ROAD WEATHER INFORMATION SYSTEM CONTRIBUTIONS TO ROAD SAFETY

AN ASSESSMENT OF WINTER CRASH HISTORIES IN ALASKA

FINAL PROJECT REPORT

by

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16. Abstract

Various transportation authorities have relied on road weather information systems (RWIS) to make informed decisions about winter road maintenance. The use of RWIS can provide a variety of advantages in terms of improving road safety. This report provides a solid foundation of information about the development of the use of RWIS across states, as well as a traffic safety analysis of the use of RWIS as a road safety countermeasure to reduce crash rates during the winter season. RWIS have been in use by the Alaska Department of Transportation since 2000; for this investigation 26 of the state's 75 statewide RWIS stations were considered. The impact of utilizing RWIS on crash rates was captured by using the Empirical Bayes technique. The authors propose that three safety performance metrics be created for winter crashes in Alaska. RWIS as a winter road safety countermeasure is novel, which is why this study established a crash modification factor. The results showed that RWIS implementation has the potential to reduce fatal and serious winter crashes by 36 percent with an expected cost to benefit ratio of approximately 1:27.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	$candela/m^2$	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

ACRC:	Alaska Climate Research Center
AKDOT&PF:	Alaska Department of Transportation & Public Facilities
AWSSI:	Accumulated Winter Season Severity Index
CMF:	Crash modification factor
EB:	Empirical Bayes
FCC:	Federal Communications Commission
FHWA:	Federal Highway Administration
GPS:	Global Positioning System
MAD:	Mean absolute deviance
MARWIS:	Mobile Advanced Road Weather Information System
MDOT:	Michigan Department of Transportation
MDSS:	Maintenance Decision Support System
MDT:	Montana Department of Transportation
MnDOT:	Minnesota Department of Transportation
MPB:	Mean prediction bias
MSPF:	Mean squared prediction error
mRWIS:	Mobile road weather information system
NWS:	National Weather Service
PacTrans:	Pacific Northwest Transportation Consortium
RWIS:	Road weather information system
SPFs:	Safety performance functions
USDOT:	United States Department of Transportation
VTrans:	Vermont Agency of Transportation
WADT:	Winter average daily traffic
WRM:	Winter road maintenance
WSC:	Winter severe accidents
WSDOT:	Washington State Department of Transportation

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EXECUTIVE SUMMARY

Many transportation agencies located in cold and snowy climates depend on road weather information systems (RWIS) to make informed, data-driven winter road maintenance decisions. RWIS have the potential to improve road safety in several ways, including more timely and appropriate maintenance response and better distribution of travel condition information to the public. This report provides a solid foundation of knowledge about the evolution of RWIS throughout states and presents a traffic safety study of its application as a winter road safety countermeasure. The Alaska Department of Transportation and Public Facilities has used RWIS since 2000. In this study, 26 RWIS stations and proximal winter crashes were investigated. Using Empirical Bayes , we compared crash rates with and without RWIS present (i.e., pre- and post-installation). This research proposed three safety performance functions for Alaska winter crashes. Using RWIS as a direct safety countermeasure is innovative; hence, a crash modification factor was established. The analysis suggested that RWIS installation could reduce fatal and major winter crashes by 36 percent, with a cost-to-benefit ratio of 1:27

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CHAPTER 1. INTRODUCTION

A strong economy depends on a well-functioning transportation network. In 2014, the United States invested about $165 billion in more than 4,071,000 miles of public highways; 45 percent of the expenses were operational services (Geddes and Madison, 2017). Winter road maintenance (WRM) services costs of approximately $2 billion every year to federal, state, and municipal governments include chemical and abrasive spreading, snow plowing, and moving snow with trucks (Minsk et.al, 1998). WRM is necessary to keep roadways operational in the winter and to decrease the adverse effects of ice and snow accumulation on roads. WRM can be affected by weather and geography. That is, regions with cold climates experience considerably variable seasons of snow, ice, and subzero temperatures. In addition to environmental factors, road administrators also have to keep in mind the road users' general awareness for dealing with challenging weather driving conditions when they plan their winter travel strategy (Norem, 2001).

Different transportation agencies use a wide range of approaches to enhance WRM decisions to ensure optimum cost effectiveness. One technique is to use road weather information systems (RWIS) data to inform maintenance operations. RWIS are an integrated technology that collects, processes, sends, and produces weather and road condition information to assist agencies and the people responsible for WRM in making proper decisions. The first case of RWIS operation was recorded in the 1970s, and they became more common throughout the 1980s, primarily focused on supporting WRM decision-making.

Figure 1.1 shows a typical RWIS station setup. The RWIS system gathers data with different types of sensor stations and produce real-time reports that describe roadway surface conditions and the weather. That information plays a critical role in both cost-effective WRM and road users' decision-making for their travel (Kwon et.al, 2016).

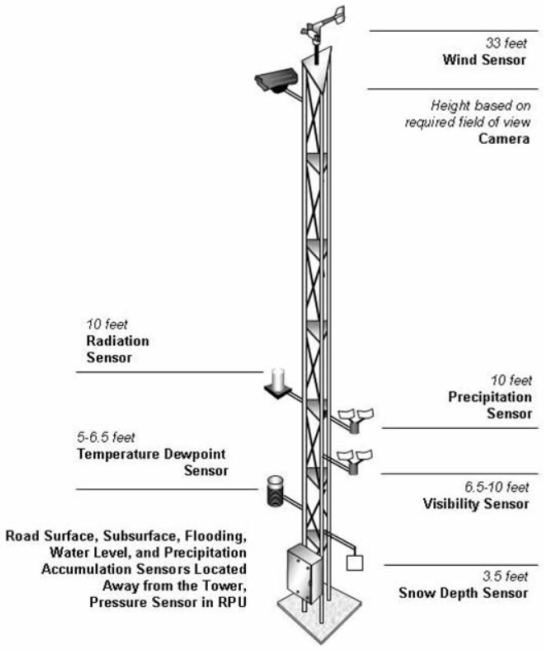

Figure 1.1 Typical RWIS station (FHWA, 2020)

The work presented herein reflects a modification to the original scope of work, as PacTrans did not approve the purchase of mobile RWIS (mRWIS) units. The new tasks included the following:

1. Perform network screening and an Empirical Bayes (EB) analysis of winter-related crashes and the deployment of RWIS in Alaska.
2. Develop winter-related crash safety performance functions (SPFs), controlling for RWIS deployment, to generate crash modification factors (CMFs) and estimate the locally calibrated benefits of RWIS.
3. Identify potential gaps in RWIS coverage by using a spatial model that controls for state crash history.

The objectives were to quantify the benefits of RWIS integration from a winter safety perspective and to identify potential locations for further RWIS deployment that considered safety and other relevant maintenance factors. The researchers intended to explore how to further integrate RWIS into the Alaska Department of Transportation & Public Facilities' (AKDOT&PF) workflow and to evaluate the safety benefits of general RWIS technologies.

