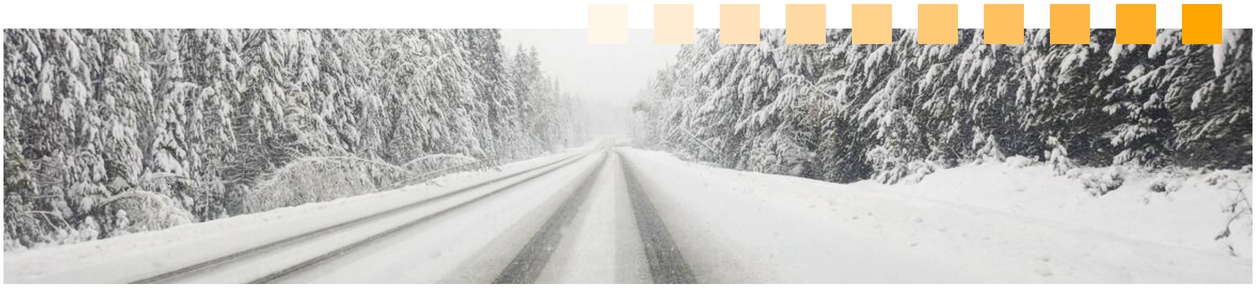


TAC ROAD SAFETY

ENGINEERING AWARD NOMINATION

BC Road Weather Information System and Variable Message Sign Integration

BRITISH COLUMBIA

Ministry of
Transportation
and Infrastructure

Project Description

The Province of British Columbia is committed to eliminating serious injuries and fatalities. One way to reach this goal is through increased use of intelligent transportation technologies. The Road Weather Information Systems (RWIS) combined with variable message signs (VMS) are an innovative safety tool that is being rolled out in British Columbia in areas that experience changing road conditions due to weather events.

Weather in BC can change rapidly, especially in winter. Adverse weather conditions create an environment in which it is difficult for drivers to navigate safely. RWIS and VMS integrations can be utilized to provide travelers with information on current weather and road conditions via electronic variable message signs and reduce the frequency and severity of winter collisions. The Ministry of Transportation and Infrastructure has combined RWISs and VMSs at seven locations on rural highways that experience extreme winter weather conditions and a poor safety performance.

Highway 6
Snowstorm in the
area of Beasley

Innovation

Due to the impact of severe winter conditions in BC, the ministry developed a weather network starting in the 1970s. It includes 92 road weather stations, 67 avalanche weather stations, and 89 frost probe stations. All the stations in the network are installed and maintained by a dedicated team of Environmental Electronics Technicians.

Highway 97
Hush Lake Road
Weather Station

Road Weather
Station Sensors

Highway 97 Variable Message Sign controlled by Highway Hush Lake Road Weather Station

The ministry has leveraged this technology and combined it with safety data to determine locations that would benefit from RWIS/VMS installations. The first automated RWIS/VMS system was introduced in BC in 2011 and ever since the ministry has been expanding.

Highway 4 Variable Message Board

Each system comprises of a RWIS connected to two VMSs, one in each travel direction. The RWIS system automatically analyses weather and road conditions every 15 minutes and an algorithm selects an appropriate sign message to provide real time information to the road users. The message is selected from a hierarchical list sorted from most to least severe in relation to advisory content. The message is displayed on both VMSs in a flashing/alternating format to draw drivers' attention. Automatic mode can also be over-ridden by operators in the traffic management centre to post other priority messages based on operational requirements.

Message	Condition
Road Icy/Slow Down	Snowy or icy surface with extreme low level of grip
Slippery Sections/Use Caution	Slushy, frosty, snowy, or icy surface with moderate level of grip
Heavy Snowfall/Use Caution	Snowfall with acceptable level of grip
Water Pooling on Road/Use Caution	Rainfall with surface temperature above freezing
Standard Safety Messaging (static, not flashing)	Absence of triggering conditions for the higher priority messages

Safety Benefits

Drivers rely on their personal judgment during adverse weather conditions to determine an appropriate operating speed. Variable messaging systems improve safety during inclement weather by providing real-time messaging to drivers.

