working to advance road weather information systems technology

Road Weather Information Systems (RWIS) Life-Cycle Cost Analysis

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Aurora Project 2018-01

Final Report
May 2020

About Aurora

Aurora is an international program of collaborative research, development, and deployment in the field of road and weather information systems (RWIS), serving the interests and needs of public agencies. The Aurora vision is to deploy RWIS to integrate state-of-the-art road and weather forecasting technologies with coordinated, multi-agency weather monitoring infrastructures. It is hoped this will facilitate advanced road condition and weather monitoring and forecasting capabilities for efficient highway maintenance and real-time information to travelers.

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16. Abstract

Life-cycle cost analysis (LCCA) is a data-driven tool that provides a detailed account of the total costs of a project over its expected life. LCCA has been proven to create short-term and long-term savings for transportation agencies by helping decision-makers identify the most beneficial and cost-effective projects and alternatives. To help state departments of transportation (DOTs) make more informed decisions with regard to budget planning for the various costs associated with the use of a road weather information system (RWIS), the Aurora Pooled Fund Program initiated the RWIS Life-Cycle Cost Analysis research project. The objectives of this research were to develop guidelines to do the following:

- Help quantify the costs and benefits associated with RWIS sites
- Better assess costs arising from RWIS assets over the life cycle
- Provide a framework for calculating net present worth
- Assess alternatives and associated cost implications
- Determine long-term RWIS life-cycle costs and the optimal point to replace RWIS equipment
- Support decisions on repair versus replacement based on projected expenses
- Assist in planning and funding the replacement or repair of RWIS infrastructure

This report provides methods and general guidelines to assist public agencies with determining RWIS site life-cycle costs. Public agencies can follow the information provided herein to gather necessary data and perform the analysis to help quantify the costs and benefits associated with RWISs. The methodologies presented in this report provide a framework for calculating life-cycle costs and net present worth, which helps agencies make more informed decisions in repairs and replacement of RWIS sites. It also helps assess and compare alternatives and associated cost implications.

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ROAD WEATHER INFORMATION SYSTEM LIFE-CYCLE COST ANALYSIS

Final Report
May 2020

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EXECUTIVE SUMMARY

A road weather information system (RWIS) is a combination of advanced technologies that collects, transmits, processes, and disseminates road weather and condition information. RWIS stations collect road weather data, which include atmospheric, pavement, and/or water level data. Once the data have been collected, central RWIS hardware and software are used to process observations from the sensors to develop nowcasts or forecasts and display or disseminate road weather information in a format that can be easily interpreted by maintenance and traffic operations personnel as well as the public. The information collected by the system can provide improvements in the effectiveness of road maintenance operations and help motorists make more informed decisions for their travel.

Agencies that deploy and use RWIS applications would likely be interested in knowing the costs associated with the ongoing use of these systems. To help state departments of transportation (DOTs) make more informed decisions with regard to budget planning for the various costs associated with the use of RWIS, the Aurora Pooled Fund Program initiated the RWIS Life-Cycle Cost Analysis (LCCA) research project. LCCA is a data-driven tool that provides a detailed account of the total costs of a project over its expected life. LCCA has been proven to create short-term and long-term savings for transportation agencies by helping decision-makers identify the most beneficial and cost-effective projects and alternatives.

The objectives of this research were to develop guidelines to:

- Help quantify the costs and benefits associated with RWIS sites
- Better assess costs arising from RWIS assets over the life cycle
- Provide a framework for calculating net present worth (NPW)
- Assess alternatives and associated cost implications
- Determine long-term RWIS life-cycle costs and the optimal point to replace RWIS equipment
- Support decisions on repair versus replacement based on projected expenses
- Assist in planning and funding the replacement or repair of RWIS infrastructure

To accomplish the objectives, a comprehensive literature review was conducted to identify documents from previous projects that are relevant to RWIS life-cycle costs and to provide a summary of the current practices for determining the cost and potential savings of RWIS stations. Key RWIS elements to be considered for evaluation as part of the cost analysis were identified and categorized as either capital or operations and maintenance elements, with consideration for entire RWIS stations as well as individual components. Those elements are defined as follows:

- **Capital costs:** Costs associated with equipment installation and capital improvements, such as hardware and software
- **Operations and maintenance costs:** Items with future cost implications, such as ongoing operations, maintenance, rehabilitation, communications, and replacement costs

Two surveys were conducted to gather RWIS product information: one for RWIS manufacturers/vendors and another for public agencies. The surveys were designed to obtain estimates of RWIS equipment costs and design service life from RWIS manufacturers/vendors and state DOT agencies. Information on actual service life, applicable warranties, and recommendations regarding preventive maintenance (including frequency, which may impact life expectancy) were also collected, among other information.

To develop guidelines on performing an LCCA, quantification of costs and benefits associated with RWIS is essential. Data for quantifying RWIS-associated costs and benefits were gathered through the surveys, a literature review, and transportation agencies' experience. A review of the data collected was conducted to determine the applicability of this data with respect to the LCCA. Information and guidelines available from existing life-cycle benefit/cost models and other LCCA tools were also reviewed to aid in performing the analysis.

The use of RWIS requires capital, installation, operations, and maintenance costs. However, there are benefits to the RWIS that may be recognized through a reduction in unnecessary winter road maintenance operations (labor, equipment, and material), a potential reduction in weather-related crashes, and mobility improvements in travel costs and emission reduction.

This report provides methods and general guidelines to assist public agencies with determining RWIS site life-cycle costs. Public agencies can follow the information provided herein to gather necessary data and perform the analysis to help quantify the costs and benefits associated with RWISs. The methodologies presented in this report provide a framework for calculating life-cycle costs and NPW, which helps agencies make more informed decisions in repairs and replacement of RWIS sites. It also helps assess and compare alternatives and associated cost implications.

The steps for performing an LCCA for RWIS sites present the principles of life-cycle cost analysis and serve as a guide to perform the analysis. These steps for performing a life-cycle cost analysis for an RWIS site are summarized as follows:

1. **Determine RWIS deployment strategy:** Determine the components and other details of an RWIS site, including types of sensors, infrastructure (e.g., tower, pole, and foundation), communications, and power source. The location of the RWIS should be considered as it may have an impact on installation costs.
2. **Collect data:** Collect costs and life span information at an individual component level or entire RWIS site level. Data at an individual component level is preferred. Data presented herein or collected from other agencies can also be used to fill data gaps. Capital, installation, maintenance, and operational costs should be collected.
3. **Estimate RWIS benefits and savings:** The benefits and savings of RWIS are realized through winter maintenance savings, crash reduction/collision cost savings, and mobility improvements. Methods to estimate the benefits and savings in these areas are described herein. Other models to estimate the benefits and savings, particularly in crash reduction and mobility improvements, also can be used.
4. **Estimate expected life-cycle cost and NPW:** Net present worth is an important indicator to

support RWIS implementation decisions. NPW is determined using the costs and benefits associated with RWIS over its life cycle.

The report also presents a simulated case study demonstrating the use of the methodology described in the report for an LCCA. Using a hypothetical example, the report demonstrates the methods for estimating the costs as well as potential benefits associated with deploying an RWIS site. It illustrates the value of using a comprehensive assessment by taking into account the capital, operations, and maintenance costs and the estimated benefits over the useful life span of an RWIS to support investment strategies and decisions.

Finally, the report offers a set of conclusions that outlines guiding principles for consideration in performing LCCA and life-cycle planning for RWIS. The conclusions and guiding principles note that technology-oriented RWIS may have different characteristics than conventional transportation assets such as pavement or bridges. Applying conventional LCCA and life-cycle planning practices to RWIS may not always be appropriate. As such, it is vital to establish a practical life-cycle planning framework and LCCA methodology for RWIS that considers stochastic treatments of the unique characteristics of technology-oriented RWIS.

CHAPTER 1. INTRODUCTION

Throughout the US, there are many states that experience recurring patterns of inclement weather events, particularly during winter months. The occurrence of these weather events can in turn have a detrimental impact on the safety and mobility of motorists. Generally, road collision rates increase dramatically during inclement weather conditions due to the degradation of visibility and traction on the roadway.

One approach to improving the decision-making process for roadway maintenance personnel is to use real-time information (i.e., for monitoring current road conditions) and forecasts (i.e., for predicting near-future road conditions) provided by innovative technologies such as road weather information systems (RWISs). An RWIS can be defined as a combination of advanced technologies that collects, transmits, processes, and disseminates road weather and condition information to help maintenance personnel make timely and proactive maintenance-related decisions. The system collects data using environmental sensor stations (ESSs) and provides real-time road weather and surface conditions information.

RWIS stations are used to collect road weather data, which includes atmospheric, pavement, and/or water level data. Once the data have been collected by the ESS, central RWIS hardware and software are used to process observations from the sensors to develop nowcasts or forecasts and display or disseminate road weather information in a format that can be easily interpreted by maintenance and traffic operations personnel as well as the public. The information collected by the system can provide improvements in the effectiveness of road maintenance operations and help motorists make more informed decisions for their travel.

1.1. Background

Agencies that deploy and use RWIS applications would likely be interested in knowing the costs associated with the ongoing use of these systems. To help state departments of transportation (DOTs) make more informed decisions with regard to budget planning for the various costs associated with the use of RWISs, the Aurora Pooled Fund Program initiated the RWIS Life-Cycle Cost Analysis (LCCA) research project. The objectives of this research were to develop guidelines to do the following:

- Help quantify the costs and benefits associated with RWIS sites
- Better assess costs arising from RWIS assets over the life cycle
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To accomplish the objectives, a comprehensive literature review was conducted to identify documents from previous projects that are relevant to RWIS life-cycle costs, and to provide a summary of the current practices for determining the cost and potential savings of RWIS stations. A list of key RWIS elements to be considered for evaluation as part of the cost analysis were identified and categorized as either capital or operations and maintenance (O&M) elements, with consideration for entire RWIS stations as well as individual components. Two surveys were conducted to gather RWIS product information: one for RWIS manufacturers/vendors and another for public agencies. Information gathered from the literature review and the manufacturer and public agency surveys was used to develop guidelines for determining RWIS life-cycle costs for entire RWIS stations and individual RWIS elements.

1.2. Report Organization

This report is organized into the following seven chapters and two appendices:

- Chapter 1 outlines the general problem examined by the project and provides background information on RWISs and their various applications.
- Chapter 2 presents the information gathered during a comprehensive literature review of the life-cycle costs associated with the operation, maintenance, and replacement of RWIS equipment.
- Chapter 3 presents the RWIS components identified as elements to be considered during the analysis of overall life-cycle costs for individual RWIS equipment and entire stations.
- Chapter 4 describes the methodology used for collecting data from key stakeholders. It includes the development of two online surveys asking RWIS manufacturers and state DOTs to provide information about their RWIS products, costs, and maintenance information.
- Chapter 5 develops methodologies and offers guidelines to perform a life-cycle cost analysis for an RWIS.
- Chapter 6 presents a simulated case study of performing a life-cycle cost analysis using the methodologies developed in Chapter 5.
- Chapter 7 provides key findings and conclusions of this project and serves as a reference guide to help public agencies make more informed investment decisions regarding various elements of their RWIS systems.
- Appendix A summarizes the survey responses from RWIS manufacturers.
- Appendix B summarizes the survey responses from the state DOTs.

CHAPTER 2. LITERATURE REVIEW

This chapter presents a literature review that outlines several studies related to RWIS life-cycle costs. The goal of the literature review is to summarize the current practices for determining the cost of and potential savings from RWIS stations. Additionally, this literature review helped to develop the optimal methodology for building a tool to help transportation agencies budget for the ongoing costs of installing and maintaining RWIS sites.

McKeever et al. (1998) set a standard methodology for calculating the cost and savings associated with RWIS. Other studies have cited the results from the McKeever et al. (1998) study and built upon it, such as developing methods to determine the optimal density and location of RWIS stations. Though life-cycle methods previously have been developed, there is a need to update the methodology with current costs and reevaluate.

2.1. Life-Cycle Cost-Benefit Model for Road Weather Information Systems

McKeever et al. (1998) defines the life-cycle cost-benefit associated with deploying RWIS technology. Along with the methodology for the life cycle, a case study was presented using an RWIS installed on I-20 near Abilene, Texas. McKeever et al. (1998) was a development from Haas et al. (1997).

Many datasets were utilized for McKeever et al.'s analysis. Table 1 presents some of the input data considered when building the decision-support tool.

Table 1. RWIS decision support tool input data

Level of aggregation	Type of data	How data are used
State	• Aggregation of all data	• Budget establishment
District	• Number and groupings of potential RWIS sites (snow/ice) • Aggregated accident data (snow/ice) • Aggregated frequency data (snow/ice) • Winter maintenance expenditures	• Project scheduling • Allocation of funds • Fixed RWIS costs • Social savings (snow/ice) • Indirect savings (snow/ice)
County	• Number and groupings of potential RWIS sites (floods) • Aggregated accident data (floods) • Aggregated frequency data (floods) • Flood warning expenditures	• Project prioritization • Social savings (floods) • Indirect savings (floods)
Group of sites	• Primary site to be monitored in group • Group membership	• Cost and benefits aggregated for group
Site	• Location • Type of site • Frequency of events • Accident data • Annual average daily traffic (AADT) • Distance from maintenance office	• Site-related cost and benefits • Ranking of sites by need

Sources: Haas et al. 1997 and McKeever et al. 1998

As shown in Table 1, many data inputs were obtained and used in the model outline. Inclement weather crash data are needed as well as budget information for the acquisition, installation, operation, and maintenance costs associated with an RWIS station. The analysis considered direct cost, direct savings, indirect savings, and potential social savings. The variables used in the analysis are presented in Table 2.

Table 2. RWIS cost-benefit variables

Type	Variables
Direct cost	RWIS systems Communication and central processing unit (CPU) with software Life span Upgrade for remote processing unit (RPU) and CPU O&M Phone charges Meteorological services
Direct savings	Winter maintenance Labor Equipment Materials
Indirect savings	Reduced risk of liability - will be treated as a qualitative factor in an economic assessment
Social savings	Travel cost Pollution cost Accident cost

Sources: Haas et al. 1997 and McKeever et al. 1998

Some of the values set for these variables are presented in Table 3. The values set for each of these variables are based on 1997 data and specific to the location of the case study.

Table 3. Cost and savings calculated for Abilene, Texas

Variables	Average	Units
RWIS systems capital cost	$42,010	per site
RPU and CPU capital cost	$10,446	per site
Life span	25	year
Interest rate	5	%
Upgrade for RPU and CPU	$10,446	per 5 years
O&M	$3,000	per year per unit
Phone charges	$360	per year per unit
Meteorological services	$2,100	per year per unit
Winter maintenance savings	$12,720	per year
Accident savings	$48,100	per year

Sources: Haas et al. 1997 and McKeever et al. 1998

When determining the 50-year life cycle, the NPW of the RWIS in this location was found to be $923,000. Other benefits noted in the study were reduced risk of liability, better planning for road work, and lower travel times, which reduces pollution cost.

2.2. Road Weather Management Benefit Cost Analysis Compendium

The Federal Highway Administration (FHWA) built a compendium to assist transportation agencies with reviewing benefit-cost analyses conducted throughout the US regarding road weather management (RWM), which would include RWIS stations (Lawrence et al. 2017). A custom spreadsheet was developed to assist with cost-benefit estimations. The compendium includes the fundamentals of benefit-cost analysis, the tool developed, and case studies. Multiple case studies were reviewed, and these case study subjects included the following:

- Surveillance, monitoring, and prediction – this includes RWIS deployment studies conducted in Idaho, Michigan, and Utah
- Information dissemination
- Decision support, control, and treatment
- Weather response or treatment

The fundamentals of the cost-benefit analysis included a section on the discount factor and reviewed the elements that should be considered in the analysis. Table 4 presents the cost elements to include, as presented in the compendium.

Table 4. Cost and benefit elements

Agency benefits/costs	User benefits/costs associated w/ transportation system management & operations & road weather management projects	Externalities (non-user impacts, if applicable)
• Design and engineering • Land acquisition • Construction • Reconstruction/Rehabilitation • Preservation • Routine maintenance • Mitigation (e.g., noise barriers)	• Travel time and delay • Reliability • Crashes • Vehicle operating costs	• Emissions • Noise • Other societal impacts

Source: Lawrence et al. 2017

Lawrence et al. (2017) presents the various ways to determine the benefit-to-cost ratio and also the values used, as well as an overview of benefit-cost analysis tools that have been developed. Table 5 presents the reported tools from a variety of studies.

