weather data, road closure information, corridor location, VSL implementation dates, traffic volume data, delay costs, and Wyoming crash costs. Data from October 2007 to April 2012 were used to ensure adequate time periods both before and after VSL implementation on the VSL corridors. The following subsections describe the data used to modeling and evaluating benefits for this research.

Crash Data

The crash data files for the VSL corridors were obtained from WYDOT and the base bulk data was used for this research. The base bulk data set contains information on accident time, location, accident type, impact type, severity level, reported weather conditions, lighting condition, road condition, roadway geometry for each accident. For this research study accident route, location, and crash date and time are needed. TABLE 2 shows the field name from the crash base-bulk file along with a description of the field.

TABLE 2 Data Fields in Accident Data File

Field Name	Description
Route	Highway name
MP	Route milepost, given in hundredths of a mile
Date	Date of crash
Time	Time of crash
Light	Light type: daylight, darkness unlighted, dawn, dusk
RoadCondi	Road condition: ice/frost, dry, snow, wet, slush, sand of icy road
Weather	Weather Type: clear, snowing, blowing snow, severe wind only, blizzard, cloudy, raining, fog, sleet/hail/freezing rain, blowing dust/sand/dirt, smoke
Grade	Grade type: level, uphill, unreported, hillcrest, sag
HoriAlign	Horizontal align type: straight, curve right, legacy-curve, curve left.

For roadway segments where weather is a large influence on roadway safety, it is necessary to address the variations in winter seasons from year to year. In FIGURE 2, a comparison of crash frequencies between summer and winter for the Elk Mountain VSL system is shown. On average, there were 203 reported crashes in winter and 72 reported crashes in summer, which shows winter crashes are 2.82 times higher than summer crashes. It also shows the annual variation of crashes in the winter is much higher than that of summer crashes. This trend was also seen in the other three VSL corridors.

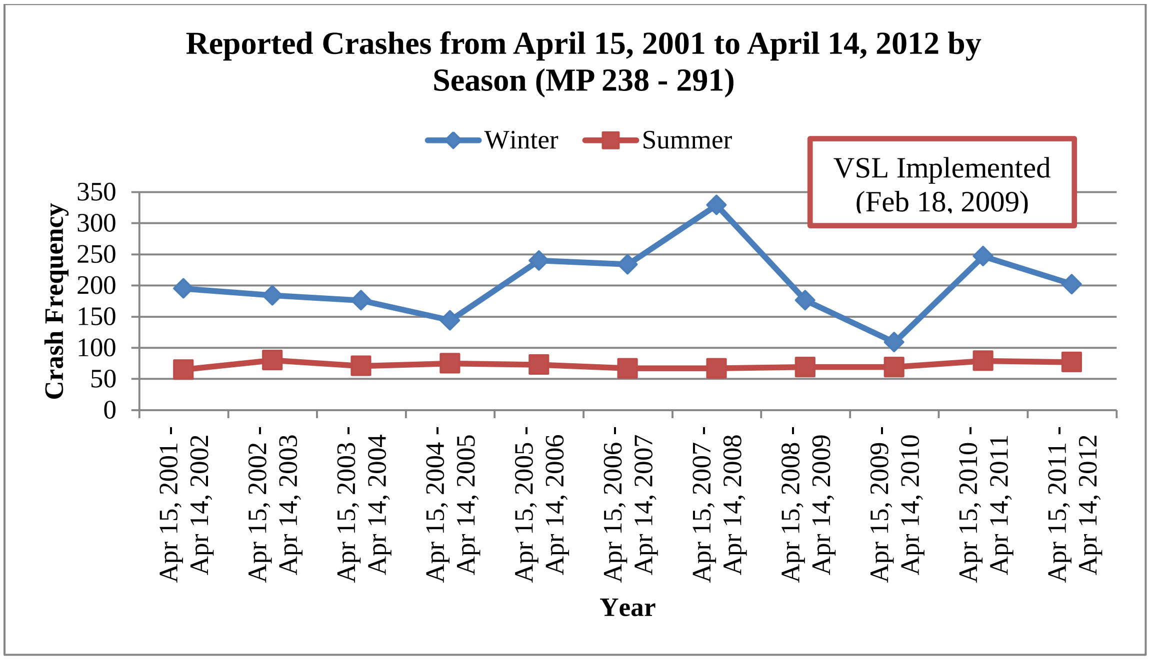

FIGURE 2 Elk Mountain Seasonal Variation of Crash Frequency, 2001 to 2012

This research developed a 7-days model in which each row of input dataset included 7-day crash frequency as the response variable. Initially, the raw input dataset were filtered using VSL corridors and analysis period. As the lengths of VSL corridors are different, the 7-day crash frequency was normalized by 100 miles. After normalization, the crash dataset for different VSL corridors were merged into a single dataset for using in the model.