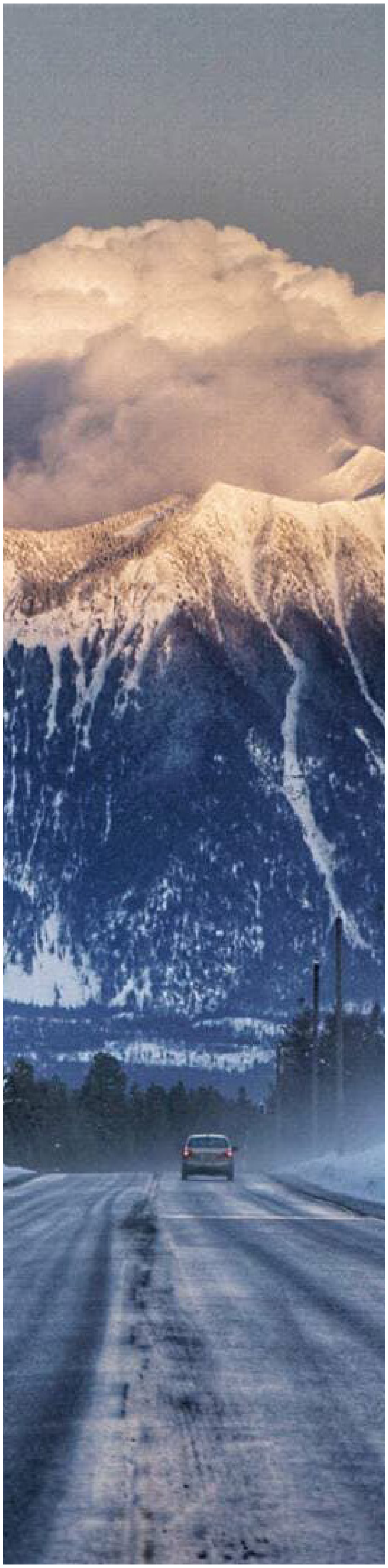
An analysis was completed at six different locations on rural undivided highways in BC between 2011 and 2014. The analysis made use of police-attended serious crashes (i.e., fatal + injury) that took place during winter seasons. Depending on the implementation date, three or four winter seasons were available as a before-implementation period, while three to six winter seasons were available as an after-implementation period.

An Empirical Bayes (EB) approach was employed to ensure that the evaluation results were reliable and to account for the regression-to-the-mean artifact. Safety performance functions (SPFs) were developed using data collected at similar sites. The EB evaluation results showed an overall statistically significant reduction of 32.7% in all winter serious collisions (WSC).

An economic evaluation showed that the systems led to a benefit-cost ratio of 4.8 and an overall net present value of more than Can$12 million.

The safety benefits for implementing a RWIS/VMS were evident with an overall reduction of over 30% in severe winter collisions. The benefits of implementing a RWIS/VMS exceeded the cost, with an overall benefit-cost ratio of 4.8. This indicates that the implementation of RWIS/VMS in British Columbia was an effective investment in improving highway safety.

The full report can be found in Appendix 1.



Transferability

While BC is unique in its geographic and environmental challenges, the RWIS/VMS system can be applied anywhere that has rapidly changing or severe weather conditions and poor safety performance. In addition, this technology can be adapted to provide real time information to drivers with other ITS technologies. For example, the Ministry is adapting this system with LED equipped static signs to alert motorists to specific road conditions (fog or ice) in areas that are known to have specific weather challenges. The process for collecting data is similar; however, the information provided to drivers is specific to that micro climate. This is an example of how the ministry is leveraging technology and innovation to meet the strategic objectives of the Road Safety Strategy.

In addition to providing real time information during adverse weather conditions, the VMS system can have secondary value as a traffic control tool for planned events, including incident management. This improves highway safety and operation during summer months when severe weather is less likely.

The Ministry has proven that RWIS/VMS systems in a rural, Canadian, mountainous environment are possible and practical. The Ministry developed a network of sensors to implement this type of road safety device. There have been lessons learned that we are sharing with the transportation community at conferences and through other communication channels. We are hopeful that others pick up on the effectiveness of this technology and use it to the best of their advantage in locations where drivers' response to severe weather and road conditions is not appropriate. The safety benefit reported may motivate transportation agencies and stakeholders to pursue similar systems for mitigating weather-related safety problems. It is our responsibility to provide a reliable driving experience to keep highways safe and operational during all conditions.

APPENDIX 1: Safety Assessment of the Integration of Road Weather Information Systems and Variable Message Signs in British Columbia

Research Article

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Safety Assessment of the Integration of Road Weather Information Systems and Variable Message Signs in British Columbia

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Abstract

Adverse weather conditions create an environment in which it is difficult for drivers to navigate safely. Reducing weather-related collisions is a target for road safety professionals in British Columbia (BC), Canada. This study reports the safety benefits of installing road weather information systems (RWISs) coupled with variable message signs (VMSs) on provincial rural highways in BC. The RWIS/VMS system comprises road and weather sensors, as well as two VMSs. The road and weather sensors collect data on pavement surfaces and weather conditions. Information on adverse road/weather conditions are conveyed to road users via the VMSs. The system had been installed at six different locations on rural undivided highways in BC between 2011 and 2014. The analysis made use of police-attended serious crashes (i.e., fatal + injury) that took place during winter seasons. Depending on the implementation date, three or four winter seasons were available as a before-implementation period, while three to six winter seasons were available as an after-implementation period. An Empirical Bayes (EB) approach was employed to ensure that the evaluation results were reliable and to account for the regression-to-the-mean artifact. Safety performance functions (SPFs) were developed using data collected at similar sites. The EB evaluation results showed an overall statistically significant reduction of 32.7% in all winter serious collisions (WSC). An economic evaluation showed that the systems led to a benefit-cost ratio of 4.8 and an overall net present value of more than Can$12 million. The results of this study may motivate transportation agencies and stakeholders to pursue similar systems for mitigating weather-related safety problems.

