Report No. UT-21.34

# TIME AND COST BENEFITS FOR TRAFFIC THROUGH SNOWPLOW OPERATIONS

**Prepared For:**

Utah Department of Transportation
Research & Innovation Division

**Final Report**
**October, 2021**

RESEARCH
Keeping Utah Moving
Utah Department of Transportation - Research Division
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16. Abstract

The Utah Department of Transportation (UDOT) has difficulty conveying to the public all of the user benefits that result from UDOT's snowplow operations. This project is focused on communicating the importance to travelers of snowplow operations in terms of travel time saved and travel time improved vs. not plowing. This information will be added to the Snowplow Operations Dashboard that was developed previously to answer questions related to where and when snowplows had operated during a previous storm and will provide overall operational statistics by shed.

UDOT developed methodologies for incorporating the benefits to the traveling public of snow-plowing operations into the Snowplow Operations Dashboard. This dashboard initially visualized big data from two UDOT sources: Road Weather Information Systems (RWIS) and Automatic Vehicle Location (AVL). This research effort identified the best available methodology to reflect the potential snowplow operations-related benefits to safety and delay. It was initially anticipated that the methodologies for identifying benefits would be found within existing research studies, but suitable methodologies were not found. In the absence of a suitable methodology, UDOT worked to identify a method. The methods contained in this report had certain limitations and assumptions as defined herein. The results of these methodologies are published on the current UDOT Snowplow Operations Dashboard.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| AVL | Automatic Vehicle Location |
| FHWA | Federal Highway Administration |
| FY21 | Fiscal Year 2021 |
| RWIS | Road Weather Information System |
| TOC | Traffic Operations Center |
| UDOT | Utah Department of Transportation |

# EXECUTIVE SUMMARY

The Utah Department of Transportation (UDOT) is developing a dashboard that can display information regarding winter storm events. This project is focused on creating a one-stop shop for decision-making tools and will serve to inform operations managers who will be making decisions based on feedback from the dashboards. The recommendations in this report will help the Maintenance Operations management team understand their options for snowplow data management. Literature support and data collection methods had already been established in previous efforts, so this project focused on extending current knowledge into better and more integrated analysis tools.

Challenges remain for parsing largescale data, such as big-data collection issues and platform instability. Currently, the snowplow dashboard offers a simple view of the cost of operations and the associated benefits. Other tools (such as letter grade, duration, and maximum intensity) will be integrated when the platform is adequately stable and as other data enhancements are made.

UDOT developed methodologies for incorporating the benefits to the traveling public of snow-plowing operations into the Snowplow Operations Dashboard. This dashboard initially visualized big data from two UDOT sources: Road Weather Information Systems (RWIS) and Automatic Vehicle Location (AVL). This research effort identified the best available methodology to reflect the potential snowplow operations-related benefits to safety and delay. It was initially anticipated that the methodologies for identifying benefits would be found within existing research studies, but suitable methodologies were not found. In the absence of a suitable methodology, UDOT worked to identify a method. The methods contained in this report had certain limitations and assumptions as defined herein. The results of these methodologies are published on the current UDOT Snowplow Operations Dashboard. Future efforts may result in expanding and improving the methodology for purposes of developing a performance measure for snowplow operations.

# 1.0 INTRODUCTION

## 1.1 Problem Statement

The Utah Department of Transportation (UDOT) has difficulty conveying to the public all of the user benefits that result from UDOT's snowplow operations. This project is focused on communicating the importance to travelers of snowplow operations in terms of travel time saved and travel time improved vs. not plowing. This information will be added to the Snowplow Operations Dashboard that was developed previously to answer questions related to where and when snowplows had operated during a previous storm and will provide overall operational statistics by shed.

## 1.2 Objectives

The primary objective of this research project was to calculate the estimated operational costs and user benefits from snow-plowing operations through the use of iPeMS data, snowplow Automatic Vehicle Location (AVL) data, and Road Weather Information Systems (RWIS) data. The secondary objective was to provide the information on an online virtual dashboard.

## 1.3 Scope

By building on work performed in previous years, management was able to review a post-storm analysis of the estimated costs and benefits to the traveling public. This research project focused on creating a spot on the dashboard to capture these calculations as well as assessing prior efforts with the goal of further development into operational performance measures. Spatially, the scope includes the snowplow-shed management areas for the state and for state routes. Temporally, the data is collected and updated in real time for the state fiscal year units.

The primary intended audience of the dashboard are the operations managers who will be making real-time decisions based on feedback from the dashboards. However, because this is also an effort to steward state resources and ensure transparency, the actual audience may expand to include executive and legislative state leadership, UDOT executive management, and members of the public with an interest in government transparency.

### 1.4 Outline of Report

This report is divided into six sections:

- Introduction
- Research Methods
- Data Collection
- Dashboard Development
- Conclusions
- Recommendations and Implementation

# 2.0 RESEARCH METHODS

## 2.1 Overview

In the early stages of this project, it was anticipated that existing literature to support a method for costs and benefits would be available. During an initial literature review, it was clear that the desired literature support was lacking, and the needed benefit calculation methods would have to be developed from scratch. The main tasks to be accomplished included:

1. **Determining a data repository** for the storage and publication of the data;
2. **Developing data workflows** to support the calculation and display of the information;
3. **Determining methods for calculated metrics**;
4. **Determining the best configurable display application**; and
5. **Deployment, testing and refinement of** the information and display.

The timeline of developments of this project followed three major milestones. For the first of these milestones, the data repository was tested and adjusted for performance, and a literature review was completed. When the literature review determined that support for a methodology was lacking, the next milestone consisted of developing the metrics and methods by which the costs and benefits values would be calculated. This led to the final milestone, which was the effort to deploy the metrics, develop the display, and review the results using the dashboard.

While developing the dashboard, it was determined that, in addition to the nearly real-time estimated operational costs, the actual costs as recorded at a later date would also be displayed as a part of the dashboard.

Problems were encountered. For example, the GeoEvent Server workflow repeatedly failed, crashing the entire GeoEvent Server. After much effort and tweaks to find a working solution, this workflow was discontinued, and the dashboard no longer uses data from the

GeoEvent Server. Instead, a Python script captures and processes the AVL data directly from the geodatabase where it is stored.

## 2.2 Overall Methodology Assumptions

The first component of the methodology development was to identify the estimated costs based on the available data immediately following a winter storm. Several parameters had to be identified from existing data for this calculation. These include the following:

1. The area by which to summarize the costs for a storm, which was to be each shed maintenance area;

2. Storm timing, which was defined by an indication of snowfall from the RWIS sensors with an average snowfall rate of at least 1 inch per hour (an assumption was made that both RWIS data for snowfall and plow activity from the AVL data was necessary for a snowfall event to be considered a storm);

3. Personnel time definition, which was identified as a truck's beginning and end times, with an additional hour at each end of the work period to account for preparation and cleanup, multiplied by the average loaded wage rate of $35.64 (average pay rate of $20.24 with a loaded rate multiplier of 1.76);

4. Salt estimation cost, which was identified as the average application rate for salt at 250 pounds per lane-mile during the months of December and January, and half the spreading rate at 125 pounds per lane-mile during the months of November, February, and March, multiplied by the cost of salt associated with each shed location (these costs ranged from $18.52 to $69.24 per ton); and

