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DEPARTMENT OF TRANSPORTATION

Winter Severity Index Development

FINAL REPORT

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By:

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COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

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16. Abstract The goal of this project was to further refine a basic Winter Severity Index (WSI) for the Pennsylvania Department of Transportation (PennDOT) linking weather events to impact in terms of PennDOT winter maintenance costs. This report documents the development of a revised, pilot WSI equation for use by PennDOT as a winter metric, and its Pilot Program testing. The report details the findings from the collection of winter weather data from free, public sources along with PennDOT winter maintenance data and the necessary processing and analysis for development of the WSI. A Pilot WSI equation and series of recommendations relating to the continuation of the Pilot Program, the usability of a WSI formula, weather data collection, winter maintenance data collection, and future refinement of the equation were proposed.					
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Introduction

Explanation of WSI

A Winter Severity Index (WSI) is a metric used to relate the impact of one winter season's weather to another. When combined with other performance measures, a WSI becomes a powerful tool to determine the efficiency and effectiveness of winter maintenance activities. The index is a numerical value, measuring the intensity of weather events generated by an equation which accounts for multiple winter weather factors. The numerical value is often established as lower values indicate a less severe winter and higher values indicate a more severe, impactful winter. Commonly used weather factors are snowfall and freezing rain accumulations, the number or duration of events, temperature, and drifting snow conditions. Equations are usually created specifically for the state or region for which the WSI value is calculated. This is due to the nature of a WSI; it attempts to quantify how more or less severe the season was compared to the historical trends for the area. The importance and impact of maintenance activity types required for specific weather factors can impact the weight of a weather factor in the equation.

Generally, historical weather data for a region is collected and reduced. The data is manipulated and weighted to create an equation which will give an average value to an average season, low values to seasons with activity below average, etc. Additional weighting of the weather factors can occur to further refine the equation based on winter maintenance activity, not just historical trends. The calculated WSI value serves as objective measures of a winter's severity which is then compared to other metrics such as costs, salt use, time to bare road, and response times to track the performance of maintenance activities relative to the experienced weather.

Goal

The goal of this project is to further refine a basic Winter Severity Index to link to PennDOT winter maintenance costs. The WSI will address winter events and winter seasons.

Project Overview

MTA was tasked with continuing and refining the WSI pilot program, research data sources, and provide guidelines for the use of a Winter Severity Index. Considering the early stage of WSI development and the likely issues with data collection, the focus was primarily on snow and freezing rain as WSI inputs. Monthly meetings occurred with the working group to discuss aspects and the status of the project. This final report summarizes the pilot program, project results, and recommendations.

Summary of the Clear Roads Survey Responses

A brief set of questions were given to the attendees of the Clear Roads Technical Advisory Committee Meeting (March 25-27, 2014) regarding WSI programs and their related data collection efforts. The questions are as follows:

1. Does your state have an active WSI program, or has had one at some point?
2. How do you currently obtain weather data?
3. Is winter maintenance cost data assigned to specific storms? For example, do you use a Storm ID system?
4. Are the benefits of obtaining detailed winter data worth the additional effort in records keeping?

Responses were received from individuals in the following state DOT's: Vermont, Kansas, Wyoming, Missouri, Nebraska, Wisconsin, North Dakota, New Hampshire, Illinois, West Virginia, Idaho, Ohio, Massachusetts, Colorado, Washington, Iowa, Michigan, Utah, and Montana.

For clarification, a WSI will assign a point based rating to a specified date range (such as 1 month or a season) or a specific storm. An equivalent refers to any winter weather data tracking system which can also be used to predict or evaluate maintenance activity without assigning a point values. An example of a WSI equivalent is the Maintenance Decision Support System (MDSS) from Meridian.

Question 1

Of the 19 states responding, 7 have an active Winter Severity Index or equivalent. These states are New Hampshire, Vermont, Kansas, Wisconsin, Idaho, Iowa, and Washington.

The specific equation used by each state varies. For example, Kansas uses the 1993 SHRP formula, Wisconsin uses a custom equation that rates at the state and regional levels and Iowa has multiple indices detailing various aspects of winter weather and its associated maintenance (weather, salt, traffic speed, and labor). Iowa also has the capabilities to rate individual storms, but tends to evaluate on bi-weekly or longer timescales. States typically assign a WSI per month or per season.

Wyoming, North Dakota, Michigan, Missouri, and Utah are either actively researching or have investigated a Winter Severity Index system or equivalent. Wyoming plans to evaluate the 2013/2014 winter season with their unpublished WSI. They are attempting to adjust multiples and modifiers to the specifics of the state's weather patterns. Michigan is attempting to tie the severity index to user delay costs which is an unusual approach as most states use a WSI to evaluate the weather's impact on winter maintenance crews. Missouri is testing a WSI calculator developed by Aurora. Other responses were less detailed or implied a more traditional WSI program.

Question 2

All states responding actively collect winter weather data. The nature and means of the collection are varied. The most common winter weather data sources are RWIS, MDSS, and the National Weather Service. Other data sources are provided by: Meridian, Iteris, the University of Washington, Northwest WeatherNet Inc., CoCoRAHS, state climatologists, Telvent DTN, and NOAA.

Iowa supplements RWIS data with physical observations by winter maintenance crews. Wisconsin uses only observations from maintenance crews but desires an automated system to decrease bias and inconsistencies.

Some states also mentioned using Internet based sources for forecasts. The specific sites are not listed but they are noted as free or commercially available.

Question 3

The use of a Storm ID system or the attempt to explicitly tie maintenance activity to a winter event is rare. This question was inspired by the findings of the Clear Roads/Parson Brinkerhoff report "Understanding the True Cost of Snow and Ice Control". The research team had difficulty processing winter maintenance data due to the inability to tie most maintenance activity (cost and materials) to a specific winter weather event. The authors of the report recommended assigning an identification number to an event and all associated maintenance work.

Maine does track work per weather event. Each winter weather event is given an identifier, as are each maintenance crew. From the email response, "All work performed as a result of that storm is associated to it." Drifting and cleanup are associated with the previous event (the most likely source of the blowing snow). Wisconsin also tracks events, which they define as snow, ice, frost, blowing/drifted, clean-up, and bridge deck clean-up. Further details were not given.

Some states, such as Illinois and Washington, will track work per event for major storms and/or named storms. Other states may assign specific types of maintenance work or overtime hours to a storm event. However, the common approach is to summarize monthly/seasonal costs and monthly/seasonal weather. Colorado uses SAP and records costs per day. North Dakota mentioned the capability to record costs and material use per storm but noted the approach is usually not applied.

Question 4

The general response to winter weather data collection, winter maintenance data collection, and/or WSI programs is positive. A common response is the use of a WSI or data collection efforts has made it easier to obtain and justify additional funding. No states gave negative responses about the usefulness of obtaining winter data. Some states without WSI programs or expansive winter weather collection efforts seemed hesitant to answer, however, many of them saw potential uses for WSI programs or expanded data collection. Most of the responders could only give anecdotal evidence.

New Hampshire was able to successfully analyze salt usage, correlating the amount of salt used and the WSI rating for a season. They were able to show the state environmental services that salt use was decreasing relative to the severity of a winter.

Literature Review

The project began with a review of previous work by PennDOT and other organizations.

Winter Maintenance Cost Studies

An essential aspect to a Winter Severity Index is its ability to relate to other performance metrics and maintenance data. A common approach is to use a WSI to determine the cause of increases or decreases in winter maintenance costs. The precision of a Winter Severity Index can be improved by relating it to a region's specific maintenance approach, giving more weight to certain activities.

Parsons Brinckerhoff & Clear Roads: "Understanding the True Cost of Snow and Ice Control" (January 2014)

This study attempted to connect levels of service to work completed during storm events. Costs of winter maintenance and the level of service achieved on a roadway during a storm along with storm data were correlated. The research team evaluated data from multiple states and reached the conclusion that no link between Level of Service (LOS) and lane-mile maintenance costs exists. Also, the number and intensity of storms could not be linked with their costs based off assumptions made in the study.

