Winter Roadway Maintenance Material Enhancers (field) Evaluation

FINAL REPORT

April 06, 2018

By: Huichun (Judy) Zhang, Benoit Van Aken, Xiang Li, Bechara Abboud, Zhigen Zhao, Ahmed Faheem, Erica Mckenzie

Temple University

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

CONTRACT # 4400011166
WORK ORDER # TEM 005

Page Intentionally Left Blank

1. Report No. FHWA-PA-2018-003-TEM WO 05	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle

Winter Roadway Maintenance Material Enhancers (Field) Evaluation

5. Report Date
April 6, 2018

6. Performing Organization Code

7. Author(s)
Huichun (Judy) Zhang, Benoit Van Aken, Xiang Li, Bechara Abboud, Zhigen Zhao, Ahmed Faheem, Erica Mckenzie

8. Performing Organization Report No.
TEM-WO-005

9. Performing Organization Name and Address
Temple University
1947 N. 12th St.
Philadelphia, PA 19122

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
4400011166, TEM WO 5

12. Sponsoring Agency Name and Address
The Pennsylvania Department of Transportation
Bureau of Planning and Research
Commonwealth Keystone Building
400 North Street, 6th Floor
Harrisburg, PA 17120-0064

13. Type of Report and Period Covered
Final Report; 03/25/2016 – 04/06/2018

14. Sponsoring Agency Code

15. Supplementary Notes
Technical advisor: William Davenport | Roadway Programs Manager
Bureau of Maintenance and Operations
Winter Section
400 North Street – 6th Floor
Harrisburg PA 17120
Phone: (717) 787-1199 | Fax: (717) 705-5520
wildavenpo@pa.gov

16. Abstract
In this study, the performance and cost analysis of four deicers products, i.e., Aqua Salina (AS), Beet Heet (BH), Green Blast (GB), Magic Minus Zero (MMZ), and two references, Rock Salt (RS) and/or Salt Brine (SB) were evaluated through parking lot tests and on-road tests. The rankings from the different tests were compared and discussed. The parking lot tests using the PennDOT's formulation for field operations (i.e., mixing the deicer product with SB 50:50 in volume before pre-wetting RS with 10 gallons per ton, application rate 500 lb/lane mile) gave the following ranking: BH ≈ GB ≈ MMZ > AS ≈ RS > SB, while the parking lot test using the manufacturer's recommendations provided an overall ranking that can be summarized as GB > AS > RS ≥ BH ≥ MMZ ≈ SB. Considering only the significant results, the road tests suggested that AS ≈ BH and GB > AS ≈ RS. The ranking of GB > AS ≈ RS is consistent with the parking lots test using PennDOT's formulation for field operations. Ranking deicer products based on these tests gave relatively inconsistent results, primarily because of the different formulations and application rates used. Because of the low statistical significance and partial ranking from the on-road tests, only results from the parking lot tests were used to perform the cost analysis. Using the manufacturer's recommended application rates and the price of the deicers provided by PennDOT, the cost difference between the deicer products under study and SB was calculated showing the following ranking (per gallon basis): BH (cost difference 10.4) > MMZ (cost difference 8.6) > GB (cost difference 7.4) > AS (cost difference 4.5) > SB (cost difference 1.0). Results from the first parking lot test were used to calculate the differences in performance between the deicers product under study and the reference, SB. It can be concluded that the performance of AS was 2.8 – 8.8 times better than SB (AS is 4.5 times more expensive), performance of GB was 3.3 – 12.4 times better than SB (GB is 7.5 times more expensive), the performances of BH and MMZ were not statistically different from SB (BH and MMZ are 10.4 and 8.6 times more expensive, respectively). Results from the second parking lot test were also used to calculate the differences in performance. It can be concluded that AS, BH, GB, and MMZ performed 20%, 51.3%, 66.7%, and 86.2% better than SB, respectively, although the cost differences by comparison to SB were 4.5, 10.4, 7.5 and 8.6 times, respectively.

17. Key Words
Deicing material, anti-icing material, parking lot test, antiskid test, on-road tests, RWIS, AVL

18. Distribution Statement
No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 39	**22. Price** N/A

Page Intentionally Left Blank

DISCLAIMER

STATEMENT OF CREDIT

This work was sponsored by the Pennsylvania Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

CONTENTS

CONTRACT NO. 4400011166
TEM WO 005

DELIVERABLE 6 – FINAL REPORT

APRIL 06, 2018

Summary

Proper use of de-icing materials protects road safety but bears significant costs. New deicing formulations are continually developed, necessitating testing to evaluate product performance and financial costs. Laboratory testing can provide information about direct effects under strictly controlled conditions, however, previous research has demonstrated that field results are often different than laboratory results, likely due to a range of factors, including variable environmental and traffic conditions. These factors could significantly affect the product performance.

The purpose of this project was to perform parking lot and on-site real-time road tests of the deicer products that were evaluated in a prior laboratory study under Work Order TEM 003 entitled "Effective Use and Application of Winter Roadway maintenance Material Enhancers". Six deicers were tested in the parking lot tests: AquaSalina (AS), Beet Heet (BH), Green Blast (GB), and Magic Minus Zero (MMZ), and RS (RS) and RS pre-wetted with Salt Brine (SB) as the reference chemicals. Five deicers were tested in the road tests: AS, BH, GB, and MMZ, and RS as the reference chemical.

In **Task 1.1**, a reliable protocol for the simple garage/parking lot deicing tests was developed to simulate field conditions. This protocol includes deicer sample preparation, selection of deicer application rates for both solid and liquid deicers, set-up of the test grid, deicer spreading process, general and specific information collection, image collection, data collection, and image analysis method development.

The purpose of the next task, **Task 2.1**, was to perform two parking lot tests to evaluate the product deicing performance using different mixing ratios and application rates. Evaluation of deicer performances was based on analysis of photographs taken during the tests. The deicer performances were evaluated based on the snow melting percentages determined by visual analysis, in which researchers assigned visual scores to each image, and image analysis, which was based on software 'Image J'. Comparison between the two methods generally produced similar results for deicer performances.

During the **first parking lot test**, deicers were prepared based on the manufacturers' recommendations. The results showed that higher application rates almost always led to better deicing performance during the entire test duration. Qualitative rankings of solid deicers were <u>RS ≈ BH > SB ≈ MMZ</u> (visual method) and <u>RS > BH ≈ SB ≈ MMZ</u> (Image analysis method). For the liquid deicers, the ranking was <u>GB > AS</u> (visual and image analysis methods).

The second parking lot test was conducted with the deicer mixing ratio following the PennDOT field operations (mixing deicer products with SB 1:1 v/v before pre-wetting RS) and constant application rate of 500 lb/lane mile. The qualitative ranking was <u>BH ≈ GB ≈ MMZ > RS ≈ AS > SB</u>, which is different than the rank based on the first test, likely because of the different preparation methods of the deicers. The observed melted percentages during the parking lot tests were much lower than what was observed during the preliminary real-time on-road field tests.

In **Task 1.3**, the skid resistance was evaluated in simple garage/parking lot tests to evaluate the effect of the six deicers on the surface conditions. A single application rate of 500 lb/lane mile was selected. Results showed a general improvement in skid resistance compared to wet conditions (plowing with no deicers used). The results could not lead to conclusive ranking, except for AS which consistently show the lowest performance.

In **Task 1.4**, statistical analysis of the results for the two parking lot tests and the skid resistance test was performed to determine more objectively the ranking of deicer products. The analysis was based on multivariate regression models, including the melted snow percentage as dependent variable and three independent variables (time, deicer type, and application rate) for the first parking lot test and two independent variables (time and deicer type) for the second parking lot test (Task 1.2). Based on the optimal model for each deicer and pair-wise comparison between deicer products, the ranking for the first parking lot test was GB ≈ AS > RS > BH ≈ MMZ ≈ SB, which is slightly different from the visual and image analysis in Task 1.2. Following a similar strategy, analysis of the second parking lot test provided the ranking GB ≈ MMZ ≈ BH > RS ≈ AS > SB. This ranking matches well the visual and image analysis in Task 1.2. The statistical analysis of the skid resistance test data (Task 1.3) showed no statistically significant difference among the deicer products.

Task 2.1 included the development of a field, on-road test protocol. The protocol considered three different phases: 'pre-operation', 'during operation', and 'post-operation' phases. In the 'pre-operation' phase, preliminary information about the stations, trucks, routes, type of deicers, application rates, spreading time, as well as historical data from RWIS and AVL were to be collected. For the 'during operation' phase, the Temple Team had to have a vehicle available to go to the test areas and collect selected data on-site. In the 'post-operation' phase, data were to be collected from the RWIS and AVL systems and through communication with PennDOT. Relevant data were to be formatted, compiled, and classified. Ranking the deicers was to require statistical treatment in order to extract the impact of the deicer application from a range of other environmental variables. As in Task 1.4, multivariate regression models were to be build, including the melted snow percentage (or another indicator of the snow condition) as dependent variable and a variety of data from the RWIS and AVL system as independent variables (e.g., deicer type, application rate, weather conditions). The goal of the statistical analysis was to detect significant differences in the performance of deicer products and rank the deicer products.

In **Task 2.2**, the protocols for the field testing were finalized and preliminary on-road real-time observations were collected from the RWIS and AVL systems (using RS and SB products only) and discussed. In addition to the protocols described in Task 2.1, the finalized testing protocol includes additional information about the storms to be monitored, data to be collected about the deicer application (AVL system), weather information (RWIS system), criteria for assigning visual scores, and statistical analysis of the data.

Preliminary data for the on-road real-time storm events were collected between December 2016 and January 2017. Qualitative data analysis showed correlation between surface temperature and snow melted percentage, and between surface temperature, dew point, and air temperature. Analysis of data from the AVL and RWIS system allowed to us observe that deicer application resulted in increase in the grip level in some cases and decrease in other cases, which was attributed to continuing precipitation. A good correlation was observed between ice layer, snow layer, and precipitation. It was also observed that in many instances, photographs were not usable because of darkness.

In **Task 3.1**, on-road real-time field tests were conducted to evaluate the performances of four deicers (AS, BH, GB, and MMZ) and a reference (RS) at different RWIS observation sites. **Task 3.1** describes and discusses the data collected at **e**ight sites during the winter 2016-2017. **Task 3.2** describes and discusses the data collected at five sites during the winter 2017-2018 (referred to as winter 2017 thereafter).

During the **winter 2016-2017**, the deicers were evaluated via paired experiments including each of the treatment site (treated with the deicer to be tested) and a nearby reference site (treated by the reference RS) – eight sites in total (**Task 3.1**). Initially, the primary performance indicator for the deicers was the snow melted percentage derived from photographs taken by on-site cameras. Data collected revealed that few events allowed the use of photographs because of darkness, poor visibility, and/or technical issues. Additional tentative indicators were then considered, including the grip level and salt concentration. At the sites equipped with grip level sensors, the grip level decreased with precipitation and increased after deicer applications. At the sites equipped with salt concentration sensors, the salt concentration was in general inversely correlated with precipitation, but fluctuated largely for unknown reasons. The grip level was then identified as a more robust indicator of the snow condition and deicer performance. Only three sites in the winter 2016-2017 were equipped with grip level sensors, preventing statistical analysis and deicer ranking.

During the **winter 2017**, the same deicers were evaluated using five sites all equipped with grip level sensors (one site for each deicer tested and one for the reference RS) (**Task 3.2**). Data at these sites were collected until December 31, 2017. Due to technical issues independent of the Team's responsibility, only data of one storm event were collected for GB and data were not collected for BH and MMZ. Correlation matrix analyses showed significant correlations between the grip level, snow level, precipitation 1-hour, and snow melted percentage. Overall, both the grip level and snow layer appear to be reliable indicators of the snow condition of the road and deicing performance. After deicer application, we generally observed a rapid increase of the grip level and snow melted percentage, which reflected the efficiency of the deicer product applied. However, in some cases, the application did not result in significant recovery of the grip level and snow melted percentage, which may be caused by ongoing snow precipitation.

In **Task 4**, the performance of four deicers products was evaluated using **statistical methods** based on the data collected in on-road real-time tests conducted over the winter 2016-2017 and winter 2017 from the RWIS and AVL system. The deicer products were then ranked using the results from all tests. Finally, a **cost analysis** was conducted using performance results and the cost of deicer products.

As in Task 1.4, the **statistical analysis of the on-road tests** was performed using multivariate linear regression models, which included an indicator of deicer performance (snow melted percentage or grip level) as the dependent variable and a range of independent variables (deicer type – categorical variable, weather and deicer application data from RWIS and AVL system). Initially, the model was supposed to integrate all data from all storms and all deicers (i.e., all sites) in order to derive an overall ranking (comparison) of deicer products. Because two different indicators of deicer performance were used and because data from the two winters could not be integrated into the same model due to differences in the deicer application methods, four different models were computed (see below). Because of various technical issues, only limited or no data were collected for some deicers, preventing the comparison between all five products. In addition, in several cases, the analysis could not establish a ranking because of the low statistical significance of the model. Only partial comparison between deicers was then obtained.

The statistical analysis of **winter 2016-2017 data based on the grip level** as the performance indicator included only two deicer products, GB and RS. The ranking analysis indicated that RS and GB were not statistically different.

The statistical analysis of **winter 2016-2017 data based on the snow melted percentage** as the performance indicator included only three deicer products, AS, BH, and RS. The ranking analysis indicated that AS ≈ BH, with *moderate* evidence that AS, BH > RS.

The statistical analysis of **winter 2017 data based on the grip level** as the performance indicator included only three deicer products, AS, GB, and RS. The ranking analysis indicated that GB > AS ≈ RS.

The statistical analysis of **winter 2017 data based on the snow melted percentage** as the performance indicator included only three deicer products, AS, GB, and RS. The ranking analysis indicated that RS is not statistically different than GB and AS, with *moderate* evidence that AS > GB.

In order to summarize the results, we then performed **ranking of the deicer products** based on the numerical or comparative performances obtained from different tests: a discrete numeric score from 1 to 6 was assigned to each product and the references. However, integrating the rankings from different tests into a single indicator was not feasible primarily because the preparation methods of the products were different in each test.

The parking lot tests provided several ranking depending on the preparation and analysis method. The test using the PennDOT's formulation for field operations (i.e., mixing the deicer product with SB 50:50 in volume before pre-wetting RS with 10 gallons per ton, application rate 500 lb/lane mile) gave consistent results with both analysis methods (visual scores and statistical models) with a ranking BH ≈ GB ≈ MMZ > AS ≈ RS > SB. Considering results from both analytical methods, the test using the manufacturer formulation indicated that the 'liquid' deicers performed better with GB > AS, and that among 'solids deicers', RS performed better than the other, with an overall ranking that can be summarized as GB > AS > RS ≥ BH ≥ MMZ ≈ SB. When compared with results from the laboratory tests (Phase I – TEM WO 003), the parking lot tests using manufacturer recommendations and statistical analysis showed some similarities: AS ranked first and BH ranked last (together with MMZ and SB) in both tests. On the other hand, little similarity was observed between laboratory tests and parking lot tests using PennDOT's formulation, which is not surprising considering the difference in product preparation. Results from the road tests gave partial ranking with limitation related to the statistical significance. Considering only significant results from all three models, the analysis indicates that AS ≈ BH and GB > AS ≈ RS. The ranking GB > AS ≈ RS is consistent with parking lots test results using PennDOT's formulation.

The **cost analysis** of the deicer products were then conducted using performance data and the costs of the products. Because of different conditions under which the different tests were conducted and because of the absence of significant results in some cases, it was not possible to integrate the results of all tests to conduct the cost analysis. In addition, the results from skid resistance test and the on-road tests did not show no or low statistical significance and/or partial ranking of the products and were not considered in the cost analysis.

Only the performance data from both parking lot tests were therefore used to perform the cost analysis. Using the manufacturer's recommended application rates and the price of the deicers provided by

PennDOT, the **cost difference** between the deicers products under study and SB was calculated showing the following ranking (on a gallon per line mile basis): BH (cost difference 10.4) > MMZ (cost difference 8.6) > GB (cost difference 7.4) > AS (cost difference 4.5) > SB (cost difference 1.0).

Results from the **first parking lot test** (using the manufacturer's recommendations) were used to calculate the differences in performance between the deicers product under study and the reference, SB. It can be concluded that the performance of AS was 2.8 – 8.8 times better than SB (AS is 4.5 times more expensive), the performance of GB was 3.3 – 12.4 times better than SB (GB is 7.5 times more expensive), and the performances of BH and MMZ were not statistically different from SB (BH and MMZ are 10.4 and 8.6 times more expensive, respectively).

Results from the **second parking lot test** (using PennDOT's formulation for field operations, i.e., mixing the deicer product with SB 50:50 in volume before pre-wetting RS with 10 gallons per ton, application rate 500 lb/lane mile) were also used to calculate the differences in performance. It can be concluded that AS, BH, GB, and MMZ performed 20%, 51.3%, 66.7%, and 86.2% better than SB, respectively, although the cost differences by comparison to SB were 4.5, 10.4, 7.5 and 8.6 times, respectively.

SUMMARY OF INDIVIDUAL TASKS

SUMMARY FOR TASK 1.1 – PARKING LOT TEST PROTOCOL

The parking lot test protocol includes information about the parking lot tests conduction, including deicer preparation, test grid set-up, application of deicer, general information collection, specific information collection, anti-icing test, image collection and deicing test.

The deicers were prepared per manufacturer recommendations. The selected application rates are based on either manufacturer's recommendations or published data. We used a parking lot grid that was set-up prior to the storm. During or after the snowfall, the deicer was applied on the test areas. The solid deicers were well shaken out of their bottle/bags by hand using protective gears and distribute evenly through the test area. Liquid deicers were spread in a straight horizontal line down on the test area.

Before the storm event, general information was documented, including date and time of test, location of the test; pavement type, etc. Specific information was also collected, including the type of deicer, how the deicer is prepared, etc. Anti-icing test were performed 12 to 24 hours before the storm event.

During the testing of deicers, pictures were taken every 10-15 minutes of each 3 ft x 3 ft test area. The pictures were taken with the same type of camera on a tripod with fixed height and angle of inclination.

SUMMARY FOR TASK 1.2 – REPORT DETAILING DEICER PERFORMANCE FOR THE SIMPLE GARAGE/PARKING LOT DEICING/ANTI-ICING TEST

The purpose of this task was to perform two parking lot tests to evaluate the deicer deicing performance at two different mixing ratios and four application rates. The six deicers tested in this project are: AS, BH, GB, MMZ, RS, and RS pre-wetted with SB. The last two deicers were examined as the reference chemicals.

First, a reliable protocol for simple garage/parking lot deicing tests was developed based on real field conditions. This protocol includes deicer sample preparation, selection of deicer application rates for both solid and liquid deicers, test grid set-up, deicer spreading process, general information collection, specific information collection, image collection, data collection and image analysis method development. This protocol provided a practical guidance for this parking lot test; moreover, this protocol will effectively guide future deicer performance testing.

For the image processing, two photo analysis methods have been developed in this work. They are visual analysis and Image J (binary) analysis methods. For visual analysis, two researchers assigned scores to each image independently. There were also three replicates for each test, so the visual scores were based on an average of six scores. For Image J analysis, all scores were based on an average of three replicate images. To ensure that the photo analysis data were reliable, the parking lot test photos were analyzed with both methods. Based on the comparison, the two methods generally yielded similar results for all the deicer performance. However, the two methods have their respective advantages and disadvantages. For example, there are some unexpected errors when the Image J method was used. On the contrary, the visual analysis showed more stable and time-efficient results (e.g., 3-5 min for Image J versus around 1 min for visual analysis). When continuous snowing processes are taken into consideration, the Image J method has some advantage in calculating the extent of melting for some liquid deicers.

During the first parking lot test, the deicers were prepared based on the manufactures' recommendations. Four application rates were applied for the four solid deicers (i.e., 200, 350, 500, and 700 lb per lane mile for RS, RS pre-wetted with SB, BH and MMZ) and the two liquid deicers (i.e., 20, 35, 50, and 70 gallons per lane mile for GB and AS). Based on the results we can conclude that higher application rates almost always led to better deicing performance during the whole reaction period (0-75min) (e.g., the average melting percentage increased from 1% to 7% based on Image J analysis).

Qualitative rankings of both the solid and liquid deicers were obtained based on the testing results: for the solid deicers: RS > BH ≈ SB ≈ MMZ (Image J analysis method), or RS ≈ BH > SB ≈ MMZ (Visual analysis method). For the liquid deicers: GB > AS (Both Image J and visual analysis methods). The average melted percentages of different deicers are between 2%~7% for Image J analysis and 2%~17% for visual analysis during the entire testing period (0-75min). These melted percentages are much lower than what we observed during the preliminary real-time on-road field tests (typically 20%-100% melted), which likely yielded relatively larger errors during the data analysis process. As a result, it led to smaller differences in the deicing performance of all the deicer products. Future statistical analysis should provide more quantitative evaluation of the deicer performance in the next part of the project.

The second parking lot test was conducted with the deicer mixing ratio following Penn DOT field operations (i.e., mixing deicer products with Salt Brine 50:50 in volume before pre-wetting RS10 gallons per ton). The application rate was 500 lb/lane mile. During the entire reaction time, all the deicers had an increasing trend in the melting efficiency. The visual scores were based on an average of six scores from two researcher and triplicate tests. All the melted percentage values ranged from around 3% to 7% during the 75-min reaction time. The qualitative rank is as follows: BH ≈ GB ≈ MMZ > RS ≈ AS > SB. The difference between this rank and the rank above based on the first test may be attributed to the fact that when we blended these deicers with Salt Brine at 50:50 before pre-wetting RS, the real mass loading of each deicer was much lower than when they directly pre-wetted RS. As a result, the melted percentages may not be significantly high enough to yield substantial differences among the deicers (e.g., up to 17% melted in the first parking lot test vs. only up to 7% melted in the second test by the end of 75-min).

When compared with the previous lab test results where the deicers were prepared in the same way as in the first parking lot test, the overall product ranking is different. For the laboratory test, the ranking is as follows: AS ≥ GB > MMZ > RS ≈ SB > BH. In the lab test, two product performance tests were conducted: the modified ice melting test and eutectic curves. The existing laboratory tests may not accurately predict field performance. This may be attributed to the fact that the environmental conditions are more complicated, and the melting performance on the ice versus on the snow could be different. In the future, real-time on-road field tests should be conducted to evaluate the deicers performance to obtain a more reliable deicer ranking.

SUMMARY FOR TASK 1.3 – REPORT DETAILING DEICER SKID RESISTANCE DATA AND RANKINGS FOR THE SIMPLE GARAGE/PARKING LOT DEICING/ANTI-ICING TEST

Skid resistance was used to evaluate the effect of six (6) deicer products on the surface conditions at the application rate of 500 lb. per lane mile. The six products are: AS, BH, GB, MMZ, RS, and RS pre-wetted with SB. The four novel deicers were prepared based on the manufacturers' recommendations. Parking lot test sections were used such that each product was applied to an area of 3'x 3'. Testing results show general improvement in skid resistance compared to wet conditions (plowing only with no deicers) with the exception of a few data points during the test. For ranking purposes, the results are inconclusive, except for one product (AS) which consistently had the lowest performance on skid resistance.

SUMMARY FOR TASK 1.4 – REPORT TO INCLUDE PRODUCT STATISTICAL ANALYSIS AND RANKING APPROACHES FOR THE SIMPLE GARAGE/PARKING LOT DEICING/ANTI-ICING TEST

In the two parking lot tests conducted at Temple University (see Final Report for Task 1.2), two photo analysis methods were employed for image analysis and evaluated for their effectiveness in obtaining the percentages of melted areas. Using these two analytical methods, qualitative rankings were given to the six deicers for their deicing performances. However, such evaluation can only give us a qualitative ranking result. In this task, statistical analysis based on scientifically established models was conducted for processing the results from the two parking lot tests and the skid resistance test (Task 1.3).

For the first parking lot test (Task 1.2), the model includes one response variable, melted snow percentage, and three independent variables, including time, deicer type, and application rate. Both time and application rate are continuous variables, while the deicer type is a categorical variable. To address the issue of non-Gaussian distribution of the response variable, a Box-Cox transformation was used. In order to consider the interactions between the independent variables (for example, shown below as Time:Deicer, Rate:Deicer, etc.), nine candidate models were evaluated based on the Akaike information criterion (AIC). AIC is a measure of the relative quality of statistical models for a given set of data, taking into the consideration of the complexity of the models. The smaller the AIC value is, the better the model can explain the data set. Therefore, after the calculation of AIC, the best working model was selected to be:

Melt% ~ Time + Ln(Rate) + Deicer + Ln(Rate):Deicer + Time:Deicer + Ln(Rate):Time + Ln(Rate):Deicer: Time.

Note that we use Ln(Rate) instead of Rate here in the model. This is because when using Ln(Rate), the R-squared is 0.8039, AIC is 680. When using Rate, the R-squared is 0.79, AIC is 717. So the model with Ln(Rate) is better, and the fitted equations for the six deicers are:

RS: $\hat{y} = -5.61 - 0.09\times Time + 0.96\times Ln(Rate) + 0.018\times Time\times Ln(Rate)$;
GB: $\hat{y} = -6.02 - 0.03\times Time + 1.18\times Ln(Rate) + 0.013\times Time\times Ln(Rate)$;
AS: $\hat{y} = -5.00 - 0.01\times Time + 0.96\times Ln(Rate) + 0.007\times Time\times Ln(Rate)$;
BH: $\hat{y} = -3.43 - 0.12\times Time + 0.49\times Ln(Rate) + 0.022\times Time\times Ln(Rate)$;
SB: $\hat{y} = -3.96 - 0.07\times Time + 0.59\times Ln(Rate) + 0.013\times Time\times Ln(Rate)$;
MMZ: $\hat{y} = -5.96 - 0.016\times Time + 0.967\times Ln(Rate) + 0.001\times Time\times Ln(Rate)$

Since we combined the same parameters in the above equations, only three variables remain in the final model for each deicer. For example, for each deicer, the coefficients for Time and Time: Deicer were combined as one coefficient for Time. Based on the established models, we could then construct 95% confidence intervals for the predicted melted% for any given time and application rate for all the deicers. We could thus obtain the deicer statistical ranking as follows:

$$GB \approx AS > RS > BH \approx MMZ \approx SB.$$

The ranking is slightly different from the visual analysis in Task 1.2 (the qualitative ranking result was BH ≈ RS > MMZ ≈ SB for solid deicers, and GB ≈ AS for liquid deicer), however, this ranking is based on rigorous statistical analysis. Here, '≈' means there is no statistically significant difference between two deicers in terms of deicing performance.

The second parking lot test was conducted using the PennDOT field operation mixing ratios (Task 1.2). Because there are only two independent variables, Time and Deicer, we consider two candidate models (i.e., melted% ∼ Time + Deicer and melted% ∼ Time + Deicer + Time:Deicer).

After comparing them using the AIC test, the best model was determined to be:

$$\text{Melted\%} \sim \text{Time} + \text{Deicer}$$

Based on pair-wise comparison, the statistical ranking is GB ≈ MMZ ≈ BH > RS ≈ AS > SB. This ranking matches well with the qualitative ranking in the visual analysis process, which indicates that the modeling results and the visual analysis results are consistent.

The statistical analysis for the skid resistance test of the six deicers was also conducted (results in Task 1.3), and there was no statistically significant difference among the deicers. To obtain more reliable statistical analysis, however, additional data should be collected in the future.

SUMMARY FOR TASK 2.1 – FIELD TEST PROTOCOL

The field test protocol provides information about the 'pre-operation', 'during operation' (collection from RWIS and AVL), and 'post-operation' phases (data analysis, deicer ranking statistical analysis).

In the 'pre-operation' phase, testing stations were identified well ahead of time. Preliminary information about the station, trucks, and historical data from RWIS and AVL about the site was collected. Drivers and trucks for each test station, back-up trucks (in the case of mechanical issues), the routes of the trucks and locations of the test were identified. The type of deicer, amount of deicer to spread, time of spreading, and frequency of spreading were decided by PennDOT and communicated to the Temple Team. General information was also collected, including date and time, location of the test, pavement type, pavement conditions, type of the precipitation, material applicator, etc.

In the 'during operation' phase, the Team should have a vehicle available to take them to the test areas and collect all needed data. After completing the first round of testing, the site was monitored for the 2nd passing of the same truck, which indicates the test has restarted. A 3rd passing is recommended. If RWIS was used for data collection, a truck passing was marked as time zero.

In the 'post-operation' phase, data needed for on-road evaluation of deicers were collected both from RWIS and AVL and through communication with PennDOT. Data was collected about the condition of the camera capture system. Vehicles location was based on latitude and longitude. Weather conditions were obtained from RWIS for each site, where data were collected every five minutes, and included temperature, precipitation, wind speed, wind direction, etc.

For each test, relevant data extracted from the above list were compiled and organized in a multiple-sheet Excel files. Data were classified as (a) metadata, (b) performance data derived from picture analysis and team observations, (c) deicer application data, (d) weather condition data, and (e) traffic data. Ranking the deicer materials was based on the collected data, during different storms, under different road and weather conditions, which required statistical treatment in order to extract the impact of the deicer material type and rate of application from other relevant environmental variables.

A statistical model was built to establish relationships between the performance of deicer products and independent variables, including application rate, weather conditions, and traffic density. The goal of the statistical analysis was (i) to detect if there is any significant difference among the performance of the deicer products and (ii) to rank the deicer products.

Summary for Task 2.2 – Report Detailing Test Observations and Finalized Testing Protocols for On-Road Real Time Testing

This task presents preliminary on-road real-time test observations and finalized the protocols for field testing.

In addition to the description provided in Task 2.1, the finalized testing protocol includes the following elements:

1. A snow storm of 0.5-1 inch per hour was optimum, although lighter and heavier storms could also be monitored as references. PennDOT notified the Temple Team no later than 24 hours prior to a monitoring event. The type of deicer, rate of application, time of application, and frequency of application were determined by Penn DOT and communicated to the Temple Team.

2. Each test run for about 1-2 hour. All relevant information was collected for each passing. All data were screened to identify outliers and nonsensical data. Deicer application information such as solid material, solid rates, solid spread, etc. was collected in AVL system. Weather information such as surface temperature, air temperature, precipitation, wind speed, etc. was collected in RWIS system.

3. Criteria for assigning reasonable visual scores were set up. Before collecting RWIS data, it was important to ensure that the RWIS station camera functions properly and the AVL station offers all the needed information. When giving visual scores, the researcher tried to ignore the interference of camera conditions. During the test, if the precipitation was too heavy, the storm should not be treated as a representative storm event for data collection purposes.

4. For each test, relevant data included snow melting efficiency from picture analysis and Team observations, deicer application rate, weather condition, and traffic. Each time point corresponded to a picture/observation collected during the test. RWIS/AVL pictures were taken every 5 minutes.

5. For statistical analyses based on multivariate regression, melting efficiency data were treated as the dependent variable, while operational parameters including deicer application data, weather condition data, and traffic data were treated as the independent variables. Several models were tested for establishing a relationship between melting efficiency and operational parameters. Based on multivariate regression models, scores were obtained for each deicer and were used to rank the deicer performance.

Preliminary data for the on-road real-time storm events were monitored between December 2016 and January 2017 (28 storm events in total). Based on these preliminary data, we concluded that there was a clear relationship between surface temperature and snow melted percentage. Generally speaking, the surface temperature, dew point temperature, and air temperature correlated with each other. There was no clear correlation between the melted percentage and relative humidity, rain intensity, wind speed, visibility, and barometric pressure. Generally speaking, the snow melted percentage increased faster when there was a higher surface and air temperature.

During the testing period, the weather conditions were collected from RWIS for each site every five minutes. At the same time, weather information was collected from another online weather service, Weather Underground, comparison with the RWIS station data. Results shows that the weather data from all two sources were in agreement.

A preliminary data collection for a storm event with freezing rain on January 2017 was conducted in the northern part of the state. The photo qualities, however, were too dark to give a visual score for each image during the snow event. Twenty-four-hour observation was conducted during the entire testing time. When the truck passed, the surface temperature slightly increased. The grip level increased significantly during the first two times when the truck passed by, however, it decreased significantly during the last six times of passing. There was a good correlation between ice layer, snow layer, and precipitation.

SUMMARY FOR TASK 3.1 – INTERIM REPORT TO INCLUDE ON-ROAD REAL-TIME PERFORMANCE ANALYSIS OF EACH DEICER

In this part of the study, on-road real-time field tests were conducted to evaluate the deicer performance on eight RWIS observation sites. Four deicers were evaluated via a paired treatment-reference site experiment design, thus necessitating eight sites in total, they are as follows: Site I-80@ Exit 35, milepost (MP) 37 for AS and the reference site is I-79 @ MP 136, Crawford/Mercer Line (RS); Site I-79 @ Exit 88 for BH and reference site I-79 @ MP 100; Site I-81 @ Exit 223, New Milford for GB and the reference site I-80 @ Exit 211 Lenox (RS); Site I-81 @ Exit 77, Manada Hill for MMZ and the reference site I-81 @ Exit 223, New Milford, see Table 1 below. For some sites, the sensor was designed for measuring the grip levels, while others for salt concentrations, both two sensors were installed for the road conditions.

Site I-80 @ Exit 35 MP 37 – AquaSalina

There were five useable snow events at site I-80 @ Exit 35 MP 37 (24-hour time window at one site is considered one snow event). At this site, the underground sensor recorded the salt concentration. The salt concentration and precipitation rolling average past 1 hour (referred to as precipitation hereafter) generally had an opposite trend. For all the snow events on Jan-05, Jan-31, Feb-08, Feb-09, and Mar-13 2017, the salt concentration decreased when there was snow precipitation and the deicer was applied. At the same time, the surface snow melted percentage recovered to 100% (i.e., no surface snow) within

30 min. Therefore, the deicer application was clearly effective at removing the surface snow. The deicer performance did not seem to be well reflected by the salt concentration. In many cases, it was too dark to collect on-road real-time images from the RWIS system, preventing to obtain snow melted percentage data.

Site I-79 @ MP 136 Crawford/Mercer Line – Reference (Rock Salt) for AquaSalina

RS was applied at this site. The four snow events were recorded: 08-Feb-2017 19:00–09-Feb-2017 19:00, 09-Feb-2017 19:00–10-Feb-2017 19:00, 12-Feb-2017 19:00–13-Feb-2017 19:00, and 28-Jan-2017 20:00–29-Jan-2017 20:00. At this site, the underground sensor recorded the grip level. During all snow events, the grip level remained at high value (~0.8) when there was no precipitation. When there was precipitation, the grip levels decreased dramatically. The grip level was closely related to precipitation. After deicer application, the melted percentage increased significantly to 100% within about 60-90 min. It was noted that the grip level and melted percentage showed very similar trends, which indicates that the grip level can be considered as a potentially indicator of the snow condition and deicer performance.

Site I-79 @ Exit 88 – Beet Heet

There were five snow events at site I-79 @ Exit 88: Feb 08, 2017, Feb 12, 2017, Feb 15, 2017, Jan 30, 2017, and Jan 31, 2017. The underground sensor recorded the salt concentration. Generally, when the precipitation increased, the salt concentration decreased. After deicer applications, the melted percentage increased to 100%, which indicated that the deicer application was effective. Again, the snow condition was not well reflected by the salt concentration.

Site I-79 @ MP 100 – Reference (Rock Salt) for Beet Heet

There was only one usable snow event at this site: Feb 08, 2017. The underground sensor recorded the salt concentration. The salt concentration and precipitation had opposite trends. After precipitation and deicer application, the snow melted percentage recovered to 100% within about 25 min. The salt concentration fluctuations did not appear to be explained by any environmental factor or winter maintenance strategy.

Site I-81 @ Exit 223 New Milford – Green Blast & Site I-81 @ Exit 211 Lenox – Reference (Rock Salt)

There was only one snow event at site I-81 @ Exit 223 New Milford and the reference site, I-81 @ Exit 211 Lenox: Feb 08, 2017. However, GB was applied at both sites. The underground sensors recorded the grip level. There was clear trend showing that when the precipitation increased (e.g., from 0.0 to 0.2 in.), the grip level decreased (e.g., from 0.8 to 0.4). This provides some evidence that the grip level and precipitation have a good correlation.

Site I-81 @ Exit 77 Manada Hill – Magic Minus Zero & Site I-81 @ Exit 223 New Milford – Reference (Rock Salt)

There was only one snow event at site I-81 @ Exit 77 Manada Hill: Feb 08, 2017, and none at the reference site, I-81@ Exit 223 New Milford. The underground sensor recorded the salt concentration. Although the precipitation was heavy at some point, the salt concentration recovered to a high level shortly after the precipitation ceased, showing that the deicer application was effective. The grip level and snow melted percentage showed similar trends, which provides further evidence that the grip level can be a good indicator of the snow conditions on the road.

Correlation Matrices at Grip Level Sites

We computed correlation matrices for the three grip level sites (I-79 @ MP 136 Crawford/Mercer Line – RS, I-81 @ Exit 223 New Milford – GB, and I-80 @ Exit 211 Lenox – RS) because the grip level appeared to be the indicator of choice for assessing the snow condition on the road and deicer performance. The correlation matrix analyses showed that at the RS site – but not at the GB sites, the surface temperature correlated well the air temperature. Besides, significant correlations were observed at both sites between the significant variables with respect to the snow condition: the grip level, snow layer, and snow melted percentage (the latter being only available for the RS site). In addition, a good correlation was observed between the grip level and precipitation at the GB sites. Both the grip level and snow layer appear then to be very reliable indicators of the snow condition on the road and, therefore, the deicing performance.

In summary, at sites equipped with grip level sensors, the grip level decreased quickly when there was precipitation, but it recovered after deicer applications. Also, after deicer applications, the melted percentages increased to 100% within a short period of time, which means that the deicers were efficient. At sites equipped with salt concentration sensors, the salt concentration and precipitation show a generally opposite trend. However, the salt concentration level fluctuated over a wide range for reasons that are unknown. Because few events allowed obtaining the snow melted percentage and because the salt concentration fluctuated widely, the grip level was identified as a more robust indicator of the snow condition and deicer performance.

SUMMARY FOR TASK 3.2 – FINAL REPORT TO INCLUDE DEICER PERFORMANCE DURING REAL-TIME ROADWAY TESTING

In this part of the study, on-road real-time field tests were conducted to evaluate the deicer performance at several RWIS observation sites. Five sites were used during the winter 2017-2018[1]).

During the winter 2017-2018, the same four deicers as in Task 3.1 were evaluated using five sites (one site for each of the four products tested, AS, BH, GB, MMZ, and one site for the reference, RS). All sites were equipped with grip level sensors, as the grip level was estimated to be a more convenient and consistent performance indicator than the snow melted percentage or salt concentration (see above). Because the ranking method required introducing all data from all sites and all storm events into *one* single statistical model, it was decided that only one reference site (RS) would be sufficient. The selected sites were site SR 322 W/B - Venango-Mercer Co. Line for AS, site I-78 WB @ MM27 Berk Co. for Magic Minus Zero, site I-81 @ Exit 223 New Milford for GB, site I-79 N/B @ Exit 60 Carfton Allegheny Co. for Beet Heet, and site I-80 @ MP 11 Mercer Co. for the reference, RS (Table 2.2). Data at these sites were collected during November and December 2017. Data collection ended on December 31, 2017 in order to proceed with data analysis and the estimation of deicer ranking. Three to six significant storm events were collected at each of these sites. Due to technical issues independent of the Team's responsibility, only data of one storm event were collected for GB and no data were collected for Beet Heet. Also, the Team did not have the truck information for the MMZ site, which prevented them from performing any data analysis.

Site SR 322 WB Venango-Mercer Co. Line – AquaSalina

[1] No data were collected beyond December 2017. We still refer the second winter as 2017-2018.

For all six snow events recorded at this site, the grip level data was obtained from the RWIS system. The snow melted percentages were obtained from the RWIS photographs for four events. The correlation matrix analysis between all recorded variables shows that the primary performance indicator, the grip level, correlated well other 'significant' variables with respect to the snow condition on the road: the snow layer, precipitation 1-hour, and snow melted percentage. Other variables recorded by the system show low correlation with the grip level, snow layer, precipitation, or snow melted percentage. Both the grip level and snow layer appears to be good indicators of the road condition and, therefore, the deicing performance. Application of AS resulted in a sharp increase in the grip level and/or snow melted percentage, although the effect of the application was much less apparent when heavy precipitation was ongoing.

Site I-79 NB @ Exit 60 Carfton Allegheny Co. – Beet Heet
No data were recorded at the RWIS site in winter 2017-2018.

Site I-81 @ Exit 223 New Milford – Green Blast
Only one snow event was recorded at this site. The correlation matrix showed that the grip level during this storm correlated well with the snow layer and snow melted percentage. This indicates again that both the grip level and snow layer are good indicators of road condition and deicer performance. The snow layer showed a low correlation with the precipitation and melted percentage. Unlike what was observed at other sites, the absence of good correlation between the four significant variables appears to be due to the limited data available at this site. The application of GB generally resulted in a significant increase in the grip level and snow melted percentage, except when heavy precipitation was ongoing.

Site I-78 WB @ MM 27 Berk Co. – Magic Minus Zero
Four snow events were recorded at this site. The correlations matrix shows that the grip level correlated well with other significant variables: snow layer, precipitation 1-hour, and snow melted percentage. The graphical analysis also indicated that both the grip level and snow layer are good indicators of the road condition and, therefore, of the deicing performance. The effect of the application of MMZ was not discussed as no truck information was not available at the time this report was prepared.

Site I-80 @ MP 11 Mercer County – Rock Salt
Five snow events were recorded at this site. According to correlations matrix analysis, the grip level only correlated with the snow layer. However, graphical analyses of the profile of the significant variables revealed that during two storm events, there were discrepancies in the data recorded by the sensors (e.g., precipitation not associated with snow layer, grip level, and snow melted percentage). Removing these two storms from the data set resulted in good correlation between the four significant variables. The effect of the application of RS was not discussed as no truck information was available at the time this report was prepared.

In summary, the correlation matrix analyses showed that at all sites, the surface temperature correlated very well with air temperature. Besides, significant correlations were observed at most sites between the significant variables with respect to the snow condition, i.e., the primary indicator of the snow condition, the grip level, and other variables expected to be related to snow on the road: the snow level, precipitation 1-hour, and snow melted percentage. Overall, both the grip level and snow layer appear to be very reliable indicators of the snow condition of the road and, therefore, the deicing performance. The profile of significant variables during selected storms showed again a strong correlation between the precipitation 1-hour, snow layer, grip level, and snow melted percentage. After deicer application, we generally observed a rapid increase of the grip level and snow melted percentage, which reflected the efficiency of the deicer product applied. However, in some cases, the application did not result in significant recovery of the grip level and snow melted percentage, which may be caused by ongoing snow precipitation.

SUMMARY FOR TASK 4 – REPORT TO INCLUDE PRODUCT STATISTICAL ANALYSIS AND RANKING APPROACHES FOR THE ON-ROAD REAL-TIME TESTS

In Task 4, the performance of four deicers products was evaluated using statistical methods based on data collected in on-road real-time tests conducted over the winter 2016-2017 and winter 2017 from the RWIS and AVL system. Then, deicer products were ranked using the results from all tests. Finally, a cost analysis was conducted using performance results of the parking lot tests and the cost of deicer products.

Statistical Analysis of On-Road Real-Time Tests

In previous on-road real-time tests conducted over the winter 2016-2017 and winter 2017-2018 (until December 31, 2018, referred to as winter 2017 hereafter), a large number of data were collected from the RWIS and AVL systems, and used to conduct a statistical analysis and tentatively a ranking of the deicer products. During the two data collection campaigns, one site was used per deicer product (except during the winter 2016-2017, where four sites were used for the reference, RS). The multivariate linear regression method including all data from all storms and all deicers (i.e., all sites) was applied in order to build a model descriptive of the deicer performance (i.e., the snow condition on the road). Because two indicators of the deicer performance were used and because data from the winter 2016-2017 and 2017 could not be integrated into the same model due to differences in the application method, four models were computed: (1) winter 2016-2017 data using the snow melted percentage as performance indicator, (2) winter 2016-2017 data using the grip level as performance indicator, (3) winter 2017 data using the snow melted percentage as performance indicator, and (4) winter 2017 data using the grip level as performance indicator. The statistical models include one dependent variable indicative of the snow condition on the road – either the grip level or the snow melted percentage, and a series of independent variables including categorical variables representing the deicer product. Because of various technical issues, only limited or no data were collected for some deicer products, preventing the comparison between all the five products. In addition, in several cases, the analysis could not determine a ranking with statistical significance. Only partial comparison between deicers was obtained.

The **statistical analysis of winter 2016-2017 data using the grip level** as the performance indicator included 1,439 observations, 14 variables (Deicer type, surface temperature, air temperature, dew point temperature, snow layer, relative humidity, barometric pressure, precipitation 1 hour, wind speed, max wind speed, solid rate, speed of deicer truck, deicer prewet rate, and deicer type), and only two deicer products, GB and RS. After removing the outliers, the adjusted R-squared for the model was 0.8522. The ranking analysis showed that there is <u>no significant evidence showing that GB performs better than RS</u>.

The **statistical analysis of winter 2016-2017 data using the snow melted percentage** as the performance indicator included 465 observations, 10 variables (Deicer type, surface temperature, dew point temperature, rain, relative humidity, barometric pressure, precipitation 1 hour, wind speed, and speed of deicer truck), and only three deicer products, AS, BH, and RS. After removing the outliers, the ranking analysis showed that <u>AS and BH are similar</u>. There exists <u>moderate evidence showing that AS</u>

and BH may perform better than RS. The R-square is only 0.1637 and considered as low, making the statistical significance of the ranking questionable.
The **statistical analysis of winter 2017 data using the grip level** as the performance indicator included 2,005 observations, 12 variables (surface temperature, air temperature, dew point temperature, snow layer, relative humidity, barometric pressure, precipitation in 1 hour, wind speed, max wind speed, solid rate (deicer application rate), speed of deicer truck, and deicer type), and only three deicer products, AS, GB, and RS. After removing the outliers, the adjusted R-squared for the model was 0.7166. The ranking analysis showed that there exists sufficient statistical evidence that GB performed better than AS, while AS is similar to RS.

The s**tatistical analysis of winter 2017 data using the snow melted percentage** as the performance indicator included 669 observations, 13 variables (surface temperature, air temperature, dew point temperature, snow layer, relative humidity, barometric pressure, precipitation in 1 hour, wind speed, wind spread, max wind speed, solid rate (deicer application rate), speed of deicer truck, and deicer type), and only three deicer products, AS, GB, and RS. After removing of the outliers, the adjusted R-squared for the model was 0.6519. RS is not shown statistically different than GB and AS. On the other hand, there exists moderate evidence that GB performs worse than AS (p-value = 0.0118).

Ranking of Deicer Products Based on All Tests

In order to summarize the results, we ranked all the deicer products based on the numerical or comparative performances obtained from different tests: a discrete numeric score from 1 (best performance) to 6 (worse performance) was assigned to each product and the references.

Table 1 shows the ranking obtained from all performance tests conducted in Phase I (TEM WO 003) and II (TEM WO 005) of this project. Results from environmental and ecotoxicology testing performed in Phase I are not included as they did not show significant differences between the deicer products and because of the difficulty to weigh these rankings together with the performance rankings.

__Table 1__ Deicer product ranking in different tests performed (rank values range from 1–best to 6–worse)

		AS	BH	GB	MMZ	SB	RS
Laboratory tests	De-icing	1	6	3	2	4	4
	Anti-freezing	1	6	2	3	4	4
Parking lot tests - visual ranking							
Manufacturer formulation							
Image J	Solid		2		2	2	1
	Liquid	2		1			
Visual scores	Solid		1		3	3	1
	Liquid	2		1			
PennDOT's formulation		4	1	1	1	6	4
Parking lot tests - statistical analysis							
Manufacturer formulation		1	4	1	4	4	3
PennDOT's formulation		4	1	1	1	6	4
Skid resistance tests		N/A					
On-road real-time tests	Winter I - grip level	1					1
	Winter I - snow melted	1	1				2(1)
	Winter II - grip level	2		1			2
	Winter II - snow melted	1		2(1)			1-2

(1) Moderate evidence.

Integrating ranking from different tests into a single indicator was not feasible primarily because the preparation methods of the products were different in each test. We however discussed the ranking performances obtained from the lab test (Phase I) and the parking lots tests (Phase II). The skid resistance test (Phase II) did not show any significant difference between the deicer products and was not considered. Similarly, difficulties arose from the low statistical significance and partial ranking from the on-road tests (Phase II), which were not considered.

The parking lot tests provided several rankings depending on the preparation and analysis method. The test using the PennDOT's formulation for field operations (i.e., mixing the deicer product with SB 50:50 in volume before pre-wetting RS with 10 gallons per ton, application rate 500 lb/lane mile) gave consistent results with both analysis methods (visual scores and statistical models) with a ranking BH ≈ GB ≈ MMZ > AS ≈ RS > SB. Considering results from both analytical methods, the test using the manufacturer formulation indicated that the 'liquid' deicers performed better with GB > AS, and that among the 'solids deicers', RS performed better than the others, with an overall ranking of GB > AS > RS ≥ BH ≥ MMZ ≈ SB. When comparing the results from the laboratory tests (Phase I – TEM WO 003) with those from the parking lot tests, both using manufacturer recommendations for deicer preparation, statistical analysis showed some similarities: AS ranked first and BH ranked last (together with MMZ and SB) in both tests. On the other hand, little similarity was observed between the laboratory tests and the parking lot tests using PennDOT's formulation, which is not surprising considering the difference in product preparation. Results from the road tests gave partial ranking with limitation related to the statistical significance. Considering only significant results from all three models, the analysis indicates that AS ≈ BH and GB > AS ≈ RS. The ranking GB > AS ≈ RS is consistent with the parking lots test results using PennDOT's formulation.

Cost Analysis

Because of different conditions under which the different tests were conducted and because of the absence of significant results in some cases, it was not possible to integrate the results of all tests to conduct the cost analysis. The lab tests (Phase I – TEM WO 003) were not included in the analysis as no statistical models were computed and/or are available. The skid resistance test did not show any significant differences between the deicer products and was not considered either. Similarly, difficulties arose from the low statistical significance and partial ranking from the on-road tests, which were not considered.

Performance data from each parking lot tests and the costs of the products were used to perform the cost analysis. Table 2 shows the application rates of different deicers according to manufacturers' recommendations for the novel deicers and based on Gerbino-Bevins (2011) for SB.

Table 2 Recommended application rates for all deicers.

Deicer	Application	Recommended Rates
AS	De-icing and anti-icing	35-70 gal/LM
	Pre-wetting	8-10 gal/ton
GB	20% to salt brine	
BH	Deicing (mix with SB 50:50 in V)	35-45 gal/LM
	Anti-icing (mix with SB 50:50 in V)	15-25 gal/LM
	Pre-wetting	5 gal/ton
	Pre-wetting (cut with brine)	7 gal/ton
MMZ	Pre-wetting	6-8 gal/ton
SB	De-icing	20-80 gal/LM

Based on the recommended application rates and the price of each deicer as provided by PennDOT (March 2018), we selected three representative rates for de-icing, two for anti-icing, and three for pre-wetting, and calculated the deicer costs at these rates. The cost difference between the deicers products under study and SB was then calculated by dividing the cost of the deicer by that of SB (Table 3). This comparison shows that based on manufacturer recommendations, the costs of deicer products on a per gallon basis rank as BH (most expensive) > MMZ > GB > AS > SB (least expensive).

Table 3 *Cost of all deicers at different application rates.*

		De-icing, cost/mile			Anti-icing, cost/mile		Pre-wet, cost/100 lbs			Cost diff.
Deicer	**$ per gallon**	35 gal/LM	50 gal/LM	70 gal/LM	15 gal/LM	25 gal/LM	5 gal/ton	8 gal/ton	10 gal/ton	
SB	$0.16	$5.60	$8.00	$11.20	$2.40	$4.00	$0.04	$1.40	$2.00	1.0
AS	$0.72	$25.20	$36.00	$50.40	$10.80	$18.00	$0.18	$6.30	$9.00	4.5
BH	$1.66	$58.10	$83.00	$116.20	$24.90	$41.50	$0.42	$14.53	$20.75	10.4
GB	$1.20	$42.00	$60.00	$84.00	$18.00	$30.00	$0.30	$10.50	$15.00	7.5
MMZ	$1.38	$48.30	$69.00	$96.60	$20.70	$34.50	$0.35	$12.08	$17.25	8.6

The statistical analysis of the first parking lot test (using the manufacturer recommendations) concluded that GB ≈ AS > RS > BH ≈ MMZ ≈ SB. Based on the statistical analyses conducted in Task 1.4, the melted percentages at any given time and application rate were calculated. Then, the difference in performance between the deicers under study and SB were determined using on the following equation:

Difference = [(melted % of deicer – melted % of SB)/melted % of SB] *100 (1)

Using equation (1), we obtained the differences in AS vs. SB (Table 4) and GB vs. SB (Table 5). Since no statistically significant difference was observed between BH, MMZ and SB, no further calculation was conducted for BH and MMZ.

Table 4 *Increase in melted percentage as calculated based on equation (1) when AS was applied as the deicer as compared to SB at different times and application rates*

Time (min)	**Rate lbs/LM**				
	100	**200**	**350**	**500**	**700**
10	302%	289%	282%	278%	275%
20	524%	407%	354%	330%	311%
30	875%	554%	433%	383%	347%
40	-	736%	520%	438%	383%
50	-	-	614%	495%	418%
60	-	-	716%	554%	452%

Table 5 *Increase in melted percentage as calculated based on equation (1) when GB was applied as the deicer as compared to SB at different times and application rates*

Time (min)	**Rate lbs/LM**				
	100	**200**	**350**	**500**	**700**
10	330%	387%	420%	438%	452%
20	585%	561%	549%	543%	538%
30	996%	783%	694%	656%	627%
40	-	1064%	858%	775%	717%
50	-	-	1040%	902%	809%
60	-	-	1241%	1034%	901%

As shown in Table 4 and 5 and summarized in Table 6, AS melted between 2.8 and 8.8 times more snow than SB at different times and application rates, while GB melted between 3.3 and 12.4 times more snow than SB. Larger differences were observed at longer times and higher application rates.

Based on these data, we can conclude that AS is 4.5 times more expensive than SB, but its performance is 2.8 – 8.8 times better; GB is 7.5 times more expensive than SB, but its performance is 3.3 – 12.4 times better. BH and MMZ are 10.4 and 8.6 times more expensive than SB, but their performances are not statistically different from SB.