CHAPTER 2. LITERATURE REVIEW

RWIS data have been implemented in several applications, ranging from automated road deicing to evacuation preparation. The most common uses of RWIS are to provide data for guidance on WRM decisions and to report weather-related driving risks to the public (Tessier and Russel, 2016). Below is a discussion of RWIS applications in select states, including costs and benefits, impacts on road safety, how maintenance strategies are informed by RWIS, and how RWIS impact weather prediction models.

2.1. Applications of RWIS (Case Studies)

The Montana Department of Transportation (MDT) operates 73 RWIS stations in different locations throughout the state. Those 73 RWIS stations have been a primary source of weather data for transportation purposes. The MDT RWIS program has realized several benefits from the RWIS, including to MDT itself and to the traveling public. The benefit-cost ratios for agency-specific benefits, such as savings on labor, materials, and equipment, range from 1.1:1 to 11:1. When safety, operational, and other societal benefits are also taken into account, benefit-cost ratios can be above 40:1. MDT has made recommendations to expand and improve the current RWIS system, including adding new RWIS hardware, software, and sensors choices to allow the integration of different equipment that may cut the cost regardless of the supplier. Also, RWIS camera images and data need to be updated every 15 minutes or less for all locations. Most of the literature has suggested that a period of 15 minutes significantly affects winter maintenance treatment, especially at the start of a storm (Ewan et.al, 2017).

The Michigan Department of Transportation (MDOT) has over 100 RWIS stations that gather data on pavement conditions, road weather conditions, traffic images, and subsurface temperatures. The collected data from 2019 could reach hundreds of gigabytes. However, despite this wealth of data and increasing investments in facilities and equipment, MDOT claims that using such data to assist in maintenance decision-making and road operations is still not ideal under the current model, and it is seeking to use a web-based method in the future (Liu et.al, 2021).

In 1988, the Minnesota Department of Transportation (MnDOT) implemented its first RWIS station in the Minneapolis area. Shortly afterward, a temporary organization was formed to study the performance of a statewide integrated RWIS. Seventeen more RWIS stations were installed through the state by the end of that same year. MnDOT reported that after the first stage

of installing RWIS stations, additional data from RWIS allowed WRM processes to be proactive rather than reactive to mitigate the effects of extreme weather circumstances and lower the probability of vehicle crashes. MnDOT recognized the advantages of adding RWIS stations to its network, so the number of RWIS stations has increased through the years. At present, MnDOT has 93 RWIS stations, and this number is projected to grow in the future (Kwon et.al, 2017).

According to the Vermont Agency of Transportation (VTrans), 38 RWIS stations currently operate across Vermont. These stations are supplied with a variety of instruments that record data about the weather, traffic flow, and road surface conditions. Two additional variables are imputed when the data are recorded (usually in 10-minute intervals). Rain state and rain on/off are computed for 30 and 26 RWIS stations, respectively. Of Vermont's RWIS stations, 23 are on Interstates, six are on U.S. highways, and nine are on state highways. Twenty-one RWIS stations were set to record level of grip in the winter of 2016-17; however, two of those devices had technical issues and were unable to do so throughout that year (Dong et.al, 2019).

There are 86 RWIS stations throughout Iowa (Ye et.al, 2009). Since 1988, the Iowa Department of Transportation has used RWIS to manage snow and ice. It collaborated with SAS, a data analytics firm, to create a model that predicts present and anticipated winter road conditions. Data from RWIS and manually produced winter road condition reports were used to build the model (Crowson, 2020).

In New Hampshire, 12 RWIS stations record observations every 6 to 10 minutes. Additional stations will be installed when the budget allows. The state of New Hampshire has reduced funding for DOT projects in its 10-year plan, making it uncertain whether the number of RWIS will be extended. Maine Department of Transportation operates nine RWIS stations throughout the state. These are being utilized to collect data to better understand weather and road condition patterns (Rubin et.al, 2010).

The Colorado Department of Transportation manages an RWIS network with 109 stations along Colorado roads. Every 15 minutes the network measures air temperature, dew point, relative humidity, barometric pressure, wind speed, wind direction, wind gust, precipitation type, and intensity. At some sites, statistics on precipitation accumulation and visibility are also available (Brown et.al, 2012).

According to the AKDOT&PF ITS Coordinator, there are about 75 RWIS sites in the state of Alaska (A. Stevens, personal communication, August 29, 2021). Alaska DOT&PF is in

the middle of a pilot project to add mini-RWIS sites. Alaska DOT&PF installed five more in summer 2021. Public interest funding is used to supply the RWIS equipment. The AKDOT&PF budget is $800,000 per year for the RWIS sites, including a contract for maintenance and utilities (power and communication). In addition, AKDOT&PF budgets $863,000 per year for 511 maintenance and enhancements (contractor).

2.2. The Expenses and Advantages of Using RWIS

Despite their documented advantages, RWIS stations are costly to install and operate. The typical installation cost per station (depending on the kind and number of sensors included) may be as high as $100,000 (Kwon et.al, 2017). The high cost of RWIS installation and operation is a concern for transportation authorities. They must present justifiable reasons for their RWIS network development strategy, such as improvements in road surface conditions and thus safety and maintenance operations. This section documents previous efforts regarding RWIS cost-benefit analyses by year.

A 2008 report focused on a case study of Utah Department of Transportation's nationally unique Weather Operations/RWIS program to evaluate the advantages and costs of weather information. Using an artificial neural network method, the researchers reported that the benefit–cost ratio connected with the program was above 11:1, based only on the labor and materials cost reductions related to winter maintenance. Because additional program users' economic advantages were not included as part of that research, the actual benefit–cost ratio of the program may have been higher (Strong et.al, 2008).

Ye et al. (2009) provided a generic method for estimating winter maintenance expenditures. To identify the major input factors that had substantial impacts on costs and to examine how weather information affected winter maintenance expenses, a technique that combined neural networks and sensitivity analysis approaches was employed. The findings of the study showed that improved accuracy and greater utilization of meteorological data could lower winter maintenance expenditures. Finally, a benefit–cost study revealed that weather data could help enhance winter maintenance while also lowering agency expenses. The impact of weather information frequency and accuracy on expenses was examined in that study. It determined that when the frequency or accuracy rose, the mean cost dropped.

A report from 2011 (Cluett et.al, 2011) provided valuable information about the benefit-cost ratio of using RWIS to cut WRM costs for different states. For Michigan, the projected

benefit-to-cost ratios for rural RWIS installations ranged from 2.8 to 7.0, depending on the area. A benefit-cost study performed as part of MDOT's regional pre-deployment studies revealed possible advantages in terms of decreased travel time, crash prevention, and cheaper operating costs. RWIS was found to have benefit-cost ratios of 1.8 to 36.7 in Iowa and Nevada, with winter maintenance expenses decreased by $272,000 to $814,000. Finally, the Utah Department of Transportation's Weather Operations/RWIS program had a benefit-to-cost ratio of 11:1 as a result of lower winter maintenance expenditures. According to the model used, the value and further savings potential of the Utah DOT weather service were projected to be between 11 and 25 percent for materials and labor expenses and between 4 and 10 percent for winter maintenance.