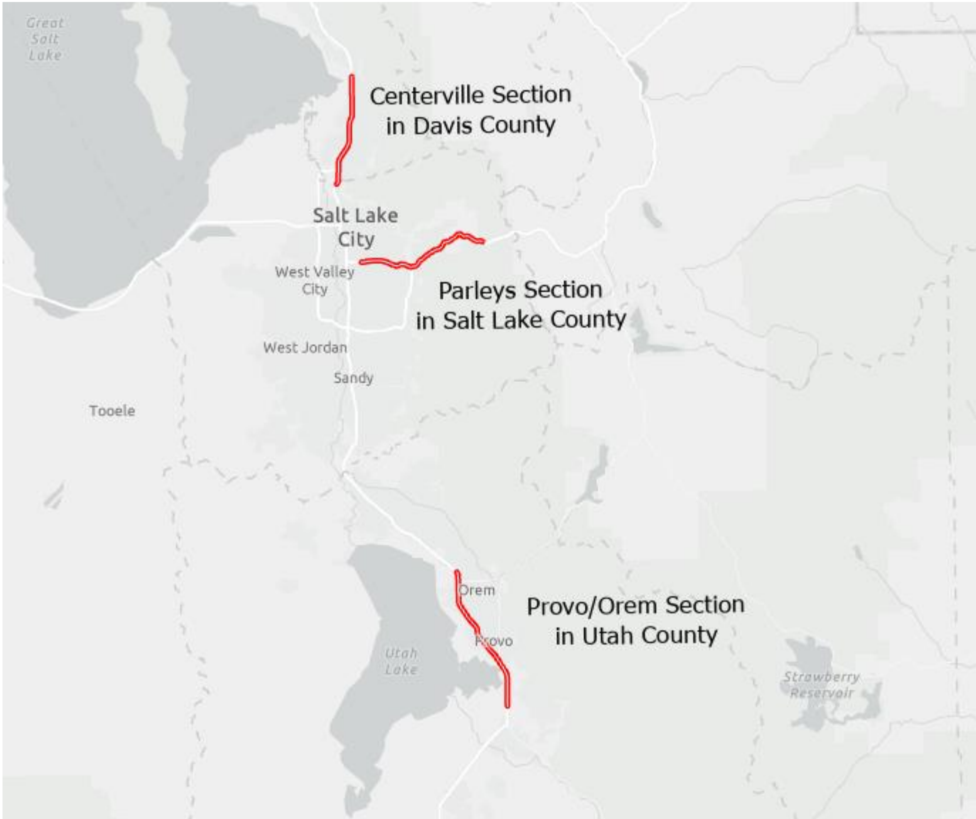
5. Equipment usage cost, which was calculated by equipment usage time multiplied by equipment cost per hour based on an average vehicle cost of $55 per hour (truck at $30 with head plow at $15, wings at $3.33, spreader at $3, and a tow plow at $30, which averaged $55 between all trucks).

To easily communicate the benefits of snow-plowing operations that accrue to travel time and safety, these benefits were also calculated in dollars.

To identify methodologies for benefits to travel time and safety, routes were selected for several data qualities. These included the following:

1. A consistent data history for multiple years;
2. Up-to-date, functioning sensors for the RWIS data;
3. High confidence in sensors for travel times and volumes; and
4. Varying geographic conditions with steady traffic in multiple locations of the state where snowfall during winter months is anticipated and where different maintenance crews are responsible for snow-plowing operations.

The routes used as a basis for developing the benefits methodology were U.S. Interstate 15 (I-15) in Centerville in Davis County, U.S. Interstate 80 (I-80) in Parleys Canyon in Salt Lake County, and I-15 in Provo/Orem in Utah County.




## 2.3 Travel-Time User-Benefit Methodology

The literature review to identify a published method for estimating travel-time savings to the traveling public did not support a methodology, so a methodology was developed from scratch. To develop the estimated benefits to the traveling public, based on the travel time saved due to snow-plowing operations, it was hypothesized that if the travel time under plowed conditions could be compared to the travel time in unplowed conditions, it would result in a quantification of travel-time savings. The challenge was that the routes are not left unplowed to allow for this calculation. Instead, it was determined that there is a particular gap in time between when a storm begins and when the plows can reach any particular area. This gap was used to generate a comparison in the Storm Intensity Index and the anticipated delay.

This methodology relies on the following analysis and assumptions which developed a correlation between the Storm Intensity Index and a particular travel time:

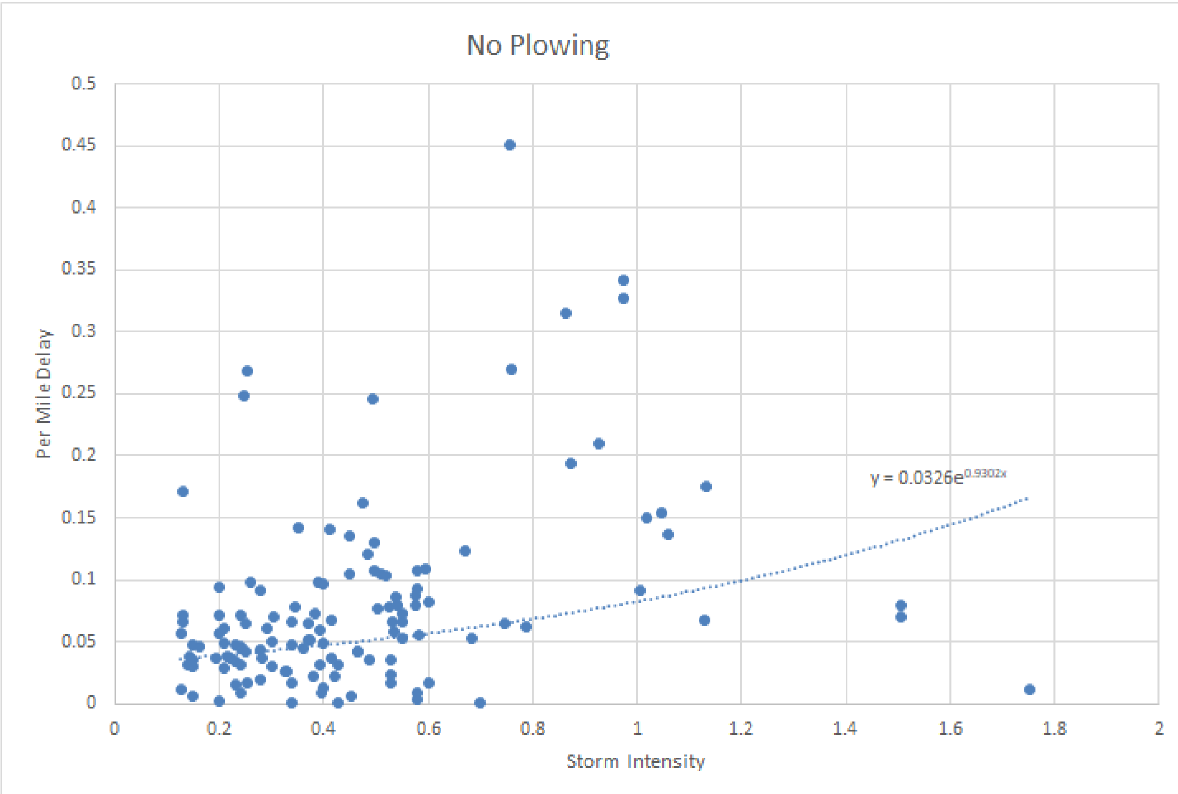
1. Travel-time delay was calculated as the difference between the actual travel time and the average travel time.