Adverse weather conditions create an environment in which it is difficult for drivers to navigate safely. Reducing weather-related collisions is a target for many road safety professionals in British Columbia (BC). Traditional safety countermeasures and programs, as well as intelligent transportation systems (ITS), which allow the implementation of innovative solutions, have been proposed to mitigate weather-related safety problems. Road weather information systems (RWISs) are one example of an ITS innovation, where the goal is to improve safety for all the motoring public on the provincial highway system during unfavorable winter weather conditions. A RWIS can be utilized to provide travelers with information on weather and road conditions via electronic variable message signs (VMSs), thereby presenting possible safety benefits by reducing the frequency and severity of winter collisions. The objective of this study was to evaluate the safety impact associated with RWIS/VMS installed on rural undivided highways in BC between 2011 and 2014. The evaluation was undertaken using winter serious collision (WSC) data. Three to four winter seasons of before-implementation data were used in the evaluation along with three to six winter seasons of after-implementation data. Reference site data were also used to evaluate the safety performance of the treatment sites.

RWISs in BC

The BC Ministry of Transportation and Infrastructure (BC MoTI) has built a network of 81 road weather stations (RWSs), 58 avalanche weather stations (AWSs),

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Table 1. Message List and Triggering Conditions for RWISs

Message	Triggering conditions
Road Icy/Slow Down	Snowy or icy surface with extreme low level of grip
Slippery Sections/Use Caution	Slushy, frosty, snowy, or icy surface with moderate level of grip
Heavy Snowfall/Use Caution	Snowfall > 3 cm/h with acceptable level of grip
Water Pooling on Road/Use Caution	Rainfall > 2 mm/h with surface temperature above freezing
Standard Safety Messaging (Static, Not Flashing)	Absence of triggering conditions for the higher priority messages

and 85 frost probe stations (FPSs) around the province to collect and analyze various weather data. An RWS utilizes optical pavement sensors and atmospheric sensors. Optical pavement sensors measure surface temperature, surface thicknesses of water, snow, and ice, surface conditions (i.e., dry, moist, wet, slushy, frosty, snowy, or icy), and level of grip (i.e., a pseudo co-efficient of friction of the road surface, derived from the coverage thickness values). A standard suite of atmospheric sensors measures the remaining set of parameters such as air and dew point temperatures, wind speed and direction, precipitation and snowfall rates and accumulations, and barometric pressure. The term "RWIS" is used to refer to the integration of RWSs, analysis algorithms, and data archiving.

The BC MoTI has integrated RWISs and VMSs at six locations on rural highways where each system comprises one RWIS connected to two VMSs, one in each travel direction. The locations of RWIS/VMSs installation were noted as having severe winter weather conditions and poor road safety performance during winter conditions. The purpose of the systems therefore is to provide a safer and more reliable driving environment by using real-time road and weather conditions to trigger the display of specific advisory messages to notify drivers of adverse conditions.

A RWIS system automatically analyzes weather and road conditions every 15 min and an algorithm in the RWS's data logger selects an appropriate sign message according to the collected data. The message is selected from a hierarchical list sorted from most to least severe in relation to advisory content. The message is displayed on both VMSs in a flashing/alternating format to draw drivers' attention. A typical message list is presented in Table 1. Automatic mode can also be over-ridden by operators in the traffic management center to post other priority messages based on operational requirements.

Previous Work

Jurisdictional Review in North America

The Ministry of Transportation in Ontario (MTO) owns and operates 148 stations across the province. The collected data is primarily used to support winter maintenance operations. In New Brunswick, the RWIS network comprises 41 weather stations on highways. The information collected at these stations provide road managers with a picture of actual weather and road conditions on an entire highway network. The weather information network in Alberta includes 112 road weather information stations, 10 mobile RWSs, 17 digital messaging signs, 10 road camera stations, and three road condition warning stations. A pilot project for the installation of a RWIS in Magog, Quebec was implemented in December 2016 where its evaluation was planned after two years (*1*).

The Washington State Department of Transportation has deployed RWIS to support maintenance operations and to provide public information. The network is composed of roadside sensor stations, a statewide communication network, data tools for maintenance personnel, weather forecasting abilities, weather modeling, pavement modeling and prediction, and an online database (*2*). There are currently over 400 weather stations in Washington State and the Department of Transportation made the data collected at these stations available online.

Safety Evaluations of RWISs

Drivers rely on their personal judgment during adverse weather conditions to determine an appropriate operating speed. Variable speed messaging systems improve safety during inclement weather by providing real-time messaging to drivers. Rämä and Kulmala (*3*) evaluated three test sites in Finland over two winters to determine the effectiveness of variable messaging systems in slippery conditions. Driving speed and headway were used as surrogate measures to evaluate the effectiveness of weather-controlled sign systems. Lowering the speed limit from 100 to 80 km/h on a weather-controlled road resulted in a mean speed reduction of 3.4 km/h in winter months. During dry but adverse weather conditions such as black ice a reduction of 5.3 km/h was observed. A reduction in headways was not found to be significant.