In Minnesota, a 2014 study discussed a cost-benefit analysis to explicitly account for the possible advantages of an RWIS network for location and density planning. The method was based on the premise that a highway segment with an RWIS station would be more likely to receive better WRM than a highway section without one. Given a network of 45 RWIS stations in northern Minnesota, a case study based on the existing RWIS network indicated that the highest estimated 25-year net benefits were about $6.5 million, with a cost-benefit ratio of 3.5 (Kwon et.al, 2015).

According to research performed in New York State in 2015, the benefit-cost ratio for 38 new RWIS sites ranged from 10.80 to 15.52, depending on the cost of installation and maintenance choices. To produce benefit-cost ratios for particular areas or individual stations, more data inputs would have be gathered. For example, different sensors (such as precipitation, air/pavement temperature, and camera pictures) placed at different locations could result in varying installation and maintenance costs (Zhao et.al, 2015).

The findings of these studies, and a lack of consideration of RWIS as a direct road treatment, prompt the need for a more comprehensive analysis that takes into consideration the effects of using the RWIS on winter crashes.

2.3. RWIS Impacts on Road Safety

Weather forecasting plays an important role in traffic safety and mobility, particularly for cold and snowy climates. Weather data and information can be provided to the traveling public through a number of platforms, such as radio, television, and weather mobile applications. RWIS stations can contribute significantly to these weather predictions by measuring road

weather characteristics and providing larger spatial coverage for weather model calibration and validation. Different studies have demonstrated the positive relationship between the spread of RWIS stations and enhanced road safety. According to a 2012 study by Greening, a well-maintained RWIS network could decrease accident rates by a considerable amount, resulting in significant savings (Greening et.al, 2012).

The present method of choosing RWIS station sites is heavily reliant on the expertise and experience of field operators. The positive correlation between RWIS and decreases in adverse weather crashes has prompted more researchers to think about choosing RWIS locations in relation to areas with high crash rates. In 2014, research suggested a new spatial optimization method that worked with weather-related crash rates to ensure that the installed sensor system could offer sufficient coverage for regions where weather-related safety was an issue. The suggested method could be used in the selection of new RWIS network locations, as well as for adding stations to a present system (Jin et.al, 2014). In 2019 El Esawey claimed that RWIS offered a safety advantage in a study performed in British Columbia, with a statistically significant reduction of 32.7 percent for winter severe accidents (WSC). The studied systems had a benefit-cost ratio of 4.8 and a net benefit of more than $12 million, according to an economic analysis (El Esawey et.al, 2019).

Another study conducted in Illinois (Atallah et.al, 2012) concluded that in regions where snowstorms are frequent and the demand for road treatment is considerable, a decrease in the number of crashes primarily due to adverse weather could be on the scale of 20 percent. Crashes caused by slick weather or poor visibility often involve several cars and cost approximately $250,000, not including time lost as a result of the collision. If one less accident occurs each weather event and there are 60 weather events per year, as in McHenry County, the municipality could expect to save approximately $13 million per year by using a road decision model rather than guessing when to treat the roads without one. Every year, this could equate to 52 fewer accidents. Similarly, the number of deaths and severe injuries caused by weather-related incidents could drop by up to 40 percent. If deaths and severe injuries cost an average of $4.2 million, the city could save approximately $22 million per year if the roads were properly maintained, and five lives could be saved each year. Another community advantage linked to safety is better access for emergency vehicles to assist individuals in trouble during weather

events, whether as a result of traffic crashes or other circumstances. Over $35 million in savings to the city might therefore be ascribed to increased traffic safety during bad weather.

2.4. How RWIS Informs Maintenance Strategies

Since 1999, the Federal Highway Administration's (FHWA) Road Weather Management Program has invested in the creation of a Maintenance Decision Support System (MDSS) to assist highway maintenance agencies in ensuring the safety and mobility of the traveling public. The MDSS has progressed from an idea to a working application through collaborations with a group of national labs and a stakeholder community of public, commercial, and academic players. In general, the MDSS is a computer-based, configurable instrument that delivers route-specific weather prediction information and treatment suggestions to winter maintenance workers. The MDSS offers route-specific weather and road condition predictions at different intervals, as well as optimal treatment suggestions for type, quantity, and application timings. It also educates new maintenance workers by utilizing tailored rules of practice and historical replay capabilities. All of these functions combine to produce a more secure and efficient transport network (Federal Highway Administration, 2020a).

AKDOT&PF, like many other state DOTs, has effectively adopted the MDSS, allowing maintenance and operations teams to prepare for winter storms rather than react to them. When anti-icing is used in conjunction with RWIS data, the savings could reach 10 percent to 20 percent (Goselly et.al, 2001). To enhance the weather algorithms utilized in the MDSS, the AKDOT&PF developed a program of weather data collection that utilizes a mobile weather data collection device supplied by Weather Cloud, Inc. At a cost of $1,250 per unit installed (including the cost of the cell phone and sensors) and $1,250 per year for the license charge, the system gathers air temperature, relative humidity, pavement temperature, location, vehicle direction, and vehicle speed. Data collection and transmission to the MDSS, as well as cellular data costs, are included in the license price. Weather Cloud was approached to determine whether these inexpensive multiple sensor devices might be included into a limited cost and limited power RWIS. The goal was not to replace current RWIS stations but rather to supplement existing systems and enhance the density of RWIS at a low cost (Connor, 2018). The RWIS stations measure real-time data, some of which are used by the U.S. National Weather Service (NWS) to assist with forecasting in specific regions. In 2001, the NWS and the FHWA collaborated on a study to determine how RWIS data might be utilized most effectively for both

road condition prediction and weather forecasting in general. One of the project's objectives was to encourage the exchange of RWIS observations and sophisticated meteorological modeling methods to enhance road condition forecasts for road repair, operations, and travel choices. Enhancing the NWS's forecasting skills by building and evaluating high-resolution, meso-scale and regional scale-simulations was also one of the project's objectives (Pisano et.al, 2002).

2.5. Availability of Road Weather Information to the Public

One of the primary advantages of RWIS is to improve the mobility of the traveling public (Kwon et.al, 2013). Transportation administrators develop roadway warning systems, interactive telephone systems (e.g., 511), and websites to gather and publish road weather information to travelers in order to improve their choices. This information allows drivers and passengers to make decisions about departure time, travel mode, vehicle type, and route. On March 8, 1999, the U.S. Department of Transportation (USDOT) asked the Federal Communications Commission (FCC) to establish a national three-digit telephone number for passenger information. Seventeen state departments of transportation, 32 transit operators, and 23 metropolitan planning organizations and municipal governments signed the petition. The FCC established "511" as the unified traffic information telephone number for states and local jurisdictions throughout the nation on July 21, 2000 (Federal Highway Administration, 2020b). The information about road weather conditions could be delivered to drivers by several methods. DOT websites are a great way for road users to learn about possible road and weather conditions. Additionally, dynamic message signs installed on the side of the road provide travelers with updated information about road situations ahead.