Table 5. Summary of existing benefit cost analysis tools and methods for RWM

Tool/Method	Developer	Website
BCA.net	FHWA	http://www.fhwa.dot.gov/infrastructure/asstmgmt/bcanet.cfm
CAL-BC	Caltrans	http://www.dot.ca.gov/hq/tpp/offices/eab/LCBC_Analysis_Model.html
Clear Roads Cost-Benefit Toolkit	Montana State University under contract to Clear Roads Consortium	http://clearroads.org/cba-toolkit/
COMMUTER Model	U.S. Environmental Protection Agency	N/A
Evaluation Model for Freeway Intelligent Transportation Systems (ITS) Scoping (EMFITS)	New York State DOT	N/A
The Florida ITS Evaluation (FITSEval) Tool	Florida DOT	N/A
ITS Deployment Analysis System (IDAS)	FHWA	N/A
Multimodal Benefit-Cost Analysis (MBCA)	TREDIS Software	http://www.tredis.com/mbca
Screening Tool for ITS (SCRITS)	FHWA	N/A
Surface Transportation Efficiency Analysis Model (STEAM)	FHWA	N/A
Tool for Operations Benefit/Cost (TOPS-BC)	FHWA	http://www.ops.fhwa.dot.gov/plan4ops/topsbctool/index.htm
Trip Reduction Impacts of Mobility Management Strategies (TRIMMS)	Center for Urban Transportation Research at the University of South Florida	http://www.nctr.usf.edu/abstracts/abs77805.htm

Source: Lawrence et al. 2017

Additionally, current safety impact defaults were presented in Lawrence et al. (2017) to assist with values for crash rates, volume/capacity ratios, and impact assumptions for various types of systems.

The three case studies summarized in Lawrence et al. (2017) are discussed in the following sections.

2.2.1. Michigan DOT

The Michigan DOT reviewed regional pre-deployment of RWIS stations in rural regions. ESSs and maintenance decision support systems (MDSSs) were deployed in four regions. To measure the benefits, the travel time, safety, and operational cost were reviewed (Krechmer et al. 2010). The Intelligent Transportation Systems (ITS) Deployment Analysis System (IDAS) model was used for the analysis. Default accident rates, vehicle fuel efficiency, and emissions rate were used in the calculation. The study was conducted for two years (2000–2002). Annualized capital costs, operational costs, and maintenance costs were included. The rural RWIS deployment found a 2.8–7.0 cost-benefit ratio depending on the region. The cost data were used for these ratios as follows:

- North region – 50 stations with a capital cost of $4.02 million and annual O&M cost of $460,000
- Bay region – 15 stations with a capital cost of $2.06 million and annual O&M cost of $256,000
- Superior region – 34 stations with a capital cost of $3.463 million and annual O&M cost of $358,000
- Grand region – No data on number of stations, but capital cost was $2.272 million and annual O&M cost of $233,500

Table 6 presents the overall cost breakdown.

Table 6. Benefit-cost analysis results from a Michigan DOT study

Benefits and costs	North	Bay	Grand	Superior
Travel time savings	$354,000	$2,289,700	$1,036,000	$573,000
Crash reduction	$1,519,000	$968,000	$1,269,000	$1,630,000
Operating costs	$565,000	$94,000	$115,000	$203,000
Total annual benefits	$2,438,000	$3,351,700	$2,420,000	$2,406,000
Annualized cost	$870,000	$482,000	$471,000	$713,000
Net benefits	$1,568,000	$2,289,700	$1,949,000	$1,693,000
Benefit-cost ratio	2.8	7.0	5.1	3.4

Source: Lawrence et al. 2017, Krechmer et al. 2010

Overall, Krechmer et al. (2017) found that there was a winter maintenance cost decrease with an increase in weather information.

2.2.2. Utah DOT

The Utah DOT created a weather operations and RWIS program. Within this program, Utah reviewed its RWIS sites, regional traffic operations center (TOC), incident management and freeway service patrols, anti-icing system, communications, advanced traffic management systems, and other various applications. The overall goal for this program was to determine the benefits and cost associated with outputs from the weather operations program.

The Utah DOT utilized an artificial neural network (ANN) model for winter maintenance costs (Strong and Shi 2008). The model calculated the labor and materials cost for each maintenance/material facility and was based on 2004–2005 winter maintenance cost data. Based on all the factors reviewed in the winter operation and RWIS program, the Utah DOT found a savings of more than $2.2 million, which results in a 11:1 benefit-cost ratio (Strong and Shi 2008).

2.2.3.Idaho Transportation Department (ITD)

Idaho has invested $15 million in expanding and renovating its RWIS network statewide. Nearly every site has pavement temperature, layer type and thickness, and coefficient of friction data. The goal of Koeberlein et al. (2014) was to compare the benefits and cost of the Idaho system when compared to others using the TOPS-BC tool (see the previous Table 5 for details on this tool). Using the TOPS-BC tool, a baseline model was run with no RWIS sites, then an implementation of 9 sites in 2011–2012 was modeled, and then a model was separately run for the 2012–2013 season when 24 RWIS stations were deployed. Crash reduction, travel time reduction, safety factors, energy benefits, O&M cost, capital cost, and life span variables were used in this model. The 2011–2012 season found a 34:1 benefit cost ratio, while the 2012–2013 season found a 19:1 ratio (Koeberlein et al. 2014).

2.3. RWIS Network Planning: Optimal Density and Location

Kwon and Fu (2016) looked at various approaches for optimal density and locations for RWIS stations. The report reviewed three alternative methods as follows:

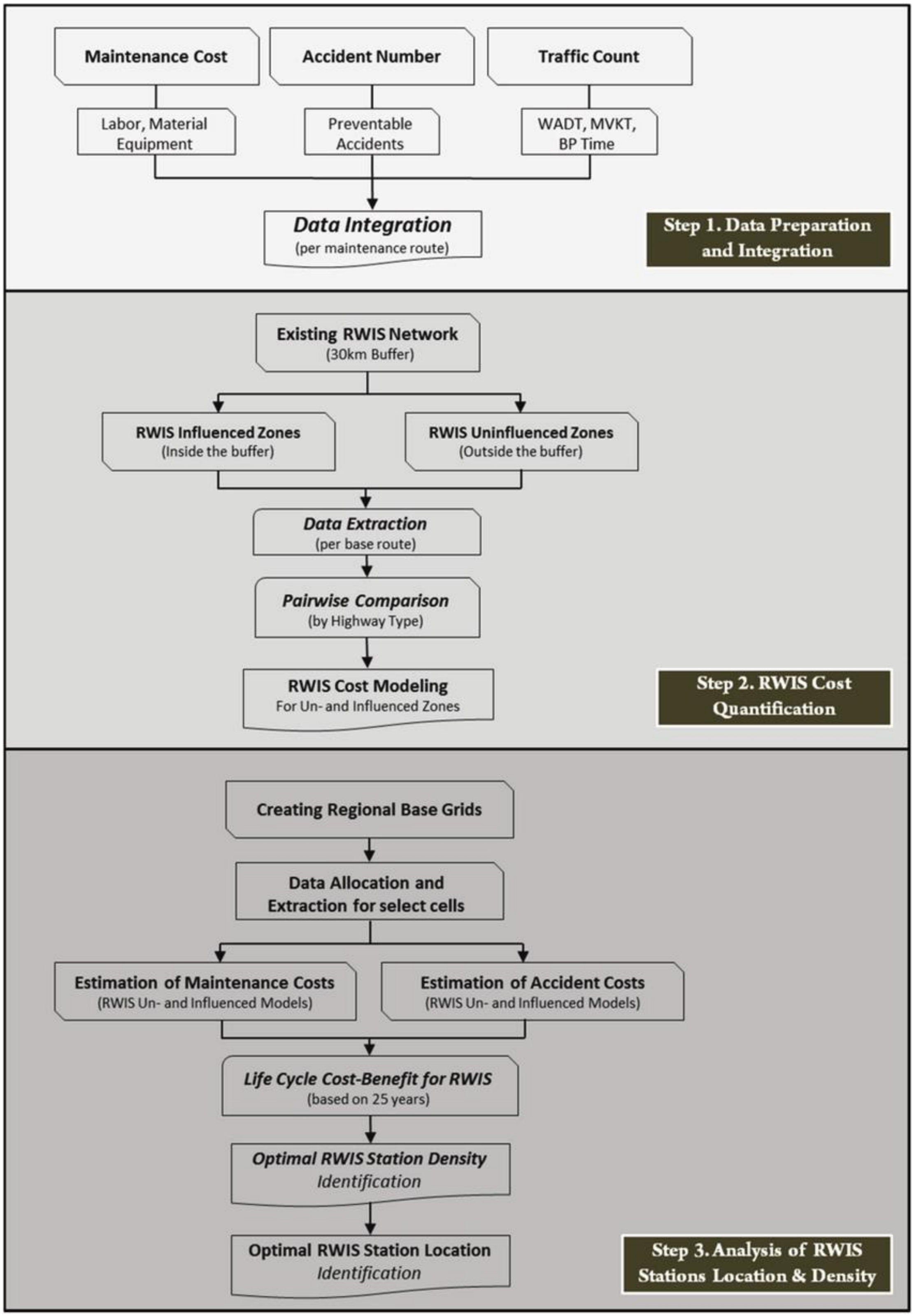
1. A surrogate measure-based approach that reviews traffic, weather, and maintenance benefits
2. A cost-benefit method, which is presented in this section
3. A spatial inference method, which required less data and utilized kriging analysis for the optimal solution

The report outlined the limitations of each approach and provided survey answers that were collected during the project as well. These data may be useful when reviewing the life-cycle cost of RWIS. Kwon et al. (2016a) further presented the cost-benefit approach, and Kwon et al. (2016b) presented the alternative three approaches based on the Kwon and Fu (2016) research.

Overall, Kwon and Fu (2016) and Kwon et al. (2016a) are the optimal resources for RWIS optimization for location and cost-benefits.

The goal of Kwon and Fu (2016) was to develop a method for determining the optimal number of RWIS stations an area should have to get the most value. Additionally, once the optimal number of RWIS stations is established, a method for finding the best placements for these new stations is offered. Kwon and Fu (2016) presented the methodology for this analysis and used northern Minnesota as a case study.

The overall methodology is presented in a flowchart shown in Figure 1.

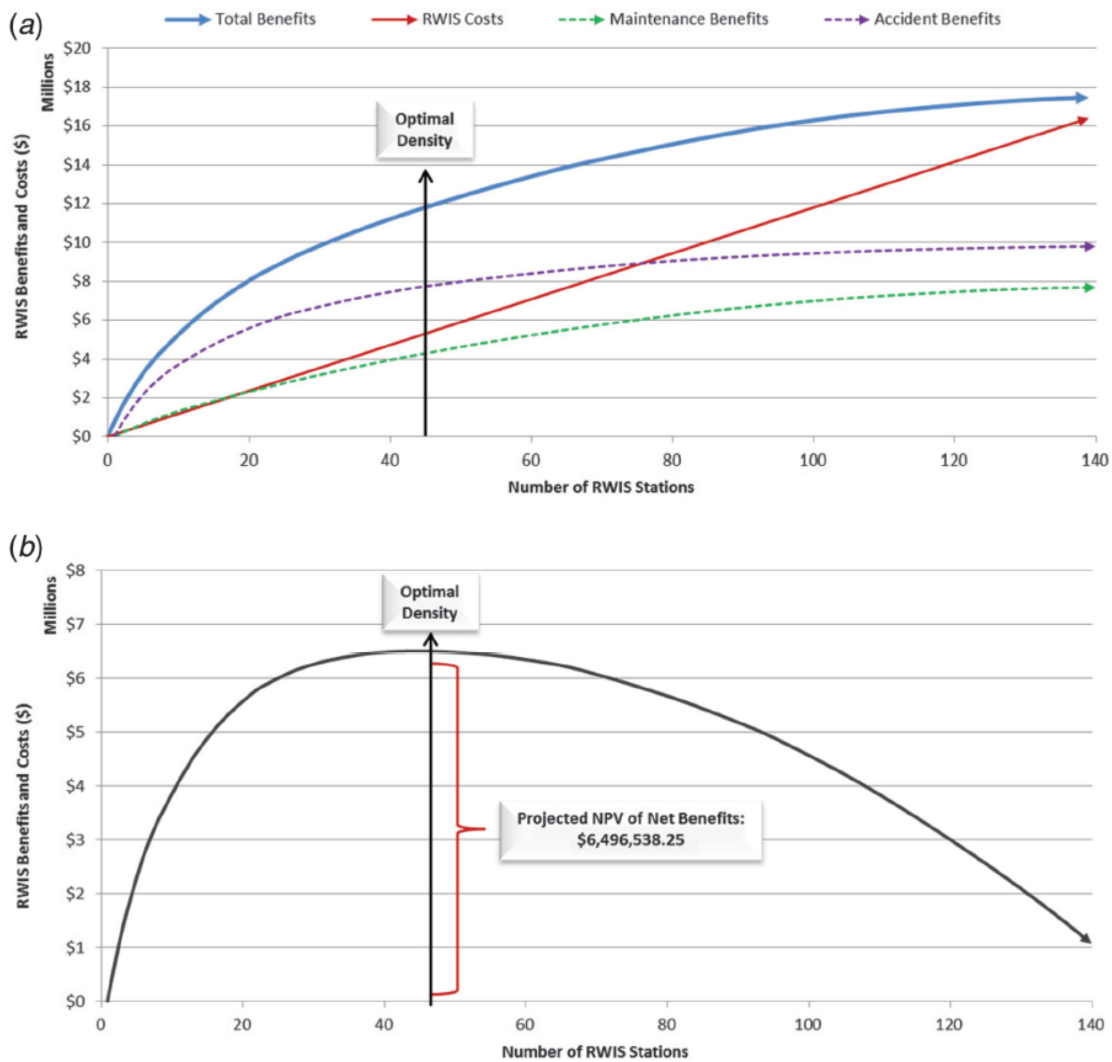


Kwon and Fu 2016

Figure 1. Methodology for analysis

Step one presented in Figure 1 shows the dataset utilized in Kwon et al. (2015). Step two is the cost component of the analysis, which utilized the methods developed in Haas et al. (1997). Step three allows users to see the optimal density and location for RWIS based on cost.

Figure 2 presents the results from northern Minnesota.

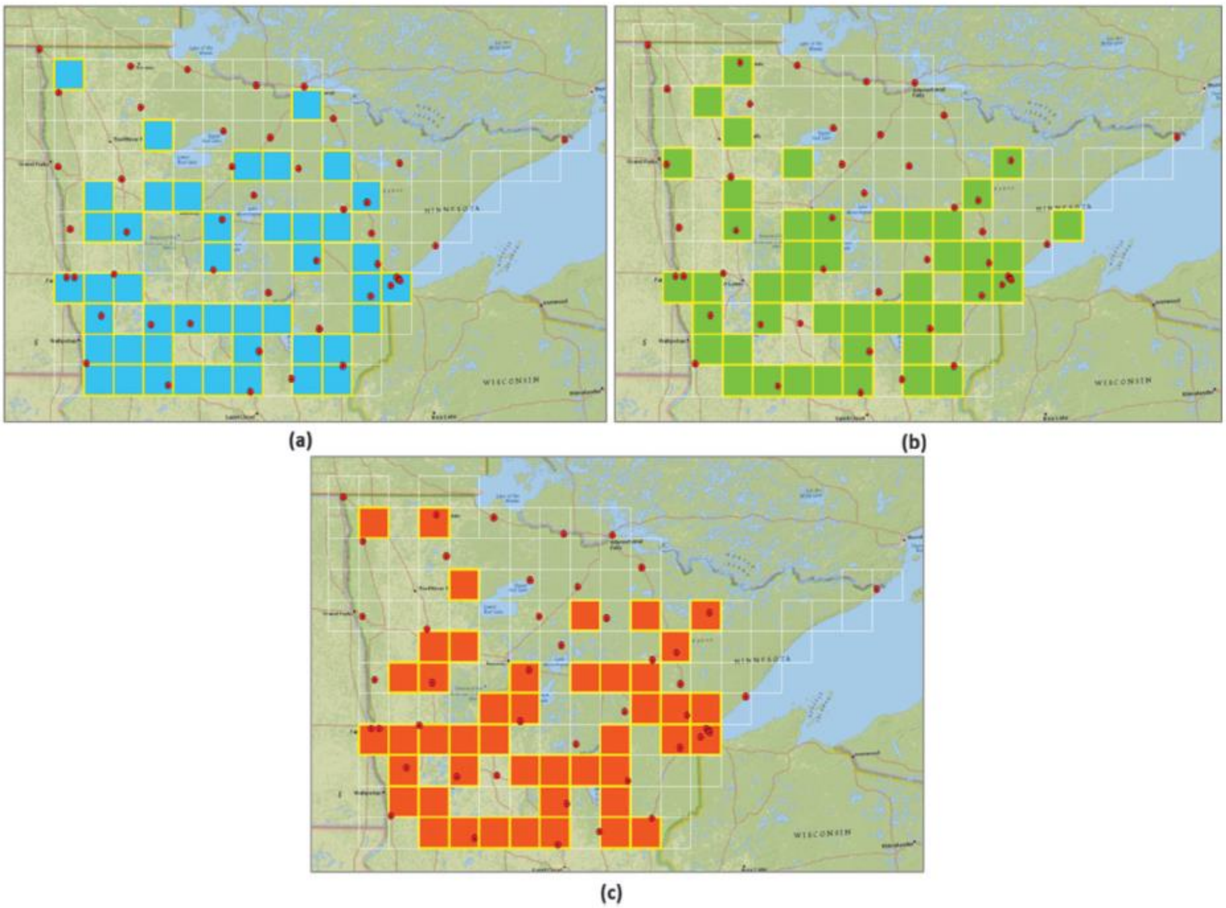


Kwon and Fu 2016

Figure 2. Net present value for a 25-year life cycle RWIS (a) benefits and cost (b) and projected net benefits

As presented in Figure 2a, users should review the RWIS cost compared to the total benefits and find the point where there is the highest difference. In the case of northern Minnesota, this was at 45 RWIS stations. Note that this optimal number includes the current installed RWIS network. Figure 2b shows the projected net present value (NPV) of the benefits.