Speed reductions and headways are not ideal surrogate measures given that they cannot be directly attributed to the weather messaging system as the speed reduction may have been a result of inclement weather rather than the system itself. Regression modeling like the Negative binomial (NB) regression technique employed by Saha et al. (*4*) provides a more accurate analysis for evaluating the safety impact. Challenging roadway was a characteristic of this study as the road sections evaluated were over mountainous terrain. The crash risk for these locations was found to be 82% higher in winter than in summer. Four road weather system corridors were evaluated over five years to study the relationship between roadway geometrics and adverse weather conditions on variable speed limit (VSL) freeway corridors. This study employed a seven-day crash frequency as the response variable while weather, traffic, and geometric variables were used to determine whether the VSL system was efficient in reducing winter crashes. The results showed that horizontal curves did not significantly impact winter crashes. On the other hand, steep grades were found to be statistically significant in reducing crashes. The research findings concluded that a VSL system which utilizes geometric variables in addition to real-time weather reports would be considered valuable.

Kolisetty et al. (*5*) investigated the effectiveness of VMS on driver behavior under adverse fog conditions. A driver simulation experiment was conducted over an 8.5 km replicated section of highway in Japan with two sign conditions (with and without VMS). The study found that 40% of subjects received the VMS system effectively, and ANOVA results indicated, on average, a 10 km/h reduction in speed over a one-kilometer roadway section before and after VMS installation.

Gudmundur et al. (*6*) evaluated VMS and in-vehicle traffic advisory systems on a 61-km segment through a mountainous pass in Washington. This section of Interstate 90 experienced a high number of collisions because of challenging roadway geometrics and adverse weather conditions. An NB model of overall collision frequency was developed and showed that grade, maximum rainfall, number of rainy days, and maximum daily snowfall all contributed to a significant positive accident occurrence. The model framework indicated that drivers who receive cautionary messages reduce their speed beyond what a driver who had not received the message would; however, drivers were found to return to their original speed shortly after. Before-and-after conditions for VMS were not able to be observed for this study and the importance of such a study was noted for an effective analysis of VMS.

The value in predictive capabilities for road safety is highlighted by Kim et al. (*7*) where the FHWA Road Weather Management Program's weather responsive traffic management tools (WRTM) is discussed. The WRTM framework discussed includes real-time operations (during inclement weather), short-term tactical planning (12–48 h before the weather event), and long-term strategic planning. The study noted that agencies with severe weather conditions require methods to predict the impact adverse weather may have on drivers.

Methodology

Evaluating a road safety initiative is typically done by comparing the level of safety before the initiative was implemented with the level of safety after the initiative was implemented. Collision frequency is most commonly used to define the level of safety and was the basis for this study. The anticipated safety benefit is represented by the difference between the number of collisions that occurred after the safety initiative compared with what would have been the number of collisions had the safety initiative not been implemented.

A simple cause-and-effect relationship is rare in road safety. Usually, several other factors occur simultaneously and may influence road safety performance; therefore, the effect of these other factors should be separated from the treatment effect. These confounding factors include history, maturation, and the regression to the mean (*8*). History refers to the possibility that factors other than the countermeasure being investigated caused all or part of the observed change in collisions. Maturation refers to the effect of collision trends over time. The regression to the mean refers to the tendency of extreme events to be followed by less extreme values, even if no change has occurred in the underlying mechanism that generates the process. The method adopted in this study corrects for the regression-to-the-mean effects, which is an important consideration in road safety analysis by using an Empirical Bayes (EB) technique. The method uses before-and-after collision and traffic volume data to correct for the changes in traffic trends over time. The method is described in detail in the Highway Safety Manual (HSM) (*9–11*). The evaluation method employs Safety Performance Functions (SPFs), which are mathematical models that relate the collision frequency experienced by a road entity to various traffic and geometric characteristics of this entity. The models are developed via a generalized linear modeling approach (GLM) which assumes a non-normal distribution error structure (usually Poisson or NB). The functional form of the SPF used in this study relates the expected frequency of serious winter collisions on a road section to traffic volume and section length such that:

$$E(\Lambda_i) = \mu_i = a_0 \cdot V_i^{a_1} \quad (1)$$

where

μ_i = expected mean seasonal collision frequency per kilometer on road section i,

V_i = seasonal average daily traffic (ADT) volume on road section i, and

a_1, a_1, a_2 = model parameters.

The variance of the predicted mean collision frequency, $Var(\mu_i)$, at location i can be calculated as follows:

$$Variance = Var(\mu_i) = \frac{\mu_i^2}{k} \tag{2}$$

where k = dispersion parameter of the NB model.

The EB technique refines the estimate of the expected number of collisions at a location by combining the observed number of collisions with the predicted number of collisions as obtained from SPFs. The reduction in the number of collisions at the treatment sites can be calculated using the odds ratio (O.R.) such that:

$$O.R. = \frac{D}{\hat{B}} \tag{3}$$

$$E(O.R.) = \frac{O.R.}{\left(1 + \frac{Var\hat{B}}{\hat{B}^2}\right)} \tag{4}$$

where $\hat{B}$ = EB safety estimate of collisions in the treatment group had no treatment taken place during post improvement period and D = Observed number of collisions in the treatment group during post improvement period.