Data collection varied between the studied states. The manner of tracking the amount of work differed from the way costs were considered in most of the studied states. The researchers concluded that data collection issues led to the lack of cost/LOS/weather links. In response to the data collection issues, the authors created a storm data collection spreadsheet with the goal of creating a uniform, analyzable database. The criteria for the collected data were: the database must be relational, the use of unstructured collection should be minimized, and fields should not be concatenated (multiple items stored as one). The criteria lead to each storm and crew/region having a unique identification with costs allocated to each unique storm and crew/region ID. The cost data is separated by its specific use and weather data is separated by type of precipitation along with the associated accumulation.

Nakame et. al.: "Development of a Cost Management Method for Road Snow Removal in Cold, Snowy Regions" (December 2010)

A group of researchers in Japan performed a cost effectiveness study of snow removal across the Japanese roadway network. Their study focused on determining the cost of removing a unit of snowfall accumulation. A linear regression model of snow removal and hauling costs versus cumulative snowfall, Equation 1, was developed.

$$p = f(x) = ax + b \quad 1$$

Where:

$p=f(x)$ =snow removal costs

x =cumulative snowfall (accumulation)

a =slope of the plotted line (coefficient expressing snow removal cost per centimeter of cumulative snowfall)

b =snow removal costs that is independent of any accumulation (winter support)

The linear regression model, Equation 1, was expanded upon to account for snow lane miles, generating the Unit Cost of Snow Removal (UCSR) or Equation 2.

$$y = ax^{\beta} + \gamma \quad 2$$

Where:

$\alpha = b/L$

$\gamma = a/L$

L =length of roadway on which maintenance is performed

β is initially assumed to be -1

The variables “ a ” and “ b ” are defined in Equation 1.

The resulting plot forms a decreasing power curve with increasing cumulative snowfall totals. According to the devolved equation, the relationship between the cost of a storm and the accumulation is not linear: an 8 inch snowstorm will cost more than a 4 inch storm, but not double the amount. As accumulations increase the relative cost increase slows.

The UCSR line was found to have the highest coefficient of determination for regions with high snowfall accumulations each season. Snowy, mountainous regions of Japan (ex: Hokuriku) have coefficients of 0.9 or greater, but regions with less snowfall per season saw coefficients as low as 0.26. Values of the coefficient closer to 1 indicate a better relationship between the snow removal costs and accumulation. The UCSR decreasing power curve trend was still observed when years with record-breaking snowfall were counted.

Winter Weather Data Studies

All WSI equations are centered on winter weather. Understanding which data is useful, how to collect it, and how to analyze the data is necessary for a successful WSI program.

Clear Roads & Meridian Environmental Technology, Inc.: "Mapping Weather Severity Zones"
(September 2012)

Meridian processed 30 years of winter weather data across the U.S. to "develop a methodology for mapping weather severity across regions." National weather data maps were developed to relate a winter season's weather to average historical data. A historical Winter Severity equation was developed from this evaluation and used to assign ratings.

Meridian determined that the following weather data parameters were the most useful in their study: average annual magnitudes of snowfall accumulation, snowfall duration, freezing rain duration, and blowing and/or drifting snow duration. Typical WSI weather data categories such as the number of events and temperature were ignored. The number of storms does not consider the timing of events, two storms occurring only a day apart will lead to a much different effect than the same two storms separated by a week. Also, individual winter storms vary widely in their magnitude and required response. Tying the number of events with duration enables a more nuanced investigation. Temperature data was excluded; however, the potential use of temperature during an event was noted. Average daily temperature was considered insufficient.

Weather data was pulled from multiple sources; National Oceanic and Atmospheric Administration (NOAA) databases were the most widely used. Data validity issues with NOAA weather stations became apparent; "biases in weather sensors.. ...are very common and often present a much stronger signal in the data than the true, underlying variations in weather conditions from one location to the next." A system of computer modeling, algorithms, and data set processing were developed to create the maps rather than use raw station data to overcome the error. The assumptions made for the blowing/drifting snow parameter is notable. Data from the Advance Very High Resolution Radiometer (AVHRR) was provided to determine areas where the potential for blowing snow existed. No direct measurements were used, and the final values are the likelihood of drifting, not the actual observed hours of the condition. Also, direct measurements of drifting snow were difficult to obtain.

A WSI equation was created based off the historical weather data collected in the study.

$$\begin{aligned} & \textit{Winter Severity} \\ & = 0.5(\textit{average annual snowfall in inches}) \\ & + 0.05(\textit{annual duration of snowfall in hours}) \\ & + 0.05(\textit{annual duration of blowing snow in hours}) \\ & + 0.10(\textit{annual duration of freezing rain in hours}) \end{aligned} \quad 3$$

A national average 10:1 ratio for annual snowfall accumulation and the annual duration of snowfall was found during the study, the weight factors have a 10:1 ratio due to the findings. Freezing rain was considered to have more impact than an equivalent duration of snowfall, with the authors doubling its weight. The duration of blowing snow is counted only when no snowfall is occurring.

Winter Severity Index Programs

In addition to the core of the WSI equations, existing indices were reviewed. The development and implementation of WSI equations was of importance in evaluating the effectiveness of previous PennDOT work and continuing the pilot program.

MaineDOT: "A Winter Severity Index for the State of Maine" (January 2009)

A winter severity index equation was developed by Victor Nouhan of the National Weather Service for the Maine Department of Transportation, using data from winters up to 2006. A statistical analysis of weather data from 1980 to 2006 (plus the historic highest snowfall season and lowest snowfall season on record) was performed to develop the WSI. Daily high and low temperatures, daily snowfall totals, and the total daily precipitation accumulations were used.

Point values were assigned to daily snowfall totals. A set of "bonus points" were assigned to daily temperatures: colder temperatures gained more points to account for the decreasing effectiveness of salt at lower temperatures. The events for each season were summed, and a normalization of the seasonal point totals was performed. The resulting WSI ratings range from 0 to 100 (least impact to most impact). A separate WSI was calculated for each MaineDOT region.

A review of the WSI values led MaineDOT to the inclusion of freezing rain points. The initial approach was similar to snowfall; freezing rain accumulations were assigned a point value and then added with snowfall points to create new daily ratings. However, the combined WSI ratings were considered overestimates. For example the 1997-1998 winter season obtained a WSI of 56 points from a snow only rating, increasing to 103 when the freezing rain points were added. The season had only one significant freezing rain event and an evaluation of the season's other activity did not support the doubled WSI. A new system of accounting for freezing rain was developed using the Modified Daily Snowfall equation. The Modified Daily Snowfall equation, Equation 4, follows:

$$\text{Mod Daily Snfl} = (\text{Est Daily Snfl}(\text{ratio}) - \text{Measured Daily Snfl}) * 1.25 + \text{Measured Daily Snfl} \quad 4$$

Where:

Estimated Daily Snowfall (ratio) is the estimated accumulation of snowfall determined by the ratio in the following table. In Table 1, “inch rain” is the total daily precipitation as inches of water:

Table 1: MaineDOT Snow to Liquid Rain Ratios

Temperature Range (°F)	Snow to Liquid Rain Ratio
<12	12 inches of snow = 1 inch rain
12 - 24	10 inches of snow = 1 inch rain
24 - 28	7 inches of snow = 1 inch rain
28 - 31	5 inches of snow = 1 inch rain

Measured Daily Snowfall = observed daily snowfall accumulation (inches of snowfall)

This equation is used when the minimum temperature for the day is $20\text{ }^{\circ}\text{F} \leq T_{\text{min}} \leq 30\text{ }^{\circ}\text{F}$ and the maximum temperature is $25\text{ }^{\circ}\text{F} \leq T_{\text{max}} \leq 35\text{ }^{\circ}\text{F}$ for the day.