To determine the optimal location for these RWIS sites, a grid was placed over the project area and current RWIS sites. Then, the areas with the greatest maintenance benefits (reduction in maintenance cost) and collision benefits (reduction in crashes) were mapped and compared. Figure 3 presents the mapping conducted in Kwon et al. (2015).



Kwon and Fu 2016

Figure 3. Optimal location for RWIS sites with (a) highest maintenance benefits, (b) highest crash benefit, and (c) combining both

This location process may allow agencies to evaluate their current RWIS network and see where the best placement may be if the optimal number is greater than their current RWIS network.

The methodology for determining RWIS density and location is ideal for agencies; however, the cost data was pulled from Haas et al. (1997). Therefore, to get better values for the life-cycle cost, the values for each variable should be updated and set for northern Minnesota.

2.4. U.S. DOT ITS Benefits, Costs, and Lessons Learned Database

In addition to reviewing individual studies, the U.S. DOT ITS database was reviewed. This database allows users to view state transportation agencies' experiences with specific ITS equipment. These experiences include their costs, benefits, and lessons learned when implementing specific ITS equipment. Table 7 presents the RWIS cost data pulled from the site.

Table 7. Sample RWIS data from U.S. DOT ITS Database

Location	Summary	Cost data	Year
Washington State DOT	RWIS stations, CCTV cameras, and VMS on 1-5 were deployed.	RWIS and CCTV cameras (capital and installation cost) $165,000 in 2003. O&M cost is approximately $1,200.	June 2009
Ohio DOT	Added 86 new RWIS stations, therefore managing a total of 158 stations.	RWIS on the highways total cost of deployment $2.2 million. RWIS deployed at county offices $1.3 million. Training cost $15,000 and warranty/service agreement was $185,000. Communication cost $49.95 per site per month for the main phone; a second phone is installed and cost $12.95 per site per month.	Dec. 2003
Michigan DOT	Completed architecture and pre-deployment plans for five of the seven regions.	Capital cost for the North region $4.02 million with an O&M annual cost of $460,000. Capital cost for the Bay region $2.06 million with an O&M annual cost of $256,000. Capital cost for Grand region $2.27 million with an O&M annual cost of $233,500. Capital cost for Superior region $3.46 million with an annual O&M cost of $358,000.	Jan. 2010
Washington State DOT	Spokane region implementation at several sites.	Weather station and installation cost at Sherman Pass $170,006 and $83,403 for the Laurier RWIS site.	Jan. 2004
Kansas City, Missouri	Six RWIS devices were installed. Note that the installation costs were reduced due to the power and cabinet installation were part of a route expansion project.	Capital cost for six RWIS devices $55,000. O&M cost per unit per year is $3,800.	Mar. 2010

Source: https://www.itskrs.its.dot.gov/its/itsbcllwebpage.nsf/KRHomePage

These data points show cost data from multiple public agencies around the nation. These agencies may be ideal candidates to connect with in the data gathering effort for this current project.

2.5. Additional RWIS Studies

Many state agencies have developed RWIS implementation plan reports. One implementation report was created by New York State DOT in 2014 (Chien et al. 2014). The report presents the current RWIS sites, the current weather data available, and potential new RWIS sites in New York. Additionally, Chien et al. (2014) presents the benefit-cost (B/C) ratio results from other sources and found the B/C ratio ranged from 2:1 and 10:1.

The Washington State DOT reviewed the potential benefits of the integration of RWIS (Bradshaw Boon and Cluett 2002). The report includes cost-efficient snow and ice maintenance strategies and ways to increase safety and mobility. The north central region expected a 10% savings in direct snow and ice control costs, which would result in a 1.4 B/C ratio. The Washington State DOT projects a $2.5 million savings for 10 years with the expansion of their RWIS program (Bradshaw Boon and Cluett 2002).

Singh et al. (2016) built upon Kwon et al. (2015) by focusing on the methodology for determining the optimal location for RWIS sites. The main difference in Singh et al.'s (2016) analysis was they reviewed weather-related crashes more closely to determine if the crash was truly caused by the change in weather. Their model includes two main components for planning, spatial coverage, and reliability of the system if one RWIS sensor fails. Singh et al. (2016) also presented a case study of the RWIS deployment in the Texas DOT's Austin district.

2.6. Other Equipment Life-Cycle Studies

Brom et al. (2016) reviewed the life cycle of energy equipment. In the study, the researchers reviewed two product life-cycle management models. The cost variables that were considered, when applying these models to gas turbines at a power plant, were installations, investment/capital cost, operation cost, planned maintenance, unplanned maintenance, disposal, opportunity cost (downtime losses), and the price of electrical energy. The models' results were shown not to be precise due to the changes in the market, but the methodology of the models was appropriate (Brom et al. 2016).

Bengtsson and Kurdve (2016) looked at the life-cycle costs for machining equipment while accounting for dynamic maintenance costs. The study looked at a large automotive driveline system manufacturing site. The energy, fluid, and maintenance costs were dynamic variables, and other variables were linear. Four stages were developed with regard to the cost: project cost, acquisition costs, life support cost, and life operations cost. Three options were reviewed: replacing the existing machines with a new one, reconditioning the existing machine, and running the existing machine and risking downtime. No specific equations were presented for this model. The study used historical data and literature reviews to get values for these variables to determine the best option. The NPVs for all three options were presented in graphic form, and it appears that purchasing a new machine is the most cost-effective option (Bengtsson and Kurdve 2016).

The Ohio DOT (ODOT) has conducted multiple winter maintenance projects that include a cost analysis (Schneider et al. 2014, 2015). Schneider et al. (2014) reviewed a tow-behind trailer that contains a plow and salting system that is able to swing out and treat another lane of roadway. Schneider et al. (2015) reviewed several different types of plow blades and compared them by performance and cost. The cost analysis for both studies utilized Monte Carlo simulations, which allow each variable to be a distribution and then a simulation will randomly select from within the distribution. The result is an average and range of the simulation, which is a more realistic value since it accounts for the variation within each variable.

CHAPTER 3. RWIS ELEMENTS

The project team identified key RWIS components to be considered as part of the RWIS LCCA. The RWIS elements were identified based on the information gathered during the literature review and discussion with the Aurora committee for this project.

ESS sites have been deployed as a method to capture, manage, and utilize road weather data. Traditional ESS sites were designed to provide RWISs with pavement conditions and associated weather conditions that affect the pavement conditions. Traditional RWIS platforms, ESS sites, and field processors have evolved and now may integrate sensors that have the capacity to monitor any of the following environmental parameters:

- Meteorological and pavement conditions
- Stream flow, stream depth, and localized flood depths in flood prone or flash flood areas
- Traffic conditions and traffic flow using remote monitoring devices
- Snow depth and blowing snow
- Visibility
- Environmental pollutants and toxic materials
- Solar and terrestrial radiation
- Soil temperature and soil moisture

However, most deployed ESS sites still focus on pavement and meteorological conditions.

A modern RWIS may include the following:

- A network of ESSs to collect road weather, traffic-related, environmental data, and potentially camera images
- Instrumented vehicles to collect road weather data and maintenance treatment activities
- Weather support services designed to address highway-specific requirements
- Decision-support systems designed to transform the various sources of road weather data into operational guidance to aid operational decisions
- Road weather data coordination and distribution system for both internal use and traveler information outlets

Presented in Table 8 is a listing of key RWIS components that were considered in this research.

Table 8. Key RWIS elements

RWIS elements
RPU
CPU
Telecommunications equipment to transmit data (modem)
Tower support structure
Enclosure - cabinet
Internet Protocol (IP) surveillance system (closed-circuit television [CCTV]) - optional
Software for CPU
Software for end user computer
Sensors
Pavement condition sensor
Surface temperature sensor
Subsurface sensor
Air temperature/Relative humidity sensor
Wind direction and speed sensor
Precipitation sensor
Barometric pressure sensor
Visibility sensor
Presence of precipitation sensor
Water level sensor
Solar radiation kit
Traffic sensor (e.g., microwave vehicle detection system [MVDS])

CHAPTER 4. DATA COLLECTION

Based on the RWIS elements identified in Chapter 3, the project team conducted online surveys to obtain estimates of RWIS equipment costs and design service life from RWIS manufacturers/vendors and state DOT agencies. Information on the expected service life, applicable warranties, and recommendations regarding preventive maintenance (including frequency, which may impact life expectancy) were also collected through the surveys, among other information.

4.1. Manufacturer Survey

A survey was developed and distributed to various RWIS manufacturers in September 2019 to gather information on their products, including costs, design service life, applicable warranties, and recommendations regarding preventive maintenance as related to their RWIS systems. The survey was made available to responders in an online format and sent out to the manufacturers via email, which included a link to access the survey.

4.1.1. Manufacturer Survey Background Information

A total of three manufacturers responded to the survey. Table 9 presents the three manufacturers that responded to the survey, as well as contact information for each respondent.

Table 9. RWIS manufacturer responded to survey

Manufacturers	Name	Title	Phone	Email
High Sierra Electronics, Inc.	Brett Hansen	RWIS product manager	530-273-2080	sales@hsierra.com
Campbell Scientific	Michael Burton	Market development manager	780-454-2505	mike.burton@campbellsci.ca
OTT HydroMet (Lufft)	Erik Wright	Sales manager - road weather	805-886-2828	erik.wright@lufftusainc.com

4.1.2. Summary of Manufacturer Survey Responses

The RWIS manufacturer survey asked the manufacturers various questions concerning their RWIS products, including the following:

- General RWIS product information
- Information for each individual RWIS component, including:
    - Air temperature/Relative humidity sensor
    - Surface temperature sensor
    - Pavement condition sensor
    - Wind direction and speed sensor
    - Visibility sensor

    - Precipitation sensor
    - Ultrasonic snow depth sensor
    - Subsurface sensor
    - Barometric pressure sensor
    - Water level sensor
    - Solar radiation kit
    - Traffic/Vehicle detection sensor
    - CCTV camera
- The following information was inquired for each component:
    - Product name and model
    - Equipment cost
    - Recommended preventative maintenance activities and frequencies
    - Estimated annual maintenance cost
    - Warranty period
    - Warranty cost
    - Expected life span
- Software product name(s) and cost(s)
- Features/capabilities of the software products
- Software license fee information and limitations/requirements
- Telecommunication requirements and costs
- Data storage solution(s) and cost(s)

Presented in Table 10 is a listing of the general RWIS product information provided by the manufacturers who responded to the survey. Comprehensive survey responses received from the manufacturers are presented in Appendix A.

Table 10. General product information provided by RWIS manufacturers

Manufacturers	RWIS products
High Sierra Electronics, Inc.	High Sierra Electronics (HSE) provides a full range of road weather equipment to support the road weather management community. A typical complete RWIS site includes road and atmospheric sensors. Other considerations include the equipment structure, power (AC or solar/alternative energy), and communications. HSE's typical RWIS: 5410 StormLink(R) RWIS Datalogger/RPU 5433 IceSight non-intrusive road condition and/or intrusive road sensor options Model 5422 and 5721 5432 Present weather sensor for precipitation/visibility 5723 Air temperature and relative humidity 5714 Ultrasonic anemometer or 5712 mechanical anemometer Some alternative sensors include snow depth and solar radiation
Campbell Scientific	Recently standardized as "Campbell Scientific, Intelligent Route Information Systems" and consisting of component parts manufactured by Campbell Scientific in USA and other parts from national and international manufacturers. All systems are based on Campbell Scientific CR Data Loggers (RPU).
OTT HydroMet (Lufft)	LCOM – RPU WS100 - Precipitation sensor (type and intensity) WS200 - Wind speed and direction WS300 – Relative humidity/Temp/Pressure WS600 - All in one (3 above combined) VS2K - Visibility sensor up to 2,000 m VS20K - Visibility sensor up to 20,000 m NIRS – Non-invasive road condition sensor IRS31Pro - Embedded passive pavement sensor with removable electronics MARWIS - Mobile road condition sensor

4.2. DOT Survey

A similar survey was developed and distributed to various state DOTs in September 2019 to gather information on their RWISs, including costs, design service life, applicable warranties, recommendations regarding preventive maintenance, software, procurement methods, and plans for future deployments as related to RWIS. The survey was made available to responders in an online format and was distributed to various agencies via the Snow-Ice listserv maintained by the University of Iowa, to which several winter maintenance agencies and professionals subscribe to as a means of sharing and gathering information on winter maintenance operations. This listserv included the Aurora member states, in addition to city, county, and state agencies, as well as international agencies.

4.2.1. DOT Survey Background Information

A total of 10 agencies responded to the survey. Provided in Table 11 are the 10 responding agencies as well as their contact information.

Table 11. DOT survey participants

Agency	Name	Title	Phone	Email
North Dakota DOT	Travis Lutman	ITS manager	701-328-4274	tlutman@nd.gov
Minnesota DOT	Jon Bjorkquist	Statewide RWIS coordinator	218-828-5722	jon.bjorkquist@state.mn.us
New Hampshire DOT	Lee Savary	Communications technician 1	603-271-1669	Lee.Savary@dot.nh.gov
	Susan Klasen	TSMO administrator	603-271-6862	susan.klasen@dot.nh.gov
Michigan DOT	James Roath	Roadway operations engineer	517-230-5361	RoathJ1@michigan.gov
British Columbia Ministry of Transportation and Infrastructure	Simon Walker	Weather and climate specialist	778-974-5376	simon.walker@gov.bc.ca
Alaska DOT & PF	Lisa Idell-Sassi	ITS coordinator	907-465-8952	lisa.idell-sassi@alaska.gov
Utah DOT	Jeff Williams		801-887-3703	JeffWilliams@utah.gov
Pennsylvania DOT	Vincent Mazzocchi	Roadway programs manager for winter/incident management	717-705-1439	vmazzocchi@pa.gov
Wisconsin DOT	Mike Adams	RWIS program manager	608-266-5004	michael.adams@dot.wi.gov
Iowa DOT	Tina Greenfield	RWIS coordinator	515-233-7746	Tina.Greenfield@iowadot.us

4.2.2.Summary of DOT Survey Responses

The RWIS DOT survey asked public agency members various questions concerning their RWIS, including the following:

- Number of RWIS stations deployed
- Number of years utilizing RWIS technology
- Procurement methods
- Brand(s)/Manufacturer(s) of RWIS products deployed
- General RWIS product information
- Information for each individual RWIS component, including:
  - Air temperature/Relative humidity sensor
  - Surface temperature sensor
  - Pavement condition sensor
  - Wind direction and speed sensor
  - Precipitation sensor
  - Visibility sensor
  - Ultrasonic snow depth sensor
  - Subsurface sensor
  - Barometric pressure sensor
  - Water level sensor
  - Solar radiation kit
  - Traffic/Vehicle detection sensor
  - CCTV camera (IP surveillance system)
  - The following product information was inquired for each component:

        - Product name/Model
        - Capital cost
        - Average annual costs for preventative/routine maintenance
        - Average number of times non-routine maintenance required per year
        - Average non-routine maintenance cost per year
        - Usefulness/Importance
        - Expected life span
- Product information for entire RWIS station(s):
    - The following product information was inquired for RWIS stations at a station level:
        - System brand/Model
        - Capital/System cost
        - System installation cost
        - Average annual costs for preventative/routine maintenance
        - Average non-routine maintenance cost per year
        - Usefulness/Importance
        - Expected life span
- Software product(s) used to store, manage, and/or analyze RWIS data
- Cost of the software/Licensing cost of software
- Cost of data storage/Number of years of data stored
- Types of communications used by RWIS to transfer data
- Monthly telecommunications cost per site
- Annual staffing costs associated with ongoing RWIS operations
- Does your agency purchase the warranty on RWIS components? Cost of warranty?
- Who performs preventative/routine maintenance on your RWIS?
- Who performs non-routine maintenance on your RWIS?
- Have winter maintenance costs been reduced due to data provided by your RWIS network?
- Agency sharing of document(s) relating to their RWIS
- Does your agency plan to install additional RWIS in the future?
- Number of additional RWIS station(s) your agency plans on installing in the next 5 years

Presented in Table 12 is a listing of the general RWIS product information provided by the DOT members who responded to the survey.