The EB safety estimate and its variance for a location i are calculated as follows:

$$(EB_i)_b = \gamma_i \cdot \mu_i + (1 - \gamma_i) \cdot y_i \tag{5}$$

$$Var(EB_i)_b = \gamma_i \cdot (1 - \gamma_i) \cdot \mu_i + (1 - \gamma_i)^2 \cdot y_i \tag{6}$$

$$\gamma_i = \frac{1}{1 + \frac{\mu_i}{k}} \tag{7}$$

where y_i = observed collisions in the before period for location i and γ_i = weight assigned to the predicted value for location i.

The value $\hat{B}$ in the O.R. is adjusted to account for traffic volume changes in the after period:

$$\hat{B} = (EB_i)_a = (EB_i)_b \times \frac{(\mu_i)_a}{(\mu_i)_b} \tag{8}$$

$$Var\hat{B} = Var(EB_i)_a = Var(EB_i)_b \times \left[\frac{(\mu_i)_a}{(\mu_i)_b}\right]^2 \tag{9}$$

where

$(EB_i)_a$ = EB safety estimate of treated site i in the "after" period had no treatment taken place,

$(EB_i)_b$ = EB safety estimate of treated site i in the "before" period,

$(\mu_i)_a$ = expected mean collision frequency given by the SPF for a treated site i using its traffic volume in the "after" period, and

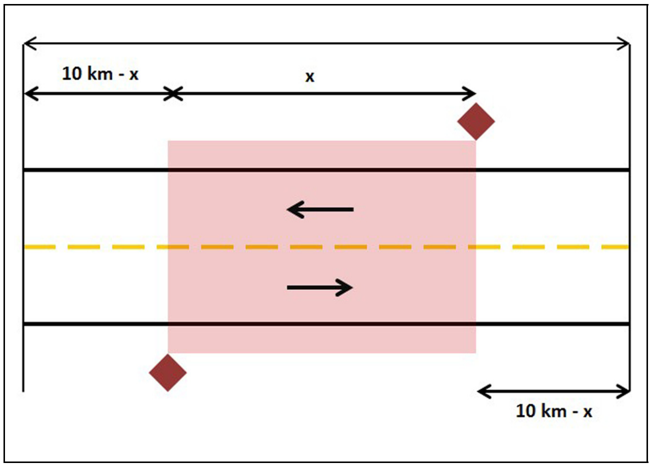

Figure 1. RWIS analysis length diagram.

$(\mu_i)_b$ = expected mean collision frequency given by the SPF for a treated site i using its traffic volume in the "before" period.

The effect of the treatment is determined by subtracting 1 from the O.R., as shown below:

$$Effect = E(O.R.) - 1 \tag{10}$$

To estimate the significance of the effect, the $T_{\text{Statistic}}$ is calculated as:

$$Var(O.R.) = \frac{(O.R.)^2 \times \left(\frac{1}{D} + \frac{Var\hat{B}}{\hat{B}^2}\right)}{1 + \frac{Var\hat{B}}{\hat{B}^2}} \tag{11}$$

$$T_{Statistic} = \frac{E(O.R.) - 1}{\sqrt{Var(O.R.)}} \tag{12}$$

Data Description

The evaluation of the safety impact of an improvement requires two sets of data: WSC and traffic volume data for the before-and-after implementation periods. The data is required for two groups of locations: the evaluation sites (i.e., treatment group) and the reference population.

Evaluation Sites

The safety evaluation was undertaken for six rural arterial undivided (RAU) highway sections in BC. Four sections had a two-lane cross section (RAU2), while the other two had four lanes (RAU4). A 10-km area of influence following the VMS in each direction of travel was assumed. The total analysis length of a RWIS/VMS section was defined as 20 km minus the distance between the VMS signs. This definition led the RWIS evaluation sections to vary. The RWIS/VMS section length definition is depicted in Figure 1.

Table 2. Attributes of Evaluation Sections and RWIS Installation Dates

Section ID	Road class	Hwy #	L (km)	Installation date	No. of seasons before	SADT (before)	No. of seasons after	SADT (after)
1	RAU2	4	13.0	2011-03-07	3	1376	6	1487
2	RAU2	1	19.3	2012-02-08	3	6573	5	8947
3	RAU2	3A	16.3	2013-02-07	3	7408	4	8537
4	RAU2	97	10.0	2013-12-04	4	3370	3	3322
5	RAU2	97	10.0	2013-12-04	4	3027	3	3052
6	RAU4	97	15.1	2014-01-22	4	2771	3	3072
7	RAU4	97	12.0	2014-01-24	4	18666	3	19345

For example, if the distance between two VMSs was 6 km, the total length of analysis would be 14 km. If the distance between the two VMSs exceeded 20 km, then the section would be sub-divided. Two VMSs were more than 20 km apart at one location, which was further subdivided into two different sections. As such, the final evaluation included seven sections at six different locations.