2. The delay per mile for each segment was calculated and standardized for application to other segments.

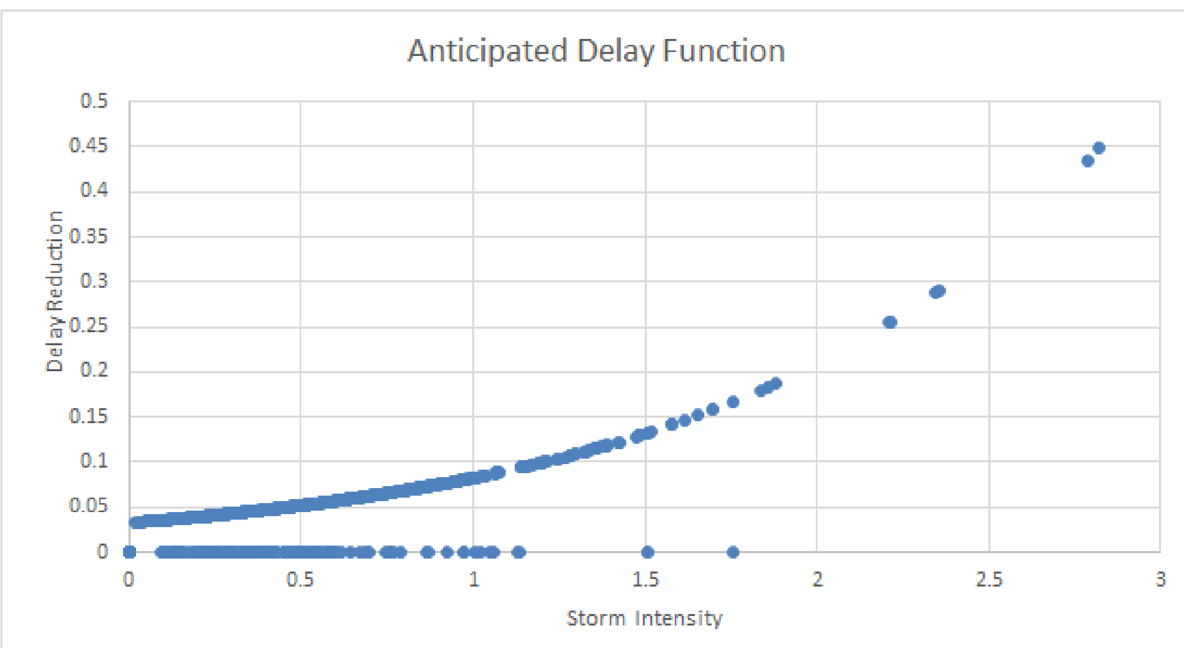
3. High variability in delay by storm intensity was observed. Higher than average delays are likely due to conditions other than storm intensity, such as, crashes, visibility, and the snowplowing itself.

4. A hypothesis was made that delay will increase with increasing storm intensity in the absence of snow-plowing operations.

5. Using available data for certain storm time periods that had no snowplowing of identified routes, a scatterplot of the relationship was examined. Again, high variability in delay by storm intensity was observed. An exponential trendline based on these data provided an initial representation of the assumed/hypothesized relationship.




6. The formula from this trendline was used to calculate an amount of delay due to storm intensity that would be reduced by snow-plowing activity for the given level of storm intensity per vehicle per 10 minutes.



7. The delay reductions are a subset of total delay. This is expected because of the high variability in delay, but it likely underestimates the total delay that would be caused by unplowed roadways during storms.

The method uses the Storm Intensity Index to identify the anticipated reduction in delay per mile. This is based on the above formula and multiplies this delay in reduction by the following parameters based on the percentage of traffic composition for a particular route:

1. Passenger vehicles at a value of $17.67 per hour, per person, with a vehicle occupancy for each passenger car assumed at 1.2 people (this is based on collaboration between subject matter experts at UDOT) for a value of $21.204 per 60 minutes or $0.3534 per minute;

2. Trucks at a value of time of $94.04 per hour; and

3. Vehicle running costs assumed at $3.5 per gallon of fuel with a fuel efficiency of 20 miles per gallon or $0.175 per mile.

Additionally, during a storm, it is anticipated that there is also a loss in productivity for the trips that are not taken due to storm intensity. To account for these trips, the average traffic volumes were compared to traffic volumes during storm days before snowplowing began, and it was determined that traffic volumes were reduced by 20 percent. The reduction in the loss of productivity for the trips not taken was based on the estimated trip reductions, which was calculated based on 20 percent of the average volume multiplied by the above values per person for an 8-hour workday.

To validate this formula, we calculated the anticipated delay reduction and compared the results to the actual delay observed. For the Centerville location, 20 minutes of delay reduction from snow-plowing operations was estimated, and the total observed delay in the data was 105 minutes. For the Parleys location, 36 minutes of delay reduction from snow-plowing operations was estimated, and the total observed delay in the data was 325 minutes. For the Provo-Orem location, 14 minutes of delay reduction from snow-plowing operations was estimated and the total observed delay in the data was 318 minutes. Any crashes in the data may account for large delays, but even so, these results are likely a conservative estimate of delay reduction. Without the exception of summing delay, a method to account for the persistence of delay from the lack of snow removal over multiple days for a given storm intensity has not been identified.

### 2.4 Safety User-Benefit Methodology

During the literature review, the best information discovered was included in a brochure for the Roadway Safety Foundation of an unknown date that referenced a Marquette University Study with no publication information. This brochure stated that there was an 88.3-percent reduction in crash frequency and an individual crash-cost reduction of 10 percent. This publication also stated that deicing pays for itself within the first 25 minutes after salt is spread, and that, during the first 4 hours after salt is applied, the direct road-user benefits are $6.50 for every $1.00 spent on direct maintenance costs for the operation. This did not correlate directly to snow removal, but to the deicing usually associated with snow-plowing operations. With the unknown publication date and details, it was determined that another method would need to be employed to generate the needed information. The UDOT Traffic and Safety group proposed a method based on the following assumptions:

1. UDOT's Storm Intensity Index correlates with pavement surface condition; and

2. Current snow-plowing efforts result in the improvement of one level of surface condition.

Using these assumptions and applying the resulting crash-modification factors (CMFs), the perceived benefit in crash reduction could be calculated. This calculation uses the following parameters:

1. Median Storm Intensity Index and anticipated CMFs;

2. Reduction of AADT for the given storm event; and

3. The predicted crashes per day based on historical trends for the route segments plowed.

These parameters are used to identify the anticipated reduction in crashes based on the CMF application of the pavement surface condition correlated to the Storm Intensity Index. This was prorated for the duration of the storm and snow-plowing operations, and multiplied by the cost of individual crashes based on type. Additional details can be found in Appendix A: Safety Benefit of Snow-Plowing Efforts on Utah Highways Memorandum.

### 2.5 Summary

The methodology outlined above resulted in a functional dashboard with features that are usable as a post-assessment of snowplow operations costs and benefits for any given storm in both mobile and desktop formats. The following sections detail the data processing and generation of the dashboard display.

# 3.0 DATA COLLECTION

## 3.1 Overview

This research project does not generate any new data; rather, the goal was to create a more usable output and employ calculations for performance metrics for the data that is already collected by UDOT. The following sections contain descriptions that mostly concern the adaptation of these existing sources into a usable output.

## 3.2 Snowplow Location

The first attempt for a stable dashboard used the following workflow. As snowplows are running, location information is periodically recorded and made available via Verizon's NetworkFleet API. Esri's ArcGIS GeoEvent Server automatically receives the location information, converts it into GIS points, and saves the data in a Spatiotemporal Big Data Store database. The data are pushed out as an Esri Feature Service named "AVL_Storage." The data are then filtered into a view named "FY21_Snowplow," which contains only snowplow locations during the fiscal year 2021 (FY21).

This workflow proved unsustainable. It resulted in frequent breakdowns, so a different workflow was established.

UDOT was also saving snowplow location data obtained from Verizon's NetworkFleet into a file geodatabase. A new workflow was developed using a Python script to pull the data from the geodatabase, clean the data by removing duplicates recorded in error, and appending it to a feature-class on Portal named "Snowplows21."

### 3.3 Supporting Data

For the first attempt, supporting data were gathered, prepped, and published as a Feature Service named "Support_Data." These data contain RWIS station locations, maintenance shed information, snowplow components, and equipment rates.

Now the supporting data are included in the "SnowDash21_lines" Map Image Layer along with the location data.

### 3.4 Benefit Calculation

As described in detail in the previous section, this research developed formulas to estimate the dollar benefit of reduced travel-time delays and reduced crashes that result from snow-plowing operations.

#### 3.3.1 Avoided Crashes Benefit

Historical crash and storm data were analyzed. The analysis produced the following formula to estimate the dollar amount of avoided crashes from snow-plowing operations:

Fi_Pre_Perday * (CMF – CMF_Stepdown) * KABC_Crash_Cost = $ Avoided Crashes Benefit

*Where:*

Fi_Pre_Perday: Calibrated predicted total winter snowplowing fatal and injury crashes per day during the winter plowing seasons.