Weather Data

Weather data were collected from NorthWest Weathernet, which is the weather forecasting service WYDOT has used for many years for winter maintenance activities. This service consists of a text-based forecast two or three times daily *(9)* An example of a typical forecast is shown in FIGURE 3. Weather data can also be collected from Road Weather Information System (RWIS) stations, which provides the observed weather conditions at the roadway. Using RWIS weather data instead of forecast data would have been preferred since it represents the weather conditions that acutely occurred as opposed to forecasted weather. For this research, it was not possible to use RWIS weather data because RWIS stations were installed at the time of VSL system implementation and three years of data was needed before VSL implementation. There were a few RWIS stations on I-80 before the VSL systems but the coverage of the VSL corridors was not viewed as adequate and when the archived RWIS data was reviewed, there were issues with missing data. As mentioned above, the forecast data has been used by WYDOT for many years and is viewed by WYDOT maintenance personnel as being highly reliable.

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Blowing and drifting snow will be an ongoing concern on Friday, strongest W-SW winds (up to 50-60 mph) and lowest v

1) BAGGS (789, 70, Continental Divide 7,100')
.FRI … Threat snow showers E70, esp. after 1200. Threat snow showers Baggs after 13/1400. W-SW 20-25, G40 N789 towar
SNOW Concern = 7, ICE = 7, FROST = 0, HIGH WIND = 6, I/BS = 5 (N 789)
.FRI NIGHT … Light snow shower threat continuing mainly E 70. W-SW 15-35. Blow/drift with any new snowfall. Teens. 1
SNOW Concern = 7, ICE = 0, FROST = 0, HIGH WIND = 5
.SAT … Additional light snow showers focused E 70 through 12/1300. W 20-40 strongest 789 with blow/drift wherever ne
SNOW Concern = 7, ICE = 7, FROST = 0, HIGH WIND = 6, I/BS = 5

2) RAWLINS (I-80, US30, US287/WY789, 71, Continental Divide 7,100' on 287)
.FRI … Threat light snow after 13/1400. W-SW 15-20, G35, decreasing after 1200. Lower 30s. Dustings, threat ½".
SNOW Concern = 3, ICE = 3, FROST = 0, HIGH WIND = 5
.FRI NIGHT … Light snow shower threat continuing but most hours dry. W-SW 15-35. Near 20. ½" or less.
SNOW Concern = 4, ICE = 0, FROST = 0, HIGH WIND = 4
.SAT … A few light snow showers mainly through 1200. W 20-40. Lower/mid 30s. 1" or less.
SNOW Concern = 6, ICE = 6, FROST = 0, HIGH WIND = 5
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FIGURE 3 Sample Weather Forecast Data

The forecast weather dataset provided numerical values of each variable (Snow, Frost, Ice, and Wind) ranked from 0 to 10 where 10 represents the worst condition and 0 represents the best condition. In order to determine the weather effects, the weather variables (Snow, Ice, Frost, and Wind) were categorized based on their 7-day average values according to the scales shown in TABLE 3. For all weather variables, the higher the category (Snow 2 versus Snow 3) the worse the forecasted weather conditions. Each of the four variables within the weather categories was transformed into a binary variable with 1 representing a forecasted condition with that categories range and 0 otherwise.

TABLE 3 Category of Weather Variables

Forecast Value	Snow	Ice	Frost	Wind
0-2.5	Snow1	Ice1	Frost1	Wind1
2.5-5	Snow2	Ice2	Frost2	Wind2
5-7.5	Snow3	Ice3	Frost3	Wind3
7.5-10	Snow4	Ice4	Frost4	Wind4

<u>Road Closure Data</u>

A road closure database is maintained by the WYDOT Statewide Traffic Management Center (TMC) in Cheyenne. The TMC road closure database records variables related to road closures such as the time and date that the road is closed and opened, route numbers, the direction the road was closed, the mileposts that are affected by a specific closure, the reason it was closed, and any other special notes related to the closure. TABLE 4 shows a representative sample of the road closure data. The dataset provided by WYDOT contains road closure information on all routes in Wyoming but road closures were filtered to consider only road closures on I-80 since the focus of this research is the impact of the I-80 VSL corridors on road closures. The raw road contains some closure event that cover multiple VSL closures such as ones that began at 1 mile post and ended at 370 mile post, spanning the width of the state. For modeling purposes, those closures were divided into individual closure events for each VSL corridor affected. Note that for the case of determining benefits due to freight delay, a single road closure needs to be considered instead of the four to avoid overestimating of benefits but this issue will be discussed further in the road closure benefit section.