The equation converts the liquid measurement of precipitation into an estimated snowfall depth, which is then reduced by the observed snowfall. The remainder is the assumed freezing rain accumulation converted to an accumulation of snowfall, which is then increased by a factor of 1.25 to account for an assumed 25% increased costs with removing ice compared to snow. The converted freezing rain accumulation is then summed with the observed snowfall amount to give a modified daily snowfall accumulation accounting for both real snow and freezing rain.

The modified daily snowfall is then assigned the same points as snow events leading to new ratings which appear more representative of the season.

The developed WSI equation was found to generally correlate to the weather events for a season and the actual winter maintenance work performed. Discrepancies in the correlation appeared when comparing the WSI to the winter maintenance costs. However, these discrepancies often arose from the increased cost of material or labor for a season rather than the WSI predicting a less impactful season. The report notes that the WSI can be improved; some seasons were over/under rated when compared to the work performed. Also, Maine’s DOT regions contain areas with multiple historical weather patterns. A more accurate WSI could be calculated if it is calculated by areas of similar weather patterns instead of DOT jurisdiction.

Maine did not adopt the methods described in their WSI report. The significant expansion in data collection efforts required to support the WSI was cited as a major reason for not implementing the program.

Wisconsin DOT: "Annual Winter Maintenance Report 2012-2013: Learning to use Less Salt Without Compromising Safety" (2013)

This report summarizes winter maintenance for the Wisconsin DOT during the 2012/2013 winter season. Wisconsin utilizes a Winter Severity Index to evaluate the relative performance of its winter maintenance activities across regions and years. Along with rating performance, the methods used by WisDOT to support its WSI program are mentioned. The 2012/2013 was considered relatively severe for the state, especially compared to the mild season of 2011/2012. Consequently, the WSI value for 2012/2013 was higher than the 10 year average across the state, and for nearly every county. Values for WSI in the state are often proportional to salt use, with high WSI values leading to a higher use of salt and low WSI values leading to less salt use.

WisDOT notes that the number of winter weather events has more impact on their expenditures than the accumulation per event. The effort to mobilize crews is considered impactful, with the report noting that crews "may be mobilized even if only 0.1 inches of snow or freezing rain falls". The state no longer accounts for bridge specific winter maintenance costs in the WSI. Results are biased for regions with a higher number of bridges, the removal of the bridge specific portion of the index leads to a greater consistency in reporting. In addition to a WSI, WisDOT tracks other performance metrics such as crew response time, time to bare/wet pavement after an event, winter weather related crashes, and costs/expenditures. The additional metrics are compared to the season's WSI to determine if any changes in performance are due to a more/less severe winter or another factor. For example, the WSI increased 53% from 2011/2012 to the 2012/2013 season. Total winter maintenance costs increased 69%. The increased severity of the winter was considered a contributing factor to the increased costs.

Weather data is collected and analyzed by multiple methods for use by winter maintenance crews. A weekly report, Winter Storm Reports, is completed by each county department to track weather and maintenance activity. These forms are completed manually and are used as inputs for the WSI in addition to other metrics. Weather data is also collected through the state's Road Weather Information System (RWIS) for use by the DOT and county departments. WisDOT also utilizes the Maintenance Decision Support System (MDSS) for additional weather forecasting and metrics.

Previous PennDOT Work

A pilot Winter Severity Index program was developed by PennDOT and implemented in 2013. The pilot program covers the previous two winter seasons in three counties selected due to differing historical weather patterns. PennDOT District 8 investigated the cost of a winter weather event in terms of plowing and support costs in a study separate from the WSI pilot program.

District 8 Study of Winter Maintenance Costs and Winter Weather in York County (2013)

A study separate from the WSI pilot program was conducted by PennDOT District 8 into winter maintenance costs and seasonal weather for York County during the 2009/10 to 2012/13 winter seasons. Weather data was provided for events by Millersville University. Observations were performed at four sites within the county, snow accumulations and the event's start and end date were recorded. District 8 obtained cost maintenance work data from the PennDOT SAP database. Costs were defined as Snow Removal or Winter Support Costs, definitions used by the SAP products database. Snow Removal covers plowing, spreading anti-skid and chemical applications. Winter Support costs covers other general work.

Data was tabulated per season, and further separated by event. The costs of each event includes the event days defined by Millersville University's weather data plus the day proceeding and the day following the weather event. If the storm was defined as January 13th to 14th, costs were collected from the 12th to the 15th. District 8 considered work from the day before and day after an event to cover the preparation and cleanup associated with the snowfall. The District also recorded the Salt Usage per event in tons.

PennDOT Winter Team Developed WSI (Summer 2013)

A Winter Severity Index was developed by District 3 and the Winter team for further study. Points were assigned for snow accumulation during an event, freezing rain accumulation, bonus points for the temperature during an event, occurrences of a frost cycle, and assumed days with drifting.

The District 3 point scale was used to rate the 2011/2012 and 2012/2013 winter seasons in Crawford, Snyder, and Bucks County by PennDOT. Weather data was obtained from Millersville University for the pilot counties. Events were defined based on the Millersville data and costs associated with the event were collected.

Freezing rain accumulations were calculated rather than directly measured. If the air temperature was 32°F or less while rainfall was measured, the precipitation was counted as freezing rain. Weather factors assigned points were Drifting, Frost, Snow, Temperature and Freezing Rain. Drifting conditions were given 2 points per day if there were wind speeds greater than 15mph and snow was assumed to be on the ground. Frost Cycles were given 2 points per day with a high temperature of over 32 °F and a low of less than 32 °F. The snow, freezing rain, and temperature point scales are shown in the following set of tables and are considered the Event Severity Points.

Table 2: Winter Team WSI Point Values for Event Severity

Inches of Snow

Minimum Snowfall (in)	Maximum Snowfall (in)	Points
0	0.499	0
0.5	0.99	1
1	1.99	3
2	2.99	5
3	3.99	6
4	4.99	7
5	5.99	10
6	6.99	12
7	7.99	14
8	8.99	17
9	9.99	20
10	10.99	23
11	11.99	26
12	12.99	30
13	13.99	34
14	14.99	38
15	15.99	42
16	16.99	47
17	17.99	52
18	18.99	58
19	19.99	64
20	20.99	70
21	21.99	76
22	22.99	82
23	23.99	88
24	24.99	94
25	25.99	100

Temperature at Time of Snow Event

Temp (°F)	Points
<0 - 10	16
10-20	12
21-26	8
27-31	4
>32	0

Freezing Rain

Rainfall (in)	Rainfall (in)	Points
0	0.49	2
0.5	0.99	5
1	1.99	8
2	2.99	11
3	3.99	14
4	4.99	17
5	5.99	20
6	6.99	23
7	7.99	26
8	8.99	29
9	9.99	32
10	10.99	35

No points were assigned to snow accumulations under 0.5 inches. Storms with small accumulations still required a response from PennDOT maintenance crews so the impact should be measured. The lack of points for events less than 0.5 inches could lead to undervaluation in regions with lower per event snowfalls or seasons with many small events. A minimum point value is needed to account for the impact of mobilizing winter maintenance crews.

Multiple districts have stated that ice has a higher impact on winter maintenance activity compared to the same accumulation of snow. Typically, 0.1 inch of ice requires the response of a multi-inch snowstorm. In this point scale 5 inches of freezing rain is equivalent to a 9 inch snowstorm, and 0.5 inch ice event is given less weight than a 2 inch snowstorm. For comparison, Maine's approach equates about 1 inch of rain (as freezing rain) to over 10 inches of snow.

Points values were calculated each day according to the three sets of point scales: Event Severity, Frost, and Drifting.. The total value for each day was the sum of Event Severity, Frost, and Drifting Points. Due to insufficient weather data, temperature points were assigned based on the average daily temperature, $(\text{high temp} + \text{low temp})/2$, if winter weather occurred on that day. A similar approach was taken for freezing rain, if the average daily temperature was 32 °F or below the day's rainfall would count as freezing rain. This method leaves out the potential for freezing rain at higher air temperatures; it also fails to account for the timing of rain with temperature. Point scales were not adjusted for each county to account for differing historical weather patterns and expected maintenance response levels.