The AKDOT&PF has launched a new 511 road condition alert system that combines crowd-sourced data with navigation to provide drivers with the most updated information. In Alaska, people can access the new system by visiting 511.alaska.gov, calling 511, or downloading the 511 Alaska mobile app. The system has been made more user-friendly and mobile-friendly. The website is compatible with mobile phones, which means users are able to zoom in/out of the travel map and click on specific areas for more information. Users can also set personalized routes to places they travel frequently to receive notices and alerts for those areas (Williams, 2019).

2.6. Mobile Road Weather Information Systems (mRWIS)

Current RWIS technology is restricted to reporting conditions near the stations, necessitating the deployment of large, expensive networks or leaving large data gaps over a region. Many RWIS suppliers have created mobile, vehicle-mounted weather sensors as an alternative option to complement fixed RWIS sites and fill in data gaps so that road conditions are more properly represented. Four types of vehicle-mounted sensors are discussed in this section (Minge et.al, 2019).

2.6.1. Lufft MARWIS

The first version of Lufft's Mobile Advanced Road Weather Information System (MARWIS) was released in November 2014, followed by a second edition in April 2016, as shown in Figure 2.1. The ability to gather information on ambient air temperature and humidity was introduced in version 2.0. Pavement temperature, dew point, water/ice film height, six reportable surface state variables, and a surface friction coefficient are some of the other data collected by the MARWIS. The six reportable surface state conditions are dry, moist, wet, ice, snow/ice, and critically/chemically wet. When wet conditions are observed with surface temperatures below the freezing point, the critically/chemically wet state develops (indicating the presence of chemicals or the near possibility of ice forming). Because the MARWIS is Bluetooth-enabled, the only restrictions on mounting position are the distance of a typical Bluetooth data transfer (around 30 feet) and the place where users want to gather data. A mounting height of 1 to 2 meters above the observed surface is suggested. A 15-foot cable is supplied for connection to a modem or automatic vehicle location system, although bespoke extensions of the standard wire may be ordered as needed. Sensors are fixed on the front of a car or between the tires on the back, according to Lufft. It said that the Michigan DOT has installed many of these sensors on snowplows. The Arkansas, Minnesota, Missouri, Indiana, North Dakota, Nevada, Ohio, New York City, and Colorado departments of transportation, the Michelin Tire Company (for tire testing), and many school districts on the East Coast all utilize or are testing Lufft's MARWIS. Because of the nature of a newer product, the expected useful life of each sensor is uncertain; however, Lufft had had numerous sensors in the field for over four years at the time of this report, and all were still functioning.

Figure 2.1 Lufft MARWIS (Minge et.al, 2019)

2.6.2. Teconer RCM411

Teconer's RCM411 (Figure 2.2) monitors pavement temperature, air temperature, dew point, humidity (optional), water film height, six surface states, and friction coefficient. The reportable surface states are dry, moist, wet, slush/ice/snow with water, ice, and snow. The smartphone app records speed and Global Positioning System (GPS) location. The RCM411 connects to a 50-mm ball joint towing hitch receiver on passenger automobiles. An adapter can mount the sensor on a car's rear door or bumper. The best site for installation is behind the front grill, but space is restricted there; therefore, the sensor was developed for a trailer hitch. The standard mount monitors the left tire track, but it may be changed to the right. The maximum mounting height is 2 m, although 20 to 22 in. is preferred. Three-meter cables and connections are provided for immediate usage. Teconer predicts that each RCM411 will last ten years, while bolts or safety pins may need to be replaced sooner. Several DOTs and worldwide road and airport authorities utilize the RCM411.

Figure 2.2 Teconer RCM411 (Minge et.al, 2019)

2.6.3. High Sierra Mobile IceSight

High Sierra's Mobile IceSight (Figure 2.3) debuted in 2013 and was updated in 2015. IceSight's open-architecture data output comprises air temperature, relative humidity, surface temperature, six surface state variables (dry, damp, wet, slush, snow, and ice), and a surface friction coefficient. High Sierra has collaborated with car controller companies to combine GPS data from various sources. Mobile IceSight provides multiple mounting choices and a 3- to15-ft range. A 15-ft wire connects to the sensor wherever it is installed. Depending on where the sensor is positioned and the angle at which it is pointed, the pavement detection area can range from 6 to 18 square inches, offering a vast area of detection to assure accurate readings of the whole highway surface. IceSight can be mounted within the engine compartment, behind the driver's cab, or on the road-facing roof. IceSight's usable life is five to ten years. Minnesota and New York use High Sierra's Mobile IceSight.

Figure 2.3 High Sierra Mobile IceSight (Minge et.al, 2019)

2.6.4. Vaisala DSP310

The DSP310 is Vaisala's mobile DSC-111 weather sensor, as shown in Figure 2.4. It can measure pavement surface temperature, friction coefficient, ambient air temperature, dew point, humidity, and water/ice/snow layer thicknesses. The reportable surface conditions are dry, damp, wet, snow, and ice. The DSP310 collects data via three sensors. For pavement temperature collection, the DSP101 infrared sensor needs an unobstructed view of the road. To obtain reliable ambient air data, the HMP-155 must be installed away from vehicle heat or exhaust. The DSC-111 should be installed 1.5 to 3 meters above the road. The typical mounting angle is 45 degrees to the ground. Five-meter cables connect sensors to the controller. Vaisala is developing a DSP310 replacement sensor. In 2018-2019, state agencies were evaluating the new Vaisala gadget.

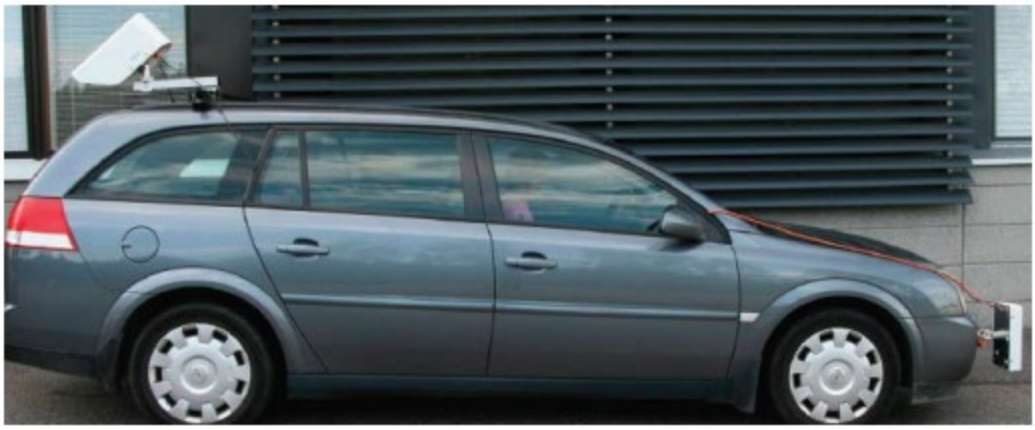

Figure 2.4 Vaisala DSP310 (Minge et.al, 2019)

CHAPTER 3. METHODOLOGY

3.1. Project Data

To introduce the RWIS as a road treatment strategy, a number of actions were taken to ensure the accuracy of this approach. First, weather data were collected both before and after the RWIS stations had been installed to ensure that any decrease in crashes was not due to an improvement in the weather. Second, crash data, the winter average daily traffic (WADT), and road geometry were collected for the RWIS station sites. Finally, crash analyses, crash modification factors, and cost-benefit analyses were employed to achieve the study's objective.