TABLE 4 Sample Road Closure Provided by TMC, WYDOT

D1 Road Closures ID	Closing Date	Closing Time	10-13 at Closing	Opening Date	Opening Time	10-13 at Opening	Road	Direction	Cause	Area Affected	Notes	District ID	Unit Closing	Unit Opening
1337	5/20/2010	21:21	81,91	05/20/2010	21:53	81,91	WY-212	Cheyenne	Other	mp 1 to mp 2	Natural Gas Leak Parsley Dr.	1	Patrol	Patrol
1331	5/31/2010	14:50	81,94, ANLT	05/03/2010	15:57	81,94, ANLT	I-80	WB Laramie	Crashes	mp 310 to mp 272	Crash MP 281 WB	1	224	224
1339	6/11/2010	21:45	82,91	06/11/2010	22:02	82,91	I-80	W Cheyenne	Accident	mp 357 to mp 359	Closed EB due to Uprighting a semi/trailer	1	Pat-405	Pat-405
1340	6/17/2010	2:09	82,94	06/17/2010	05:40	82,94	I-80	E Arlington	Accident	mp 278	Left Ln @ 0404; Right Ln @ 0540	1	Pat-56	Pat-56

A summary of the most recent full three years of road closures (Jan. 2010 to Dec. 2012) was generated to determine the recent road closure frequency and the average road closure duration by recorded closure cause (weather, crash, etc.). This data summary can be seen in TABLE 5. Duration of an average road closure and percentage by each cause were also analyzed. The corridor was closed 172 times with an average duration of 4 hours and 34 minutes. For weather related closures only, the average duration is 8 hours and 9 minutes. It also can be seen that on average 42 miles of the interstate were closed per closure event. If the number of closures is considered, weather and weather related crashes cause 35.5% of total closures, whereas crashes caused 56.4% of total road closures. Road closures due to crash events are more frequent than those related to weather (weather and crash-weather) but crash closures affect single directions and single corridors for smaller durations than weather closures.

TABLE 5 Summary of Road Closures by Cause on I-80 in Wyoming, 2010-2012

Causes	From 2010 to 2012				Percentage by	
	Number of Closures	Duration of Closure (Hours)	Duration Per Closure (Hours)	Length per Closure (miles)	Number of Closures	Duration of Closure (Hours)
Crashes	97 (56.4%)	239	2.5	22	56.4	30.1
Weather/ Crashes	16 (9.3%)	124	7.7	51	9.3	15.6
No Info	1 (0.6%)	1	0.9	0	0.6	0.1
Other	13 (7.6%)	41	3.1	74	7.6	5.1
Weather	45 (26.2%)	389	8.6	64	26.2	49.0
Total	172	794			100	100
Average			4.56	42		

Traffic Count Data

Bidirectional traffic counts were obtained from Automatic Traffic Recorder (ATR) stations collected by WYDOT *(10)*. The ATR stations are permanent count locations maintained by WYDOT statewide and provide continuous counts. Traffic count data used in this study were collected from WYDOT traffic data website *(10)*. This website only provides yearly traffic data by roadway segments in Wyoming. Due to unavailability of seasonal or monthly variation of traffic volumes, annual average has been used in this research for calculating winter traffic. The following TABLE 6 shows the winter daily traffic counts on VSL corridors.

TABLE 6 Average Winter Daily Traffic on VSL Corridors

Winter	Elk Mountain	Rock Springs	Evanston	Laramie-Cheyenne
Oct 15, 2007 - Apr 14, 2008	9,264	14,238	10,936	10,939
Oct 15, 2008 - Apr 14, 2009	8,462	14,294	10,010	10,523
Oct 15, 2009 - Apr 14, 2010	8,479	14,409	9,966	10,551
Oct 15, 2010 - Apr 14, 2011	8,504	14,362	10,007	10,569
Oct 15, 2011 - Apr 14, 2012	8,267	14,297	9,728	10,280

For the delay cost analysis due to road closures, only freight vehicles are needed to be considered since I-80 is a main route for freight vehicles. The annual average of freight vehicles is 50.5% (see TABLE 7). Due to unavailability of seasonal or monthly variation of truck traffic, annual average has been used in this research for calculating winter freight traffic.