Costs data was obtained through PennDOT's SAP system for days with winter weather. Seasonal totals were also obtained, with the winter season defined as November 1 through March 31. SAP handles daily and seasonal records differently. Daily costs are stored as estimates based of moving averages of historical costs data. Multi-date summaries reflect the actual costs charged to the activity. Costs were assigned to an event if they occurred on the same day as the event, the day before and the day after each event were included as well to capture prep and cleanup work. Approximately 70% of the total winter maintenance costs were tracked in the PennDOT study.

Correlation between the WSI per event and the cost per event is inconsistent. The strongest direct correlation as determined by the Excel calculated coefficient of determination (R^2) was observed in Crawford County during the 2012/13 winter season. Other seasons in the study exhibited minimal correlation between event costs and event WSI with large point ranges assigned to minimal costs or even some of the highest point values in the season assigned to events with an average maintenance cost.

Due to the use in the study of only two winter seasons, determining correlation between seasonal costs and the WSI for a season was not performed.

Pilot Program

The WSI pilot program included the Counties of Crawford, Bucks, and Snyder. Weather records from the five previous winter seasons were collected along with PennDOT winter maintenance work and cost data. The winter seasons in the study were 2008/09 to 2012/2013. For the purpose of the project the winter season was defined as starting on October 1st and ending at midnight on April 30th.

Winter Weather Data Sources

Winter weather data was obtained from multiple Internet based sources. They are:

- National Oceanic and Atmospheric Administration (NOAA) - National Operational Hydrologic Remote Sensing Center (NOHRSC)
- Pennsylvania State Climatologist (Penn State University) which provides access to the
 - FAA Automated Weather Observing System (AWOS)
 - Cooperative Observer Program (COOP)

NOAA and the FAA both use automated weather stations. COOP is a collection of citizen observers who perform weather data observations. The program is managed by NOAA. All weather databases accessed for WSI research are free and accessed via websites.

NOAA NOHRSC weather stations measure multiple weather points on an hourly basis. Observed data includes temperature (6-ft forcing), precipitation, and solar radiation. Multiple other measurements are modeled from the station's observations such as the current snow pack depth, snow surface temperatures, and snow melt. Data accessed on the website is available as charts, graphs or tables.

Available data varies per weather station, as does the available dates of data. Some stations provide a set of "observed" snow depth measurements, such as inches of snow accumulation, separate from the precipitation (reported as inches of water) measured automatically by the station's equipment.

FAA data obtained through the Penn State Climatologist reports weather readings once per hour. Data includes temperature, precipitation, dew point, wind speed, and humidity. Precipitation, including snow, is typically measured as inches of water. Web based data is reported as a spreadsheet table.

COOP data is reported daily, giving the day's high and low temperature, snowfall, and rainfall. Measurements of snowfall are either inches of snow or equivalent water, with no indication of the type of measurement. Weather data can be taken from automated stations or human observers. Data is reported in a spreadsheet table.

NOAA, FAA, and COOP weather records were used in the pilot program. The following data was obtained from each source:

- NOAA: The weather factors are precipitation reported in inches of water for snow, non-snow, and "unknown" (unspecified source) precipitation. Cumulative Observed Depth of Snowfall, and current precipitation type was obtained. Data is recorded in one hour intervals.

- FAA: Data obtained was maximum and minimum temperature and one-hour precipitation totals. The time increment for the FAA stations is one hour.
- COOP: Data exported from the website was daily high and low temperatures, rainfall totals, and snowfall totals. The time increment for the COOP stations is one day.

Weather Data Analysis/Processing

Weather data for the pilot counties and five winter seasons was collected from the NOAA, FAA, and COOP databases.

FAA data collection locations dictated which COOP and NOAA weather stations were selected. Temperature data used in this project was obtained from FAA stations; attempts were made to keep COOP and NOAA stations in close proximity to reduce variations of temperature with distance. Also, FAA data is recorded at only a few locations per county, typically one location. COOP data is also recorded in one or two locations per county. The NOAA weather station for each County's weather data was selected to keep distances less than 10 miles, if possible. Another factor in the selection of the NOAA station was the availability of the Observed Cumulative Depth of Snowfall measurement. If there were no NOAA stations with the Observed measurement in the 10 mile radius, the area was expanded until a station with the suitable data was located.

All weather data was compiled into an Excel spreadsheet. The records were first adjusted from Greenwich Mean Time (GMT) or UTC (equivalent to GMT) to Eastern Standard Time.

No direct measurement of freezing rain accumulations was available from the weather data sources. An assumed ice accumulation was created from sets of data. NOAA weather data lists measured precipitation as inches of water from snow, non-snow, and unknown precipitation. When FAA temperature values for the hour averaged to 34 degrees or less, the greater of the hour's non-snow or unknown precipitation was converted into freezing rain. All occurrences of freezing rain were then investigated to determine if an accumulation was feasible. Temperatures before and after the event were observed. If below freezing conditions existed for a significant time period (about 8 hours or longer) during which the freezing rain accumulation was calculated and temperatures did not drastically increase during the event, the calculated accumulation was considered valid. It was assumed that the roadway surface was cold enough to be frozen at the beginning of the event and remain frozen long enough for ice to accumulate and require removal. As a final check, PennDOT expenditures were compared for days with potential freezing rain. A day with minimal snow/ice removal costs and work hours, about 24 work hours and/or \$300 or less, lead to the removal of the day's ice accumulation.

Snow accumulation measurements were taken from the NOAA NOHRSC's "Observed Cumulative Depth of Snow" records. Out of all the free weather data from NOAA and the Penn State Climatologist, the "Observed" measurement from NOAA was the only one to consistently list snow accumulations as inches of snowfall instead of inches of liquid water. Using the liquid water accumulation records would require a conversion to snowfall depth. Given snow's inconsistent water content and the multiple factors which influence the snow to water ratio, conversions based off surface condition measurements would not accurately reflect each storm's snow to water content ratio. Observed Snowfall data is not

consistently measured hourly, the actual rate of measurement varies from once per hour to once per event. This measurement is not performed at every NOAA weather station and the observed measurement is not always recorded each year at any one station.

Event duration was manually calculated from NOAA data. The duration of an event was measured from the first occurrence of snow or freezing rain until a gap of about 6 to 8 hours between accumulations was observed. Further processing of this data also allows for the listing of snow only, ice only, and mixed precipitation hours for those hours which have measured precipitation.

Data to calculate the number of frost cycles was collected in this study, but the developed WSI does not account for frost cycles. It was assumed that the frost cycle would not impact snow removal costs significantly. The cost impact to PennDOT from frost cycles would be seen when performing maintenance to the asphalt or concrete roadway surface.

The processed weather data was then totaled by winter weather event. The recorded factors are the event total snow accumulation, freezing rain accumulation, duration, starting and ending date.

Observations on Weather Data and Processing

Modeled data from NOAA sites is inaccurate. Snowfall totals have been observed to over/under-estimate an event's accumulation by 3 to 4 inches. Snowfall rates of 5 inches an hour have been measured with NOAA's modeled data. The modeled accumulations were compared to the Observed measurements, news reports, and evidence of PennDOT maintenance activity. Often, significant snowfall would be recorded on days with no work activity or associated news report of a multi-inch storm.

COOP and FAA snowfall accumulations are measured in inconsistent units. Snowfall is recorded either in inches of water or inches of accumulated snow. The tables provided from the Penn State Climatologist give no indication of which "inches" have been recorded. Also, on rare occasions, the rainfall and snowfall totals for a day are the same measurement, implying that the observer or database gave the measurement of total precipitation as inches of water and the table reported it as both forms of precipitations.