3.1.1. RWIS Stations

The RWIS data were gathered from the AKDOT&PF's road weather web page. As shown in Figure 3.1, only 26 RWIS stations were chosen, depending on the availability of crash data and to prevent the interaction among several RWIS stations per road section. The analysis assumed that the road section would have one RWIS station and that there would be one maintenance station at the beginning of the route and another at the end. This assumption was intended to represent the relationship between the information supplied by the RWIS and the decisions made by the road maintenance stations about the road's maintenance.

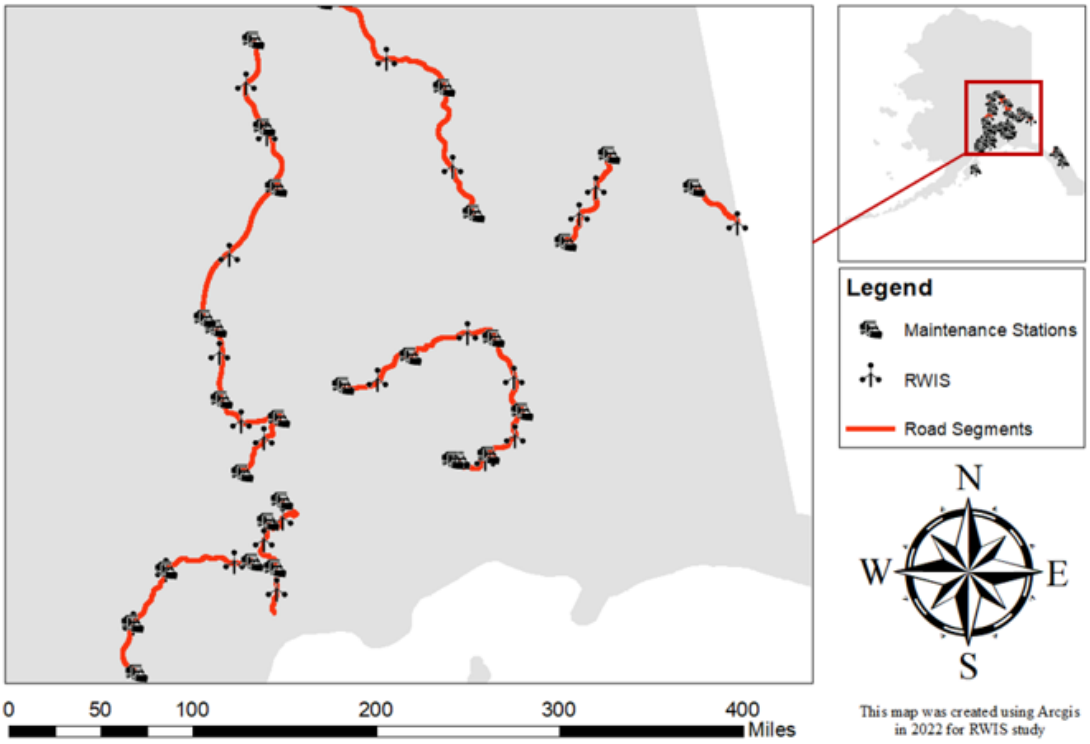

Figure 3.1 Selected RWIS and road maintenance stations in Alaska

3.1.2. Crash Data and Road Geometry

Winter crash data were compiled from the Alaska Department of Motor Vehicles' crash reports. This research included only winter crashes. For three winter seasons before installation of the RWIS stations, 3,346 crashes occurred on the 26 separate road segments, resulting in 45 deaths. For three winter seasons after the RWIS stations were employed, the overall number of crashes was 3,090, with 37 deaths. The study covered 1,030 miles of Alaskan highways. Typically, each RWIS station was positioned between two maintenance stations, and the mile markers for those maintenance stations were employed to compute the length of each road section. After the yearly average daily traffic had been obtained from the website of the Traffic Analysis and Data Application of the AKDOT&PF, , WADT was determined by making use of the winter monthly factor that was also provided by the same website. The data regarding the road segments that were analyzed for this inquiry are included in its entirety in Table 3.1. Table 3.1 also presents the average number of crashes that occurred at each RWIS location during the three winter seasons before the installation of the RWIS, as well as the three winter seasons following the installation of the RWIS.

Table 3.1 A summary of each RWIS site's statistics

RWIS ID	Year of Deploy	Road Length	3 years average AWSSI		3 years average WADT		Average number of crashes for 3 years before period			Average number of crashes for 3 years after period		
			Before	After	Before	After	Total Crashes	fatal and serious injury	Ice, Snow, Slush	Total Crashes	fatal and serious injury	Ice, Snow, Slush
22	2003	93	3118	3802	902	1018	78	3	53	101	5	44
21	2003	47	2529	2948	167	164	4	0	2	4	0	2
20	2003	28	2529	2948	885	948	8	0	5	12	0	5
18	2003	46	1546	2063	781	801	9	0	7	13	1	5
17	2003	23	1143	1453	336	509	9	0	3	4	0	2
15	2003	5	568	613	8737	8781	39	2	14	32	2	8
14	2003	5	509	574	21927	21799	21	1	12	20	0	4
13	2003	53	1130	1411	1449	1609	44	3	30	46	2	20
12	2003	32	1259	1782	1651	1716	47	2	30	44	3	30
10	2003	33	1259	1782	7267	7597	105	5	62	115	5	42
9	2003	50	2138	2936	1162	1154	42	3	37	55	4	20
8	2003	35	2138	2936	8788	8403	172	12	79	160	9	51
30	2004	13	3189	2953	263	293	0	0	0	0	0	0
24	2004	78	3324	3935	284	285	11	0	6	10	0	6
23	2004	60	3580	4135	331	279	5	0	2	4	0	2
11	2004	31	2249	2213	1844	2008	24	2	9	13	1	10
42	2005	46	1972	2311	632	592	8	1	4	5	0	2
35	2005	35	1972	2311	267	193	4	0	2	4	0	1
31	2005	90	3353	3504	697	753	43	3	19	23	1	19
46	2006	35	2088	2263	23212	25132	282	16	5	205	9	120
43	2006	34	2400	3018	2097	2078	45	5	26	30	2	16
39	2006	38	3159	3267	1329	1343	17	2	8	11	0	4
47	2007	16	636	781	194	297	0	0	0	0	0	0
44	2007	20	2218	2410	1423	1034	17	1	8	15	0	7
41	2007	54	3722	3949	1073	926	15	2	7	11	1	4
37	2007	33	4138	3876	352	302	6	0	0	3	0	1

3.1.3. Weather Data

Average snow depth and average temperature were acquired from the Alaska Climate Research Center (ACRC) and the Alaska State Climate Center to determine the winter season in Alaska during the research period. As seen in Figure 3.2, the winter season typically begins around early October and ends around early May. The rationale for limiting the selection to winter crashes was the relationship between the RWIS and winter road maintenance decision support. Inherently, the summarized crashes would have taken place in the last quarter (October through December) of one year and the first third (January through April) of the next year.