Table 12. General RWIS product information from DOT survey

Agency	RWIS manufacturers	RWIS products
Alaska DOT & PF	Vaisala, Campbell Scientific	Alaska DOT uses Novalynx tipping buckets, RM Young anemometers, windscreens, MRC temperature data probes, Judd snow depth sensors. Cameras by WTI, Axis, and Mobotix.
British Columbia Ministry of Transportation and Infrastructure	No sole manufacturer/vendor (British Columbia designs, builds, and maintains their own stations in-house)	Campbell Scientific CR1000 dataloggers, Vaisala DST/DSC pavement sensors, various other instrumentation.
Minnesota DOT	Vaisala, Lufft (Hoosier)	AXIS Q6125-LE PTZ network camera, Glen Martin tower, Great Plains tower, RM Young 05103 wind sensor. Lufft (Hoosier): LCOM RPU, WS100 UMB precipitation, VS2K visibility. Vaisala: RWS110 LX RPU, RWS200 RPU, HMP155 air temp/relative humidity, PWD22 precipitation/visibility, PTB110 barometer.
New Hampshire DOT	Original stations were SSI (Subsurface Systems Inc.), now Vaisala; Lufft (Hoosier)	Vaisala LX (21), Vaisala RWS200 (1), Lufft LCOM/UMB (3); Various brands of Vaisala sensors.
North Dakota DOT	Lufft (Hoosier) (North Dakota DOT does have several Vaisala sites and one Boschung site for their FAST)	A typical Lufft site has the following sensors: Axis Q6055-E camera, IR illuminator, LCOM, NIRS-31 sensor, WS100, WS301, WS200, and 72 in. deep subsurface probe.
Pennsylvania DOT	Vaisala	RWS200 and associated components.
Utah DOT	Vaisala, Campbell Scientific, High Sierra, Boschung	Utah DOT has too many products to list. Utah DOT customizes their instrumentation to their specific needs and requirements. Essentially, Utah DOT designs their own RWIS systems.
Wisconsin DOT	Manufacturer: Lufft (Hoosier)	WisDOT has 20 Lufft sites and 50 legacy Vaisala sites. Lufft sites have the LCOM RPU, IRS 31 pavement sensors, subsurface probe, OWI-430 precipitation sensor, Young 41382 temp/relative humidity sensor, and Young 05103 wind sensor. Vaisala sites have FP2000 pavement sensors and a variety of atmospheric sensors.
Iowa DOT	Iowa DOT's are a mix of vendors; most of their RPUs are Vaisala LX but they also have a number of Lufft LCOMs	Iowa DOT has a wide variety of sensors. Vaisala, RM Young, OSI, Lufft, Thies Clima, Axis cameras, Wavetronix traffic sensors.

The following three tables present summary information gathered from the DOT survey. Comprehensive survey responses from the DOT survey are included in Appendix B.

Table 13 presents the cost information on an RWIS at a station level provided by survey respondents. The information was the average cost for each site.

Table 13. Capital and installation costs for entire RWIS system

Agency	System brand/model	Capital/System cost	System installation cost	Additional information
Alaska DOT & PF	Campbell Scientific	$12,579 (equipment cost only)	$78,000–$385,000 (including construction and installation costs)	Typical construction and installation costs range between $90,000 and $135,000. The $78,000 construction and installation cost is a rehab of an existing site adding new power, communication features, and new sensors. The $385,000 construction and installation cost is for a remote site with no commercial power.
	Vaisala	$32,600 (equipment cost only)		
North Dakota DOT	Lufft*	$130,000 (including installation cost)*	See capital/system cost	This cost is for all equipment, installation, power connections, etc. We have to install two structures, one pole for our non-invasive near the road and a tower for all other sensors back near the right-of-way increasing the cost.
Wisconsin DOT	Lufft LCOM	$53,550 (including installation cost)	See capital/system cost	These costs combine equipment and installation, so they are total costs to put in a new site, excluding power.
	Vaisala ESP RPU	$35,000 (including installation cost)		
Pennsylvania DOT	Vaisala RWS200	$50,000 - $65,000 (equipment cost only)	$55,000	
Utah DOT	Custom	$25,000–$50,000 (including installation cost)	See capital/system cost	
Iowa DOT	Our entire stations are mixes of brands. Mostly Vaisala LX processors	$70,000 (including installation cost)		

*North Dakota DOT noted that they used Lufft, Vaisala and Boschung systems. The information provided was for the Lufft system only.

Table 14 presents the maintenance and life span information provided by survey respondents.

Table 14. Maintenance and life span information for entire RWIS system

Agency	System brand/model	Avg. annual costs for preventive/ routine maintenance	Avg. non-routine maintenance cost/year	Expected life span	Additional information
Alaska DOT & PF	Campbell Scientific	$1,778		9–11 years	
	Vaisala		$1,846	12–15 years	
North Dakota DOT	Lufft	We don't track these costs, but they are pretty low	We don't track this	12–15 years	Our staff maintains and repairs our sites. We don't have a good way of tracking all work that is done at each site. Each district replaces sensors during the life of the site, so we don't have a good way to track their replacement either. We do have sensors fail during that time that we must replace.
Wisconsin DOT	Lufft LCOM	$3,000	Unknown	16–20 years	
	Vaisala ESP RPU	$3,000	Unknown	16–20 years	
Pennsylvania DOT	Vaisala RWS200	~$6,000 (per site, per year)	N/A	16–20 years	Routine PM payment is based on monthly performance of the system, and monthly payment is reduced on a per-site basis. Over the full contract term, performance penalty became less as new sites were added to the system, while annual per-site costs also decreased.
Utah DOT	Custom	$24,657	$57,902	9–11 years	We also have an end of life replacement program, 10-year life span for most instruments, less for cameras and lead acid batteries.
Iowa DOT	Our entire stations are mixes of brands, mostly Vaisala LX processors	Bundled with all the rest of our ITS equipment, probably around $110,000		12–15 years	Individual components don't last that long, but we have some sites that are 30 years old.

Table 15 presents the general product and cost information for RWIS software provided by the survey respondents.

Table 15. RWIS software information

Agency	Software products used	Software cost/software licensing cost
North Dakota DOT	Parsons ATMS - Used for RWIS, DMS, and Cameras.	$450,000 in 2014, including 3 years of maintenance starting from install completion. $70,000/year for maintenance and upgrade fee after 3 years.
Alaska DOT & PF	Vaisala's ScanWeb. We are in the process of migrating to the MnDOT IRIS software.	N/A
Utah DOT	Campbell Loggernet, and server services. Custom software to store, manage and analyze.	One-time cost many years ago. Would take some work to dig that up.
Pennsylvania DOT	Vaisala RoadDSS Navigator	Included with web hosting and data services contract requirement, total of $108,000/year.
Wisconsin DOT	SCAN Web, Lufft	Currently no cost.
Iowa DOT	Was ScanWeb. Now have switched to DTN Totalview.	ScanWeb was $25,000 for the license, putting it on our own servers. Totalview is $54,000 per year.

CHAPTER 5. RWIS LIFE-CYCLE COST ANALYSIS GUIDELINES

This chapter presents methods and guidelines to assess the associated costs and benefits for determining life-cycle costs for RWIS systems. A review of the data collected from the literature review and surveys was conducted to determine the applicability of the data with respect to the life-cycle cost analysis. Information and guidelines available from existing life-cycle benefit/cost models and other LCCA tools were also reviewed to aid in performing the analysis. The key purposes of these guidelines include the following:

- Help quantify the costs and benefits associated with RWIS sites
- Better assess costs arising from RWIS assets over the life cycle
- Provide a framework for calculating NPW
- Assess alternatives and associated cost implications
- Support decisions on repair versus replacement based on projected expenses

Key RWIS elements to be considered for evaluation as part of the cost analysis were identified and categorized as either capital or O&M elements, with consideration for entire RWIS stations and individual components. Those elements are defined as follows:

- **Capital costs:** Costs associated with equipment installation and capital improvements, such as hardware and software
- **Operations and maintenance costs:** Items with future cost implications, such as ongoing operations, maintenance, rehabilitation, communications, and replacement costs

5.1. Quantify the Costs and Benefits

As described in Chapter 4, surveys were distributed to RWIS manufacturers and public agencies in September 2019 to gather information on their RWIS products, including costs, design service life, applicable warranties, recommendations regarding preventive maintenance, etc., as related to their RWIS systems. Quantification of the costs and benefits of RWISs are determined through data gathered from the surveys, literature review from previous studies, and transportation agencies’ experiences. These cost and benefit quantifications were combined to determine the inputs needed to perform the RWIS life-cycle analysis. Table 16 presents the cost variables that should be considered while modeling the RWIS LCCA.

Table 16. Cost variables to consider in LCCA

RWIS cost elements

Capital costs
• RPU
• Telecommunications equipment to transmit data (modem)
• Tower support structure
• Enclosure - cabinet
• IP surveillance system (CCTV) – optional
• Software (one-time cost)
• **Sensors**
    o Pavement condition sensor
    o Water level sensor
    o Air temperature/Relative humidity sensor
    o Wind direction and speed sensor
    o Precipitation sensor
    o Barometric pressure sensor
    o Visibility sensor
    o Presence of precipitation sensor
    o Traffic sensor (e.g., MVDS)
    o Ultrasonic snow depth sensor
    o Subsurface sensor
    o Solar radiation kit
    o Surface temperature sensor

Installation costs
Operational costs • Telecommunication service • Subscription-based software service • Private sector weather forecast services • Data storage fees
Maintenance costs
Other information • Sensor life

Individual agencies could refer to their own bid tabs to obtain the costs of the elements listed in Table 16. In addition, many of the variables' values may be gathered from vendors and through literature reviews.

The use of RWISs requires capital, installation, operations, and maintenance costs. However, there are benefits to RWISs that may be recognized through a reduction in unnecessary winter road maintenance operations (labor, equipment, and material), a potential reduction in weather-related crashes, and mobility improvements in travel-cost and emission reduction. Benefits within winter operations include a reduction of patrol shifts. Patrol shifts are conducted when the weather could potentially change into inclement weather that requires road treatment. Winter maintenance vehicles are then deployed on routes, and the drivers observe weather conditions in case treatment is needed, which utilizes the time and costs of the operators and equipment. With better weather data, the managers could track the weather variables associated with treatment needs and deploy resources only when needed. Therefore, better weather data may result in fewer patrol shifts. Table 17 presents the variables to consider when reviewing the benefits of RWISs.

Table 17. Benefical elements to consider in LCCA

RWIS direct and indirect beneficial elements
Winter maintenance vehicle patrol shift cost • Hours of patrol • Route miles • Fuel efficiency • Cost per gallon of fuel • Operator hourly rate • Number of events
Winter maintenance vehicle exposure cost • Life span of truck • Capital cost per truck • Total miles at end of life
Material cost • Cost per ton salt • Cost per ton sand • Cost per gallon of brine • Amount of salt used • Amount of sand used • Amount of brine used
Social cost savings • # of fatal crashes - weather related • # of injury crashes - weather related • # of property damage only crashes - weather related • Cost assigned to fatal crashes • Cost assigned to injury crashes • Cost assigned to property damage only (PDO) crashes • Inclement weather events per year • Length of RWIS road coverage • Preventable weather crashes – fatal • Preventable weather crashes – injury • Preventable weather crashes – PDO
Mobility improvement cost savings • Volume data, including percent passenger vs. commercial vehicles • Delay from inclement weather - before and after treatment • User delay cost - for commercial and passenger vehicles • Reduction in emissions

Note: Inclement weather events consist of an event that requires or can be treated by the transportation agency, such as snow, ice, and freezing rain. However, other inclement weather will see benefits as well by alerting the public of conditions for modified behavior while driving, which will result social cost savings. The length of RWIS coverage is dependent on the project setting's geographic features; however, one accepted area is a 30 km (18.6 mi) buffer zone (Kwon and Fu 2016) around the RWIS site.

These variables are dependent on the analysis boundaries; therefore, they should be gathered based on the project area being analyzed. Gathering or estimating the values of the above elements are important to enable a comprehensive LCCA. The values associated with the costs of RWISs are presented in the next section.

5.2. Cost Assessment Variables

A critical step in performing an LCCA for RWIS is the collection of cost data. As noted previously, the cost variables that should be considered for an RWIS LCCA include the costs of capital investments, installation, operations, and maintenance. Table 18 presents the costs that can be used to support an RWIS LCCA.

Table 18. Cost variables for life-cycle cost analysis

RWIS cost elements	High	Average	Low	Std. Dev.
Entire system capital cost (installed)*	$130,000	$89,358	$37,500	$40,996
Individual components capital costs (installed)*				
• RPU	$9,429	$6,053	$3,750	$2,399
• Telecommunications equipment to transmit data (modem)	$1,005	$840	$674	$234
• Tower support structure	$16,467	$12,424	$8,986	$2,990
• Enclosure - cabinet	$10,992	$8,472	$5,000	$2,220
• IP surveillance camera (CCTV) - optional	$7,280	$4,742	$2,276	$1,505
• Software (unless it is subscription, then go to operational costs)		$450,000		
Sensors				
• Pavement condition sensor	$12,722	$11,431	$9,995	$1,369
• Water level sensor	$935	$870	$771	$87
• Air temperature/Relative humidity sensor	$3,130	$1,590	$418	$992
• Wind direction and speed sensor	$4,832	$2,274	$1,093	$1,080
• Precipitation sensor	$6,765	$3,194	$768	$2,352
• Barometric pressure sensor	$998	$571	$95	$372
• Visibility sensor	$10,440	$7,195	$3,850	$2,403
• Presence of precipitation sensor	$4,857	$3,854	$2,527	$1,199
• Traffic sensor (MVDS)	$9,958	$6,540	$3,675	$2,731
• Ultrasonic snow depth sensor	$1,262	$1,029	$865	$207
• Subsurface sensor advance	$7,815	$6,539	$4,583	$1,271
• Subsurface sensor simple	$896	$680	$334	$245
• Solar radiation kit		$515		
• Surface temperature sensor advance	$14,797	$7,242	$4,036	$3,619
• Surface temperature sensor simple	$1,200	$944	$680	$217
• Data logger		$1,700		
• Temperature data probe (Alaska DOT)		$4,623		
Operational costs				
• Telecommunication service (monthly per RWIS station)	$40	$31	$20	$7
• Subscription-based software service (yearly)	$108,000	$95,333	$70,000	$21,939
• Private sector weather forecast services	$298,000	$198,341	$98,682	$140,939
Maintenance costs (per RWIS station per year)	$6,000	$2,893	$962	$1,804

Notes: *Capital costs for the entire system and individual components listed in the table include the costs for hardware, infrastructure, and installation. **Data storage was considered; however, no cost data were obtained through literature reviews or surveys with DOTs and vendors. Additionally, some data storage is a part of the subscription-based software. All data were gathered from surveys conducted in 2019, recent years of DOT bid tabs, and literature reviews.

The costs presented in Table 18 were gathered from multiple transportation agencies, primarily at the state level, as well as RWIS vendors. These data were collected from a survey created for each group (vendors and public agencies). Additionally, data were available through many agencies' bid tabs, which present all the past costs for the implementation of RWIS sites.

5.3. Framework for Calculating the Life-Cycle Cost of an RWIS System

5.3.1. Software Products and Costs

An RWIS includes many components, and individual components may have a varied life expectancy. Additionally, each RWIS system may be made up of a combination of various sensors based on an individual agency's needs. Therefore, the optimal analysis for determining the cost of an RWIS is to bring everything into terms of an annual cost.