CMF: Crash Modification Factors, the roadway condition based upon storm intensity.

CMF_Stepdown: The next lower CMF.

KABC_Crash_Cost: $345,000. The dollar amount of crashes.

#### 3.3.2 Reduced Delays Benefit

Storm times and intensity, vehicle hours of delay, and snow-plowing times of sample storms were analyzed. Delay data without snowplowing are very scarce; it is the delay that happens after a storm starts and before snowplows arrive. Correlation analysis found a correlation between storm intensity and delay.

Here is the formula to estimate the dollar amount of reduced delays from snowplowing:

(Delay Hours * Truck Percent * Truck/Hour Dollars) + (Delay Hours * Car Percent * Car Occupancy * Car Hour/Dollars) = $ Reduced Delay Benefit

*Where:*

Delay Hours: 2019 AADT * Delay Factor

Delay Factor: a parameter calculated from the correlation trendline of $y=0.0326e^{0.9302(\text{storm intensity})}$

Truck Percent: 0.159

Car Percent: 0.841

Car Occupancy: 1.2

Truck/Hour Dollars: $94.04

Car/Hour Dollars: $17.67

# 4.0 DASHBOARD DEVELOPMENT

## 4.1 Overview

This section is divided into two parts: the preprocessing steps required to set up the dashboard and the configuration of that dashboard.

## 4.2 Data Preprocessing

All the data needed to run the dashboard are in a Map Image Layer named "SnowDash21_lines." The data are updated via the 12 Python scripts that are currently run manually.

### 4.2.1 Python Scripts

The purposes of the 12 Python scripts are described below, and corresponding numbers are on the workflow diagram for reference.

Script #1 gets the snowplow location point data, cleans and prepares them by removing duplicates.

Script #2 uses the snowplow location data to identify the days that snowplows were active and adds a row for each snowplow and day in the cost table.

Script #3 uses the supporting data to estimate personnel, salt, and equipment costs and adds these estimates to the corresponding cost table rows.

Script #4 uses RWIS data from an Oracle database (#3a) and from the supporting data (#3b) to prepare RWIS points to show snow intensity on the dashboard map.

Script #5 uses RWIS data now in the RWIS prepped table and the snowplow active days now in the cost table to determine storm events and save the storm events in a table named "Storms."

Script #6 assigns the storm event ID to the cost table thereby relating the data together.

Script #7 assigns the storm event ID to the RWIS prepped data thereby relating the data together.

Script #8 converts the location points to lines, routes plowed, greatly reducing the data the dashboard map must display.

Script #9 assigns the storm event ID to the plowed routes data, thereby relating the data together.

Script #10 calculates the estimated benefit of snow-plowing operations.

Script #11 uses UDOT's accounting data to calculate the actual cost to date of UDOT's snow-plowing operations.

Script #12 conducts database maintenance and indexing of the data ensuring the data are ready for consumption in the dashboard.

Conceptually, the workflow follows the path shown in figure 4.2a.

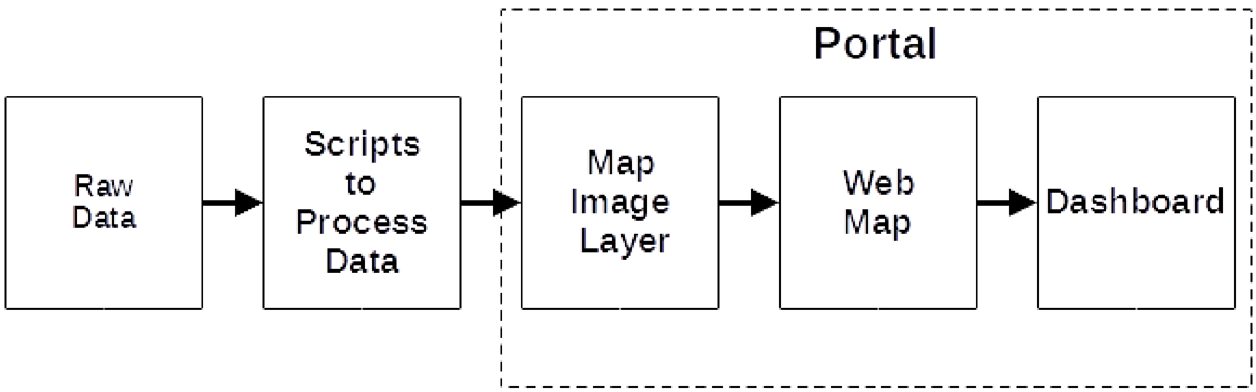



**Figure 4.2a Conceptual Workflow**

The workflow in actuality is more complex. The following diagram (Figure 4.2b) shows the workflow with more of the components, showing how the scripts prepare and relate the data.

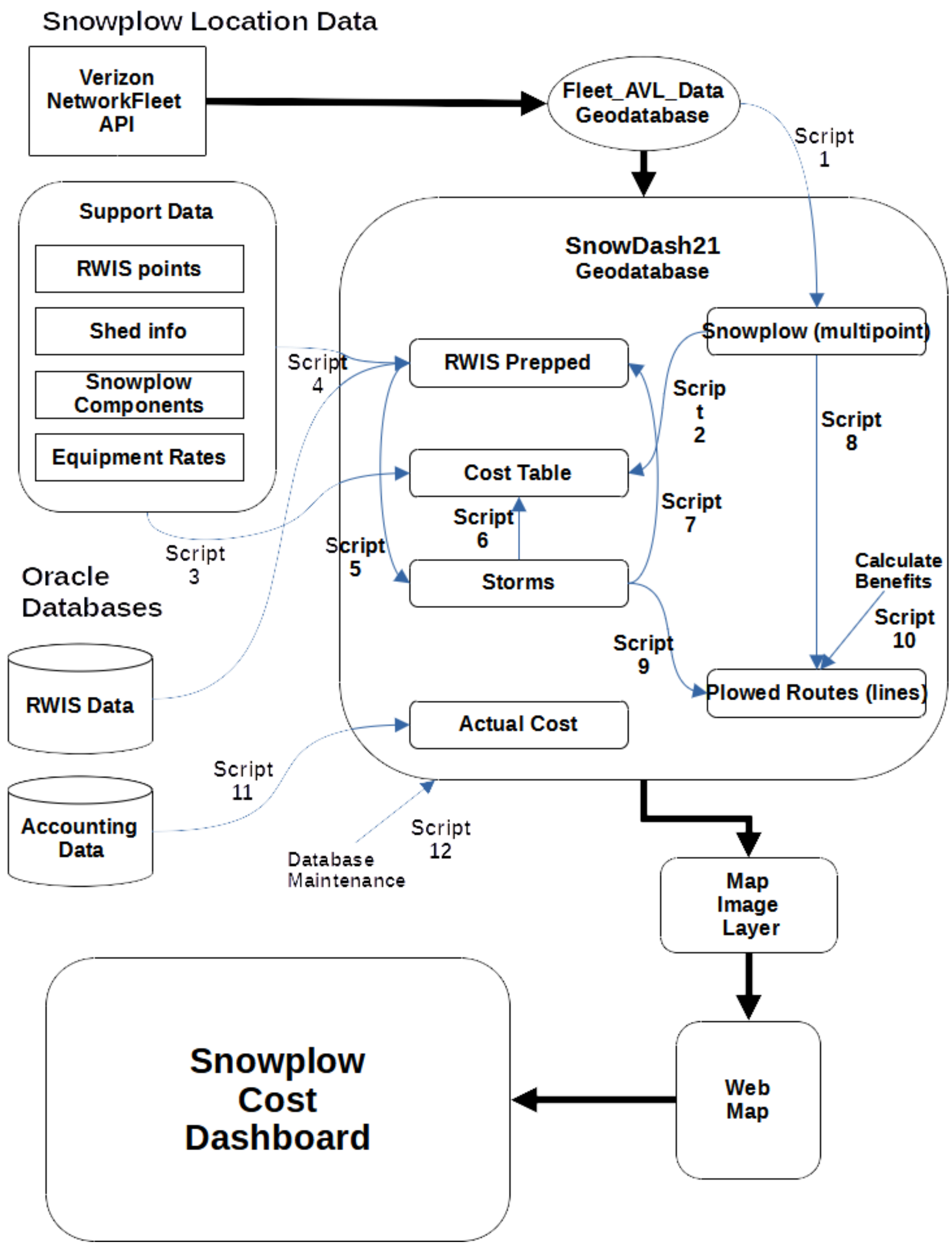



**Figure 4.2b Workflow for Preprocessing Dashboard Data**

## 4.3 Configuring Dashboards and Final Result

A web map was created that contains the FY21 data. This map "drives" the dashboard, meaning the map is the primary connection to the data that are summarized as statistics in other frames within the application.