LufftUSA sites in Perry and Fulton were considered for use in this project. However, snowfall is measured as liquid water depth by these stations. Due to the lack of direct snowfall accumulation measurements, these sites were not used in the study.

Record keeping by all sources is inconsistent. All data sources utilized had missing data points, dropping data for the hour. Some of these drops have totaled three to four consecutive days where no information was recorded. This is particularly prevalent on the NOAA Observed Snowfall data where the cumulative value would occasionally reset to 0 inches mid-month or have gaps of days between recorded measurements. Automation of data processing is complicated by the gaps and resets.

Duration of blowing and drifting snow, a common WSI factor, was not obtained. Earlier discussions by the working group and the "Mapping Winter Severity Zones" report indicated the difficulty in measuring

drifting snow. There was also the issue of determining how wide-spread drifting is across a county/region, and if the drifting conditions are significant enough to require a winter maintenance response.

Processing and reduction of the winter weather data was a considerable effort. To create the event and season totals for just one year in one county approximately 5000 hours of data was collected, recorded, reviewed, and processed. Despite efforts to automate the reduction of weather data, inconsistencies and missing data required a significant amount of manual data processing. Filling in the missing hours of records required additional time to obtain a new data set which itself needed reviewed.

PennDOT Winter Maintenance Cost and Work Data

Winter maintenance costs and work data is recorded by PennDOT's SAP products. Charges to PennDOT's 712 Winter Traffic Service program were considered in this project. Costs were further divided by activity type. There are four activities identified by a three digit number, called assemblies:

- 101 charges cover snow removal activities – “Plow Snow, Spread Anti-Skid, Chem or Plow/Spreading Simultaneously – Truck Plowing – Grader Plowing”.
- 201 charges are considered incidental work – “Snow and Ice Control – Other”.
- 301 charges are proactive anti-ice work such as spreading de-icing material prior to a freezing rain event – “Anti-Icing”.
- 401 charges are “Salt Brine Manufacture”.

SAP categorizes each charge type by work hours, money spent on personnel, materials, equipment, rentals, and a miscellaneous category. The maintenance crew is also tracked. Charges are recorded once per day and tracked by date. The specific SAP report used by the pilot program to give daily information is the Flash Report. The costs recorded by the Flash Report are estimates of final charges based on moving averages of previous costs.

Correlating Maintenance Activity to Storm Activity

Weather data recorded for the pilot counties (Bucks, Crawford, and Snyder) was correlated to PennDOT winter maintenance records to develop a WSI equation relating weather and its impact on maintenance activity. The District 8 study of York County winter weather and cost data was also utilized as a check of the pilot counties.

Snyder County weather records were only valid for the 2008/2009 and 2009/2010 winter seasons, after which NOAA sites did not record the Observed Cumulative Depth of Snowfall Measurement. Due to the lack of analyzable weather data, Snyder County's cost/weather relationships were used as a check for the trends observed in Bucks and Crawford. Based on the findings of (Nakamae et al.), regions with higher snowfall totals would see better correlations to winter maintenance costs and snowfall totals. Historically, Crawford County has higher snow accumulations than Bucks County. Weather data for Bucks showed a tendency for mixed precipitation events and storms which affected only small portions of the County. Due to these factors, Crawford County was selected for the initial correlations.

An early assumption in the project is that doubling snowfall for a storm would not double cost. The following is the seasonal snowfall and winter maintenance costs for Crawford County from the 2008/2009 to 2012/2013 winter seasons.

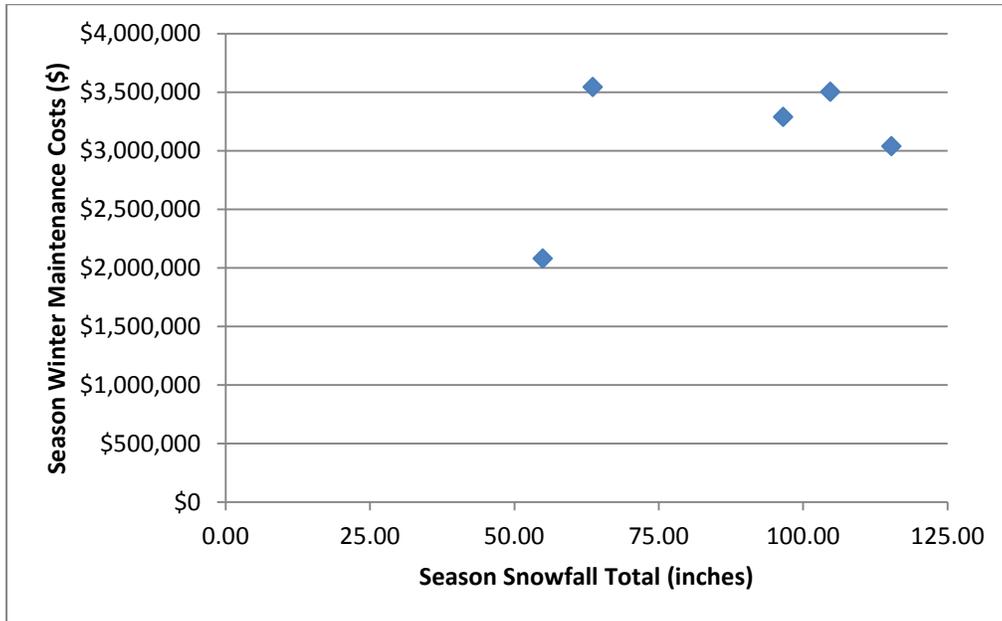


Figure 1: Seasonal Snowfall and Maintenance Costs in Crawford County

The cost in Crawford County for a 120 inch season is approximately \$3 million; a nearly 60 inch season is approximately \$2 million. When comparing seasonal totals, the assumption holds true.

Looking at individual events also supported the cost/snowfall assumption. For simplification, only snow removal charges occurring on the same day as the winter weather event were counted as the “same-day costs”. The following plot gives the individual event cost and the event’s total snowfall in Crawford County for all 5 winter seasons.

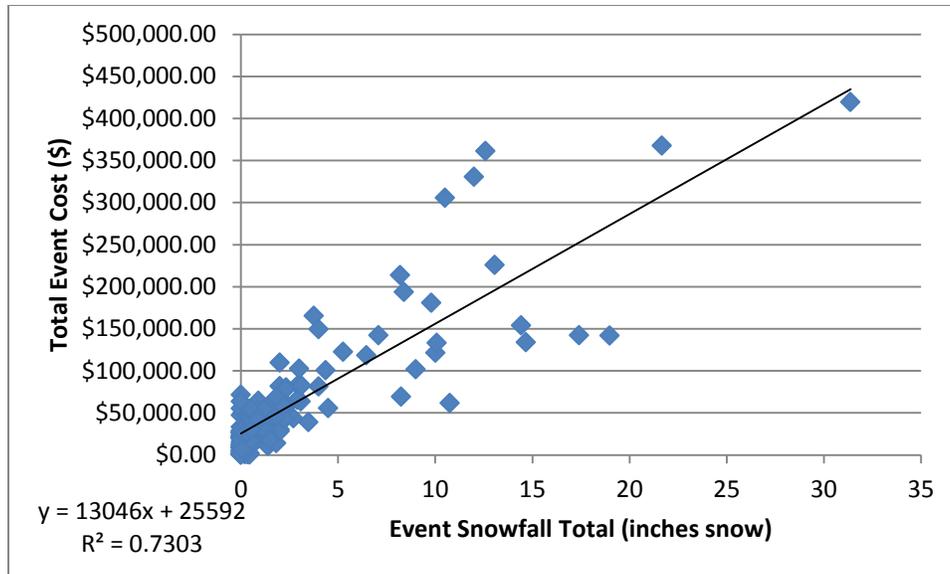


Figure 2: Event Costs and Event Snowfall Totals for Study Period in Crawford County

The linear trend line equation for all Crawford County snowfall events and their same day snow removal costs are not double cost for double the snow. The estimated cost for a 2 inch event is \$52,000, for a 4 inch event, the cost is \$77,800. Individual events were further investigated. The same trend was observed in all pilot counties and in the cost/weather study performed by District 8 for York County.