Collision data was extracted from the Collision Information System (CIS) of BC, which is a depository of police-attended collisions that have taken place on provincial highways since January 1987. The system allows its users to query and analyze different types and severity levels of collision data. All collisions in the system are linked to the Landmark Kilometre Inventory (LKI) of BC—a linear reference system used for location coding. In addition to collision data, the system also includes traffic volumes (i.e., average daily traffic (ADT)) of different road segments for different years, where in this study seasonal ADT volume was used. A query profile was created to specify the period of data extraction, the geographic boundaries of the queried data, and the required types and severity levels of collisions. Once a query profile is created, different datasets can be extracted such as the detailed collision reports, summary reports, histograms, and so forth.

Police-attended serious collision data (i.e., fatal + injury) was used in the current safety analysis. Property damage only (PDO) collision data have suffered significant underreporting in recent years in BC. As such, the use of PDO data was deemed inappropriate. Serious collision data are comprehensive and considered reliable for safety evaluation purposes. Each collision in the CIS is characterized by several attributes, for example, location, date and time of occurrence, segment geometry, roadway surface condition, land use, weather and lighting conditions, vehicle type, collision type, severity level, number of victims, and so forth.

As the installation date of each RWIS differed from one location to another, the before-and-after periods varied accordingly. Data of the installation year itself were excluded from the analysis to allow for some maturation (i.e., time of mitigation measure to become effective) before the actual evaluation. The analysis period included winter months only (October–March), with the before-and-after periods defined by the number of days to ensure accuracy. Depending on the implementation date, three to four winter seasons were available as a before-implementation period, while three to six winter seasons were available as an after-implementation period. Table 2 summarizes the attributes of the evaluation sites along with the installation dates of the barriers.

Reference Population

The EB method is based on Bayesian updating where two clues are combined to estimate the safety level at any entity: prior information and update. The prior information is typically determined from a group of sites called the reference population which includes sites that have similar characteristics and therefore can be considered replicates of the evaluation sections. Hauer (*9*) proposed calculating the mean and variance of collision frequency using the observed collision counts at reference population sites (i.e., prior). The method proposed by Hauer (*9*) was subject to further improvements over time where SPFs have been used to calculate the mean and variance of collision frequency rather than using the mean and variance of observed collision frequency. In this study, reference population data were used to develop the SPFs needed for the EB safety evaluation. The reference population belongs mainly to the same road class as the evaluation sites. Collision and traffic volume data were, therefore, extracted for two reference groups representing two road classes, RAU2 and RAU4. The data for each reference group were extracted for nine years covering all before-and-after periods for all reference sites.

Evaluation Results

Collision Frequency and Rates

Of the seven evaluation sections, all serious collision rates experienced a decrease with the exception of one, the Kalamalka RWIS/VMS section. The Kalamalka section

Table 3. Frequency and Rate of Winter Serious Collisions Before and After RWIS Implementation

Section ID	*Before SC*	*After SC*	*CF*/season (before)*	*CF/season (after)*	*% Change CF*	*CR** (before)*	*CR (after)*	*% Change rate*
1	3	3	1.0	0.5	−50.0%	0.309	0.143	−53.8%
2	15	14	5.0	2.8	−44.0%	0.218	0.089	−58.9%
3	17	22	5.7	5.5	−2.9%	0.259	0.218	−15.7%
4	21	8	5.3	2.7	−49.2%	0.860	0.443	−48.5%
5	17	8	4.3	2.7	−37.3%	0.775	0.482	−37.8%
6	7	4	1.8	1.3	−23.8%	0.231	0.158	−31.3%
Overall	**80**	**59**	**22.9**	**15.5**	**−32.5%**	**0.442**	**0.256**	**−42.1%**

Note: *CF = Collision Frequency; **CR = Collision Rate.

experienced a 54% increase in serious collisions following RWIS implementation. Upon further investigation it was found that a median barrier was installed on the Kalamalka section in 2016. The installation of this median barrier altered the conditions in the after period (October 2014–March 2017) from the before. The Kalamalka section was therefore excluded from the analysis as it no longer belonged to the same population group (RAU2 or RAU4). Table 3 presents the frequency and rate of WSC at each of the six evaluation sections in the before-and-after periods.

As shown in Table 3, both frequency and rate of WSC decreased at all sites. The reductions in WSC frequency ranged between 2.9% and 50.0%, while the counterpart reductions in WSC rates ranged between 15.7% and 58.9%. The overall reduction for all sections in WSC frequency and rate was 32.5% and 42.1%, respectively.

The observed reductions in collision frequency and rate clearly indicate an improvement in safety; however, collision frequency and rate are not appropriate evaluation measures of safety improvements, as they do not account for different confounding factors in safety analysis. A more robust safety evaluation was undertaken using the EB method and the results are presented in the following section.