When using the snowplow dashboard, a user can select a storm event to view the estimated personnel costs, salt costs, and equipment costs in their respective frames along the left-hand side of the page. Below that, the three costs are summed into a total cost, which is the estimated snow-plowing operations costs for that storm. The map updates to show the snowplow locations for the selected storm, and it displays an overview of snowfall intensity as a map overlay. The bottom-most frame shows the official year-to-date cost of snowplow operations given by the Comptroller's office. Finally, the frame directly below the map sums the benefits of snowplowing.

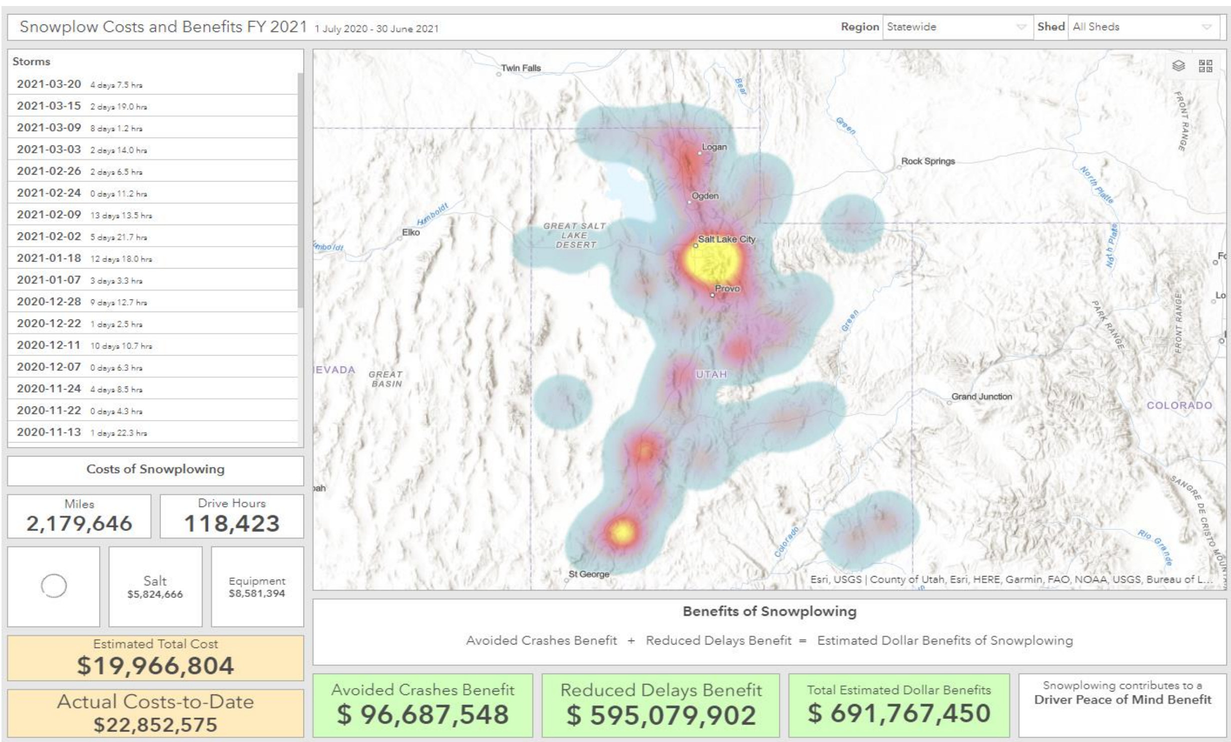



**Figure 4.3 Dashboard Overview**

# 5.0 CONCLUSIONS

## 5.1 Summary

The snowplow dashboard concept holds promise for management at varying levels within UDOT and for transparency purposes outside of UDOT. However, challenges remain, such as big-data collection issues and platform instability. These are discussed in detail below.

## 5.2 Findings

The current snowplow dashboard helps to identify where costs are being accrued relative to storm locations and snow-plowing operations. The dashboard also has the potential to align the costs with the performance analysis, establishing a cost-benefit ratio that could help improve overall effectiveness of winter-maintenance activities. By rolling this cost analysis into the "War Room concept", the general data infrastructure can be leveraged into the big-picture perspective and performance measures that UDOT desires.

## 5.3 Limitations and Challenges Overcome

The very large volume of snowplow location points causes difficulties for the dashboard, both in data preparation and in display. Many hours and attempts were required to develop a working dashboard.

First a workflow using Esri's ArcGIS GeoEvent Server was tried to receive, process, and store the storm locations. While a dashboard was created with this workflow, the ArcGIS GeoEvent Server crashed often, bringing the Feature Services and dashboard down. Because GeoEvent uses UDOT's Esri Portal hosting, whenever the ArcGIS GeoEvent Server goes down, any hosted Feature Service also goes down, even if it is not connected to the ArcGIS GeoEvent Server. Even after many hours and attempts at solving this problem, the reality is that it simply doesn't work with the current architecture and configuration. This resulted in developing an alternative workflow that does not use GeoEvent Server.

It took time to identify, locate, and connect all the data pieces needed for the dashboard. Once the connections were established, the next challenge was the difficulty involved in establishing an automatic daily update. A potential solution tried was to embed the Python scripts in an FME project, which would be scheduled to run once a day. However, UDOT's current FME server does not support projects with the latest version of ArcGIS Python scripts. Because of this, the Python scripts must be run manually each day.

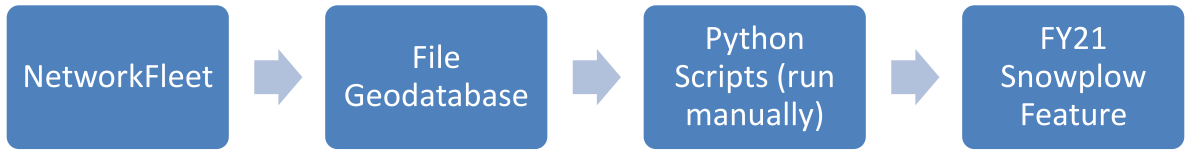
Recently UDOT added an Esri feature to Portal called Notebooks, which provides a way to store and run Python scripts in Portal. This is a potential solution to the automatic daily updates of the data. Theoretically, the scripts could be rewritten, stored in Notebooks on Portal, and scheduled to be run daily.

Finally, the large volume of snowplow location points hinders the user's experience. Because Esri's products display only a certain number of points (usually 1,000) on a web map, the user cannot view the entire state and see all the snowplow location points for a given storm. The map just "bogs down" and does not show all of the points. This also causes the dashboard to be sluggish, which further degrades the user experience. Therefore, a script was written that transfers the points to predetermined route lines. A template data layer holds ALRS routes segmented into 5-mile segments. If snowplow location points correspond to a route segment, then that segment is added to the data used in the dashboard for that day.