TABLE 7 Yearly Truck Percentage by VSL Corridors, 2007 to 2011

	2007	2008	2009	2010	2011	Average
Laramie Cheyenne	46.3	45.9	42.4	45.3	46.0	
Elk Mountain	60.7	60.8	56.4	57.2	58.3	
Rock Springs	54.7	54.7	51.7	54.0	52.6	
Evanston	45.0	46.2	41.9	44.1	46.2	
Average =	**51.7**	**51.9**	**48.1**	**50.2**	**50.8**	**50.5**

Wyoming Crash Costs

The Federal Highway Administration has developed national crash cost numbers for use in the *Highway Safety Manual* but most states have also developed locally derived numbers. For this study Wyoming comprehensive crash costs were used to calculate benefits. The Wyoming comprehensive crash costs were obtained from the WYDOT safety program and can be seen in TABLE 8 for the four crash severity categories.

TABLE 8 Wyoming Comprehensive Crash Cost

Crash Severity	Crash Severity Percentages	Cost
Critical (Fatal and Incapacitating)	2.3	$3,350,649
Serious (non-incapacitating and possible injury)	34.9	$44,918
Property Damage Only (PDO)	62.8	$13,900

For calculating safety benefits, the crash distribution was determined based on the winter crash data on the VSL corridors of I-80 in Wyoming considering the time period from October 2007 to April 2012. The crash distribution was categorized on the three levels of crash severity: Critical, Serious, and PDO (see TABLE 8) so that the distribution percentage can be used to calculate overall safety benefits.

Wyoming Truck Delay Costs

The value of time for freight carriers for unexpected delay, such as those caused by weather, is estimated conservatively for this research at $370 per hour *(5)*. This estimate includes the costs incurred by additional driver time and loss of the vehicle to other activities but does not include costs associate with delay of the freight contained in the truck such as delays in manufacturing processes or lost sales.

Combined Dataset for Safety Model

In order to determine the effectiveness of the VSL systems on reducing crash frequencies, the VSL use was incorporated as an binary explanatory variable with a value of 1 for time periods after the VSL was implemented, 0 for periods prior to implementation. The different VSL corridors were also incorporated into the model to adjust for corridor differences such as geometrics and driver familiarity. Corridor variables are binary variables with 1 representing data for that particular corridor. In this analysis, AADT was considered as the offset variable. Offset variable is used as logged variable in count data modeling in order to consider the rate. The combined dataset contains for each observation the seven-day average crash frequency, 7-day average AADT, and seven-day average weather data, VSL use and the corridor variable. Among the weather variables and VSL corridors Snow1, Ice1, Frost1, Wind1, and Elk Mountain has been considered as the base conditions. A sample dataset for the Laramie-Cheyenne VSL corridor is shown in TABLE 9.

TABLE 9 Sample Dataset for Modeling SPF

Corridor	Beg Date	End Date	VSL	Snow	Ice	Frost	Wind	Crash Frequency	AADT
LaramieCheyenne	10/15/2007	10/22/2007	0	3.11	0.00	5.50	0.50	29	13203
LaramieCheyenne	10/22/2007	10/29/2007	0	0.90	0.67	2.29	0.00	10	13203
LaramieCheyenne	10/29/2007	11/5/2007	0	0.93	1.71	2.62	0.00	10	10942
LaramieCheyenne	11/5/2007	11/12/2007	0	0.93	0.20	2.80	0.00	5	10942
LaramieCheyenne	11/12/2007	11/19/2007	0	1.24	0.19	4.05	0.00	2	10942
LaramieCheyenne	11/19/2007	11/26/2007	0	1.43	0.24	3.81	1.43	19	10942
LaramieCheyenne	11/26/2007	12/3/2007	0	1.40	0.07	5.73	3.90	48	10942

Combined Dataset for Road Closure Model

This research developed a 7-day model to match the safety model so that the same weather variables could be used. Each Road Closure Duration and Road Closure Frequency observations contain a row of input data with the 7-days average road closure data, 7-days average weather data, whether the time period was before or after VSL implementation, and corridor specific binary variable. It is important to note that only closures that include VSL corridors were considered in modeling in evaluating the effectiveness of VSL system. A sample dataset is shown in TABLE 10.