Table 6 *Cost analysis based on the first parking lot test data.*

	Cost difference	**Performance difference**
SB	1	0
AS	4.5	2.8 – 8.8
BH	10.4	Not significant
GB	7.5	3.3 – 12.4
MMZ	8.6	Not significant

The statistical analysis of the second parking lot test (using the PennDOT's formulation for field operations, i.e., mixing the deicer product with SB 50:50 in volume before pre-wetting RS with 10 gallons per ton, application rate 500 lb/lane mile) concluded that BH ≈ GB ≈ MMZ > RS ≈ AS > SB. Based on the statistical analyses conducted in Task 1.4, we calculated the melted percentage at any given time, as shown in Table 7. Note the application rate was fixed at 500 lbs per lane mile in this test. Equation (1) was then applied to calculate differences in melted percentage between the novel deicers and SB, as shown in Table 7.

Table 6 *Estimated melted percentages at different times based on the models computed in Task 1.4.*

Time (min)	**10**	**20**	**30**	**40**	**50**	**60**	**75**
SB	3.24	3.40	3.56	3.72	3.88	4.04	4.28
AS	3.98	4.14	4.3	4.46	4.62	4.78	5.02
BH	5.14	5.30	5.46	5.62	5.78	5.94	6.18
GB	5.71	5.87	6.03	6.19	6.35	6.51	6.75
MMZ	6.43	6.59	6.75	6.91	7.07	7.23	7.47

Table7 *Increase in melted percentage of the deicers calculated based on equation (1) as compared to SB at 10 – 75 min with the application rate of 500 lbs per lane mile.*

Time (min)	**10 min**	**20 min**	**30 min**	**40 min**	**50 min**	**60 min**	**75 min**
SB	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AS	22.8%	21.8%	20.8%	19.9%	19.1%	18.3%	17.3%
BH	58.6%	55.9%	53.4%	51.1%	49.0%	47.0%	44.4%
GB	76.2%	72.6%	69.4%	66.4%	63.7%	61.1%	57.7%
MMZ	98.5%	93.8%	89.6%	85.8%	82.2%	79.0%	74.5%

For each deicer, rather similar differences were observed at all time points, allowing us to use the average differences across all time points to conduct the cost comparison, as shown in Table 8. We can then conclude that, on average, AS, BH, GB, and MMZ performed 20%, 51.3%, 66.7%, and 86.2% better than SB, respectively, in melting snow between time zero and 75 min, while they are 4.5, 10.4, 7.5 and 8.6 times more expensive than SB using the same application rate.

Table 8 *Cost analysis based on the second parking lot test data.*

	Cost difference	**Performance difference**
SB	1	0
AS	4.5	20.0 ± 2.0%
BH	10.4	51.3 ± 5.0%
GB	7.5	66.7 ± 6.5%
MMZ	8.6	86.2 ± 8.4%

IMPLEMENTATION PLAN

Two different types of tests were conducted during the course of the study: parking lot tests and on-road real-time tests. For each of them, a protocol was developed based on real field conditions. The protocols include deicer sample preparation and selection of deicer application rates, general and specific information collection, data collection, and data processing. The protocols provide a practical guidance for the conduction of the tests.

The sections below summarize the different steps of the studies and provide references to the corresponding sections of the different Task Reports. In addition, guidance and evaluation of advanced statistical analyses used to process the data are provided.

PARKING LOT TESTS

Protocol

The protocol for the parking lot tests includes the deicer product preparation and determination of application rates, which are based on either the manufacturer's or the PennDOT's formulation for field operations (i.e., mixing the deicer product with SB 50:50 in volume before pre-wetting RS with 10 gallons per ton, application rate 500 lb/lane mile) (**Task 1.1 Report, Section 1**). Then, the parking lot grids are defined (3'x3'boxes, three 3'x3' boxes for each compound and corresponding loading rate) (**Task 1.1 Report, Section 2**). Next, general information (e.g., date, time, pavement type, etc.) and specific information (e.g., deicer type, application rate, weather information) are collected (**Task 1.1 Report, Sections 3, 4, and 5**). The proper amounts of deicing chemicals are then applied on their respective 3 ft x 3 ft test areas using the recommended application rates.

Data Collection

Pictures of each 3ft x 3ft test area are taken every 10-15 minutes (**Task 1.1 Report, Sections 6 and 7**). For the deicing tests, the deicers are applied when about half-an-inch of snow accumulates on the test area and pictures are taken at time zero and then every 10-15 minutes (**Task 1.1 Report, Section 8**).

Data Processing

For the image processing, two photo analysis methods were developed: the 'visual' analysis and 'Image J' analysis methods. For visual analysis, two researchers assign scores to each image independently and the scores are averaged. For Image J analysis, all scores are based on an average of three replicate images (**Task 1.2 Report, Section 2.10**). Based on the comparison operated in this study, the two methods generally yielded similar results for all the deicer performances.

Procedure Evaluation

Overall, the parking lot tests provided reliable and consistent results which allowed us to establish a ranking of the products based on their performance in term of snow melting. The advantage of the parking lot tests is that all products and application rates are tested at the same time, during the same storm, eliminating the interferences and variability due to different weather and traffic conditions. The drawback is that such controlled conditions may not reflect well the actual road conditions, in which traffic may play an important role.

Recommendations for Future Testing

Two parking lot tests were conducted using the manufacturer's and PennDOT's application rates, leading to very different performance values impossible to integrate together. The Team recommends that only one preparation and application method, which is the most relevant to PennDOT, would be decided and used.

DEICER SKID RESISTANCE TESTS

Protocol

Skid resistance tests are conducted using a setting similar to the parking lot tests described above and usually during the same storm events. The effect of products on skid resistance is tested using a British pendulum. The pendulum measures the frictional resistance between a rubber slider mounted on the end of a pendulum arm and the test surface. This provides a routine method for checking the resistance of wet and dry surfaces to slipping and skidding, both in the lab and on site. The deicer products are prepared according to the manufacturer's protocol using a single application rate of 500 lb per lane mile (**Task 1.3 Report**).

Data Collection

Measurements are taken on 3 ft x 3 ft plots within the same day. The test includes a pre-application testing, 1^{st} post-application testing, and 2^{nd} post-application, which each includes measurements at 15-min intervals for 60 min (**Task 1.3 Report**).

Data Processing

Data are analyzed by plotting the skid values at different time points and comparing the trends between deicer products (Task 1.3 Report).

Evaluation of the Test

Testing results show general improvement in skid resistance compared to wet conditions (plowing only with no deicers), with the exception of a few data points during the test. For ranking purposes, the results are inconclusive – except for one product (AS) which consistently had the lowest performance on skid resistance.

Recommendations for Future Testing

The Team recommends to adjust the time gap between applications based on real-time data for the precipitation.

Even though the testing data provide insight into the range of performance associated with the products, the results did not allow an overall ranking of the products, likely due to the different variables playing a role.

STATISTICAL ANALYSIS FOR PARKING LOT TESTS

Procedure

The linear regression method is applied to establish models for the transformed deicers performance data based on other variables, such as the time and application rate (**Task 1.4 Report, Section 2**). The statistical analysis is using the professional statistical analysis software R® Project, version 3.3.3 (https://www.r-project.org/). The model typically includes one response variable, (e.g., melted snow percentage, skid resistance) and several independent variables (e.g., time, deicer type, and application rate). Variables as time and application rate are continuous variables, while the deicer type is a categorical variable. To address the issue of non-Gaussian distribution of the response variable, a Box-Cox transformation is used.

In order to consider the interactions between all independent variables, various candidate models are evaluated based on the Akaike information criterion (AIC). Upon passing the goodness-of-fit test, the parameters from the best model are used to perform a pair-wise comparison between the different deicer products based on Tukey's adjustment for multiplicity. This allows to identity pairs of deicers that perform significantly differently from each other (**Task 1.4 Report, Section 2**).

Evaluation of the Test

For both parking lot tests, good quality regression models were obtained, allowing statistically significant ranking between the deicer products. Moreover, the ranking obtained from the statistical analysis was generally consistent with the ranking obtained from the direct visual processing of the results. On the other hand, and as already determined from the direct observations, no significant ranking was obtained for the skid resistance data. This issue is believed to be related to the data instead of the processing methods.

Recommendations for Future Testing

The Team recommends to use the described statistical method for processing results from parking lot tests.

ON-ROAD REAL-TIME TESTS

Protocol

The protocol provides guidance for three phases of the field tests: 'pre-operation', 'during operation' (collection from RWIS and AVL), and 'post-operation' phases (data analysis, deicer ranking statistical analysis).

In the 'pre-operation' phase, testing stations are identified well ahead of time (**Task 2.1 Report, Section 1**). It includes preliminary information about the station, trucks, and historical data from RWIS and AVL about the site was collected. Drivers and trucks for each test station, back-up trucks (in the case of mechanical issues), the routes of the trucks and locations of the test are identified. The type of deicer, amount of deicer to spread, time of spreading, and frequency of spreading are decided by PennDOT. General information is also collected, including date and time, location of the test, pavement type, pavement conditions, type of the precipitation, material applicator, etc.

For the 'during operation' phase, the Team should have a vehicle available to take them to the test areas and collect all needed data (Task 2.1 Report, Section 2). After completing the first round of testing, the site is monitored for the 2nd passing of the same truck, which indicates the test has restarted. A 3rd passing is recommended. If RWIS is used for data collection, a truck passing is marked as time zero.

In the 'post-operation' phase, data needed for on-road evaluation of deicers are collected both from RWIS and AVL system and through communication with PennDOT (**Task 2.1 Report, Section 3**). Data is then collected about the condition of the camera capture system, vehicles location (latitude and longitude), weather conditions (RWIS) including temperature, precipitation, wind speed, wind direction, etc. For each test, relevant data extracted from the above list are compiled and organized in a multiple-sheet Excel files. Data are classified as (a) metadata, (b) performance data derived from picture analysis and team observations, (c) deicer application data, (d) weather condition data, and (e) traffic data. Ranking the deicer materials is based on the collected data, during different storms, under different road and weather conditions, which requires statistical treatment in order to extract the impact of the deicer material type and rate of application from other relevant environmental variables (**Task 4 Report, Section 2.2**). A statistical model is built to establish relationships between the performance of deicer products and independent variables, including application rate, weather conditions, and traffic density. The goal of the statistical analysis is (i) to detect if there is any significant difference among the performance of the deicer products and (ii) to rank the deicer products.

The finalized testing protocol also includes a description of the storm (i.e., a snow storm of 0.5-1 inch per hour was optimum) and the notification of monitoring events by PennDOT (e.g., type of deicer, rate of application, time of application, and frequency of application), the duration of the tests and the relevant information to be collected for each passing, the criteria for assigning reasonable visual scores, and statistical analyses based on multivariate regression (**Task 2.2 Report**).

It is then useful to collect preliminary on-road real-time data during selected storm events (without using deicer products being tested) in order to assess the quality and accuracy of data collected from AVL and RWIS systems, including the photographs to be used for the evaluation of the deicer performances, and significant relationship between the different variables monitored (**Task 2.2 Report**).

Data Collection

Data collection has been detailed in the previous section. In brief, the data can be divided into two types: data from the RWIS system and data from the AVL system (**Task 3.1 Report, Section 2 and Appendix 1**). The RWIS system continuously tracks and stores the following data for each site; surface temperature, surface state (dry or wet), air temperature, dew point temperature, relative humidity, rain state atmospheric site, rain intensity, wind speed, wind direction, visibility, salt concentration, barometric pressure, precipitation rolling average past 1, 3, 6, 12, and 24 hours, ground temperature, water thickness, camera shots of the road condition. Data are collected every 5 min. The AVL system gives the following deicer information: solid material, solid rate, solid application time, solid spread, prewet rate, prewet spread, anti-ice rate, and anti-ice spread.

Two different strategies were used for the conduction of the on-road real-time field tests. During the winter 2016-2017, the deicers were evaluated via paired experiments including each the treatment site (treated with the deicer to be tested) and a nearby reference site (treated by the reference RS) – eight sites in total (**Task 3.1 Report**). The primary performance indicator for the deicers in this phase was the snow melted percentage derived from photographs taken by on-site cameras. During the winter 2017, the same deicers were evaluated using five sites all equipped with grip level sensors (one site for each deicer tested and one for the reference RS). The primary performance indicator for the deicers in this phase was the grip level (**Task 3.2 Report**).

Data Processing

All data collected from RWIS and AVL system, as well as the snow melted percentages from the photograph analysis (image processing is performed as described above for the parking lot tests) are organized in Excel files (**Task 3.1 Report, Section 2**). Different relevant variables are then plotted as a function of the time during the storm. The deicer application rates and truck passages are identified on the graphs, allowing the visual, qualitative analysis of the deicer efficiency. In addition, the relationships between the different variables is examined through the computation of correlations matrices including all environmental variables recorded by the RWIS system plus the snow melted percentage derived from the photographs.

The environmental variables most indicative of the road conditions and deicer field performances are temperatures (surface and air) and precipitation. Among all the precipitation variables, the 'precipitation rolling average past 1 hour' appeared to be the closest to the real-time data and is selected. Four variables representative of the road conditions are used (when available): the grip level, salt concentration, snow layer, and snow melted percentage (derived from the on-site automated cameras) (Task 3.2 Report, Section 2).

This analysis, which is essentially qualitative, does not allow ranking the deicer products, but is useful to assess the consistency and reliability of the data as well as to establish significant correlations between the variables. Statistical analysis of the data will be described in the next section.

Procedure Evaluation

During the winter 2016-2017, the primary performance indicator for the deicers was initially the snow melted percentage derived from photographs taken by on-site cameras. The data collected reveals that few events allowed the use of photographs because of darkness, poor visibility, and/or technical issues. Additional tentative indicators were then considered, including the grip level and salt concentration. At the sites equipped with grip level sensors, the grip level decreased with precipitation and increased after deicer applications. At the sites equipped with salt concentration sensors, the salt concentration was in general inversely correlated with precipitation, but fluctuated largely for unknown reasons. The grip level was then identified as a more robust indicator of the snow condition and deicer performance (**Task 3.1 Report, Section 3**).

During the winter 2017, the same deicers were evaluated using five sites all equipped with grip level sensors (one site for each deicer tested and one for the reference RS). Due to technical issues independent of the Team's responsibility, only data of one storm event were collected for GB and no data were collected for BH and MMZ.

Correlation matrix analyses showed significant correlations between the grip level, snow level, precipitation 1-hour, and snow melted percentage. Overall, both the grip level and snow layer appear to be reliable indicators of the snow condition of the road and deicing performance (**Task 3.2 Report, Section 3**).

Recommendations for Future Testing

Although the first phase of the on-road study used paired tests including each two nearby sites – one for the deicer to be tested and the other for the reference – the statistical analysis of the data requires introducing all data from all sites (all deicers) and all storm events into *one* single statistical model.

Therefore, it appears that only one reference site (RS) would be sufficient. The team thus recommends to use one site per deicer product to be tested and one for the reference.

The snow melted percentage (derived from the on-site photographs) is often not available because many storms occurred in the dark, or because poor visibility or technical issues. Also, the salt concentration levels fluctuated widely and did not correlate well with the snow melted percentages. The Team therefore recommends the use of the grip level as the performance indicator of the deicers and snow conditions on the road. The grip level was found to be well correlated with the snow melted percentage (when available).

STATISTICAL ANALYSIS FOR ON-ROAD TESTS

Procedure

A linear regression method similar to the one described for the processing of the parking lot test results is used to establish models for the prediction of transformed deicers performance data by other external variables, such as the time and application rate (**Task 4 Report, Section 2.2**).

The statistical analysis uses the professional statistical analysis software R® project, version 3.3.3 (https://www.r-project.org/).

The linear regression models is used to establish relationships between a scalar dependent variable Y (in our case the grip level and the snow melted percentage) and one or more explanatory or independent variables X (e.g., variables recorded by the RWIS system, such as surface temperature, humidity, and snow layer). All data in Excel worksheet are converted into CSV format (comma delimited) and then imported into R. The linear regression model is fitted using the ordinary least square (OLS) approach in R. Among all the deicers, the RS is set as the reference deicer. Outliers in data sets are identified as observations with standardized residues larger than 3 or less than -3 and removed. Bi-directional stepwise regression is used to select the significant variables and choose the candidate model based on the Bayesian Information Criteria (BIC) (R package MASS). After fitting and optimizing the model, pairwise comparison of all the deicers is performed using Tukey’s adjustment for the multiplicity (R package 'multcomp').

Evaluation of the Test

The multivariate linear regression method should include all data from all storms and all deicers (i.e., all sites) into one model descriptive of the deicer performance (i.e., snow condition on the road). Because two indicators of the deicer performance were used and because data from the winter 2016-2017 and 2017 could not be integrated into the same model due to differences in the application method, four models were computed: (1) winter 2016-2017 data using the snow melted percentage as performance indicator, (2) winter 2016-2017 data using the grip level as performance indicator, (3) winter 2017 data using the snow melted percentage as performance indicator, and (4) winter 2017 data using the grip level as performance indicator.

Because of various technical issues in data collection independent from the Team's responsibility, only limited or no data were collected for some deicer products, preventing the comparison between all the five products. These technical issues combined with the lack a storm events in the two phases of the study resulted in limited data sets, preventing in most cases to obtain statistically significant ranking of the deicer products. Only partial comparison between deicers was obtained.

However, in some cases (e.g., winter 2017 data using the grip level as the performance indicator), enough data were collected to obtained statistically significant ranking among some of the products, which indicates that the statistical method seems to be working, provided that enough data could be collected.

Recommendations for Future Testing

On-road tests are characterized by integrating deicer performance data collected under a wide variety of conditions (different sites, different storms) and are influenced by a multitude of external, environmental parameters. The statistical treatment of the data is performed in order to extract the impact of the deicer type and application rate from a range of other environmental variables. In order to achieve statistical significance, it is of paramount importance to collect large sets of data, which partially depends on the weather and partially in the collection strategy.

In order to maximize the size of the data sets, the Team recommends using the same performance indicator and consistent application rates and methods during the entire duration of the test.

On the other hand, traffic on the road is likely to have an impact on the snow condition on the road and should be integrated into the statistical model.

COST ANALYSIS

Procedure

Based on the application rates recommended by the manufacturer and the price of each deicer as provided by PennDOT (March 2018), the cost difference between the products under study is calculated and expressed by comparison with the reference (**Task 4 Report, Section 4**).

Then, the performance indicators collected during the tests are used to calculate the difference in performance between the deicers under study and the reference product. The following equation is used:

Difference in performance = [(deicer performance – reference performance)/reference performance] *100

The differences in performance can then be compared with the cost differences to evaluate the benefit versus cost of each deicer product (**Task 4 Report, Section 4**). In certain cases, the differences in performance are given as a range because different performance values can be obtained for different application rates.

Evaluation of the Test

Because of the different conditions under which the different tests were conducted and because of the absence of significant results in some cases, it was not possible to integrate the results of all tests to conduct the cost analysis. The skid resistance test and on-road test were not considered because they showed no or low statistical significance and/or provide only partial ranking. Only the parking lot test data were used for the cost analysis.

The differences in performance and cost differences could be used to evaluate the benefit versus cost of each deicer product. For instance, based on the second parking lot test, AS was found to perform 20% better than SB (based on the averaged snow melted percentage) but it costs 4.5 times more than SB.

The inability to use the on-road test data for the cost analysis is not related to the cost analysis method, but rather to the absence of statistically significant results on the deicer performance (as explained above). Obtaining statistically significant models for each deicer products would allow us to evaluate the benefit versus cost of the products, in a manner similar to what was done for the parking lot tests.

Recommendations for Future Testing

Because the amount of available data is the critical factor to obtain statistically significant results, the Team recommends again to maximize the size of the data sets, for instance by using the same performance indicator and consistent application rates and methods during the entire duration of the test.

CONCLUSIONS

In this study, the performances and cost analysis of four deicers products, i.e., Aqua Salina (AS), Beet Heet (BH), Green Blast (GB), Magic Minus Zero (MMZ), and the references, Rock Salt (RS) and/or Salt Brine (SB) were evaluated through parking lot tests (Task 1) and on-road tests (Task 3). In the prior phase of the project, the performances of the products were evaluated through laboratory tests (Phase I – TEM WO 003). The parking lot tests considered two performances indicators, the snow melted percentage and skid resistance. The skid resistance test (Task 1.3) results did not show significant differences between the deicer products and were not usable.

The integration of the ranking results from different tests into a single indicator was not feasible because different formulations and application rates were used in the various tests, e.g., using manufacturer's or PennDOT's formulation for field operations (i.e., mixing the deicer product with SB 50:50 in volume before pre-wetting RS with 10 gallons per ton, application rate 500 lb/lane mile), addition of anti-skid agents or not, etc. Nevertheless, the rankings from the different tests were compared and discussed. The laboratory tests (Phase I) provided the following ranking: AS performed better than GB and MMZ (GB and MMZ were equivalent), GB and MMZ performed better than SB and RS (SB and RS were equivalent), and SB and RS performed better than BH. On the other hand, the parking lot tests using the PennDOT's formulation gave the following ranking: BH, GB and MMZ were equivalent and performed all better than AS and RS (AS and RS were equivalent), and AS and RS performed better than SB, while the parking lot test using the manufacturer's recommendations provided an overall ranking that can be summarized as GB performed better than AS, AS performed better than RS, RS performed better than or was equivalent to BH, BH performed better than or was equivalent to MMZ and SB (MMZ and SB were equivalent). The second parking lot test therefore shows little consistency with the laboratory tests. Considering only the significant results, the road tests suggested that AS was equivalent to BH and GB performed better than AS and RS (AS and RS were equivalent). The ranking 'GB better than AS and RS' is consistent with the parking lots test using PennDOT's formulation. Ranking deicer products based on these tests gave relatively inconsistent results, primarily because of the different formulations and application rates used.

Because of different conditions under which the different tests were conducted and the absence of significant results and/or complete results in some cases (e.g., on-road tests), it was not possible to integrate the results of all tests to conduct cost analysis. The lab tests (Phase I) were not included in the analysis as no statistical models were computed and/or are available. Difficulties arose from the low statistical significance and partial ranking from the on-road tests (Phase II), which were not considered either.

Only the performance data from both parking lot tests (Phase II) were therefore used to perform the cost analysis. Using the manufacturer's recommended application rates and the price of the deicers provided by PennDOT, the cost difference between the deicer products under study and SB was calculated showing the following ranking (on a gallon-per-lane-mile basis): BH (cost difference 10.4) performed better than MMZ (cost difference 8.6), MMZ performed better than GB (cost difference 7.4), GB performed better than AS (cost difference 4.5), and AS performed better than SB (cost difference 1.0).

Results from the first parking lot test (using the manufacturer's recommendations) were used to calculate the differences in performance between the deicers product under study and the reference, SB. It can be concluded that the performance of AS was 2.8 – 8.8 higher than SB (AS was 4.5 times more expensive), performance of GB was 3.3 – 12.4 times higher than SB (GB was 7.5 times more expensive), the performances of BH and MMZ were not statistically different from SB (BH and MMZ were 10.4 and 8.6 times more expensive, respectively).

Results from the second parking lot test (using PennDOT's formulation for field operations) were also used to calculate the differences in performance. It can be concluded that AS, BH, GB, and MMZ performed 20%, 51.3%, 66.7%, and 86.2% better than SB, respectively, although the cost differences by comparison to SB were 4.5, 10.4, 7.5 and 8.6 times, respectively.

CONTRACT NO. 4400011166
TEM WO 005
DELIVERABLE 1.1 PARKING LOT TEST PROTOCOL

JUNE 8, 2016

1. Deicer Preparation. Deicers will be prepared per manufacturer recommendations (for the selected deicer, the manufacturer recommendations is attached in a separate file). To have enough deicers of consistent quality for all parking lot tests, deicers should be prepared in bulk quantity. The deicers will be weighed out into 5-gallon buckets, then mixed with proper amounts of additives, as shown in Table 1.1. Each deicer should then be well mixed with a stir rod and contained for later use.

Table 1.1 Deicer Preparation

Name of Deicer	Mixes With	Mixing Ratio	Mixing ratio for 5-gallon bucket*
rock salt	None	N/A	N/A
rock salt-salt brine	salt brine	1 ton rock salt/10 gallons salt brine	18143 g rock salt + 756.56 mL of salt brine
Magic Minus 0	rock salt	10 gallons Magic Minus 0/ton rock salt	18143 g rock salt + 756.56 mL of Magic Minus 0
BEET HEET	rock salt	5 gallons BEET HEET /ton sock salt	18143 g rock salt + 377.37 mL of BEET HEET
GreenBlast	salt brine	1 gallon of GreenBlast/4 gallons of salt brine	4 gallons salt brine + 1 gallon GreenBlast (3785.4 mL)
AquaSalina	None	N/A	N/A

** 5 gallon bucket of rock salt ≈ 40 lbs. (= 18143 grams); 10 gallons/ton = 0.0417 mL/gram; 5 gallons/ton = 0.0208 mL/gram.*

1.1. Deicer application rates for 3 ft. by 3 ft. test Area.

The selected application rates are based on either manufacturer's recommendations or published data. According to Druschel 2014, four different application rates (i.e., 200, 350,500, and 700 lb. per lane mile) should be tested for the solid deicers (i.e., rock salt, and rock salt pre-wetted with salt brine, BEET HEET, and Magic Minus Zero). For AquaSalina, the manufacture's recommendation is 20-70 gallons per lane mile for deicing. For the test area, 20, 35, 50, and 70 gallons per lane mile will be used. Based on the recommended application rates for salt brine (Gerbino-Bevins 2011), four application rates of 20, 40, 60, and 80 gallons per lane mile will be used for GreenBlast.

Application Rate	Deicer needed for 3' x 3' area	Deicers Rate Used For
200 lbs./Lane Mile	12.88 g	rock salt, rock salt w/ brine, Magic Minus 0, BEET HEET
350 lbs. /Lane Mile	22.54 g	rock salt, rock salt w/ brine, Magic Minus 0, BEET HEET
500 lbs. /Lane Mile	32.20 g	rock salt, rock salt w/ brine, Magic Minus 0, BEET HEET
700 lbs. /Lane Mile	45.08 g	rock salt, rock salt w/ brine, Magic Minus 0, BEET HEET
20 Gallons/Lane Mile	10.75 mL	AquaSalina, GreenBlast
35 Gallon /Lane Mile	18.81 mL	AquaSalina
40 Gallons/Lane Mile	21.50 mL	GreenBlast
50 Gallons Lane Mile	26.87 mL	AquaSalina, GreenBlast
60 Gallons/Lane Mile	32.25 mL	GreenBlast
70 Gallons/Lane Mile	37.47 mL	AquaSalina
80 Gallons/ Lane Mile	42.77 mL	GreenBlast

Example of a calculated amount of deicer for an application rate:

$$200\,\frac{lbs}{ln.mile} = 200\,\frac{lbs}{63360\,\frac{ft^2}{ln.mile}} = 0.0031\;lbs * 9\;ft^2 = \;\; 0.0284\;\frac{lbs}{9\;ft^2} = 12.88\;g/9ft^2$$

Note: Weigh/measure predetermined amounts of chemicals as needed. The deicers will be stored in pre-labeled 50-mL plastic centrifuge tubes.

2. <u>Test Grid Set-up</u>. For the parking lot test, there will be two ways to set up test grids. The primary way is to use a parking lot grid that has been set-up. The other way is to make quick grids on the ground. Quick grids may be used when test grids are not available and/or when only a few tests (< 10-20) will be carried out.

   2.1. Parking Lot Grid: Consists of 72-3’x3’boxes, three 3’x3’ boxes for each compound and corresponding loading rate (Figure 1). The 72 boxes will be arranged following a Randomized Block Design in order to minimize the impact of the box location on the parking lot (e.g., insulation, wind, local temperature variation, pavement variation). Each square has a 1’ contamination zone in which testers will be able to walk and take pictures of each grid. Each square will have rope around the nail perimeter and a sign, to designate which deicer is in use.

Figure 1. Parking Lot Grid

2.2. Quick Grids: Can be made directly in the snow with a yard stick, 3’ by 3’ grids. Quick and efficient for on the go testing. Only to be used if the parking lot grid is unavailable. Figure 2 below is an example of a quick grid.

Figure 2. Quick Grid.

3. Application of Deicer: When applying the deicer on the test areas, the solids should be well shaken out of their bottle/bags by hand using protective gears and distribute the deicer evenly through the test area. For the liquid deicer, spread in a straight horizontal line down on the test area. Be sure to spread the chemicals at a height low enough so there is no contamination to other test areas.

4. General Information Collection: Right before the storm event starts, the following general information should be documented:
   - 4.1. Date and time of test
   - 4.2. Location of the test
   - 4.3. Pavement type
   - 4.4. Pavement conditions (snow covered, ice covered)
   - 4.5. Type of precipitation (light snow, medium snow fall)
   - 4.6. Material applicator (hands, spreader, squirt bottle)
   - 4.7. Testers name
   - 4.8. Picture of each test area initial conditions

General Information Table Format

General Information

Test Performed by:	
Date of Test:	**-**
Time of Test:	**-**
Location of Test:	**-**
Pavement Type:	**-**
Pavement Condition:	**-**
Pavement Temp	**-**
Type of Precipitation:	**-**
Applicator Used:	**-**

5. Specific Information Collection: The following specific information pertaining to each test area should be documented:
   5.1. Type of deicer
   5.2. How the deicer is prepared
   5.3. Application time
   5.4. Application rate
   5.5. Pavement temperature (use temperature gun, be sure to measure the pavement temperature, not the snow or ices)
   5.6. Air temperature (use local weather station)
   5.7. Type of precipitation and precipitation amount (use local weather station)
   5.8. Cloud coverage (visual observations)
   5.9. Observations every 10-15 minutes (This includes any variance or abnormalities in the test)
   5.10. A scuff test to test slipperiness of pavement (done with testers shoe) Specific Information and Observations Format

Specific Information

Type of Deicer:	**-**
Deicer Preparation:	**-**
Application Time:	**-**
Application Rate:	**-**
Pavement Temperature:	**-**
Air Temperature:	**-**
Precipitation Amount:	**-**
Cloud Coverage:	**-**

Observations

Time (mins)	Observation:
0	
10	
20	
30	
40	
50	
60	
75	

6. Anti-icing Test: 12 to 24 hours before a winter storm event, spread proper amounts of deicing chemicals on their 3 ft by 3 ft test areas using manufacturer's application rate. (For this project, based on the manufacture's recommendations, the application rates for anti-icing are 30-50 gallons per lane mile for AquaSalina, 15-25 gallons per lane mile for BEET HEET. For GreenBlast and Magic Minus Zero, application rates are not specified by the manufactures, thus, based on the recommended application rates for rock salt and salt brine (Gerbino-Bevins 2011), the application rates are 100 or 200 lbs. of rock salt per lane mile (pre-wetted with 10 gallons of Magic Minus Zero/ton NaCl), or 20-50 gallons per lane mile for GreenBlast and salt brine.

7. Image Collection: During the testing of deicers, pictures should be taken every 10-15 minutes of each 3ft by 3ft test area. The pictures should be taken with the same type of camera on a tripod with fixed height and angle of inclination. All pictures should be in landscape format and the cameras flash should be on for all pictures. Note that Apple products should not be used since they do not function well in winter weather.

Picture Format in Excel

8. De-icing Test: When there is about half-an-inch of snow accumulated on the test area, appropriate amounts of deicers will be applied based on the table in Section 1.1, which is considered as time zero. Following the same rules as specified above, pictures will be taken at time zero and every 10-15 minutes of each 3' by 3' test area. It is recommended to take short videos of the test area at least once during the test. Note that it is not recommended to conduct parking lot tests during heavy snow events (e.g., > 0.5-1 in. of precipitation per hour), because snow can quickly cover the test area to make it difficult to observe deicer performance. Data collection will follow the above protocols specified in Sections 4, 5, and 7.

9. References:

Gerbino-Bevins, B. M. 2011, "Performance rating of de-icing chemicals for winter operations", Master's thesis, Department of Civil Engineering, University of Nebraska.

Stephen J. Druschel, Salt Brine Blending to Optimize Deicing and Anti-Icing Performance and Cost Effectiveness, Phase II, Minnesota Department of Transportation Final Report 2014-43. December 2014.

CONTRACT NO. 4400011166
TEM WO 005
DELIVERABLE 1.2 REPORT DETAILING DEICER PERFORMANCE FOR SIMPLE GARAGE/PARKING LOT DEICING/ANTI-ICING TEST

APRIL 19, 2017

SUMMARY

Proper use of deicing materials protects road safety but bears significant cost. Testing the performance of new deicer products is necessary on the winter roadway because it reflects real environmental conditions which cannot be replicated in the laboratory. The purpose of this project was to perform two parking lot tests of the deicer products that were evaluated in a prior laboratory study under Work Order TEM 003 entitled "Effective Use and Application of Winter Roadway maintenance Material Enhancers". A simple garage/parking lot test was performed to evaluate the deicer deicing performance at two different mixing ratios and four application rates. The six deicers tested in this project are: AquaSalina, BEET HEET, Green Blast, Magic minus zero, rock salt, and rock salt pre-wetted with salt brine. The last two deicers were examined as the reference chemicals.

First, a reliable protocol for simple garage/parking lot deicing tests was developed based on real field conditions. This protocol includes deicer sample preparation, selection of deicer application rates for both solid and liquid deicers, test grid set-up, deicer spreading process, general information collection, specific information collection, image collection, data collection and image analysis method development. This protocol provided a practical guidance for this parking lot test; moreover, this protocol will effectively guide future deicer performance testing.

For the image processing, two photo analysis methods have been developed in this work. They are visual analysis and Image J (binary) analysis methods. For visual analysis, two researchers assigned scores to each image independently. There were also three replicates for each test, so the visual scores were based on an average of six scores. For Image J analysis, all scores were based on an average of three replicate images. To ensure that the photo analysis data were reliable, the parking lot test photos were analyzed with both methods. Based on the comparison, the two methods generally yielded similar results for all the deicer performance. However, the two methods have their respective advantages and disadvantages. For example, there are some unexpected errors when the Image J method was used. On the contrary, the visual analysis showed more stable and time-efficient results (e.g., 3-5 min for Image J versus around 1 min for visual analysis). When continuous snowing processes are taken into consideration, the Image J method has some advantage in calculating the extent of melting for some liquid deicers.

During the first parking lot test, the deicers were prepared based on the manufacturers' recommendations. Four application rates were applied for the four solid deicers (i.e., 200, 350, 500, and 700 lb. per lane mile for rock salt, rock salt pre-wetted with salt brine, BEET HEET and Magic minus zero) and the two liquid deicers (i.e., 20, 35, 50, and 70 gallons per lane mile for AquaSalina and 20, 40, 60, and 80 gallons per lane mile for Green Blast). Based on the results we can conclude that higher application rates almost always led to better deicing performance during the whole reaction period (0-75min) (e.g., the average

melting percentage increased from 1% to 7% based on Image J analysis).Qualitative rankings of both the solid and liquid deicers were obtained based on the testing results: for the solid deicers: rock salt > BEET HEET ≈ salt brine ≈ Magic minus zero (Image J analysis method), or rock salt ≈ BEET HEET > salt brine ≈ Magic minus zero (Visual analysis method). For the liquid deicers: Green Blast > AquaSalina (Both Image J and visual analysis methods). The average melted percentages of different deicers are between 2%~7% for Image J analysis and 2%~17% for visual analysis during the entire testing period (0-75min). These melted percentages are much lower than what we observed during the preliminary real-time on-road field tests (typically 20%-100% melted), which likely yielded relatively larger errors during the data analysis process. As a result, it led to smaller differences in the deicing performance of all the deicer products. Future statistical analysis should provide more quantitative evaluation of the deicer performance in the next part of the project.

The second parking lot test was conducted with the deicer mixing ratio following Penn DOT field operations (i.e., mixing deicer products with salt brine 50:50 in volume before pre-wetting rock salt 10 gallons per ton). The application rate was 500 lb/lane mile. During the entire reaction time, all the deicers had an increasing trend in the melting efficiency. The visual scores were based on an average of six scores from two researcher and triplicate tests. All the melted percentage values ranged from around 3% to 7% during the 75-min reaction time. The qualitative rank is as follows: BEET HEET ≈ Green Blast≈ Magic minus zero > rock salt≈ AquaSalina > salt brine. The difference between this rank and the rank above based on the first test may be attributed to the fact that when we blended these deicers with salt brine at 50:50 before pre-wetting rock salt, the real mass loading of each deicer was much lower than when they directly pre-wetted rock salt. As a result, the melted percentages may not be significantly high enough to yield substantial differences among the deicers (e.g., up to 17% melted in the first parking lot test vs. only up to 7% melted in the second test by the end of 75-min).

When compared with the previous lab test results where the deicers were prepared in the same way as in the first parking lot test, the overall product ranking is different. For the laboratory test, the ranking is as follows: AquaSalina ≥ Green Blast > Magic minus zero > rock salt ≈ salt brine > BEET HEET. In the lab test, two product performance tests were conducted: the modified ice melting test and eutectic curves. The existing laboratory tests may not accurately predict field performance. This may be attributed to the fact that the environmental conditions are more complicated, and the melting performance on the ice versus on the snow could be different. In the future, real-time on-road field tests should be conducted to evaluate the deicers performance to obtain a more reliable deicer ranking.

1. Introduction

Extensive use of deicing materials bears both significant costs and potential environmental impacts which can result in ecosystem harm or degradation of drinking water quality. New deicing formulations are continuously developed, necessitating testing to evaluate product performance, environmental concerns, and financial costs. Laboratory testing can provide information about direct effects under strictly controlled conditions; however, previous research has demonstrated that field results are often different from laboratory results, likely due to a range of factors, including variable environmental and traffic conditions. These factors could significantly affect the product performance.

During this study, the deicing performance of six deicers (i.e., AquaSalina, BEET HEET, Green Blast, salt brine, rock salt, and Magic minus zero) was tested in the absence of vehicular traffic. A simple garage/parking lot test was conducted to evaluate the deicing performance of the six deicers at two different mixing ratios and four various application rates (i.e., 200, 350, 500, and 700 lb. per lane mile for the four solid deicers, 20, 35, 50, and 70 gallons per lane mile for AquaSalina and 20, 40, 60, and 80 gallons per lane mile for Green Blast). The test site was on a parking lot at Temple University. The protocol for the simple garage/parking lot deicing tests was developed for real field conditions. Two photo analysis methods were employed for image analysis and evaluated for their effectiveness in analyzing images based on the percentages of melting areas calculated. Using the analytical methods above, qualitative rankings were given to the six deicers for their deicing performances. Moreover, a second parking lot test was conducted with the deicer mixing ratio provided by Penn DOT (i.e., deicer product with salt brine 50:50 in volume before pre-wetting rock salt 10 gallons per ton). Only visual analysis was conducted for the images obtained in the second test. At last, the difference in the deicer performance between the previous laboratory test and the first parking lot test was discussed.

2. Experimental methods

2.1 Deicer preparation

Deicers were prepared per manufacturer recommendations. To have enough deicers of consistent quality for all parking lot tests, deicers were prepared in bulk quantity. The deicers were weighed into 5 gallon buckets, and then mixed with proper amounts of additives, as shown in Table 1 below. Each deicer was well mixed with a stir rod and contained for later use.

Table 1 Deicers preparation ratio per manufacturer recommendations

Name	Mixes with	Ratio	Mixing ratio for 5-gallon bucket*
rock salt	N/A	N/A	N/A
salt brine	rock salt	1 ton rock salt/10 gallons salt brine	18143 g rock salt + 756.56 mL of salt brine
Magic Minus 0	rock salt	10 gallons Magic Minus 0/ton rock salt	18143 g rock salt + 756.56 mL of Magic Minus 0
BEET HEET	rock salt	5 gallons BEET HEET /ton sock salt	18143 g rock salt + 377.37 mL of BEET HEET
Green Blast	salt brine	1 volume Green Blast/4 volume of salt brine	4 gallons salt brine + 1 gallon Green Blasts (3785.4 mL)
AquaSalina	N/A	N/A	N/A

* 5 gallon bucket of rock salt ≈ 40 lbs. = 18143 grams; 10 gallons/ton = 0.0417 mL/gram; 5 gallons/ton = 0.0208 mL/gram.

2.2 Deicer application rates for 3’ x 3’ test area

The selected application rates are based on either manufacturer’s recommendations or published data. Four different application rates, i.e., 200, 350, 500, and 700 lb. per lane mile were tested for the solid deicers (i.e., rock salt, and rock salt pre-wetted with salt brine, BEET HEET, and Magic Minus Zero) (Druschel, 2014). For AquaSalina, based on the manufacture’s recommendation of 20~70 gallons per lane mile for deicing, we tested 20, 35, 50, and 70 gallons per lane mile. For Green Blast, the four application rates tested were 20, 40, 60, and 80 gallons per lane mile based on the recommended application rates for salt brine (Gerbino-Bevins 2011).

2.3 Test grid set-up

For the parking lot test, the primary way is to use a parking lot grid that has been set up. It is to make quick grids on the ground. The tests consist of 72-3’x3’boxes, 12-3’x3’ boxes for each compound (Fig. 1). The 72 boxes were arranged following a Randomized Block Design to minimize the impact of the box location on the parking lot (e.g., insulation, wind, local temperature variation, pavement variation). Each square has a one foot containment zone in which testers were able to walk and take pictures of each grid. Each square had rope around the nail perimeter and a sign, to designate which deicer was in use.

Figure 1: Parking lot test grid set up process before snow (left) and after snow event (right)

2.4 Deicer spreading process

When spreading the chemicals on the test areas, the solids were shaken out of their bottle/bags by hand, be sure to keep an even distribution. The liquids were spread in a horizontal straight line down the test area. Note that preliminary testing with various sized fertilizer spreaders (for solid deicers) and squirt bottles (for liquid deicers) did not yield satisfactory spreading. The chemicals were spread at a low height to minimize contamination to other test areas.

2.5 General information collection

Immediately before the storm event starts, the following general information was collected:

- Data and time of test
- Location of the test Pavement type
- Pavement conditions (snow covered, ice covered etc.)
- Type of precipitation (light snow, medium snow etc.)
- Material applicator (hand, spreader, squirt bottle)
- Tester’s name
- Picture of each test area as initial conditions

2.6 Specific Information Collection

The following specific information pertaining to each test area was collected:

- Type of deicer
- How the deicer was prepared
- Application time
- Application rate
- Pavement temperature (pavement temperature was measured)

- Air temperature (use local weather station or a thermometer)
- Type of precipitation and precipitation amount (use local weather station)
- Cloud coverage (visual observations or use local website weather underground)
- Observations every 10~15 minutes (This includes any variance or abnormalities in the test)
- A scuff test to test slipperiness of pavement (done with the tester's shoe)

2.7 Image collection

When a winter storm started, pictures were taken every 10 minutes of each 3' by 3' test area. The pictures were taken with the same type of camera on a tripod, with spare batteries available, so then the camera type and height were not variables. The tripod was at a height so that the entire test area was captured. Also, the pictures were in landscape format and the camera's flash was on for all pictures.

2.8 Deicing Test

When there was about half-an-inch of snow accumulated on the test area, appropriate amounts of deicers were applied based on Table 1, which was considered as time zero. Following the same rules above, pictures were taken at time zero and every 10 minutes of each 3' by 3' test area.

2.9 Data collection

Once all the data and pictures were collected, they were organized for analysis. Below is how data were organized and how pictures were arranged in an excel sheet:

General Information	
Test Performed By:	-
Date of Test:	-
Time of Test:	-
Location of Test:	-
Pavement Type:	-
Pavement Condition:	-
Pavement Temp	-
Type of Precipitation:	-
Applicator Used:	-

Specific Information and Observations Format:

Specific Information	
Type of Deicer:	-
Deicer Preparation:	-
Application Time:	-
Application Rate:	-
Pavement Temperature:	-
Air Temperature:	-
Precipitation Amount:	-
Cloud Coverage:	-
Observations	
Time (min)	Observation:
0	
10	
20	
30	
40	
50	
60	
75	

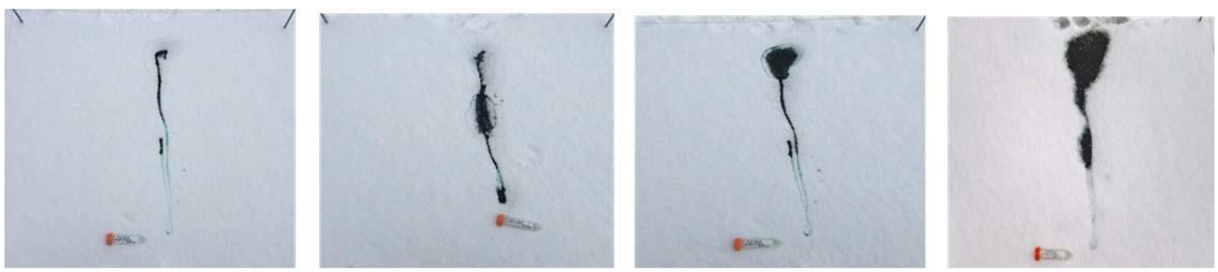
2.10 Photo analysis methods for the parking lot test

After we obtained the images, we organized these data for analysis. First, we used visual analysis to obtain the melting percentages of the tested grid areas. For this part of analysis, two researchers assigned scores (between 0% and 100% melted) to each image independently (i.e., two scores for each image). There are also three replicates for every test, so the visual scores are based on an average of six scores. Then we used the Image J software for quantification of the degrees of melting (between 0% and 100%) during the parking lot test. The image processing uses the NIH software Image J and is based on the integration of the pixel intensity over the entire plot surface. Image J software was downloaded from FIJI: http://imagej.net/Fiji/Downloads. Image processing includes the selection of the plot area, correcting the perspective, and calculating the overall pixel intensity assuming after converting the file into binary (black/white) picture (white= not melted and black = fully melted). For this Image J part of photo analysis, there were three replicates for each test, so the Image J binary scores were based on an average of three scores. The specific procedure is included in the appendix.

2.11 Examples of parking lot test images

During the parking lot test, images were taken every 10 minutes. All the images in the test were taken with the same type of camera and at the same angle, to keep the photo quality consistent and to avoid errors in the process. All the visual scores were assigned by comparing the images with the standard images shown below in Fig. 2. In Fig. 2, the top four images show the visual score criteria 2%, 5%, 10% and 15% for solid deicers. The bottom four images show the visual score criteria 2.5 %, 5%, 10% and 12.5% for liquid deicers.

Visual Score Criteria 2% Visual Score Criteria 5% Visual Score Criteria 10% Visual Score Criteria 15%



Visual Score Criteria 2.5% Visual Score Criteria 5% Visual Score Criteria 10% Visual Score Criteria 12.5%

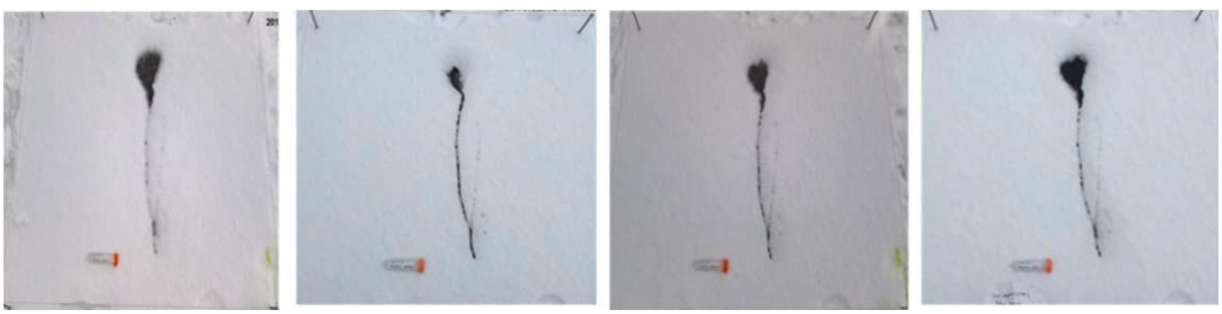
Fig. 2 Visual Images score criteria for the parking lot tests. The top four shows the visual analysis score criteria for solid deicers. The bottom four shows the visual analysis score criteria for liquid deicers.

The following pictures are three sets of images for representative deicers. Fig. 3 shows the reference deicer rock salt from 0 min to 75 min. Fig. 4 shows AquaSalina, which is a liquid deicer and Fig. 5 shows BEET HEET, which is a solid deicer. The sampling times are 0, 10, 20, 30, 40, 50, 60, and 75 min.

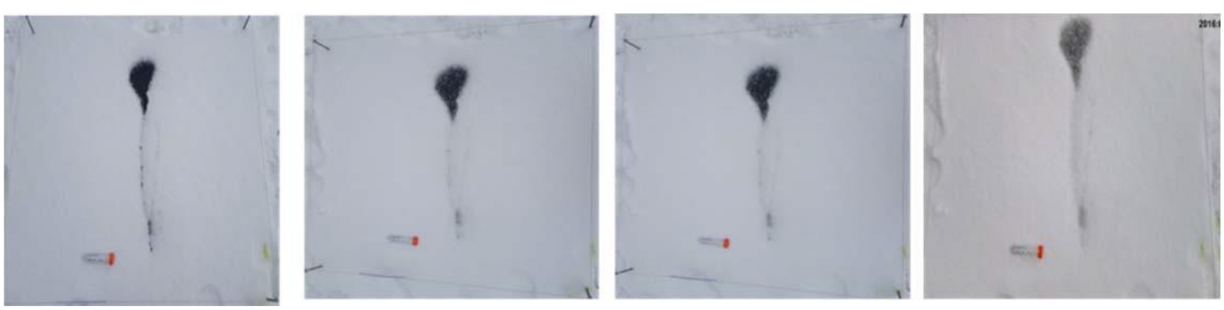
0 min Melted% 0.63/3.5 10 min Melted% 1.61/6.5 20 min Melted% 2.61/8

30 min Melted% 2.15/10.5 50 min Melted% 2.35/12 75 min Melted% 2.92/12

Fig. 3 Sampling photos for the snow melting test of rock salt at 500 lb/lane mile. The numbers below the pictures indicate the melted% scored by Image J/Visual analysis.

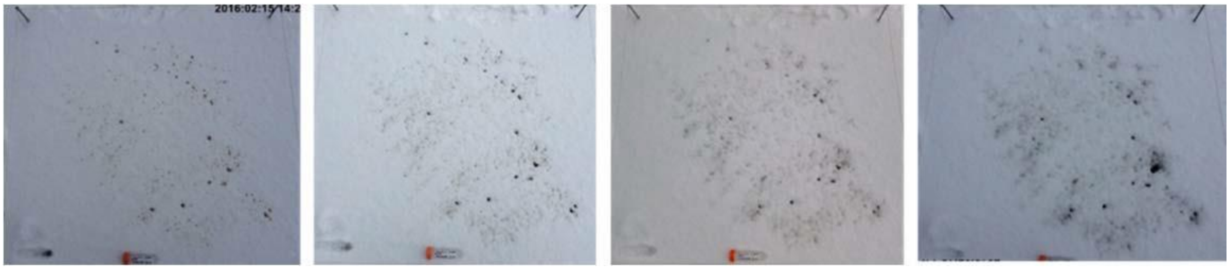


(0 min) Melted% 0.32/3.5 (10 min) Melted% 0.47/5.5 (20 min) Melted% 0.76/7.5 (30 min) Melted% 1.02/9.5



(40 min) Melted% 1.1/8.5 (50 min) Melted% 1.29/6 (60 min) Melted% 1.47/6 (70 min) Melted% 1.5/3

Fig. 4 Sampling photos for the snow melting test of AquaSalina at 50 gal/lane miles. The numbers below the pictures indicate the melted% scored by Image J/Visual analysis.



(0 min) Melted% 0.65/3.5 (10 min) Melted% 0.7/4.5 (20 min) Melted% 1.1/5.5 (30 min) Melted% 1.61/8

(40 min) Melted% 2.1/9.5 (50 min) Melted% 2.7/11.5 (60 min) Melted% 3.4/12.5 (70 min) Melted% 4.6/11.5

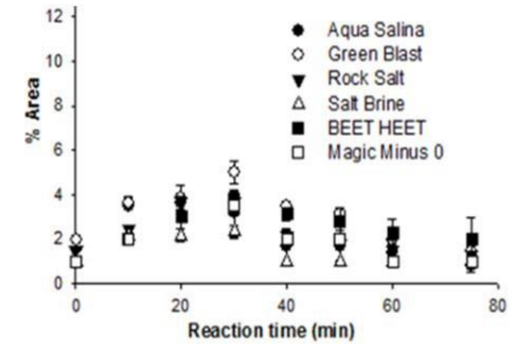
Fig. 5 Sampling photos for the snow melting test of BEET HEET at 500 lb/lane mile. The numbers below the pictures indicate the melted% scored by Image J/Visual analysis.

3. Results and discussion

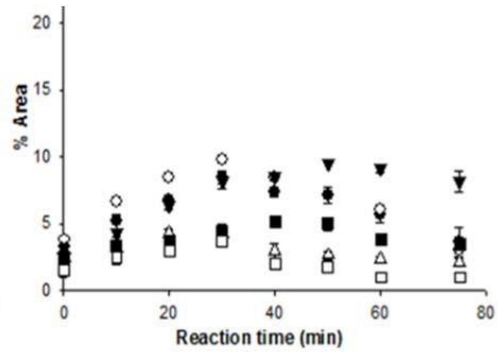
3.1 Effect of application rate on the performance of the deicer products

During the parking lot experiments, four different application rates were applied for the six deicers: the application rates of the two liquid deicers were 20, 35, 50, and 70 gallons per lane mile for AquaSalina and 20, 40, 60, and 80 gallons per lane mile for Green Blast, and those of the four solid deicers were 200, 350, 500, and 700 lb/lane mile. Fig. 6 shows the deicer performance under four application rates based on the visual analysis method. Since the liquid deicers and solid deicers have different units, i.e., gal/lane mile for the liquid deicers and lb/lane mile for the solid deicers, we will discuss the solid and liquid deicers separately in the discussion part 3.2. The discussion below is based on the melting performance of all the six deicers within the application time (0~75min) at the four representative application rates.

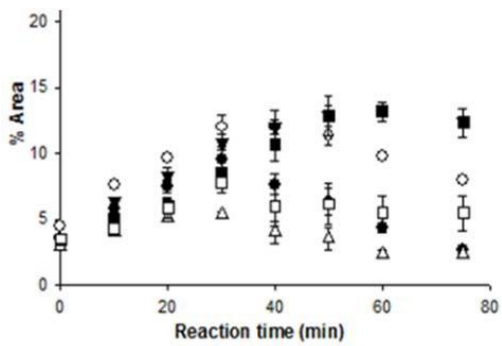
(a)



(b)



(a)



(d)

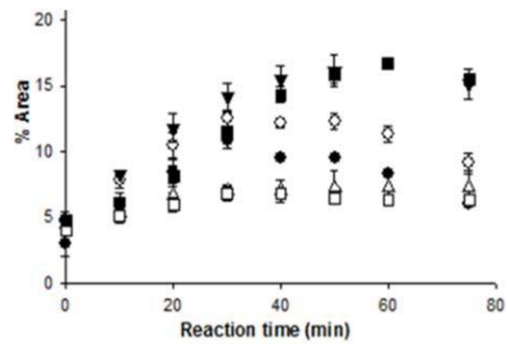


Fig. 6 Visual analysis of snow melting by various deicing products at four loading rates during the parking lot test: (a) 200 lb/lane mile for solid deicers and 20 gallon/lane mile for liquid deicers AquaSalina and Green blast; (b) 350 lb/lane mile for solid deicers, 35 gallon/lane mile for AquaSalina and 40 gallon/lane mile for Green blast. (c) 500 lb/lane mile for solid deicers, 50 gallon/lane mile for AquaSalina and 60 gallon/lane mile for Green blast. (d) 700 lb/lane mile forsolid deicers, 70 gallon/lane mile for AquaSalina and 80 gallon/lane mile for Green blast. The error bars represent the standard deviations of triplicate experiments.