<u>5.3.1 Workflow</u>

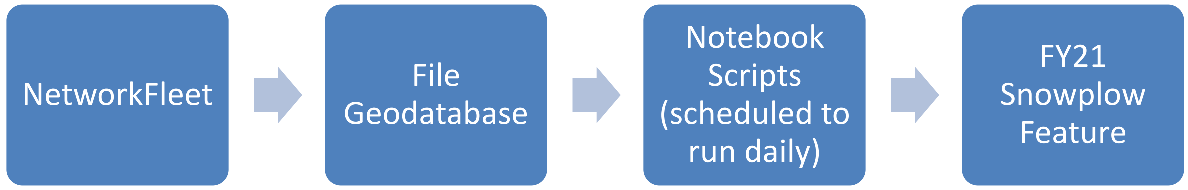
Because the initial workflow was not consistently stable, a new workflow was created. Instead of this workflow:

The following workflow is now used:




But this new workflow is not automated, so the workflow will likely change again. Notebooks in Portal seems to be a good option to schedule automatic updates to the data that drives the dashboard.

The following is a potential workflow:



# 6.0 RECOMMENDATIONS AND IMPLEMENTATION

## 6.1 Recommendations

Our first recommendation is to continue to explore ways to make the dashboard more stable. Some possible methods to achieve this are listed below.

- Use the alternative method for processing the massive amounts of snowplow location points. Bypass GeoEvent, at least until a stable installation is available.
- Avoid hosted Feature Services. Instead, store the data on UDOT servers and publish the services to Portal using data stores.
- Use collated lines to show snowplow locations instead of individual data points, unless scale thresholds are set for points.

The next recommendation is to further refine the methodology for benefit calculation, and generate a performance measure that represents snowplow operations performance in a relatable manner.

## 6.2 Implementation Plan

There are some items as discussed above that should be addressed. The current proposed implementation could proceed as shown on the next page:

**1. Technology Improvements**

- Update FME server to allow daily automatic updates through Python.
- Adopt alternative data processing to facilitate a smoother big-data processing path.

**2. Presentation and Education**

- The Maintenance Operations group will share the dashboard internally for feedback and education on how to use the dashboard and upcoming improvements.

**3. Ongoing Updates**

- Continue to resolve big-data architecture issues to implement the remaining War Room dashboard goals.
- Monitor for changes in big-data capabilities and propose updates as possible.
- As updates are made, the results are integrated into tools and education, and feedback continues in a loop.

**4. Develop Performance Measure**

- Refine the current methodology for benefit calculation.
- Develop a working group to explore a performance measure to communicate snowplow operations performance in a relatable manner

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MEMORANDUM

July 10, 2021

**TO:** **Jeff Lewis, P.E., Safety Programs Engineer**

**FROM:** Dallas Wall, P.E. WCG, Safety Analyst

**SUBJECT:** **Safety Benefit of Snow Plowing Efforts on Utah Highways**

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## Introduction

UDOT's Maintenance Division is working with the Traffic and Safety Division to estimate the safety benefit of their ongoing snowplow/deicing efforts. This memo documents the processes, estimates, and assumptions used to estimate the safety benefit. A Crash Prediction Model for plowing (CPMp) was created in order to estimate these benefits in a near real-time basis. This model does not predict the number of crashes that occur in each snowstorm. Rather the CPMp estimates the average number of crashes that might be expected if no plowing efforts were employed compared to the average number of crashes occurring with current plowing efforts. The estimate is based on a daily effort of snowplowing/deicing during a storm event. These estimates are based on a series of sub-estimates, averages, and assumptions that will be outlined herein. This process was developed based on the available data and only represents a starting point where future research might enhance the estimates contained herein.

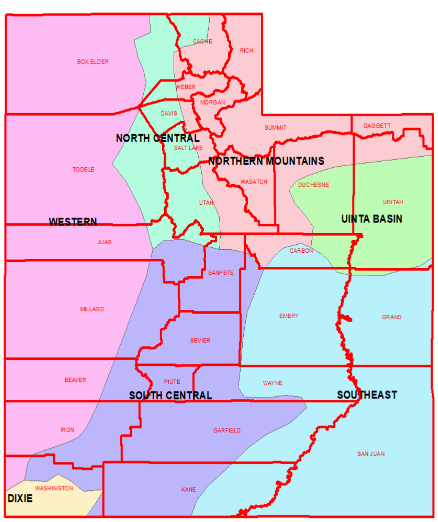


**Figure 1 Utah's Seven Microclimates**

## Winter Storm Events and Plowing Efforts

Figure 1 shows the 7 microclimates as defined by the Department's Traffic Operations Center. These microclimates were generated with weather stations throughout the State and represent zones with different weather patterns. These microclimates are used in the CPMp to help calibrate the observed crashes by roadway type.

A sample of storm readings were provided by the Traffic Operations Center to find a correlation between the storm intensity index and the pavement surface condition. A "0" reading of the storm intensity index was assumed to represent a "no storm event" and was eliminated from the analysis. Figure 2 shows a relationship between storm intensity index

**Assumption:** Storm intensity index correlates with pavement surface condition.

and the pavement surface condition. Figure 2 uses the median storm intensity index. The median is close to the average on a normal distribution but less likely to be effected by extreme events. In the original analysis "icy" pavement conditions were included in Figure 2. However, its median storm index was lower than both snow and slushy conditions. It was assumed that true icy pavement conditions are not directly related to storm intensity but other conditions on the roadway. Furthermore, the measurement of icy conditions would not truly reflect the base assumption that roads that did not get plowed would result in icy conditions. For the purposes of this analysis a extrapolated value was determined for icy conditions that might occur for the most intense storms where no plowing would occur.

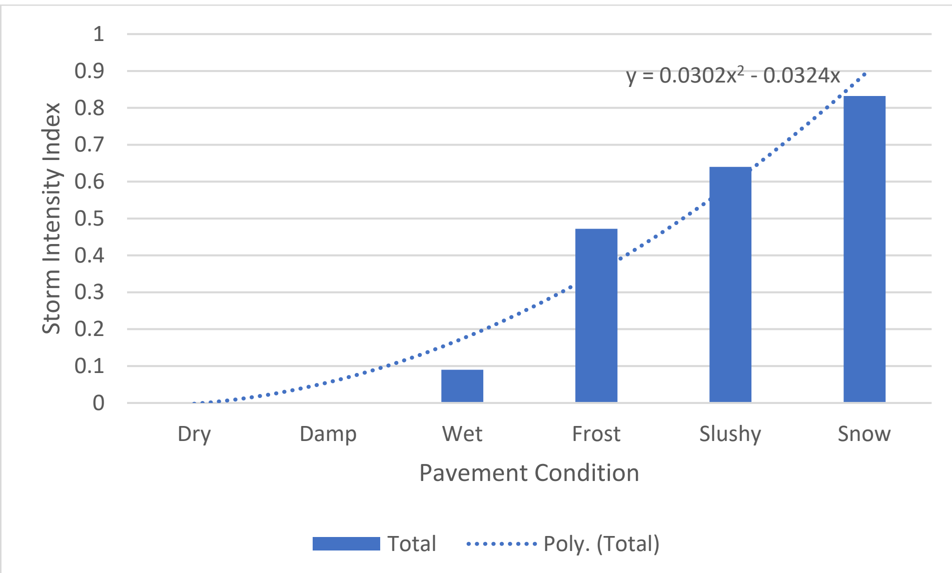


**Figure 2 Utah Relation between Storm Intensity Index and Pavement Surface Condition**

## Safety Benefit Calculation

Safety benefit for a particular countermeasure is calculated using Equation 1:

$B_p = (N_0 - N_p)\, C_{KABC}$ **Equation 1**

$B_p$ = Safety benefit of plowing.
$N_0$ = Crash frequency if no plowing effort was implemented.
$N_p$ = Crash frequency when plowing is implemented.
$C_{KABC}$ = Average Cost of crashes for fatal and injury crashes.

$N_0$ will be calculated by applying a CMF to the $N_p$ . $N_0$ represents the crashes that would have occurred if no plowing effort was implemented. $N_p$ is the predicted crash frequency with UDOT's current plowing effort. This will be discussed below in the crash modification section below.