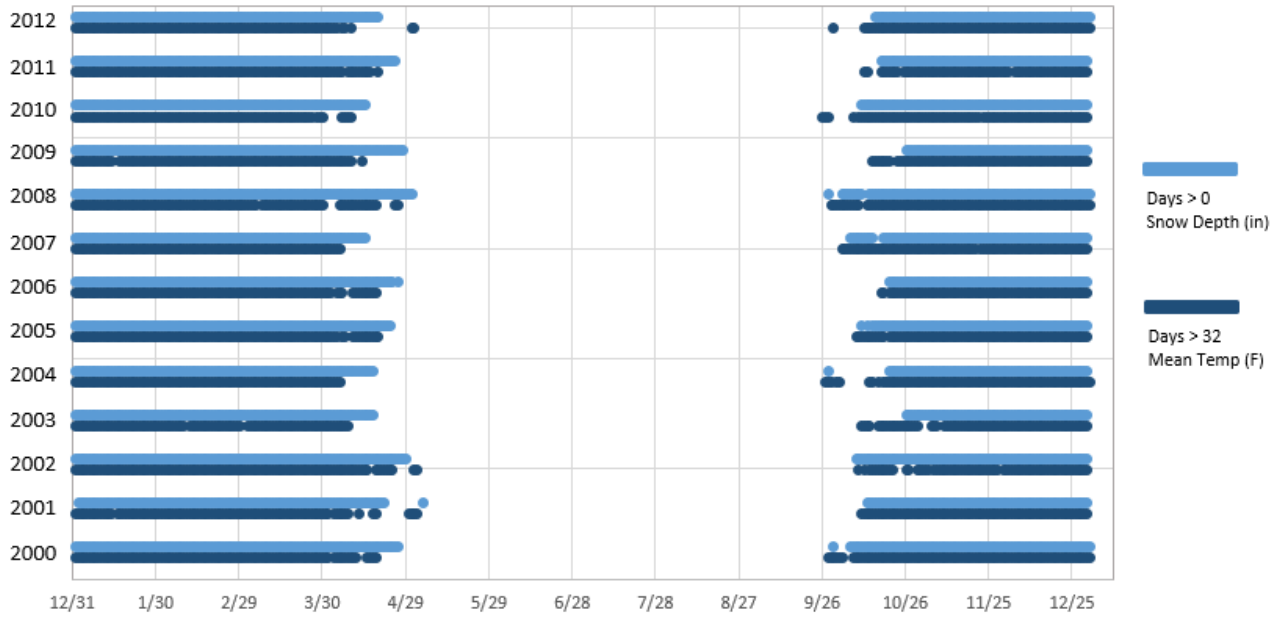

Figure 3.2 The weather data in Alaska from 2000 to 2012

A study from Iowa State University's Aurora Program described the intensity of winter storms using a variety of various approaches. The Accumulated Winter Season Severity Index (AWSSI) was chosen to quantify the severity of winter seasons before and after the deployment of the RWIS stations. The purpose of using the winter severity index was to ensure that any subsequent decrease in crashes was not due to changes in weather. Daily maximum, minimum, and average temperatures, as well as snowfall and snow depth, were obtained from the Alaska climate research center and used to compute the AWSSI. Table 3.2 shows the thresholds for maximum and minimum temperature, snowfall, and snow depth that were used to determine how

many AWSSI points were added each day. Point thresholds were set up to give more weight to extreme or rare events, which would have had a bigger impact (Mayes Boustead et.al, 2015).

Table 3.2 Point contributions to daily AWSSI

	Temperature (°F)		Snow (in.)	
Points	Max	Min	Fall	Depth
1	25-32	25-32	0.1-0.9	1
2	20-24	20-24	1.0-1.9	2
3	15-19	15-19	2.0-2.9	3
4	10-14	10-14	3.0-3.9	4-5
5	5-9	5-9	-	6-8
6	0-4	0-4	4.0-4.9	9-11
7	From-1 to -5	From -1 to -5	5.0-5.9	12-14
8	From -6 to -10	From -6 to -10	-	15-17
9	From -11 to -15	From -11 to -15	6.0-6.9	18-23
10	From -16 to -20	From -16 to -20	7.0-7.0	24-35
11	-	From -21 to -25	-	-
12	-	-	8.0-8.9	-
13	-	-	9.0-9.9	-
14	-	-	10.0-11.9	-
15	<-20	From -26 to -35	-	>36
18	-	-	12.0-14.9	-
20	-	<-35	-	-
22	-	-	15.0-17.9	-
26	-	-	18.0-23.9	-
36	-	-	24.0-29.9	-
45	-	-	-	30.0

3.2. Safety Performance Function

Network screening is a process for identifying sites for further investigation and potential treatment. In network screening, Empirical Bayes (EB) is used to determine expected crash frequency. An important aspect of the EB before-and-after analysis is the development of safety performance functions (SPFs) for the test sections. SPFs are used to predict crash frequency for a given set of site conditions. The crashes predicted from the SPFs can be used alone or in combination with the site-specific crash history (i.e., EB method) to compare the safety performance of a specific site under various conditions. The EB method is used to estimate the

expected long-term crash experience, which is a weighted average of the observed crashes at the site of interest and the crashes predicted from SPFs (Mehta, et.al, 2015).

SPF is a model that defines the relationship between crash frequency and a measure of exposure. In SPF models, the predicted crash frequency is a function of both segment length and annual average daily traffic (AADT). Two conditions included in this study were winter combined crashes and winter fatal crashes. Therefore, two SPF models were developed to deal with those different conditions. To develop the models, negative binomial regression was used. Such an approach modeled the expected number of crashes on each roadway segment as a function of one or more explanatory variables. Two equations were used to predict winter crashes on rural highways in Alaska. To apply the negative binomial regression models estimated in this study, the following functional form (Equation 1) was used:

$$Nspf = \exp [\beta 0 + \beta 1 \times \ln (Length) + \beta 2 \times \ln (ASDT) + P] \quad (1)$$

where:

Nspf	=	expected number of crashes on the roadway segment;
β0	=	regression coefficient for constant;
β1	=	regression coefficient for segment length;
Length	=	roadway segment length (miles);
β2	=	regression coefficient for WADT;
ASDT	=	average seasonal daily traffic (vehicle/day); and,
P	=	regression coefficient for level of priority for road maintenance.