As shown in Fig. 6, we can reach the conclusion that for all the six deicers during the parking lot test, there is an obvious increasing melted percentage with increasing application rates, from 20~80 gal/mile for liquid deicers and 200~700 lb/lane mile for solid deicers. For example, the melted percentage generally ranged from 1% to 5% for all the six deicers at the application rate 20 gal/lane mile for liquid deicers and 200 lb/lane mile for solid deicers. The maximum melted percentage ranged from 5% to 17% at the application rate 70 gal/lane mile for Aqua Salina (80 gal/lane mile for Green Blast) and 700 lb/lane mile for solid deicers.

At lower application rates of 20~60 gal/lane mile for liquid deicers and 200~500 lb/lane mile for solid deicers, there is an obvious trend of reaching the maximum extent of melting for most deicers. This may be attributed to the fact that it was continuously snowing during the sampling process, which competed with the snow melting initiated by the deicers over time. At the highest application rate of 700 gal/lane mile for solid deicers (or 70 gallon/lane mile for AquaSalina and 80 gallon/lane mile for Green blast), the extent of melting remained stable during the entire sampling process.

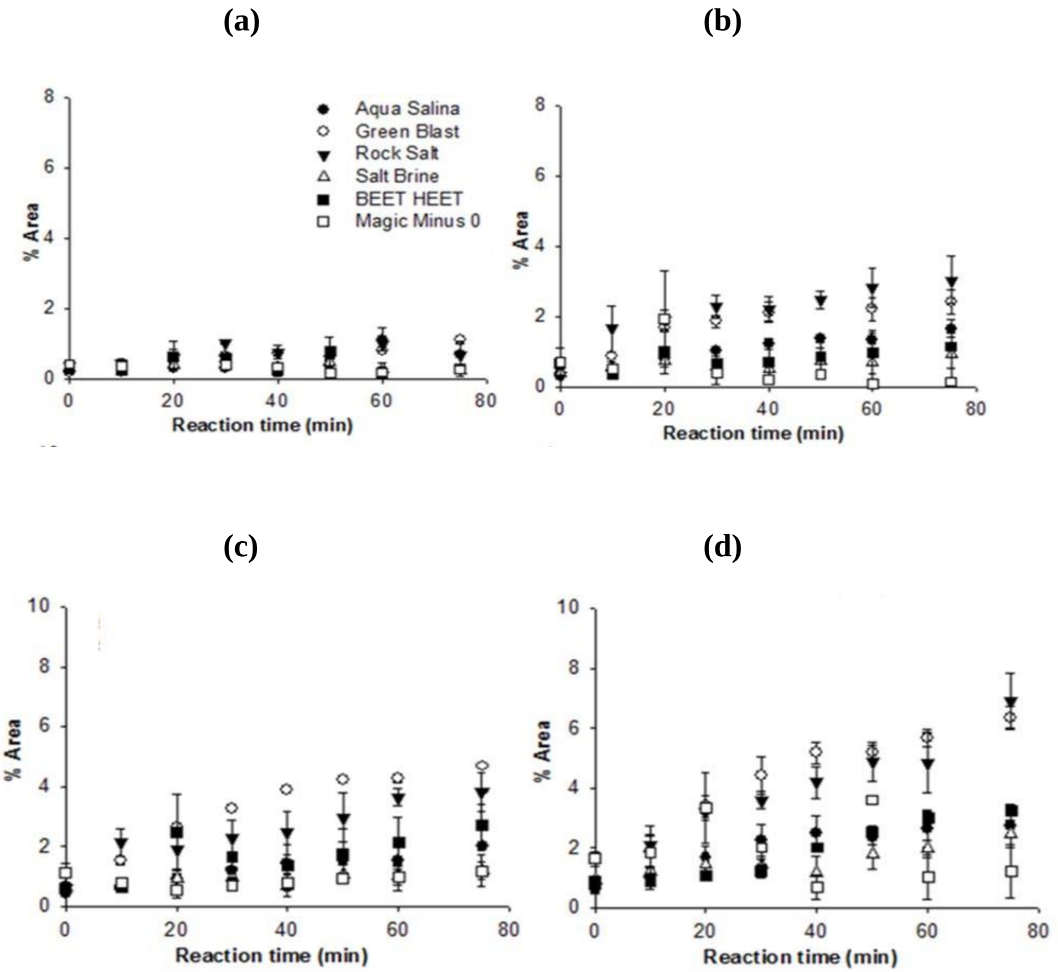


Fig. 7 Image binary analysis of snow melting by various deicing products at four loading rates during the parking lot test: (a) 200 lb/lane mile for solid deicers and 20 gallon/lane mile for liquid deicers; (b) 350 lb/lane mile for solid deicers; 35 gallon/lane mile for AquaSalina and 40 gallon/lane mile for Green blast. (c) 500 lb/lane mile for solid deicers; 50 gallon/lane mile for AquaSalina and 60 gallon/lane mile for Green blast. (d) 700 lb/lane mile for solid deicers; 70 gallon/lane mile for AquaSalina and 80 gallon/lane mile for Green blast.The error bars represent the standard deviations of triplicate experiments.

Each number in Fig. 7 is an average of three replicates based on Image J analysis. As shown in Fig. 7, we can reach a similar conclusion as observed in Fig. 6: i.e., the melted percentages increase with increasing application rate (20 to 80 gal/lane mile for liquid deicers and 200 to 700 lb/lane mile for solid deicers). When the application rate increased from 500 to 700 lb/lane mile (taken solid deicers as an example), there is an slight increase in the melted percentages for rock salt and Green Blast (especially after 40 min reaction time), however, such increase was not obvious for the other four deicers (i.e., AquaSalina, rock salt with salt brine, BEET HEET and Magic minus zero).

Generally speaking, during the entire reaction time, all the deicers at the four application rates display increase in % area melted over time, however, at the comparatively lower application rates (20~40 gal/lane mile for liquid and 200~350 lb/lane mile for solid), there is a plateau in the % area which occurs at an earlier time point or at a lower % area value suggesting that no further melting is occurring. This is consistent with the visual analysis results in Fig. 6.

Note that the error bars represent standard deviations of six data points for the visual analysis process, but standard deviations of three data points for the Image J analysis method. There are a few inevitably abnormal images included for the later method, which is likely due to unforeseen circumstances during the sampling process. The Image J binary method yielded relatively larger errors than the visual analysis process. Also, there were some unexpected errors when the Image J method was used. On the contrary, the visual analysis showed more stable and time-efficient results (e.g. 3-5 min for each Image J analysis and around 1 min for each Visual analysis).

3.2 Effects of different deicer products on the deicing performance

In this part, the melting extents of the six deicers were compared based on the parking lot test results. Fig. 8 shows the melted percentages at the four application rates (from 200 to 700 lb/lane mile) for the four solid deicers (i.e., salt brine, rock salt, BEET HEET and Magic minus 0). Generally speaking, at all four application rates, rock salt has surprisingly the best performance. At the lowest application rate of 200 lb/lane mile, the four solid deicers have comparably low melted percentages, as shown in Fig. 8. When the application rates were 350 to 700 lb/lane mile, the four solid deicers (salt brine, BEET HEET, Salt Brine and Magic minus zero) have comparable melting performances. The performance of BEET and Magic minus zero is slightly better than that of salt brine, based on the figure below. However, when the error bars are considered, the difference does not seem to be substantial. In this case, when the Image J method was applied, the solid deicers ranking is qualitatively assigned as follows: rock salt > BEET HEET ≈ salt brine ≈ Magic Minus zero.

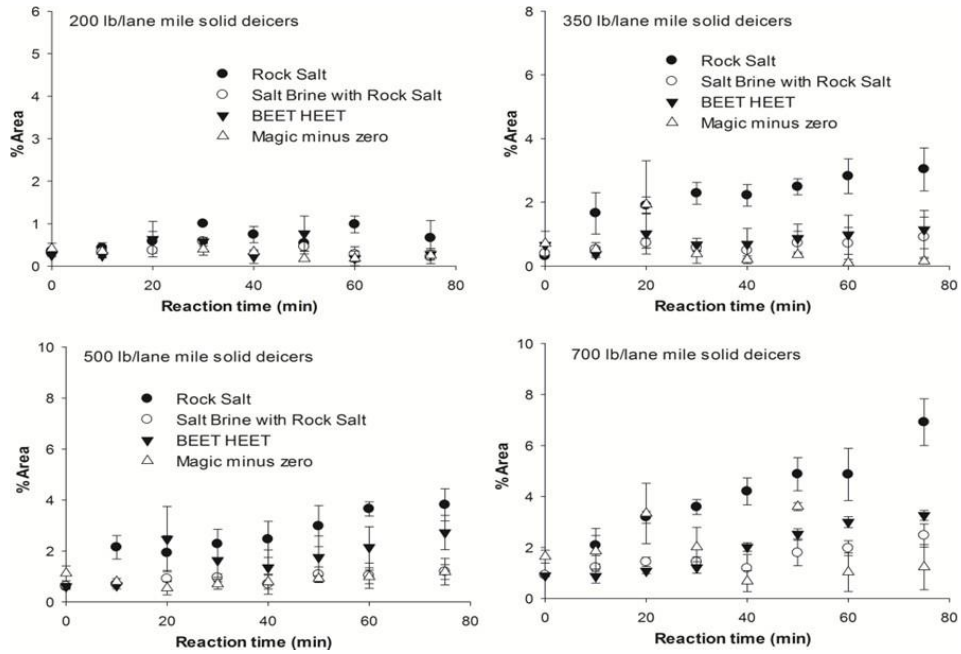


Fig. 8 Image J analysis of snow melting by four solid deicing products at four loading rates during the parking lot test. The error bars represent the standard deviations of triplicate experiments.

When the visual analysis was applied to the images for the solid deicers, the comparison results are shown in Fig. 9 below. At the application rate of 200 lb/lane mile, we can reach the same conclusion as above, that is, generally the four deicers have comparable melted percentages. However, when higher application rates were applied (350-700 lb/lane mile), rock salt and BEET HEET have comparably better deicing performance than that of salt brine and Magic Minus zero. The qualitative ranking result is thus as follows: rock salt ≈ BEET HEET > salt brine ≈ Magic minus zero

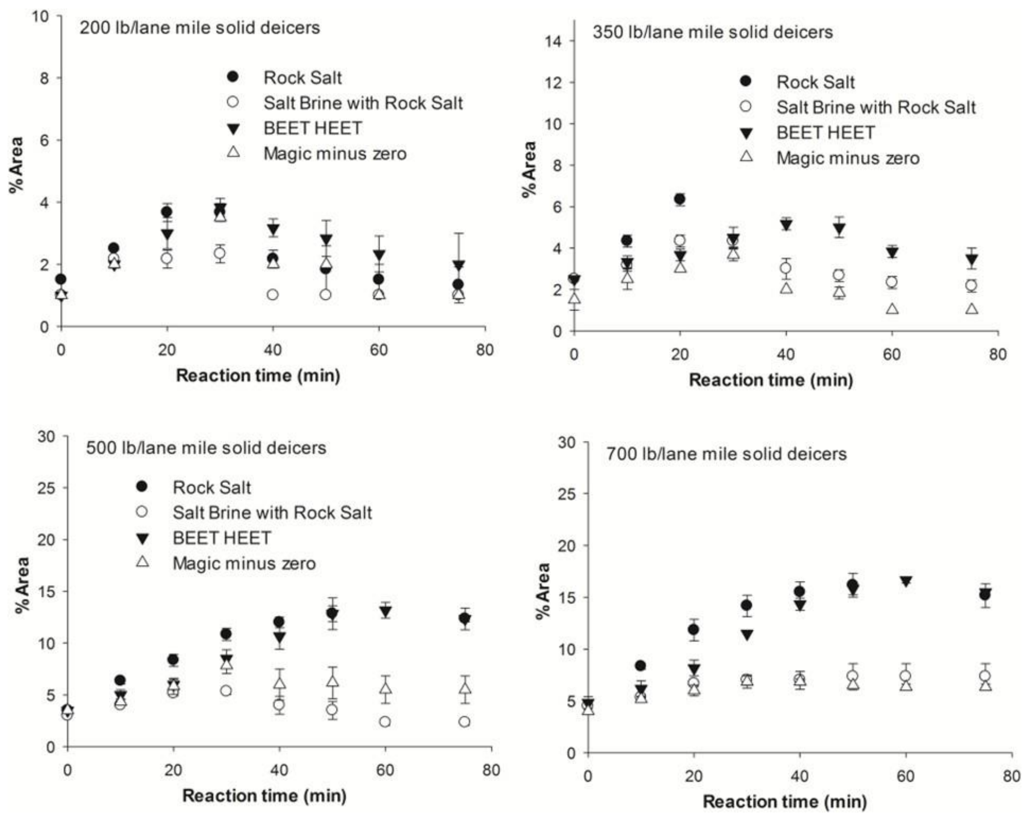


Fig. 9 Visual analysis of snow melting by four solid deicing products at four loading rates during the parking lot test. The error bars represent the standard deviation of triplicate experiments.

Fig. 10 compares the melted percentages of the two liquid deicers (AquaSalina and Green Blast). As can be seen, AquaSalina and Green Blast have comparable deicing performance at the application rate of 20 gallon/lane mile. Obviously, Green Blast has a better performance than AquaSalina when the application rate was 35 to 80 gallon/lane mile.

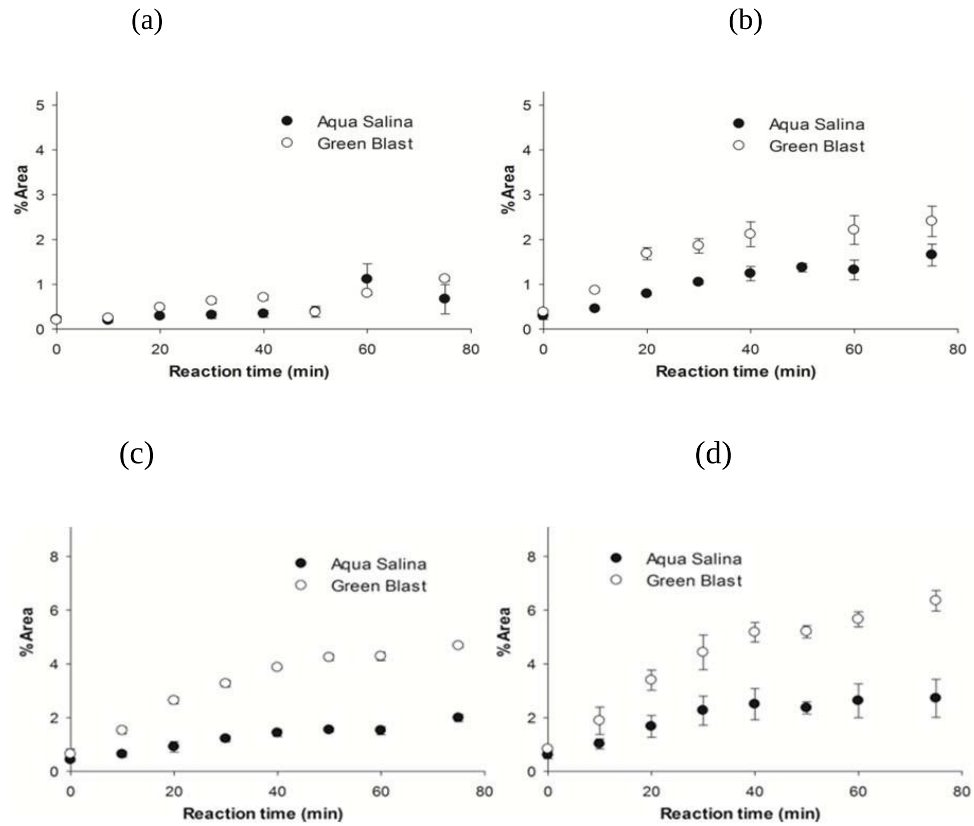


Fig. 10 Image J analysis of snow melting by two liquid deicing products at four loading rates during the parking lot test. (a) 20 gallon/lane mile for liquid deicers (b) 35 gallon/lane mile for AquaSalina and 40 gallon/lane mile for Green blast. (c) 50 gallon/lane mile for AquaSalina and 60 gallon/lane mile for Green blast. (d) 70 gallon/lane mile for AquaSalina and 80 gallon/lane mile for Green blast. The error bars represent the standard deviation of triplicate experiments.

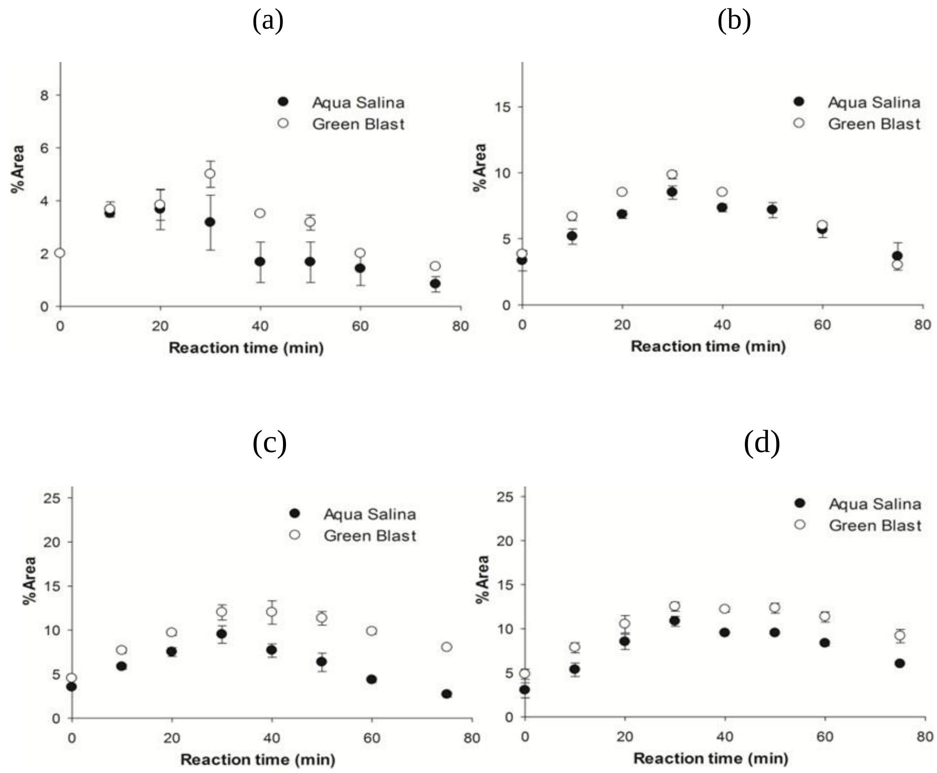


Fig. 11 Visual analysis of snow melting by two liquid deicing products at four loading rates during the parking lot test. (a) 20 gallon/lane mile for liquid deicers (b) 35 gallon/lane mile for AquaSalina and 40 gallon/lane mile for Green blast. (c) 50 gallon/lane mile for AquaSalina and 60 gallon/lane mile for Green blast. (d) 70 gallon/lane mile for AquaSalina and 80 gallon/lane mile for Green blast. The error bars represent the standard deviation of triplicate experiments.Image J analysis was also applied to analyze the liquid deicer performance. As clearly shown in Fig. 11, Green Blast has a better performance than AquaSalina, which is similar to the Image J analysis results for the liquid deicers.

Despite the comparison above, the liquid and solid deicers were prepared using different units, i.e., the solid deicers have the unit of lb. per lane mile, while the liquid deicers have the unit of gallon per lane mile. Thus, we limited the ranking to within the solid or liquid deicers. Also, note that the above comparison was only qualitative. Further statistical analysis will be conducted and more quantitative ranking will be established based on statistical models, as will be included in the report for Task 1.4. The statistical model analysis will provide more realistic deicers performance evaluation.

3.3 Compare two photo analysis methods: visual versus Image J (binary) method

The two photo analysis methods were compared based on the percentages of melting areas calculated. The analytical methods are visual analysis and Image J (binary) method. The melted percentages of all the six test deicers at four different application rates were calculated using both the visual and Image J analysis.

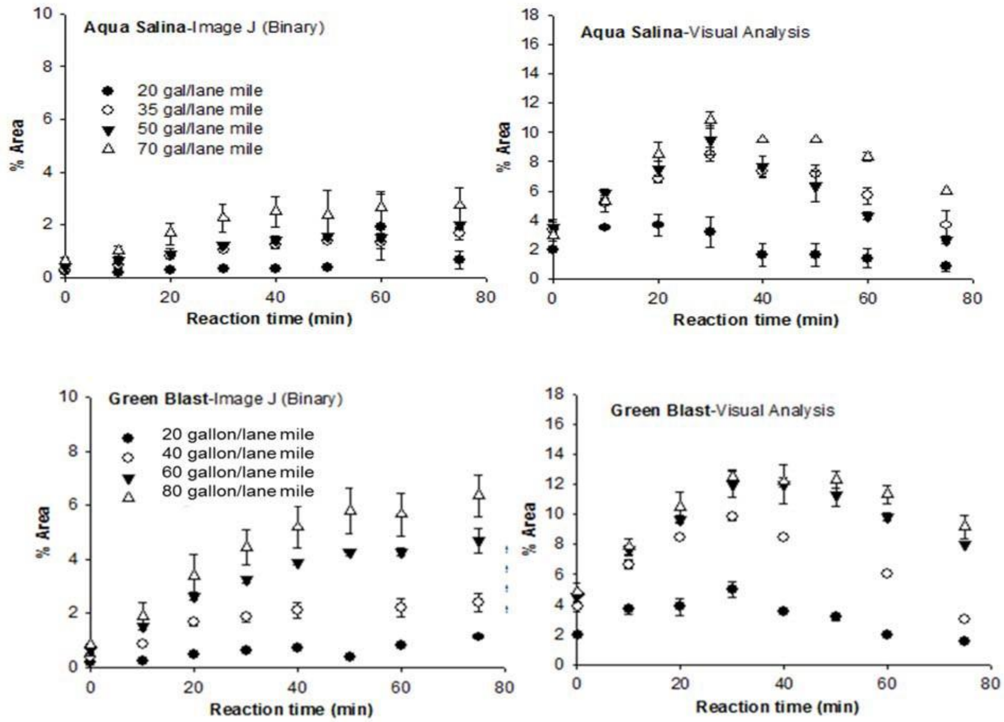


Fig 12 Image J binary) versus visual analysis of snow melting of the two liquid deicing products (AquaSalina, Green Blast) at four various loading rates (20, 35, 50 and 70 gal/lane mile for AquaSalina and 20, 40, 60 and 80 gal/lane mile for Green Blast). The error bars represent the standard deviation of triplicate experiments.

Melting of the two liquid deicers (AquaSalina and Green Blast) is compared in **Fig. 12**. As shown, the melting efficiency increased as the application rate was increased from 20 to 80 gal/lane mile for both liquid deicers. Visual analysis and binary analysis results yielded the same trend. For both liquid deicers, there is an obvious trend of reaching the maximum extents of melting. Thus, when continuously snowing processes are taken into consideration, the Image J method has some advantage in calculating the extent of melting.

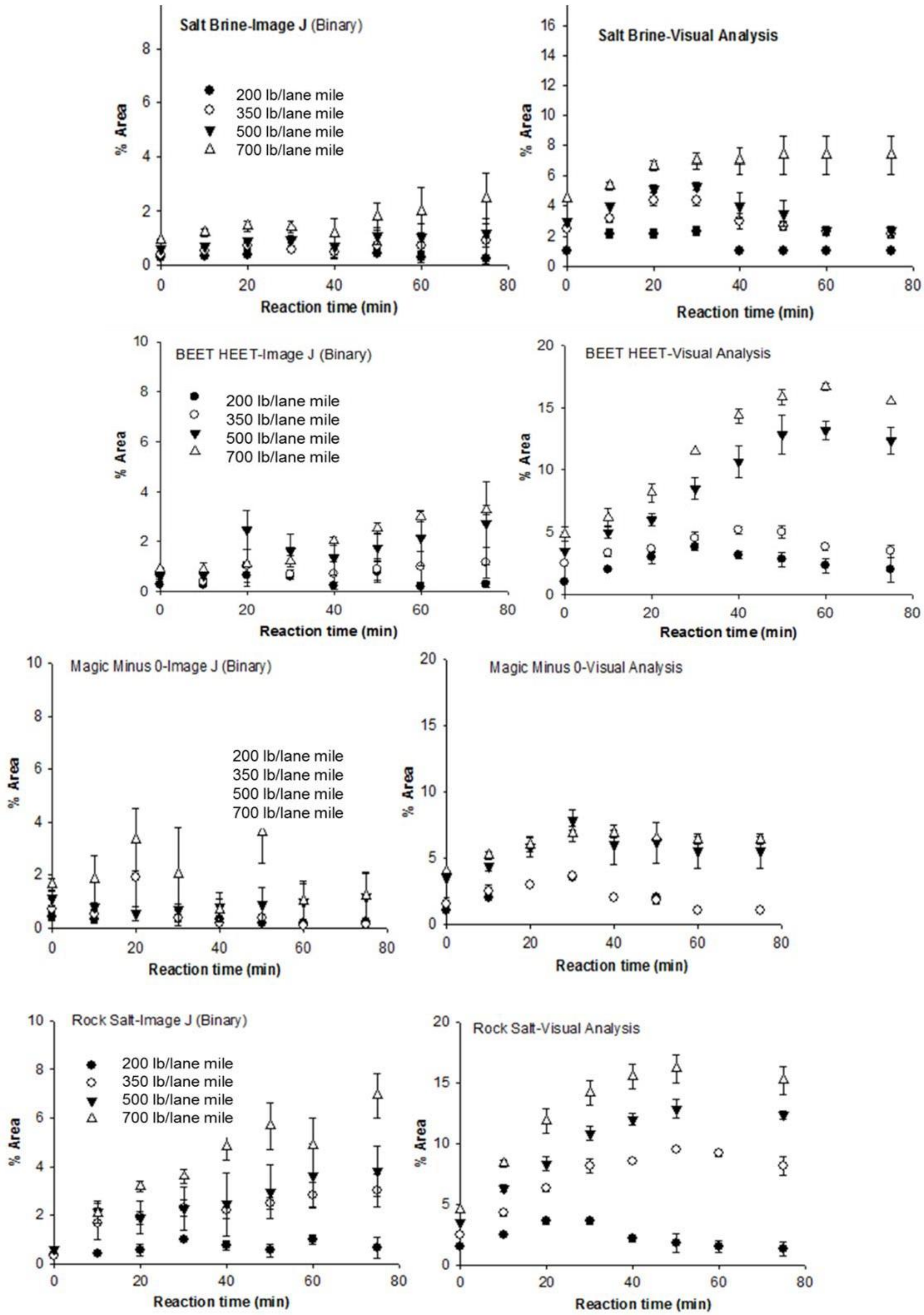


Fig. 13 Image J (binary) versus visual analysis of snow melting of four solid deicing products (rock salt,

BEET HEET, salt brine and Magic Minus zero) at four various loading rates. The error bars represent the standard deviation of triplicate experiments.

Melting of the four solid deicers is compared in **Fig. 13**. For all deicers, the melting efficiency increased as the application rate was increased from 200 to 700 lbs/lane mile. Results based on Image J (binary) and visual analyses are comparable. Generally, there is an increasing trend during the entire reaction time (0~75min). The solid deicers also showed a similar trend as the liquid deicers, that is, a trend of reaching the maximum extents of melting.

In general, when the two different image score methods (Visual analysis and Image J analysis method) were applied in the parking lot test, the results are largely comparable.

3.4 Second parking lot test with the mixing ratio adopted from PennDOT field tests (deicer: salt brine = 50:50 v/v)

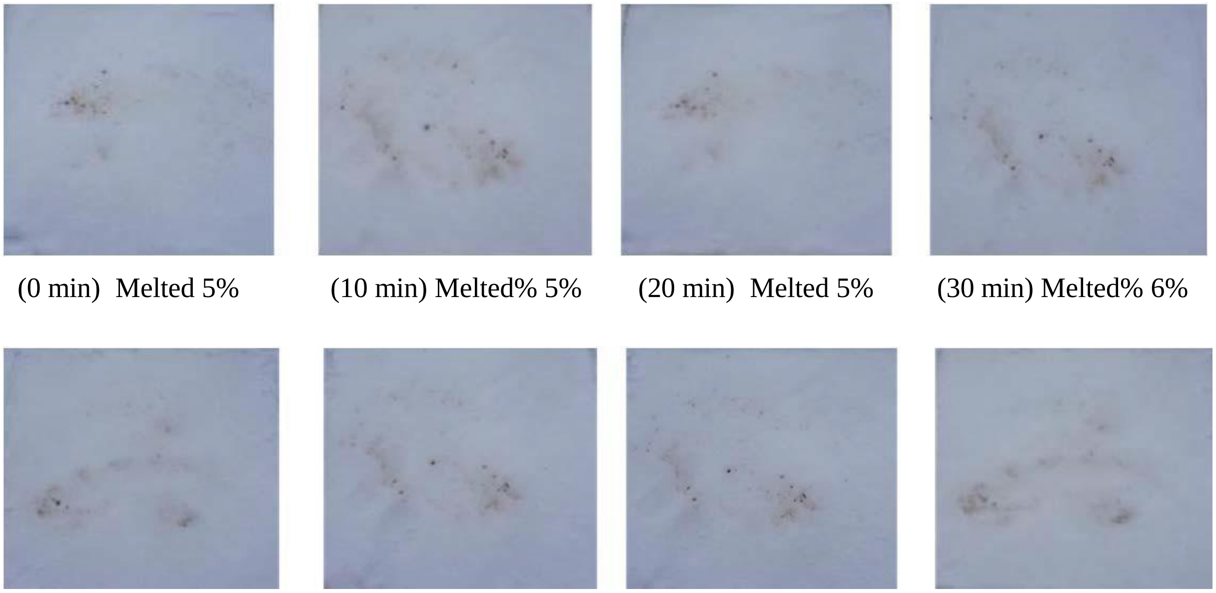
The test discussed above in Sections 3.1 and 2.2 used deicers prepared based on the manufacturers' recommendations. However, during PennDOT field operations, the selected counties usually blend these deicer products with salt brine at 50:50 (based on volume) before pre-wetting rock salt 10-15 gallons per ton. Because of this, another set of parking lot test was conducted on March 14, 2017 (1:25 pm to 2:40 pm) using the new mixing ratio, as shown in **Table 2** below.

Table 2 All six deicers with PennDOT field test mixing ratio in the parking lot test

Num ber	**Deicer**	**Mixing method for the parking lot test**
1	Rock salt	Stock rock salt
2	Salt brine	Rock salt prewetted with 10 gallons of salt brine/ ton
3	BEET HEET	Rock salt Prewetted with 50/50 BEET HEET and salt brine
4	Magic minus zero	Rock salt Prewetted with 50/50 Magic minus zero and salt brine
5	Green Blast	Rock salt Prewetted with 50/50 Green Blast and salt brine
6	AquaSalina	Rock salt Prewetted with 50/50 AquaSalina and salt brine

Note: The amount of deicers used was 32.2 g for each 3'×3' test grid area (500 lb/lane mile); the prewet rate was 10 gallon/ton rock salt for all 50/50 mixes.

The application rate was 500 lb/lane mile. Pavement type is asphalt. Surface coverage condition was 2.9 inch snow above the pavement. The average pavement temperature was 32.9 ^{0}F as measured by the temperature gun during the test. No precipitation was observed during the whole parking lot test. Cloud coverage was overcast.



(0 min) Melted 5%   (10 min) Melted% 5%   (20 min) Melted 5%   (30 min) Melted% 6%

(40 min) Melte% 6%   (50 min) Melted% 6%   (60 min) Melted% 6%   (75 min) Melted%
6%

Fig. 14 Sample photos of rock salt at 500 lb/lane miles during the second parking lot test.

Fig. 14 shows representative image photos of the deicers' melted percentages (rock salt as an example). For this visual analysis, two researchers assigned scores to each image independently, so there are two scores for each image. There are also three replicates for each test, so the visual scores are based on an average of six scores. The results are shown in **Fig. 14.**

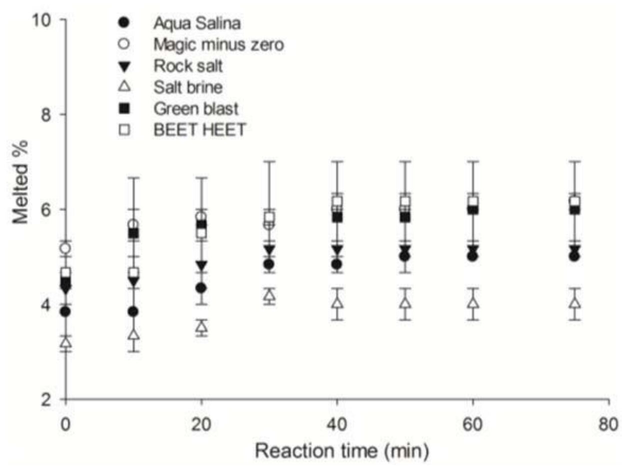


Fig. 15 Visual analysis of snow melting by various deicer products at the loading rate of 500 lb. /lane mile during the second parking lot test. The error bars represent the standard deviation of triplicate experiments.

From **Fig. 15,** we can see that during the entire reaction time, all the deicers have an increasing trend in the melting efficiency. When we compared the deicer performance, all the melted percentage values ranged from around 3% to around 7% during the 75-minute reaction time. Salt brine shows the relatively lowest performance with the melted percentages ranged from around 3% to 4% during the 75-minute reaction time.

Generally speaking, the performance of Green Blast, Magic minus zero and BEET HEET was comparable, but slightly better than that of AquaSalina and rock salt during the entire reaction time (0-75min). Therefore, we can assign a qualitative ranking as follows: BEET HEET ≈ Green Blast ≈ Magic minus zero > rock salt ≈ AquaSalina > Salt brine. In Section 3.2 above, we already obtained a qualitative ranking of rock salt ≈ BEET HEET > salt brine ≈ Magic minus zero for the solid deicers, and Green Blast > AquaSalina for the liquid deicers. In comparison, the rankings of the liquid deicers are the same based on both tests, but quite different for the solids deicers. We do not have a good explanation for this difference in the rankings. However, we speculate that when these deicers were blended with salt brine at 50:50 and then pre-wetting rock salt in the second test, the real mass loading of each deicer to each test area was much lower than in the first test, as a result, the melted percentages were much smaller (e.g., up to only 7% in the second test versus up to 17% in the first test). Note that the pavement temperature for the two parking lot tests was 25.8 ^{0}F and 23 ^{0}F, respectively; thus the pavement temperature did not make a different in the melted percentages between the two tests. Based on the discussion above, the better performance of the larger amounts of the deicers in the first test likely yielded more meaningful qualitative ranking.

Another important note, the parking lot experiments miss some important factors such as traffic. Without intensive mixing with snow and spreading of deicers by passing vehicle, the extent of deicing seems to be much less than what we would observe on the road, as the melted percentages on the road (typically 20-100%) being much higher than those observed in the parking lot experiments. Therefore, it remains to be tested whether the parking lot test can represent the field performance of the deicers.

3.5 Comparison between the parking lot test and the lab test

Our previous lab study evaluated the product performance of five deicers (salt brine and rock salt as reference, AquaSalina, BEET HEET, Green Blast and Magic minus zero). The deicers were prepared in the same way as in the first parking lot test. In the lab test, two product performance tests were conducted: the modified ice melting test and eutectic curves. The ranking of the deicers, based on the results of these two tests, was AquaSalina ≥ Green Blast > Magic minus zero > rock salt ≈ salt brine > BEET HEET.

The lab testing result is quite different from the parking lot test results. In the parking lot test, the ranking of the solid deicers is as follows: rock salt > BEET HEET ≈ salt brine > Magic minus zero. The ranking of the liquid deicers is Green Blast > AquaSalina. This difference indicated that the deicer performance on the real snow versus on the ice (as generated in the lab) is different. Indeed, the laboratory techniques and equipment used to measure the performance of various deicers are different from the devices used in the field. Therefore, when comparing the deicer performance, more field conditions should be taken into consideration. Although many laboratory tests have been conducted to assess performance of deicers, correlations between laboratory performance and field performance are not addressed in most studies (Alatyppo and Jutila, 2010, A.muthumani et al., 2014). We tend to believe that the existing laboratory tests do not accurately predict field performance. In the future, real-time on-road field tests should be conducted to evaluate the deicers performance to obtain a more reliable deicer ranking.

1. Conclusions

Based on the discussion above, we can reach the following conclusions:

1.1 A protocol for simple garage/parking lot deicing tests was developed based on real field conditions. The protocol includes deicer sample preparation, selection of deicer application rates for both solid and liquid deicers (four different application rates, i.e., 200, 350, 500, and 700 lb. per lane mile for the solid deicers; 20, 35, 50, 70 gal/lane mile for AquaSalina and 20, 40, 60 and 80 gal/lane mile for Green Blast), test grid set-up (e.g. consist of 72-3’x3’boxes, 12-3’x3’ boxes for each compound), deicer spreading process, general information collection, specific information collection, and image analysis method development.

1.2 Two photo analysis methods, i.e., visual analysis and Image J analysis, were compared based on the calculated percentages of melted areas. After comparing the melted percentages of all the six deicers at four different application rates, we conclude that the results by the two methods are largely comparable.

1.3 For all the six deicers (i.e., AquaSalina, Green Blast, salt brine, rock salt, BEET HEET and Magic minus 0), higher application rates (200, 350, 500, and 700 lb. per lane mile for the solid deicers; 20, 35, 50 and 70 gal/lane mile for AquaSalina; and 20, 40, 60 and 80 gal/lane mile for Green Blast) typically yielded better deicer performance.

1.4 Based on the first parking lot test in which the deicers were prepared in accordance with the manufactures' recommendations, the ranking of the deicers is as follows: for solid deicers: rock salt > BEET HEET ≈ salt brine ≈ Magic minus zero (ImageJ analysis method); while rock salt ≈ BEET HEET > salt brine ≈ Magic minus zero (Visual analysis method); for liquid deicers: Green Blast > AquaSalina (both ImageJ and visual analysis methods).

1.5 The second parking lot test was conducted with the deicer mixing ratio following Penn DOT field operations (i.e., mixing deicer products with salt brine 50:50 in volume before pre-wetting rock salt 10 gallons per ton). The ranking is as follows: BEET HEET ≈ Green Blast ≈ Magic minus zero > rock salt ≈ AquaSalina > salt brine. This ranking is different from the one obtained above, and may be attributed to the fact that when we blend these deicer products with salt brine at 50:50 before pre-wetting rock salt, the real mass loading of each deicer was much lower. As a result, the melted percentages were not high enough (only up to 7% melted by the end of 75-min) to yield substantial differences among the deicers (up to 17% melted in the first parking lot test).

1.6 When compared with the previous lab test results, the overall product ranking is different. For the laboratory test, the ranking is as follows: AquaSalina ≥ Green Blast > Magic minus zero > rock salt ≈ salt brine > BEET HEET. The existing laboratory tests do not seem to accurately predict field performance. This may be attributed to the fact that the environmental conditions are more complicated, and the melting performance on the ice versus snow could be different. In the future, real-time on-road field tests should be conducted to evaluate the deicer performance to obtain a more reliable deicer ranking.

2. Appendix

Parking Lot Photograph Analysis for Quantification of Degree of Melting: A Protocol Using Image J

The protocol below describes a simple step-by-step procedure to quantify the 'degree of melting' on square test plot from photographs. The image processing uses the NIH software ImageJ and is based on the integration of the pixel intensity over the entire plot surface.

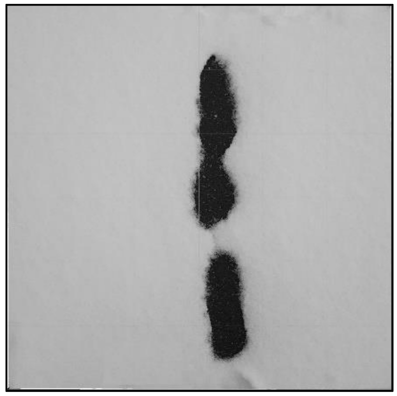
1. Download ImageJ2 from FIJI: http://imagej.net/Fiji/Downloads. You must save the .exe file after extraction in your desktop domain and run it each time you want to use the application.
2. Run the application and open the picture (.jpg), save it as 'processed'.

3. Using the 'Polygon Selection' tool, select the plot area (use the base of the nail as corner mark).
4. Clear the outside area: Edit/Clear Outside.
5. Create a grid: Analyze/Tools/Grid.

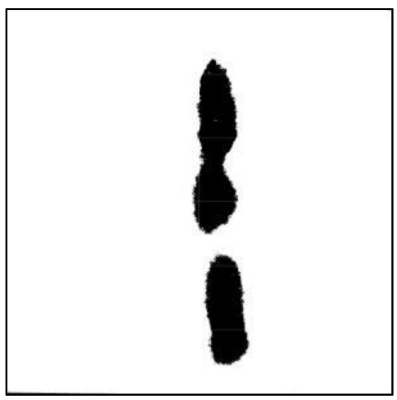
6. Correct the perspective: Plugins/Transform/Interactive Perspective (adjust the corner selection for to the corners of a 6x6 grid square).
7. Using the 'Rectangle Selection' tool, select the plot area or 6x6 grid square.
8. Crop the selection to make the picture like a 2-D representation of the plot: Image/Crop.
9. Convert the picture into a gray tone picture: Image/Type/32-bit

10. Erase any unwanted object (e.g., marker): Using the 'Rectangle Selection' tool, copy and paste a background area over the object.

11. Save the picture as 'processed ready-to-analyze'



There are now two ways to proceed:
a) Create a binary (black/white) picture and calculate the melted area as the percentage of black area (faster):
12a. Convert picture into black & white image: Process/Binary/Make Binary.

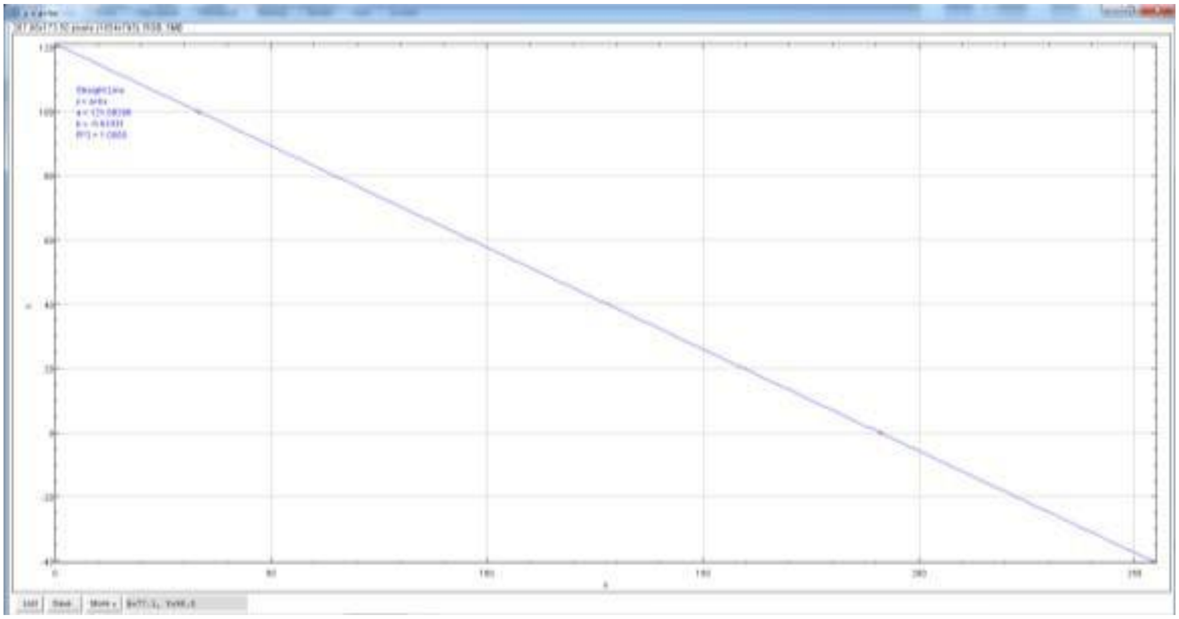


13a. Analyzed the image: Analyze/Set Measurement, then select 'Area Fraction'. Determine the percentage of melted (black) area: Analyze/Measurement, the **'Area Fraction'** is the melted area fraction.

	Area	Mean	Min	Max	%Area
1	7075600	15.515	0	255	6.085

b) Calibrate the picture as background = 0% melted and fully melted area = 100% melted and integrate over the entire picture (longer):

12b. Calibrate the picture: Using the 'Rectangle Selection' tool, select a representative 'fully-melted' area, then analyze: Analyze/Measurement, then record the 'Mean' value (100% melted). Then do the same for a representative 'not melted area' and record the 'Mean' value (0% melted). Then calibrate the picture: Analyze/Calibrate (Function 'Linear', Unit 'Melting (%)', calibration plots: (Mean fully melted; 100), (Mean not melted; 0), save file, OK). The calibration curve will be displayed.



13b. Analyze the image: Analyze/Measurement, the **'Mean'** value is now the melting percent of the plot.

	Area	Mean	Min	Max
1	22815	33.295	4	98
2	231336	191.194	164	200
3	7075600	9.434	-40.412	121.083

7. Reference

Gerbino-Bevins, B. M. 2011, “Performance rating of deicing chemicals for winter operations”, Master’s thesis, Department of Civil Engineering, University of Nebraska.

Stephen J. Druschel, Salt Brine Blending to Optimize Deicing and Anti-icing Performance and Cost Effectiveness, Phase II, Minnesota Department of Transportation Final Report 2014-43. December 2014.

Alatyppö, V., Jutila, K., 2010. Efficiency of runway de-icing chemicals in practice. Paper presented at XIII International Winter Road Congress, February 8–11, in Quebec, Canada

Anburaj Muthumani [a], Laura Fay [a], Michelle Akin [a], Shaowei Wang [a], Jing Gong [b], Xianming Shi [a], Correlating lab and field tests for evaluation of deicing and anti-icing chemicals: A review of potential approaches, 2014, Cold Regions Science and Technology, 97, 21-32

Analysis of Skid Resistance

Summary:

Skid resistance was used to evaluate the effect of six (6) deicer products on the surface conditions at the application rate of 500 lb. per lane mile. The six products are: AquaSalina, BEET HEET, Green Blast, Magic Minus Zero, rock salt, and rock salt pre-wetted with salt brine. The four novel deicers were prepared based on the manufacturers' recommendations. Parking lot test sections were used such that each product was applied to an area of 3'x3'. Testing results show general improvement in skid resistance compared to wet conditions (plowing only with no deicers) with the exception of a few data points during the test. For ranking purposes, the results are inconclusive, except for one product (AquaSalina) which consistently had the lowest performance on skid resistance. Further statistical analysis of the obtained data will be important to rank the skid performance of the deicers.

The effect of products on skid resistance is tested using a British pendulum. The pendulum measures the frictional resistance between a rubber slider mounted on the end of a pendulum arm and the test surface. This provides a routine method of checking the resistance of wet and dry surfaces to slipping and skidding, both in the lab and on site. It is based on the Izod principle: a pendulum rotates about a spindle attached to a vertical pillar. At the end of the tubular arm a head of known mass is fitted with a rubber slider. The pendulum is released from a horizontal position so that it strikes the sample surface with a constant velocity. The distance travelled by the head after striking the sample is determined by the friction of the sample surface. A reading of Skid Resistance is obtained. This device is employed in this project to measure frictional properties of the pavement surface according to ASTM E303 (Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester). This device measures low-speed friction (about 10 km/h) and is commonly used to assess the microtexture of pavement surfaces (Lee et al., 2005, Lu and Steven 2006).

Field testing was conducted at a controlled parking lot to avoid traffic control issues during snow events. During the snow event on March 14th, 2017, the measurements were taken at the following intervals within the same day. Please note that the weather condition is written next to each interval:

1- Pre application of de-icing treatment (0 minutes) (**Pavement temperature -5.6°C/22°F**)
2- Post 1st application
   a. After 15 minutes of application (**No Precipitation**)
   b. After 30 minutes of application (**No Precipitation**)
   c. After 45 minutes of application (**Precipitation started again**)
   d. After 60 minutes of application (**Heavy Precipitation**)
3- Post 2nd application (**@ 60 minutes of the 1st application, immediately after the 4th**

reading)

a. After 15 minutes of application (**Light Precipitation**)
b. After 30 minutes of application (**No Precipitation**)
c. After 45 minutes of application (**Light Precipitation**)
d. After 60 minutes of application (**Light Precipitation**)

The products used were applied on test areas of 3ft × 3ft for each product. During the snow event the snow was removed, and the deicing product was applied according to the recommended rates, as shown in the following table (Table 1).

Table 1. Application amount for 3'x3' Test Area

Product	**Mixes with**	**Ratio**	**Amount**
Magic Minus Zero	rock salt	10 gallons Magic Minus Zero/ton rock salt	32.2 g
Salt Brine	rock salt	1 ton rock salt/10 gallons salt brine	32.2 g
Green Blast	salt brine	1 volume Green Blast/4 volume of salt brine	26.87 mL
BEET HEET	rock salt	5 gallons BEET HEET /ton sock salt	32.2 g
Rock salt	N/A	N/A	32.2 g
AquaSalina	N/A	N/A	26.87 mL

At each test spot, two readings were taken and the average is reported. The following graphs are prepared to evaluate the skid resistance after snow plowing and application of the products, with higher values indicating better performance on skid resistance.

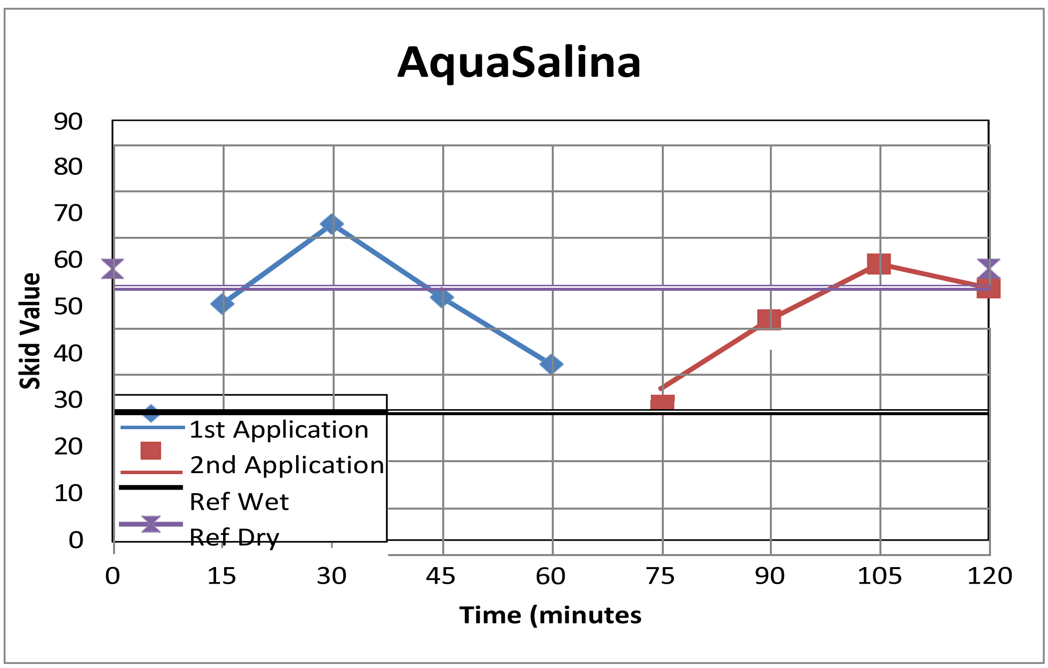


Figure 1 Skid resistance for AquaSalina

Figure 1 shows the measured skid resistance at the test area after the first and second application of the product. The horizontal lines show the skid value for the test area in dry conditions at the same temperature, and the skid value of the surface after plowing the snow and before the application of the product, respectively. In effect these two lines show the drop-in skid due to the snow event after plowing. Therefore, they provide a good reference for the effectiveness of the products in attaining skid resistance close to the dry conditions. In addition, the time profile provides insight to the time needed for the product to achieve a safe level of skid resistance and how long it can maintain this level between applications.

As can be noted in Figure 1, AquaSalina increased the skid resistance for the reading at 15 minutes from the first application. The resistance continued to increase for the 30-minute reading. However, the resistance decreased as the snow precipitation took place. The second application increased the skid resistance to the same level attainted under dry conditions at 105 minutes. The final reading shows that the product is able to maintain similar levels of the skid value.

It is important to note that the reading at 75 minutes (15 minutes after the second application) did not show any improvement in skid resistance compared to the wet reference condition. This could be due to the heavy snow fall that started at the 60 minutes mark after the beginning of testing.

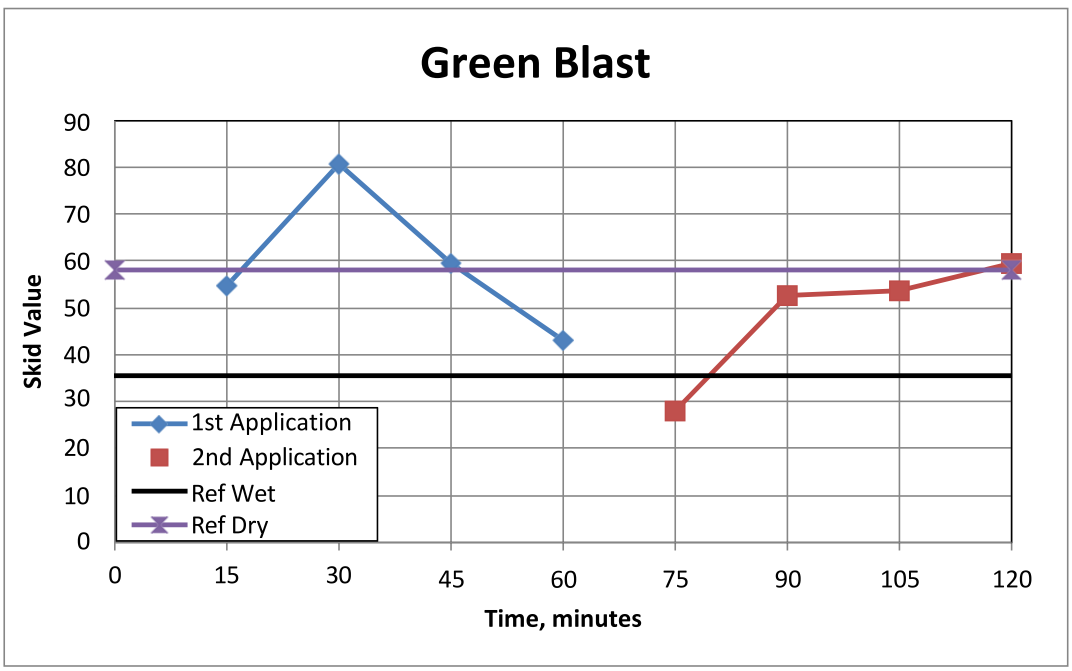


Figure 2 Skid Values for Green Blast

The skid values for the Green Blast product show the same trend as Aqua Salina after the first application. The reading at the 75-minute mark also shows the influence of the heavy snow fall at the 60-minute mark. However, this product shows improvement as shown by the skid values of the last 3 readings (@90, 105, and 120 minutes). The skid values at these readings are at the same level as the dry condition.