Crashes occurring during winter adverse pavement conditions (wet, standing water, slush, snow, or ice) are less severe than the typical crash severity distribution. This is assumed to be attributed to the reduction of vehicle speed during winter events. Because they are less severe a recalculated crash cost value will be used for this model to estimate the benefits more accurately. Recalculating the crash costs for winter adverse pavement conditions estimates the typical fatal or injury crash cost of $345,000.

## Predictive Modeling

Predictive modeling is used to estimate the average crash frequency to a given segment based on the overall average number of crashes for similar roadway segments. The CPMp was segmented based on the 2019 striping asset management inventory. This was done for convenience of other models being developed concurrently by Traffic and Safety. For the purposes of this analysis the Safety Performance Functions (SPFs) from the Highway Safety Manual (2010, 2014) were used to calculate the crash frequency of fatal and injury crashes (KABC) for both multi-vehicle and single vehicle crashes. For simplicity, no CMFs in part C of the HSM (also known as “adjustment factors”) were applied to individual roadway segment SPFs. SPFs were then multiplied by the following factors to get $N_p$ (crash frequency with powing). Equation 2 shows the base predictive equation including the SPF:

$$N_{fi,mv,winter} = D\, S_{Dist}\, e^{(a + b\, ln(c\, T_{Reduced}\, AADT)\, + ln(L))} \quad \textbf{Equation 2}$$

D = Divided roadway factor; 1= undivided, 0.5 = Divided. The SPFs in the HSM calculate the crash frequency in both directions of travel on divided highways, however, the CPMp segments divided roadways in both directions to correspond to the crashes which are reported by direction of roadway.

$S_{Dist}$ = Severity distribution factor; rural two-way two-lane roads = 0.2962, all other roadway types = 1.0. The SPFS for the HSM were developed for KABC crashes except the SPF for rural two-way two-lane roads. This factor is applied to adjust the SPF accordingly.

a, b, c = curve fitting variables as published in the HSM for a given roadway type and KABC crashes.

$T_{Reduced}$ = AADT adjustment factor to account for the reduction in travel during a storm event. This variable will be provided by UDOT Maintenance as estimated for storm intensity.

AADT = Annual Average Daily Travel, 2019 as reported by UDOT.

L = Length of the roadway segments.

Equation 2 represents the predicted number of multivehicle KABC crashes that occur during the winter plowing season i.e. crashes per season. Equation 2 is also used for single vehicle crashes ($N_{fi,sv,winter}$) for each roadway segment by adjusting the SPFs for single vehicle crashes (i.e. applying the appropriate curve fitting veriables). The sum of $N_{fi,mv,winter}$ and $N_{fi,sv,winter}$ provide the total KABC (i.e. $N_{fi,tot,winter}$) crashes for the winter plowing season.

### *Calibration*

For the purposes of this analysis, only roadway segment crashes were considered in the calibration effort. Crashes that have been classified as “intersection related” were not used in calibration. Calibration is applied to the $N_{fi,tot,winter}$ based on both the roadway type and the microclimate shown in Figure 1. The observed winter plowing season crashes (November – February) of each roadway segment is compared to the predicted value. There are a few roadway microclimate/segment types that did not have any winter weather crashes in the 5-year history. It is assumed that these segments do not require snowplow/deicing efforts and result in a zero plowing benefit. The calibrated value is then divided by 119 days, to convert the $N_{fi,tot,winter}$ to a daily crash frequency (i.e. $N_{fi,tot,winter,daily}$).

## *Crash Modification Factors*

Crash modification factors (CMF) are multipliers used to predict how a roadway condition impacts the crash frequency for a given change along the segment. The CMFs used in this analysis are based on research done by Fu and Usman (2014). CMFs are based on pavement surface condition and the resulting number of crashes that would occur. Table 1 shows the estimated CMFs based on research and the storm intensity indexes shown previously in Figure 2. Added categories were extrapolated for both storm intensity and related CMFs.

**Table 1 Relationship between Storm Intensity Index and Resulting Crash Modification Factors.**

| Level | Storm Intensity Index Range | Assumed Surface Condition | % Reduction If Dry Condition | CMF (Currently Dry / Previously Wet) | CMF (Currently Wet / Previously Dry) |
|---|---|---|---|---|---|
| **0** | 0-0.04 | Dry | 0 | 1 | 1.00 |
| **1** | 0.04-0.16 | Damp | 12 | 0.88 | 1.14 |
| **2** | 0.16-0.34 | Wet | 23 | 0.77 | 1.30 |
| **3** | 0.34-0.59 | Frost | 32 | 0.68 | 1.47 |
| **4** | 0.59-0.74 | Slushy | 40 | 0.6 | 1.67 |
| **5** | 0.74-0.89 | Partly Snow Covered | 54 | 0.46 | 2.17 |
| **6** | 0.89-0.97 | Snow Covered | 73 | 0.27 | 3.70 |
| **7** | 0.97-1.05 | Snow Packed | 84 | 0.16 | 6.25 |
| **8** | 1.05+ | Icy | 87 | 0.13 | 7.69 |

**Assumption:** Current plowing efforts result in the improvement of 1 level of the surface condition e.g. a storm that would have resulted in partly snow covered roads (5) actually only reached a slushy level (4).

A preliminary assessment was investigated to determine the change in crashes given our current plowing methods during the winter plowing season along I-15 in Salt Lake County. This analysis suggested that crashes increase by 30% during winter storm events based on UDOT’s current plowing/deicing efforts. UDOT’s current performance goal for snow plowing/deicing efforts is to maintain freeway segments with 2-3 lanes open (wet conditions) for a typical storm event. This independent assessment seems to correspond to the results in Table 1 i.e maintaining rowadway surface conditions to a wet standard results in a CMF of 1.3 or a 30% increase. The median storm intensity index for the analysis was 0.40 which would correspond in Table 1 to an assumed surface condition of “frost”. This suggests that UDOT’s current plowing effort lowers the assumed surface condition by 1 level e.g. a storm event that would have left the pavement frost covered (3), resulted in wet conditions (2). This level of performance becomes a critical assumption to the calculation of the CPMp.

## *Example Calculation*

The following logic is used by the CPMp to calculate the change in crashes and the corresponding safety benefit due to the plowing/deicing effort:

$B_p = (N_0 - N_p)\, C_{KABC}$ **Equation 3**

$N_0 = N_{fi,tot,winter,daily} CMF_{no\ plow}$
$N_p = N_{fi,tot,winter,daily} CMF_{plow}$
$C_{KABC}$ = $345,000

By combining terms, the benefit calculation is:

$$B_p = 345{,}000\ N_{fi,tot,winter,daily}(CMF_{no\ plow} - CMF_{plow})$$

For a storm that had a median storm intensity index of 0.40, in Salt Lake County on mainline I-15 (MP 286-312.6, mainline only) the daily plowing benefit would be as follows:
$N_{fi,tot,winter,daily}$= 2.06 crashes
$CMF_{no\ plow}$ =1.47
$CMF_{plow}$ =1.3

Safety benefit = 345000 x 2.06 x (1.47-1.3) = $121,000 per day

**Key Concept:** Safety benefit is calculated by day, not based on each time a snowplow touches the roadway segment.

The CPMp is based on predicted crashes per day. Because storms are of various durations (1 day, 3 days etc). The benefit is calculated daily for the plowing/deicing efforts that were performed for the storm event that day. If the same segment was plowed twice in one day, only one benefit calculation is made for the day. If a segment was plowed each day for three days, the benefit would be calculated for consecutive 3 days. The safety benefit of plowing/deicing for a storm with a median storm intensity index > 1.05 would be about $1.0 million per day. Note that in the previous example assumed that UDOT Maintenance has determined that a 0.4 storm intensity index results in no reduction to the number of trips per day.