TABLE 10 Sample Dataset for Road Closure Modeling

ClosedHours	Frequency	VSL	LaramieCheyenne	ElkMountain	Evanston	RockSprings	Snow1	Snow2	Snow3	Snow4	Ice1	Ice2	Ice3	Ice4	Frost1	Frost2	Frost3	Frost4	Wind1	Wind2	Wind3	Wind4
0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0
4.6	2	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	1	0	0

28.4	3	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0
0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	1	0	0

SAFETY BENEFIT ANALYSIS

This research developed a 7-days model using crash frequency observations for each 7-day period and provides 7-day average weather data, the binary variable for whether the VSL was implemented or not during that period, and a corridor specific binary variable. The reason for using a 7-day model instead of a daily crash frequency model is that a large number of zero observations in response variable can be avoided. The sample dataset for the Laramie-Cheyenne VSL corridor is shown in **Erreur ! Source du renvoi introuvable.**9.The final dataset contained all four VSL corridors.

For the model, crash frequency for the seven day period was the response variable and Corridor, VSL, AADT, Snow, Ice, Frost, and Wind are the explanatory variables. The weather parameter I/BS was excluded from the analysis because of having too many missing observations since it was not always provided in the daily forecasts.

Count data modeling techniques (Poisson, Negative Binomial, Zero-inflated Negative Binomial, and Zero-inflated Poisson) were investigated to identify the best modeling technique. In this case Negative Binomial appears to be the best model.

TABLE 11 shows the results of the both the initial (all variables) and final (all significant variables) models. The p-value indicates the significance of the variable. A 90% statistical significance level was selected as the threshold for determining statistical significance so all variables with p-values less than 0.1 were included in the final model. Variables with p-values above 0.1 were removed one at time starting with the variable with the highest p-value in the initial model. This process was continued until all variables is the final model were statistically significant.

TABLE 11 Safety Performance Function for VSL Corridors using NB Count Model

	Initial Model		Final Model	
Independent Variables	Estimate	Pr(>|z|)	Estimate	Pr(>|z|)
(Intercept)	-0.0015	<0.0001*	-0.0015	<0.0001*
Snow2	2.0453	<0.0001	2.0689	<0.0001*
Snow3	1.2746	0.490		
Snow4	NA	NA		
Ice2	1.1216	0.506		
Ice3	-0.7264	0.600		
Ice4	NA	NA		
Frost2	-0.7863	0.732	-0.7075	0.087*
Frost3	1.0920	0.901		
Frost4	-0.3503	0.291	-0.3038	0.092*
Wind2	1.3169	0.077*	1.3543	<0.05*
Wind3	1.5623	<0.05*	1.6258	<0.01*

Wind4	1.0035	0.995		
VSL	-0.7573	<0.05*	-0.7487	<0.01*
LaramieCheyenne	-0.8796	0.857		
Evanston	-0.6123	<0.01*	-0.6262	<0.001*
RockSprings	-0.7475	0.0668*	-0.7587	<0.05*

* indicates p-value<=0.10

The coefficients indicate that for every one unit increase in explanatory variables, the log count of expected crash frequency is expected to increase by the value of estimates. For example, when the value of Snow2 is increased by one unit (i.e. the average snow forecast ranking is increased from 2.5 to 3.5), the expected crash frequency is expected to increase by 2.07 crashes per seven days. For the model in TABLE 11, the base condition is considered the Elk Mountain Corridor, prior to VSL implementation, and with weather conditions in their lowest severity category (Snow1, Ice1, Frost1, and Wind1) so all model interpretation is relative to this base condition.

From the model results, an estimate of the safety benefits from implementing the VSL systems can be estimated. The model coefficient for the VSL variable was estimated as -0.75 crashes per week per 100 miles of VSL corridor length. This crash reduction estimate can then be converted from a weekly to a winter season value to get 19.4 crashes avoided per winter season per 100 miles of VSL corridor. To get total crashes avoided per season this value is then multiplied by the ratio of 143/100 to adjust for the total length of the VSL corridors (TABLE 1) for an annual crash reduction estimate of 27.7.

To monetize the safety benefits, estimates of both the crash severity distribution and costs by crash severity must be determined. The crash cost values were obtained from the WYDOT as discussed in the data section. The crash severity distribution was determined from Wyoming I-80 crash distribution. Using these values and the crash reduction estimates the monetized annual safety benefit due to VSL implementation is estimated to be approximately $2.8 million per winter (TABLE 13).