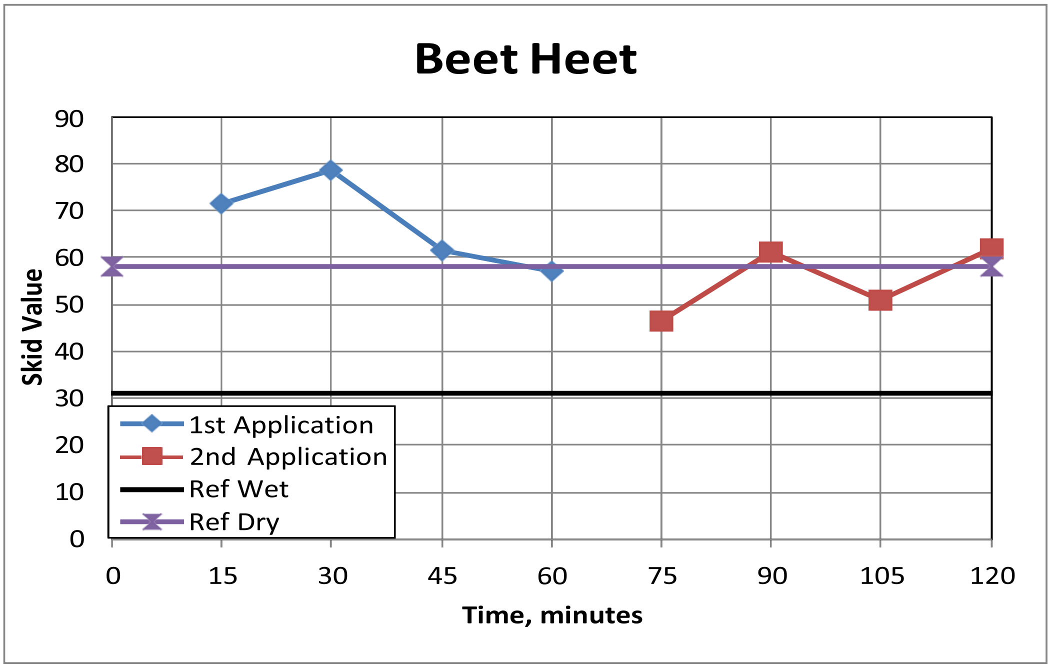


Figure 3 Skid Values for BEET HEET

Figure 3 shows the skid values for BEET HEET. As can be noted, the first reading shows significant increase in skid resistance. The remainder of the readings continues to maintain the skid resistance value of the dry surface. In comparison, the product shows the most consistency in maintaining the skid resistance of the surface at the dry condition levels. It is important to note that this product did not show significant influence of the heavy snow fall that took place after 60 minutes of the testing. As the data show, the drop in the skid resistance reached a level that is still higher than that of the wet condition.

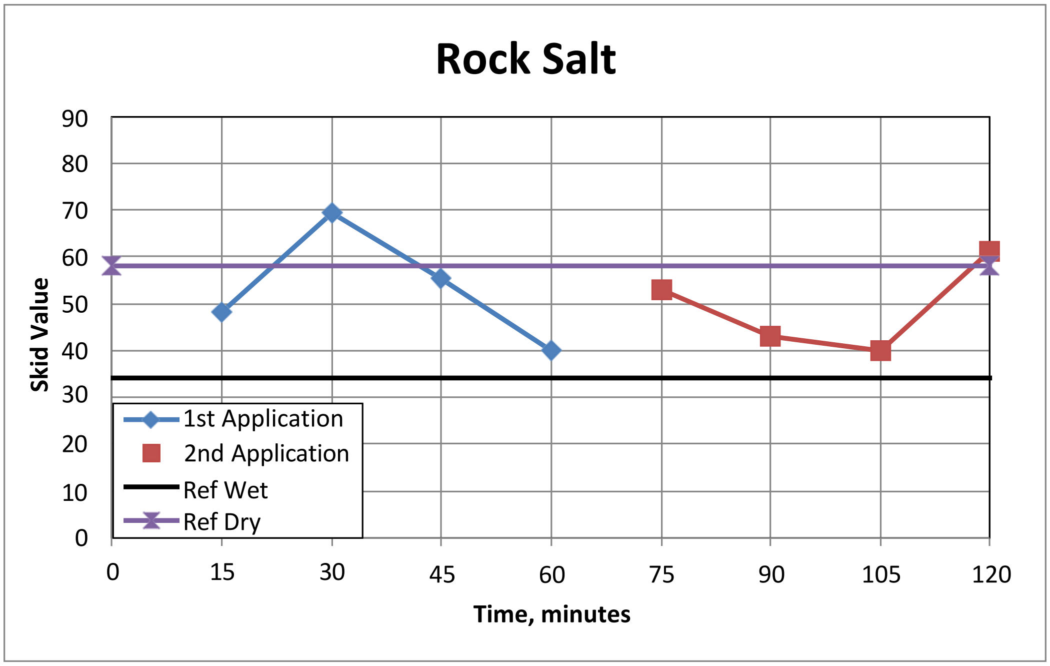


Figure 4 Skid Values for Rock Salt

Rock salt continues with the same trend as the other products where the skid value increased after the first application. For this product, a second application was needed to maintain a consistent level of skid resistance. Yet, the rock salt performance was consistently below that of the dry condition except for the final reading where the reading was at the level of the dry condition. This product also showed an interesting trend. While the previous products showed a drop in the skid resistance after 60 minutes due to the heavy snow fall, this product shows that the second application was able to quickly recover the skid values as demonstrated by the reading at 75 minutes.

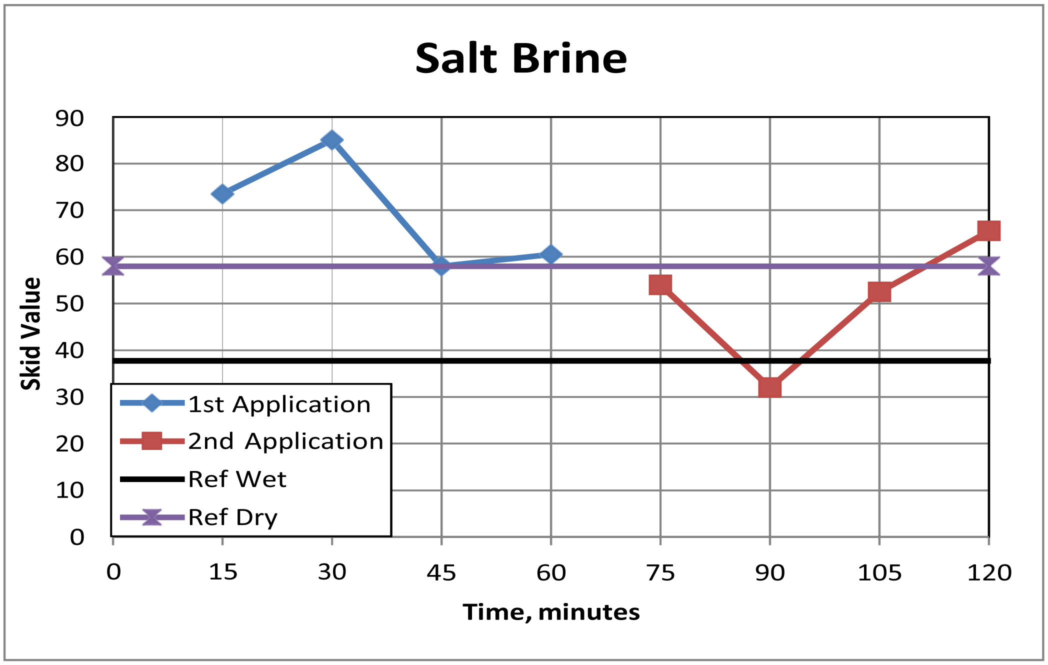


Figure 5 Skid Values for the Salt Brine

The salt brine displayed a unique trend. The skid value rapidly increased after the first application. Yet the effect of the heavy snow fall was not observed until the reading at 90 minutes. This drop was quickly recovered in the 105-minute reading to a level similar to that of the dry surface, and it even increased at the 120 minutes reading.

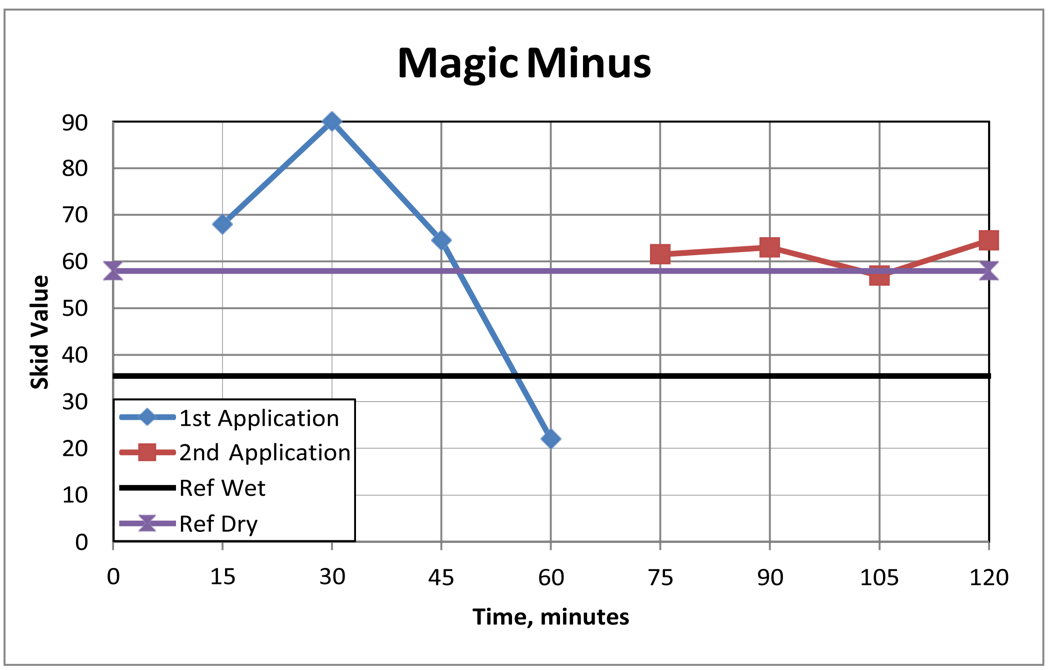


Figure 6 Skid Values for the Magic Minus Zero

This product lost its ability to maintain skid resistance rapidly after the first application. However, the second application was enough to maintain the skid values at the dry surface levels. Surprisingly, the skid values do not show any sensitivity to the heavy snow fall after 60 minutes. This could be because the application rate was not enough to attain the needed results after the first application, which led to rapid dissipation in the melting capability after 30 minutes. Figure 7 shows the results of the skid test for all the products.

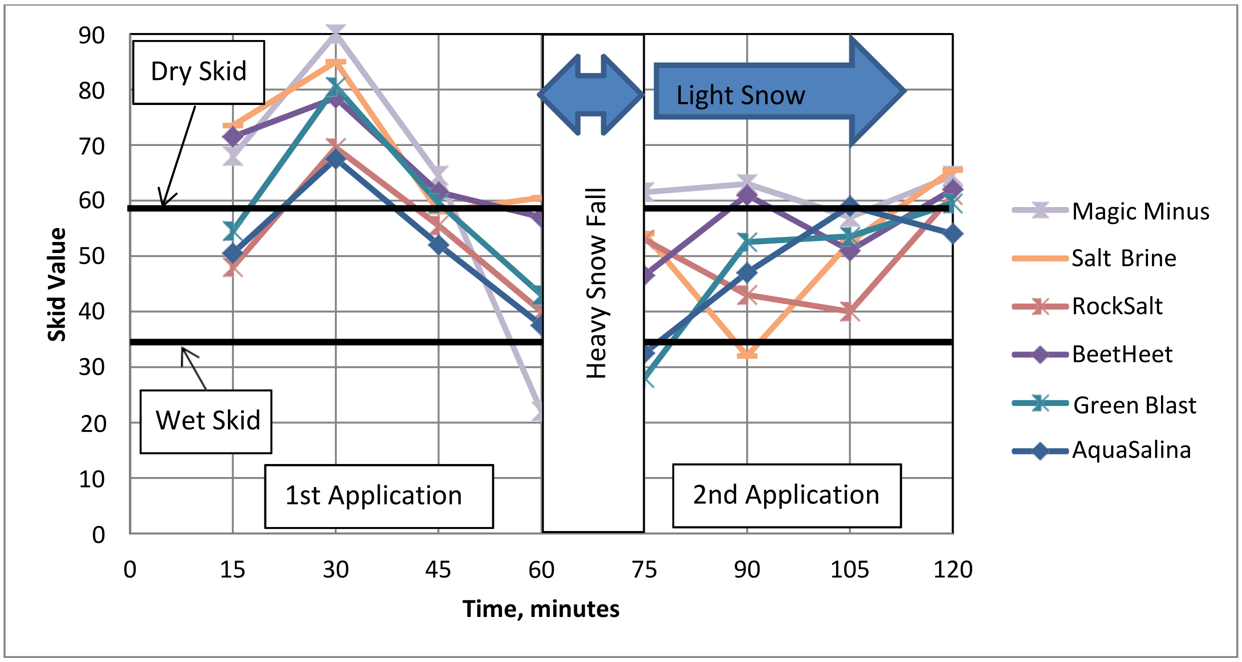


Figure 7 Comparison of Skid Results for all Products

Figure 8 shows the relative Skid Values. These values are calculated by dividing the measured skid values by the dry surface skid. This means that if the skid value is greater than one (1.0), it increased skid beyond the dry conditions. Less than one (<1.0) indicated reduction in skid compared to dry conditions.

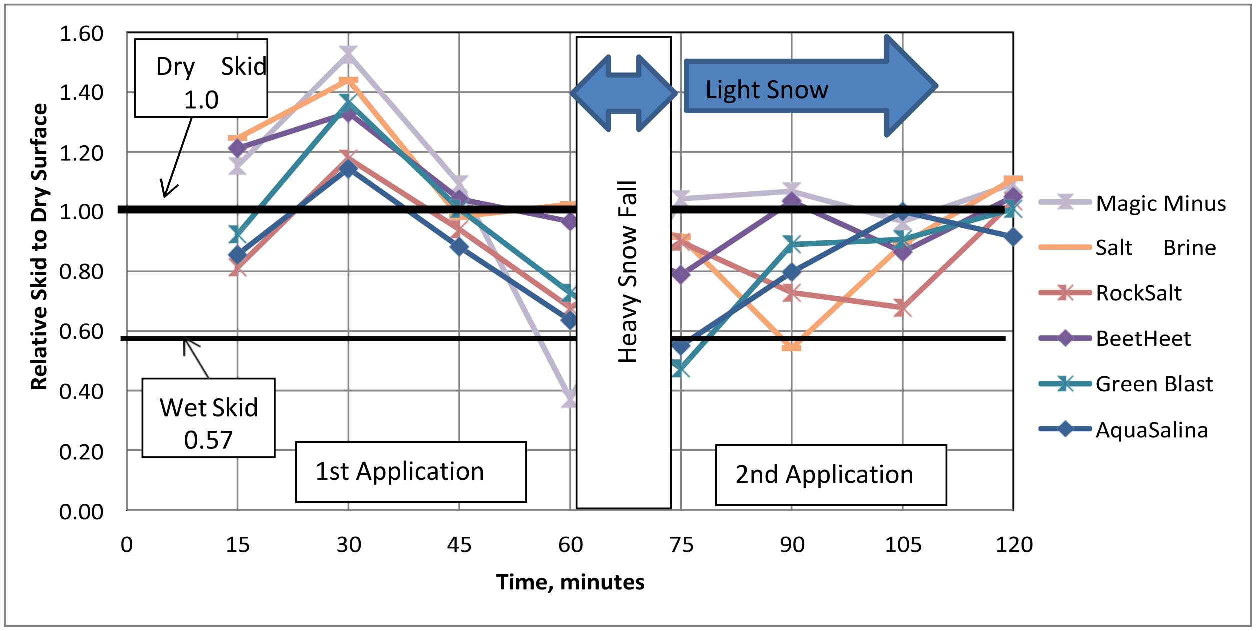


Figure 8 Relative Skid Values

Given the information in Figure 8, it can be observed that three of the products show 15-25% increase in skid after 15 minutes of application. These products are Magic Minus (15%↑), BEET HEET (21%↑) and salt brine (25%↑). In addition, three products show skid values below the dry surface conditions. These are Green Blast (8%↓), AquaSalina (14%↓), and rock salt (19%↓).

After thirty minutes of application, all products show skid values higher than the dry surface. The range is 14-53% increase. Beyond the thirty minutes mark, the skid values start to decrease and vary more dramatically from one product to another. The trends observed do not provide enough evidence to propose overall ranking of the performances recorded. Therefore, to provide side by side comparison of the performance of these products, ranking of the skid value at mid- point (30 minutes) and the end of the first application (60 minutes), and mid-point (90 minutes) and the end of the second application (120 minutes) is provided in Table 2. This approach will help evaluate the consistency of the products throughout the testing period. It is important to repeat that after the 60-minute mark, heavy snow started falling for about 10 minutes followed by light precipitation for the rest of the testing period.

Table 2. Ranking of the Products Based on the Skid Values

Rank	30 Minutes	60 Minutes	90 Minutes	120 Minutes
1	Magic Minus Zero	Salt Brine	Magic Minus Zero	Salt Brine
2	Salt Brine	Beet Heet	Beet Heet	Magic Minus Zero
3	Green Blast	Green Blast	Green Blast	Beet Heet
4	Beet Heet	Rocksalt	AquaSalina	Rocksalt
5	Rocksalt	AquaSalina	Rocksalt	Green Blast
6	AquaSalina	Magic Minus Zero	Salt Brine	AquaSalina

The information provided in Table 2 is not intended for finalizing ranking of the data but rather to compare the performances over the testing duration. The following observations can be noted:

1- Magic Minus Zero shows the most range of performance in the first application, with the highest skid value after 30 minutes and the lowest value after 60 minutes. Recommendation: Revisit application rate for the product**.**

2- Salt Brine shows the highest sensitivity to snowing between applications, with the lowest skid value after heavy snow, followed by the highest value for skid at 120 min.
Recommendation: Adjust time gap between applications based on real-time data for precipitation**.**

3- BEET HEET and rock salt show consistent performance with the lowest level of fluctuation in skid value during the testing periods.

4- Green Blast shows the lowest drop after the heavy snow, and then returns to consistent readings after the second application.
Recommendation: Adjust time gap between applications based on real-time data for precipitation.

5- AquaSalina shows the lowest range of skid values compared to all the other products.

6- Further statistical analysis of the obtained data will be important to rank the skid performance of the deicers.

Conclusions

In conclusion, the testing data provide insight into the range of performance associated with these products. The results do not allow for a generalized ranking due to the different variables influencing the results. The only product that can be ranked is AquaSalina with the lowest range of skid values.

Future Work

Statistical comparison between each pair of deicers will yield quantitative ranking on skid resistance. To yield more reliable ranking, the Temple team is proposing to conduct another round of testing before the end of the project to combine the results with the first round. This will help in normalizing the effects of external variables (such as heavy snow fall, effect of dosage, time gap between dosages, etc.). Listed recommendations mentioned above will be incorporated in the second round of parking lot testing.

CONTRACT NO. 4400011166
TEM WO 005
DELIVERABLE 1.4 REPORT TO INCLUDE PRODUCT STATISTICAL ANALYSIS AND RANKING APPROACHES FOR THE SIMPLE GARAGE/PARKING LOT DEICING/ANTI-ICING TEST

APRIL 28, 2017

Summary

Deicing materials can protect the road safety. In the recent years, new deicer products have been developed. It is necessary to evaluate the deicers performance in field tests, such as simple Garage/Parking lot tests and On-Road Real-Time tests. The performance of six deicers, i.e., Aqua Salina (AS), BEET HEET (BH), Green Blast (GB), salt brine (SB), rock salt (RS), and Magic Minus Zero (MMZ), is evaluated in this report. In the previous two parking lot tests conducted at Temple University (see Final Report for Task 1.2), two photo analysis methods were employed for image analysis and evaluated for their effectiveness in obtaining the percentages of melted areas. Using these two analytical methods, qualitative rankings were given to the six deicers for their deicing performances. However, such evaluation can only give us a qualitative ranking result. In this task, statistical analysis based on scientifically established models was conducted for processing the results from the two parking lot tests and the skid resistance test (Task 1.3).

For the first parking lot test (Task 1.2), the model includes one response variable, melted snow percentage, and three independent variables, including time, deicer type, and application rate. Both time and application rate are continuous variables, while the deicer type is a categorical variable. To address the issue of non-Gaussian distribution of the response variable, a Box-Cox transformation was used. In order to consider the interactions between the independent variables (for example, shown below as Time:Deicer, Rate:Deicer etc.), nine candidate models were evaluated based on the Akaike information criterion (AIC). AIC is a measure of the relative quality of statistical models for a given set of data, taking into the consideration of the complexity of the models. The smaller the AIC value is, the better the model can explain the data set. Therefore, after the calculation of AIC, the best working model was selected to be:

Melt% ~ Time + log(Rate) + Deicer + log(Rate):Deicer + Time:Deicer + log(Rate):Time + log(Rate):Deicer: Time.

Note that we use log(Rate) instead of Rate here in the model. This is because when using log(Rate), the R-squared is 0.8039, AIC is 680. When using Rate, the R-squared is 0.79, AIC is 717. So the model with log(Rate) is better, and the fitted equations for the six deicers are:

RS: $\hat{y}$ = -5.61 - 0.09×Time + 0.96×log(Rate) + 0.018×Time×log(Rate);

GB: $\hat{y}$ = -6.02 - 0.03×Time + 1.18×log(Rate) + 0.013×Time×log(Rate);

AS: $\hat{y}$ = -5.00 - 0.01×Time + 0.96×log(Rate) + 0.007×Time×log(Rate);

BH: $\hat{y}$ = -3.43 - 0.12×Time + 0.49×log(Rate) + 0.022×Time×log(Rate);

$$SB: \hat{y} = -3.96 - 0.07\times Time + 0.59\times \log(Rate) + 0.013\times Time\times \log(Rate);$$

$$MMZ: \hat{y} = -5.96 - 0.016\times Time + 0.967\times \log(Rate) + 0.001\times Time\times \log(Rate).$$

Since we combined the same parameters in the above equations, only three variables remain in the final model for each deicer. For example, for each deicer, the coefficients for Time and Time:Deicer were combined as one coefficient for Time. Based on the established models, we could then construct 95% confidence intervals for the predicted melted% for any given time and application rate for all the deicers. We could thus obtain the deicer statistical ranking as follows:

$$GB \approx AS > RS > BH \approx MMZ \approx SB.$$

The ranking is slightly different from the visual analysis in Task 1.2 (the qualitative ranking result: BH ≈ RS > MMZ ≈ SB for solid deicers, and GB ≈ AS for liquid deicer), however, this ranking is based on rigorous statistical analysis. Here, "≈" means there is no statistically significant difference between two deicers in terms of deicing performance.

The second parking lot test was conducted using the PennDOT field operation mixing ratios (Task 1.2). Because there are only two independent variables, Time and Deicer, we consider two candidate models (i.e., melted% ∼ Time + Deicer and melted% ∼ Time + Deicer + Time:Deicer). After comparing them using the AIC test, the best model was determined to be:

$$Melted\% \sim Time + Deicer$$

Based on pair-wise comparison, the statistical ranking is: $B \approx MMZ \approx BH > RS \approx AS > SB$. This ranking matches well with the qualitative ranking in the visual analysis process, which indicates that the modeling result and the visual analysis result are consistent.

The statistical analysis for the skid resistance test of the six deicers was also conducted (results in Task 1.3), and there is no statistically significant difference among the deicers. To obtain more reliable statistical analysis, however, additional data should be collected in the future.

1. Introduction

In Task 1.2, the deicing performance of six deicers (i.e., AquaSalina, BEET HEET, Green blast, salt brine, rock salt, and Magic Minus Zero) was tested in the absence of vehicular traffic. A simple garage/parking lot test (referred to as the first parking lot test) was conducted to evaluate the deicing performance of six deicers at two different mixing ratios and four various application rates, i.e., 200, 350, 500, and 700 lb per lane mile for the four solid deicers, 20, 35, 50, and 70 gallons per lane mile for AquaSalina and 20, 40, 60, and 80 gallons per lane mile for Green blast. (The units for the liquid deicers have been converted to lb per lane mile to keep consistent, details in Section 2 "Experimental methodology".) The second parking lot test was conducted at a fixed application rate of 500 lb per lane mile, while all deicers were pre-mixed with SB 50:50 (v:v) before pre-wetting RS at 10 gal per ton. The mixture of AS and salt brine will still be referred to as AS, and the same applies to other deicers.

In Task 1.2 (see Final Report for Task 1.2), two photo analysis methods were employed for image analysis and evaluated for their effectiveness in obtaining the percentages of melted areas. Using the two analytical methods, qualitative rankings were given to the six deicers for their deicing performances. However, the evaluation can only give us qualitative ranking results. To further understand the ranking of all the six deicers, statistical analysis based on several scientific models were conducted in this part of study. Statistical analysis was also used to understand the results from the skid resistance test (Final report for Task 1.3).

2. Statistical Data Analysis

All the statistical analysis was based on a professional statistical analysis software R® project. R version 3.3.3 is a free software environment for statistical computing and graphics (https://www.r-project.org/). It compiles and runs on a wide variety of UNIX platforms, Windows and MacOS. All the codes in the models were written from R. R provides a wide variety of statistical (linear and nonlinear modeling, classical statistical tests, time-series analysis, classification, clustering) and graphical techniques, and is highly extensible.

In the statistical analysis, the linear regression method was applied to establish models for the transformed deicers performance data. In statistics, linear regression is an approach for modeling the relationship between a scalar dependent variable Y (e.g., melted %) and one or more explanatory variables (or independent variables) denoted X. In linear regression, the relationships are modeled using linear predictor functions whose unknown model parameters are estimated from the data.

During the first parking lot test, the liquid and solid deicers were prepared using different protocols based on the manufactures' recommendations, i.e., the solid deicers were applied at a rate expressed in lb. per lane mile, while the liquid deicers were applied at a rate expressed in gallon per lane mile. The previous report (Task 1.2) limited the ranking to within the solid or liquid deicers. In this report, all the units were kept consistent. The units for GB and AS were converted to lb. per lane mile based on the deicers salt contents. After conversion, the GB application rate 20 gallon/lane mile equals 60 lb./lane mile. The AS application rate 20 gallon/lane mile equals 45 lb/lane mile. Thus, all the units in the R analysis process were lb/lane mile.

3. Results and Discussion

3.1 First Parking lot experiment on deicer melting performance

We first run a regression analysis between the melted percentage, i.e., the response variable Y, and a set of independent variables, including time, deicer type, and application rate. The tests were conducted at a fixed temperature so it is not a variable here. The model is given as following:

$$\text{Melted \%} \sim \text{Time} + \log(\text{Rate}) + \text{Deicer}$$

We used log(Rate) instead of Rate here as an independent variable. The reason to use the log transformation is that if we use Rate, the interpretation of the corresponding coefficient is: increasing Rate by one unit, we expect the melted% will increase by "coefficient" unit. If using log(Rate), the interpretation is: increasing Rate by 1 percent, we expect the melted% will increase by "coefficient"/100 units. In the latter case, we are interested in the effect when increasing the Rate by a certain multiplier, which can be better interpreted. Besides, log transformation is a widely used transformation approach, and it offered a slightly better modeling results. For example, when using log(Rate), the R-squared is 0.8039 for Model #9 (details later in Table 1). When using Rate, the R-squared is 0.79 for Model #9, so the model with log(Rate) is better. The normal quantile-quantile (QQ) plot for the residuals of the above model is displayed in Figure 1. If the residuals follow a normal distribution, we expect the points to fall approximately along the reference line. Such a large discrepancy shown in Figure 1 indicates that the normality assumption is violated, which means that the model exhibits lack-of-fit.

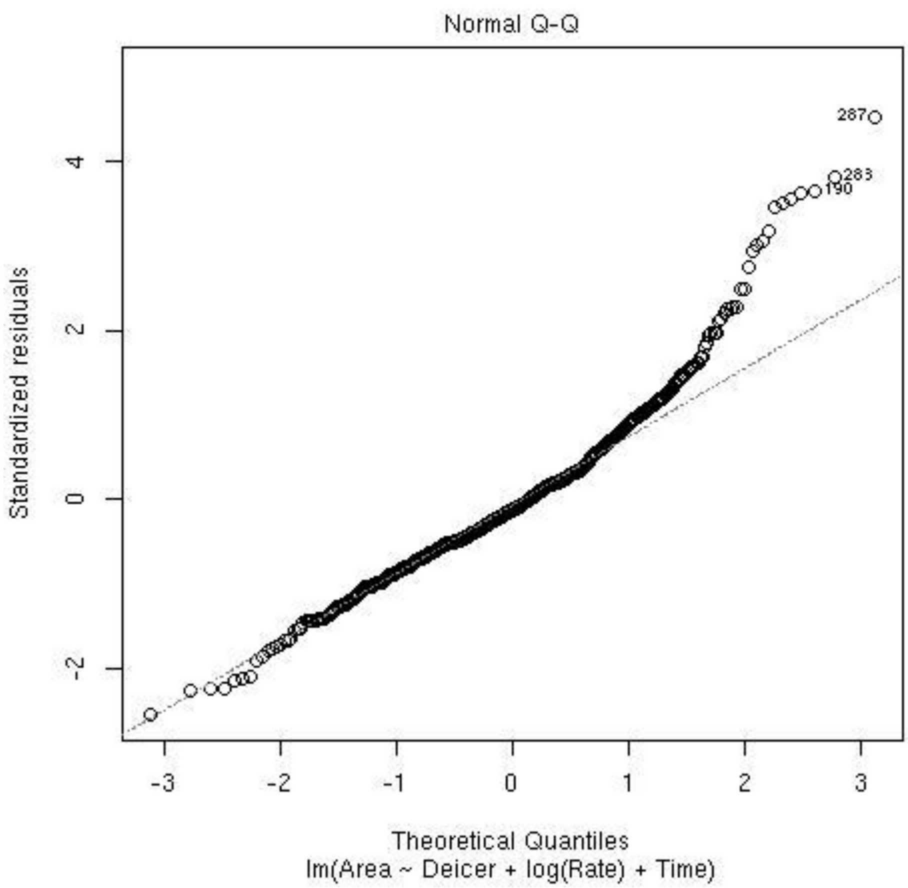


Figure 1 Normal quantile-quantile (QQ) plot for the residuals in the above model

To address this issue, we applied the Box-Cox transformation to the response variable. Note that for a given λ, the Box-Cox transformation of a variable Y is given as follows,

$$Y_\lambda = \begin{cases} \frac{Y^\lambda - 1}{\lambda}, \lambda \neq 0 \\ log(Y), \lambda = 0 \end{cases}$$

After a few attempts, we chose λ, the tuning parameter for the Box-Cox transformation, as 0.3 such that the residuals follow a normal distribution. After transforming the data, we need to further choose an appropriate model, including the above one with the main effects only. In Figure 2, we plot the average melted percentages for four solid deicers under the same application rate, 700 lb per lane mile, as a function of time. From Figure 2, it is clear that the effect of Time (i.e., slopes of the lines) depends on the deicer type. The melted percentage increases to a larger extent for RS than for BH and SB at a later time, while it does not change much over time for MMZ. In other words, there exist interactions between Deicer and Time (if there were no interactions between Time and the Deicer type, we would expect to see parallel lines in Figure 2). We therefore consider nine candidate models in Table 1.

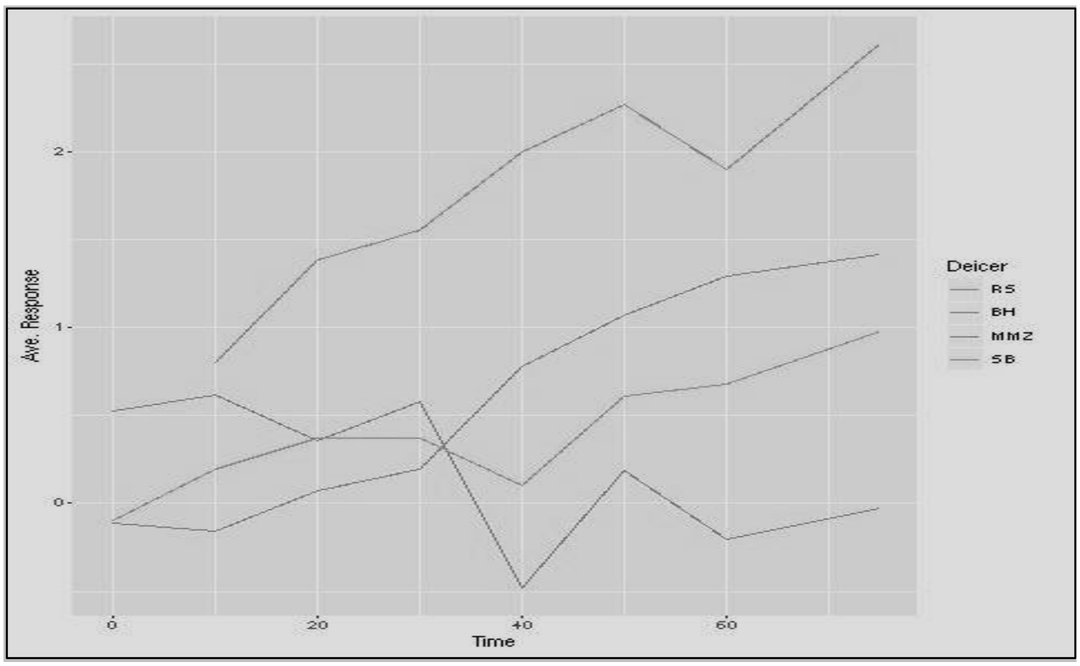


Figure 2 Effect of time on the deicing performance (Y axis is average melted%) for different deicers. Application rate: 700 lb. per lane mile

The candidate models include sets of independent variables, including time, deicer type, and application rate (log(Rate)), and variables related to interactions between the independent variables, including log(Rate): Deicer (i.e., interactions between log(Rate) and Time), Time:Deicer, log(Rate):Time, and log(Rate):Deicer:Time. Based on these independent variables, the candidate models can be expressed in Table 1 below.

Table 1 Nine candidate models for the results from the first parking lot test. Y = melted % with Box-Cox transformation

Model #	**Model Formula**
1	Y ~ Time + log(Rate) + Deicer
2	Y ~ Time + log(Rate) + Deicer + log(Rate):Time
3	Y ~ Time + log(Rate) + Deicer + log(Rate):Deicer
4	Y ~ Time + log(Rate) + Deicer + Time:Deicer
5	Y ~ Time + log(Rate) + Deicer + log(Rate):Time + log(Rate):Deicer
6	Y ~ Time + log(Rate) + Deicer + log(Rate):Time + Time:Deicer
7	Y ~ Time + log(Rate) + Deicer + log(Rate):Deicer + Time:Deicer
8	Y ~ Time + log(Rate) + Deicer + log(Rate):Deicer + Time:Deicer + log(Rate):Time
9	Y ~ Time + log(Rate) + Deicer + log(Rate):Deicer + Time:Deicer + log(Rate):Time + log(Rate):Deicer:Time

We then calculated the Akaike information criterion (AIC) for each model. AIC is a measure of the relative quality of statistical models for a given set of data. It is a tradeoff between goodness-of-fit and the complexity of the model. Especially, it is given as

$$AIC = 2k - 2\log(L),$$

where k is the number of parameters (measure of complexity), and (L) is the maximum likelihood (measuring goodness-of-fit). When k is increasing while keeping on adding variables to the model, $2k$ will always increase and $-2\log(L)$ will always decrease, which balances the model. Among all the candidate models, the model with the smallest AIC value is preferred. The obtained AIC for all nine models are listed in Table 2.

Table 2 Obtained AIC for all nine candidate models.

Model #	AIC	Model #	AIC	Model #	AIC
1	891	2	888	3	875
4	755	5	872	6	710
7	731	8	685	9	680

Model #9 with the lowest AIC (680) was selected as the working model. It indicates that all the parameters and interactions sufficiently contributed to understanding variability in the response parameter (transformed melted %). In the next figure, we plotted the normal QQ-plot for Model #9, showing that the points centered on the reference line better.

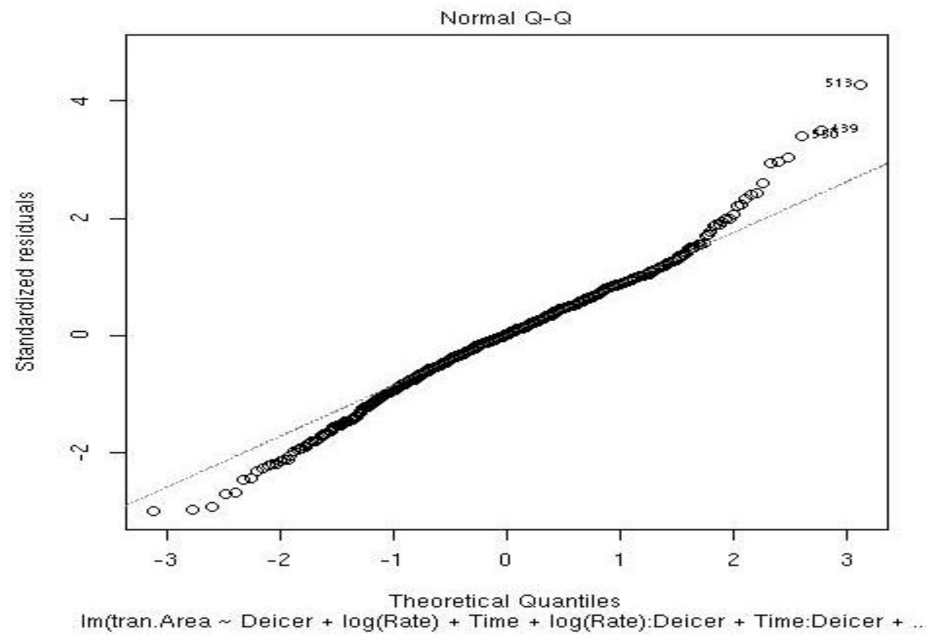


Figure 3 Normal quantile-quantile (QQ) plot for the residuals of Model #9

The hypothesis that the response follows a normal distribution can be tested using the Kolmogorov-Smirnov test. The null hypothesis states that the normality assumption is true. The resultant p-value is 0.30, much higher than a cut-off value of 0.05. We therefore fail to reject the null hypothesis and conclude that there is no evidence showing that the response does not follow a normal distribution. Namely, the model is a good fit for the data. The R-squared of this model is 0.804. The fitted equations for six deicers are shown in Table 3.

Table 3 The model fitting equations based on Model #9 for all deicers. Note: $\hat{y}$ stands for the model calculated response variables.

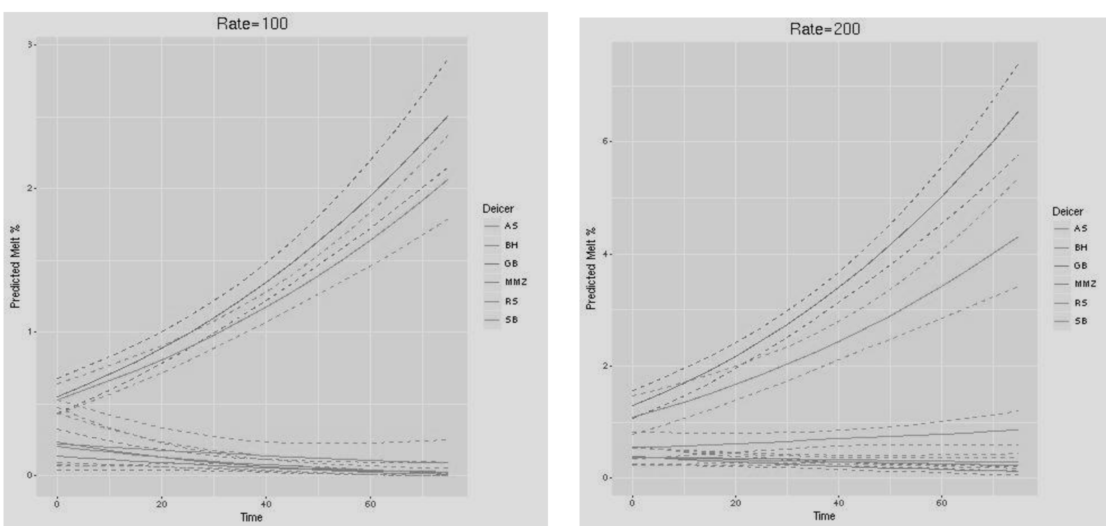
Deicer	Model Equation
RS	$\hat{y} = -5.61 - 0.09 \times Time + 0.96 \times log(Rate) + 0.018 \times Time \times log(Rate)$
GB	$\hat{y} = -6.02 - 0.03 \times Time + 1.18 \times log(Rate) + 0.013 \times Time \times log(Rate)$
AS	$\hat{y} = -5.00 - 0.01 \times Time + 0.96 \times log(Rate) + 0.007 \times Time \times log(Rate)$
BH	$\hat{y} = -3.43 - 0.55 \times Time + 0.49 \times log(Rate) + 0.022 \times Time \times log(Rate)$
SB	$\hat{y} = -3.96 - 0.07 \times Time + 0.59 \times log(Rate) + 0.013 \times Time \times log(Rate)$
MMZ	$\hat{y} = -5.96 - 0.016 \times Time + 0.967 \times log(Rate) + 0.001 \times Time \times log(Rate)$

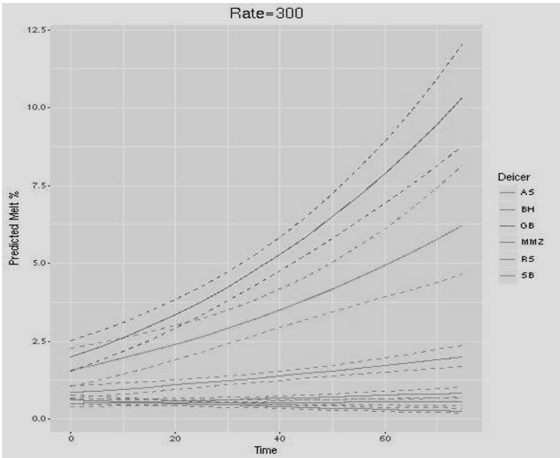
For each deicer, according to the model equation #9, there is a common intercept for all deicers and a deicer-specific intercept. Combining these two numbers will be the intercept for the deicer (e.g., -5.61 for RS). Similarly, there is a common Time effect for all deicers and a deicer-specific Time effect (from the interaction of Time:Deicer). Combining these two will be the effect of time for the deicer (e.g, -0.09 for RS). Also, there is a common Rate effect for all deicers and a deicer-specific Rate effect (from the interaction of Rate:Deicer), combining these two will yield the effect of log(Rate) (e.g., 0.96 for RS). Finally, there is a common effect of log(Rate):Time for all deicers and a deicer-specific log(Rate):Time effect (from the interaction of Rate:Deicer:Time), combining these two yielded the coefficient for Time $\times$ log(Rate) (e.g., 0.018 for RS).

Next, we used the above models to predict the melted percentages under different application rates and reaction time for each deicer. In Figure 4, we plotted the melted percentages versus time at four different application rates: 100, 200, 300, and 500, respectively. Different colors represent different deicer types. The dotted lines represent the boundaries of 95% confidence intervals. Note that all these lines are not straight because we have used Box-Cox transformation, a non-linear transformation. From these graphs, we can clearly see that

$$GB \approx AS > RS > BH \approx SB \approx MMZ$$

In the final report for Task 1.2, the qualitative ranking result was: BH ≈ RS > MMZ ≈ SB for the solid deicers. For the liquid deicers, AS and GB have comparable deicing performance at a lower application rate of 20 gallon/lane mile and GB has a better performance than AS when the application rates are higher (35 to 80 gallon/lane mile). In the visual analysis process, the liquid and solid deicers were prepared using different units, i.e., the solid deicers have the unit of lb. per lane mile, while the liquid deicers have the units of gallon per lane mile. Thus, we limited the ranking to within the solid or liquid deicers. In the statistical analysis process, we unified the deicers units to lb/lane mile. Therefore, statistical analysis gave us a more quantitative ranking based on the statistical models established above.





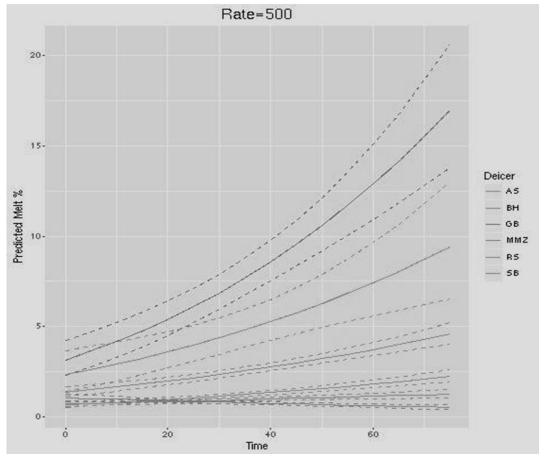


Figure 4 Predictive modeling results for the melted percentages of the six deicers under different application rates (unit: lb/lane mile) and reaction time (0 min to 75 min). Y axis is the predicted melted %. The solid lines are the predicted value and the dotted lines correspond to the 95% confidence interval. Note that it was continuously snowing during the test, so the decreasing trend in the melted% means that the melting rate is slower than the precipitation rate.

3.2 Second Parking Lot Experiment

In this section, we analyzed another data set obtained from the second parking lot test. The application rate of the six deicers was fixed at 500 lb. per lane mile. Therefore, the independent variables are only Time and Deicer. We considered the multiple linear regression model as follows:

$$Melted \sim Time + Deicer,$$

And the model with interaction between Time and Deicer (i.e., Time:Deicer):

$$Melted \sim Time + Deicer + Time{:}Deicer.$$

The AIC of these two models are 427 and 430, respectively. Because of the smaller AIC, the first model was used for further analysis. First, the Kolmogorov-Smirnov test for testing whether the data follows a normal distribution shows that the p-value is 0.14, much higher than the cut-off value of 0.05. We therefore fail to reject the null and conclude that the normality assumption is reasonable. The estimated coefficients in the model equation are listed in Table 4. Note that the reference level is AS (In fact, we can choose any reference level for this model, the choice of reference levels does not influence the model ranking results).

Table 4. The established model equations for all deicers in the second parking lot test. Note the constant for each deicer has been combined with the common intercept for all deicers to form the new intercepts shown.

Deicer	Model description
BH	$Y = 0.016 \times Time + 4.98$
GB	$Y = 0.016 \times Time + 5.55$
MMZ	$Y = 0.016 \times Time + 6.27$
RS	$Y = 0.016 \times Time + 4.25$
SB	$Y = 0.016 \times Time + 3.08$
AS	$Y = 0.016 \times Time + 3.82$

In order to give a statistical ranking to all the six deicers in the second parking lot test, we then ran pair-wise comparison using Turkey's adjustment and obtained Table 5. In the method of pair-wise comparison, each candidate deicer is matched one- on-one with each of the other candidate deicers. This process will award each candidate deicer one point for each head-to-head comparison. Then the candidate deicer with the largest estimate value is the best performer. Positive values indicated that the product listed first performed better, while negative values indicate the second listed product performed better; larger numbers indicate a greater difference between the two compared products' performance. For instance, let's compare BH and RS in Table 5 (i.e., BH – RS). The estimated value is 0.74, which means the average difference between the two deicers is 0.74. BH thus had a better performance than rock salt in the second parking lot test (the pair-wise difference between BH and RS is larger than zero). In addition, the parameter "Pr (>|t|)" in the table is smaller than 0.001, which means the pairwise difference between BH and RS is significant; the lower the Pr value, the greater the confidence that the two products are not performing equivalently.

Table 5 Pairwise comparison in linear regression models for six deicers

	Estimate	Std. Error	t value	Pr(>|t|)	Significant
AS - RS	-0.42	0.18	-2.32	0.19	
BH - RS	0.74	0.18	4.11	<0.001	***
GB - RS	1.31	0.18	7.30	<0.001	***
MMZ - RS	1.02	0.18	-5.68	<0.001	***
SB - RS	-1.17	0.18	-6.49	<0.001	***
BH - AS	1.16	0.18	6.43	<0.001	***
GB - AS	1.73	0.18	9.62	<0.001	***
MMZ - AS	1.44	0.18	8.00	<0.001	***
SB - AS	-0.75	0.18	-4.17	<0.001	***
GB - BH	0.57	0.18	3.19	0.02	**
MMZ - BH	0.28	0.18	1.57	0.62	
SB - BH	-1.91	0.18	-10.60	<0.001	
MMZ - GB	-0.29	0.18	-1.62	0.58	
SB - GB	-2.48	0.18	-13.79	<0.001	***
SB - MMZ	-2.19	0.18	-12.17	<0.001	

Based on the pair-wise comparison result in Table 5, each two deicers were compared one to one, and the statistical ranking result is as follows:

$$GB \approx MMZ \approx BH > RS \approx AS > SB$$

Based on the established model, we also predicted the melted percentages and the corresponding 95% confidence interval which are shown in Figure 5. The figure confirms the above ranking. In the Report for Task 1.2 about the second parking lot part, the performance of GB, MMZ and BH was comparable, but slightly better than that of AS and RS during the entire reaction time (0-75min). Thus the visual analysis qualitative ranking is as follows: GB ≈ MMZ ≈ BH > RS ≈ AS > SB. Therefore, the statistical ranking in the established model matches with the qualitative ranking in the visual analysis process very well.

The above ranking is different from the ranking from the first parking lot test (i.e., $GB \approx AS > RS > BH \approx SB \approx MMZ$). Explanations have been given in the report for Task 1.2.

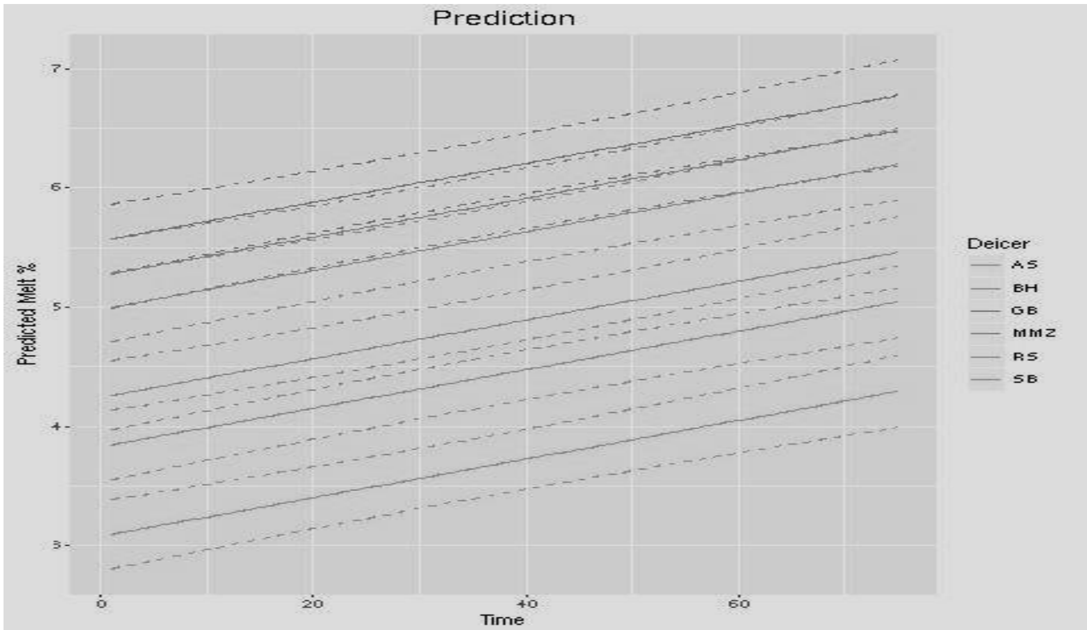


Figure 5 Modeling results for the predicted mean melted % (Y axis) of six deicers between reaction time 0 and 75 min in the second parking lot test.

3.3 Skid resistance

In this data set, the measurements were taken at 9 different time points, from 0 min to 120 minutes with 15 minutes interval for each deicer. There are two replicates for each setting. In the statistical analysis, we first computed the difference of skid resistance between one time point and the next. We then run a two-sample t-test for each pair of deicers. The smallest p-value is 0.005, occurs between GB and BH at 90 minutes and 105 minutes. However, we would not recommend rejecting the null hypothesis (i.e., there is no significant difference between GB and BH) due to the following reasons:

1. There is an issue of multiplicity because we are testing 120 hypotheses simultaneously to detect a potential significance. Such a small p-value may just happen by chance because of the large number of hypotheses. The nominal level must be adjusted to a much smaller value to address this issue. After that, no rejection of the null hypothesis is declared;

2. The two-sample t test we used relies on the normality assumption of the data set. With only two replicates, such an assumption is true and the resultant p-value is not reliable.

In conclusion, no statistically significant difference exists among the deicers in terms of their skid resistance. To obtain more reliable statistical analysis, however, additional data should be collected in the future.