EB Analysis

A SPF was required for each road class of RWIS section to undertake the EB analysis. Reference populations of provincial highway segments with RAU2 and RAU4 road classes were used to develop two SPFs. NB models were coded and developed using a statistical analysis system (SAS). The quality of the developed models was assessed using several goodness-of-fit criteria, including logicality of coefficient signs and statistical significance of the explanatory variables. Other common goodness-of-fit measures for NB models are the *Pearson* χ^2 statistic and the scaled deviance (SD). Both the *Pearson* χ^2 and *SD* are asymptotically χ^2 distributed with n-p-1 degrees of freedom. Both developed models showed good fit to the data. A summary of the models is presented in Table 4.

The models were applied to the six evaluation segments to estimate the predicted number of WSC at each segment. An EB refinement was then computed for each segment and the evaluation methodology was applied to all evaluation segments. Table 5 shows the predicted number of collisions, EB estimates (before and after the correction for volume changes), and the O.R.

The results show a significant decrease in WSC for all RWIS/VMS sections. The overall reduction in WSC was 32.7% and was statistically significant at a 95% level. The reduction had a relatively small standard error indicating that the lower limit of the collision reduction was exclusively negative. In general, the results of the evaluation showed significant safety benefits in relation to collision reductions.

Benefit-Cost Analysis

A benefit-cost analysis was performed to determine the safety benefit in monetary terms. The capital cost for each RWIS implementation varied based on the unique aspects of each location. The cost associated with each system was determined from project records and covers all aspects of RWIS installation (e.g., equipment, labor and material, power connection, etc.). The maintenance and operating annual cost was estimated to be Can$10,000. The cost of the RWIS/VMS at the first site was relatively high compared with other sites because of the high commissioning premiums of hydro-electricity connection costs. The cost estimates of a fatal and injury collisions in 2012 were Can$6.395 million and Can$135,577, respectively. Using an inflation rate of 1.54%, the estimates of fatal and injury collisions were Can$6.89 million and Can$146,343, respectively. The weighted average cost of a serious collision was calculated based on the proportions of injury and fatal collisions at the six sites. A value of Can$505,801 was used in the benefit-cost analysis. A nominal interest rate of 6% was used in the economic analysis, which follows the MoTI guidelines for benefit-cost studies.

Table 4. Results of SPFs Development

	Evaluation group	a_o	a_1	k	DF*	Deviance	χ^2	χ^2 (0.05)
Winter serious collisions	RAU2	0.0000919	0.8993	4.93	638	694.1	623.8	697.9
	RAU4	0.0001475	0.8345	3.57	44	48.4	46.9	60.5

Note: *Degree of Freedom = sample size; no. of model parameters − 1.

Table 5. Summary Results of Safety Evaluation

ID	$(\mu_i)_b$	Var $(\mu_i)_b$	γ_i	$(EB_i)_b$	Var $(EB_i)_b$	$(\mu_i)_a$	Var $(\mu_i)_a$	$(EB_i)_a = \hat{B}$	Var $(EB_i)_a$ = Var $(\hat{B})$	Observed after (D)	E (O.R.)
1	2.4	1.2	0.674	2.58	0.84	5.1	5.3	5.54	3.87	3	0.481
2	14.4	42.3	0.255	14.86	11.07	31.7	204.4	32.67	53.56	14	0.408
3	13.6	37.4	0.266	16.09	11.80	20.6	85.8	24.37	27.08	22	0.863
4	5.5	6.1	0.474	13.64	7.17	4.0	3.3	10.10	3.93	8	0.763
5	5.0	5.0	0.498	11.00	5.52	3.8	2.9	8.31	3.15	8	0.920
6	6.6	12.4	0.349	6.88	4.47	5.4	8.3	5.62	2.99	4	0.650
Overall								**86.6**	**94.6**	**59**	**0.673**
								Overall reduction			**–32.7%**
								Overall variance			**0.014**
								Standard error (SE)			**0.116**
								T-stat			**2.81**
								***p*-value**			**0.005**

Although PDO collisions were excluded from the safety evaluation as they are frequently underreported, for the case of cost evaluation, PDO collisions are valuable to include. Many claims are made to the Insurance Cooperation of British Columbia (ICBC) without reporting the collision to the police, therefore only accounting for police-attended crashes would underestimate the total collision reduction savings. In this case, a PDO multiplier was used to determine the collision reduction estimate for PDO collisions. The PDO multiplier represents the ratio between the number of PDO collision claims reported to ICBC and police-attended serious collisions. The multiplier was used to determine the potential reduction in the number of WSC as well as winter PDO. The average cost of a PDO claim was Can$11,367. The present value of costs was equal to the installation costs. The ratio of the present worth of benefits to the present worth of costs was determined for an overall benefit-cost ratio.

The present worth of costs and benefits for each RWIS/VMS segment are presented in Table 6. The benefit-cost ratio ranged between 1.1 and 38.0 with an overall benefit-cost of 4.8. The net present value (NPV) ranged between Can$85,347 and Can$9,147,738 with an overall NPV of Can$12,028,588. These economic indices demonstrate the financial feasibility of RWIS implementation on rural highways with severe weather conditions.