TABLE 12 Annual VSL Safety Benefits

	Rural Interstate	Crashes	Cost	Total
Critical, K & A	2.3	0.6	$ 3,350,649	$ 2,145,231
Serious, B & C	34.9	9.7	$ 44,918	$ 436,378
PDO, O	62.8	17.5	$ 13,900	$ 242,992
Sum	**100**	**27.8**	**Sum =**	**$ 2,824,601**

The two most representative VSL corridor installation costs are from the Green River-Rock Springs and the Evanston-Lyman corridors. The bid lets price for these two projects averaged approximately $1 million each. Using an estimate of $1 million per VSL corridor for installation costs for each of the four VSL corridors, the benefits of the VSL corridor implementation exceed costs in the first two years of system use. There is ongoing operation and system maintenance costs also associated with VSL use and also excludes capital costs associated with the existing WYDOT TMC.

ROAD CLOSURE BENEFIT ANALYSIS

In the previous section, the effectiveness of the VSL system in terms of safety was analyzed and shown that VSL systems help to reduce crash frequency. This section focuses on the effectiveness of the VSL system in terms of road closures. In this section, how effective the VSL system is in helping to reduce the duration and frequency of road closures is discussed.

In the VSL corridors, weather has a large influence on the safety and operation of the road. To isolate the effects of a treatment like a VSL system, it is necessary to address the variation in winter seasons from year to year. The frequency or duration of road closures in an extreme winter season will be inherently higher than those in a mild winter season regardless of the treatments installed to reduce these. To isolate the effects of weather on road closures, statistical modeling was performed where Road-Closure-Hours and Road-Closure-Frequency are considered as the response variables and weather parameters (wind, snow, frost, and ice), corridor variables (Laramie Cheyenne, Elk Mountain, Rock Springs, and Evanston) , and VSL implementation as explanatory variables.

In this modeling, data from October 2007 to April 2012 were used to ensure adequate time periods both before and after VSL implementation on the four VSL corridors. The same roadway forecast weather parameters used in the safety analysis were used in this analysis. Four categories of severity for Snow, Ice, Frost, Wind, and Ice/Blowing Snow (I_BS) were defined based on the thresholds shown in the safety section where 1 represents low severity conditions and 4 represents the highest severity conditions for that type of weather. Corridor variables are binary variables with 1 representing data for that particular corridor.

This research developed a 7-day model to match the safety model so that the same weather variables could be used. Each Road Closure Duration and Road Closure Frequency observations contain a row of input data with the 7-days average road closure data, 7-days average weather data, whether the time period was before or after VSL implementation, and corridor specific binary variable. It is important to note that only closures that include VSL corridors were considered in modeling in evaluating the effectiveness of VSL system. A sample dataset is shown in TABLE 10.

Road Closure modeling was divided into two separate models: a road closure-duration (in hours) model and a road closure frequency model. The only difference between these two models is the different road closure response variables. During modeling, it was found that there are significant numbers of zero values present in the response variable, which led to use of Zero-inflated modeling techniques. There are two Zero-inflated modeling techniques: Zero-inflated Poisson (ZIP) and Zero-inflated Negative Binomial (ZINB). If overdispersion is present in the response variable, ZINB must be chosen otherwise either a ZIP or ZINB can be applied. In this research, Zero-inflated Negative Binomial was considered as the statistical method for both models since it controls for overdispersion if present in the data and is identical to the ZIP model if overdispersion is not present.

To determine which dataset should be modeled (road closure frequency or road closure duration) it was decided to utilize a goodness-of-fit test to determine which dataset was best suited for a negative binomial model estimation. The results from the Goodness-of-fit test for both models can be seen as follows:

Goodness-of-fit (GOF) test was performed to determine whether or not observed data fits well with negative binomial distribution. The most commonly used GOF test statistics are Pearson's χ^2. Pearson's χ^2 is generally calculatred as $\sum\left(\frac{y_i-\mu_i}{\sigma_i}\right)^2$. Where $y_i$is the observed data, μ_i is the true mean and σ_i represents the error. On the basis of the statistical analysis, the null hypothesis is that there is no difference between the observed data distribution and negative binomial distribution. If the chi square value results in a probability that is less than 0.01, it is considered as statistically significant. Therefore the null hypothesis is rejected. The results from the Goodness-of-fit test of Road Closure Duration and Frequency Models can be seen as follows.