In order to convert the cost into an annualized cost, the first step is to use the life span to find the annualized factor for each RWIS component, as shown in equation 1.

$$Annualized\ Factor = \frac{i}{1-(1+i)^{-n}} \quad (1)$$

where, *i* is the discount rate, *n* is the number of periods, which in this scenario is the expected life span, in years, of each RWIS component.

The discount rate used in an LCCA typically ranges from 3% to 7%. The U.S. Office of Management and Budget releases a yearly report identifying the discount rate, which should be utilized in an LCCA. The most recent report, from 2019, states that the discount rate for a long-lived (10+ years) project should be 7%. The annualized factor is calculated and applied to each of the individual components and the first-time installation cost of the RWIS site, as shown in equation 2.

$$Annualized\ Capital\ Cost_j = Capital\ Cost_j\ x\ Annualized\ Factor_j \quad (2)$$

where, *j* is the component being reviewed.

The annualized capital cost is the cost associated with the purchase and installation of the RWIS component. These factors require an investment at the start of the life cycle; therefore, as the value of money increases over time, the annualized cost is adjusted to account for investing when the value of money is lowest during the RWIS site's life cycle. Once the annualized capital cost for each component is determined, the annualized capital cost of an RWIS site can be calculated through equation 3.

$$Annualized\ Capital\ Cost\ of\ RWIS\ Site = \sum Annualized\ Capital\ Cost_j \quad (3)$$

This analysis allows agencies to evaluate the investment for each RWIS based on the unique sensors/components selected for that site.

5.3.2. Operations and Maintenance Costs

O&M costs are incurred throughout the life cycle of an RWIS. Operational costs are costs associated with day-to-day operations of the system, such as costs of telecommunications, meteorological services, software subscriptions, and training. Some of the yearly operational costs, such as the costs of software subscriptions, meteorological services, and training, should be divided by the number of RWIS sites within the network before adding to the overall per site yearly cost.

Maintenance costs typically include the costs of labor and materials for calibration, preventive maintenance, repairs, and replacement of damaged equipment. Costs associated with spare parts and inventory management also should be considered in determining the maintenance costs. Maintenance data for RWIS components gathered from the vendor survey is included in Appendix A as a resource.

5.3.3. Annualized Cost

The annualized cost, or the equivalent annual cost, of an RWIS site is the cost per year for owning and maintaining the RWIS site over its life span. Calculating the annualized cost is useful in making budget decisions by converting the cost of an RWIS site to an equivalent annual amount. The annualized cost helps compare the cost-effectiveness of two or more RWIS sites or implementation alternatives.

Once the annualized capital cost and the average yearly operational and maintenance costs for an RWIS site are determined, the annualized cost of an RWIS site can be calculated through equation 4.

$$Annualized\ Cost\ of\ RWIS\ Site = Yearly\ Operational\ Cost\ per\ Site + Yearly\ Maintenance\ Cost\ per\ Site + \sum Capital\ Cost_j\ x\ Annualized\ Factor_j \quad (4)$$

5.3.4. Benefits

The benefits of RWISs are realized through winter maintenance savings, crash reduction/collision cost savings, and mobility improvements.

With reliable weather data, winter maintenance crews may improve situational awareness, which increases winter maintenance efficiency and results in reduced expenditures for labor, materials, and equipment. These benefits are based on the amount and locations of the RWIS sites. A potential benefit of implementing an RWIS is a reduction of the need for routine patrols for monitoring road conditions, resulting in reduced equipment usage and improved labor productivity. Road maintenance supervisors can be more efficient in mobilizing the available crew and equipment in terms of time and location. In addition, an RWIS can provide road conditions to assist an agency with proactively performing winter maintenance activities, which leads to reduced labor, equipment, and anti-icing chemical usage.

To estimate winter maintenance savings, an agency should first gather the unit costs for labor, equipment, and materials for winter maintenance. An agency can then apply the unit costs to the numbers of patrol shifts reduced, labor hours reduced, amount of materials reduced, etc., to estimate the winter maintenance savings.

$$Winter\ Maintenance\ Savings = Winter\ Maintenance\ Patrol\ Savings + Labor\ Savings + Equipment\ Savings + Material\ Savings \quad (5)$$

Crash reduction and collision cost savings are estimated as a cost reduction in the expected number of crashes due to inclement weather for the project area selected and categorized by crash severity. Reduced crash costs from RWIS implementation can be estimated using the standard cost for each type of crash multiplied by the expected reduction of those types of crashes due to RWIS implementation. Estimated standard unit costs for various types of crashes, as presented in Table 19, are published in the FHWA Crash Costs for Highway Safety Analysis (Harmon et al. 2018). The FHWA publication also includes unit costs for states.

Table 19. National crash unit costs

Severity	Comprehensive crash unit cost (2016 dollars)
Fatal crash (K)	$11,295,400
Serious/Incapacitating injury crash (A)	$655,000
Minor/Non-incapacitating injury crash (B)	$198,500
Possible injury crash (C)	$125,600
Property damage only crash (O)	$11,900

Source: Harmon et al. 2018

Mobility improvement-related cost savings include a reduction in travel costs and pollution costs. RWIS implementation may result in a reduction in travel costs and vehicle emissions by improving traffic flow during inclement conditions.

In addition, a fully integrated RWIS includes information delivery mechanisms such as websites, variable message signs, automated phone systems, Highway Advisory Radio broadcasts, etc. The integration of an RWIS with traveler information systems allows for the dissemination of important weather and road conditions information to the traveling public. The benefits associated with providing better traveler information include better informed and prepared drivers, safer travel behavior, and reduced travel during poor conditions, which result in fewer crashes, fatalities, injuries, and property damage, as well as improved mobility and increased customer satisfaction.

Multiple methods and software tools can be utilized for estimating the benefits. A list of available tools and methods specific for RWM projects was summarized in Lawrence et al. (2017).

Once the annualized cost and savings are estimated, the differences provide an overall yearly savings when implementing RWIS systems.

5.4. Alternative Assessment and Associated Cost Implications

There are two alternative system technologies that collect and distribute weather data: connected vehicle (CV) technology equipped with weather sensors and mobile data collection units such as automatic vehicle location (AVL) or mobile data computer (MDC) units. These technologies would require a broad and heavy investment for users in order to provide enough data to be useful for transportation agencies and maintenance crews.

CV technologies and applications have been expanding within the market. CV applications have the ability to share basic information about the vehicle. These real-time data may be relayed to other vehicles (vehicle to vehicle [V2V]) or to infrastructure throughout the travel network (vehicle to infrastructure [V2I]). Vehicle information may indicate the weather condition, such as wiper status and rate, air temperature, tire friction, traction control enable/disable, and speed. V2V communication may assist with a reduction in crashes; however, these data won’t assist with reducing winter maintenance treatment, since maintenance crews will not have access to the data. V2I would allow agencies to obtain vehicle information in real-time and utilize it for maintenance decisions. V2I would require an investment in infrastructure and would rely on vehicles having these technologies while being equipped with the desired weather sensor/data.

Similarly, the AVL or MDC technology would be equipped on weather maintenance vehicles, and then use telecommunications to relay sensor data to winter maintenance managers for decision-making. However, these technologies rely on the winter maintenance vehicles patrolling the area; therefore, patrol shifts may increase instead of decrease.

5.5. Decision Support on Repairs or Replacements

The expected life span for each RWIS component was requested and reviewed from the vendor and DOT surveys. Based on the various responses, Table 20 presents the expected life span for each component.

Table 20. Life span reported through survey and literature review

Components	Average (year)	Std. Dev.
Entire RWIS station	15	3.3
IP surveillance system (CCTV) - optional	7	1.1
Pavement condition sensor	8	2.5
Water level sensor	4	N/A
Air temperature/Relative humidity sensor	9	1.6
Wind direction and speed sensor	9	1.6
Precipitation sensor	10	1.6
Barometric pressure sensor	10	N/A
Visibility sensor	8	2.3
Ultrasonic snow depth sensor	9	1.5
Subsurface sensor	8	3.1
Solar radiation kit	10	N/A
Surface temperature sensor	8	2.9

Note: If no life expectancy was provided, a default of eight years is used, which is the average of the sensor life spans presented above (sensors only).

If an agency would like to determine when to replace or repair an RWIS component, the following data would be required:

- Replacement capital cost for the specific component
- Average maintenance cost including the cost to check, pull, and re-install for the specific component
- Probability of failure
- Warranty span

During the survey, the maintenance cost per component was requested. However, insufficient data was provided by the vendors and the agencies. Agencies that responded to the survey provided the overall maintenance costs to the extent possible.

Another factor to consider in performing an LCCA is the probability of system or component failure. The probability of failure may be collected based on the number of failures the component has during its life span. It should be noted that the probability of failure may be impacted by the age of the equipment. Changes in the probability of failure through the equipment life cycle should be carefully considered in a more complex, detailed LCCA. Using an average probability of failure should be sufficient for a planning level analysis.

5.5.1. Life-Cycle Cost Model

Once these points are collected, the total expected life-cycle cost and the annualized life-cycle cost can be estimated. The estimated life span of an RWIS site is between approximately 20 and 25 years. The RPU and CPU will likely need to be replaced or upgraded every 5 years, and other sensors and RWIS components will need to be replaced every 8 to 10 years as noted in the previous Table 20. As such, the life-cycle cost consists of three components: the initial equipment and installation cost, the total O&M costs, and the component upgrade/replacement costs. Equation 6 presents the equation that can be used to calculate the expected life-cycle cost of an RWIS site.

$$Expected\ Life\ Cycle\ Cost = Capital\ Cost + Total\ O\&M\ Cost + Total\ Replacement\ \&\ Upgrade\ Cost \quad (6)$$

The total replacement and upgrade cost can be estimated using equation 7.

$$Expected\ Total\ Replacement\ \&\ Upgrade\ Cost = \sum\left[(Cost\ of\ Replacement\ \&\ Upgrade)_{j,k} \times (Probability\ of\ Failure)_{j,k}\right] \quad (7)$$

where, *j* is the index for an RWIS component, and *k* is the index for a failure limit state.

5.5.2. Net Present Worth

The NPW of an RWIS is an important indicator to support implementation decisions. The steps to determine the NPW of implementing an RWIS include: (1) determining the costs and benefits associated with implementing an RWIS site over its life cycle and (2) using these results to calculate the incremental NPW of an RWIS site. The incremental NPW can then be compared to alternatives such as not installing an RWIS or installing an RWIS with varying levels of components.

The NPW of an RWIS can be calculated using equation 8.

$$Net\ Present\ Worth\ (NPW) = -(Capital\ Cost) + \{(Annual\ Savings) - [(Annual\ O\&M\ Cost) + (Annual\ Replacement\&Upgrade\ Cost)]\} \times (Aggregate\ Series\ Discount\ Factor) \quad (8)$$

The annual savings are derived from reductions in winter maintenance costs, crash reduction and collision cost savings, and mobility improvement-related cost savings, as discussed in Chapter 4. The discount factor in equation 8 is the aggregate series discount factor that is assumed to be uniform over the life cycle and is calculated using equation 9.

$$Present\ Value\ of\ Aggregate\ Series\ Discount\ Factor = \frac{(1+i)^n - 1}{i \times (1+i)^n} \quad (9)$$

where, *i* is the discount rate, and *n* is the expected life span in years.

Using equation 8, the NPW of RWIS alternatives can be calculated and compared. The alternative with the highest NPW is the most cost-effective alternative.

5.6. Summary

An LCCA is a data-driven tool that provides a detailed account of the total costs of a project over its expected life. An LCCA has been proven to create short-term and long-term savings for transportation agencies by helping decision-makers identify the most beneficial and cost-effective projects and alternatives. Recognizing its benefit, agencies have implemented LCCA programs and have successfully saved significant sums of money. However, there are still many challenges to creating or expanding the use of LCCA in transportation, in particular for technology-related projects and systems.

This chapter of the report provides methods and general guidelines to assist public agencies with determining RWIS site life-cycle costs. The next chapter of the report presents an example, illustrating the use of the methods and guidelines to perform an LCCA and estimate a benefit-cost ratio for an RWIS deployment in a hypothetical case. Public agencies can follow the information in this and the next chapter to gather the necessary data and perform the analysis to help quantify the costs and benefits associated with RWISs.

CHAPTER 6. SIMULATED CASE STUDY

This chapter presents a simulated case study demonstrating the use of the methodology for an LCCA as described in Chapter 5 of this report. A hypothetical example is used to demonstrate the methodology and the analysis. The example illustrates a state DOT that would like to evaluate the costs as well as potential benefits associated with deploying a new RWIS site.

The intent of the hypothetical state agency's evaluation is to perform a comprehensive assessment that takes into consideration the capital costs, annual cost to maintain the site, and the estimated benefits from the new RWIS site over its useful life span. The agency would like to use the evaluation result to assist with making more informed decisions on its RWIS investment. It was assumed that the new RWIS site under consideration is in an urban area with high volume of travelers on the roadways.

6.1. Annualized Costs

It was assumed that the agency desires to deploy an RWIS station that includes a suite of sensors, equipment, and capabilities, as listed in Table 21.

Table 21. Hypothetical agency's RWIS cost and life span records

RWIS elements	Average costs	Life span (years)
Individual components capital costs (installed)		
• RPU	$6,053	10
• Telecommunications equipment to transmit data (modem)	$840	10
• Tower support structure	$12,424	20
• Enclosure - cabinet	$8,472	20
• CCTV camera	$4,742	7
• **Sensors**		
○ Pavement condition sensor	$11,431	8
○ Water level sensor	$870	4
○ Air temperature/Relative humidity sensor	$1,590	9
○ Wind direction and speed sensor	$2,274	9
○ Precipitation sensor	$3,194	10
○ Barometric pressure sensor	$571	10
○ Visibility sensor	$7,195	8
○ Presence of precipitation sensor	$3,854	8
○ Traffic sensor	$6,540	9
○ Ultrasonic snow depth sensor	$1,029	9
○ Subsurface sensor advance	$6,539	8
○ Surface temperature sensor advance	$7,242	8
Operational costs		
• Telecommunication service (monthly per RWIS station)	$31	
• Subscription-based software service (yearly)	$95,333	
Maintenance costs (per RWIS station per year)	$2,893	

Based on data recorded from the hypothetical agency's previous RWIS deployment and its RWIS program to date, the agency identified the costs and expected life spans of the RWIS components, as presented in Table 21.

Applying equation 10, also described in Chapter 5, annualized factors for various RWIS components can be obtained.

$$Annualized\ Factor = \frac{i}{1-(1+i)^{-n}} \qquad (10)$$

where, *i* is the discount rate, *n* is the number of periods, which in this scenario is the expected life span, in years, of each RWIS component. The discount rate, *i*, used in an LCCA typically ranges from 3% to 7%.

In this scenario, the agency used a 5% discount rate on all equipment with an expected life span below 10 years and 7% for equipment with an expected life span of 10 years or more to take into account longer-term uncertainty. The calculated annualized factors are shown in Table 22.

Table 22. Annualized factors based on discount rates and expected life span of equipment

Expected life span (years)	Discount rate	Annualized factor
4	5%	0.2820
7	5%	0.1728
8	5%	0.1547
9	5%	0.1407
10	7%	0.1424
20	7%	0.09439

The annualized factor was applied to each of the individual components to calculate the capital cost of the RWIS site using equations 11 and 12. The annualized cost of the RWIS site, which includes the annualized capital, operational, and maintenance costs, is then calculated through equation 13.

$$Annualized\ Capital\ Cost_j = Capital\ Cost_j\ x\ Annualized\ Factor_j \quad (11)$$

$$Annualized\ Capital\ Cost\ of\ RWIS\ Site = \sum Annualized\ Capital\ Cost_j \quad (12)$$

$$Annualized\ Cost\ of\ RWIS\ Site = Yearly\ Operational\ Cost\ per\ Site + Yearly\ Maintenance\ Cost\ per\ Site + \sum Capital\ Cost_j\ x\ Annualized\ Factor_j \quad (13)$$

Table 23 presents the breakdown and total annualized cost for the new RWIS site.