Discussion

The safety benefits for implementing a RWIS/VMS were evident in this study with an overall WSC reduction of 32.7%. The benefits of implementing a RWIS/VMS were exceeded by the cost for all locations, with an overall benefit-cost ratio of 4.8. This indicates that the implementation of RWIS/VMS in British Columbia was an effective investment in improving highway safety. Despite the confirmation of safety benefits of the system, there is room for further research to optimize the safety benefits associated with RWIS/VMS. The EB analysis indicated a WSC reduction for each RWIS/VMS segment which varied from 8.0% to 59.2%. Given that each location used the same time period (nine years), and annual average daily traffic (AADT) was normalized, the range in safety improvement indicates that some sites stood to benefit from RWISs more than others. Variables such as rainfall, temperature, snowfall, roadway geometry, and vehicle type could be analyzed to determine what site characteristics define an optimal RWIS location, which is a potential area for future research. A linear model was developed by Zhao (*12*) to determine optimal RWIS sites, and a similar study for BC highways would be beneficial to optimize the safety benefit of RWISs.

Table 6. Results of Benefit-Cost Analysis

Location	PWC	PWB (SC + PDO)	NPV	B/C
Kennedy Lake VMS	–Can$ 1,249,173	Can$ 1,334,547	Can$85,374	1.1
Quartz Creek VMS	–Can$ 247,173	Can$ 9,394,911	Can$9,147,738	38.0
Beasley VMS	–Can$ 447,082	Can$ 1,706,065	Can$1,258,983	3.8
Husk Lake northbound VMS	–Can$ 274,673	Can$ 1,315,849	Can$1,041,176	4.8
Hush Lake southbound VMS	–Can$ 274,673	Can$ 364,275	Can$89,602	1.3
Begbie Summit VMS	–Can$ 676,902	Can$ 1,082,617	Can$405,715	1.6
Overall	–Can$ 3,169,677	Can$15,198,265	Can$12,028,588	4.8

It is important for the before-and-after conditions to be consistent during the safety evaluation period to eliminate the influence additional factors may have on safety. EB analysis is robust and eliminates confounding factors that may influence the accuracy of evaluating safety.

Two of the six RWIS locations (i.e., Quartz Creek and Begbie Summit) were subjected to a speed limit increase before the analysis period was completed. The influence this may have had on the collision data could not be quantified, and it is possible that this confounding factor may have influenced the safety analysis undertaken by this study. There are two possible outcomes that the speed limit increase may have had. Firstly, the safety improvement of RWIS/VMSs may be higher than estimated, as the increase in speed limit may have negatively impacted safety. The alternative outcome would be that an increase in the speed limit had no impact on safety, as the controlling factor for driver speed selection was the weather conditions and not the increased speed limit. This outcome would indicate that the EB analysis results were accurate.

Summary and Conclusions

This paper reports on a safety evaluation of RWIS/VMS systems on provincial highways in BC, Canada. The study made use of WSC and traffic volume data for the treatment (i.e., installation) sections as well as a group of similar locations with no installation. An EB analysis was undertaken to assess the safety gains of the systems implemented. The evaluation made use of three to four years of pre-implementation data along with three to six years of post-implementation data. The results showed significant safety improvements at RWIS/VMS sections where reductions in WSC frequency ranged between 2.9% and 50.0%, with the corresponding reductions in WSC rates ranging between 15.7% and 58.9%. The overall reduction for all sections in WSC frequency and rate was 32.5% and 42.1%, respectively. The EB analysis showed that the safety impact differed from one RWIS section to another, where the reduction in WSC ranged between 8.0% and 59.2%, with an overall significant reduction of 32.7% across all RWIS sections. The significant reduction in WSCs demonstrated the safety effectiveness of RWISs on rural undivided highways in British Columbia. These results are generally consistent with the studies found in the literature.

Complications of this study included: one RWIS/VMS site becoming a divided highway, making it no longer eligible for the analysis, and two other RWIS/VMS sections being subject to a speed limit increase in the after period. The speed limit increase was discussed and, at worst, would likely not have impacted safety whatsoever; at best, it would have caused an underestimate in the RWIS/VMS safety improvement.

An economic evaluation was undertaken for the six systems where benefits were expressed in relation to monetary values of collision reductions. The benefit-cost ratio and NPV were calculated for each site and for all RWISs. The benefit-cost ratio ranged between 1.1 and 38.0 with an overall benefit-cost of 4.8. The NPV ranged between Can$85,374 and Can$9.15 million with an overall NPV of more than Can$12 million. These numbers demonstrate the economic feasibility of RWIS/VMSs integration as a successful ITS safety measure.

Overall, the results of this study show that RWISs are effective in enhancing driving conditions under severe weather and consideration should be given to expanding their use. The results of this study can be useful for transportation agencies and stakeholders who are interested in pursuing similar systems for mitigating weather-related safety problems.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: MEE and SW; data collection: SW and CS; analysis and interpretation of results: MEE and CS; draft manuscript preparation: CS and JS. All authors reviewed the results and approved the final version of the manuscript.

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