Goodness-of-fit test for Road Closure Duration Model:
Goodness-of-fit test for nbinomial distribution

	X^2	df	P(> X^2)
Pearson	69.301	49	0.0296

Goodness-of-fit test for Road Closure Frequency Model:
Goodness-of-fit test for nbinomial distribution

	X^2	df	P(> X^2)
Pearson	4.115	6	0.6611

From the GOF test of Road-Closure-Duration model, Road-Closure-Duration model doesn't fit well with negative binomial distribution at the 90% confidence level. The poor GOF results erroneous outputs. On the other hand, from the GOF test of Road-Closure-Frequency model the calculated value of χ^2 for 6 degrees of freedom is 4.115, which is significantly small compared to critical value at the 90% confidence level. So null hypothesis can be accepted. From the GOF test results of Road-Closure-Frequency model, it can be concluded that observed data fits well with negative binomial distribution.

During the last six winter seasons for road closures, it can be seen that there is a considerable variation in the number of road closure hours among seasons. The modeling results shown in TABLE 13 indicate that the VSL system implementation is not a statistically significant variable (p-value = 0.86) in the road closure duration model. After implementing VSL system, the average duration of a road closure may be increased so that there was no considerable difference of average duration between before and after VSL. This is the likely reason the VSL implementation variable was not found to be significant in this model.

TABLE 13 Road Closure Hours for VSL Corridors using ZINB

	Initial Model		Final Model	
Independent Variables	Estimate	Pr(>|z|)	Estimate	Pr(>|z|)
(Intercept)	13.3752	<0.05*	14.6375	<0.001*
Snow2	2.6216	0.1275		
Snow3	2.1092	0.5003		
Snow4	NA	NA		
Ice2	-0.3656	0.1616	-0.5496	<0.05*
Ice3	NA	NA		
Ice4	NA	NA		
Frost2	-0.4185	0.3893	-0.3860	<0.05*
Frost3	-0.4283	0.3584		
Frost4	NA	NA		
Wind2	-0.4653	0.3292		
Wind3	-0.3529	0.3756		
Wind4	NA	NA		
VSL	1.2066	0.7640	1.0431	0.8637
LaramieCheyenne	NA	NA		
Evanston	-0.7442	0.8163		
RockSprings	0.7163	0.7293		
Log (theta)	-0.3152	<0.01*	1.8421	<0.001*

After estimating the Road-Closure-Duration model, a Road-Closure-Frequency model was estimated to see if statistical significance could be found using a different response variable. In this model, ZINB technique was also used. The results from road closure frequency model estimation can be seen in TABLE 14. For the initial model estimation, all available explanatory variables are included. The road closure frequency for each 7-day period was considered as the response variable.

TABLE 14 Road Closure Frequency Model for VSL Corridors

	Initial Model		Final Model	
Independent Variables	Estimate	Pr(>|z|)	Estimate	Pr(>|z|)
(Intercept)	1.1101	0.8766	-0.9020	0.8867
Snow2	-0.8844	0.8133		
Snow3	-0.2655	0.1271		
Snow4	NA	NA		
Ice2	1.6019	0.4586		
Ice3	NA	NA		
Ice4	NA	NA		
Frost2	-0.1609	<0.01*		
Frost3	NA	NA		
Frost4	NA	NA		
Wind2	1.8419	0.1361		
Wind3	NA	NA		
Wind4	NA	NA		
VSL	-0.4257	<0.05*	-0.3886	0.0720*
LaramieCheyenne	1.0379	0.9414		
Evanston	-0.0283	<0.001***	-0.0396	<0.001***
RockSprings	-0.1894	<0.05*		
Log(theta)	1.0243	0.9740	-0.6340	0.7369

From the initial model, it was found that among the weather variables (Snow, Wind, Ice, and Frost); only wind shows positive values indicating as wind increases, expected number of road closures increase. So it was determined that the best possible combination of snow, ice, and frost along with other significant variables is the best initial model. The best initial model was chosen based on the Akaike Information Criterion (AIC) value among the models considered with different combination of snow, ice and frost. In the following TABLE 15, the AIC values can be seen from eight different models considering all the possible combinations of Snow, Ice, and Frost. Among the AIC values, Model 2 has the minimum AIC value (367.29). So Model 2 has been chosen as the initial best model.

TABLE 15 AIC Values from Eight Different Models using ZINB

NB	Inputs	AIC
Model 1	All	370.91
Model 2	Snow	367.29
Model 3	Ice	377.15
Model 4	Frost	376.64
Model 5	SnowIce	369.58
Model 6	SnowFrost	368.79
Model 7	IceFrost	376.83
Model 8	None	376.85

After the AIC step, variables with p-values greater than 0.1 were considered statistically insignificant at the 90% confidence level and excluded from the model. One variable was dropped from the model per iteration starting with the least significant. The process was repeated until all variables in the final model had p-values of 0.1 or less. TABLE 14 shows the results of the both the initial (all variables) and final (all significant variables) models for road closure frequency. For the model shown in TABLE 14, the base condition is considered the Elk Mountain Corridor, prior to VSL implementation, with weather conditions in their lowest severity category (Snow1, Ice1, Frost1, and Wind1) so all interpretation of model coefficients is relative to this base condition.