3.3. Goodness-of-Fit Measures

Goodness-of-fit statistics are used to scale the level at which estimated models fit the study data. Table 3.3 shows the statistical measures for evaluating the goodness-of-fit and statistical adequacy of the model. In this study, R-squared, a mean absolute deviance (MAD), mean prediction bias (MPB), and a mean squared prediction error (MSPE) were used to determine how well the models fit the observed data (Long and Scott, 1997).

Table 3.3 Goodness-of-fit measures

Validation measure	Equation	Description
MAD	$MAD = \frac{\sum_{i=1}^{n}\left\|\widehat{Y}_i - Y_i\right\|}{n}$	MAD is the sum of the absolute value of predicted validation observations minus observed validation observations, divided by the number of validation observations. It gives the average magnitude of variability of prediction. Smaller MAD values are favored to larger values.
MSPE	$MSPE = \frac{\sum_{i=1}^{n}\left(\widehat{Y}_i - Y_i\right)^2}{n}$	MSPE is the sum of squared differences between observed and predicted crash frequencies, divided by the sample size minus the number of model parameter. MSPE is typically used to assess error associated with a validation or external data sets. A lower value for MSPE indicates a better model.
MPB	$MPB = \frac{\sum_{i=1}^{n}\left(\widehat{Y}_i - Y_i\right)}{n}$	The MPB is the sum of predicted accident frequencies minus observed accident frequencies in the validation data set, divided by the number of validation data points. The MPB can be positive or negative. This statistic provides a measure of the magnitude and direction of the average model bias as compared to validation data. The smaller the average prediction bias, the better the model is at predicting observed data.
R-squared	$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Y_i - \widehat{Y}_i\right)^2}{\sum_{i=1}^{n}(Y_i - \overline{Y}_i)^2}$	R-squared is the percentage of the response variable variation that is explained by a linear model-squared is always between 0 and 100%. In general, the higher the R-squared, the better the model fits your data. However, there are important conditions for this guideline.

3.4. Empirical Bayes Before-After Studies

After safety performance functions had been developed, an EB adjustment was applied to the crash predictions. The EB method used a weighted average between observed crash history for a site and the predicted crash frequency from the SPFs to obtain a better estimate of predicted crash frequency, as described in Equation 2.

$$\mathrm{N_{EB}} = \mathrm{W} * \ \mathrm{N_{pr}} + (1 - \mathrm{W}) * \mathrm{N_{obs}} \qquad (2)$$

where:

NEB = EB adjusted predicted crash frequency (crashes/year);

W = weight for EB adjustment;

N_pr = predicted crash frequency from the SPF (crashes/year); and

N_obs = observed mean crash frequency from crash history (crashes/year).

The strength of the EB method is in the use of a weighting factor (W) that is based on real data; in this study it was based on the crash frequency predicted by the SPF and the mostly overdispersion parameter. Overdispersion resulted from the variance exceeding the mean in the crash frequency distribution. The weighting factor was obtained from the SPF model by using Equation 3. After the expected crash values had been estimated, the safety effectiveness (θ) was projected, and the standard deviation of θ was calculated according to equations 4 and 5.

$$W = \frac{1}{1 + \frac{\sum N_{pr}/L}{K}} \tag{3}$$

where:

$\sum N_{pr}$ = sum of predicted crash frequency for each year of crash history;

W = segment length (miles); and

N_pr = overdispersion parameter from the SPF model.

$$\theta = \frac{A_{sum}/B_{sum}}{1 + [Var(B_{sum})/B_{sum}^2]} \tag{4}$$

$$Stddev(\theta) = \left[\frac{\theta^2\{[Var(A_{sum})/A_{sum}{}^2] + [Var(B_{sum})/B_{sum}{}^2]\}}{[1 + Var(B_{sum})/B_{sum}^2]^2}\right]^2 \tag{5}$$

where: A_{sum} = sum of observed crash frequency, and B_{sum} = sum of expected crash frequency.

3.5. Study Designs to Develop CMFs

Next we used the same methodology for calculating the expected number of crashes by using the control sites described earlier in the before-and-after comparison group analysis. The crash modification factor (CMF) for wider pavement markers was calculated by adding the observed crashes for both the treatment and comparison groups for the two time periods, before and after. The CMF and its variance were estimated from equations 6 and 7 (Frank et.al, 2012). The developed CMFs produced a value indicating how the number of winter crashes would change after RWIS stations were installed in Alaska.

$$\mathrm{CMF} = \frac{\left(\frac{N_{observed,T,A}}{N_{expected,T,A}}\right)}{1 + \frac{\mathrm{Var}(N_{expected,T,A})}{N_{expected,T,A}^{2}}} \quad (6)$$

$$\mathrm{variance}(\mathrm{CMF}) = \frac{\mathrm{CMF}^{2}\left(\frac{1}{N_{observed,T,A}}\right) + \left(\frac{\mathrm{Var}(N_{expected,T,A})}{N_{expected,T,A}^{2}}\right)}{\left(1 + \frac{\mathrm{Var}(N_{expected,T,A})}{N_{expected,T,A}^{2}}\right)^{2}} \quad (7)$$

where:

$N_{Expected,T,A}$ = expected number of crashes without wider edge line markings treatment.

$N_{Observed,T,A}$ = observed number of crashes in the after period for the treatment group.

CHAPTER 4. DATA ANALYSIS AND RESULTS

4.1. Weather Data

The AWSSI was calculated for three seasons before and after the deployment of RWIS stations. The greater the AWSSI rating, the harsher the winter. The findings provided compelling evidence that the *after* era saw far more severe winters than the preceding one. The mean AWSSI value for the three seasons before the use of RWIS was 2225, whereas the figure for the *after* period was 2545. Using the paired t-test with an alpha of 0.05, the P-value was 2×10-6, which was less than 0.05, indicating that the difference between the *before* and *after* periods was statistically significant. There was a solid case to be made that any drop in crashes was uncorrelated to the intensity of the winter season. Furthermore, the *after* period had a higher AWSSI score, indicating harsher weather than in the *before* period.

4.2. Safety Performance Functions

SPFs were developed by using total winter crashes and fatal winter crashes on rural highways in Alaska. Table 4.1 shows the outcome of the negative binominal regression for the SPFs for total crashes and fatal winter crashes. R-Studio, a statistical analysis software package, was used to complete the two negative binomial regression models. This part of the study considered only crashes that occurred before the deployment of RWIS stations as the baseline circumstances. R-Studio output regression coefficients for the intercept and any of the explanatory variables. These coefficients are denoted by the values β0, β1 and β2.