4. Conclusions

Based on the discussion above, we can reach the following conclusions:

4.1 In the first parking lot test, a regression analysis between the melt percentages was conducted. The model includes the response variable Y (melted %), and a set of independent variables, including time, deicer types, and application rate. There were nine candidate models in this study. After calculation of the Akaike information criterion (AIC), "melted% ~ Time + log(Rate) + Deicer + log(Rate):Deicer + Time: Deicer + log(Rate):Time + log(Rate):Deicer: Time" was selected as the working model. The model is a good fit for the data. The R-squared of this model is 0.804. The fitted equations for six deicers are:

Deicer	Model Equation
RS	$\hat{y} = -5.61 - 0.09 \times Time + 0.96 \times log(Rate) + 0.018 \times Time \times log(Rate)$
GB	$\hat{y} = -6.02 - 0.03 \times Time + 1.18 \times log(Rate) + 0.012 \times Time \times log(Rate)$
AS	$\hat{y} = -5.00 - 0.01 \times Time + 0.96 \times log(Rate) + 0.007 \times Time \times log(Rate)$
BH	$\hat{y} = -3.43 - 0.12 \times Time + 0.49 \times log(Rate) + 0.022 \times Time \times log(Rate)$
SB	$\hat{y} = -3.96 - 0.12 \times Time + 0.49 \times log(Rate) + 0.013 \times Time \times log(Rate)$
MMZ	$\hat{y} = -5.96 - 0.076 \times Time + 0.967 \times log(Rate) + 0.001 \times Time \times log(Rate)$

Based on the established model we obtain the deicer statistical ranking as follows: GB ≈ AS > RS > BH ≈ SB ≈ MMZ. The result is slightly different from the visual analysis results (the qualitative ranking result: BH ≈ RS > MMZ ≈ SB for solid deicers, and GB ≈ AS for liquid deicer).

4.2 The second parking lot test was conducted using PennDOT field operation mixing ratios. After comparing two candidate models in the AIC test, "melted % ∼ Time + Deicer" was selected as the working model. After the pair-wise comparison, the statistical ranking is as follows: $GB \approx MMZ \approx BH > RS \approx AS > SB$. This result matches well with the qualitative ranking score in the visual analysis process.

4.3 Statistical analysis for the skid resistance test of six deicers was conducted, and there is no statistically significant difference among the deicers. To obtain more reliable statistical analysis, however, additional data should be collected in the future.

CONTRACT NO. 4400011166
TEM WO 005
DELIVERABLE 2.1 FIELD TEST PROTOCOL

NOVEMBER 03, 2016

1. Pre-Operation

a. A testing station needs to be identified well ahead of time. Preliminary information about the station and the trucks, and historical data from RWIS and AVL about the site should be collected.

b. Drivers and trucks for each test station must be known. Back-up trucks should be known as well in case of mechanical issues. The same truck should be used for each site to improve consistency.

c. Routes of the trucks and the locations of the test, e.g., section of the route, should be available to the team.

d. It is important to decide which storm to monitor. Data collection during heavy snow storms will be problematic, while light storms are not representative. A snow storm of 0.5-1' per hour is deemed to be optimum, although lighter and heavy storms will also be monitored as baselines. PennDOT will notify Temple team no later than 24-hours prior to a monitoring event.

e. The type of deicer to spread, the amount of deicer to spread, time of spreading, and frequency of spreading will be decided by PennDOT and communicated to the Temple team.

f. The following general information should be collected:

- Date and time of test
- Location of the test
- Pavement type. This isn't listed on RWIS, so we will either need to determine based on visual inspection (photos or in-person) or get a more technical specification from PennDOT
- Pavement conditions (snow covered, ice covered) based on visual inspection
- Type of precipitation (light snow, medium snow fall) based on visual inspection and weather forecast
- Material applicator used by PennDOT
- Tester's name
- Pictures of each test area at initial conditions

g. Have all materials ready (deicers, trucks, cameras, teams, etc.)

2. During-Operation

a. Temple will have vehicle available to take the team to the test areas. Four wheel drive vehicles are preferred because they can handle well in snowy conditions. Warm clothing and hot beverages (e.g., thermos) are strongly suggested and are the responsibility of the individuals.

b. Collect all needed data as specified in Section 3 below.

c. After completing the first round of testing, the site should be monitored for the 2nd passing of the same truck, which indicates the test has restarted. A third passing is recommended. Each test will run for about an hour (i.e., one truck pass). If RWIS is used for data collection, a truck passing will be marked as time zero for a test. During Temple's on-road test-run, the starting time will also correlate with truck passing. All relevant information will be collected for each passing.

3. Data needed for on-road evaluation of deicer effects will be collected both from RWIS and AVL and by communicating with PennDOT.

a. Data QA/QC

- All data will be screened to identify outliers and nonsensical data

b. Date and time each data point

- It is anticipated that we will have a data point suite (i.e., all of the below info) for each picture which will be collected at 5 minute intervals
- For parameters with multiple data points collected in the 5 minute interval, a five minute average is suggested

c. Location of the test – taken from RWIS

- Below are the currently identified sites

Pavement:

Site Number	District	County	Location	Stockpile Number	Truck	Product	Pavement Type
1001	10	Butler	I-79 @ Exit 88	0004	5138076	Beet Heat	Black top
1035	10	Butler	I-79 @ MP 100	0004	4968077	Salt Ref	Black top
1039	8	Lebanon	I-81 @ I-78 Split	0007	4038077	Salt Ref	Concrete
1010	8	Dauphin	I-81 @ Exit 77, Manada Hill	0007	3898077	Magic 0	Concrete

Non-Invasive:

1016	4	Susquehanna	I-81 @ Exit 223, Nev Milford	0007	P3028077	Green Blast	Black top
P9	4	Susquehanna	I-81 @ Exit 223 Nev Milford	0021	P2308077	Salt Ref	Black top
B7	1	Venango	SR 0322 @ Venango Mercer Line	0001	P5538077	Aqua salina	Black top
B5	1	Mercer	I-79 @ MP 136 Crawford/Mercer Line	0008	P3358087	Salt ref	Black Top

d. Deicer application – data to be collected either manually or from AVL for each site

- Data will be identified for around the camera capture system – for an identified vehicle based on the latitude and longitude; at present, this identification is likely going to be manual, though we may be able to streamline this
- Product – identified by PennDOT (not sure if it will show up in AVL)
- Solid material
- Solid rate
- Solid application time
- Solid spread
- Prewet rate
- Prewet spread
- Anti-ice rate
- Anti-ice spread
- AVL has columns for air and road temp, but they do not appear to be working in example spreadsheet

e. Weather conditions – taken from RWIS for each site, data point every five minutes

- Temperatures
    - Surface temperature (use temperature gun to measure manually, be sure to measure the pavement temperature, not the snow or ices)
        a. They also present base and ground temperature – need to identify which is the most important
    - Air temperature (use local weather station)

- Precipitation
  - Rain state and intensity – this will indicate snow intensity
  - Average precipitation last 1 hr
- Wind speed and direction
- Camera shots
  - Recorded by the ground team
  - Will be retrieved from RWIS, but since RWIS only allows retrieving photos one by one, Temple will request, via PennDOT, Vaisala to provide batches of photos for a given storm.
  - Or can download pictures manually (one at a time)

f. Weather conditions – from weather station

- What data is available will depend on weather station options/selection
- Desired data includes: Cloud coverage (could be variable as it is only available on some RWIS pictures)

g. Traffic conditions

- PennDOT can provide the ADT (average daily traffic)
- An exact count of the number of vehicles will be obtained either by the ground team or by watching real-time camera as the vehicles go through.

4. Post-Operation – Data Analysis

For each test, relevant data extracted from the above list will be compiled and organized in a multiple-sheet Excel file. Data will be classified as (a) metadata, (b) performance data derived from picture analysis and team observations, (c) deicer application data, (d) weather condition data, and (e) traffic data. Metadata are defined as additional data which summarizes basic information about other data. Except for metadata, which will be listed in a separate spread sheet, data (b-e) will be organized as time series: one column per data type, and one row per time point. Each time point will correspond to a discrete picture/observation collected during the test: RWIS/AVL pictures taken every 5 minutes and on-site pictures and observations collected by the team.

Ranking the deicer materials based on the collected data, during different storms under different road and weather conditions, will require statistical treatment in order to extract the impact of the deicer material type and rate of application from other relevant environmental variables. For such downstream statistical analyses, which may include multivariate regression or redundancy analysis, data (b-e) will need to be organized further as either dependent variable, i.e., performance data (b), or independent or explanatory variables, i.e., deicer application data (c), weather condition data (d), and traffic data (e).

The following data will be included in the Excel file:

a. Metadata: Metadata will be displayed on the first sheet of the Excel file and include data listed in 1f and 3b-c above:

i. Test date

ii. Testing station/location

iii. Pavement type/condition

iv. Storm type/category

v. Precipitation type

vi. Deicer type

vii. Applicator type

viii. Driver and truck number

ix. Number of truck passing

x. Test duration

xi. Number of pictures taken and/or on-site observations recorded

xii. Investigator names

b. Performance data (dependent variable): Time series data (including performance data, deicer application data, weather condition data, and traffic data) will be displayed in subsequent sheets – multiple sheets will be necessary to group data relative to different passings. Performance data will be derived from the analysis of pictures obtained from the RWIS/AVL system and/or taken by the investigators on-site. In addition, visual observations may be directly recorded by the investigators on-site.

In order to evaluate and quantify the deicing performance of each treatment, pictures will be 'visually' analyzed. For 'visual' analysis, the pictures will be independently observed by each team member and scores for melting performance will be assigned – e.g., scoring will be from '0' to '5', '0' being no melting has occurred, '5' being fully melted. Scores given by each analyst will be displayed in a separate column. Average scores and standard deviations will be displayed in additional columns. Alternatively, the team has started evaluating the possibility of using image analysis software to provide additional 'quantitative' figures representing the pavement icing conditions during the test. This 'quantitative' method is a more accurate approach, which would use imaging software to measure the optical density of pixels in pictures. For instance, 'ImageJ' is an advanced image analysis software that was originally developed by NIH to measure staining in tissues. One potential limitation of this approach will likely be the format and resolution of the pictures obtained from the RWIS/AVL system. In any cases, a performance score will be determined from deicing performance data.

c. Deicer application data (independent variable): Deicer application data around the camera capture system or on-site observation points (listed in 3d above) will include the following:

i. Product(s)

ii. Solid rate

iii. Solid spread

iv. Prewet rate

v. Prewet spread

vi. Anti-ice rate

vii. Anti-ice spread

d. Weather condition data (independent variable): Weather condition data around the camera capture system or on-site observation points (listed in 3e-f above) will include:

i. Surface temperature

ii. Air temperature

iii. Precipitation (snow) intensity

iv. Average precipitation last 1 hour

v. Wind speed and direction

vi. Developed layers

e. Traffic data (independent variable): Traffic data around the camera capture system or on-site observation points (listed in 3g above) will include the number of vehicles recorded per hour passing through the test site.

5. Post-Operation – Deicer Ranking Statistical Analysis

We plan to develop a statistical model to build the relationship between the performance of various deicer products and all other variables, including deicer type, application rate, weather conditions, and traffic. The performance of the products is time-dependent. In our first attempt, we will add time scale as a predictor and model it using different methods. The goal of this analysis is two-fold: (i) to detect if there is any significant difference among the effects of all the deicer products; and (ii) to rank all the deicer products.

Let Y_{itk} be the k-th replicate of the performance data of the i-th deicer product at the t-th time point. Let X_{it} be the time-related covariates, including surface temperature, air temperature, wind speed, average precipitation within 1 hour, and traffic data. Let Z_i be the time-unrelated covariates, including deicer type and application rate. We start from the following simple model where

$$Y_{itk} = \beta_0 + \beta_{it}X_{it} + \gamma_{i1}Z_{i1} + \gamma_{i2}Z_{i2} + f(t) + \epsilon_{itk} \qquad (1)$$

Here $f(t)$ is used to model the average performance over time. We will start from the linear case where $f(t) = \beta t$. ϵ_{itk} is the random noise which is assumed to be independent and identically distributed as $N(0, \sigma^2)$. The model assumption will be checked based on the Kolmogorov-Smirnov test ([Kolmogorov(1933), Smirnov(1948)]) on the residual. If there exists a strong evidence of lack-of-fit, we will assume $f(t)$ to be a quadratic function, and an exponential function of t.

Upon passing the goodness-of-fit test, we will make inference toward the scientific goals. Our primary interest is γ_{i1}, the parameter corresponding to various deicer types. After fitting the model, we will run pairwise comparison on the hypothesis H_{ij}^0: $\gamma_{i1} = \gamma_{j1}$ based on Tukey's adjustment for multiplicity ([Tukey(1949)]). This is to identity pairs of deicers that perform significantly differently from each other. In the pair-wise comparison, we can also rank the performance based on the magnitude and the sign of the effects γ_{i1}.

6. References

[Kolmogorov(1933)] A N Kolmogorov. Sulla determinazione empirica di una leggi di distribuzione. *G. Inst. Ital. Attuari*, 4, 1933.

[Smirnov(1948)] Nickolay Smirnov. Table for estimating the goodness of fit of empirical distributions. *The annals of mathematical statistics*, 19(2): 279–281, 1948.

[Tukey(1949)] Tukey JW. 1949. Comparing individual means in the analysis of variance. Biometrics 5:99- 114.

Appendix I

<u>Pavement Site Information:</u>

1. Site 1001, I-79 @ Exit 88, Butler County: District 10
    a. Coordinates- 80° 7' 30" W; 40° 47' 30" N
    b. Altitude- 1086 ft.
    c. Camera pictures are focus on left lane, north bound.
    d. Corresponding truck- P5138076 - AVL# - 1020-513-8076
        i. No Truck data found for known snow storm dates.
2. Site 1035, I-79 @ MP 100, Butler County: District 10

a. Coordinates- 80° 7' 59" W; 40° 58' 32" N
b. Altitude- 1230 ft.
c. Camera pictures are focused on center of left lane, north bound.
d. Corresponding Truck- P4968077- AVL# - 1020-496-8077
    i. Primary Route (on 1/23/16) – Navigates along I-79
    ii. Does not pass site on 1/23/16
    iii. Main compound being used is solid compound SALT-100

3. Site 1039, I-81 @ I-78 Split
    a. Coordinates- 76° 31' 21" W; 40° 25' 29" N
    b. Altitude- 525 ft.
    c. Camera pictures are focused on right lane, northeast bound.
    d. Corresponding Truck- P4038077- AVL#- 0880-403-8077
        i. Primary Route (on 1/22/16) – Navigates along I-81, I-78, Rte. 22, Rte. 72 and Fisher Ave.
        ii. Within 24 hour period (1/22-1/23) truck passes the site 9 different times.
        iii. Main compound being used is solid compound SALT-100.
        iv. No common landmark names noted.
4. Site 1010, I-81 @ Exit 77, Manada Hill
    a. Coordinates- 76° 44' 3" W; 40° 20' 59" N
    b. Altitude- 502 ft.
    c. Camera pictures are focus on left lane, southwest bound.
    d. Corresponding truck- P3898077- AVL#- 0850-389-8077
        i. Primary Route (on 1/22/16) - Along I-81 and Rte. 22. Various side streets too, most likely to turn around on interstate/ highway.
        ii. Within 24 hour period (1/22-1/23) truck passes site 11 different times.
        iii. Main compound used was solid compounds: 25A-75S and 75A-25S
        iv. Common Landmark passed is named “Blue Ridge”.

<u>Non-Invasive Site Information:</u>

5. Site 1016, I-81 @ Exit 223, New Milford., Susquehanna , District 4
    a. Coordinates- 75° 42' 0" W; 41° 52' 0" N
    b. Altitude- 98 ft.
    c. Camera pictures are focused on right lane, southeast bound.
    d. Corresponding truck- P3028077- AVL#- 0450-302-8077
        i. Primary Route (on 1/23/16) - Along I-81
        ii. No truck travel data on storm dates.
        iii. Looks to be filled with 75A-25S on 1/23/16
6. Site P9, I-81 @ Exit 223, New Milford., Susquehanna , District 4
    a. Coordinates- 75° 42' 0" W; 41° 52' 0" N
    b. Altitude- 98 ft.
    c. Camera pictures are focused on right lane, southeast bound.
    d. Corresponding truck- P2308077- AVL#- 0450-230-8077
        i. No truck data found on AVL for known winter storm events.

7. Site B7, SR 0322 @ Venango/ Mercer Line, Venango , District 1
    a. Coordinates- 79° 59' 39" W; 41° 28' 51" N
    b. Altitude- 1306 ft.
    c. Camera pictures are focused on both lanes, east and west bound.
    d. Corresponding truck- P5538077- AVL#- 0150-553-8077
        i. No truck data found on AVL for known winter storm events.
8. Site B5, I-79 @ MP 136, Crawford/ Mercer Line., Mercer , District 1
    a. Coordinates- 80° 9' 59" W; 41° 28' 52" N
    b. Altitude- 1371 ft.
    c. Camera pictures are focused on right lane, north bound.
    d. Corresponding truck- P3358087- AVL#- 0140-335-8087
        i. Primary Route- Along I-79

No truck travel data on storm dates.

CONTRACT NO. 4400011166

TEM WO 005

DELIVERABLE 2.2 REPORT DETAILING TEST OBSERVATIONS AND FINALIZED TESTING PROTOCOLS FOR ON-ROAD REAL TIME TESTING (WITHOUT RWIS AND AVL SYSTEMS)

FEBRUARY 27, 2017

Summary

1. **Pre-Operation**

   a. Testing stations need to be identified well ahead of time. Preliminary site selection information and historical data should be collected manually.

   b. The same method and vehicle should be used for each site to improve consistency.

   c. Site selection or roadway for testing should be available to the team.

   d. It is important to decide which storm to monitor. Data collection during heavy snow storms will be problematic, while light storms are not representative. A snow storm of 0.5-1’ per hour is deemed to be optimum, although lighter and heavy storms will also be monitored as references.

   e. The type of deicer, rate of application, time of application, and frequency of applications should be communicated to the team. Also, the deicer preparation should be based on manufacturers’ recommendations.

   f. The following general information should be collected:

      - Date and time of test
      - Location of the test
      - Pavement type. We need to determine it based on visual inspection (photos or in-person) or get technical specification from PennDOT
      - Pavement conditions (e.g., snow cover, ice cover) based on visual inspection
      - Type of precipitation (e.g., light snow, medium snow, heavy snow) based on visual inspection and weather forecast
      - Material applicator used
      - Tester’s name
      - Pictures of each test area at initial conditions

   g. Have all materials ready (deicers, trucks, cameras, teams, etc.)

2. **During-Operation**

    a. The testing team will have vehicle available to take the team to the test sites. Four-wheel drive vehicles are preferred because they can handle well in snowy conditions. Collect all needed data as specified below.

    b. If using truck applications after completing the first round of testing (1^{st} truck passing), the site should be monitored for the 2^{nd} passing of the same truck, which indicates the test has restarted. A third passing is recommended. Each test will run for about 1-2 hour (i.e., one truck pass). During the on-road testing, the starting time needs to match with truck passing. All relevant information will be collected for each passing.

    c. Data QA/QC: All data will be screened to identify outliers and nonsensical data

    d. Date and time each data point

It is anticipated that we will have a suite of data points (i.e., all of the below info) for each picture which will be collected at 5-minute intervals. For parameters with multiple data points collected in the 5-minute interval, a five-minute average will be computed.

    e. Location of the test –See appendix 1.

    f. Deicer application – data to be collected manually for each site

        i. Data will be identified for around the camera capture system – for an identified vehicle based on the latitude and longitude;

        ii. Product

        iii. Solid material

        iv. Solid rate

        v. Solid application time

        vi. Solid spread

        vii. Prewet rate

        viii. Prewet spread

        ix. Anti-ice rate

        x. Anti-ice spread

    g. Weather conditions –Weather information will be collected from online weather services, for example, Weather Underground (https://www.weatherground.com/), from which we can obtain several weather parameters such as temperature, pressure, visibility, cloud coverage, wind chill, humidity, wind speed, and precipitation. The testing team will collect the data from Weather Underground every five minutes for each site.

i. Temperature

1. Surface temperature: measured by a temperature gun
2. Air temperature: measured by a thermometer

ii. Precipitation

1. Storm state and intensity – this will indicate mixed snow and rain intensity
2. Average precipitation over one hour

iii. Wind speed and direction

iv. Developed layers

v. Camera shots

1. Recorded by the ground team

vi. Cloud coverage (from weather stations, Weather Underground, etc.)

h. Traffic conditions

i. The number of vehicles passing the observation site in five minutes will be obtained by the ground team.

3. On-Road Real-time Testing Data Collection

a. Criteria for assigning reasonable visual scores: Every time when a visual score is given to an image photo, the researcher should compare it to the reference surface coverage levels given below (see Fig. 1), in order to ensure the score percentages are consistent for further research.

Fig. 1. Examples of pavement surface coverage. From left to right: 40% melted, 50% melted, and 60% melted.

b. The photos should include clear roadway with adequate visibility. For example, Figures 2 and 3 show two photos with poor quality. Fig. 2 should not be considered because of the darkness. Fig. 3 should not be considered because the snow was 100% melted during the entire testing time window.

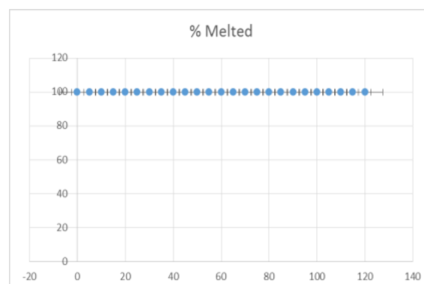


Fig. 2. 07-Jan-2017 from06:11from site SR0322@Venango/Mercer

Fig. 3. 14-Dec-2017 from07:11from site SR0322@Venango/Merc er

c. When the road is plowed by the truck prior to deicer application, the photos taken at that time are likely not useful because one cannot visually observe changes in the extent of snow melting.

d. When giving visual scores, the researcher should try to ignore the interference of photo conditions, e.g., lightness in the Fig.4 and Fig.5 below differs a lot, possibly leading to inaccurate scoring. In such a case, the researchers should avoid the interference of different lightness, in order to give accurate visual scores according to the criteria listed above.

Fig. 4. 15-Jan-2017 at 07:41AM from site SR0322@Venango/Mercer

Fig. 5. 15-Jan-2017 at 07:36 AM from site SR0322@Venango/Mercer

e. During the test, if the precipitation is too heavy, the storm should not be treated as a representative storm event for visual data collection purposes. Heavy precipitation may cause recording a biased, lower trend in melted percent because of the snowing process. See Fig.6 below as an example.

		% Melted			
Time	Time (Mins)	Ryan	Xiang	AVG	STDEV
5:51:00 AM	0	25	10	17.5	10.6066
5:56:00 AM	5	30	20	25	7.071068
6:01:00 AM	10	35	25	30	7.071068
6:06:00 AM	15	45	30	37.5	10.6066
6:11:00 AM	20	45	30	37.5	10.6066
6:16:00 AM	25	45	40	42.5	3.535534
6:21:00 AM	30	45	50	47.5	3.535534
6:26:00 AM	35	45	50	47.5	3.535534
6:31:00 AM	40	45	60	52.5	10.6066
6:36:00 AM	45	40	55	47.5	10.6066
6:41:00 AM	50	35	40	37.5	3.535534
6:46:00 AM	55	35	50	42.5	10.6066
6:51:00 AM	60	35	50	42.5	10.6066
6:56:00 AM	65	40	50	45	7.071068
7:01:00 AM	70	45	50	47.5	3.535534
7:06:00 AM	75	45	50	47.5	3.535534
7:11:00 AM	80	35	45	40	7.071068
7:16:00 AM	85	25	25	25	0
7:21:00 AM	90	25	25	25	0
7:26:00 AM	95	35	35	35	0
7:31:00 AM	100	35	35	35	0
7:36:00 AM	105	35	35	35	0
7:41:00 AM	110	35	35	35	0
7:46:00 AM	115	35	35	35	0
7:51:00 AM	120	35	35	35	0

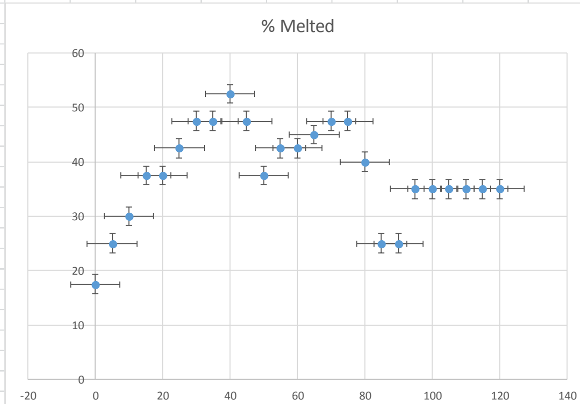


Fig. 6. Photo analysis results on Dec 08, 2016 at SR0322 Venango Mercer Line 08

4. Post-Operation – Data Analysis

For each test, relevant data extracted from the above list will be compiled and organized in a multi-sheet Excel file. The data should include the following:

(a) Melting efficiency from team observations,

(b) Deicer application rate,

(c) Weather condition,

(d) Traffic,

(e) Material concentration, and

(f) Material re-freezing point

Each time point will correspond to an observation collected during the test.

a. Model establishing process

For statistical analyses based on multivariate regression, melting efficiency data (a) will be treated as the dependent variable, while operational parameters including deicer application data (b), weather condition data (c), and traffic data (d) will be treated as the independent variables. Several models will be tested for establishing a relationship between melting efficiency and operational parameters. We will first use the ordinary least square (OLS) model with several evaluation parameters, such as the "residuals versus fits plot", R square, and standard error, to select the best fitted parameters. An alternative model will be the weighted least square model.

The linear regression model can be expressed as % melted Area （Y）as a function of Deicer Rate, Time, Weather, Road Conditions, and Deicer Type. Since the "Deicer type" is a categorical variable with six levels, we will consider rock salt (RS) as the reference and introduce five dummy variables corresponding to the remaining deicers X_{II}, $X_{III} \cdots X_{VI}$. The linear model will be expressed as the equation below：

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5^{II} X_{II} + \beta_5^{III} X_{III} + \ldots \beta_5^{VI} X_{VI} + \epsilon$$

where X_1 represents the loading rate, X_2 represents the time, X_3 represents the type of deicer, X_4 represents road conditions and β_i is the regression coefficient for the corresponding parameter *i* (*i* = 1,2,3,4). β_5^{II} is the relative melting efficiency of the second deicer when compared to the reference level. The larger the β_5^{II} value, the better type II deicer is in affecting the melting efficiency.

b. Comparison of deicer performance based on the established models

Based on the above linear regression, scores will be obtained for each deicer which will be used to rank the deicer performance. Rock salt will be chosen as the reference, and its β_5 value will be set at zero. For all other deicers, their respective β_5 values will be their performance scores, assuming all other parameters are the same. A large positive β_5 value indicates the deicer is significantly better than rock salt, while a more negative β_5 value indicates the deicer is significantly worse than rock salt. Pair-wise comparison, based on the Turkey's adjustment for multiplicity, will be carried out between any two deicers to test if a significant difference exists between them. For example, if $\beta_{5A} > \beta_{5B}$ and the adjusted p-value is small, then A is ranked higher than B.

CONTRACT NO. 4400011166
TEM WO 005
DELIVERABLE 2.2 REPORT DETAILING TEST OBSERVATIONS AND FINALIZED TESTING PROTOCOLS FOR ON-ROAD REAL TIME TESTING (WITH RWIS AND AVL SYSTEMS)

FEBRUARY 27, 2017

SUMMARY

1. Pre-Operation

a. Testing stations need to be identified well ahead of time. Preliminary site selection information about the stations and the trucks (see appendix I) and historical data from RWIS and AVL about the sites should be collected.

b. Drivers and trucks for each test station must be known. Back-up trucks should be known as well in case of mechanical issues. The same truck should be used for each site to improve consistency.

c. Routes of the trucks and the locations of the test, e.g., section of the route, should be available to the team.

d. It is important to decide which storm to monitor. Data collection during heavy snow storms will be problematic, while light storms are not representative. A snow storm of 0.5-1' per hour is deemed to be optimum, although lighter and heavy storms will also be monitored as references. PennDOT will notify Temple team no later than 24-hours prior to a monitoring event.

e. The type of deicer, rate of application, time of application, and frequency of application shall be determined by PennDOT and communicated to the Temple team. Also, the deicer preparation should be based on manufacturers' recommendations and PennDOT practices. Application rates for field testing will vary from one site to another.

f. The following general information should be collected:

- Date and time of test
- Location of the test
- Pavement type. This is not listed on RWIS, so we will need to either determine it based on visual inspection (photos or in-person) or get technical specification from PennDOT

- Pavement conditions (e.g., snow cover, ice cover) based on visual inspection
- Type of precipitation (e.g., light snow, medium snow, heavy snow) based on visual inspection and weather forecast
- Material applicator used by PennDOT
- Tester's name
- Pictures of each test area at initial conditions

g. Have all materials ready (deicers, trucks, cameras, teams, etc.)

2. During-Operation

a. Temple will have vehicle available to take the team to the test sites. Four-wheel drive vehicles are preferred because they can handle well in snowy conditions. Collect all needed data as specified below.

b. After completing the first round of testing (1^{st} truck passing), the site should be monitored for the 2^{nd} passing of the same truck, which indicates the test has restarted. A third passing is recommended. Each test will run for about 1-2 hour (i.e., one truck pass). If RWIS is used for data collection, each truck passing will be marked as time zero for a test. During Temple's on-road test-run, the starting time will also match with truck passing. All relevant information will be collected for each passing.

c. Data QA/QC: All data will be screened to identify outliers and nonsensical data
d. Date and time each data point

It is anticipated that we will have a suite of data points (i.e., all of the below info) for each picture which will be collected at 5-minute intervals. For parameters with multiple data points collected in the 5-minute interval, a five-minute average will be computed.

e. Location of the test – taken from RWIS. See appendix 1.
f. Deicer application – data to be collected either manually or from AVL for each site
   i. Data will be identified for around the camera capture system – for an identified vehicle based on the latitude and longitude;
   ii. Product – identified by Penn DOT
   iii. Solid material
   iv. Solid rate
   v. Solid application time
   vi. Solid spread

vii. Prewet rate

viii. Prewet spread

ix. Anti-ice rate

x. Anti-ice spread

xi. AVL has columns for air and road temperature

g. Weather conditions – weather information will be taken from RWIS for each site, data point every five minutes. For comparison, weather information will be collected from other online weather services, for example, Weather Underground (https://www.wunderground.com/) , from which we can obtain several weather parameters such as temperature, pressure, visibility, cloud coverage, wind chill, humidity, wind speed, and precipitation. The Temple team will collect the data from both the RWIS and Weather Underground at specific times, which will allow the validation of RWIS station data.

i. Temperature

1. Surface temperature

2. Air temperature

ii. Precipitation

1. Storm state and intensity – this will indicate mixed snow and rain intensity

2. Average precipitation over one hour

iii. Wind speed and direction

iv. Developed layers

v. Camera shots

1. Recorded by the ground team

2. Retrieved from RWIS. Since RWIS only allows retrieving photos one by one, Temple will request, via PennDOT, Vaisala to provide batches of photos for a given storm

3. Alternatively, download pictures manually (one at a time)

vi. Cloud coverage (from weather stations, Weather Underground, etc.)

h. Traffic conditions

i. PennDOT can provide the ADT (average daily traffic)

ii. A more accurate count of the number of vehicles will be obtained either by the ground team or by watching real-time camera as the vehicles go through.

3. On-Road Real-time Testing Data Collection from RWIS and AVL

a. Criteria for assigning reasonable visual scores: Every time when a visual score is given to an image photo, the researcher should compare it to the reference surface coverage levels given below (see Fig. 1), in order to ensure the score percentages are consistent for further research.

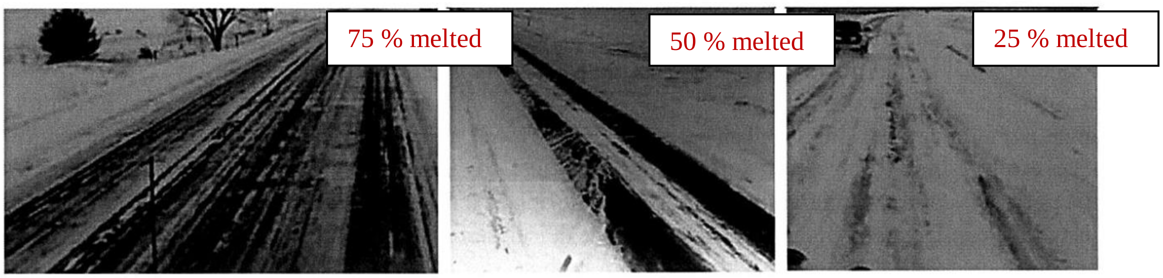
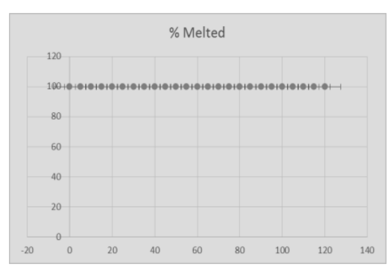


Fig. 1. Examples of pavement surface coverage. From left to right: 75% melted, 50% melted, and 25% melted. (Adapted from Gerbino-Bevins 2011)

b. Before collecting RWIS data, it is important to ensure that the RWIS station camera functions properly to give meaningful visual scores, for example, the photos should include clear roadway with adequate visibility. For example, Figures 2 and 3 show two photos from a RWIS station. Fig. 2 should not be considered because of the darkness. Fig. 3 should not be considered because the snow was 100% melted during the entire testing time window.

Fig. 2. 07-Jan-2017 from06:11from site SR0322@Venango/Mercer

Fig. 3. 14-Dec-2017 from07:11from site SR0322@Venango/Merc
er



c. Before collecting the RWIS data, ensure that the AVL station offers all the needed information, e.g., the solid material and solid application rate are the most important parameters.

d. When the road is plowed by the truck prior to deicer application, the subsequent photos are likely not useful because one cannot visually observe changes in the extent of snow melting.

e. In the case of site SR0322@Venango/Mercer, the camera focuses on both directions of the target road, the truck passes by the site two times (only a few minutes apart), so the second truck time should be set as time zero because we need to ensure both lanes are being treated with the deicer. However, it is also important to include at least two photos prior to the second deicer application as the baseline for comparison. This applies to all sites.

f. When giving visual scores, the researcher should try to ignore the interference of camera conditions, e.g., lightness in the two figures below differs a lot, possibly leading to inaccurate scoring. In such a case, the researchers should avoid the interference of different lightness, in order to give accurate visual scores according to the criteria listed above.

Fig. 4. 15-Jan-2017 at 07:41AM from site SR0322@Venango/Mercer

Fig. 5. 15-Jan-2017 at 07:36 AM from site SR0322@Venango/Mercer

g. During the test, if the precipitation is too heavy, the storm should not be treated as a representative storm event for visual data collection purposes. Heavy precipitation may cause recording a biased, lower trend in melted percent because of the snowing process. See Fig.6 below as an example.

		% Melted			
Time	Time (Mins)	Ryan	Xiang	AVG	STDEV
5:51:00 AM	0	25	10	17.5	10.6066
5:56:00 AM	5	30	20	25	7.071068
6:01:00 AM	10	35	25	30	7.071068
6:06:00 AM	15	45	30	37.5	10.6066
6:11:00 AM	20	45	30	37.5	10.6066
6:16:00 AM	25	45	40	42.5	3.535534
6:21:00 AM	30	45	50	47.5	3.535534
6:26:00 AM	35	45	50	47.5	3.535534
6:31:00 AM	40	45	60	52.5	10.6066
6:36:00 AM	45	40	55	47.5	10.6066
6:41:00 AM	50	35	40	37.5	3.535534
6:46:00 AM	55	35	50	42.5	10.6066
6:51:00 AM	60	35	50	42.5	10.6066
6:56:00 AM	65	40	50	45	7.071068
7:01:00 AM	70	45	50	47.5	3.535534
7:06:00 AM	75	45	50	47.5	3.535534
7:11:00 AM	80	35	45	40	7.071068
7:16:00 AM	85	25	25	25	0
7:21:00 AM	90	25	25	25	0
7:26:00 AM	95	35	35	35	0
7:31:00 AM	100	35	35	35	0
7:36:00 AM	105	35	35	35	0
7:41:00 AM	110	35	35	35	0
7:46:00 AM	115	35	35	35	0
7:51:00 AM	120	35	35	35	0

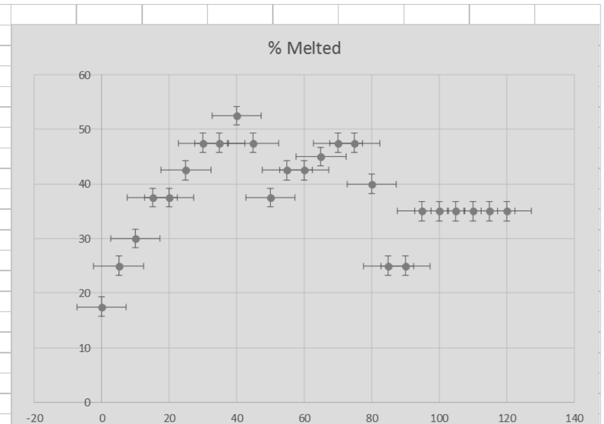


Fig. 6. Photo analysis results on Dec 08, 2016 at SR0322 Venango Mercer Line 08

4. **Post-Operation – Data Analysis**

For each test, relevant data extracted from the above list will be compiled and organized in a multi-sheet Excel file. The data should include the following:

(a) Melting efficiency from picture analysis and team observations
(b) Deicer application rate
(c) Weather condition
(d) Traffic
(e) Chemical concentration and/or Grip level
(f) Other relevant RWIS data

Each time point will correspond to a picture/observation collected during the test: RWIS/AVL pictures taken every 5 minutes and on-site pictures and observations collected by the team.

c. Model establishing process

For statistical analyses based on multivariate regression, melting efficiency data (a) will be treated as the dependent variable, while operational parameters including deicer application data (b), weather condition data (c), and traffic data (d) will be treated as the independent variables. Several models will be tested for establishing a relationship between melting efficiency and operational parameters. We will first use the ordinary least square (OLS) model with several evaluation parameters, such as the "residuals versus fits plot", R square, and standard error, to select the best fitted parameters. An alternative model will be the weighted least square model.

The linear regression model can be expressed as % melted Area （Y）as a function of Deicer Rate, Time, Weather, Road Conditions, and Deicer Type. Since the "Deicer type" is a categorical variable with six levels, we will consider rock salt (RS) as the reference and introduce five dummy variables corresponding to the remaining deicers X_{II}, $X_{III} \cdots X_{VI}$. The linear model will be expressed as the equation below:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5^{II} X_{II} + \beta_5^{III} X_{III} + \ldots \beta_5^{VI} X_{VI} + \epsilon$$

where X_1 represents the loading rate, X_2 represents the time, X_3 represents the type of deicer, X_4 represents road conditions and β_i is the regression coefficient for the corresponding parameter *i* (*i* = 1,2,3,4). β_5^{II} is the relative melting efficiency of the second deicer when compared to the reference level. The larger the β_5^{II} value, the better type Ⅱ deicer is in affecting the melting efficiency.

d. Comparison of deicer performance based on the established models

Based on the above linear regression, scores will be obtained for each deicer which will be used to rank the deicer performance. Rock salt will be chosen as the reference, and its β_5 value will be set at zero. For all other deicers, their respective β_5 values will be their performance scores, assuming all other parameters are the same. A large positive β_5 value indicates the deicer is significantly better than rock salt, while a more negative β_5 value indicates the deicer is significantly worse than rock salt. Pair-wise comparison, based on the Turkey's adjustment for multiplicity, will be carried out between any two deicers to test if a significant difference exists between them. For example, if $\beta_{5A} > \beta_{5B}$ and the adjusted p-value is small, then A is ranked higher than B.

5. Preliminary Data for the On-Road Real-time Storm Events Monitored between December 2016 and January 2017

a. Examples of visual scores given to the on-road real-time storm images

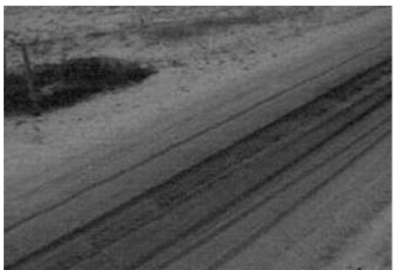


Fig. 7. 6-26 AM 11-20-16
17.5 % melted
SR0322@Venango/Mercer

Fig. 8. 7-56 AM 11-20-16
22.5% melted
SR0322@Venango/Mercer

Fig. 9. 9-01 AM 11-20-16
50% melted
SR0322@Venango/Mercer

b. List of storm events monitored

The list below includes the storm events monitored during the time window between December 2016 and Jan 2017. There are 28 storm events in total. The storm events were monitored according to the above mentioned protocol. In Table 1, the storms that are shaded are deemed useful based on the criteria in "Data Collection" (useful data means the data has a clear trend in the graph showing suitable melted percentages for subsequent data analysis), which are discussed in the section below.

Table 1 storm events monitored during the time window between December 2016 and Jan 2017

N	Test site	Time window	Vehicle #	Travel Tim 1	Travel Tim 2
1	SR 0322 @ Venango/Mercer Line	19-Nov-2016 12:00 → 20-Nov 2016 12:00	0150-553-8077	11/19/2016 22:15	11/19/2016 22:04
2	SR 0322 @ Venango/Mercer Line	19-Nov-2016 12:00 → 20-Nov 2016 12:00	0150-553-8077	11/20/2016 17:45	11/20/2016 17:57
3	SR 0322 @ Venango/Mercer Line	08-Dec-2016 12:00 → 09-Dec 2016 12:00	0150-553-8077	12/9/2016 5:49	12/9/2016 5:57
4	SR 0322 @ Venango/Mercer Line	08-Dec-2016 12:00 → 09-Dec 2016 12:00	0150-553-8077	12/9/2016 8:19	12/9/2016 8:28
5	SR 0322 @ Venango/Mercer Line	09-Dec-2016 12:00 → 10-Dec 2016 12:00	0150-553-8077	12/9/2016 13:20	12/9/2016 13:30
6	SR 0322 @ Venango/Mercer Line	09-Dec-2016 12:00 → 10-Dec 2016 12:00	0150-553-8077	12/9/2016 15:16	12/9/2016 15:26
7	SR 0322 @ Venango/Mercer Line	09-Dec-2016 12:00 → 10-Dec 2016 12:00	0150-553-8077	12/9/2016 17:21	12/9/2016 17:34
8	SR 0322 @ Venango/Mercer Line	09-Dec-2016 12:00 → 10-Dec 2016 12:00	0150-553-8077	12/9/2016 21:38	12/9/2016 21:54

9	SR 0322 @ Venango/Mercer Line	10-Dec-2016 12:00 → 11-Dec 2016 12:00	0150-734-8076	12/11/2016 6:49	12/11/2016 6:57
10	SR 0322 @ Venango/Mercer Line	11-Dec-2016 12:00 → 12-Dec 2016 12:00	0150-553-8077	12/11/2016 13:27	12/11/2016 13:38
11	SR 0322 @ Venango/Mercer Line	11-Dec-2016 12:00 → 12-Dec 2016 12:00	0150-553-8077	12/11/2016 15:44	12/11/2016 15:57
12	SR 0322 @ Venango/Mercer Line	11-Dec-2016 12:00 → 12-Dec 2016 12:00	0150-553-8077	12/11/2016 18:48	12/11/2016 19:01
13	SR 0322 @ Venango/Mercer Line	11-Dec-2016 12:00 → 12-Dec 2016 12:00	0150-553-8077	12/11/2016 21:49	12/11/2016 22:03
14	SR 0322 @ Venango/Mercer Line	11-Dec-2016 12:00 → 12-Dec 2016 12:00	0150-553-8077	12/12/2016 2:20	12/12/2016 2:31
15	SR 0322 @ Venango/Mercer Line	11-Dec-2016 12:00 → 12-Dec 2016 12:00	0150-553-8077	12/12/2016 8:27	12/12/2016 8:51
16	SR 0322 @ Venango/Mercer Line	13-Dec-2016 12:00 → 14-Dec 2016 12:00	0150-553-8077	12/13/2016 13:25	12/13/2016 13:36
17	SR 0322 @ Venango/Mercer Line	13-Dec-2016 12:00 → 14-Dec 2016 12:00	0150-553-8077	12/13/2016 16:25	12/13/2016 16:37
18	SR 0322 @ Venango/Mercer Line	13-Dec-2016 12:00 → 14-Dec 2016 12:00	0150-553-8077	12/13/2016 18:30	12/13/2016 18:42
19	SR 0322 @ Venango/Mercer Line	13-Dec-2016 12:00 → 14-Dec 2016 12:00	0150-553-8077	12/14/2016 6:13	12/14/2016 6:36
20	SR 0322 @ Venango/Mercer Line	14-Dec-2016 12:00 → 15-Dec 2016 12:00	0150-553-8077	12/15/2016 6:02	12/15/2016 6:12
21	SR 0322 @ Venango/Mercer Line	14-Dec-2016 12:00 → 15-Dec 2016 12:00	0150-553-8077	12/15/2016 8:44	12/15/2016 8:57
22	SR 0322 @ Venango/Mercer Line	14-Dec-2016 12:00 → 15-Dec 2016 12:00	0150-553-8077	12/15/2016 10:33	12/15/2016 10:40
23	SR 0322 @ Venango/Mercer Line	15-Dec-2016 12:00 → 16-Dec 2016 12:00	0150-553-8077	12/15/2016 14:09	12/15/2016 14:18
24	SR 0322 @ Venango/Mercer Line	16-Dec-2016 12:00 → 17-Dec 2016 12:00	0150-553-8077	12/17/2016 3:25	12/17/2016 3:34
25	SR 0322 @ Venango/Mercer Line	16-Dec-2016 12:00 → 17-Dec 2016 12:00	0150-553-8077	12/17/2016 7:08	12/17/2016 7:18
26	SR 0322 @ Venango/Mercer Line	16-Dec-2016 12:00 → 17-Dec 2016 12:00	0150-553-8077	12/17/2016 9:30	12/17/2016 9:44
27	SR 0322 @ Venango/Mercer Line	17-Dec-2016 12:00 → 18-Dec 2016 12:00	0150-553-8077	12/18/2016 5:25	12/18/2016 5:36
28	SR 0322 @ Venango/Mercer Line	17-Dec-2016 12:00 → 18-Dec 2016 12:00	0150-553-8077	12/18/2016 9:14	12/18/2016 9:22

c. Summary of the storm events

Among all the storm events (twenty-eight in total), data for four storm events were not available because “RWIS station camera was not functioning during 14:31 PM to 8:21 AM.” Ten additional storm events did not meet the quality criteria because of continuous heavy precipitation. When the precipitation was too heavy, the snow continuously covered the surface, which led to lower visual scores and we observed that the melted % decreased overtime. For example, the melted percentage firstly reached a maximum value and then decreased with time. During the other four storm events, snow was 100% melted, most likely due to plowing of the road before the deicer application. Four other storm events had the melted percentages unchanged over time. Finally, six storm events had an increasing trend in melted percentages after the deicers had been applied. The table below shows results for the six storm events that were deemed most useful during the data collection process.

Table 2 Six storm events with useful melted percentage data, as summarized in the following discussion. The deicer was always 67A-33S.

N	Test site	Time window	Vehicle #	Travel Time 1	Travel Time 2
A	SR 0322 @ Venango/Mercer Line	11-Dec-2016 12:00 → 12-Dec 2016 12:00	0150-553-8077	12/11/2016 13:27	12/11/2016 13:38
B	SR 0322 @ Venango/Mercer Line	11-Dec-2016 12:00 → 12-Dec 2016 12:00	0150-553-8077	12/11/2016 18:48	12/11/2016 19:01
C	SR 0322 @ Venango/Mercer Line	13-Dec-2016 12:00 → 14-Dec 2016 12:00	0150-553-8077	12/13/2016 18:30	12/13/2016 18:42
D	SR 0322 @ Venango/Mercer Line	14-Dec-2016 12:00 → 15-Dec 2016 12:00	0150-553-8077	12/15/2016 8:44	12/15/2016 8:57
E	SR 0322 @ Venango/Mercer Line	16-Dec-2016 12:00 → 17-Dec 2016 12:00	0150-553-8077	12/17/2016 7:08	12/17/2016 7:18
F	SR 0322 @ Venango/Mercer Line	16-Dec-2016 12:00 → 17-Dec 2016 12:00	0150-553-8077	12/17/2016 9:30	12/17/2016 9:44

Besides the melted percentages, the Temple team collected environmental parameters from the RWIS site, including surface temperature, air temperature, dew point temperature, level of grip, snow layer, relative humidity, rain intensity, wind speed, visibility, barometric pressure, precipitation rolling averages (1-h and 3-h), and maximum wind. All data were collected together with melted percentage every 5 minute. At the same time, the AVL system also offered truck information, including the vehicle number, travel time and distance, last record time, GPS fix, direction, speed, latitude, longitude, solid material, solid rate, solid spread, solid spread, prewet rate, anti-ice rate, etc.

According to the data from the six storms, there was not a significant correlation between the temperatures (surface temperature, air temperature and dew point temperature) and the application rate (e.g. 220, 250, 260 and 275 lbs/lane mile). As shown in Fig. 10b, the trend seems to be random, suggesting that the operators did not select the application rates based on the environmental temperature conditions. Note that Penn DOT has rather comprehensive field guidelines for the application rates to be used under different precipitation and temperature conditions. For example, the guidelines recommend "plowing only, with possible usage of abrasive" when temperature is below 15 F. For the range of application rates applied, the melted percentages did not show a significant correlation with the solid rate (Fig. 10a). Figure 10a shows that when the temperature was 12 F, the application rate was approximately 250 lbs 67A-33S (67% anti-skid and 33% salt) per lane mile. At such low temperature, the snow was not much melted within the two-hour period (note that the precipitation in one-hour average was about 0.04' within the first hour, partially contributing to the lower % melted observed).

The figure suggests that temperature is critical in determining the application rate. At low temperatures, it takes much longer to melt, and it needs more deicer to start the melting process.

(a) (b)

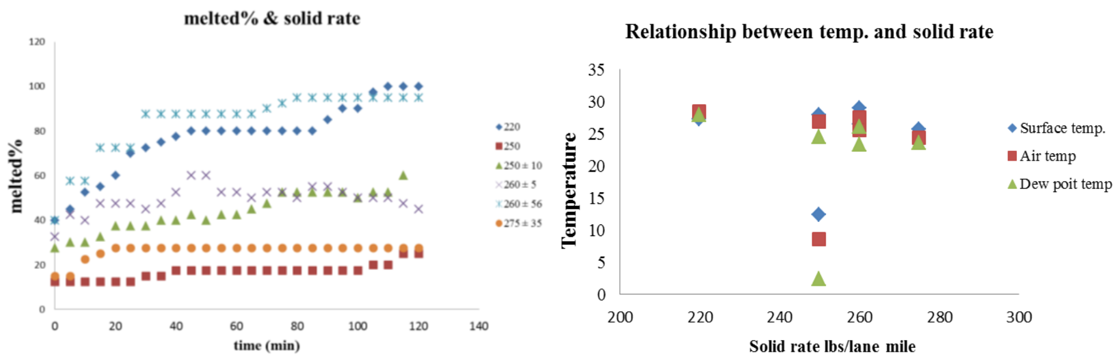


Fig. 10. Relationship between percentage melted and time at various solid application rates during on-road real-time testing at site 0322@Venango/Mercer Line in December 2016.

Based on these preliminary data, we can conclude that there is a clear relationship between surface temperature and %melted. For example, we have recorded six different surface temperatures between 12 and 29 F (Figure 11a). When the surface temperature is 29 F, the snow started to melt within five minutes. The melted percentage started at 40% and reached approximately 90% within 30 minutes. When the temperature was 25~26 F, the snow started to melt within 5 minutes, however, the maximum melted percentage reached only 50%. When the temperature dropped to 12 F, there was little to no melting in the first 30 minutes. When the time was 30-40 minutes, there was a slight increase in melting, from 10% to 20%.

(a) (b)

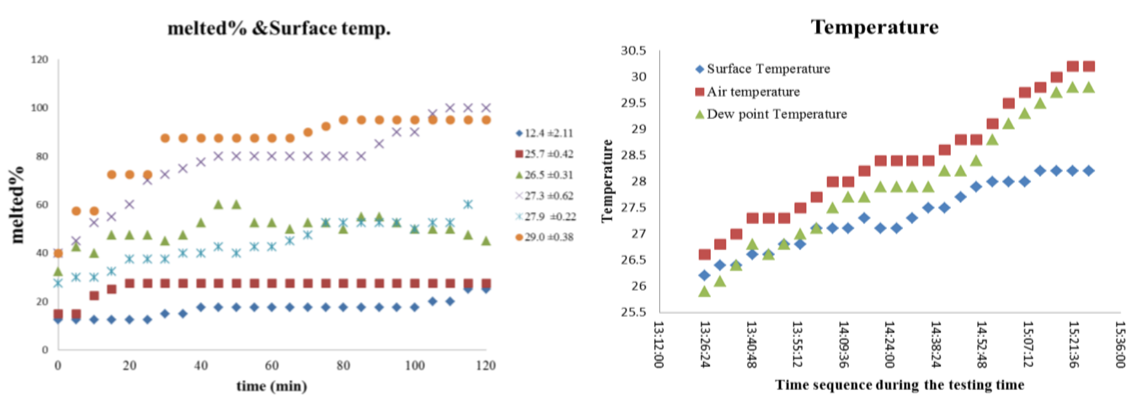


Fig. 11. Relationship between % melted and time for different surface temperatures (a) during on-road real-time testing at site SR 0322@Venango/Mercer Line in December 2016. (b) Surface, air and dew point temperature variation relationship during one example storm event (Dec 16 to 17, 2016)

Figure 11b summarizes the three temperatures offered by RWIS station: surface temperature, air temperature and dew point temperature. We take one case storm event (16-Dec-2016→17-Dec-2016) as an example. As shown in Fig. 11b, there is a similar trend among the three temperatures. Generally speaking, it is expected that surface temperature, dew point temperature and air temperature correlate with each other well.

Figure 12 below shows how the parameters affected the snow melting at site SR 0322@Venango/Mercer Line on December 13 to 14, 2016. This part of study aimed at showing how main environmental parameters affect the melted percentage. With decreasing precipitation with time, there is decrease in snow layer and increase in grip level. During the same period, the melted percentage continued to increase until reaching a steady level at about 95%. There was no clear correlation between the melted percentage and relative humidity, rain intensity, wind speed, visibility, and barometric pressure with the melted percentage, so data are not shown.