## Implementation

The example above only addressed one storm event on one roadway segment. The CPMp should be applied to all routes that were plowed during a storm event. Implementation logic of the CPMp is outlined as follows:

1. During a storm event (based on geo-location for given RWIS and associated routes), segments addressed by snowplows are flagged as having been plowed.
2. Post process (based on geo-location for given RWIS and associated plowed routes) for each day.
    a. Determine the daily median storm intensity index for each segment that was plowed (exclude zero reports) and use as follows:
    b. Calculate reduction in travel demand (independent of CPMp).
    c. Determine the AADT reduction (i.e. $T_{Reduced}$ = 1- % Reduced from previous step).
    d. Look up Level/CMF of storm event from Table 1 based on the storm intensity index ($CMF_{no\ plow}$).
    e. Determine the CMF due to current plowing effort (i.e. $CMF_{no\ plow}$ Level -1, and get corresponding CMF from Table 1, this becomes $CMF_{plow}$).
    f. Calculate the $N_{fi,tot,winter,daily}$ for each segment that was plowed.
3. Sum safety benefit of all plowed roadway segments.

$$Safety\ Benefit = \$345{,}000\ x \sum_{All\ Segments}\left(N_{fi,tot,witner,daily}\left(CMF_{no\ plow} - CMF_{plow}\right)\right) \quad \textbf{Equation 4}$$

## Model Documentation

The CPMp consists of an Excel spreadsheet that requires the following inputs from the UDOT Maintenance:

- Median Storm Intensity Index from the RWIS stations and the geographic area that that reading represents.
- The reduction of AADT for the given storm event. This is expressed as a multiplier to the current AADT. If the storm is anticipated to reduce the travel by 20% then $T_{Reduced}$ = 1 – reduction, or an 80% multiplier.
- The routes segments that were plowed that day.

All other values are calculated in the model. The following list of fields for the CPMp is provided with a description of the contents:

| Field Name | Description |
|---|---|
| **ROUTE** | Standard route name with direction of route for divided segments. P = positive, N = negative |
| **MainRt** | The route number. For ramps this only includes the mainline route number |
| **Direction** | Direction of route P = positive, N = negative. |
| **ExitID** | The exit number associated with an off/on ramp |
| **RAmpID** | Ramp ID number |
| **Ramp** | True/false; any record with an exit number or ramp number, other than 0, is a ramp. |
| **START_ACCUM** | Starting mile point of the segment. This is based on the ALRS |
| **END_ACCUM** | Ending mile point of the segment. This is based on the ALRS |
| **Length** | The length of the segment in miles |
| **PDirBMP** | The nearest beginning $10^{th}$ of a mile point in the positive direction of the route. This was used because the crash data does not currently use the ALRS so negative direction route's mile point would not correspond to the crash data. |
| **AADTBMP** | Identifier to extract the AADT for the given roadway segment. UDOT reports AADT for both directions of travel, direction in ignored. |
| **OBJECTID** | A unique identifier for each record |
| **MLObjectID** | An identifier that uses the mainline milepoint. The number is the same as the OBJECTID for most segments, however, for ramps it uses the exit number as the mile point. |
| **REGION** | UDOT Region |
| **BEG_LONG** | Longitude of the beginning point of the segment |
| **BEG_LAT** | Latitude of the ending point of the segment |
| **Posted Speed Limit** | Posted speed limit for the segment based on the 2019 speed limit data. For ramps the MLObjectID is used to get the speed limit of the main line. |
| **Median** | Median type |
| **TWLTLPresent** | Whether a two-way-left-turn-lane was present. This data was used to help QC the data. |
| **IsUrban** | True/false; is this classified as Urban or Rural |
| **IsFreeway** | True/false; is this segment a freeway |

| Field Name | Description |
|---|---|
| **HSMPredictMultiplier** | This corresponds to the variable “D” in Equation 2. This is the multiplier of whether the roadway is divided or not. The HSM calculates crashes on divided highways for both directions, however this model lists both N and P directions separately so the results must be halved for divided highways but not for undivided highways. It should be noted that UDOT is not consistent with their definition of a divided highway, so this is applied based on whether the route has a “N” direction or not. |
| **MLAADT** | The 2019 AADT for each segment, 2018 AADT for the ramps. |
| **AADTStormReduction** | **INPUT PROVIDED BY UDOT MAINTENANCE.** This is the multiplier representing the proportion of the AADT that will be traveling due to the intensity of the storm event. If the reduction in travel will be 20% the multiplier would be 80% (i.e. 1-reduction). |
| **Lanes** | Number of lanes |
| **HSMSPF_Filtered** | The roadway type based on urban/rural, number of lanes, and the median type. This field is used to calibrate the model. It should be noted that a 6T configuration is the filtered type for calibration. But the there is no SPF in the HSM for the 6T configuration. |
| **HSMModelAs** | What roadway type the segment will be assigned to so that an HSM SPF can be assigned. A 6T configuration would be calibrated with other 6T roadway segments but it will use the SPF of the 5T. |
| **RV_Address** | Roadview hyperlink address |
| **RVLink** | Roadview hyperlink |
| **GMapAddress** | Google Maps hyperlink address |
| **GM_Link** | Google Maps hyperlink |
| **FI-MV-Intercept** | SPF intercept variable from the HSM for KABC multivehicle crashes |
| **FI-MV-Slope** | SPF Slope variable from the HSM for KABC multivehicle crashes |
| **FI-MV-AADT** | SPF AADT variable from the HSM for KABC multivehicle crashes |
| **FI-MV-KABC-Distribution** | This field corresponds to $S_{Dist}$ in Equation 2. The distribution of KABC multivehicle crashes from the HSM SPF. All SPFs except the rural-two-way two-lane roads has an SPF specific for KABC crashes. This multiplier is applied only to rural-two-way two-lane roads. |
| **FI-MV-Predicted** | Predicted KABC multivehicle crashes based on the SPF |
| **FI-MV-Observed** | 5 year average (2016-2020) observed multivehicle KABC crashes for the segment. These only include the winter plowing months November-February. |
| **FI-SV-Intercept** | SPF intercept variable from the HSM for KABC single vehicle crashes |
| **FI-SV-Slope** | SPF Slope variable from the HSM for KABC single vehicle crashes |
| **FI-SV-AADT** | SPF AADT variable from the HSM for KABC single vehicle crashes |
| **FI-SV-KABC-Distribution** | This field corresponds to $S_{Dist}$ in Equation 2. The distribution of KABC single vehicle crashes from the HSM SPF. All SPFs except the rural-two-way two-lane roads has an SPF specific for KABC crashes. This multiplier is applied only to rural-two-way two-lane roads. |
| **FI-SV-Predicted** | Predicted KABC single vehicle crashes based on the SPF |

| Field Name | Description |
|---|---|
| **FI-SV-Observed** | 5 year average (2016-2020) observed single vehicle KABC crashes for the segment. These only includes the winter plowing months November-February. |
| **TotalObserved** | Sum of the observed crashes (FI-SV-Observed + FI-MV-Observed) |
| **FI-PredTotal** | Sum of the predicted crashes (FI-SV-Predicted + FI-MV-Predicted) |
| **TotalCalibration** | Calibration factor for the total fatal and injury crashes. |
| **FI_PredictedUtah** | Calibrated predicted total winter plowing fatal and injury crashes for Utah. |
| **FI_Pre_PerDay** | Calibrated predicted total winter plowing fatal and injury crashes per day during the winter plowing season (FI-PredictedUtah / 119 days). |
| **StormIntensity** | **INPUT PROVIDED BY UDOT MAINTENANCE.** This is the median storm intensity index readings for each storm from the RWIS station that is associated geospatially with the given roadway segment |
| **Intensity Group** | The storm intensity group used to look up CMFs from Table 1. |
| **FunctionalClass** | Roadway functional class for each segment. This was provided because UDOT Maintenance will provide travel reduction factors based on functional class |
| **Benefit** | Safety benefit calculated by using an average winter snow plow KABC crash cost of $345,000 |
| **MicroClimate** | The microclimate zone (from Figure 1) assigned to the roadway segment |
| **CalibrationID** | A combination of the MicroClimate field and the HSMSPF_Filtered field. This category is used in calibration. |