Looking at the results of the final model in TABLE 14, it can be seen that when VSL system is implemented, the expected road closure frequency are decreasing significantly at the 90% confidence level. The estimates of the VSL variable show that the expected number of road closures is expected to decrease by 0.39 per seven days. It is interesting to note that among the VSL corridors, only the Evanston corridor has lower estimated number of road closures compared to Elk Mountain. No weather variables were found to be significant at the 90% confidence level. This reduction in the number of road closures can be converted from a weekly value to a winter season to get 10.14 closures reduced per winter.

Regarding road closure benefit analysis, there is a double counting issue. As road closure benefits come from avoiding delays due to road closure by trucks, it is important to consider that when trucks are delayed by one closure, delay caused by a downstream closures should not be considered for those particular trucks since they are unable to reach the downstream closure. In this research there are two types of reduced closures were considered to avoid double counting when calculating road closure benefits. The first type was a single closure that was split into four closures in modeling. For example, in our raw road closure data, there are some closures began at 1 mile post and ended at 370 mile post. For our modeling purposes, those closures were divided into four closures considering the four different VSL corridors between those mileposts. For the case of determining benefits, the single road closure needs to be considered instead of the four. Second, when one truck starts moving after opening of an upstream closure, that truck might face another closure. Here how long the second closure occurred before that truck arrives was considered as overlapping with the first upstream closure.

For the first type of double counted road closures, in the road-closure-frequency model, data from October 2007 to April 2012 were considered. In the dataset, there are 86 road closures during that time period. When a closure starts at 1 mile post and ended at 370 mile post in a travel direction, considers as the four separate closures. Therefore, the number of overlapped closures was three. Total number of closures with first type of double counting issues is 33 out of 86 (38.4%).

For the second type of double counted road closures, when one truck starts moving after opening of an upstream closure, that truck might face another closure. Here, how long second closure occurred before that truck arrives was considered as overlapping with the first upstream closure. It can be seen that there are total 68.2 hours of closures that does not cause delay. Previously it was found that on average one weather-related road closure closes a corridor 8.41 hours long. So there are on average 8.1 number of closures (68.2 divided by 8.41) overlapped in this type of double counting which is 15.3% (8.1 divided by 86 minus 33) of total.

From the above analysis of two types of double counting, it can be concluded that first and second type of double counting issues results 38.4% and 15.3% reduction of road closures respectively for a total of 53.7% of closure frequency that should not be considered in calculating benefits. From the modeling, it was determined that road closures have been reduced by 10.14 per winter after implementing VSL system. After accounting for the double counted closures, it can be found that the actual closures for calculating monetary benefits were reduced to 4.69.

For an average 8 hour and 25 minute closure, an average delay cost of $370 per hour of delay per truck (see data section), and the average truck volume on the corridor, a cumulative impact of $11.68 million per road closure is estimated. Using this values and the reduction of road closure, the monetized road closure benefit in a winter due to implementation is approximately $54.7 million per year. This very large and is reflective of the importance of freight travel along this interstate.

CONCLUSIONS

The overall goal of this research is to estimate safety and road closure benefits after the implementation of VSL system on a rural freeway where harsh winter plays the most important role in reducing safety and increasing delay. In order to isolate the effects of the VSL from the effects of mild versus severe winters, it was necessary to perform a weather-based safety and road closure analyses. Three different models were performed to estimate the effectiveness of VSL system: crash frequency model, road closure duration model and road closure frequency model. The crash frequency model found that there was a statistically significant result that VSL implementation reduced crashes by 27.7 every winter on the corridors when weather was controlled for. Crash reductions and comprehensive crash cost estimate the monetized annual safety benefit is approximately $2.8 million per year. The road closure duration modeling results indicate that the VSL system implementation is not a statistically significant variable. From the road closure frequency model, it can be seen that when the VSL system is implemented, the expected road closure frequency is expected to decrease by around 0.39 per seven days. To monetize the road closure benefits, the truck percentage and truck volume of VSL corridors and the value of time for freight carriers for unexpected delay were used to estimate the road closure benefits. Using these values it was estimated that the monetized road closure benefit due to VSL implementation is approximately $54.7 million per winter.

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