Table 4.1 SPF model output

Model	Parameter	Estimate
Ice Slush Snow Crashes	β0	-9.05
	β1	1.19
	β2	0.99
	Over dispersion	1.5973
	P_B	-0.31
	P_C	-36.60
Total Crashes	β0	-7.26209
	β1	1.02371
	β2	0.93271
	Over dispersion	4.6288
	P_B	-0.45019
	P_C	-1.68334

Model	Parameter	Estimate
Fatal And Serious	β0	-11.28
	β1	1.08
	β2	1.03
	Over dispersion	23.40
	P_B	-0.02
	P_C	-34.28

4.3. Goodness-of-Fit Measures

The preceding models were evaluated by using four statistical tests. As seen in Table 4.2, MAD values varied between 0 and 5, indicating that the models were developed accurately. For MPB values, they were less than 0, which indicated that the prediction model's assumptions were correct. In terms of R-squared values, the model for all combined winter crashes had a high value of 0.84, indicating a strong match. While the winter ice, slush, and snow crashes model had a lower R-squared value of 0.601, it still had a respectable R-squared value in comparison to the R-squared values in the *Highway Safety Manual*. The MSBE values were dependent on the number of crashes, which is why they ranged from 218.7272 for the combined winter crashes model to 0.3055 for the winter fatal and serious injury crashes model.

Table 4.2 Performance measures for SPFs

Model	*MAD*	*MPB*	*MSBE*	*R-Squared*
Ice Slush Snow Crashes	3.1520	-0.6032	111.3124	0.601
All combined Winter Crashes	4.7072	-1.0619	218.7272	0.845
Winter Fatal and Serious Injury Crashes	0.2341	-0.0072	0.3055	0.763

4.4. Empirical Bayes Before-After Studies

After the models had been validated, predicted and expected crashes for each condition were determined by using the EB approach for the test locations. Table 4.3 summarizes the observed crashes, predicted crashes using SPF models, and expected crashes using the EB approach. The percentage of change in crashes indicates how the number of crashes changed when RWIS stations were not utilized (expected and predicted crashes) vs when RWIS stations were used (observed crashes). As indicated in Table 4.3, the values for SPF-predicted crashes were 0.69 for total winter crashes and 0.63 for fatal and serious injuries winter crashes, implying that the number of total winter crashes fell by 31 percent and the number of fatal and serious injuries winter crashes decreased by 37 percent following installation of RWIS stations.

Additionally, the values for EB projected crashes were 0.84 for total winter crashes and 0.64 for fatal and serious injuries winter crashes, indicating a 16 percent reduction in total winter crashes and a 36 percent reduction in fatal and serious injuries winter crashes following the deployment of RWIS stations.

Table 4.3 Comparison between observed, SPF, and EB estimated crash frequencies

Crash Type	Count of Crashes After Treatment	SPF		EB	
		Number of Crashes	the safety effectiveness θ	Number of Crashes	the safety effectiveness θ
Total Crashes	2820	3417	0.82	3302	0.85
Fatal and Serious Injuries	134	200.2	0.66	200	0.66
Ice Slush Snow Crashes	1279	1775	0.72	1643	0.77

4.5. Crash Modification Factors

The results of computing CMFs by using the EB method are shown in Table 4.4. All combined winter crashes had a value of 0.8375, which was significant at a 99 percent confidence level. For winter fatal crashes, the CMF value was 0.6457, which was significant at a 99 percent confidence level. Finally, ice, snow, and slush crashes had a CMF value of 0.7715, which was also significant at a 99 percent confidence level.

Table 4.4 Evaluated CMFs for RWIS

Crash type	CMF	*Var* (CMF)	*SE*
All combined Winter Crashes	0.8375***	0.00038	0.019
Winter Fatal and Serious Injury Crashes	0.6457***	0.00301	0.054
Ice Slush Snow Crashes	0.7715***	0.00056	0.023

(Note: *** Significant at a 99% confidence level)

4.6. Cost-Benefit Ratios for RWIS

In Alaska, the difference between three years of crashes with and without RWIS stations (anticipated crashes using the EB method) was 597 winter crashes. Table 4.5 presents the

percentage of total roadway segment crashes based on the *2010 Highway Safety Manual* (HSM) and an FHWA 2016 report on crash unit cost values. Crash severity as a percentage of total crashes was calculated on the basis of 12 winter seasons of crash data in Alaska, from 2000 to 2012. Total crashes were used under the presumption that the adoption of RWIS saved around $99 million over a three-year period. According to recent research, RWIS stations cost around $100,000 to install and $10,000 each year to maintain (Liu et al. 2021). Twenty-six RWIS stations were included in this analysis, with an initial cost of $2.6 million and maintenance costs of $1 million over a three-year period, for a total of $3.6 million. The cost-benefit ratio of establishing RWIS stations in the state for one year was assessed to be roughly 1:27.

Table 4.5 Estimating the savings of using RWIS stations

Crash Severity	Unit Cost	Percentage of Total Crashes Without Fatal Crashes for 3 years	The number of crashes averted with the use of RWIS In 3 winter seasons	Total Cost
K	$11,295,400	1.00%	5.97	$67,433,538
A	$198,500	3%	17.91	$3,555,135
B and C	$162,050	24%	143.28	$23,218,524
O	$11,900	72%	429.84	$5,115,096
	Total		597	$99,322,293

CHAPTER 5. CONCLUSIONS

The results of a before-and-after study to examine the safety effect of RWIS as a winter roadway safety countermeasure was presented in this report. Empirical Bayes before-and-after analyses were employed to define the RWIS effect on road safety. This study provides sufficient evidence to recommend that RWIS are effective at helping to reduce crashes, especially in preventing fatal and serious injury crashes during the winter season.

For crash frequency, the Empirical Bayes unbiased estimates for the reduction of crashes as a result of the deployment of RWIS were 15 percent for total crashes and 34 percent for fatal and severe injury crashes. The reduction in crash rates for total crashes was statistically significant ($\alpha < 0.1$). The reduction in crash rates for fatal and severe injury crashes was also statistically significant ($\alpha < 0.05$). The two CMFs were significant: the CMF value for all crashes was 0.83 with $\alpha < 0.001$, and the CMF value for fatal and serious injury crashes was 0.64 with $\alpha < 0.001$. The calculated cost-to-benefit ratio of deploying RWIS throughout the state's highway segments was approximately 1:27.

This study provided sufficient evidence to recommend that RWIS are effective at helping to reduce crashes, especially at preventing fatal and serious injury crashes during the winter season. This research was novel, as it developed SPF and EB analyses that used a realistic time frame (i.e., October through May) for the winter season spanning over the New Year. In addition, we incorporated weather data in the form of AWSSI into the SPF and EB models.

This study had a few limitations worth noting. First, the AWSSI technique utilized to calculate winter severity was not calibrated for Alaska. However, this index still provides a reliable way to control for weather variability across seasons. Future work will seek to develop a winter storm severity index that is calibrated to Alaska's climate. Second, weather station data are not always exactly coincident with RWIS location. In the event that a weather station was not co-located with an RWIS, we determined the nearest station and used those data as a proxy for the weather conditions present at the RWIS location. Lastly, snowfall and snow and ice accumulation can be highly variable and may change significantly over space. To the best of our ability, we controlled for this in the model by incorporating multiple weather stations over the analysis segments where available.

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