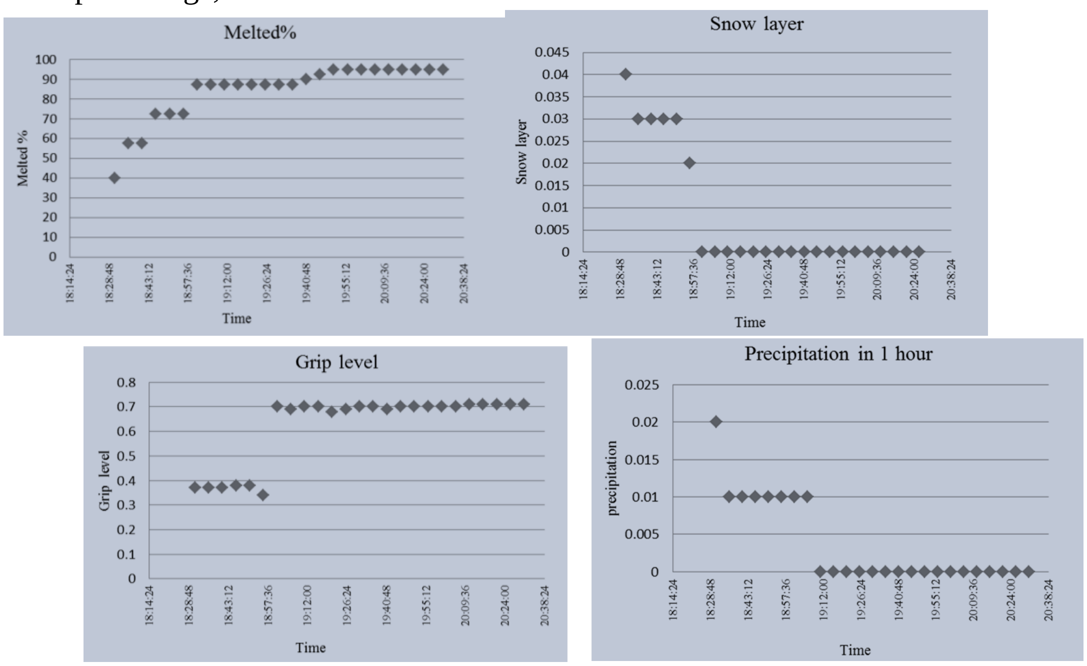


Fig. 12. Melted % and RWIS station parameters (snow layer, grip level and precipitation in 1 hour) during on-road real-time testing at site SR 0322@Venango/Mercer Line on December 13 to14, 2016.

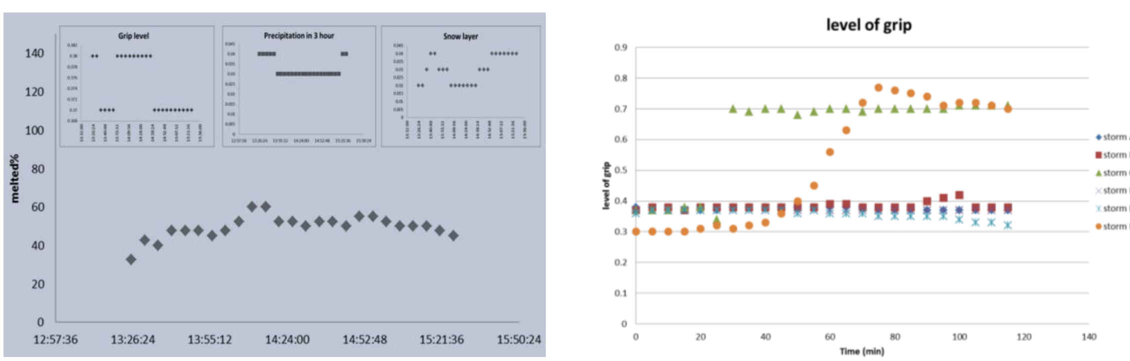


Fig. 13. Melted % and RWIS station parameters (grip level, precipitation in 1 hour, and snow layer) during on-road real-time testing at site SR 0322@Venango/Mercer Line on December 10 to 11, 2016, from time 13:26 to15:26 (storm A)

Figure 13 (left panel) shows the melted percentage and RWIS station parameters (grip level, precipitation in 1 hour, and snow layer) during on-road real-time testing at site SR 0322@Venango/Mercer Line on December 10 to11, 2016, from time 13:26 to15:26 (storm A). During the whole testing process, there is a slightly increasing trend in melted percentage over time. The level of grip (the inset of Figure 13 left) decreased substantially when precipitation increased substantially at the same time. Generally, the snow layer showed a good correlation with the precipitation, as expected. Figure 13 right shows the grip levels of the six storm events, maintaining at around 0.3-0.4 when there is snow on the road.

As it can be seen from Figure 13, it is reasonable that the snow layer, grip level and precipitation in one hour are good indicators of the melted percentages. For example, when precipitation was not too heavy (Figure 12), the melted percentage continuously increased during the whole testing time. Also, it is reasonable that the snow layer decreased and the grip level increased substantially with time because of the continuous snowing process. From the figures we suggest that it would be better to adjust the deicer application rate according to the temperature variation to achieve optimal melting results. Among all the environment parameters, the surface/air temperature seems to have the best correlation with melting percentage. Generally speaking, the melted percentage increased faster when there was a higher surface and air temperature.

d. Weather information comparison

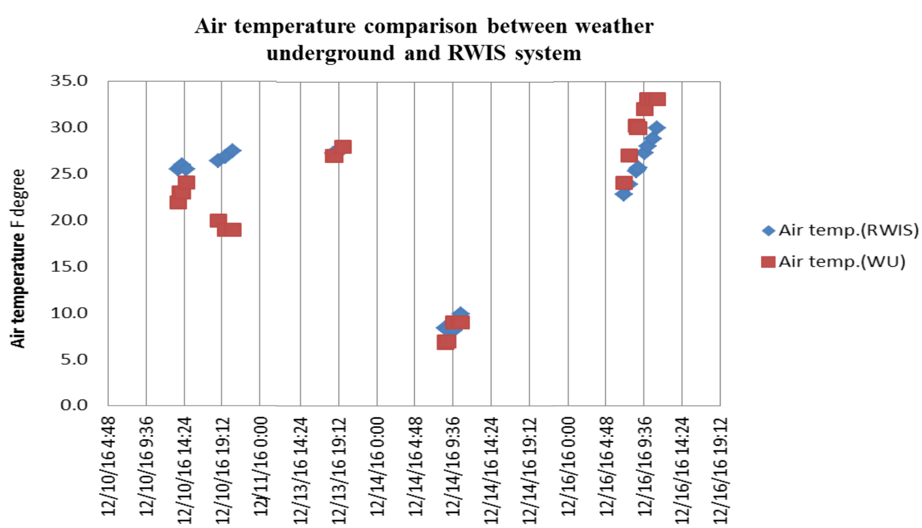


Fig.14. Weather information comparison of RWIS station and Weather Underground between 12/10/2016 and 12/16/2016.

During the testing period, the weather conditions were collected from RWIS for each site every five minutes. At the same time, weather information was collected from another online weather service, Weather Underground, from which we can obtain several weather parameters such as temperature, visibility, cloud coverage, wind chill, humidity, pressure, wind speed, and precipitation. This makes the comparison with the RWIS station data possible. At the same time, the weather website offers supplementary information that RWIS does not offer, such as cloud coverage. Figure 14 shows that the weather information between RWIS station and Weather underground are largely comparable.

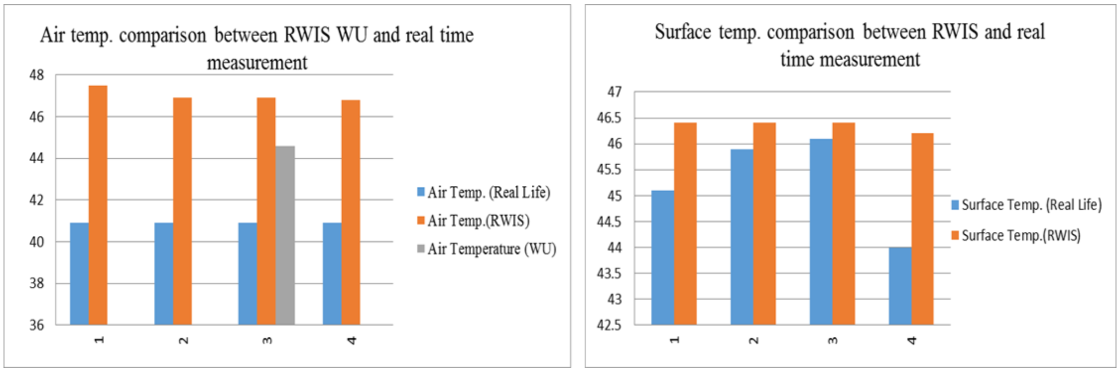


Fig. 15. Weather information comparison between RWIS station, Weather Underground (WU), and Temple team measurements (Real Life) on Route 309 (1/21/2017). The four sets of bars are for four different time points at the same site.

Fig. 15 shows the comparison of real time weather information either measured manually by the Temple team at a RWIS site, or collected from the RWIS station and from Weather Underground for the site. It shows that the weather data (both air temperature and surface temperature) from all three sources are largely comparable. In conclusion, RWIS station offers reliable weather information for subsequent data analysis.

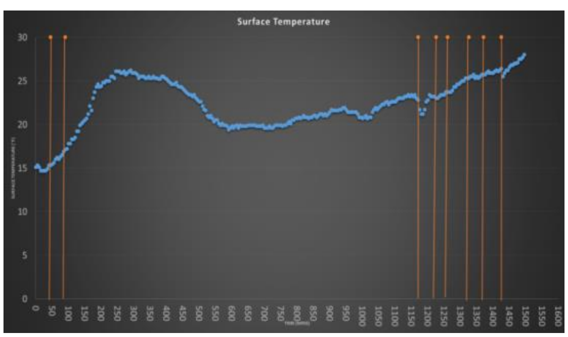
e. Preliminary data collection for a storm event with freezing rain on Jan 09/10, 2017

On Jan 9^{th} to 10^{th}, a winter storm event came with freezing rain in the northern part of the state at site SR 0322@Venango/Mercer Line and @SRI-79 MP-136 in District-01. The photo qualities, however, were poor (too dark) to give a visual score for each image during the snow event. During the test, the weather information, such as pressure, visibility, cloud coverage, wind chill, humidity, pressure, wind speed, precipitation, was collected from RWIS. Twenty-four-hour observation was conducted during the entire testing time. Figures 16-17 below show weather information as a function of time. In the figures, eight vertical lines were added as related to the eight times of truck passing (Table 3), which helps to understand how deicer applications affect all the parameters over a long period. From AVL station, truck 0140-465-8087 passed the site eight times during this storm event. Table 3 below shows the vehicle information during the storm event. (Distance traveled miles 318.88; Travel time 9:44; Count of stops: 16; Last record address: 4133 Greenvile; City: Clarks Miles State or Province: PA)

Table 3 Truck information during the monitoring storm event on Jan 09/10, 2017

Last Record	D	Speed	Solid Material	Solid Rate	Solid Spreac	Prewet	Spread Widtl
1/9/2017 9:47	N	39	50A-50S	40	540	6	25
1/9/2017 10:34	N	47	50A-50S	50	2127	6	35
1/10/2017 4:35	N	43	SALT-100	140	884	6	25
1/10/2017 5:27	N	34	SALT-100	140	5495	6	30
1/10/2017 6:05	N	36	SALT-100	140	7838	6	25
1/10/2017 7:11	N	45	SALT-100	130	12365	6	25
1/10/2017 7:53	N	35	SALT-100	130	16440	6	25
1/10/2017 8:50	N	34	SALT-100	110	19802	6	25

Fig. 16 shows during the entire 24-h testing, there is a variation in surface temperature and grip level. When the truck passed by, the surface temperature slightly increased. The right graph shows that the grip level increased significantly during the first two times when the truck passed by, however, the grip level decreased significantly during the last six times of passing. These phenomena might be because the precipitation during the last six times of passing was too heavy, as shown below.



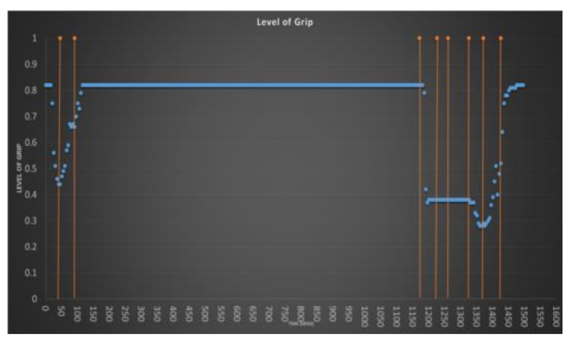


Fig. 16. Surface temperature (left) and level of grip (right) variation during the entire 24 hours. Truck 0140-465-8087 passed the site eight times during the storm event, which was marked with vertical lines (eight lines with orange color)

Fig. 17 shows a good correlation among ice layer, snow layer and precipitation. When the truck passed by the site during the last six times, there was a clear correlation between the three parameters. That is, when the precipitation increased, the snow layer and ice layer increased correspondingly, which explains the observed decrease in grip levels during the same time window as show in Fig 15. In another word, precipitation is critical in determining the grip level and deicer performance. If snow precipitation is too heavy, it can influence the melted percentages and data collection.

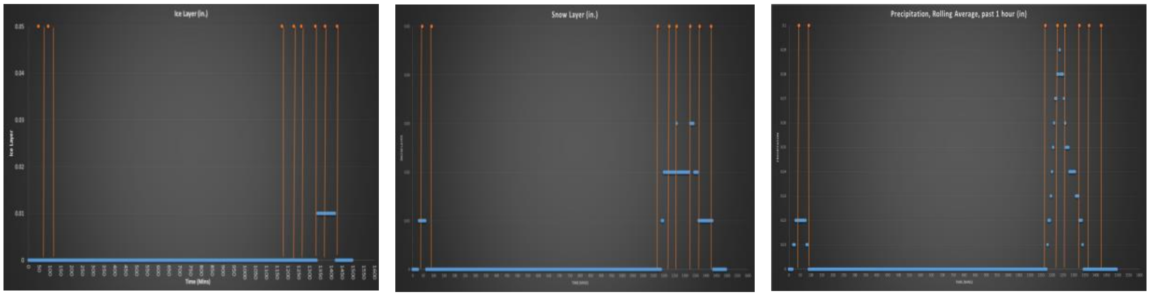


Fig. 17. Left to right: ice layer, snow layer and precipitation variation during the entire 24-hour period. Truck 0140-465-8087 passed the site eight times during the storm event, which was indicated with vertical lines (eight lines with orange color)

During the snow event on Jan 09/10, 2017, the images were too dark for the researchers to assign visual scores. Another limitation appeared when the melted% was 100%, which does not allow making reliable comparison between the images. It is noted that the solid materials applied also changed. At 9:47 and 10:34 AM on 1/9/2017, the solid material was 50A-50S, while during the last six times, the solid material was SALT-100. This might also have contributed to the observed differences in the grip levels, although additional data need to be collected to examine the detailed effect of each parameter.

Fig. 18. RWIS station data during the storm event on Jan 09/10 2017. Left: time 6:05 am, Jan 10, 2017 (too dark to give a visual score); Right: time 10:34 AM, Jan 9, 2017 (100% melted on the road)

Site SR0322-Venango-Mercer line 09 and @SRI-79 MP-136 in District One were chosen as the comparison sites during on-road real-time field testing. During the Jan 09/10, 2017 snow event, the truck passed by Site SR0322-Venango-Mercer line 09 three times. Among the three snow events, the images for two of them were too dark for the researchers to give a score. Figure 19 below shows the image scores for the third event that are useful for data analysis. The figure shows that the melted% increased continuously and reached a maximum value after 60 min. As expected, the snow layer decreased dramatically after 100 min. During the whole process, there was no precipitation (the precipitation rolling average in past one hour was zero). However, the level of grip shows a slight decreasing trend, with reasons unknown. It is noted that the three temperatures show a good positive correlation, as it was observed in the examples previously. However, the reference site (@SRI-79 MP-136) in District One did not show precipitation patterns comparable with the site SR0322-Venango-Mercer line 09 during this storm, which raised question about its validity as a reference site. Further data collection is warranted to further test the usefulness of @SRI-79 MP-136 as a reference site for deicer performance at Site SR0322-Venango-Mercer line 09.

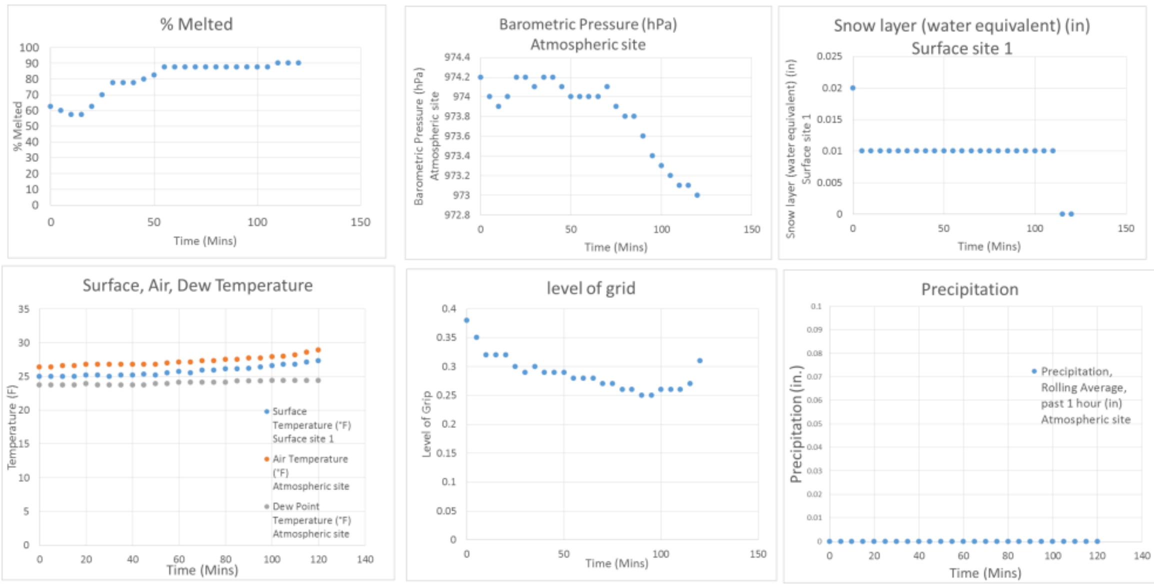


Fig. 19. RWIS station data (melted percentage and several environmental parameters) after the truck passing during the storm event on Jan 09 to 10, 2017, Site SR0322-Venango-Mercer line 09.

Appendix I

Pavement Site Information:

9. Site 1001, I-79 @ Exit 88, Butler County: District 10
    a. Coordinates- 80° 7' 30" W; 40° 47' 30" N
    b. Altitude- 1086 ft.
    c. Camera pictures are focus on left lane, south bound.
    d. Corresponding truck- P5138076 - AVL# - 1020-513-8076
        i. No Truck data found for known snow storm dates.
10. Site 1035, I-79 @ MP 100, Butler County: District 10
    a. Coordinates- 80° 7' 59" W; 40° 58' 32" N
    b. Altitude- 1230 ft.
    c. Camera pictures are focused on center of left lane, south bound.
    d. Corresponding Truck- P4968077- AVL# - 1020-496-8077
        i. Primary Route (on 1/23/16) – Navigates along I-79
        ii. Does not pass site on 1/23/16
        iii. Main compound being used is solid compound SALT-100

11. Site 1039, I-81 @ I-78 Split
    a. Coordinates- 76° 31' 21" W; 40° 25' 29" N
    b. Altitude- 525 ft.
    c. Camera pictures are focused on right lane, northeast bound.
    d. Corresponding Truck- P4038077- AVL#- 0880-403-8077
        i. Primary Route (on 1/22/16) – Navigates along I-81, I-78, Rte. 22, Rte. 72 and Fisher Ave.
        ii. Within 24-hour period (1/22-1/23) truck passes the site 9 different times.
        iii. Main compound being used is solid compound SALT-100.
        iv. No common landmark names noted.
12. Site 1010, I-81 @ Exit 77, Manada Hill
    a. Coordinates- 76° 44' 3" W; 40° 20' 59" N
    b. Altitude- 502 ft.
    c. Camera pictures are focus on left lane, southwest bound.
    d. Corresponding truck- P3898077- AVL#- 0850-389-8077
        i. Primary Route (on 1/22/16) - Along I-81 and Rte. 22. Various side streets too, most likely to turn around on interstate/ highway.
        ii. Within 24-hour period (1/22-1/23) truck passes site 11 different times.
        iii. Main compound used was solid compounds: 25A-75S and 75A-25S
        iv. Common Landmark passed is named "Blue Ridge".

Non-Invasive Site Information:

13. Site 1016, I-81 @ Exit 223, New Milford., Susquehanna, District 4
    a. Coordinates- 75° 42' 0" W; 41° 52' 0" N
    b. Altitude- 98 ft.
    c. Camera pictures are focused on right lane, southeast bound.
    d. Corresponding truck- P3028077- AVL#- 0450-302-8077
        i. Primary Route (on 1/23/16) - Along I-81
        ii. No truck travel data on storm dates.
        iii. Looks to be filled with 75A-25S on 1/23/16
14. Site P9, I-81 @ Exit 223, New Milford., Susquehanna, District 4
    a. Coordinates- 75° 42' 0" W; 41° 52' 0" N
    b. Altitude- 98 ft.
    c. Camera pictures are focused on right lane, southeast bound.
    d. Corresponding truck- P2308077- AVL#- 0450-230-8077
        i. No truck data found on AVL for known winter storm events.
15. Site B7, SR 0322 @ Venango/ Mercer Line, Venango, District 1
    a. Coordinates- 79° 59' 39" W; 41° 28' 51" N
    b. Altitude- 1306 ft.
    c. Camera pictures are focused on both lanes, east and west bound.
    d. Corresponding truck- P5538077- AVL#- 0150-553-8077
        i. No truck data found on AVL for known winter storm events.
16. Site B5, I-79 @ MP 136, Crawford/ Mercer Line., Mercer, District 1

a. Coordinates- 80° 9' 59" W; 41° 28' 52" N
b. Altitude- 1371 ft.
c. Camera pictures are focused on right lane, north bound.
d. Corresponding truck- P3358087- AVL#- 0140-335-8087
    i. Primary Route- Along I-79
    ii. No truck travel data on storm dates.

CONTRACT NO. 4400011166
TEM WO 005
DELIVERABLE 3.1 INTERIM REPORT TO INCLUDE ON-ROAD REAL-TIME PERFORMANCE ANALYSIS OF EACH DEICER

JUNE 27, 2017

Summary

In this part of the study, on-road real-time field tests were conducted to evaluate the deicer performance on eight RWIS observation sites. Four deicers were evaluated via a paired treatment-reference site experiment design, thus necessitating eight sites in total, they are as follows: Site I-80@ Exit 35, milepost (MP) 37 for AquaSalina and the reference site is I-79 @ MP 136, Crawford/Mercer Line (Rock Salt); Site I-79 @ Exit 88 for BEET HEET and reference site I-79 @ MP 100; Site I-81 @ Exit 223, New Milford for Green Blast and the reference site I-80 @ Exit 211 Lenox (rock salt); Site I-81 @ Exit 77, Manada Hill for Magic Minus Zero and the reference site I-81 @ Exit 223, New Milford, see Table 1 below. For some sites, the sensor was designed for measuring the grip levels, while others for salt concentrations, both two sensors were installed for the road conditions. For all precipitation events, the surface and air temperature have a similar trend during 24 hours. Usually in the morning, the temperature is the lowest, while in the afternoon around 14:00 is the highest. The parameters measured are listed in Section 2 “Experimental Methods”.

Site I-80@ Exit 35, MP 37 – AquaSalina:

There were 5 events at site I-80@ Exit 35, MP 37 (24 hours’ time window at one site is considered one snow event). At this site, the underground sensor was designed for measuring the salt concentration. The salt concentration and Precipitation Rolling Average past 1 hour (referred to as precipitation hereafter) generally have an opposite trend. For all the snow events (5 in total) on Jan-05; Jan-31; Feb-08; Feb-09 and March- 13, 2017, when there was snow precipitation and trucks passed, the salt concentration decreased to a large extent, at the same time, the surface snow melted % recovered to 100% (i.e, no surface snow) within 30 min. Therefore, the deicer application was clearly effective in removing the surface snow; however, the performance did not seem to be reflected in the measured salt concentrations. In some cases it was too dark to collect on- road real-time images from the RWIS system (camera history).

Reference site: I-79@MP 136 Crawford/Mercer line.

Rock salt was applied at this site. The 4 snow events for this site were: 08-Feb-2017 19:00–09-Feb-2017 19:00; 09-Feb-2017 19:00–10-Feb-2017 19:00; 12-Feb-2017 19:00–13-Feb-2017 19:00 and 28-Jan-2017 20:00–29-Jan-2017 20:00. At this site, the underground sensor was designed for measuring the grip levels. During all the snow events, when there was no precipitation, the grip level kept a high value of ~0.8. When there was precipitation, the grip levels decreased dramatically with the precipitation. The grip level values are closely related with the precipitation during the snow events. For the melted%, after the deicer application, the melted percentage increased significantly to

100% within about 60~90 min. It is noted that the grip level and the melted% hold very similar trends, which indicates that the grip level can be considered as a potentially effective indicator of melted percentages and deicer performance.

Site I-79@ Exit 88 – BEET HEET;

There were five snow events at site I-79@ Exit 88; they were on Feb 08, 2017; Feb 12, 2017; Feb 15, 2017; Jan 30, 2017 and Jan 31, 2017. The underground sensor was designed for measuring the salt concentration. Generally, when the precipitation level increased, the salt concentration decreased accordingly. After several deicer applications, the melted percentage remained 100%, which indicated the deicer applications were effective. Again, this was not reflected in the recorded salt concentrations.

Reference site: I-79@MP 100

There was one snow event at this site. The underground sensor was designed for measuring the salt concentration. The salt concentration and precipitation have an opposite trend in general during 24 hours. After the precipitation, the melted% recovered to 100% effectively within around 25 min. The salt concentration fluctuations did not appear to correspond to any environmental factor or winter maintenance strategy.

Site I-81@ Exit 223 New Milford –Green Blast:

There was one snow event for site I-81 @ Exit 223 New Milford & reference site I- 81@Exit 211 Lenox. Green Blast was applied by PennDOT at both sites. The underground sensor was designed for measuring the grip level. There is an obvious trend showing that when the precipitation increased (from 0 to 0.2 inch), the grip level decreased significantly (from 0.8 to 0.4). Therefore, this is strong evidence that the grip level and precipitation have a good correlation.

Site I-81@Exit 77, Manada Hill – Magic Minus Zero:

There was one snow event at the site and the reference site is site I-81@Exit 223, New Milford. The underground sensor was designed for measuring the salt concentration. Although the precipitation was heavy from 1:12 to 8:00 am on Feb 09, 2017, the salt concentration recovered to a high level at around 9:00. That means the deicer applications were very effective. The grip level variable and melted% hold very similar trends, which is also strong evidence that the grip level and precipitation are well correlated.

In summary, when there was precipitation, the grip levels decreased dramatically but recovered after deicer applications. After the deicer applications, the melted percentages increased significantly to 100% within a short period of time, which means that the deicers worked well, however, we need to collect data from additional events to evaluate the differences between various deicers. The salt concentration and precipitation show an opposite trend. The salt concentration level fluctuated over a wide range, for reasons that are unknown. Therefore, we suggest to replace all the salt concentration sensors to grip level sensors, which perform more consistently and correlate well with melted%. Because the grip level values are closely related with both precipitation and snow melted% during the snow events, we believe the melted% might be advantageously replaced by the grip level. We will continue to evaluate the effectiveness of the grip level as a deicer performance indicator, in place of melted%, in future field tests.

1. Brief Introduction

In Tasks 1.2 and 1.3, the six deicers (i.e., AquaSalina, BEET HEET, Green blast, salt brine, rock salt, and Magic Minus Zero) were tested in parking lot tests. During parking lot tests, several environmental variables were evaluated, including deicer type, application rate and sample time. However, various environmental variables have not been taken into consideration, such as precipitation level, grip level and surface temperature etc. Therefore, in this part of the study, on-road real-time field tests were conducted to evaluate the deicers performance at eight RWIS observation sites. They were four pairs of sites for each deicer: Site I-80@ Exit 35, MP 37 for AquaSalina and the reference site is I-79 @ MP 136, Crawford/Mercer Line; Site I-79 @ Exit 88 for BEET HEET and the reference site is I-79 @ MP 100; Site I-81 @ Exit 223, New Milford for Green Blast and the reference site is I-80 @ Exit 211 Lenox; Site I-81 @ Exit 77, Manada Hill for Magic Minus Zero and the reference site is I-81 @I-78, Split. The field tests incorporated real world conditions, including variable weather information (from RWIS system) and real application conditions (from AVLs system). After careful data collection and data analysis, we were able to provide some suggestions about how to collect field data, conduct data analysis, perform evaluation of the deicers, and assess the effectiveness of RWIS, AVL and the field operations based on the obtained data. However, comparison among the deicers performances is not feasible because there are only a limited number of field data available. Further data collection and data analysis will be conducted next winter to fulfill this goal.

2. Experimental methods

The data collection can be divided into two parts: RWIS data collection and AVLs data collection. The detailed, specific procedure to collect data from RWIS and AVLs can be found in **Appendix I**.

RWIS stands for road weather information system (http://rds.vaisala.com/apps/), this website continuously tracks and stores the following data for each site; Surface Temperature (°F); Surface State (dry or wet); Air Temperature (°F); Dew Point Temperature (°F); Relative Humidity (%); Rain State Atmospheric site; Rain Intensity (in/h); Wind Speed (mph); Wind Direction; Visibility (Ft); Salt Concentration (g/l); Barometric Pressure (hPa); Precipitation Rolling Average past 12 hours; Precipitation Rolling Average past 1 hour; Precipitation Rolling Average past 24 hours; Precipitation Rolling Average past 3 hours; Precipitation Rolling Average past 6 hours; Ground Temperature (°F); Water Thickness (in) and camera shots of the road condition. The AVLs system (https://q3.webtechwireless.com/wtw/jsp/QSecurity/login.jsp) offers the following deicer information: Solid material, Solid rate, Solid application time, Solid spread; Prewet rate; Prewet spread; Anti-ice rate and Anti-ice spread.

Preliminary data analysis showed that the only two environmental variables that are somewhat indicative of deicer field performances are temperature (surface and air) and precipitation. Therefore, in the "Results and Discussion" part below, only these two variables will be discussed. Among all the precipitation variables, we decided to focus on "Precipitation Rolling Average past 1 hour" because it is the closest to the real-time data, and will refer it to as "precipitation" hereafter. For deicer performance evaluation, three parameters will be discussed when available: grip level, salt concentration, and snow melted percentage.

Table 1 Information of the eight sites (four pairs, each with a reference site) for on-road real-time field tests in this research

Number	**Site name**	**Deicers**	**District**
1	Site I-80@ Exit 35, MP 37	AquaSalina	1
	I-79 @ MP 136, Crawford/Mercer Line	Rock Salt (reference)	1
2	I-79 @ Exit 88	BEET HEET	10
	I-79 @ MP 100	Rock Salt (reference)	10
3	I-81 @ Exit 223, New Milford	Green Blast	4
	I-80 @ Exit 211 Lenox	Rock Salt (reference)	4
4	I-81 @ Exit 77, Manada Hill	Magic minus zero	8
	I-81 @ Exit 223, New Milford	Rock Salt (reference)	8

With the field images obtained from RWIS, snow melted percentage scores were visually assigned by two different researchers independently; the final melted percentages are the average of the two scores. When the Temple team assigned the scores, the visual score criteria shown in Figure 2.1 were used to standardize the scoring process.

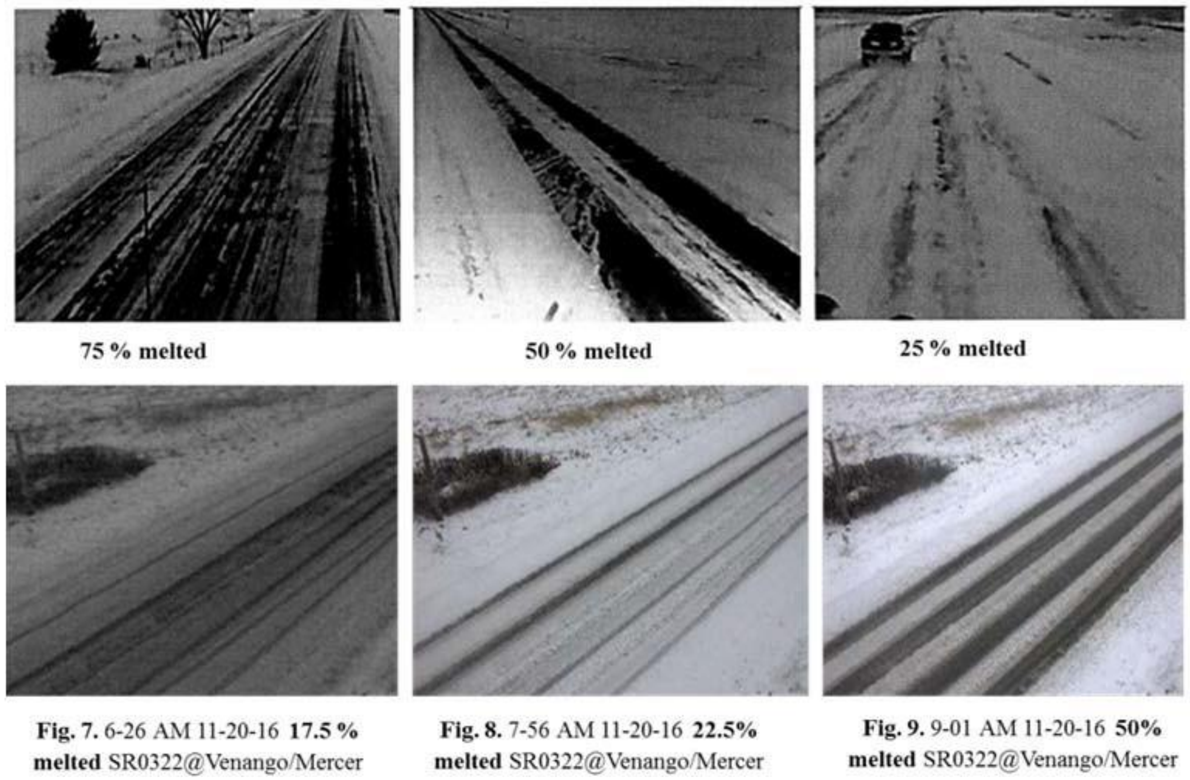


Fig. 2.1 Standard images of visual scores during on-road real-time field tests

During this field test from winter in December 2016 to March 2017, 36 snow events have been collected based on the weather history on the RWIS website. However, some snow events were not summarized in this report because some data were partially missing, such as truck information, camera images, or road melted conditions. **Table 2** summaries all the snow events monitored and useful snow events at the eight RWIS sites.

Table 2 All snow events and useful snow events list of eight RWIS sites

Site name	Deicers	Sensor	All Snow Events	Useful Events
Site I-80@ Exit 35, MP 37	AquaSalina	Salt conc.	12	5
I-79 @ MP 136, Crawford/Mercer Line	Rock salt	Grip level	8	4
I-79 @ Exit 88	BEET HEET	Salt conc.	7	4
I-79 @ MP 100	Rock salt	Salt conc.	2	1
I-81 @ Exit 223, New Milford	Green Blast	Grip level	3	1
I-80 @ Exit 211 Lenox	Rock salt	Grip level	3	1
I-81 @ Exit 77, Manada Hill	Magic minus zero	Salt conc.	1	1
I-81 @I-78, Split	Rock salt	Salt conc.	0	0

3.Results and discussion

3.1.AquaSalina (I-80@ Exit 35, MP 37) & reference site (I-79@MP136, Crawford/Mercer Line)

I. Site I-80@ Exit 35, MP 37

There were 5 events at site I-80@ Exit 35, MP 37 (24 hour at one site is considered one snow event). They were 05-Jan-2017 16:00–06-Jan-2017 17:00; 31-Jan-2017 01 :00–01-Feb-2017 01:00; 08-Feb-2017 14:00–09-Feb-2017 14:00; 09-Feb-2017 17:00–10-Feb-2017 17:00 and 13-Mar-2017 20:00–14-Mar-2017 20:00. In the following section, the different snow events will be discussed separately.

a). Jan-05-2017

One Truck passed the site 17 times during 24 hours from 12:00 Jan-05 2017 to 12:00 Jan- 06 2017. The solid application rates (unit: lbs. /lane mile) of each truck passing are marked on the top of each application in Figure 3.1.

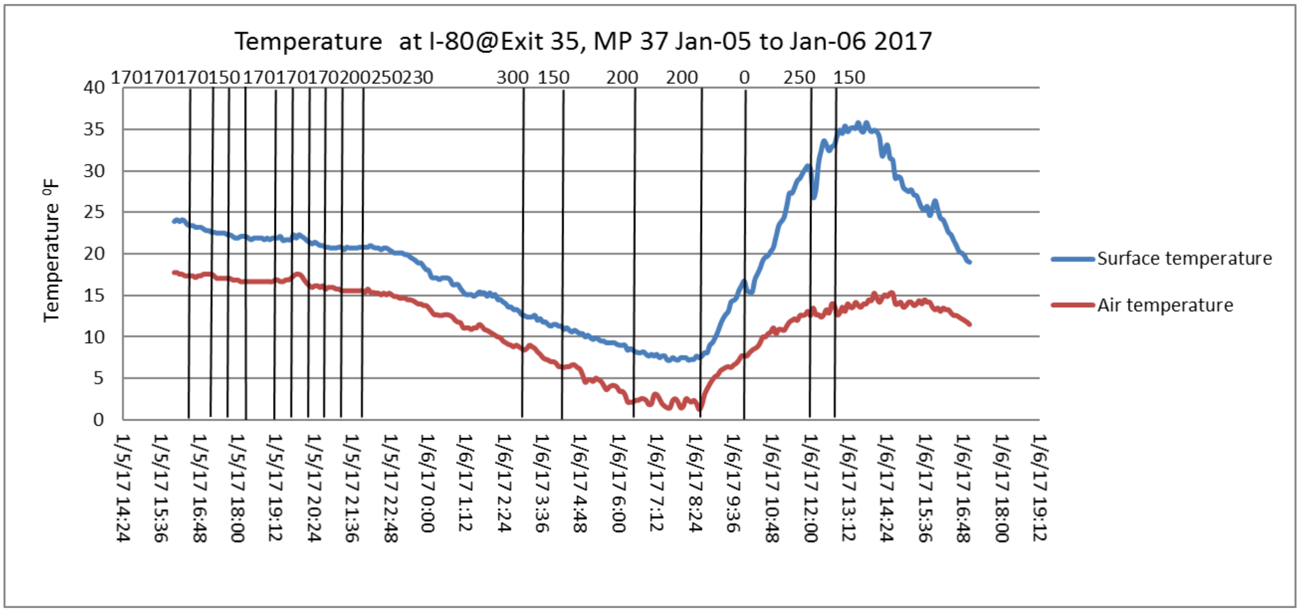


Fig.3.1 Temperature (surface temperature and air temperature) variables during 24 hours from 05-Jan-2017 16:00 to 06-Jan-2017 17:00 at site I-80@ Exit 35, MP 37. Vertical solid lines indicate the times of deicer application, with the deicer application rates in lb. per lane mile indicated immediately above the lines; and the same applies to all other plots below.

Fig. 3.1 shows that the surface temperature and air temperature have similar trend during 24 hours. Around 2:00 pm the temperatures are the highest; and 6:00-8:00 am had the lowest temperature. The highest surface temperature can reach around 35 ^{0}F, while the lowest surface temperature was around 7 ^{0}F.

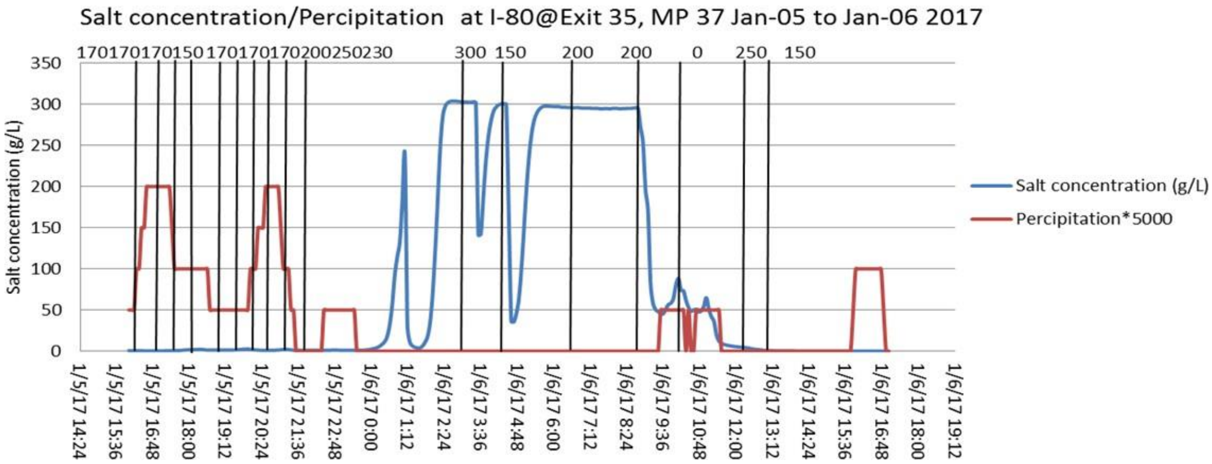


Fig.3.2 Salt concentration (g/L) and precipitation (inch) during 24 hours from 05-Jan- 2017 1600 to 06-Jan-2017 1700 at site I-80@ Exit 35, MP 37. Note that the precipitation values were multiplied by 5000 so they can be plotted on the same figure, for direct comparison purposes.

Figure 3.2 shows that when the precipitation increased during the whole event, the salt concentration decreased accordingly. Between 15:36~21:36 there was heavy continuous snow precipitation, during the same time, the truck passed by the site many times. Also the salt concentration remained at 0 during this time window. After snow stopped at about 0:00, the salt concentration started to increase sharply to almost 250 g/L within about 30 min. The salt concentration remains largely at 300 g/L when there was no precipitation, but decreased to < 50 g/L as soon as snow started again at 19:36. At this site, no photos could be collected for this event because RWIS did not have them online or the camera was not functioning.

b). Jan-31-2017

Two trucks passed the site 19 times during 24 hours from 31-Jan-2017 01:00 to 01- Feb-2017 01:00. They were truck 0150-425-8077 and truck 0150-118-8077. The Truck 0150-425-8077 was recorded at 406 Mercer St, the Latitude 41.19 and Longitude -79.82. The prewetting rate was 10 gallons per ton for all the applications during this event. The second truck number is 0150-118-8077; the travel time was 15:38:02 according to AVL. The last recorded address was 3130-PA-208. Travel city was Emlenton. The latitude and longitude were 41.19 and -79.82 separately. Travel Street was Interstate 80.

The temperature in this case ranged from 22 ^{0}F (around 00:00 to 2:00 am Jan-31-2017) to 36 ^{0}F (around 13:00 to 14:00 Jan-31-2017), as shown in Fig.3.3.

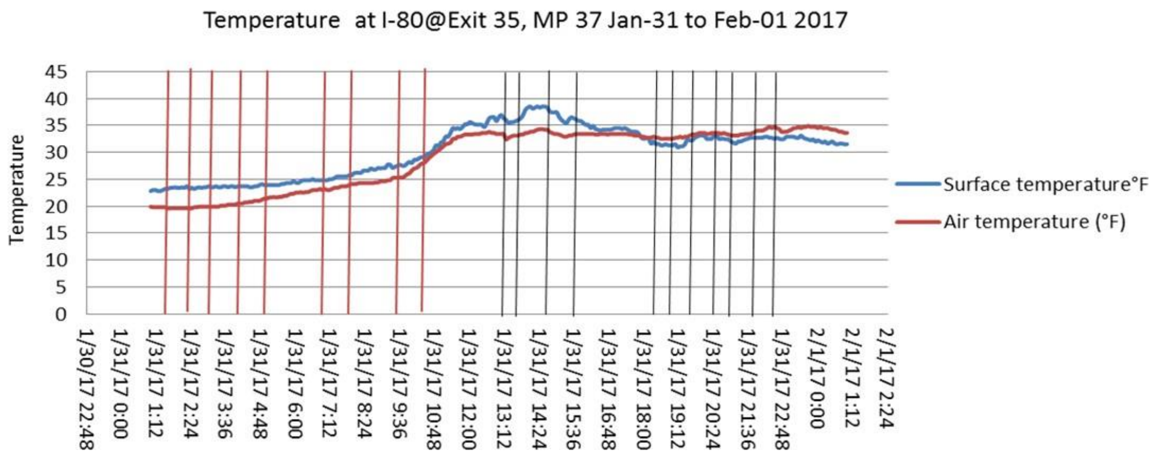


Fig.3.3 Temperature (surface temperature and air temperature) variables during 24 hours from 31-Jan-2017 1600 to 01-Feb-2017 1700 at site I-80@ Exit 35, MP 37. The vertical lines have two colors, indicating two different trucks.

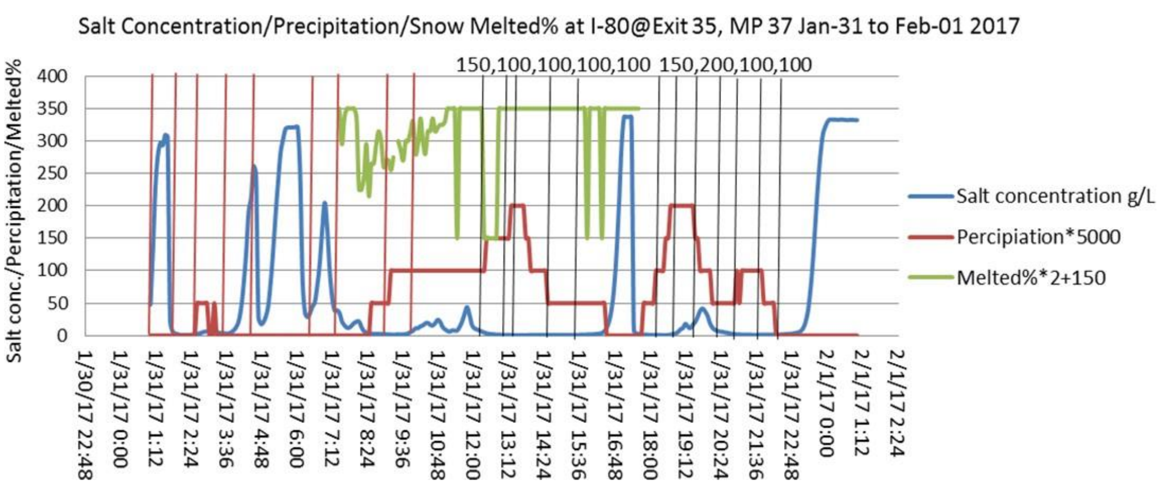


Fig.3.4 Salt concentration (g/L), precipitation and snow melted percentage variables during 24 hours from 31-Jan-2017 16:00 to 01-Feb-2017 17:00 at site I-80@ Exit 35, MP
37. (Precipitation was multiplied by 5000; melted percentage was multiplied by 2 plus 150 in order to get a comparable level in the figure, so the reading of 350 is equivalent to 100% melted)

Figure 3.4 shows the salt concentration, precipitation and melted% variables during 24 hours from 31-Jan-2017 16:00 to 01-Feb-2017 17:00 at the site I-80@ Exit 35, MP 37. As can be seen from Fig. 3.4, the salt concentration and precipitation have an opposite trend during the 24 hours, similar to what was observed in Figure 3.2. For example, from 3:36 am Jan-31-2017 to 8:24 am Jan-31-2017, there was no precipitation, and then the salt concentration increased significantly during the same time period. After around 8:30 in the morning, there was a precipitation from 0.02 inch to 0.04 inch on the ground, and the salt concentration remained at lower levels from 0 to 40 g/L. The same phenomenon was observed from time 18:00 Jan-31, 2017 to 22:48 Jan-31, 2017. Therefore, it seems that as long as there is precipitation, the salt concentration is at a low level, no matter how much deicer has been applied to the road, so it remains unknown whether the salt concentration is an effective parameter to evaluate deicer performance.

On the other hand, around 8:24 am, there was snow precipitation, as a result, the melted percentage decreased and showed some fluctuations. Note that the photos taken priors to 8:24 am were all too dark to assign reliable scores. After several passings of the trucks, the melted percentage increased effectively and then remained at a stable level of 100% from 12:00 to 15:30, despite the fact that there was constant precipitation during the period. Therefore, the deicer application was clearly effective in removing surface snow. However, that performance does not seem to be reflected in the measured salt concentrations.

c). Feb-08-2017

One truck passed though the site 12 times during 24 hours from 12:00 Jan-31 2017 to 12:00 Feb-01 2017. The truck number was 0150-425-8077, the travel time was 08:53:59; Last record address was 408 Mercer St; the city that the truck 0150-425-8077 passed this site was Clintonville. The following section discussed the temperature (surface temperature and air temperature) and salt concentration/ precipitation variables from 12:00 Jan-31 2017 to 12:00 Feb-01 2017.

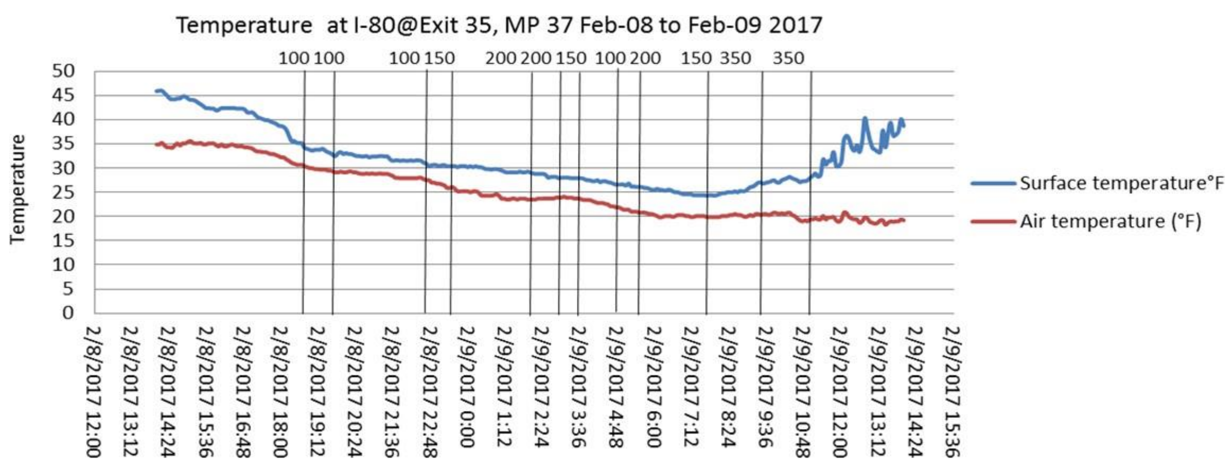


Fig. 3.5 Temperature (surface temperature and air temperature) variables during 24 hours from Feb 08, 2017 1600 to Feb 09, 2017 1700 at site I-80@ Exit 35, MP 37.

As can be seen from **Fig. 3.5**, the surface temperature remained between around 25 ^{0}F to 45 ^{0}F, while the air temperature remained between 20 ^{0}F to 35 ^{0}F during the same time period. Generally, the surface temperature and air temperature have a similar trend. Similar patterns have been observed for all other snow events at this and other sites, as will be shown below for selected events.

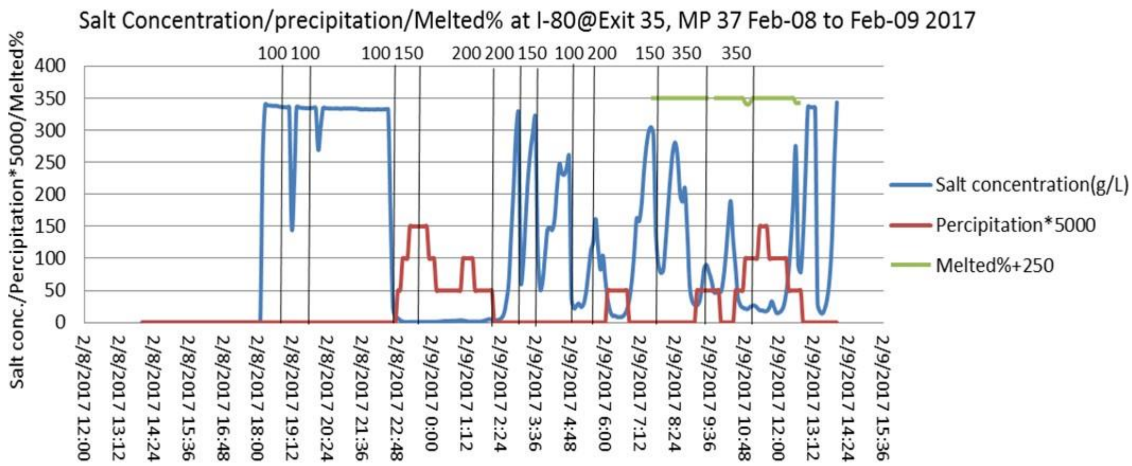


Fig. 3.6 Salt concentration (g/L), precipitation and snow melted percentage variables during 24 hours from Feb 08, 2017 1600 to Feb 09, 2017 1700 at site I-80@ Exit 35, MP 37. (Precipitation was multiplied by 5000; melted percentages were added 250 in order to get a comparable level in the figure)

As can be seen from Fig. 3.6, the salt concentration variable has a trend opposite to that of precipitation. That is to say, with the increasing in precipitation, the salt concentration decreased accordingly. The phenomenon is similar to the events we have discussed above. The precipitation for this event was between zero and 0.03 inches. There was a lot of precipitation from 22:48 on Feb 08, 2017 to 2:24 am on Feb 09, 2017. During this time, it was too dark to collect on-road real-time images from the RWIS system (camera history).

However, there was another heavy precipitation from 9:00 am to 13:00 on Feb 08, 2017, as shown in Figure 3.6. In this time period, we could download useful RWIS images and give visual scores. The results indicate that the melted percentages remain stable (100%) from 7:30 to 11:30 in the morning even during snow precipitation, indicating the deicer application was very effective. However, within the same time period, the salt concentration changed wildly between < 25 g/L and 250 g/L, again leading us to question the usefulness of this parameter in accessing deicer performance.

d). Feb-09-2017

One truck passed the site 2 times during 24 hours from 12-00 Feb-09 2017 to 12-00 Feb- 10 2017.

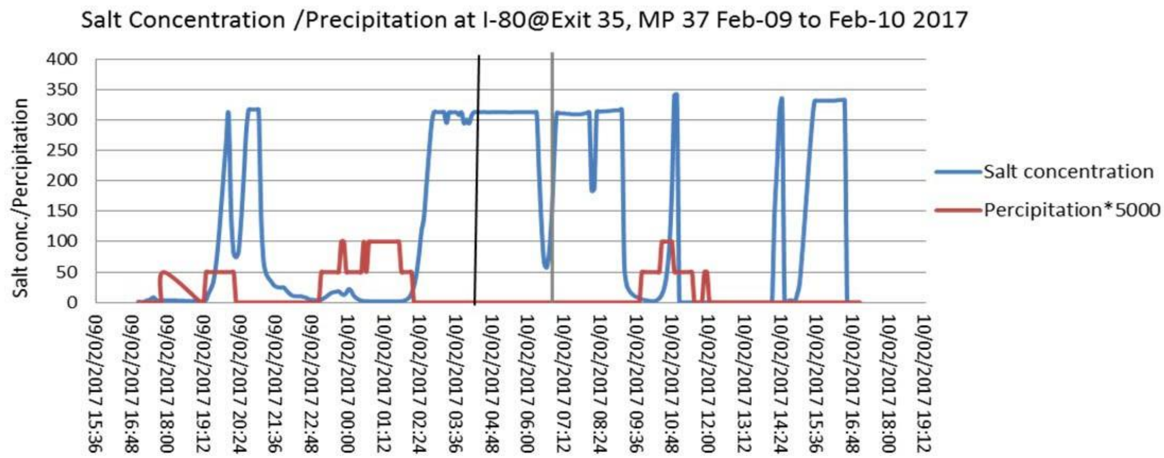


Fig. 3.7 Salt concentration (g/L), precipitation variables during 24 hours from Feb 09, 2017 1500 to Feb 10, 2017 2000 at site I-80@ Exit 35, MP 37. (Precipitation was multiplied by 5000 in order to get a comparable level in the figure 3.7 above).