A plot of an event's unit costs per inch snowfall was created by taking the event's cost and dividing by the event's accumulation. The unit cost was then plotted against the event accumulations. It is a modified version of the UCSR line which does not account for the number of snow lane miles maintained during the event. Following is a plot of the same day unit-cost and event snowfalls for Crawford County during the 2008/09 winter season.

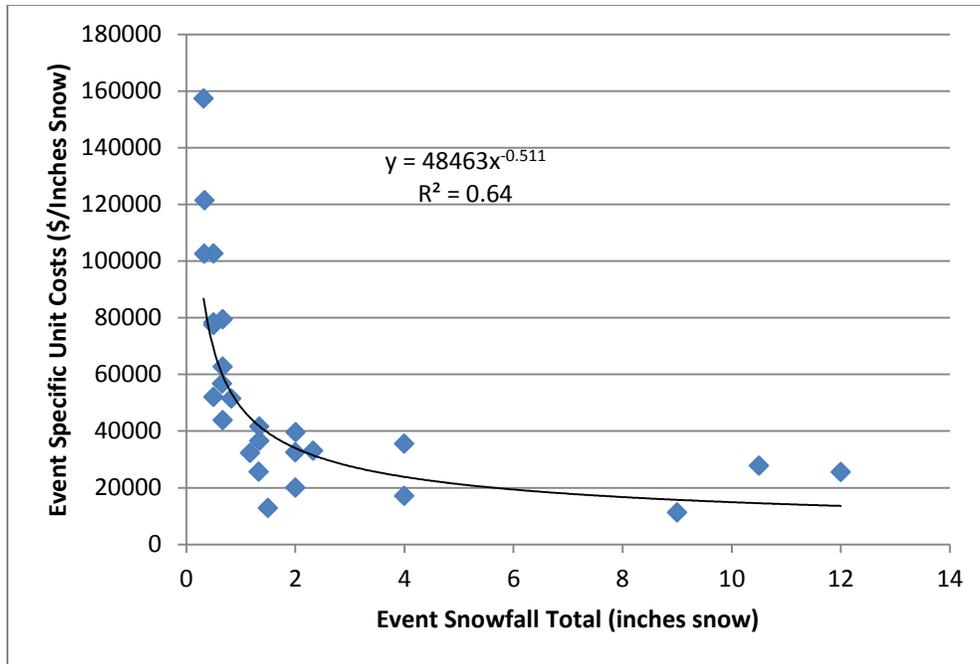


Figure 3: Unit Cost of Snow per Event in Crawford County, 2008/09 Season

The impact of additional snowfall lessens drastically as the event’s accumulation increases. The best fit curve for this plot is a decreasing power curve. Storms with smaller accumulations have much higher costs per inch than those with larger accumulations. The conclusion drawn from this analysis is the additional points gained for each additional unit of snowfall should decrease. The increase in cost from a 2 inch to a 4 inch snow event should be around 60%, and it follows that the assigned points should not double for the same situation. Also, the cost of mobilizing the winter maintenance response is significant enough to warrant a point value per event.

The decreasing unit-cost trend was observed in all pilot counties and in the York County study.

Correlating cost/work with snowfall totals is less reliable for storms considered “trace” events, typically less than 1 inch of snow. Trace snows were analyzed separately to determine if a blanket statement about their costs could be made. For Crawford, the cost per trace event is approximately 60% of the cost of a 1 to 2 inch snow event each season. Similar correlations were observed in Snyder, Bucks, and York County. Trace events correlated work and weather more strongly with event duration instead of event accumulations.

Ice events also proved problematic. Generally, ice and trace snow events give the strongest correlation when comparing event duration with costs. The relatively small number of ice events compared to snow events during the study period, and the use of calculated ice accumulation rather than direct measurements further complicates the analysis of freezing rain. No correlation could be made between the amount of freezing rain and the event cost or work in any pilot county. Duration of the freezing rain event has a moderate correlation to work and costs, but it is highly inconsistent. Per event, the average freezing rain accumulation, cost, duration, and work hours were compared to snowfall

statistics. A rough relationship between the average cost of an ice event and snow event costs was formed from the Crawford and Bucks County data. In Crawford County the relationship is 0.1 inches of ice equating to 2-3 inches of snow in event costs. In Bucks, the relationship is closer to 0.1 inches of ice equating to 1 inch of snow.

Snowfall rate during an event had little correlation to the work and costs of winter maintenance. Instead, the duration of the event had a stronger correlation with costs. As mentioned for trace and ice accumulations, event duration was a better indication of costs than the accumulation alone. However, above the trace event magnitude of accumulation, snowfall accumulation and event duration correlated equally well with maintenance activity. Also, larger accumulations of snowfall had longer average event durations. This leads to correlations between event accumulations and maintenance work indirectly comparing the duration and maintenance activity.

WSI Point Scale Testing

A WSI point scale was developed based on cost and weather correlations in the pilot counties. Unit Cost of Snow per Event plots for the study period were used to generate a WSI equation (an example is shown in Figure 3). The WSI point scale created from the Unit Cost correlation was scaled so that point values were within a 0 to 50 point range. The equation applies only to snow accumulations per event. The scale in Table 3 is defined by the curve in Equation 5.

$$\text{Event Points} = -0.0336 * (\text{inches snow})^2 + 2.2111 * (\text{inches snow}) + 2.7872$$

5

Table 3: WSI Point Scale Defined by Equation 5 for Various Snowfall Accumulations

Snow Points		Snow Points	
Inches Snow	Points	Inches Snow	Points
0.5	4	16	30
1	5	17	31
2	7	18	32
3	9	19	33
4	11	20	34
5	13	21	34
6	15	22	35
7	17	23	36
8	18	24	37
9	20	25	37
10	22	26	38
11	23	27	38
12	24	28	38
13	26	29	39
14	27	30	39
15	28		

The new point scale was applied to the five seasons of Crawford County weather data. Each weather event was assigned a point value based on the major accumulation type, and the duration of precipitation. Snow accumulation points were calculated for any storm where a clear majority of the event’s duration (60% of event hours) was snowfall. A minimum of 4 points was assigned to a snow event. Freezing rain events, where a majority of the event duration was freezing rain, were assigned 8 points to match the 0.1” ice to 2-3” snow cost relationship. Mixed events where neither snow nor freezing rain constituted a majority of the duration, were assigned the sum of their respective freezing rain event and snow accumulation points.

WSI ratings for each event in the season were totaled to give a WSI rating for the season. The following table shows the results of the WSI evaluation of Crawford County. Summary weather data for the season is shown, the number of discrete events, the total duration of winter weather in hours, and the season total accumulations of snow and freezing rain. Next is the WSI for the season and the sum of all individual event ratings. Cost data is also displayed, both for the same day snow removal (charges to assembly 101 occurring on the day of the event), and a sum of all 712 winter maintenance costs for the season.

Table 4: Summary of Crawford County Pilot Program

Crawford County							
Season	Weather Data				WSI	All Winter Maintenance Charges	
	# Events	Event Duration	Snow Acc. (in.)	Freezing Rain Acc. (in.)	Season Total	Work (hrs)	Costs
2008-2009	43	616	63.6	2.87	283	60973	\$ 3,543,682
2009-2010	26	440	115.3	2.01	235	49547	\$ 3,036,979
2010-2011	20	320	96.6	0.66	232	54918	\$ 3,287,393
2011-2012	24	233	54.9	0.94	216	36400	\$ 2,078,934
2012-2013	23	523	104.8	0.54	263	56666	\$ 3,502,064

WSI values for the Crawford County data have a consistently stronger correlation, as calculated by the coefficient of determination, to PennDOT winter maintenance costs than comparison of maintenance costs to the number of events or seasonal snowfall accumulation. The 2009/2010 and 2010/2011 winter season are similar in weather and PennDOT winter maintenance charges. The WSI ratings for each season reflect the similarity, with ratings of 235 and 232.