Table 23. Annualized cost for the case study RWIS site

RWIS cost elements	Average	Life span	Annualized capital cost
Individual components capital costs (installed)*			
• RPU	$6,053	10	$861.81
• Telecommunications equipment to transmit data (modem)	$840	10	$119.60
• Tower support structure	$12,424	20	$1,172.74
• Enclosure - cabinet	$8,472	20	$799.70
• IP surveillance camera (CCTV)	$4,742	7	$819.51
• **Sensors**			
○ Pavement condition sensor	$11,431	8	$1,768.63
○ Water level sensor	$870	4	$245.35
○ Air temperature/Relative humidity sensor	$1,590	9	$223.70
○ Wind direction and speed sensor	$2,274	9	$319.93
○ Precipitation sensor	$3,194	10	$454.75
○ Barometric pressure sensor	$571	10	$81.30
○ Visibility sensor	$7,195	8	$1,113.22
○ Presence of precipitation sensor	$3,854	8	$596.30
○ Traffic sensor	$6,540	9	$920.11
○ Ultrasonic snow depth sensor	$1,029	9	$144.77
○ Subsurface sensor advance	$6,539	8	$1,011.73
○ Surface temperature sensor advance	$7,242	8	$1,120.50
Operational costs			
• Telecommunication service (monthly per RWIS station)	$31		$372
• Subscription-based software service (yearly)	$95,333		$6,000
Maintenance costs (per RWIS station per year)	$2,893		$2,893
Total annualized cost			**$21,038.63**

6.2. Estimation of Benefits and Savings

Once the total costs for the new RWIS system were calculated, the next step is to estimate the indirect and direct benefits for the new site. As described in Chapter 5, benefits associated with an RWIS can be recognized through a reduction in unnecessary winter road maintenance operations (labor, equipment, and material), a potential reduction in weather-related crashes, mobility improvements, and emission reduction. The direct costs and savings associated with winter road maintenance are ones that the agency can observe within their budget. These are the costs and savings associated with winter maintenance vehicle patrol shifts, vehicle exposure, and material usage. Indirect benefits are additional savings not fully or directly impacting the agency's budget. Indirect benefits include the social savings (via crash reduction), mobility user delay cost, and mobility reduction in emissions. The elements needed to estimate these benefits are presented in Table 24.

Table 24. Variables for benefit estimation

RWIS direct and indirect beneficial elements	Agency's variables
Winter maintenance vehicle patrol shift cost	
Hours of patrol	3 hours per event, plus 6 eight-hour patrol-only shifts
Route miles	40 mi
Fuel efficiency	3.5 mpg
Cost per gallon of fuel	$3.00
Operator hourly rate	$30
Inclement weather events per year	40 per season
Winter maintenance vehicle exposure cost	
Life span of truck	12 year
Capital cost per truck	$200,000
Total miles at end of life	250,000
Material cost	
Cost per ton salt	$55
Cost per cubic yard of sand	$20
Cost per gallon of brine	$0.15
Amount of salt used per event	16 ton
Amount of sand used per event	100 yd^3
Amount of brine used per event	150 gal
Average reduction from RWIS	15%
Social cost savings	
# of fatal crashes – weather-related per year	1
# of injury crashes (a) – weather-related per year	5
# of injury crashes (b) – weather-related per year	10
# of injury crashes (c) – weather-related per year	23
# of property damage only (PDO) crashes – weather-related	60
Cost assigned to fatal crashes	$11,295,400
Cost assigned to injury crashes (a)	$655,000
Cost assigned to injury crashes (b)	$198,500
Cost assigned to injury crashes (c)	$125,600
Cost assigned to PDO crashes	$11,900
Inclement weather events per year	40 per season
Length of RWIS road coverage	40 mi
Preventable weather crashes – fatal	6.8%
Preventable weather crashes – injury	7.1%
Preventable weather crashes – PDO	6.7%
Mobility improvement cost savings	
Volume data (AADT)	100,000
Percent passenger vehicles	95%
Percent commercial vehicle	5%
Average speed without RWIS	45
Average speed with RWIS	50
Hourly user delay cost passenger	$18.40
Hourly user delay cost commercial	$32.30
Fuel cost savings per hour per gal of fuel - passenger	$1.28
Fuel cost savings per hour per gal of fuel - commercial	$6.06
Carbon dioxide per gal of fuel (metric ton) - passenger	0.00889
Carbon dioxide per gal of diesel (metric ton) - commercial	0.01018

Note: Fuel savings based on Glover 2020. Fuel savings calculated with U.S. EPA Greenhouse Gases Equivalences Calculator. Gallons of gasoline saved calculated with the U.S. EPA Fact Sheet: Social Cost of Carbon (2016).

In this simulated case study, it was assumed that the hypothetical agency is able to obtain data to support the estimates based on historical data, with additional sources to supplement data gaps as explained in the Table 24 note.

6.2.1. Winter Maintenance Savings – Patrol

The overall patrol savings can be broken down into three main areas as presented in equation 14.

$$Patrol\ Savings = Labor\ Savings + Fuel\ Savings + Truck\ Exposure\ Savings \quad (14)$$

The labor and fuel savings can be calculated based on the number of patrol hours per season. To determine the truck exposure savings, the winter maintenance truck capital cost and the miles at end of life of the truck provide the cost per mile of truck exposure.

$$Exposure\ Cost\ per\ Mile\ for\ Winter\ Maintenance\ Truck = \frac{Capital\ Cost\ of\ Vehicle}{Average\ Miles\ at\ End\ of\ Life} \quad (15)$$

$$Exposure\ Cost\ per\ Mile\ for\ Winter\ Maintenance\ Truck = \frac{\$200{,}000}{250{,}000} = \$0.80$$

With the exposure cost per mile determined, the patrol savings may be calculated with equation 16.

$$\begin{aligned} Patrol\ Savings &= (Hours\ of\ Patrol \times Labor\ rate) + (Hours\ of\ Patrol\ \times \\ &\quad Average\ Speed\ of\ Winter\ Maintenance\ Vehicle\ \div Fuel\ Economy\ \times \\ &\quad Cost\ per\ Gallon\ of\ Fuel) + (Exposure\ Rate\ per\ Mile\ \times Miles\ Saved) \end{aligned} \quad (16)$$

$$\begin{aligned} &Patrol\ Savings \\ &\quad = (168\ hr \times \$30) + (168\ \times 40\ mph\ \div 3.5\ mpg\ \times \$3.00) \\ &\quad + (\$0.80\ \times 80{,}640) = \boldsymbol{\$75{,}312\ per\ year} \end{aligned}$$

Using these equations, the patrol savings per year is estimated to be $75,312.

6.2.2. Winter Maintenance Savings – Material Savings

Winter maintenance material savings can be calculated using equation 17.

$$\begin{aligned} Material\ Savings &= Percent\ Reduction\ \times Number\ of\ Events\ per\ Year\ \times \\ &\quad Material\ used\ per\ Event\ \times Cost\ of\ Material \end{aligned} \quad (17)$$

Based on RWIS data readily available from previous implementation, the hypothetical agency estimated that there is a 15% reduction in material cost. In this scenario, the agency uses rock salt, sand, and liquid brine; therefore, equation 13 is applied for each material type used to calculate the savings.

$$\begin{aligned} &\mathit{Material\ Savings} \\ &\quad = 0.15 \times 40 \\ &\quad \times [(16\ ton \times \$55\ per\ ton) + (100 yd^3 \times \$20) + (150\ gal \times \$0.15)] \\ &\quad = \$\mathbf{17,415\ per\ year} \end{aligned}$$

Based on the estimated material reduction and current usage amounts, the material savings would be $17,415 per year for the areas within the new RWIS zone.

6.2.3. Social Cost Savings

Multiple methods can be utilized for estimating social cost savings and benefits, as noted in Chapter 5. For illustration purposes, it was assumed that the agency estimates the reduction of crashes by severity type based on findings from previous research through estimated exposure to ice and wetness, combined with the crash rates per million vehicle-miles. Based on their research, the estimated reductions of fatal, injury (all severity types), and PDO crashes due to RWIS are 6.8%, 7.1%, and 6.7%, respectively. Using the cost per crash type and the average number of crashes for the RWIS area, the estimated social savings can be estimated using equation 18.

$$\mathit{Social\ Savings} = \sum \mathit{Crash\ reduction\ percentage} \times \mathit{Cost\ of\ crash\ by\ severity} \times \mathit{Average\ number\ of\ crashes\ by\ severity} \quad (18)$$

The social savings is the summarization of the crash reduction by cost for each severity type.

$$\begin{aligned} &\mathit{Social\ Savings} \\ &\quad = (6.8\% \times 1\ crash \times \$11{,}295{,}400)_{Fatal} \\ &\quad + (7.1\% \times 5\ crash \times \$655{,}000)_{InjuryA} \\ &\quad + (7.1\% \times 10\ crash \times \$198{,}500)_{InjuryB} \\ &\quad + (7.1\% \times 23\ crash \times \$125{,}600)_{InjuryC} \\ &\quad + (6.7\% \times 120\ crash \times \$11{,}900)_{PDO} = \$\mathbf{1,442,328\ per\ year} \end{aligned}$$

This indirect social savings is estimated to be $1,442,328 per year based on crash reductions within the new RWIS zone.

6.2.4. Mobility Improvement Cost Savings

In this scenario, the agency has seen an increase in average speed of 5 mph during inclement weather when RWIS data is used to support winter maintenance strategies. The average travel speed on the major roads in the hypothetical proposed RWIS area is usually 45 mph during inclement weather. It is anticipated that, with RWIS deployment, the average speed will increase to 50 mph. Using the number of vehicles affected during inclement weather events and average hourly cost of delay, the user delay cost (UDC) may be found.

$$Hours\ saved\ per\ vehicle\ each\ hour\ of\ inclement\ weather = \frac{Miles\ of\ RWIS\ Zone}{Speed\ without\ RWIS} - \frac{Miles\ of\ RWIS\ Zone}{Speed\ with\ RWIS} \quad (19)$$

$$Hours\ saved\ per\ vehicle\ each\ hour\ of\ inclement\ weather = \frac{40\ miles}{45\ mph} - \frac{40\ miles}{50\ mph} = 0.08889\ hours$$

$$Vehicles\ count\ during\ inclement\ weather = Hourly\ traffic\ volume\ \times Number\ of\ events\ \times Average\ hours\ per\ event \quad (20)$$

$$Vehicles\ count\ during\ inclement\ weather = 4167\ vehicles \times 40\ events\ per\ year \times 12\ hours\ per\ event = 2{,}000{,}000\ vehicles$$

$$Mobility\ Savings = Hour\ saved\ per\ vehicle\ each\ hour\ of\ inclement\ weather\ \times [(vehicle\ count\ \times passenger\ percentage\ \times cost\ for\ passenger\ vehicle) + (vehicle\ count\ \times commerical\ percentage\ \times cost\ for\ commerical\ vehicle)] \quad (21)$$

$$Mobility\ Savings = 0.08889\ hours \times [(2{,}000{,}000\ \times 95\%\ \times \$18.40) + (2{,}000{,}000\ \times 5\%\ \times \$32.30)] = \$\mathbf{3,394,666\ per\ year}$$

The total user delay cost estimated savings is $3,394,666 per year.

Emissions savings can be calculated using the total hours of delay saved through the following equations:

$$Gallons\ of\ fuel_{Passenger} = (Total\ hours\ delay\ saved\ \times Fuel\ Cost\ Saving\ per\ hour\ per\ gal\ of\ fuel\ saved\ \div Cost\ of\ fuel) \quad (22)$$

$$Gallons\ of\ fuel_{Commerical} = (Total\ hours\ delay\ saved\ \times Fuel\ Cost\ Saving\ per\ hour\ per\ gal\ of\ fuel\ saved\ \div Cost\ of\ fuel) \quad (23)$$

$$Gallons\ of\ fuel_{Passenger} = (168{,}888.8\ hours \times \$1.28\ \div \$3.00) = 72{,}059\ gal$$

$$Gallons\ of\ fuel_{Commerical} = (8{,}888.8\ hours \times \$6.06\ \div \$3.00) = 17{,}956\ gal$$

$$Emissons\ Savings_{Passenger} = (Gallons\ saved\ Passenger \times Carbon\ Dioxide\ per\ Gallon\ of fuel\ in\ metric\ tons \times Cost\ per\ ton) \quad (24)$$

$$Emissons\ Savings_{Commerical} = (Gallons\ saved\ Commercial \times Carbon\ Dioxide\ per\ Gallon\ of fuel\ in\ metric\ tons \times Cost\ per\ ton) \quad (25)$$

$$Emissons\ Savings_{Passenger} = (72{,}059\ gal \times 0.00889\ CO_2 per\ gal\ (metric\ ton) \times \$89) = \$\mathbf{57,014}\ \boldsymbol{Per\ ton\ per\ year}$$

$$Emissons\ Savings_{Commerical} = (17{,}956\ gal \times 0.01018\ CO_2 per\ gal\ (metric\ ton) \times \$89) = \$\mathbf{16,268}\ \boldsymbol{Per\ ton\ per\ year}$$

The total emissions savings is determined to be $73,282 per year.

6.3. Summary for Benefit Savings and B/C Ratios for the Proposed RWIS Site

The total estimated benefits for the new RWIS site are presented in Table 25.

Table 25. Case study benefit summary

Benefits	Savings
Direct benefits	
Patrol savings	$75,312.00
Material savings	$17,415.00
Indirect benefits	
Social savings	$1,442,328.00
Mobility - UDC savings	$3,394,666.67
Mobility - emissions savings	$73,282
Total benefits	$5,003,003.77

Based on these yearly benefits and the annualized cost, the following B/C ratios in Table 26 are presented for the direct benefits and total (direct plus indirect) benefits. The total annualized cost was determined to be $21,038.63, as shown in Table 23 in section 6.1.

Table 26. Case study B/C ratios

Variable	B/C ratio
Direct benefits/annualized cost	4.41
Total benefits/annualized cost	237.8

CHAPTER 7. KEY FINDINGS AND CONCLUSIONS

This chapter presents a summary of the project's key findings and conclusions. The findings and conclusions will serve as a reference guide to Aurora Board members to help them make more informed investment decisions regarding various elements of their RWIS systems, including when to replace RWIS components, funding needs based on RWIS system age, and how to address ongoing RWIS enhancements, repairs, and operations with rapid changes in technology.

The methodologies presented in this report provide a framework for analyzing life-cycle costs and NPW, which helps agencies make more informed decisions in repairs and replacement of RWIS sites. It also helps assess and compare alternatives and associated cost implications.

The steps for performing a life-cycle cost analysis for an RWIS site are summarized below. These steps present the principles of LCCA for RWIS sites and serve as a guide to perform the analysis, and they are as follows:

- **Determine RWIS deployment strategy:** Determine the necessary components and other details of an RWIS site, including types of sensors, infrastructure (e.g., tower, pole, and foundation), communications, and power source. The location of the RWIS also should be considered as it may have an impact on installation costs.
- **Collect data:** Collect costs and life span information at an individual component level (preferred) or the entire RWIS site level. Data presented herein or collected from other agencies can also be used to fill data gaps. Capital, installation, maintenance, and operational costs should be collected.
- **Estimate RWIS benefits and savings:** The benefits and savings of RWIS are realized through winter maintenance savings, crash reduction/collision cost savings, and mobility improvements. Methods to estimate the benefits and savings in these areas are described herein. Other models to estimate the benefits and savings, particularly in crash reduction and mobility improvements, can also be used.
- **Estimate expected life-cycle cost and NPW:** Net present worth is an important indicator to support RWIS implementation decisions. NPW is determined using the costs and benefits associated with RWIS over its life cycle.

A Life-cycle cost analysis is one of the well-known economic evaluation tools for transportation infrastructure management, planning, and decision-making support in the development of sound investment strategies. An LCCA provides decision-makers with the ability to determine the least-cost solution for a transportation investment requirement and is therefore a natural fit within the asset management framework.

Technology-oriented RWISs have different characteristics than conventional transportation assets such as pavement or bridges. Applying conventional LCCA and life-cycle planning practices to RWISs may not always be appropriate. The main differences between RWIS (and its associated technology infrastructure) and traditional transportation systems regarding LCCA and life-cycle planning may include the following:

- **Degradation behavior.** The conditions of traditional infrastructure assets typically degrade gradually as a result of wear and environmental conditions. The condition of many RWIS components is binary; they are either operational or not operational.
- **Maintenance strategies.** A condition-based strategy is typically used to maintain traditional transportation assets. Some ITS assets, including RWIS, may be more suited to a cyclic maintenance strategy than a condition-based strategy. Maintenance strategies may also be influenced by historical performance or the service life estimated by the manufacturer.
- **Functionality changes.** RWIS can have components and/or software that can be upgraded to change or improve their functionality. This may impact the life-cycle cost of RWIS and its maintenance and replacement strategies.
- **Risks in technical obsolescence.** Technology assets can become obsolete without physically degrading. Rapid innovations in ITS technology may reduce the life cycle of RWIS components as new products may be made available to market and offer improved functionalities or cost-efficiency.
- **Uncertainty.** When new RWIS technologies are first used, they have insufficient records or historical data on their unit costs and how they perform under different conditions over time.
- **Inflation behavior.** Assuming technology- or component-specific inflation rates to be the same as general transportation inflation rates may not be appropriate.
- **Life span.** The life cycle of technology systems is usually shorter than that of traditional transportation assets. They may be subject to more frequent needs for maintenance, repair, and replacement.
- **Inventory management.** An important consideration for the ongoing operations and maintenance of RWIS is the need for spare parts. Spare parts inventory management of essential components of RWIS equipment should be considered in the life-cycle planning and life-cycle cost analysis.
- **Downtime due to unavailability of spare parts.** Unavailability of spare parts for RWIS components resulting in lengthier system downtime may lead to increased safety impacts, increased delay, and increased fuel consumption, which may lead to increased user cost and social cost.