Figure 3.7 shows the salt concentration (g/L) and precipitation variables during 24 hours from Feb 09, 2017 15:00 to Feb 10, 2017 20:00 at the site. As in the discussion above, the salt concentration and precipitation have an opposite trend.

e). March-13-2017

Four trucks passed the site 10 times during 24 hours from 12:00 March-13, 2017 to 12:00 March-14, 2017. They were trucks 0150-425-8077, 0150-118-8077, 0150-206-8087, and 0150-352-5077. When the trucks passed by the RWIS site with deicer applications, the salt concentration generally decreased, however, we need more data to explain this phenomenon. Obviously, when the precipitation increased from 12:00 to 16:00 on March-14-2017, the salt concentration decreased significantly, as can be seen from Figure 3.8.

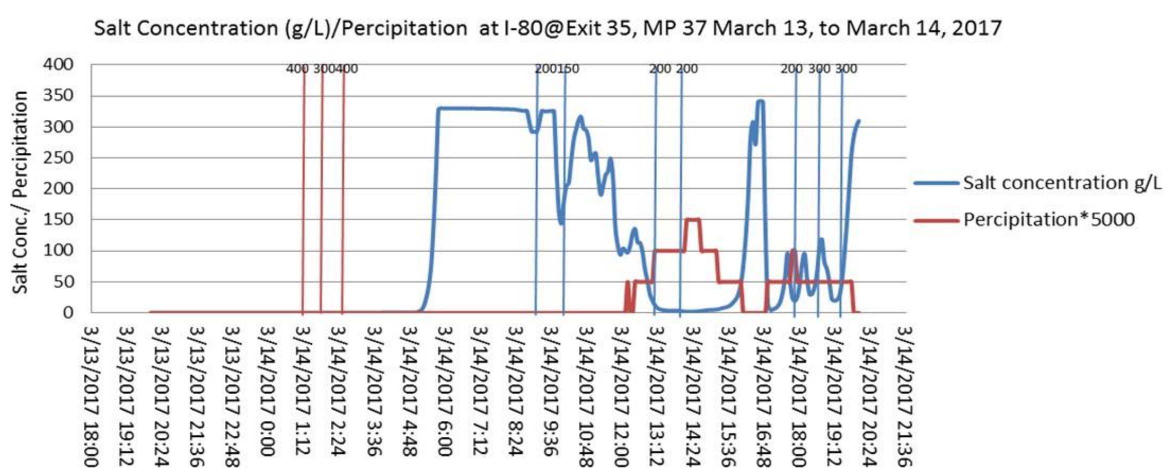


Fig.3.8 Salt concentration (g/L), precipitation variables during 24 hours from March 13, 2017 1800 to March 14, 2017 2200 at site I-80@ Exit 35, MP 37. (Precipitation was multiplied by 5000 in order to get a comparable level in the figure).

II. Site I-79@MP136 Crawford/Mercer Line (Reference site for AquaSalina)

Site I-79@MP136 Crawford/Mercer Line in this research was chosen as the reference site for deicer AquaSalina. The 4 snow events for this site are as follows: 08-Feb-2017 19:00 –09-Feb-2017 19:00; 09-Feb-2017 19:00–10-Feb-2017 19:00; 12-Feb-2017 19:00–13- Feb-2017 19:00; and 28-Jan-2017 20:00–29-Jan-2017 20:00. Each 24-hour period is considered as one snow event in the following discussion. The above snow events are discussed in the following section separately.

a). Jan-28-2017

Seven Trucks passed the site I-79@ MP136, Crawford/Mercer line, 62 times during 24 hours from 28-Jan-2017 20:00 to 29-Jan-2017 20:00. They are trucks 0140-256-8087, 0140-465-8087, 0140-335-8087, 0140-085-8077, 0110-493-8077, 0110-094-8077 and 0110-070-5090. All the GPS Fix is F, Direction is N. Latitude is 41.48069, Longitude is - 80.1667. The truck information from AVL system is as follows in Table 3.1.

Table 3.1 Trucks information at site I-79@ MP136, Crawford/Mercer line, 62 times during 24 hours from 28-Jan-2017 20-00 to 29-Jan-2017 20-00.

Vehicle	Last Record	Speed	Solid Material	Solid Rate	Prewet Rate	Anti-ice Rate
0140-256-8087	28/01/2017 22:30	45	SALT-100	120	0	0
0140-256-8087	28/01/2017 23:14	44	SALT-100	120	0	0
0140-256-8087	29/01/2017 01:25	41	SALT-100	120	0	0
0140-256-8087	29/01/2017 02:44	34	SALT-100	120	0	0
0140-256-8087	29/01/2017 03:49	40	SALT-100	100	0	0
0140-256-8087	29/01/2017 07:38	41	SALT-100	80	0	0
0140-256-8087	29/01/2017 08:45	44	SALT-100	120	0	0
0140-256-8087	29/01/2017 09:31	41	SALT-100	120	0	0
0140-256-8087	29/01/2017 10:07	41	SALT-100	120	0	0
0140-256-8087	29/01/2017 10:32	41	SALT-100	100	0	0
0140-256-8087	29/01/2017 10:54	37	SALT-100	100	0	0
0140-256-8087	29/01/2017 11:06	37	SALT-100	100	0	0
0140-256-8087	29/01/2017 12:02	41	SALT-100	100	0	0
0140-256-8087	29/01/2017 12:22	39	SALT-100	120	0	0
0140-256-8087	29/01/2017 12:59	36	SALT-100	100	0	0
0140-256-8087	29/01/2017 13:47	41	SALT-100	100	0	0
0140-256-8087	29/01/2017 16:19	41	SALT-100	120	0	0
0140-256-8087	29/01/2017 18:25	30	SALT-100	120	0	0
0140-256-8087	29/01/2017 18:42	29	SALT-100	120	0	0
0140-256-8087	29/01/2017 19:29	34	SALT-100	100	0	0
0140-465-8087	29/01/2017 12:53	42	50A-50S	120	3	0
0140-465-8087	29/01/2017 16:38	43	50A-50S	130	2	0
0140-465-8087	29/01/2017 18:12	39	50A-50S	100	2	0
0140-465-8087	29/01/2017 18:34	39	50A-50S	100	2	0
0140-465-8087	29/01/2017 19:25	36	50A-50S	70	2	0

0140-335-8087	28/01/2017 20:19	42	SALT-100	80	10	20
0140-335-8087	28/01/2017 21:09	42	SALT-100	80	10	20
0140-335-8087	28/01/2017 21:26	47	SALT-100	80	10	20
0140-335-8087	28/01/2017 21:44	37	SALT-100	100	10	20
0140-335-8087	28/01/2017 22:20	49	SALT-100	100	10	20
0140-335-8087	28/01/2017 23:04	52	SALT-100	80	10	20
0110-493-8077	29/01/2017 01:12	30	SALT-100	100	9	15
0110-493-8077	29/01/2017 05:01	27	SALT-100	125	9	15
0110-493-8077	29/01/2017 07:15	35	SALT-100	100	9	15
0110-493-8077	29/01/2017 08:26	36	SALT-100	100	9	15
0110-493-8077	29/01/2017 09:48	39	SALT-100	100	9	15
0110-493-8077	29/01/2017 11:06	35	SALT-100	100	9	15
0110-493-8077	29/01/2017 12:35	32	SALT-100	250	9	15
0110-493-8077	29/01/2017 13:42	36	SALT-100	100	9	15
0110-493-8077	29/01/2017 15:28	41	SALT-100	100	9	15
0110-493-8077	29/01/2017 15:44	42	SALT-100	200	9	15
0110-493-8077	29/01/2017 16:36	41	SALT-100	100	9	15
0110-493-8077	29/01/2017 18:35	34	SALT-100	200	8	15
0110-070-5090	29/01/2017 01:05	43	SALT-100	75	16	0
0110-070-5090	29/01/2017 07:15	34	SALT-100	75	15	0
0110-070-5090	29/01/2017 08:26	34	SALT-100	100	15	0
0110-070-5090	29/01/2017 09:48	35	SALT-100	100	15	0
0110-070-5090	29/01/2017 11:07	34	SALT-100	125	15	0
0110-070-5090	29/01/2017 12:35	29	SALT-100	250	14	0
0110-070-5090	29/01/2017 13:46	32	SALT-100	100	14	0
0110-070-5090	29/01/2017 13:47	35	SALT-100	100	14	0
0110-070-5090	29/01/2017 19:19	27	SALT-100	100	19	0
0110-070-5090	29/01/2017 19:24	24	SALT-100	150	19	0

The figure below shows the temperature variables during 24 hours from 28-Jan-2017 20- 00 to 29-Jan-2017 20-00. The solid application rates are marked on the top of each application. The units of the application rates are lbs./lane mile. The different trucks are marked with different colors.

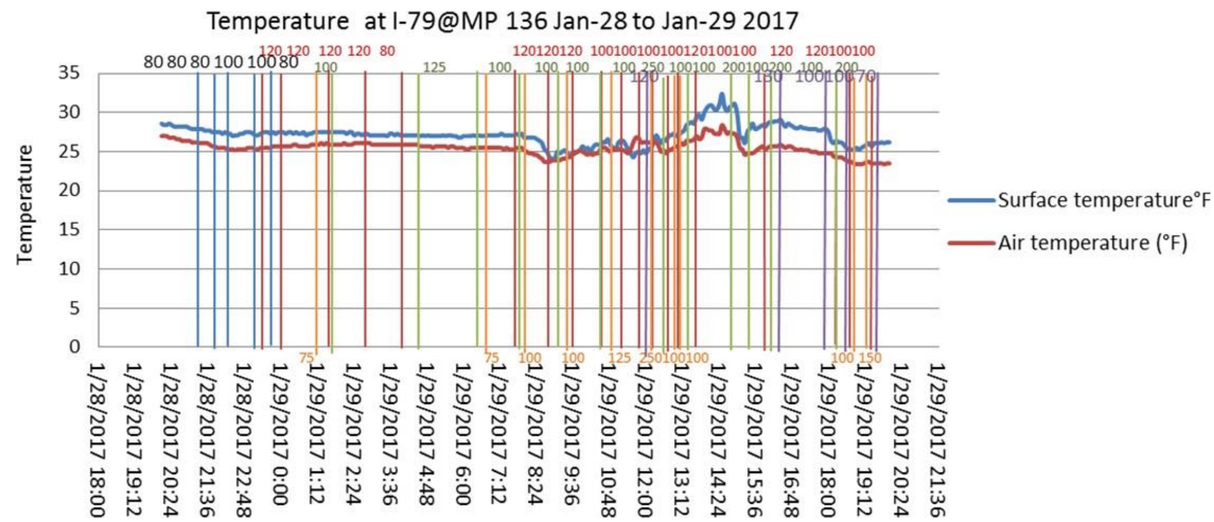


Fig. 3.9 Temperature (surface temperature and air temperature) variables during 24 hours from 28-Jan-2017 20-00 to 29-Jan-2017 20-00 at site I-79@MP136 Crawford/Mercer line.

From Figure 3.9 we can see the surface temperature remained 24 ^{0}F to 33 ^{0}F, while the air temperature remained around 24 ^{0}F to 27 ^{0}F during the whole 24 hours. The highest temperatures, both surface and air temperature were observed at around 14:00 in the afternoon, while the lowest temperature is always in the morning, around 8:00 am. In this case, the temperature difference between the highest temperature and lowest temperature is not very significant.

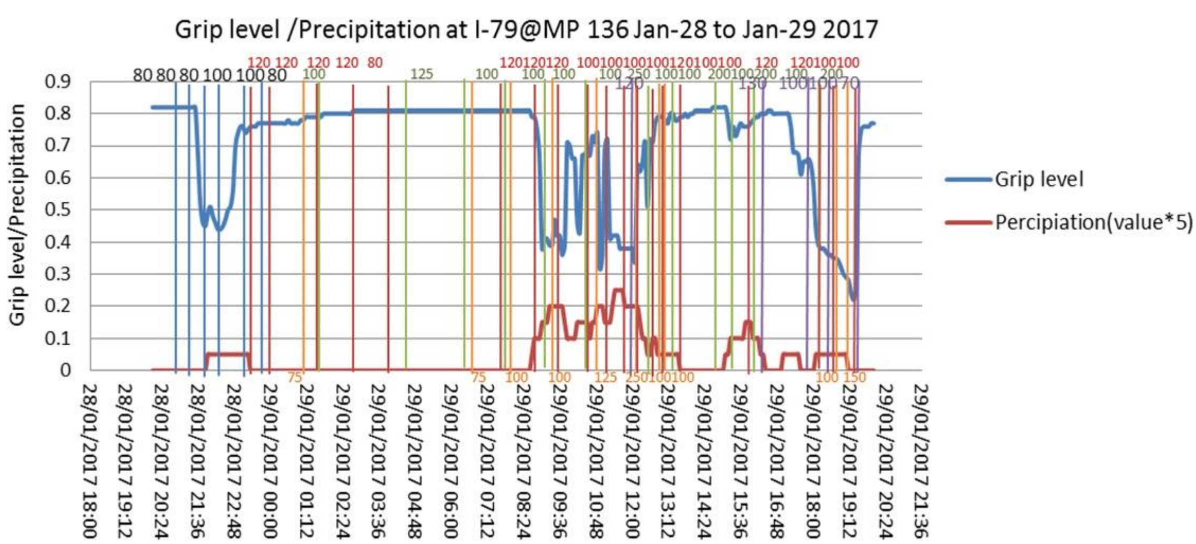


Fig. 3.10 Grip level and precipitation (value×5) variables during 24 hours from 28-Jan- 2017 20-00 to 29-Jan-2017 20-00 at site I-79@MP136 Crawford/Mercer line.

Figure 3.10 shows the grip levels and precipitation (value×5) variables during 24 hours from 28 Jan, 2017 20:00 to 29 Jan, 2017 20:00 at site I-79@MP136 Crawford/Mercer line. It is clear that there were several precipitations during the whole 24 hours. For example, from 21:36 Jan-28-2017 to 23:00 Jan-

28-2017, there was 0.01 precipitation, from 8:24 am to 13:20 Jan 29, 2017, there was a lot of precipitation (0.01~0.05), also from 14:30 Jan 29, 2017 to 19:12 Jan 29, 2017, there was continuous precipitation with a maximum of 0.03 in. Accordingly, the grip levels during these time periods decreased dramatically (from > 0.8 to 0.25–0.45), as can be seen from **Figure 3.10**. However, when there was no precipitation, the grip level kept at a high value of 0.8 (levels above 0.7 can be considered a safe road status according to the RWIS system), probably meaning that the deicer application effectively restored surface grip levels. Therefore, we can conclude that the grip level values are closely related with the precipitation status during the entire snow events.

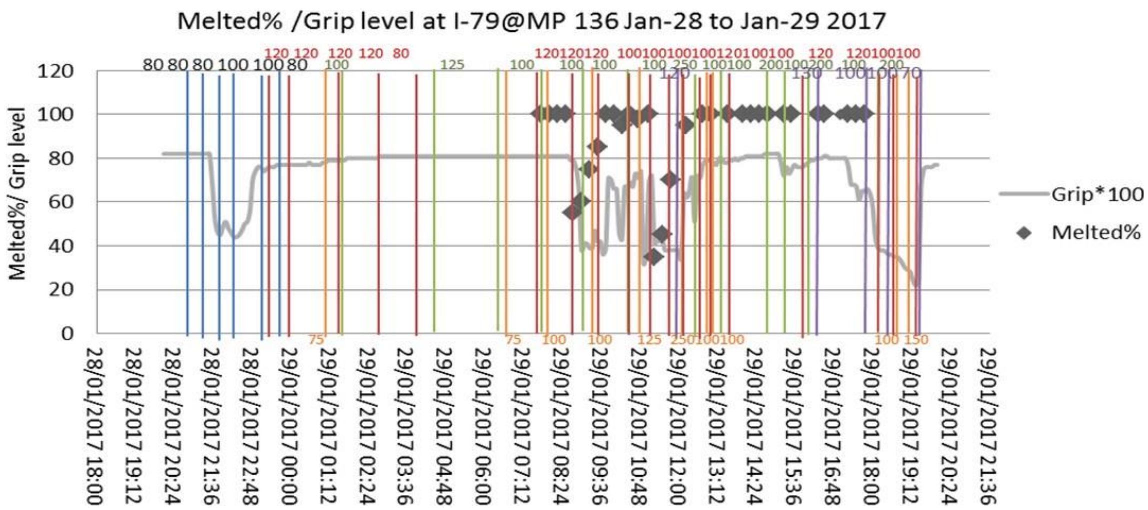


Fig. 3.11 Melted% and grip level variables during 24 hours from 28-Jan-2017 20-00 to 29-Jan-2017 20-00 at site I-79@MP136 Crawford/Mercer line.

Figure 3.11 shows the snow melted% and grip level values at site I-79@MP136 Crawford/Mercer line. Prior to 8:30 am on Jan 29, 2017, there was no precipitation and the melted% remained at 100%. From 8:30 am, precipitation began to accumulate then the melted% percentage decreased to around 50% within 60 min. When deicers were applied many times (according to **Figure 3.11**), the melted percentage increased significantly to 100% within about 60~90 min (from 8:44 am ~55% melted%, to 100% melted at 9:44, while the second time from 11:14 am 35% melted to 100% melted at 12:44 Jan-29, 2017). The selected RWIS photos for the discussion above are shown in **Figure 3.12** and **Figure 3.13** below.

It is obvious that the melted percentages have a close relationship with the grip levels, according to Figure 3.11. For instance, in the image for 8:44 Jan 28, 2017, the melted percentage decreased dramatically probably due to the heavy precipitation, at the same time, the grip level decreased from 0.8 to 0.38. After several times of deicer application by different trucks with various application rates, the melted% increased within one hour, and then the grip level increased from 0.38 to around 0.75 accordingly. Then when the snow precipitation increased again at 11:14 Jan 28, 2017, the melted% decreased to around 35%, also, the grip level decreased to around 0.37, from Figure 3.11. Therefore, we can reach the conclusion that the grip level variable and the melted% followed a comparable trend. This is a very promising finding because the grip levels are readily available from RWIS, while collecting melted% is a labor and time intensive process. It remained to be tested whether the grip level can be an effective indicator of deicer field performance in additional snow events.

Fig. 3.12 Photos downloaded from RWIS site I-79@MP136 Crawford/Mercer line. Time from 7:44 am Jan 28, 2017 to 9:44 Jan 28, 2017 (Snow Melted% scores were assigned by two different researchers and given an average value).

Fig. 3.13 Photos downloaded from RWIS site I-79@MP136 Crawford/Mercer line. Time from 11:04 am Jan 28, 2017 to 12:44 Jan 28, 2017 (Snow Melted% scores were assigned by two different researchers and given an average value).

b). Feb-08-2017

Five trucks passed the site 29 times during 24 hours from 12:00 March-13, 2017 to 12:00 March-14, 2017. The truck numbers are 0110-493-8077; 0140-213-2072; 0110-552-8077; 0140-256-8087 and 0110-070-5090.

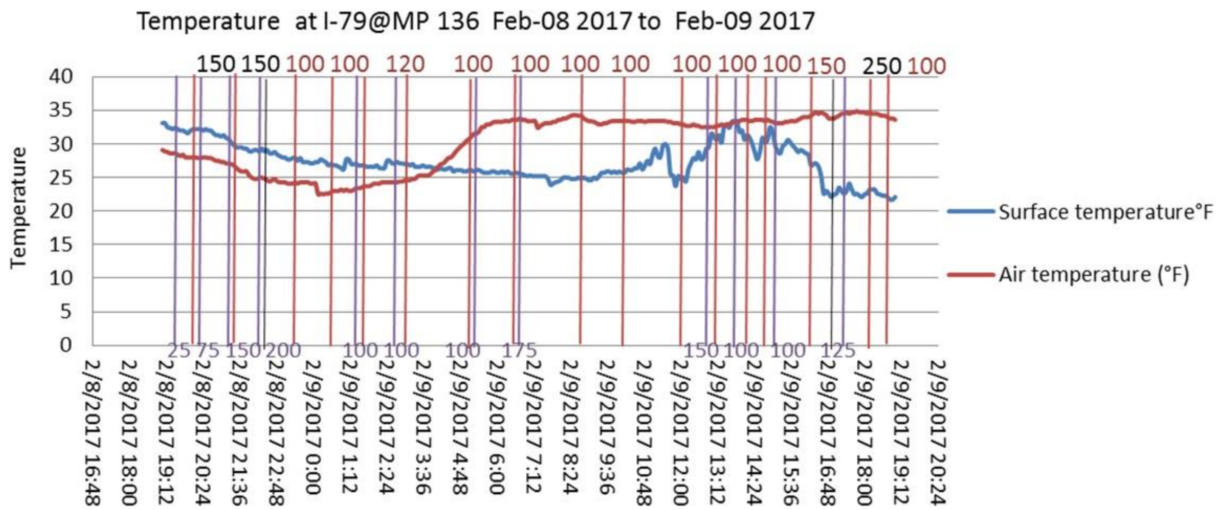


Fig. 3.14 Temperature (surface temperature and air temperature) variables during 24 hours from Feb 08, 2017 16:00 to Feb 09, 2017 21:00 at site I-79@MP136 Crawford/Mercer line.

Figure 3.14 shows during 24 hours from Feb 08, 2017 16-00 to Feb 09, 2017 21-00 at site I-79@MP136 Crawford/Mercer line, air temperature varies from 22 ^{0}F to 34 ^{0}F, while the surface temperature varies from 23 ^{0}F to 34 ^{0}F, which was similar to air temperature.

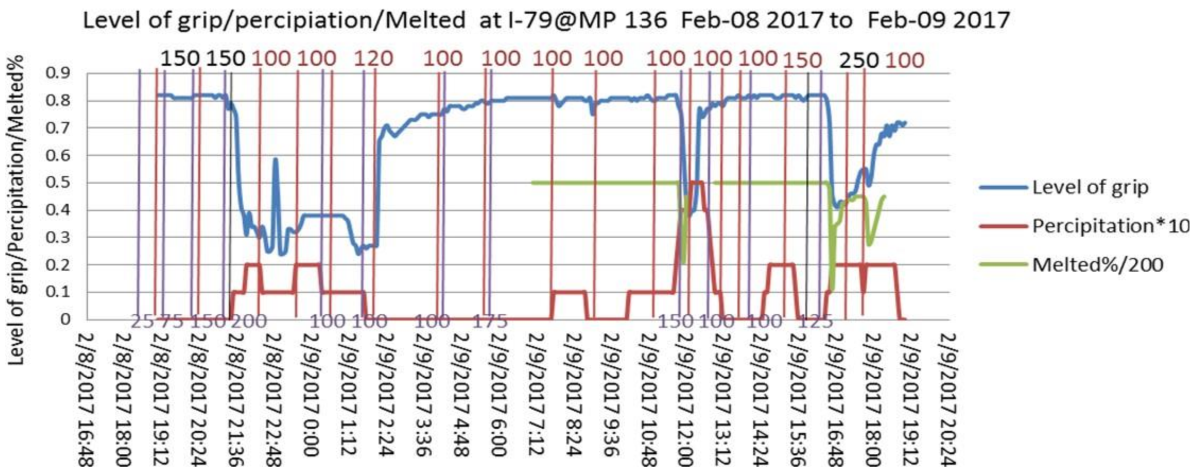


Fig. 3.15 Grip levels/precipitation/snow melted% variables during 24 hours from Feb 08, 2017 16-00 to Feb 09, 2017 21-00 at site I-79@MP136 Crawford/Mercer line.

In Figure 3.15, grip levels/precipitation/snow melted% varied during 24 hours from Feb 08, 2017 16:00 to Feb 09, 2017 21:00 at site I-79 @ MP136 Crawford/Mercer line, First, when the precipitation increased during some time, for example, from 21:30 Feb 08, 2017 to 1:30 Feb 09, 2017; from 10:00 Feb 09, 2017 to 15:36 Feb 09, 2017 and from 16:48 Feb 09, 2017 to 19:12 Feb 09, 2017, there was snow precipitation of 0~0.02,0~0.05 and 0~0.02 in, respectively, as a result, the grip level decreased significantly from 0.8 to 0.25, 0.38, 0.42, respectively. Thus, the grip level and precipitation data show opposite trends.

The green line in Figure 3.15 shows the snow melted percentages during the 24 hours from Feb 08, 2017 16-00 to Feb 09, 2017 21-00 at site I-79 @ MP136 Crawford/Mercer line. The RWIS photos offer the images from 7:00 am to 19:30 Feb 09, 2017. At 11:54 2/9/2017, the melted percentage decreased to 42.5%, then at 2/9/2017 11:59, the melted percentage recovered to about 90% within only 10 min despite the relatively heavy snow precipitation, indicating the effectiveness of the frequent deicer applications. At 16:39 Feb 09, 2017, the snow melted% decreased to about 22.5%, after it had been snowing for some time. After two times of deicer applications, the melted% increased again to 90% at 17:24 Feb 09, 2017. Within the same time periods, the grip levels changed accordingly. Therefore, the grip level can be considered a potential indicator of melted percentages and deicer performance.

Figures 3.16 and 3.17 below show the photos downloaded from RWIS site I- 79@MP136 Crawford/Mercer line. Time from 16:29 Feb 08, 2017 to 17:24 Feb 08, 2017 and Time from 11:44 Feb 08, 2017 to 11:59 Feb 08, 2017.

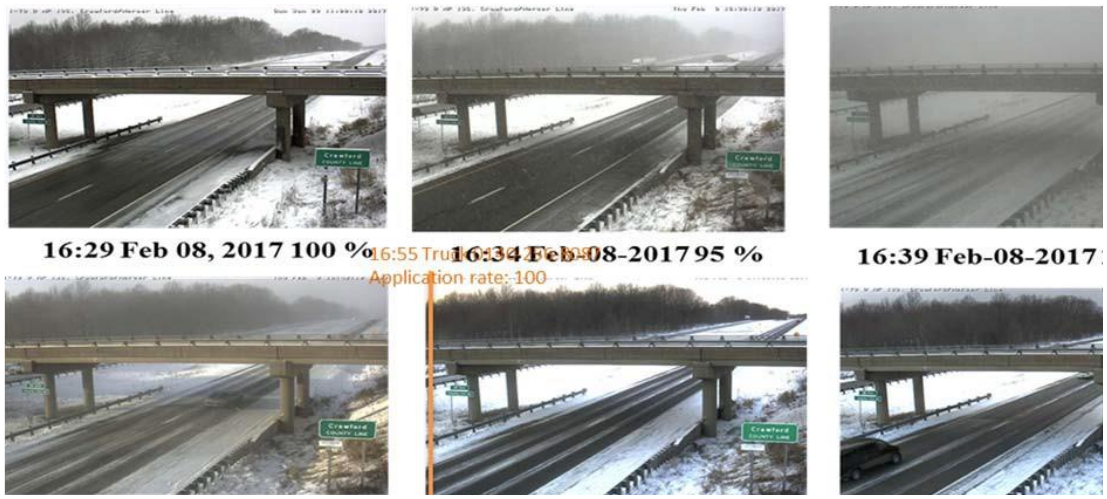


Fig. 3.16 Photos downloaded from RWIS site I-79@MP136 Crawford/Mercer line. Time from 16:29 Feb 08, 2017 to 17:24 Feb 08, 2017 (Snow Melted% scores were assigned by two different researchers and given an average value).

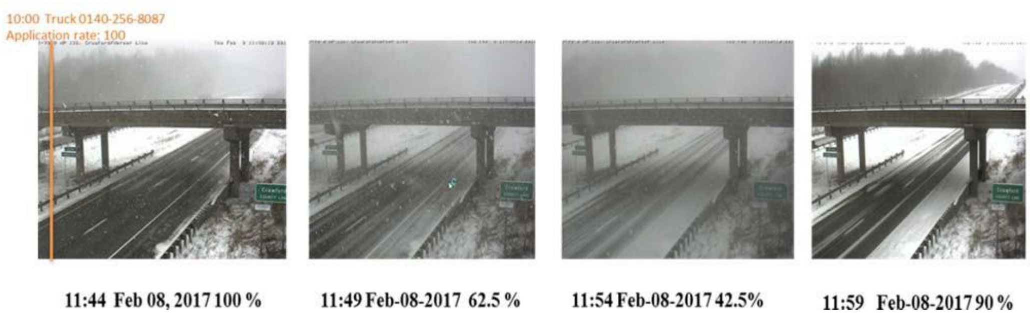


Fig. 3.17 Photos downloaded from RWIS site I-79@MP136 Crawford/Mercer line. Time from 11:44 Feb 08, 2017 to 11:59 Feb 08, 2017 (Snow Melted% scores were assigned by two different researchers and given an average value).

c). Feb-09-2017

Six trucks passed site I-79@ MP136, Crawford/Mercer line, 18 times during 24 hours from 12-00 Feb 09, 2017 to 12-00 Feb 10, 2017. In this case, there was precipitation around 0.1 in from 2:30 to 6:00 in the morning, after the trucks passed by the site, the grip levels increased effectively to around 0.8, which indicated that the deicer applications were very effective. No RWIS photos were available.

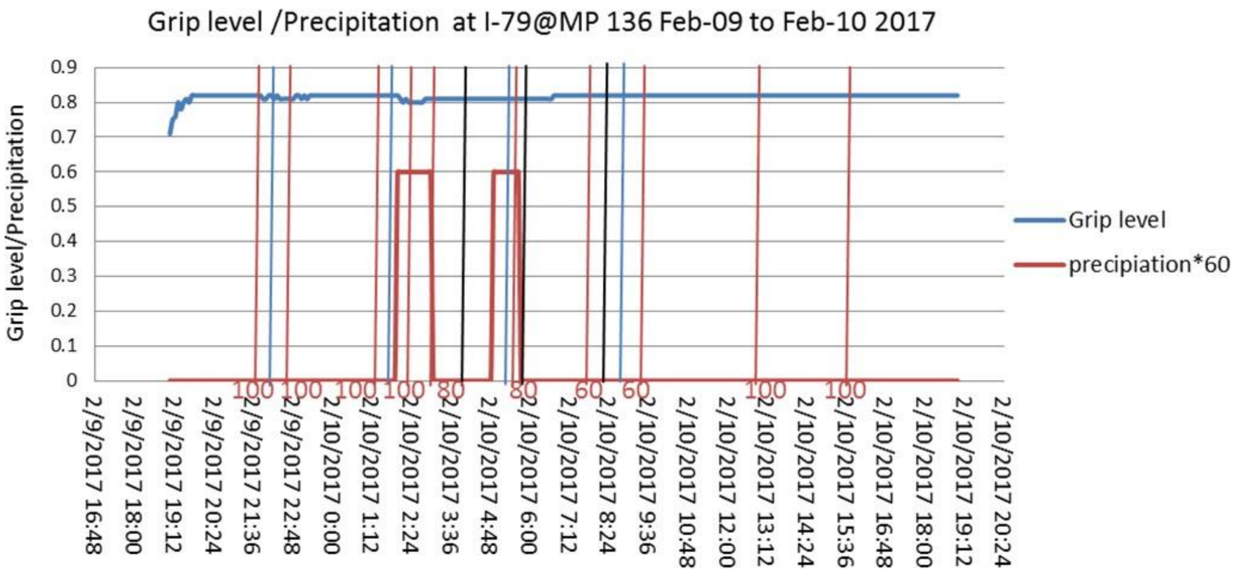


Fig.3.18 Grip levels/precipitation variables during 24 hours from Feb 09, 2017 16-00 to Feb 10, 2017 21-00 at site I-79@MP136 Crawford/Mercer line.

d). Feb-12-2017

One truck passed site I-79@ MP136, Crawford/Mercer line, 29 times during 24 hours from 12:00 March-13, 2017 to 12:00 March-14, 2017. **Fig. 3.19** shows Grip levels/precipitation variables during 24 hours from Feb 12, 2017 16:00 to Feb 13, 2017 21:00 at site I-79@MP136 Crawford/Mercer line. When the precipitation increased as shown in the figure below, the grip level deceased significantly. After the deicers were applied from around 21:30 to 8:30 am, the grip levels increased and then remained at a stable high value, although there was some precipitation from 0:00 to 6:00 am (above 0.7 as shown in Figure 3.19). That indicated that the deicer applications were very effective.

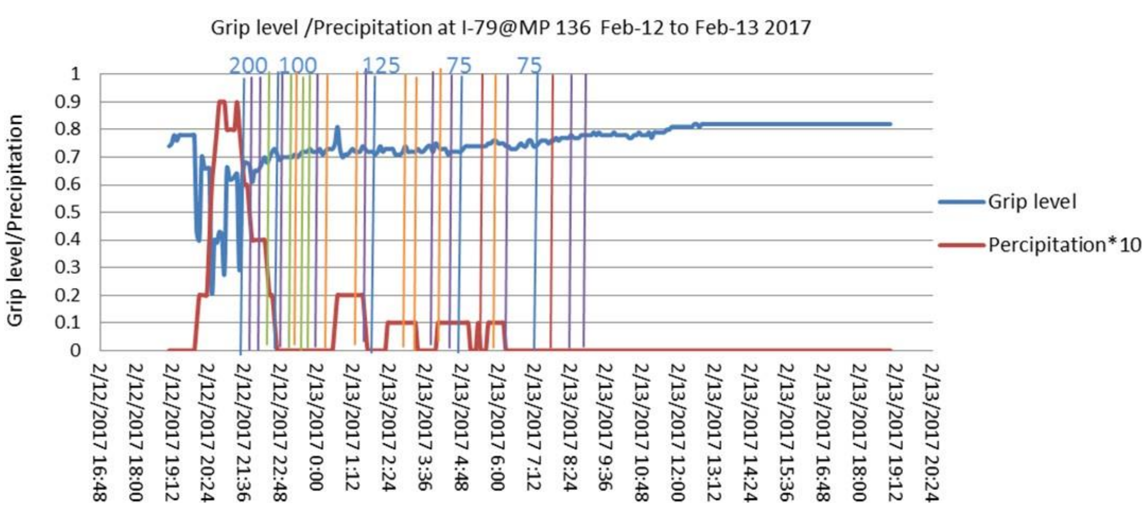
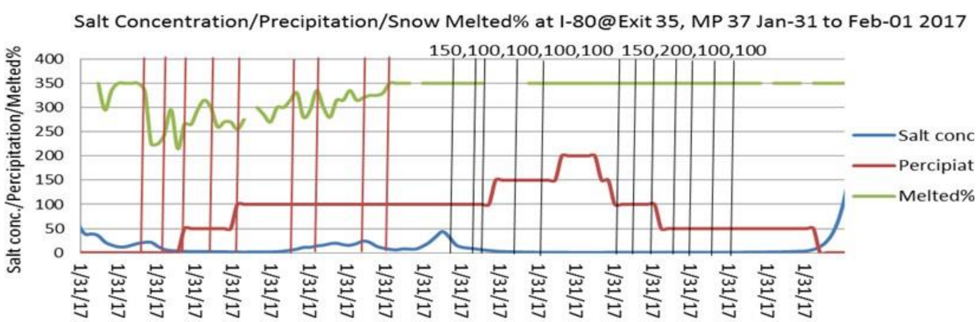


Fig.3.19 Grip levels/precipitation variables during 24 hours from Feb 12, 2017 16-00 to Feb 13, 2017 21-00 at site I-79@MP136 Crawford/Mercer line.

III. Comparison between AquaSalina and rock salt

The snow events on Jan 31, 2017 and Jan 29, 2017 are compared below at the site for AquaSalina (I-80@ Exit 35, MP 37) and its reference site (I-79@MP136, Crawford/Mercer Line). We chose these two events because there were limitations in image collection during other time periods. Because we currently have limited data collected for the other three deicers (BEET HEET, Green Blast and magic minus zero), we took this case as an example to compare the deicer performance.

(a)



(b)

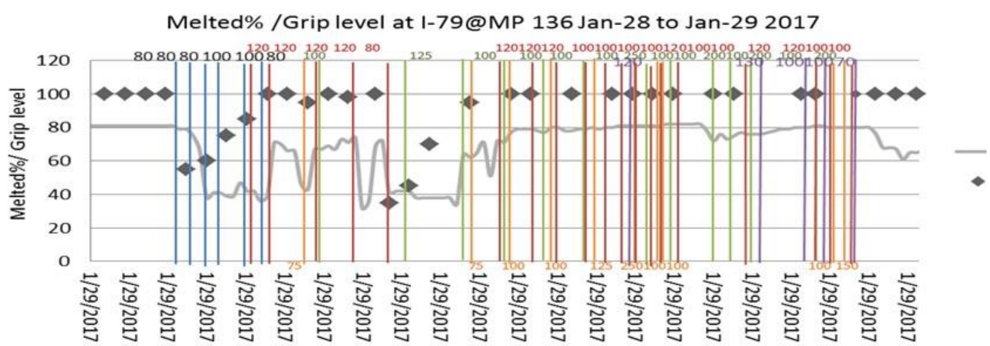


Fig. 3.20 Comparison of I-80@ Exit 35, MP 37 (a) with its reference site I-79@MP136, Crawford/Mercer Line (b).

As can be seen in **Fig. 3.20 (a)**, the snow melted percentage decreased to 72.5% from 100% (at around 7:25 to 7:30 am), and then recovered to 100% at 7:40 AM, within only 10 minutes. The second available image data during this snow event began at 7:55 AM. The melted% deceased from 100% to 37% within 15 minutes (from 7:55 AM to 8:10 AM), then the melted% increased to 82.5% within 35 min. During this period, there was a lot of precipitation which made the melted% remained at around 52.5% to 75%. During this time period, truck 0150-425-8077 applied AquaSalina 9 times (around 7:00- 11:00 AM Jan-28, 2017). Then Truck 0150-118-8077 applied AquaSalina 9 times (around 11:00-17:00 AM Jan-28, 2017), the melted% remained at 100% although there was precipitation between 0.02 inch and 0.04 inch. For comparison, at the reference site I-79@MP136, Crawford/Mercer Line, images are available from 7:44 AM to 9:44 AM, and from 9:59 AM to 12:44 AM on Jan-29- 2017. From 8:29 to

8:44, the melted percentage decreased to 55% because of the precipitation, then recovered to 100% at 9:44 AM within 60 minutes. For the second time, the melted% decreased to 35% at 11:14, then recovered to 100% at 12:44 within 90 minutes, as shown in Fig. 3.20 (b) above. The precipitation was 0.02 inch to 0.05 inch from 8:24 to 13:00 on Jan 29, 2017.

The weather information at these two sites is shown in **Table 3.20** below. The precipitation between the sites was similar (0.02-0.04 inch for I-80@ Exit 35, MP 37 and 0.02-0.05 inch I-79@MP136, Crawford/Mercer Line) and the surface temperature and air temperature were similar as well. The applicate rates were also comparable between these two events: The application rates at site I-80@ Exit 35, MP 37 were from 100 to 120 lb/lane mile, while the application rates at site I-79@MP136 were from 100 to 150 lb/lane mile. Therefore, from the obtained limited data so far, it seems that the recovery times were shorter when AquaSalina was applied. Note that this observation is only based on one event. A number of events should be recorded and analyzed before a firm conclusion can be reached. For more quantitatively comparison about deicer AquaSalina and other deicers (e.g. BEET HEET, Green Blast and Magic minus zero), we need to collect additional data and conduct further data analysis in the winter of 2018.

Table 3.20 Representative weather information between sites I-80@ Exit 35, MP 37 and its reference site I-79@MP136, Crawford/Mercer Line.

Site	Deicer	Date	Precipitation (inch)	Truck passing	Surface temp.	Air temp.
I-80@ Exit 35, MP 37	Aqua Salina	Jan-31-2017	0.02-0.04	9 times (7:00-13:00)	25.7-32.9	24.1-28.5
I-79@MP136, Crawford/Mercer Line	rock salt	Jan-28-2017	0.02-0.05	16 times (7:00-13:00)	2 4.1-31.1	24.8-26.2

3.2 BEET HEET (Site I-79@ Exit 88 & Reference site I-79@ MP 100)

For this pair of sites, I-79@ Exit 88 is for BEET HEET; Reference site I-79@MP 100 is for rock salt.

I. Site I-79@ Exit 88

For site I-79@Exit 88, the snow events were 08-Feb-2017 19:00 to 09-Feb-2017 19:00 I- 79 Exit 88; 12-Feb-2017 11:00 to 13-Feb-2017 11:00 I-79 Exit 88; 15-Feb-2017 17:00 to 16-Feb-2017 17:00 I-79 Exit 88; 31-Jan-2017 01:00 to 01-Feb-2017 01:00 I-79 Exit 88; 30-Jan-2017 17:00 to 31-Jan-2017 17:00 I-79 MP100. In the following section, the snow events are discussed separately.

a). On Feb 08, 2017

This site is equipped with the sensor for the salt concentration instead of the grip level. Figure 3.2.1 shows that the air temperature and surface temperature have a similar trend. The temperatures are in the range of 21 ^{0}F to 44 ^{0}F.

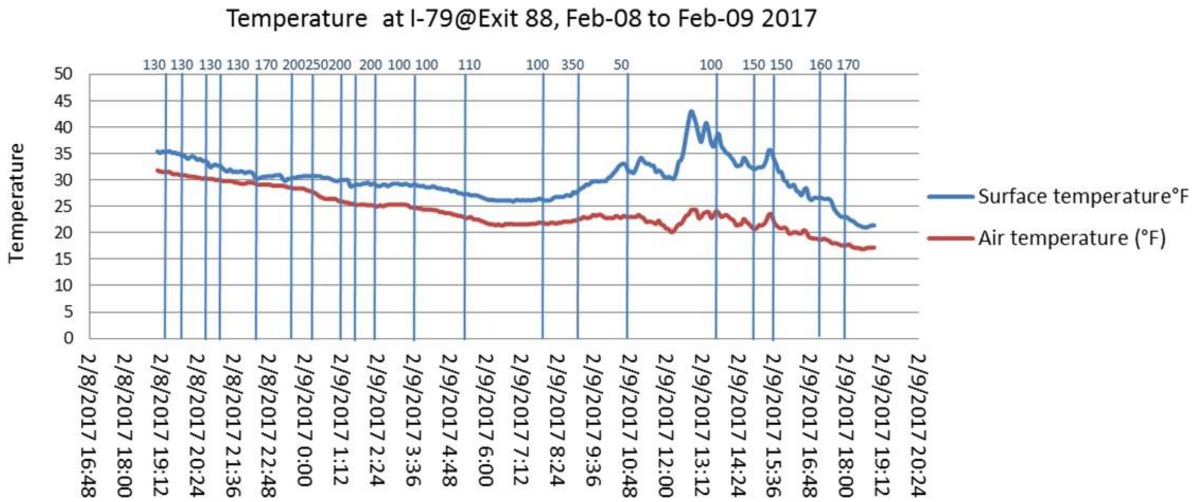


Fig.3.2.1 Temperature (surface temperature and air temperature) variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at site I-79 @ Exit 88.

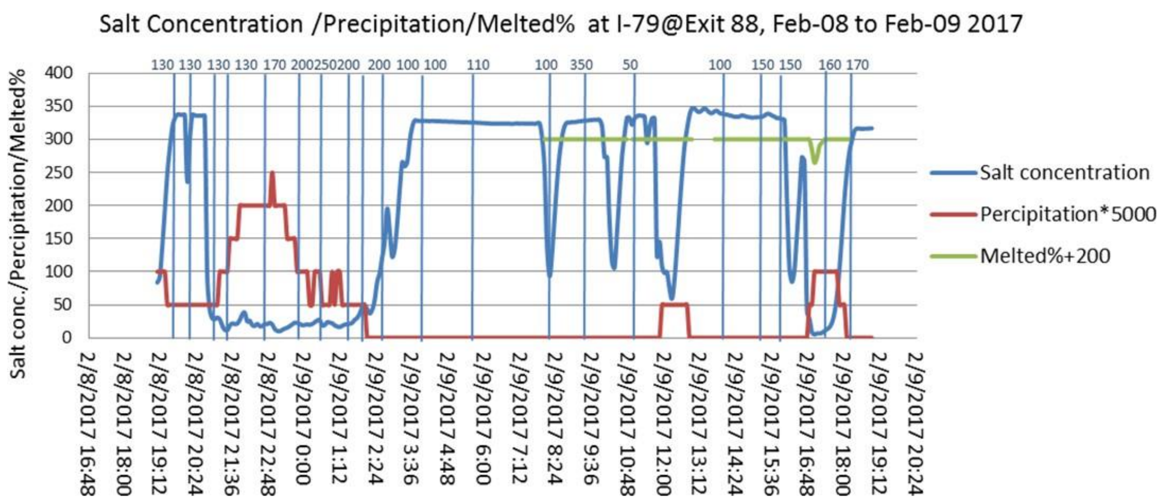


Fig. 3.2.2 Salt concentration (g/L), precipitation and melted% variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at site I-79 @ Exit 88.

Figure 3.2.2 shows the salt concentration (g/L), precipitation and melted% variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at site I-79 @ Exit 88. Generally when the precipitation level increased, the salt concentration decreased accordingly. On the other hand, the melted percentage remained 100% from 8:30 am Feb 09, 2017 to 18:00 Feb 09, 2017, which indicated the deicer applications were effective, which was again not reflected by the recorded salt concentrations.

b). On Feb 12, 2017

Three trucks passed the site I-79@ Exit 88 11 times in 24 hours' time window. Last record address was Frog's way; City was Slippery Rock in PA. GPS fixed was F. Latitude was 40.79 and longitude was -80.125.

Table 3.2.1 three trucks information from AVLs system from 12-Feb-2017 16:00 to 13- Feb-2017 17:00 at site I-79 @ Exit 88

Vehicle	Last Record	Direction	Speed	Longitude	Street
1020-839-8076	2/13/2017 0:18	S	39	-80.12509	I-79
1020-839-8076	2/13/2017 0:52	S	40	-80.12502	I-79
1020-839-8076	2/13/2017 1:29	S	48	-80.12504	I-79
1020-839-8076	2/13/2017 3:53	S	48	-80.1249	I-79
1020-839-8076	2/13/2017 4:33	S	40	-80.124916	I-79
1020-839-8076	2/13/2017 5:00	S	38	-80.12489	I-79
Vehicle	**Last Record**	**Direction**	**Speed**	**Solid Material**	**Solid Rate**
1020-496-8077	2/13/2017 2:50	S	50	SALT-100	100
1020-496-8077	2/13/2017 6:06	SW	52	SALT-100	170
1020-451-8087	2/13/2017 5:27	S	43	SALT-100	100
1020-451-8087	2/13/2017 5:52	S	44	SALT-100	120
1020-451-8087	2/13/2017 6:34	S	47	SALT-100	100

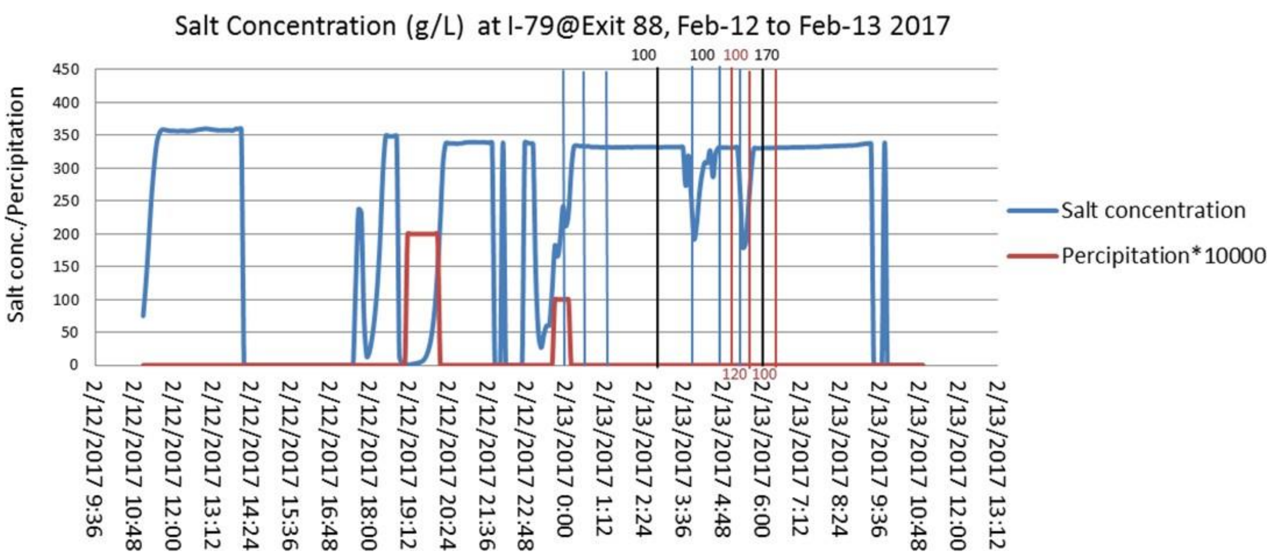


Fig.3.2.3 Salt concentration (g/L), precipitation variables during 24 hours from 12-Feb- 2017 16:00 to 13-Feb-2017 17:00 at site I-79 @ Exit 88.

From Figure 3.2.3 we can conclude that the salt concentration remained stable when the deicer BEET HEET was applied. However, the salt concentration had fluctuations to some degree. The reason is unknown.

c). On Feb 15, 2017

Seven trucks passed the site I-79@ Exit 88 11 times during 24 hours' time window. The truck numbers are 1020-535-8077; 1020-281-8077; 1020-451-8087; 1020-534-8077; 1020-108-8087; 1020-108-8087 and 1020-496-8077.

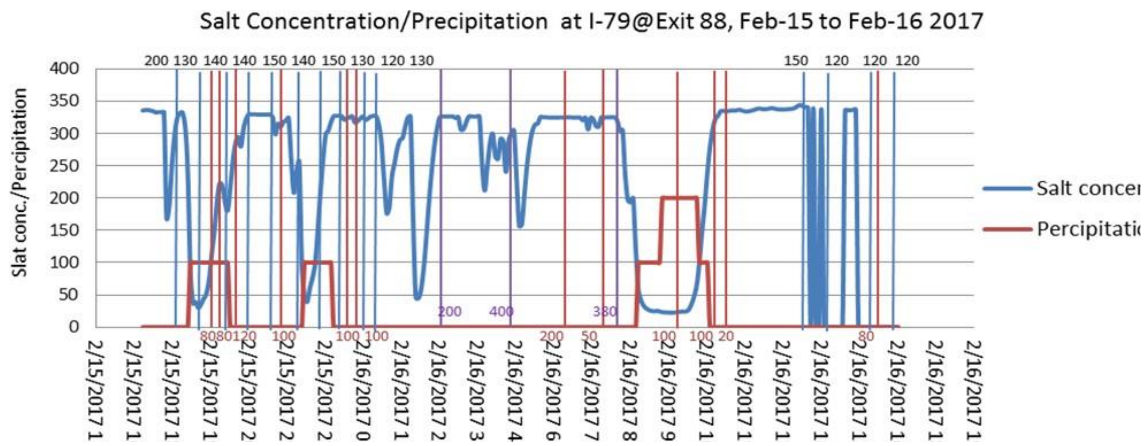


Fig. 3.2.4 Salt concentration (g/L), precipitation variables during 24 hours from 15-Feb- 2017 16:00 to 16-Feb-2017 17:00 at site I-79 @ Exit 88.

As can be seen from Fig. 3.2.4, there were many fluctuations in the salt concentration when the deicer BEET HEET was applied during the entire time. It shows the same trend as AquaSalina on Jan-05-2017, Jan-31-2017, and Feb-08-2017. when the precipitation increased, the salt concentration decreased significantly. However, when there was no precipitation, the salt concentration also fluctuated. Therefore, we can reach the conclusion that the salt concentration related with the precipitation; however, some unknown factors might also influence the salt concentration at the same time.

d). On Jan 30 and Jan 31, 2017

Fig. 3.2.4. and Fig. 3.2.5 show the salt concentration (g/L) and precipitation variables during 24 hours from 31-Jan-2017 1600 to 01-Feb-2017 1700 (Fig. 3.2.4) and from Jan- 30-2017 1600 to 31-Jan-2017 1700 (Fig. 3.2.5) at site I-79 @ Exit 88. We can reach the same conclusion as from the previous discussion, i.e., the salt concentration has an opposite trend with the precipitation in general. When there was no precipitation on the RWIS site, the salt concentration remained at a relatively high value.

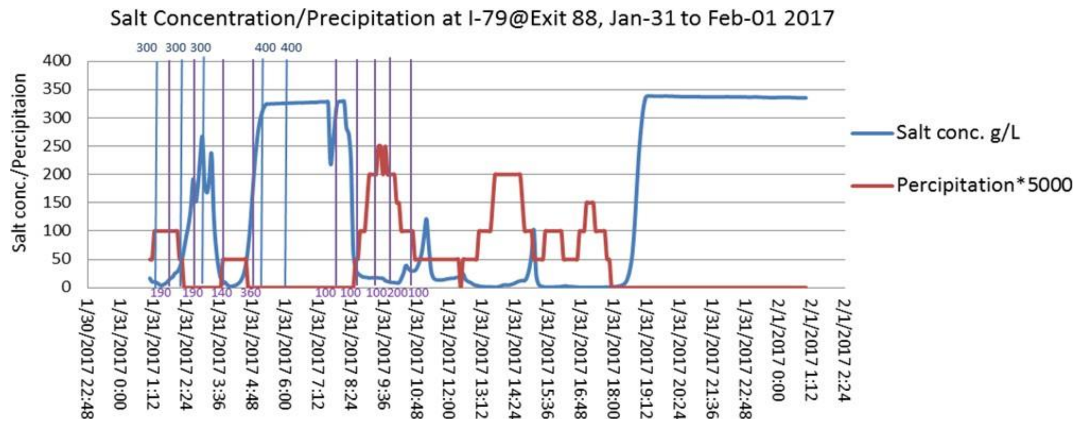


Fig. 3.2.4 Salt concentration (g/L), precipitation variables during 24 hours from 31-Jan- 2017 16:00 to 01-Feb-2017 17:00 at site I-79 @ Exit 88.