To evaluate the adaptability of the WSI Point Scale, data from Snyder and Bucks counties was evaluated. The WSI equation was applied to the processed weather data for all five studied seasons in Bucks County and for the two usable years in Snyder County. Due to the prevalence of trace events and freezing rain in the county, the two most difficult storm types to correlate, Bucks served as a stress test

of the WSI methodology. Also, Bucks County had a full five year period of weather data available for study.

The methodology used to evaluate the WSI in Crawford County was repeated for Bucks and Snyder County. Weather data from NOAA was reduced and separated into trace events, snowfall, and ice events. A point scale based on snowfall accumulation was created. The ice to snow accumulation event cost ratio for Bucks County was found to be about 0.1" ice to 1.0" of snow.

The WSI developed from the pilot counties was applied to the remaining counties (Snyder and Bucks). A summary of their weather, maintenance, and WSI values is shown in the following tables.

Table 5: Summary of Bucks County Pilot Program

Bucks County					WSI	All Winter Maintenance Charges	
Weather Data						Season Total	Work (hrs)
Season	# Events	Event Duration	Snow Acc. (in.)	Freezing Rain Acc. (in.)			
2008-2009	7	106	6.91	0.58	58	43199	\$ 4,151,662
2009-2010	14	171	32.9	1.4	155	46227	\$ 6,222,986
2010-2011	7	83	35.9	0.2	88	41003	\$ 5,895,259
2011-2012	4	77	7	0.05	40	22515	\$ 2,265,727
2012-2013	7	99	7.91	0.2	70	33446	\$ 3,310,670

Table 6: Summary of Snyder County Pilot Program

Snyder County					WSI	All Winter Maintenance Charges	
Weather Data						Season Total	Work (hrs)
Season	# Events	Event Duration	Snow Acc. (in.)	Freezing Rain Acc. (in.)			
2008-2009	19	200	15.22	2.72	128	14806	\$ 795,826
2009-2010	14	139	33.72	1.64	148	13581	\$ 783,327

As seen in Crawford County, the WSI values calculated for Bucks have a more consistent correlation to winter maintenance costs across the study period than comparing costs to the number of events or seasonal snow accumulations. Of note in the Bucks County data are the 2008/2009 and 2012/2013 winter seasons. Despite nearly identical weather data and nearly identical WSI ratings, the work and costs of maintenance for the seasons varied significantly. For these years, the WSI reflects the difficulty of the winter weather, but does not capture all of the variable cost of winter maintenance. Many factors

could contribute to the cost and work difference between 2008/2009 and 2012/2013; materials cost, labor costs, event specific duration, or the distribution of snow in the county (weather data was taken from only one point in Bucks). However, the ability of the WSI to rate the intensity of the winter season was not affected. Performance for Snyder County's two years of data is positive. A relative increase in the WSI rating is observed from the 2008/2009 to the 2009/2010 season, most likely due to the significant increase in snowfall accumulation.

Findings of the Pilot Program

WSI Point Scale

The WSI point scale was developed based on the maintenance and weather correlations in the pilot counties. Unit-cost and unit-work plots were used to create “average” events, and then were scaled to keep the points per event within a 0 to 50 range. The point scale was developed for snow accumulations only. All freezing rain events were assigned eight points based on the limited data and correlation in Crawford, Bucks, and Snyder Counties. Other potential WSI points such as event duration and drifting snow could be evaluated in further studies.

To simplify the use of the WSI system, the continuous equation was broken into steps of accumulation and a freezing rain event point value was added. The result of the stepped approach is shown in the following table. The points in Table 7 are defined by the Pilot Point Scale equation, Equation 5.

Table 7: WSI Point Scale

<i>Snow Accumulation</i>		
Min (in.)	Max (in.)	Points
<1" "trace"		4
1	1.9	6
2	2.9	8
3	4.9	11
5	6.9	15
7	9.9	20
10	14.9	25
15	19.9	31
20	24.9	36
25	29.9	38

<i>Freezing Rain Event</i>	8
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Weather Data

Many of the issues in the Clear Roads/Parsons Study, “Understanding the True Cost of Snow and Ice Control”, were mirrored in the development of the point scale. Collecting and reducing weather and cost data became a significant issue. As mentioned in the Weather Data Observations section, data taken from NOAA sources was subject to rounds of processing to create analyzable data sets. Other issues with incomplete data records led to the use of only one weather station per county each season to reduce the time spent on weather data processing. Difficulties in reducing and interpreting weather data were encountered by Meridian, who developed computer software and algorithms to overcome the time investment.

The utilization of PennDOT's Road Weather Information System (RWIS) system can reduce the time and effort of manual weather data processing. WSI specific language for the RWIS specifications was requested and the following draft was submitted:

The RWIS Website shall be capable of displaying data in a Winter Severity Index (WSI) format. The WSI shall quantify winter severity via a formula and point scale to be provided by PennDOT which may be modified at any future time using the data collected. The WSI currently factors in occurrences of trace snow (snow accumulation of less than one inch), snow accumulation and freezing rain accumulation. Additional WSI factors may be included in future revisions to the formula and point scale provided by PennDOT. The WSI shall be recorded per winter weather event and per day, and reported with the dominate weather condition during the day/event which are currently trace snow, freezing rain, and snow with an accumulation greater than one (1) inch. The dominate weather condition may be expanded to include additional WSI factors. Cumulative WSI point values for the day, event, and the dominate weather condition shall be reported by month to date and season to date. The WSI will be used by PennDOT as a planning and management tool to evaluate and estimate labor and equipment use across counties and from year to year.

The distribution of sites in the RWIS program will be key in its WSI applications. An even distribution of sites across counties and the state will allow for a nuanced evaluation of winter weather.

Cost Data

The lack of a Storm I.D. system or some indicator of which daily charges apply to which event lead to the loss of maintenance data in the development of the points scales. For the sake of consistency, event based analysis focused only on same day snow removal work and costs. For example, the 2011/2012 winter season in Bucks County totaled \$1.3 million in estimated snow removal costs for same day data. The total estimated expenditures for the same season for all 712 winter maintenance was \$2.3 million. A total of \$1 million was unaccounted for. These costs could not be assigned to specific events with any confidence.

Trace Snow and Freezing Rain

Analysis of Crawford and Bucks County data lead to the division of snow events into "trace" and all other accumulations. Trace snows are anything less than 1 inch in accumulation. These events showed minimal correlation between snow removal costs and the event accumulation. Instead, the correlation was most favorable for cost and event duration. The exact reason for the change in correlation is unclear. It may be that the trace events are highly regionalized, affecting only small portions of the county. Each crew may perform work proportional to the accumulation in their area, but the WSI relies on county wide data. Also, the use of only one weather station leads to region bias. Snow events are variable; accumulations may vary significantly in a space of only a few miles. Using one weather station to represent an entire county leads to situations where the station recorded a trace snow while the rest of the county experienced a significant accumulation and vice-versa. Subdividing the counties may solve the issue of relating trace snow to costs, but at additional cost to weather data collection.

Similar trends were seen with freezing rain events. Generally, freezing rain related costs correlated to the duration of the storm. This correlation was loose. The method for measuring freezing rain as an input into the WSI equation relies on calculated values, not direct observations. The accumulations of freezing rain used in the study are more of an indication of the potential for freezing rain. To reduce inconsistency and create some measure, a single point value was created for freezing rain per event instead of accumulation totals.