Sound life-cycle planning and cost analysis is critical to support identification of appropriate levels of funding to operate and maintain RWIS, and therefore optimize investment. Proper maintenance and timely upgrades can result in lower overall RWIS investment because existing systems can be kept in service longer. In addition, dedicated operations funding allows agencies to plan for the life of the assets rather than just for their deployment. Therefore, it is vital to establish a practical life-cycle planning framework and LCCA methodology for RWIS that considers stochastic treatments of the above factors.

REFERENCES

Bengtsson, M. and M. Kurdve. 2016. Machining Equipment Life Cycle Costing Model with Dynamic Maintenance Cost. 23rd Conference on Life Cycle Engineering. *Procedia CIRP*, Vol. 48, pp. 102–107.

Bradshaw Boon, C. and C. Cluett. 2002. *Road Weather Information Systems: Enabling Proactive Maintenance Practices in Washington State*. Washington State Transportation Center (TRAC), University of Washington, Seattle, WA.

Brom, A. E., O. V. Belova, and A. Sissinio. 2016. Lifecycle Costs for Energy Equipment: FMECA and Lifecycle Costing Models as "Decision Making" Tools for Cost Reduction During the Whole Equipment Life. *Procedia Engineering*, Vol. 152, pp. 173–176.

Chien, S., J. Meegoda, J. Luo, P. Corrigan, and L. Zhao. 2014. *Road Weather Information System Statewide Implementation Plan.* Region 2 University Transportation Research Center, New Jersey Institute of Technology, Newark, NJ.

Glover, B. 2020 (March 10). Updated Estimate of Roadway User Cost for Personal Vehicles and Commercial Trucks. Texas A&M Transportation Institute memorandum to Texas Department of Transportation Construction Division. https://ftp.dot.state.tx.us/pub/txdot-info/cst/ruc-methodology-memo.pdf.

Haas, C., J. Weissmann, B. McKeever, and R. Greer. 1997. *Road Weather Information System Decision Support Tool.* Center for Transportation Research, University of Texas at Austin, TX.

Harmon, T., G. Bahar, and F. Gross. 2018. *Crash Costs for Highway Safety Analysis*. FHWA-SA-17-071. Federal Highway Administration, Office of Safety, Washington, DC.

Koeberlein, R., D. Jensen, and M. Forcier. 2014. Relationship of Winter Road Weather Monitoring to Winter Driving Crash Statistics. National Operations Center of Excellence, Washington, DC.

Krechmer, D., G. Krueger, M. Dunzo, J. Dale, and C. G. Hedden. 2010. *Benefit-Cost Evaluation Techniques for Rural ITS Deployments*. Michigan Department of Transportation, Lansing, MI.

Kwon, T. J. and L. Fu. 2016. *RWIS Network Planning: Optimal Density and Location*. Aurora Program, Institute for Transportation, Iowa State University, Ames, IA. https://intrans.iastate.edu/app/uploads/2018/10/RWIS_network_planning_for_optimal_density_and_location_w_cvr.pdf.

Kwon, T. J., F. Liping, and C. Jiang. 2015. Road Weather Information System Stations — Where and How Many to Install: A Cost Benefit Analysis Approach. *Canadian Journal of Civil Engineering*, Vol. 42, pp. 1–10.

Kwon, T. J., L. Fu, and S. J. Melles. 2016a. Location Optimization of Road Weather Information System (RWIS) Network Considering the Needs of Winter Road Maintenance and the Traveling Public. *Computer-Aided Civil and Infrastructure Engineering*, Vol. 32, No. 1, pp. 57–71.

Kwon, T. J., L. Fu, S. J. Melles, and M. S. Perchanok. 2016b. Optimizing the Location of Road Weather Information System (RWIS) Stations – A Sampling Design Optimization Approach. *Resilient Infrastructure*, pp. TRA-901-1–11.

Lawrence, M., P. Nguyen, J. Skolnick, and M. Wahner. 2017. *Road Weather Management Benefit Cost Analysis Compendium.* FHWA-HOP-16-093. Federal Highway Administration, Washington, DC.

McKeever, B., C. Haas, J. Weissmann, and R. Greer. 1998. Life Cycle Cost-Benefit Model for Road Weather Information Systems. *Transportation Research Record*: *Journal of the Transportation Research Board*, No. 1627, pp. 41–48.

Schneider, W., M. Crow, and W. A. Holik. 2015. *Investigate Plow Blade Optimization*. Ohio Department of Transportation, Columbus, OH.

Schneider, W. H., C. Miller, W. A. Holik, and M. Crow. 2014. *Evaluation of Viking-Cives TowPlow for Winter Maintenance*. Ohio Department of Transportation, Columbus, OH.

Singh, A. K., J. Li, M. Murphy, and C. M. Walton. 2016. Optimizing Environmental Sensor Station Locations for Road Weather Management: Overview and a Generalized Modeling Framework. *Transportation Research Record*: *Journal of the Transportation Research Board*, No. 2551, pp. 18–28.

Strong, C. and X. Shi. 2008. Benefit-Cost Analysis of Weather Information for Winter Maintenance: A Case Study. *Transportation Research Record*: *Journal of the Transportation Research Board*, No. 2055, pp. 119–127.

U. S. EPA Greenhouse Gases Equivalences Calculator, https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references.

U.S. EPA. 2016. *EPA Fact Sheet: Social Cost of Carbon*. https://www.epa.gov/sites/production/files/2016-12/documents/social_cost_of_carbon_fact_sheet.pdf.

U.S. Office of Management and Budget. 2019. Appendix C in *Circular A-94: Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs.*

APPENDIX A. SUMMARY OF MANUFACTURER SURVEY RESPONSES

Table A.1. Air temperature/Relative humidity sensors

Manufacturers	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
High Sierra Electronics, Inc.	5723 Air temperature & relative humidity	$1,300	Clean one time per year and calibrate every 2–3 years		1		9 to 11 years	When calibrated properly
Campbell Scientific	HygroVUE10	$418 (10 ft cable)	We recommend replacing the sensor element annually, but clients may wish to adhere to a less frequent schedule. Less than 1% drift/year	Purchase replacement unit 35219	1	$0	9 to 11 years	Replacement sensing element $130. We integrate Air temp and RH sensors from a number of manufacturers based on what is best for the client's specific application.
OTT HydroMet (Lufft)	WS300		Clean the sensor and check cable connections yearly	Minimal. Whatever it takes to wipe down a sensor	2	$0	6 to 8 years	Also capable of measuring barometric pressure

Table A.2. Surface temperature sensors

Manufacturers	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
High Sierra Electronics, Inc.	5439 Surface Sentinel	$1,200	Clean once per year		2		9 to 11 years	Also capable of measuring air temp and RH in addition to surface temp; Non-intrusive
	5721 Road Sensor	$1,000	Inspect for damage once per year		1		9 to 11 years	Also capable of measuring road/pavement conditions (dry/wet indication); Intrusive
Campbell Scientific	Apogee SIF1H1 SS	$680	Recommend re-calibration every 2 years		4	$0	9 to 11 years	We are currently completing development of another surface temperature sensor that will be released soon
OTT HydroMet (Lufft)	NIRS		Re-calibrate yearly if you want, can be remote. Replace $200 bulb every 2 years	Should be done on a yearly maintenance trip so bundled in with everything else	2	$0	> 11 years	Also capable of measuring road/pavement conditions. If maintained and bulb changed every 2 years you should be able to keep these running for a long time. They are non-invasive and can be moved. They also do the surface conditions, water film height, freeze temp etc.
	IRS31Pro		Clean the sensor head and check wiring, same as all the others	Just a trip to the site	2	$0	3 to 5 years	IRS31Pro is an embedded passive sensor. Capable of measuring road/pavement conditions, ice percentages, water film heights, up to 2 sub-probe measurements and it has removable electronics for when a road is re-paved.
	WST2	< $1,000	Minimal, wipe down the sensor head and check cable connections	Just a yearly PM trip out	2 years (limited warranty based on defects in workmanship)	$0	3 to 5 years	

Table A.3. Pavement condition sensors

Manufacturers	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
High Sierra Electronics, Inc.	5433 IceSight	$11,000	Clean, inspect and calibrate once per year		2		9 to 11 years	Also capable of measuring surface temp/air temp/relative humidity; Non-intrusive
	5422 Intelligent Road Condition	$8,000	Inspect once per year		1		6 to 8 years	Intrusive
OTT HydroMet (Lufft)	NIRS – Non-invasive road sensor						3 to 5 years	

Table A.4. Wind direction and speed sensors

Manufacturers	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
OTT HydroMet (Lufft)	WS200		No moving parts so minimal - should be a yearly maintenance trip for all sensors	Cost of a person to go and check everything out	2	$0	9 to 11 years	Life span depends on maintenance, these should last a long time as there are no moving parts
	Ventus		No moving parts so minimal - should be a yearly maintenance trip for all sensors	Cost of a person to go and check everything out	2	$0		The Ventus is a heavy duty, metal anemometer which can handle extreme conditions. We have utilized this in coastal areas that get lots of cold and wet blowing snow. It has 2 heaters built in and can handle extreme temps.

Table A.5. Visibility sensors

Manufacturers	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
Campbell Scientific	CS120A	$3,850	System is self-regulating but we recommend calibration every 2 years		1	$0	9 to 11 years	
OTT HydroMet (Lufft)	VS2K		Sensor has a built-in random vibration to prevent bugs from nesting in its optics.	Annual trip out to clean everything	2	$0	6 to 8 years	2k (2,000 meter) range and 20k range with 100k range on the way.
	Same as the others, if taken care of they will last							

Table A.6. Precipitation sensors

Manufacturer	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
OTT HydroMet (Lufft)	WS100		Minimal, no moving parts or open tipping buckets	Annual trip to check	2	$0	> 11 years	This is a Doppler-based precipitation sensor giving you intensity and type (rain, sleet or snow). Again, if cared for we have some still in the field 10 years+ at the moment
	R2S		Minimal, no moving parts or open tipping buckets	Annual trip to check	2	$0	> 11 years	This is a Doppler-based precipitation sensor giving you intensity and type (rain, sleet or snow). Again, if cared for we have some still in the field 10 years+ at the moment
	WTB100		Minimal, no moving parts or open tipping buckets	Annual trip to check - may need to go remove leaves or build up as they are tipping buckets	2	$0	6 to 8 years	This is a tipping bucket which will give you accurate accumulation but won't differentiate between type or give intensity
	WS601		Minimal, no moving parts or open tipping buckets	Annual trip to check - may need to go remove leaves or build up as they are tipping buckets	2	$0	6 to 8 years	This is a tipping bucket which will give you accurate accumulation but won't differentiate between type or give intensity

Table A.7. Ultrasonic snow depth sensors

Manufacturers	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
Campbell Scientific	SR50A	$960 (10 ft cable)	Check Desiccant and replace if required. Replace Transducer every 3 years.		1	$0	9 to 11 years	
OTT HydroMet (Lufft)	SHM31				2	$0	6 to 8 years	Great ultrasonic snow height sensor giving up to 15m in depths. Not 100% sure but like always, maintain and things last

Table A.8. Subsurface sensors

Manufacturers	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
Campbell Scientific	CS231	$800 - $6339 (depending on depth and # of sensors)	No maintenance or calibration required		1	$0	> 11 years	This is a Doppler-based precipitation sensor giving you intensity and type (rain, sleet or snow). Again, if cared for we have some still in the field 10 years+ at the moment
OTT HydroMet (Lufft)	IRS31Pro (can have 0, 1 or 2 sub probes)						3 to 5 years	IRS31Pro is an embedded passive sensor. Capable of measuring road/pavement conditions, ice percentages, water film heights, up to 2 sub-probe measurements and it has removable electronics for when a road is re-paved.
	8160.TF50S		None	None	2	$0	3 to 5 years	Standard stand-alone sub probe with either 25m or 50m cables. In ground sensors tend to get beat up a little more so shorter period
	8160.TF25S		None	None	2	$0	3 to 5 years	Standard stand-alone sub probe with either 25m or 50m cables. In-ground sensors tend to get beat up a little more so shorter period

Table A.9. Barometric pressure sensors

Manufacturers	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
Campbell Scientific	CS100	$640	Minimum maintenance required. Inspection of connections to make sure they are secure, check cables to ensure they are dry and clean		3	$0	6 to 8 years	This product is made for us by Setra in Massachusetts
OTT HydroMet (Lufft)	WS300							Also capable of measuring RH/temp and pressure

Table A.10. Water level sensors

Manufacturers	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
Campbell Scientific	CS451	$771 - $935 (plus cable costs)	We recommend factory calibration every two years. Visual inspection at every site visit for desiccant condition and possible replacement		1	$0	3 to 5 years	Will have a 1-year life span if desiccant is not maintained
OTT HydroMet (Lufft)	RLS (radar level sensor)							This is from OTT HydroMet, our new "One Company" profile and comes from the hydro side. This sensor is easily integrated to new or existing Lufft sites
	PLS (pressure level sensor)							This is from OTT HydroMet, our new "One Company" profile and comes from the hydro side. This sensor is easily integrated to new or existing Lufft sites

Table A.11. Solar radiation kits

Manufacturers	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
Campbell Scientific	CS320		Online tool to determine if calibration is required		1	$0		We have multiple solar radiation sensors from our extensive work in renewable energy.
OTT HydroMet (Lufft)	WS301 (and stand-alones)							Lufft bought Kipp and Zonen, leaders in solar radiation monitoring. They can be bought with our all-in-one sensors that have every parameter needed, or as stand-alone sensors.
	WS401 (and stand-alones)							

Table A.12. Traffic/Vehicle detection (MVDS) sensors

Manufacturers	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
Campbell Scientific								We integrate sensors from a variety of manufacturers. If you do not have sufficient information from those manufacturers, we would be happy to Liaise with them and provide data to you.
OTT HydroMet (Lufft)	We can integrate anything WaveTronix into our systems							

Table A.13. CCTV cameras

Manufacturers	Product name and model	Equipment cost	Recommended preventative maintenance activities and frequencies	Estimated annual maintenance cost	Warranty period (years)	Warranty cost	Expected life span	Additional information
Campbell Scientific	CCFC	$2,875	Clean lens as required		1	$0	6 to 8 years	We recommend this camera for solar and remote applications. We typically use Panasonic cameras for AC powered stations requiring PTZ. Camera technology typically changes faster than the technology fails so replacement every 5-7 years is probable
OTT HydroMet (Lufft)	We can incorporate and integrate almost any camera into our RWIS sites							

Table A.14. Software products, features, and costs

Manufacturers	Software products	Features/Capabilities	License fees
Campbell Scientific	Campbell Cloud (under development, currently used in municipal applications).		
OTT HydroMet (Lufft)	Smartview3, ViewMondo (we can work with any other provider out there).	SV3 and ViewMondo can poll data in real time, give brief pavement forecast estimates, show historical data, camera images and graphs and diagrams. We also can partner with major forecasting companies such as DTN and Iteris. We are all about giving the customer what they want and what is the best fit.	ViewMondo and SV3 = $495 a year per site or mobile sensor.

APPENDIX B. SUMMARY OF DOT SURVEY RESPONSES

Appendix B presents a comprehensive listing of the results from the RWIS DOT Survey, as well as a side-by-side comparison of all agency responses for each question.

Table B.1. Number of RWIS stations/Years using RWIS

Agency	Number of RWIS stations	Number of years using RWIS	Additional information
North Dakota DOT	Less than 30	23 to 30 years	
Minnesota DOT	101 to 150	23 to 30 years	
New Hampshire DOT	Less than 30	7 to 14 years	
British Columbia Ministry of Transportation and Infrastructure	61 to 100	23 to 30 years	
Alaska DOT & PF	61 to 100	15 to 22 years	
Utah DOT	101 to 150	More than 30 years	Our RWIS data is critical for our UDOT Snow and Ice Performance Measure. Our instrumentation remains greater than 95% up time as a result. We have nearly 1500 RWIS instrumentation deployed. We will soon be deploying stand-alone road/visibility sensors only where an existing RWIS site is in the vicinity.
Pennsylvania DOT	61 to 100	Less than 7 years	PennDOT's goal with RWIS is to optimize geographic coverage and employ data to measure operational performance and drive improvements.
Wisconsin DOT	61 to 100	More than 30 years	
Iowa DOT	61 to 100	More than 30 years	We may be moving to smaller, 'mini' sites in the future as our network gets denser.