Recommendations

PennDOT currently lacks a fully objective metric to evaluate and compare the severity of a winter event or winter season from a maintenance impact perspective. The current method relies on comparing the number of events and snowfall totals. Relying on only events and snowfall paints an incomplete picture of a winter season's weather and the severity of the winter. By incorporating the Winter Severity Index into its metrics toolset, PennDOT can quickly and easily evaluate the effectiveness and efficiency of winter maintenance activities from year to year. WSI is currently used by multiple states such as Wisconsin, New Hampshire and Vermont. These states have utilized WSI ratings to justify funding and rate the performance of changing maintenance methods.

Given the benefits of a WSI system and understanding the constraints it imposes on the Department, it is recommended that PennDOT continue its pilot program into the 2014/2015 winter season. For the continued pilot program the following is recommended.

Short Term:

- Continue with the pilot program expansion into other counties in the state and utilize the Pilot Points Scale and Equation 5 which is repeated at the end of the recommendations.
- Define the appropriate time interval that determines whether any non-continuous winter weather event is considered a single or separate event.
- Weather data collection should be standardized. The inclusion of WSI specific language in the RWIS specifications should lead to simplified weather data processing and standardization. Weather factors of the most importance are air and surface temperature, event duration, precipitation type and accumulation, and wind speed.
- Focus on collecting detailed and accurate maintenance and weather data specific to trace snow events and freezing rain events. Weather data from the RWIS program can be utilized for the trace snow and ice event analysis.

Long Term:

- Investigate the use of a Storm ID or equivalent method to clearly tie winter maintenance costs activities to specific winter weather events. Also determine the impact of "support costs", such as preparation and clean-up, and how these costs affect the WSI formula.
- The inclusion of other winter weather data such as drifting or blowing snow and temperature during events should be investigated to determine how they affect the WSI equation and if they are applicable to the metric.
- Continue the evaluation of collected weather and maintenance data for the refinement of the WSI equation.

The recommended Pilot Point Scale equation is Equation 5, repeated below. The tabulated version, Table 8, is also repeated below.

$$\text{Event Points} = -0.0336 * (\text{inches snow})^2 + 2.2111 * (\text{inches snow}) + 2.7872$$

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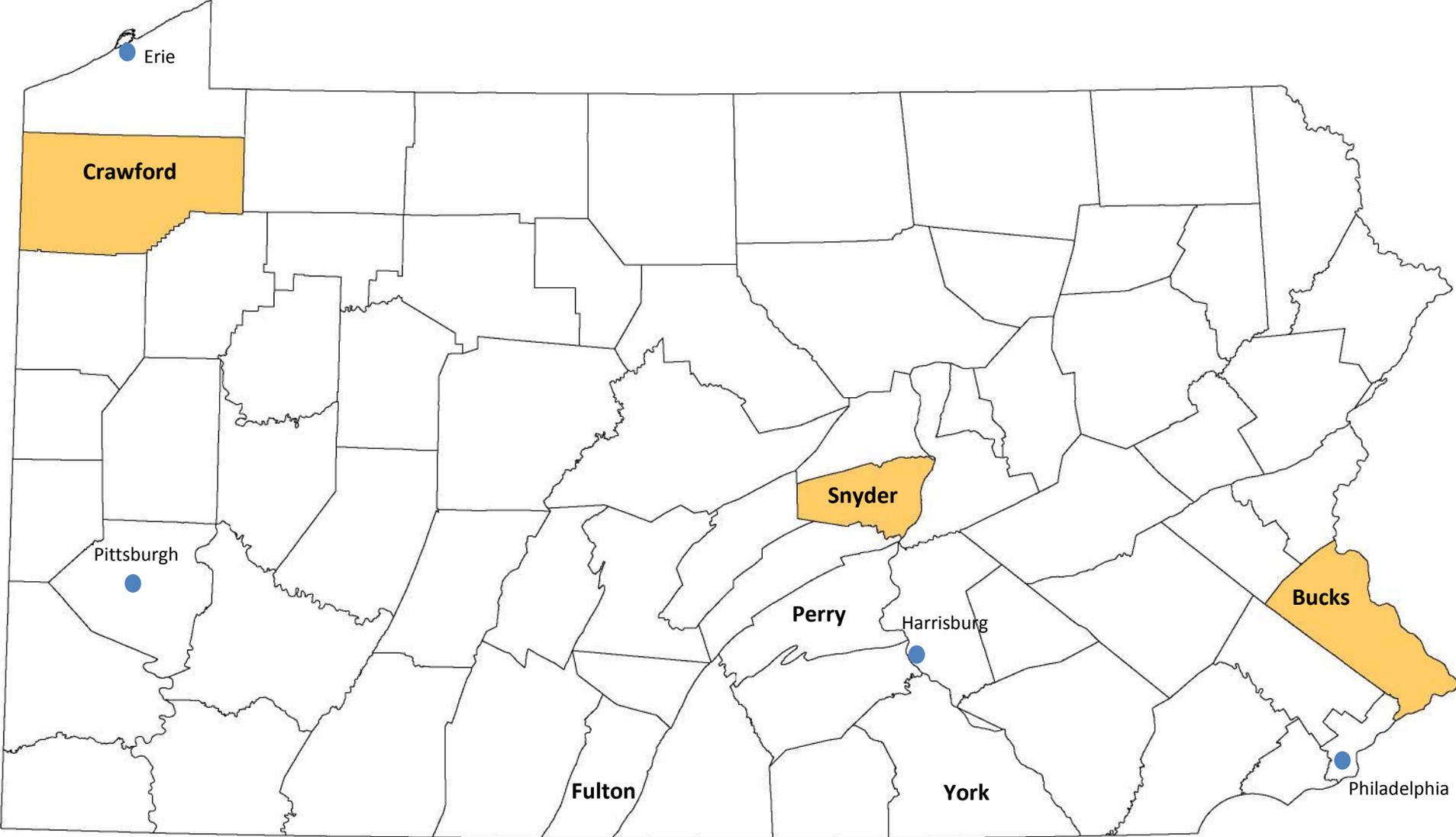
Table 8: Tabulated WSI Point Scale (Repeat of Table 7)

<i>Snow Accumulation</i>		
Min (in.)	Max (in.)	Points
<1" "trace"		4
1	1.9	6
2	2.9	8
3	4.9	11
5	6.9	15
7	9.9	20
10	14.9	25
15	19.9	31
20	24.9	36
25	29.9	38
<i>Freezing Rain Event</i>		8

Bibliography

- Cadmus, A., & Rose, D. (2014). *Understanding the True Cost of Snow and Ice Control, A Clear Roads Research Project: 10-03*. Parsons Brinckerhoff, Inc. St. Paul, MN: Clear Roads.
- Marquis, B. (2009). *Technical Report 09-1: A Winter Severity Index for the State of Maine*. MaineDOT, Technical Research Division. Augusta, ME: Maine Department of Transportation.
- Mewes, J. J. (2011). *Mapping Weather Severity Zones*. Meridian Environmental Technology, Inc. St. Paul, MN: Clear Roads.
- Nakamae, S., Hara, Dr. Eng., F., Takano, Dr. Eng., S.-E., Okawado, T., & Oshima, J. (2010). Development Of a Cost Management Method for Road Snow Removal in Cold, Snowy Regions. *Journal of the Eastern Asia Society for Transportation Studies, Vol. 8*.
- PennDOT District 8-0. (2013). District 8 Study of Winter Maintenance Costs and Winter Weather in York County. Pennsylvania: Unpublished raw data.
- PennDOT, & McCormick Taylor. (December 2013 to June 2014). Winter Severity Index - Working Group Meetings. Harrisburg, Pennsylvania.
- Wisconsin DOT. (2014). *Annual Winter Maintenance Report 2012-2013: Learning to Use Less Salt Without Compromising Safety*. Wisconsin DOT, Division of Transportation System Development, Bureau of Highway Maintenance, Winter Operations Unit. Wisconsin Department of Transportation.

Appendix 1: Pennsylvania County Reference Map



- Legend**
-  - Pilot Program County
 -  - Other Counties
 -  - City