Table B.2. Procurement methods

Agency	Request for proposals	Invitation for bids	Additional information
North Dakota DOT		X	We bid the RWIS projects the same way we bid all construction projects.
Minnesota DOT		X	MnDOT has two RWIS vendors (Hoosier & Vaisala) on state contract.
New Hampshire DOT	X	X	
British Columbia Ministry of Transportation and Infrastructure			Design, build, maintain our own stations in-house. Purchase equipment from various vendors.
Alaska DOT & PF		X	
Utah DOT			We have 5-year contract with instrumentation vendors and a separate contract for RWIS maintenance and installation.
Pennsylvania DOT	X		
Wisconsin DOT	X		
Iowa DOT	X		

Table B.3. General RWIS manufacturer information

Agency	Vaisala	Lufft (Hoosier)	Campbell Scientific	Boschung	High Sierra	Additional information
North Dakota DOT	X	X		X		
Minnesota DOT	X	X				
New Hampshire DOT	X	X				
British Columbia Ministry of Transportation and Infrastructure						No sole manufacturer/vendor (we design, build, & maintain our own stations in-house).
Alaska DOT & PF	X		X			
Utah DOT	X		X	X	X	
Pennsylvania DOT	X					
Wisconsin DOT		X				
Iowa DOT	X	X				

Table B.4. RWIS manufacturer/Product information

Agency	RWIS manufacturers	RWIS products
Alaska DOT & PF	Vaisala, Campbell Scientific	We use Novalynx Tipping Buckets, RM Young Anemometers, Windscreens, MRC Temperature Data Probes, Judd Snow Depth Sensors. Cameras by WTI, Axis, and Mobotix.
British Columbia Ministry of Transportation and Infrastructure	No sole manufacturer/vendor (we design, build, & maintain our own stations in-house).	Campbell Scientific CR1000 dataloggers, Vaisala DST/DSC pavement sensors, various other instrumentation.
Minnesota DOT	Vaisala, Lufft (Hoosier)	AXIS Q6125-LE PTZ network camera, Glen Martin Tower, Great Plains Tower, RM Young 05103 Wind Lufft (Hoosier): LCOM RPU, WS100 UMB precipitation, VS2K visibility Vaisala: RWS110 LX RPU, RWS200 RPU, HMP155 air temp/relative humidity, PWD22 precipitation/visibility, PTB110 barometer
New Hampshire DOT	Original stations were SSI (Subsurface Systems Inc.), now Vaisala; Lufft (Hoosier)	Vaisala LX (21), Vaisala RWS200 (1), Lufft LCOM/UMB (3); Various brands of Vaisala sensors
North Dakota DOT	Lufft (Hoosier) (we do have several Vaisala sites and one Boschung site for our FAST)	A typical Lufft site has the following sensors: Axis Q6055-E Camera, IR illuminator, LCOM, NIRS-31 sensor, WS100, WS301, WS200, and 72" deep subsurface probe.
Pennsylvania DOT	Vaisala	RWS200 and associated components
Utah DOT	Vaisala, Campbell Scientific, High Sierra, Boschung	We have too many products to list. We customize our instrumentation to our specific needs and requirements. Essentially, we design our own RWIS system.
Wisconsin DOT	Manufacturer: Lufft (Hoosier)	WisDOT has 20 Lufft sites and 50 legacy Vaisala sites. Lufft sites have the LCOM RPU, IRS 31 pavement sensors, subsurface probe, OWI-430 precipitation sensor, Young 41382 temp/relative humidity sensor, and Young 05103 wind sensor. Vaisala sites have FP2000 pavement sensors and a variety of atmospheric sensors.
Iowa DOT	Ours is a mix of vendors. Most of our RPUs are Vaisala LX but we also have a number of Lufft LCOMs.	We have a wide variety of sensors. Vaisala, RM Young, OSI, Lufft, Thies Clima, Axis cameras, Wavetronix traffic sensors.

Table B.5. Air temperature/Relative humidity sensors

Agency	Product name and model	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Alaska DOT & PF	Vaisala HMP155	$2,420				5	9 to 11 years	We are starting to install the HMP155 when the Thies die. So, I don't have a whole lot of data with the HMP155 yet
New Hampshire DOT		$3,000	100	0		5	9 to 11 years	Relatively few problems with these sensors
Utah DOT		$422	$185 per entire RWIS site per year. Unknown on an instrumentation level.	Estimate 50 RWIS sites require response maintenance. Unknown on an instrumentation level.	$435 per entire RWIS site per year. Unknown on an instrumentation level.	4	9 to 11 years	
Wisconsin DOT		$1,005	Unknown	0.5	Unknown	4	6 to 8 years	
Iowa DOT		$800	Bundled with the rest of our maintenance	Of a network of 72, about 7-8 go bad each year	Bundled	3	6 to 8 years	Similar for Thies, RM Young, and Vaisala version of this sensor.

Table B.6. Surface temperature sensors

Agency	Product name and model	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Utah DOT		$4,036	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	4	9 to 11 years	We also use 2 other sensors. High Sierra Sentinel ($1,525), High Sierra Icesight road temp/condition combo ($11,575)
Alaska DOT & PF (2 products)		$896 - $4,642				5	6 to 8 years	Non-invasive pavement temp sensor. Life span is dependent on whether a road project mills up the sensor
Wisconsin DOT (2 products)		$5,000 - $5,866	Unknown	0.25 - 0.5	Unknown	5	3 to 11 years	Lufft sensors seem less reliable than FP2000
Iowa DOT		$3,451 each, plus install	Bundled with contract	200+ sensors, we have at least 12-15 that need to be replaced each year	Average around $6,000 for each one that needs to be replaced (sensor + labor)	5	6 to 8 years	Majority all FP2000. A few Lufft. Construction/maintenance kills a lot. Their natural life span is probably much longer.

Table B.7. Pavement condition sensors

Agency	Product name and model	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Utah DOT		$9,995	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	5	9 to 11 years	
	High Sierra Icesight	$11,575	Unknown on an instrumentation level.		Unknown on an instrumentation level.	5	3 to 7+ years	
Alaska DOT & PF	Vaisala DSC111	$12,722				4	6 to 8 years	Non-invasive; Too early to tell what their life span will be. In addition to the DTS210, our pavement sensors include the FP2000 which I do not have costs.
Iowa DOT		$16,565	Bundled		Bundled	4	6 to 8 years	We only have a few of these sensors. Based on one failed sensor. The rest are too new to tell.

Table B.8. Wind direction and speed sensors

Agency	Product name and model	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Alaska DOT & PF	RM Young 05103	$1,240				5	6 to 8 years	
	RM Young 05106	$1,482				5	6 to 8 years	
	Vaisala WMT700 Ultrasonic Heated	$2,807				5	6 to 8 years	
Utah DOT	Standard wind sensor (Brand/model unknown)	$1,093	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	4	9 to 11 years	We use alpine version in areas of high ice riming.
	Alpine high-performance sensor (Brand/model unknown)	$2,131	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	4	9 to 11 years	
Wisconsin DOT		$1,183	Unknown	1	Unknown	3	9 to 11 years	
Iowa DOT		$1,107	Bundled	At least 4 in our network of 70-ish sites with anemometers	Bundled	4	6 to 8 years	Similar for RM Young or Vaisala brands. Bearings are replaced through regular maintenance.

Table B.9. Precipitation sensors

Agency	Product name and model	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Utah DOT	Novalynx Tipping Rain Bucket	$382	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	5	9 to 11 years	Rain buckets are very useful for alerting for potential debris flows
Alaska DOT & PF	Texas Electronic 525	$1,711						
	Vaisala DRD11A	$1,178				5	9 to 11 years	This model is replacing all of our Hawkeyes
	Novalynx 260-2500E	$768						
Iowa DOT	Lufft R2S	$4,474	Bundled	4?	Bundled	4	6 to 8 years	This is just for our Lufft R2S version.
	OSI WIVIS	$7,480	Bundled	At least 10		4	6 to 8 years	This is for our OSI WIVIS, and Vaisala PWD12s. The life is long, but sometimes they need maintenance/parts in the interim.
	Vaisala PWD12	$7,480	Bundled	At least 10		4	6 to 8 years	

Table B.10. Visibility sensors

Agency	Product name and model	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Alaska DOT & PF	Vaisala PWD12	$7,089					6 to 8 years	
	Vaisala PWD22	$10,378				5	6 to 8 years	We are hoping the PWD's last longer, but we won't know for a few more years
Utah DOT	Campbell CS125	$4,350	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	5	9 to 11 years	We also use this sensor for estimating snowfall rates for our performance measure.
Wisconsin DOT		$8,160	Unknown	1.5	Unknown	4	3 to 5 years	
Iowa DOT		$7,480	Bundled	At least 10		3. More if they'd work more reliably	6 to 8 years	Phasing these out because they're maintenance intensive. Similar for OSI or Vaisala.

Table B.11. Ultrasonic snow depth sensors

Agency	Product name and model	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Alaska DOT & PF	Judd Ultrasonic Snow Depth Sensor	$1,262					9 to 11 years	
Utah DOT		$865	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	3	9 to 11 years	More useful for mountain locations, doesn't have the sensitivity needed for valleys.

Table B.12. Subsurface sensors

Agency	Product name and model	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Alaska DOT & PF	Vaisala DTS210	$896					6 to 8 years	Life span depends on whether or not there is roadwork that destroys the sensor.
Utah DOT	Soil temp sensor (Brand/model unknown)	$82	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	5	9 to 11 years	Critical for determining snowfall rate for road snow. Soil moisture for blowing dust.
	Soil moisture sensor (Brand/model unknown)	$252	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	5	9 to 11 years	Critical for determining snowfall rate for road snow.
Wisconsin DOT		$688	Unknown	0	0	4	9 to 11 years	
Iowa DOT		$629	Bundled	5	About $2,000 per unit, more or less depending if they're doing a surface sensor too	3	9 to 11 years	This is just the single-point version. Very long-lived and trouble free if it were not for road work taking them out.
		$2,890	Bundled	At least 2 times (for only 15 total in the state).	$5,000; more or less depending on if they're also doing a surface sensor	3	< 3 years	This is for the multi-array deep probe. These seem to require a lot of maintenance to keep going.

Table B.13. Barometric pressure sensors

Agency	Product name and model	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Alaska DOT & PF	Vaisala PTB110	$998					9 to 11 years	

Table B.14. Solar radiation kits

Agency	Product name and model	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Utah DOT		$515	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	2	9 to 11 years	Most useful in canyons

Table B.15. Traffic/Vehicle detection sensors

Agency	Product name and model	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Iowa DOT	Wavetronix HD	$7,875	Bundled	4		2	9 to 11 years	Generally fairly maintenance-free. Wavetronix HD.

Table B.16. CCTV cameras

Agency	Product name and model	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Utah DOT	AXIS fixed-view camera	$899	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	5	3 to 5 years	Fixed view often has better night vision.
	AXIS Q6125-LE PTZ	$2,276	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	5	3 to 5 years	
Alaska DOT & PF	AXIS Q6114	$3,373				5	6 to 8 years	
	AXIS Q6125-LE	$3,325				5	6 to 8 years	Life span to be determined
	AXIS Q6055 PTZ	$3,709	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	5	6 to 8 years	Fixed view often has better night vision.
	AXIS Q8685-LE PTZ	$7,280				5	6 to 8 years	Life span to be determined
	WTI Viper	$3,940				5	6 to 8 years	Life span to be determined
Iowa DOT	AXIS PTZ Heated camera	$6,505	Bundled	About once per year each		4	6 to 8 years	Lots of visits, but not often the whole camera needs to be replaced; sometimes it's just a reset. Generally, the hardware is more reliable than the software. Needs lots of resets and lens cleanings/repair. Axis PTZ heated cameras.

Table B.17. Additional sensors

Agency	Product name and model	Sensor type	Capital cost	Average annual costs for preventive/routine maintenance	Average number of times non-routine maintenance required per year	Average non-routine maintenance cost per year	Usefulness / importance (1-5, 5 = most important)	Expected life span	Additional information
Alaska DOT & PF	Vaisala TDP	Temperature Data Probe	$4,623				5	6 to 8 years	
Utah DOT		Datalogger	$1,700	Unknown on an instrumentation level.	Unknown on an instrumentation level.	Unknown on an instrumentation level.	5	> 11 years	

Table B.18. Data storage cost/Number of years of data stored

Agency	Data storage cost/Years of data stored
North Dakota DOT	We store all RWIS data and only 24 hours of camera images. This is stored at NDIT and is included in our server fee.
Alaska DOT & PF	N/A
Utah DOT	Unknown. We store infinite amount of RWIS data. 3 years' worth of specified RWIS camera snapshots.
Pennsylvania DOT	Included with web hosting and data services contract requirement, total of $108,000/year. No limit to data storage during contract terms.
Wisconsin DOT	SCAN Web has no archive and Lufft has about 7 years.
Iowa DOT	DTN has 3 years, ScanWeb has 15 years. Not priced by storage.

Table B.19. Types and costs of communications

Agency	Fiber optic	Cellular	Radio	Other (please specify)	Monthly telecommunications cost per site
North Dakota DOT	X	X		Most of our sites are on cellular but we do have a couple that are on fiber.	Cellular is $40/month. Fiber is on our own network and is $1,000/month for the link and $30/month to each end point.
Alaska DOT & PF	X	X		Satellite	$30 - $112
Utah DOT	X	X			Cell: $20 - $30/month UDOT fiber: $0/month
Pennsylvania DOT		X			Included with web hosting and data services contract requirement, all services $9,000/month.
Wisconsin DOT		X		Landline	$35
Iowa DOT	X	X		DSL	Cellular is ~$15/month. DSL can be as much as $70/month.

Table B.20. Annual staffing costs for RWIS operations

Agency	Annual staffing costs for RWIS operations
North Dakota DOT	We do not track this, but we have one ITS Manager and essentially 10 technicians that take care of our ITS devices.
Alaska DOT & PF	We have a contractor who maintains all sites. Those costs are included in the estimated per site costs provided earlier.
Utah DOT	Very difficult to answer. Staff performs multiple functions that could be non-RWIS related.
Pennsylvania DOT	No internal staffing costs are directly associated with operations of RWIS.
Wisconsin DOT	$5,000
Iowa DOT	Nobody dedicates a full FTE to RWIS. Most maintenance is contracted out as previously described. Otherwise it is just a part of a few people's workload.

Table B.21. Warranty for RWIS components

Agency	Warranty purchase? (Yes/No)	Cost of warranty/Other comments
North Dakota DOT	Yes	We require a 3-year warranty at the time of purchase.
Alaska DOT & PF	No	
Utah DOT	Yes	Our 5-year RWIS parts contract has a 2-year warranty built into the contract.
Pennsylvania DOT	No	All components are covered by performance-based maintenance contract. No warranty is purchased separately.
Wisconsin DOT	Yes	Unknown
Iowa DOT	No	

Table B.22. Preventative/Routine RWIS system maintenance

Agency	RWIS vendor	Contracted services	Agency force
North Dakota DOT			X
Alaska DOT & PF	X	X	
Utah DOT		X	
Pennsylvania DOT	X		
Wisconsin DOT		X	
Iowa DOT		X	

Table B.23. Non-routine RWIS system maintenance

Agency	RWIS vendor	Contracted services	Agency force
North Dakota DOT			X
Alaska DOT & PF	X	X	
Utah DOT		X	
Pennsylvania DOT	X		
Wisconsin DOT		X	
Iowa DOT		X	

Table B.24. Reduction of winter maintenance costs due to RWIS data

Agency	Yes	No
North Dakota DOT	X	
Alaska DOT & PF	X	
Utah DOT	X	
Pennsylvania DOT	X	
Wisconsin DOT	X	
Iowa DOT	X	

Table B.25. Future RWIS installations

Agency	Additional RWIS installation timeframe	Number of additional RWIS planned within next 5 years
North Dakota DOT	Within next 3 years	Our plan is to get to 60 RWIS, so we plan to install another 31 in the coming years.
Alaska DOT & PF	Within next 3 years	5 to 8
Utah DOT	Within next 3 years	We are currently installing about 20+ RWIS sites per year and will continue to do so for several years to support our Snow and Ice Performance Measure.
Pennsylvania DOT	Within next 3 years	5 to 10
Wisconsin DOT	Within next 3 years	10
Iowa DOT	Within next 3 years	About 3

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