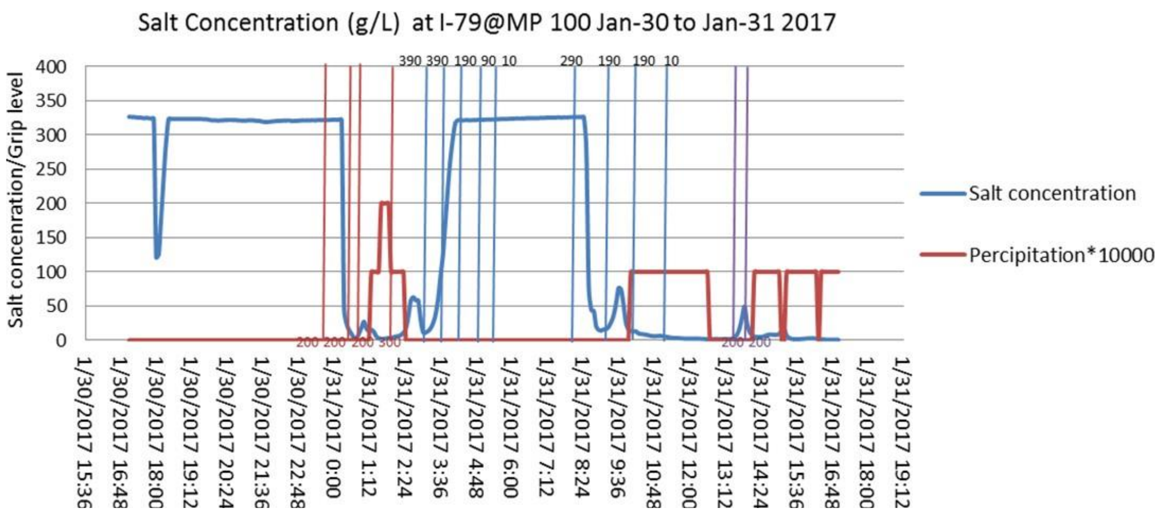


Fig. 3.2.5 Salt concentration (g/L), precipitation variables during 24 hours from Jan-30- 2017 1600 to 31-Jan-2017 1700 at site I-79 @ Exit 88.

II Site I-79@ MP100

Site I-79 @ MP 100 is the reference site of I-79@Exit88. At this site, the reference deicer rock salt was applied for a comparison with BEET HEET.

a). On Feb 08, 2017

During this event, there was one truck passing by this site during 24-hour from Feb-08- 2017 1600 to Feb-09-2017 1700 at site I-79 @ MP100. The temperatures (surface temperature and air temperature) for this event are shown in **Figure 3.2.6**. The surface temperature was around 25 to 38 ^{0}F.

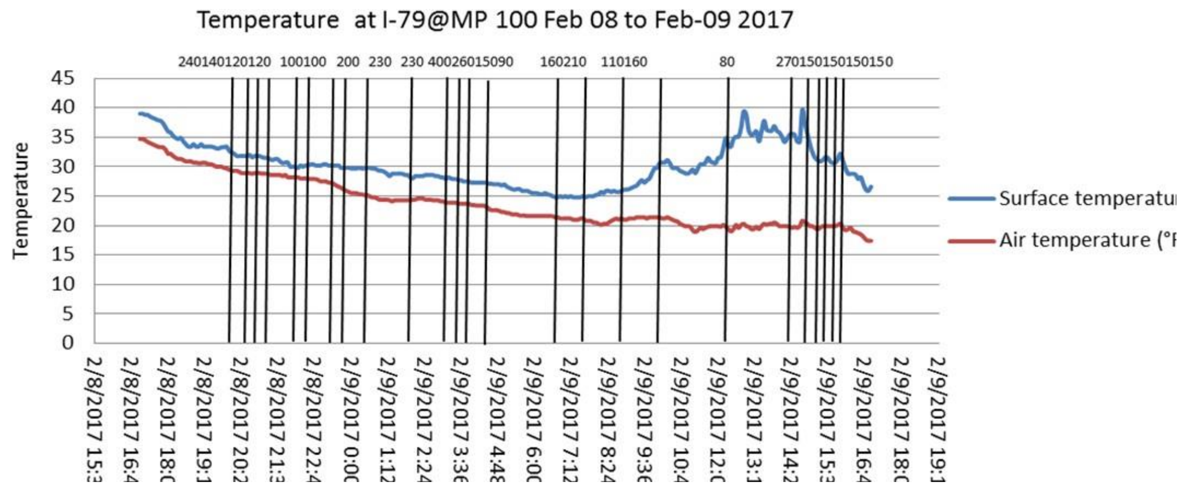


Figure 3.2.6 Temperature (surface temperature and air temperature) variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at site I-79 @ MP 100.

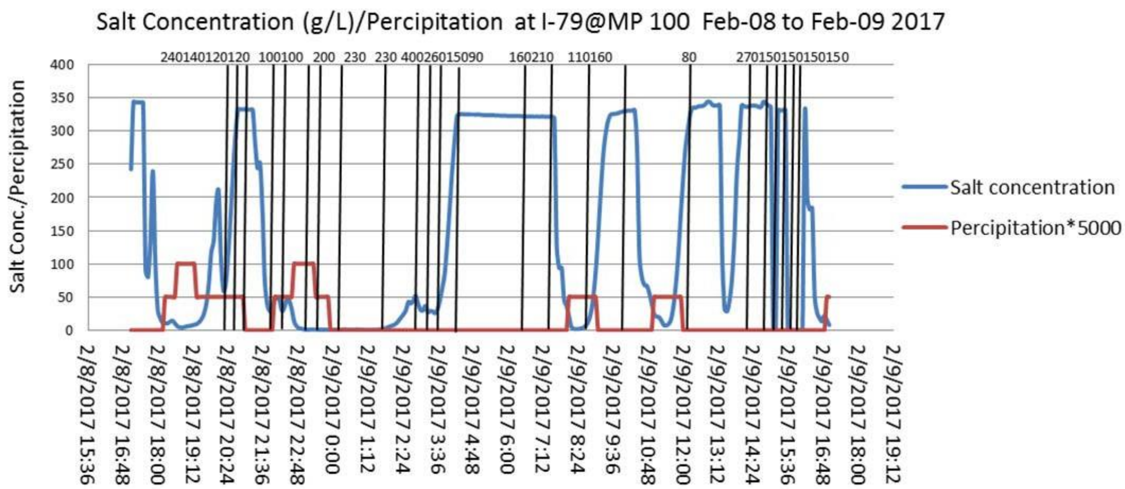


Figure 3.2.7 Salt concentration (g/L) and precipitations variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at site I-79 @ MP 100.

As can be seen in Figure 3.2.7, the precipitation increased from 18:00 to 20:00 Feb 08, 2017, from 21:30 Feb 08, 2017 to 00:00 Feb 09, 2017, from 8:00 to 9:00 Feb 09, 2017, and from 11:00 to 12:00 Feb 09, 2017 (precipitation 0.02 0.02 0.01 and 0.01 inch, respectively). During the same time period, the salt concentration decreased significantly to nearly 0 g/L (initial salt concentration above 300 g/L). This indicates the deicer applications were very effective to recover the salt concentration.

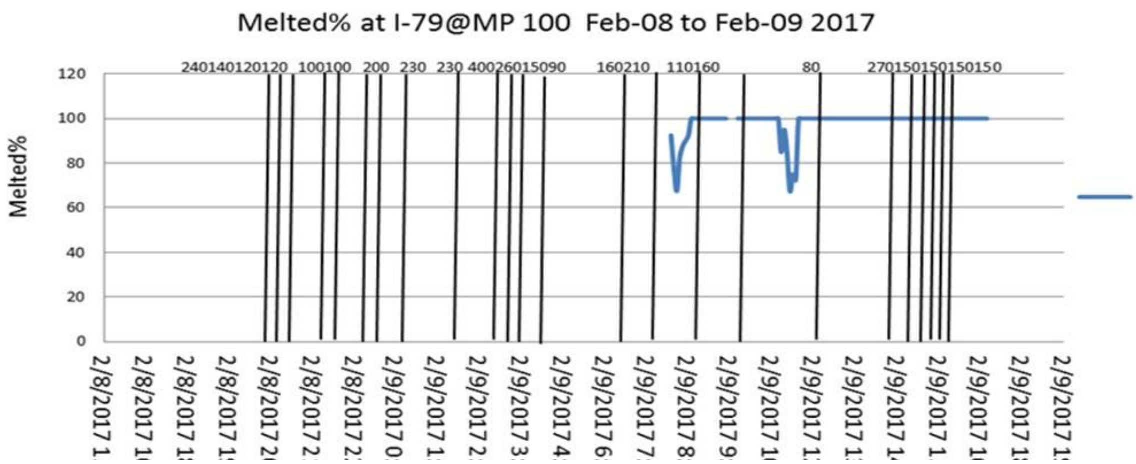


Figure 3.2.8 Snow melted% variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at site I-79 @ MP 100.

Figure 3.2.8 shows the snow melted% percentages during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at site I-79 @ MP 100. After the deicer was applied, the melted% recovered to 100% effectively within around 25 min, and remained at this level until the next precipitation started.

3.3 Green Blast: I-81 @ Exit 223 New Milford & reference site I-81@Exit 211 Lenox

I-81 @ Exit 223 New Milford was for Green Blast, and the reference site I-81@Exit 211 Lenox was for rock salt. For Feb 08, 2017, Green Blast was applied to both sites. For this pair of sites in 2017, there was not much snow. The only snow event was on Feb 08, 2017. Three trucks passed the site I-81@ Exit 223, 9 times in the 24-hour time window.

Figure 3.3.1 shows temperature (surface temperature and air temperature) variables during 24 hours from 08-Feb-2017 1600 to 09-Feb-2017 1700 at I-81 @ Exit 223 New Milford. In this case the surface temperature is relatively higher than the air temperature. The surface temperature was from 25 to 40 ^{0}F, and the air temperature was from 13 to 34 ^{0}F.

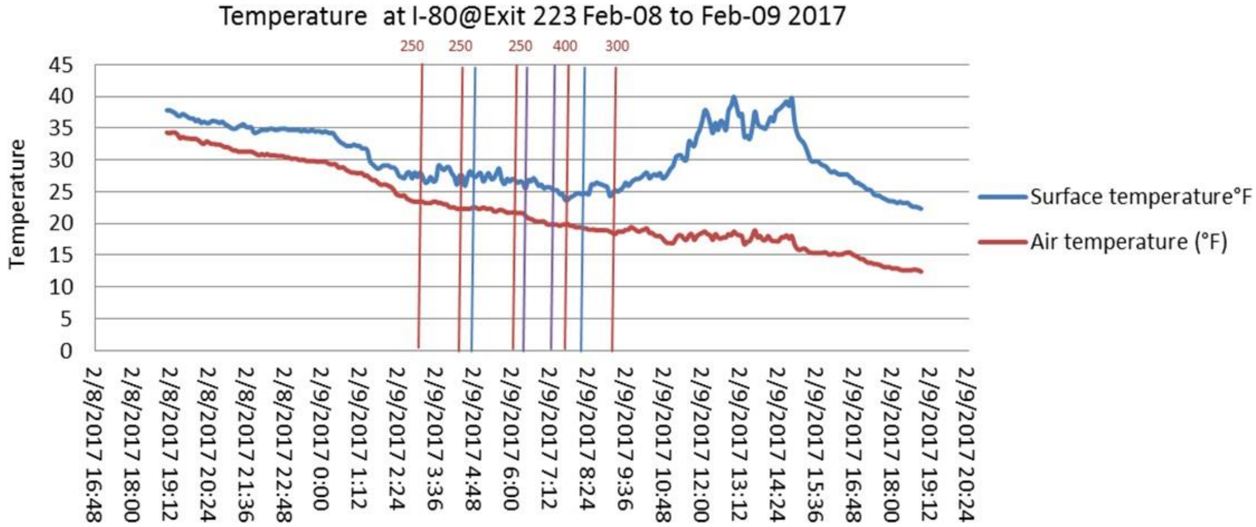


Figure 3.3.1 Temperature (surface temperature and air temperature) variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at I-81 @ Exit 223 New Milford.

Site I-81 @ Exit 223 New Milford equipped with the sensor for grip levels. **Figure 3.3.2** shows the grip levels and precipitations variables during 24 hours from 08-Feb- 2017 16:00 to 09-Feb-2017 17:00 at I-81 @ Exit 223 New Milford. There is an obvious trend that when the precipitation increased, the grip level decreased significantly. Therefore, this is a strong evidence that the grip level and precipitation have a good correlation. On the other hand, after several deicer applications, the grip level recovered to 0.72~ 0.81 again at 9:00 am Feb 09, 2017.

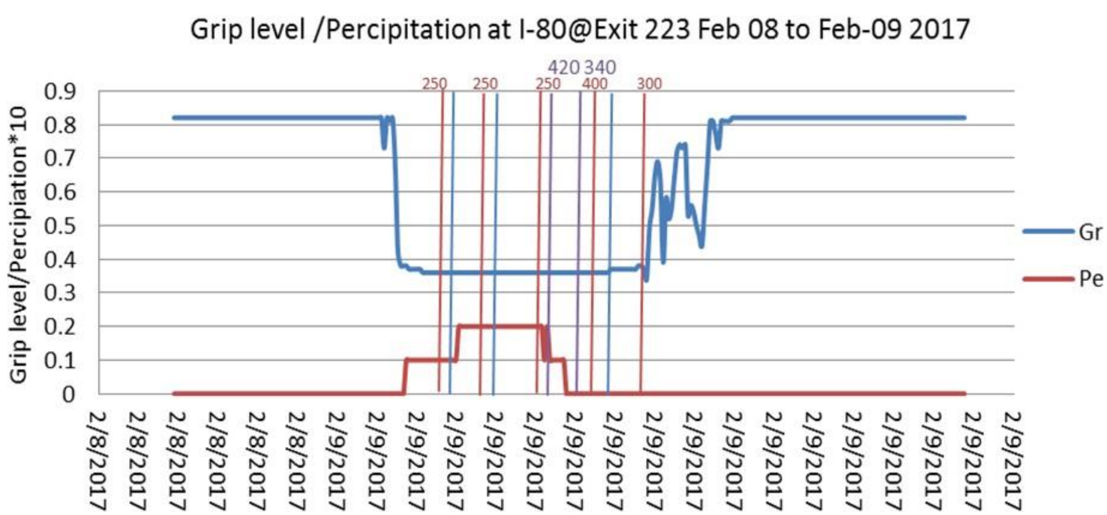


Figure 3.3.2 Grip levels and precipitations variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at I-81 @ Exit 223 New Milford.

On Feb 08, 2017, the reference site used Green blast instead of rock salt. Figure 3.3.3 shows the temperature (surface temperature and air temperature) variables during 24 hours from 08-Feb-2017

16:00 to 09-Feb-2017 17:00 at I-81 @ Exit 223 New Milford. The surface temperature was from 25 to 28 ^{0}F, and the air temperature was from 14 to 36
^{0}F.

Figure 3.3.3 Temperature (surface temperature and air temperature) variables during 24 hours from 08-Feb-2017 1600 to 09-Feb-2017 1700 at I-80 @ Exit 211 New Milford.

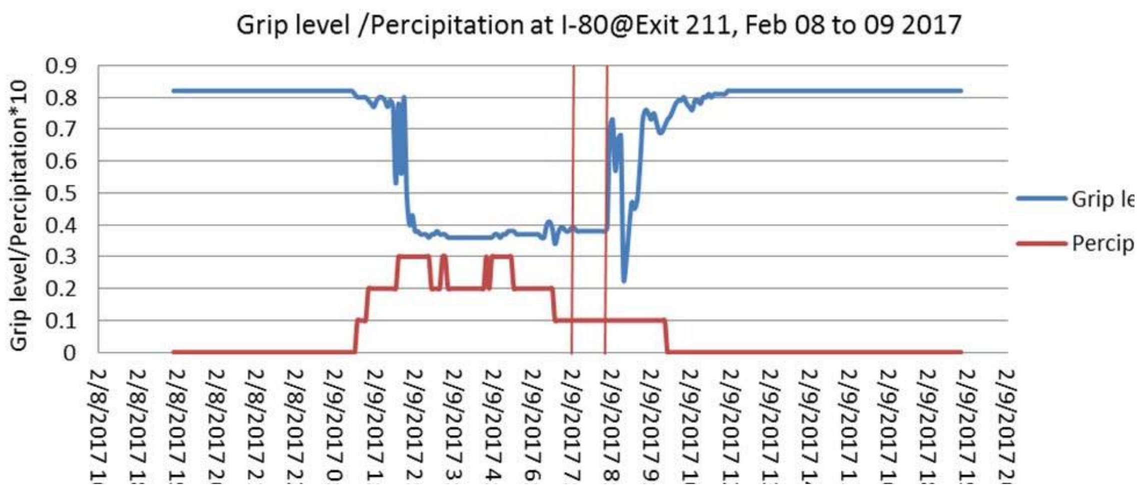


Figure 3.3.4 Temperature (surface temperature and air temperature) variables during 24 hours from 08-Feb-2017 1600 to 09-Feb-2017 1700 at I-81 @ Exit 223 New Milford.

Figure 3.3.4 shows the grip levels and precipitation variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at I-80 @ Exit 211 New Milford. There was an obvious trend that when the precipitation increased, the grip level decreased significantly, which is the same as in Figure 3.3.2. We only observed two truck passings for this snow event, but it is likely that there were other trucks operating but not tracked by AVL.

3.4 Magic minus zero: I-81@Exit 77, Manada Hill & reference site I-81@ I-78 Split

On Feb 08, 2017, two Truck passed the site I-81@ Exit 77, 32 times in 24 hours' time window. Figure 3.4.1 shows that the surface temperature was from 28 to 49 ^{0}F, and the air temperature was from 22 to 45 ^{0}F.

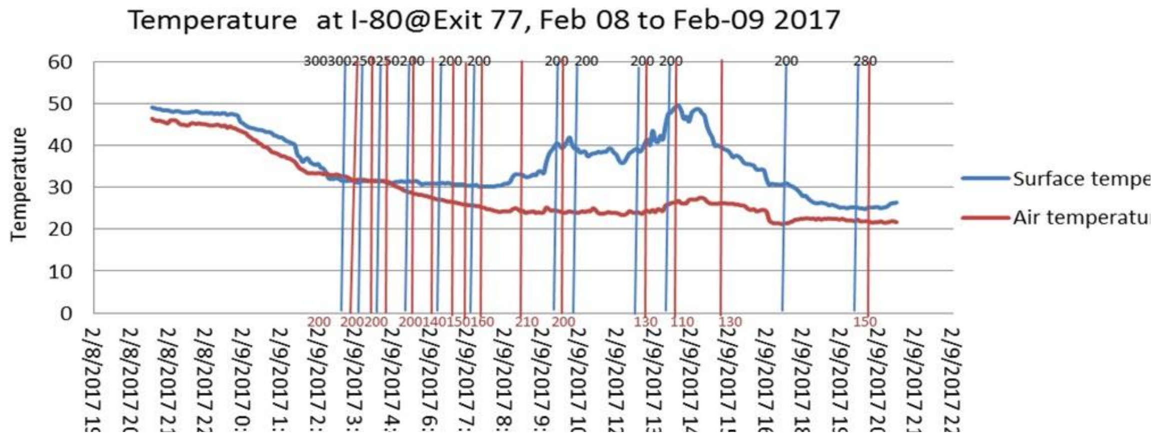


Figure 3.4.1 Temperature (surface temperature and air temperature) variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at I-80 @ Exit 211 New Milford.

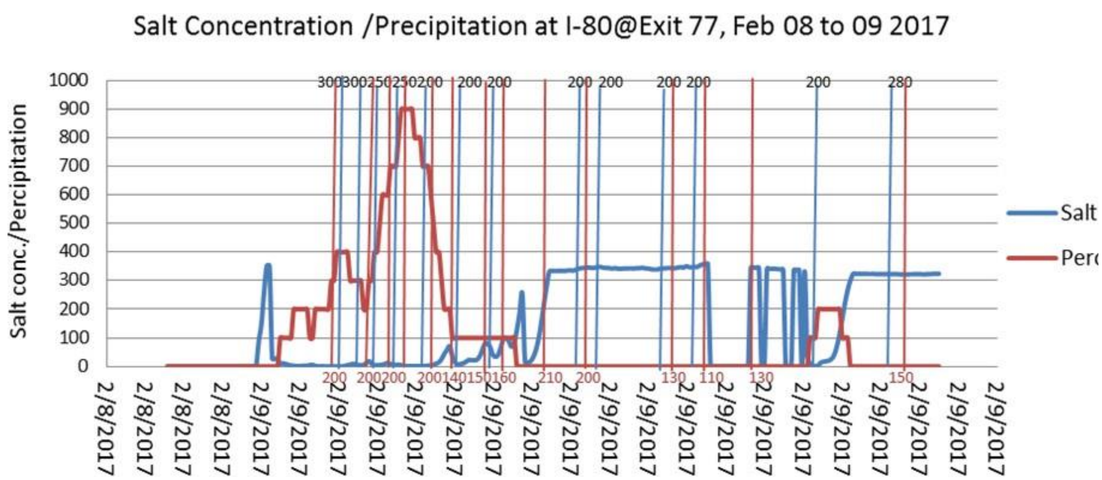


Figure 3.4.2 Salt concentration (g/L) and precipitation variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at I-80 @ Exit 77.

For this event, the precipitation was heavy, with the precipitation value of 0.9 in. The salt concentration was between 0~ 350 g/L. There were 3 trucks passing this site, they are 0850-547-8077, 0850-389-8077 and 0850-324-8077. They passed this site 30 times within 24 hours. Although the precipitation was heavy from 1:12 to 8:00 am on Feb 09, 2017, the salt concentration recovered to a high level at around 9:00. This means the frequent deicer applications were very effective.

4. Conclusions

Specific conclusions for each site:

4.1 Site I-80@ Exit 35, MP 37 – AquaSalina;

There are 7 snow events at site I-80@ Exit 35, MP 37. For all events at this site, the surface temperature and air temperature have similar trend during 24 hours. The underground sensor was for salt concentration. The salt concentration and precipitation have a generally opposite trend during the 24 hours. In some cases, it was too dark to collect on-road real-time images from the RWIS system (camera history). During snow precipitations at this site, despite the fact that there was constant precipitation, the deicer applications were clearly effective in removing surface snow, however, that performance did not seem to be reflected in the measured salt concentrations, which lead us to question the usefulness of the parameter salt concentration in accessing deicer performance.

Reference site: I-79@MP 136 Crawford/Mercer line – Rock Salt.

There are 4 snow events for this site. The underground sensor was designed for grip levels. The recorded grip level values hold a close relationship with the precipitation during the entire snow event. For the melted%, after the deicer application, the melted percentage increased significantly to 100% within about 60~90 min. Also, there is a very similar trend between grip level and melted% during the snow events. Therefore, the grip level can be considered as a potentially effective indicator of melted percentages and deicer performance.

4.2 Site I-79@ Exit 88 – BEET HEET;

There are five snow events at site I-79@ Exit 88. The underground sensor was designed for salt concentration. Generally when the precipitation level increased, the salt concentration decreased accordingly. After several applications, the melted percentage remained 100%, which indicated the deicer applications were effective, again not reflected by the reported salt concentration.

Reference site: I-79@MP 100.

There was one snow event at this site reference site. The underground sensor was designed for salt concentration. The salt concentration and precipitation have an opposite trend generally during the 24 hours. The salt concentration had fluctuations to some degree, with reasons unknown. After the precipitations stopped, the melted% recovered to 100% effectively within around 25 min.

4.3 Site I-81@ Exit 223 New Milford - BEET HEET and the reference site I- 81@Exit 211 Lenox

There is one snow event for site I-81 @ Exit 223 New Milford & reference site I- 81@Exit

211 Lenox. There is an obvious trend that when the precipitation increased, the grip level decreased significantly. Therefore, this is a strong evidence that the grip level and precipitation have a good correlation.

4.4 Site I-81@Exit 77, Manada Hill – Magic minus zero and reference site I-81@ I- 78 Split.

There was one snow event at the Reference site I-81@Exit 77. The underground sensor was designed for salt concentration. Although the precipitation was heavy from 1:12 to 8:00 am on Feb 09, 2017, the salt concentration recovered to a high level at around 9:00. That means the deicer application was very effective.

Overall, we can reach the following conclusions and recommendations:

a). The surface temperature and air temperature have similar trend during 24 hours. Usually in the morning, the temperature is the lowest, while in the afternoon around 14:00 it is the highest.

b). When there was precipitation, the grip levels during these time periods decreased dramatically, but recovered after deicer applications. The grip level values closely correlated with both precipitation and snow melted% during the snow events.

c). After the deicer applications, the melted percentages increased significantly to 100% within a short period of time, which means the deicers worked well, however, we need to collect data from additional events to evaluate the differences among the various deicers.

d). The salt concentration has trend opposite to the precipitation, however, the salt concentration level fluctuated within a wide range, with unknown reasons, Therefore, we suggest to replace all the salt concentration sensors by grip level sensors, which perform more consistently and correlates well with melted%.

e). Photo recording can be impaired by many factors, such as the light conditions (e.g. researchers cannot judge the snow conditions on the road at night) and blurry camera, on the other hand, the grip level has a good relationship with the melted%. Therefore, we believe the melted% might be advantageously replaced by the grip level. We will continue to evaluate the effectiveness of the grip level as a deicer performance indicator, in place of melted%, in future field tests.

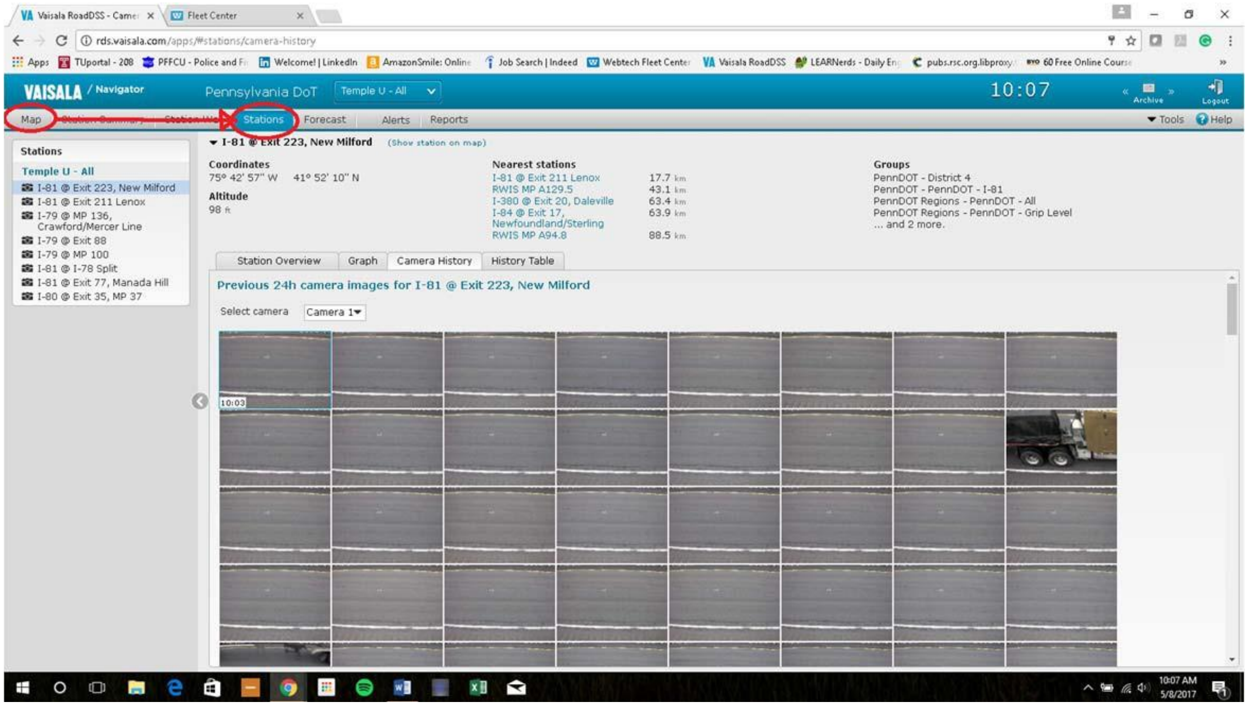
Appendix I: procedure to collect data from RWIS and AVLs

Part Two: Experimental Methods –

1. RWIS Data Collection –
    a. Log in to **RWIS** using the provided Username and Password.
    b. From the **Home: Map Tab**, left click on the **Stations Tab** and select the site that is

being observed.

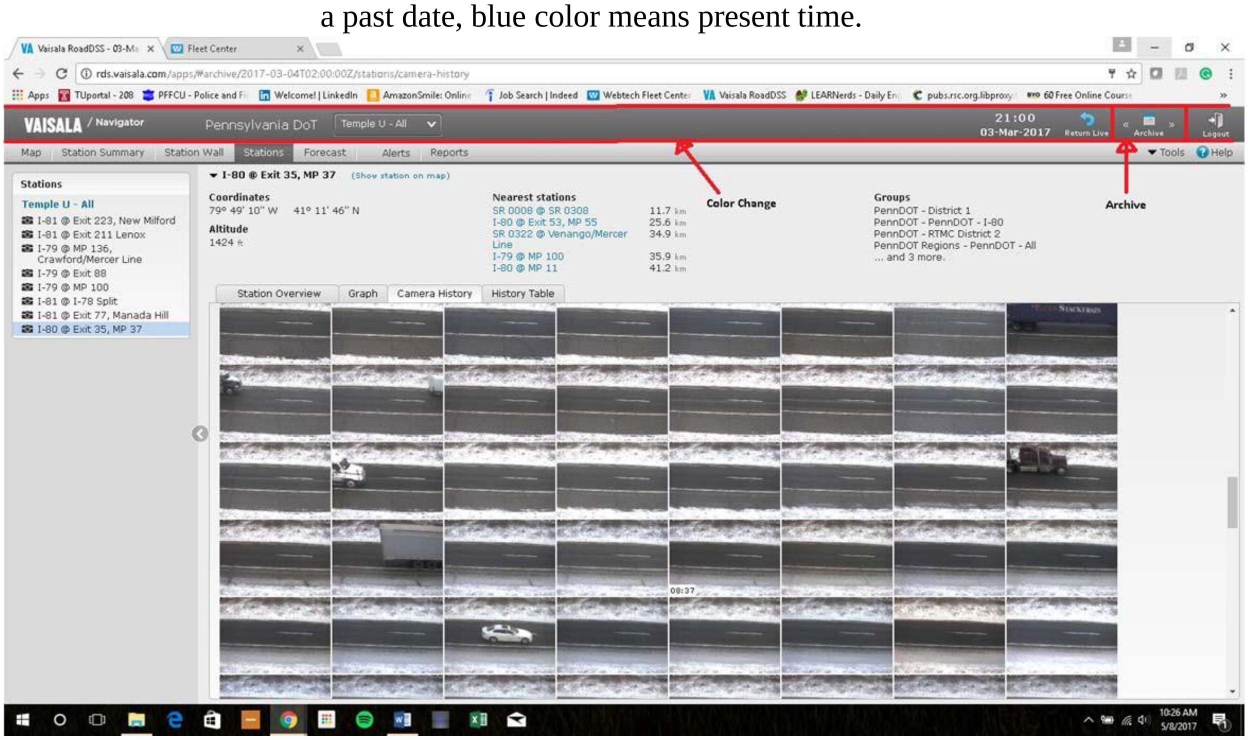
i. Sites can be found in the **Stations** menu on the left side of the screen.



c. After selecting a site, change the date on the RWIS site to the date of the observed winter storm event.

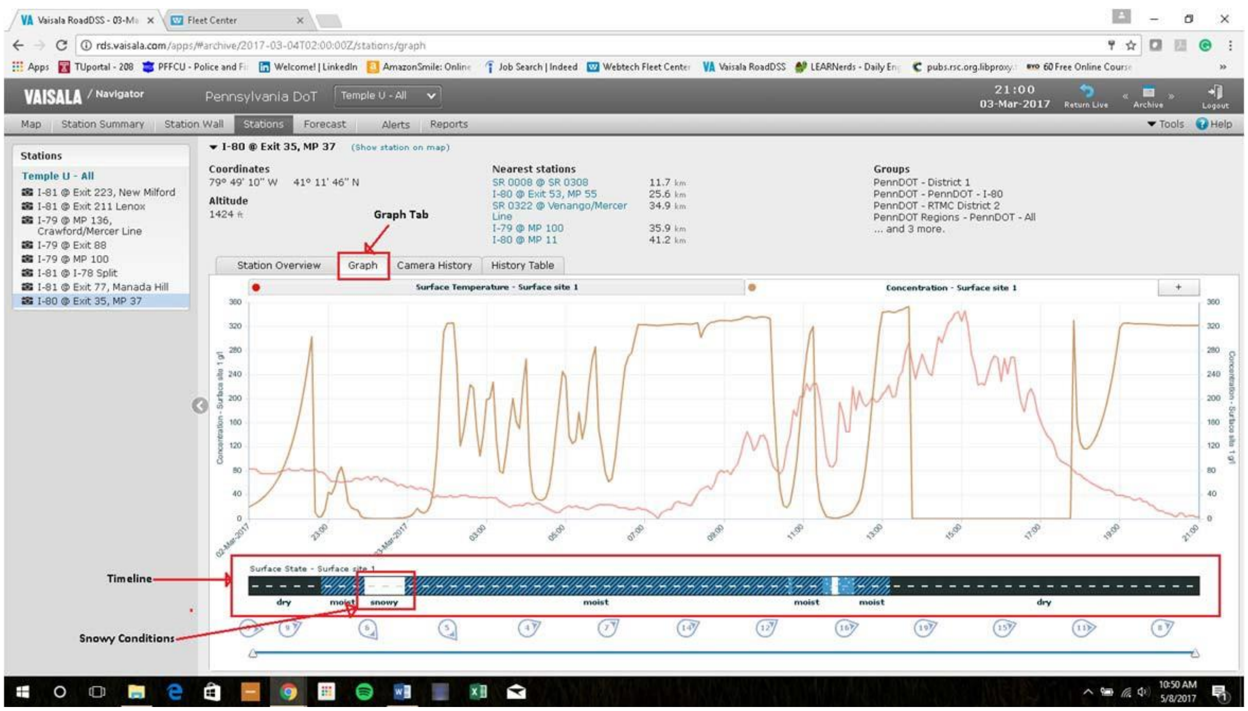
i. Dates can be changed by selecting the **Archive Calendar Symbol** in the top right of the screen.

ii. The blue bar on the top of the screen will change color to gray when looking at a past date, blue color means present time.

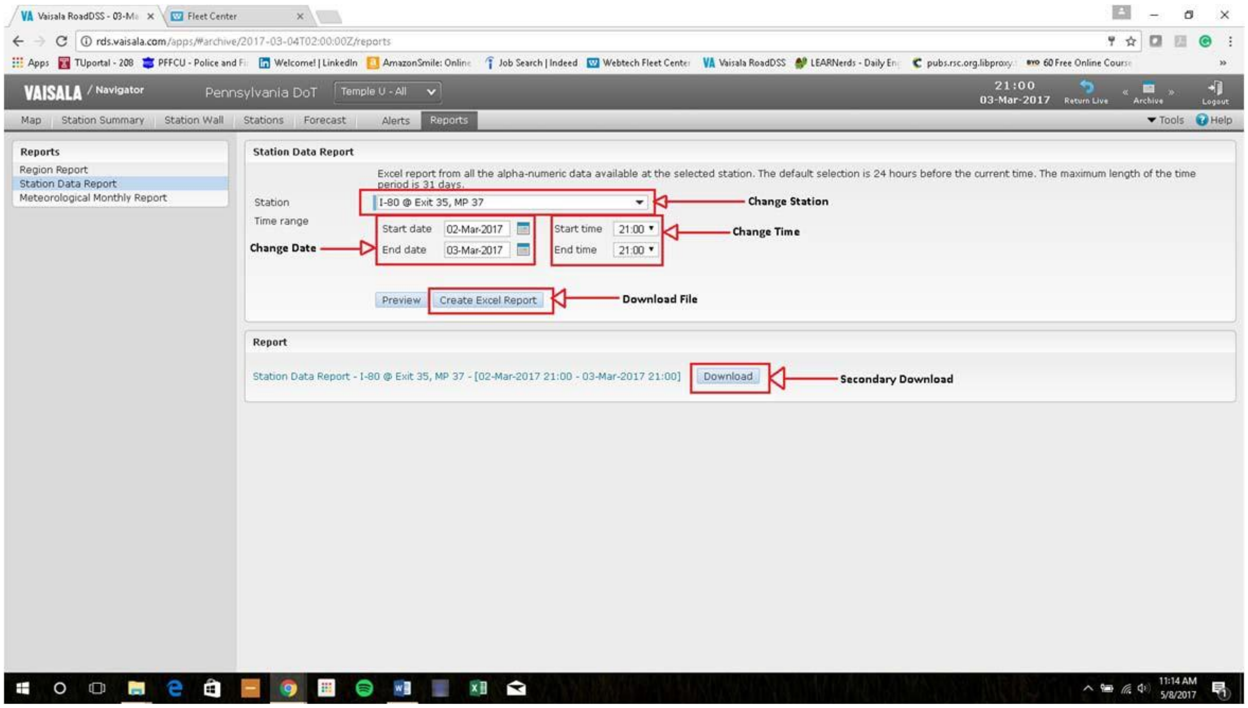


d. While in the **Station Tab** select the **Graph Tab** below the station data. Observe the timeline below and adjust the time with the **Archive** button.

i. The time should be adjusted to 1 hour before "snowy" conditions are seen, or 1 hour before a salt truck passes a point.

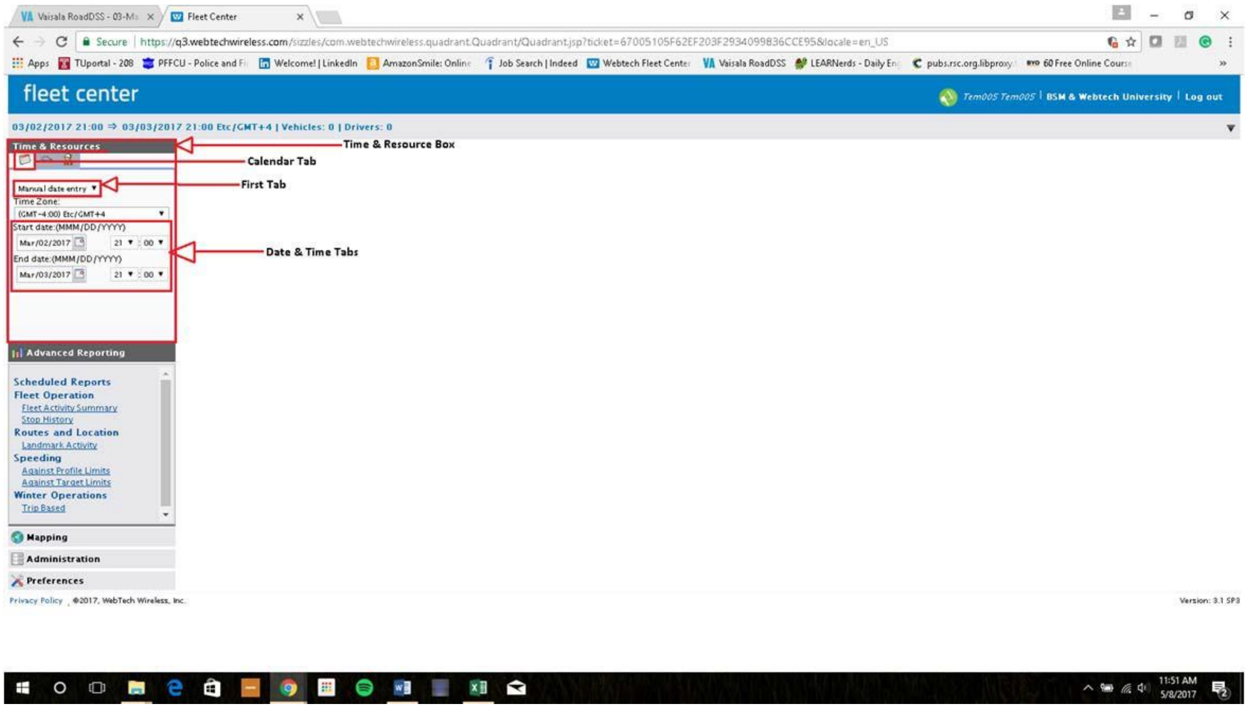


Next, select the **Reports Tab**, change the station to the one being observed and change the timeline to the one being used. Then left click **Create Excel Report**, the download of the excel file should start automatically, but if it does not click the **Download Button** that appears.



e. Once the excel file is saved to the user's computer open up the **AVL "Fleet Center"** website.

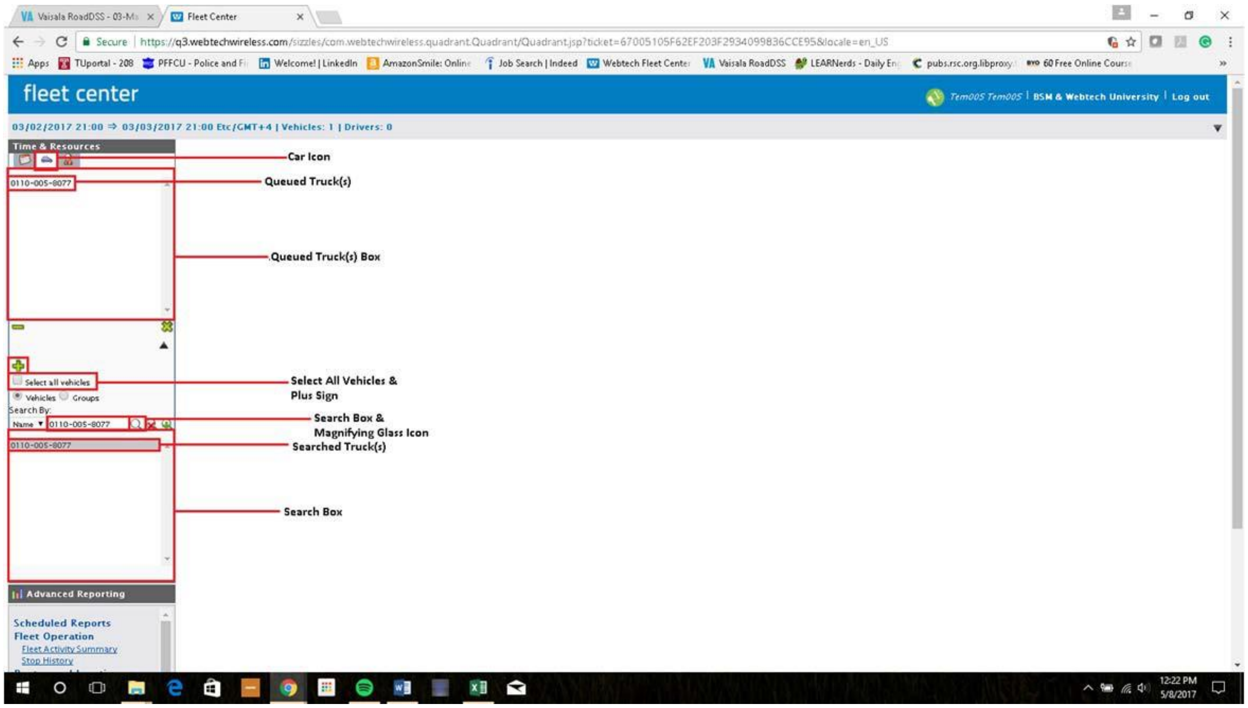
2. AVL Data Collection –
   a. Log into **AVL "Fleet Center"** using the provided Username and Password.
   b. When Fleet Center first opens look for the **Time & Resources Box**. In that box, there will be a **Calendar Tab** which will allow the user to change the dates to the specified dates and times. In the **Calendar Tab** change the first tab to **Manual Data Entry**, new tabs should appear to let the user change the **time zone**, **start date**, **end date** and **time**.
      i. Start Date, End date and the times should be changed to the same dates and times as the RWIS Excel File that was previously downloaded.
      ii. Time zone should remain as is.



c. After selecting the proper time and date, select the next tab with the **Car Icon**. In this tab, the user will be selecting the trucks that are present at the site during the time period.

   i. If the truck number is already known, the truck number can be typed into the search box in the **Car Tab**. Then click the **Magnifying Glass Icon** to search for the truck. Once the search is complete double click the truck number that appears to add it to the box above. If a second truck is needed, click the drop down tab and repeat the steps above for the second truck.

   ii. If the trucks present at the site are unknown. Click the check box designated **Select All Vehicle**, then click the **Green Plus Sign** above the check box. This will add all known trucks to the box above.



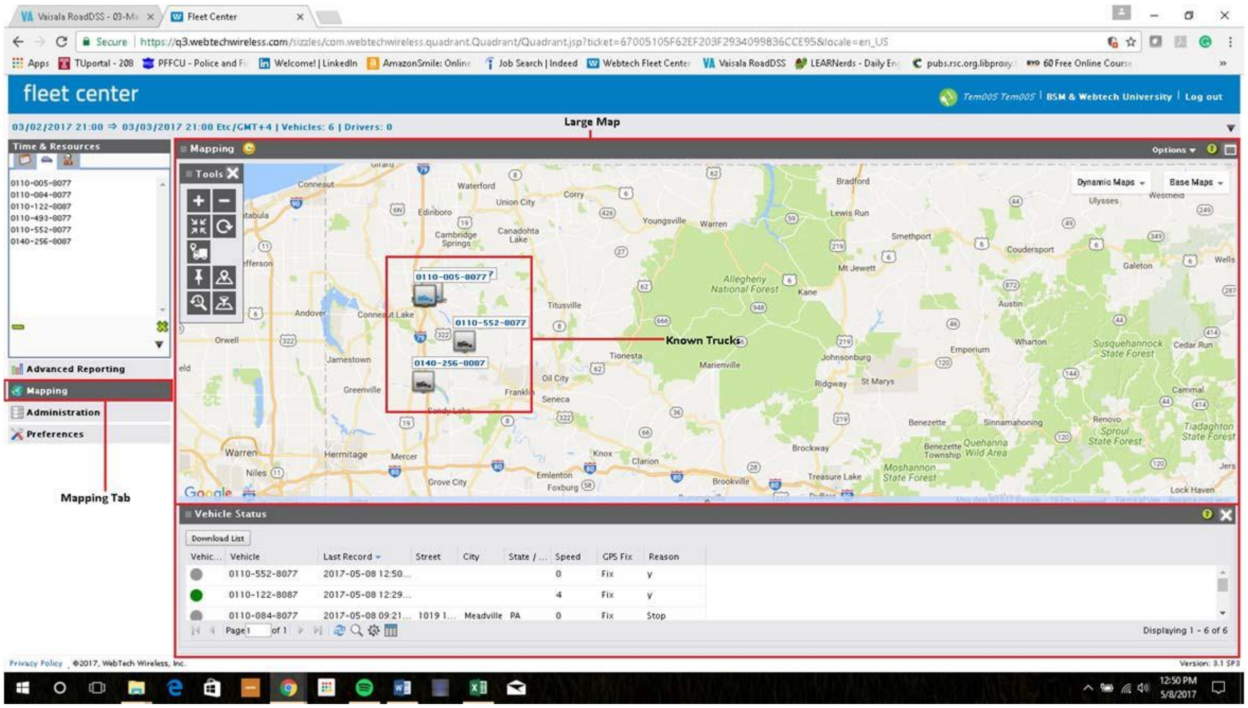
d. Once all of the trucks needed have been added to the queue, click on the **Mapping Tab** found on the left side of the screen. In the **Mapping Tab,** the user will find a **large map of the earth** on the top and a **vehicle status bar** underneath. The user will be using this tab to find the trucks' locations and see the routes taken during the winter storm event.

   i. If the trucks in the **queue trucks box** were known then the map will automatically zoom in to encompass all of the known trucks.

   ii. If the trucks were unknown, the user will have to zoom in on the area at which the RWIS station is found.

      1. To find the location of the RWIS station go to RWIS site, find the station and take the coordinates of the station from the station's information. They will be marked **Coordinates**.

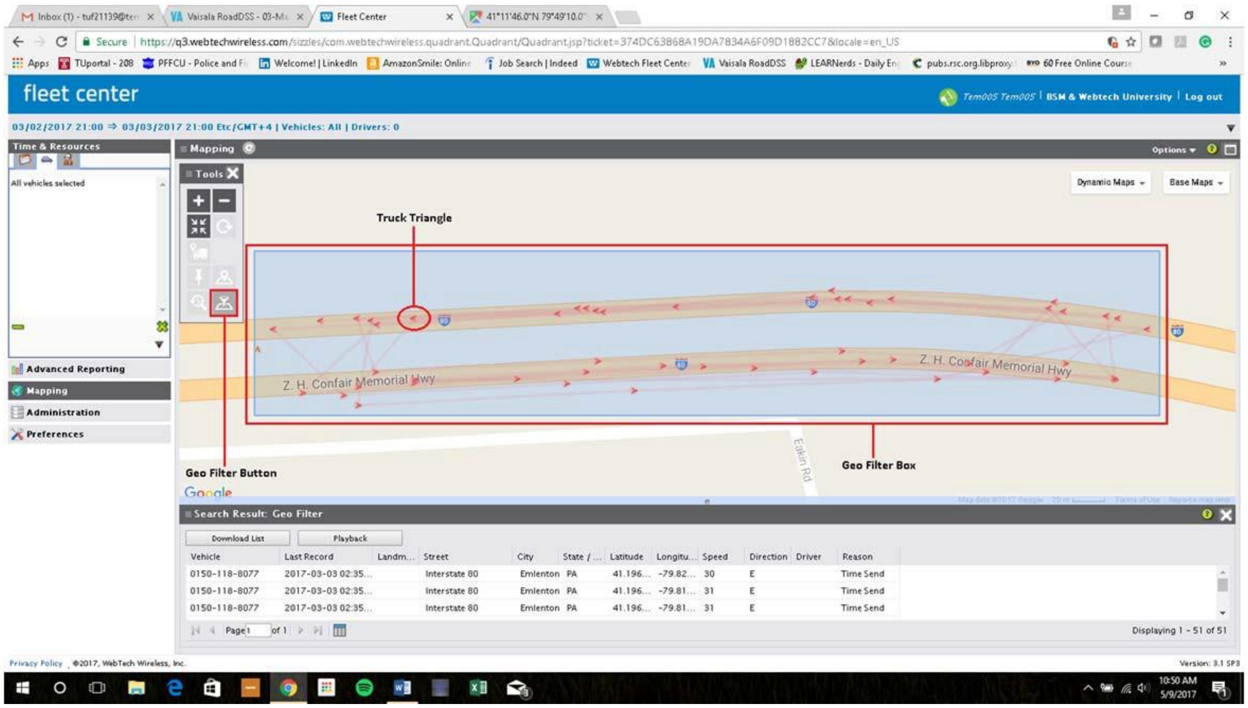
      2. Copy the coordinates into google maps and the station's location will appear. Then find that location on the AVL map.



e. If the trucks are unknown: **All vehicles** will be selected in the **queue box**, and all of the vehicles will appear on the map. The user will then find the location of the site through the method above. Once the site has been found the user will use the **Geo Filter** command to search for all know trucks that pass the site.

   i. Since the **Geo Filter** command is searching through all known trucks it may take some time to finish its search.

   ii. When the search has completed trucks coordinates will appear inside the **Geo Filter** box in the form of colored triangles. Different colored triangles indicated different trucks, while the direction of the triangle indicates the direction of the truck.

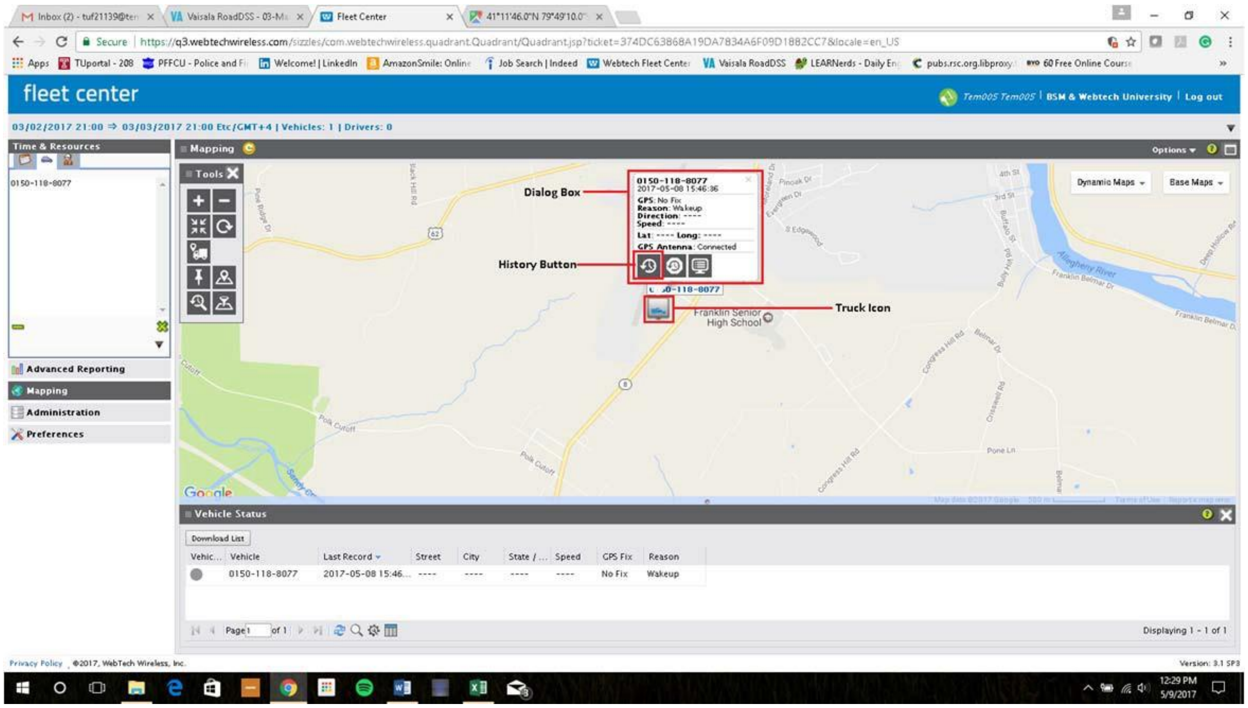


f. After finding all of the trucks that pass the site through **Geo Filter**, the user will use an excel sheet or a notepad to record all of the truck numbers that pass the site.

g. Once all of the trucks have been recorded the user will go back to **Step C** and input all of the found trucks into the queue box and remove the **All Vehicles Selected** option. Then follow the "known trucks" instructions up to **Step D**.

h. With all the known trucks on the map, the user will now select a **truck icon** and access its history. This is done by left clicking on a truck which will make a **dialog box** appear above the truck. In this dialog box, the **History Button** will be selected to get the trucks history.

   i. When the history button is selected it may take a moment for the history to load.

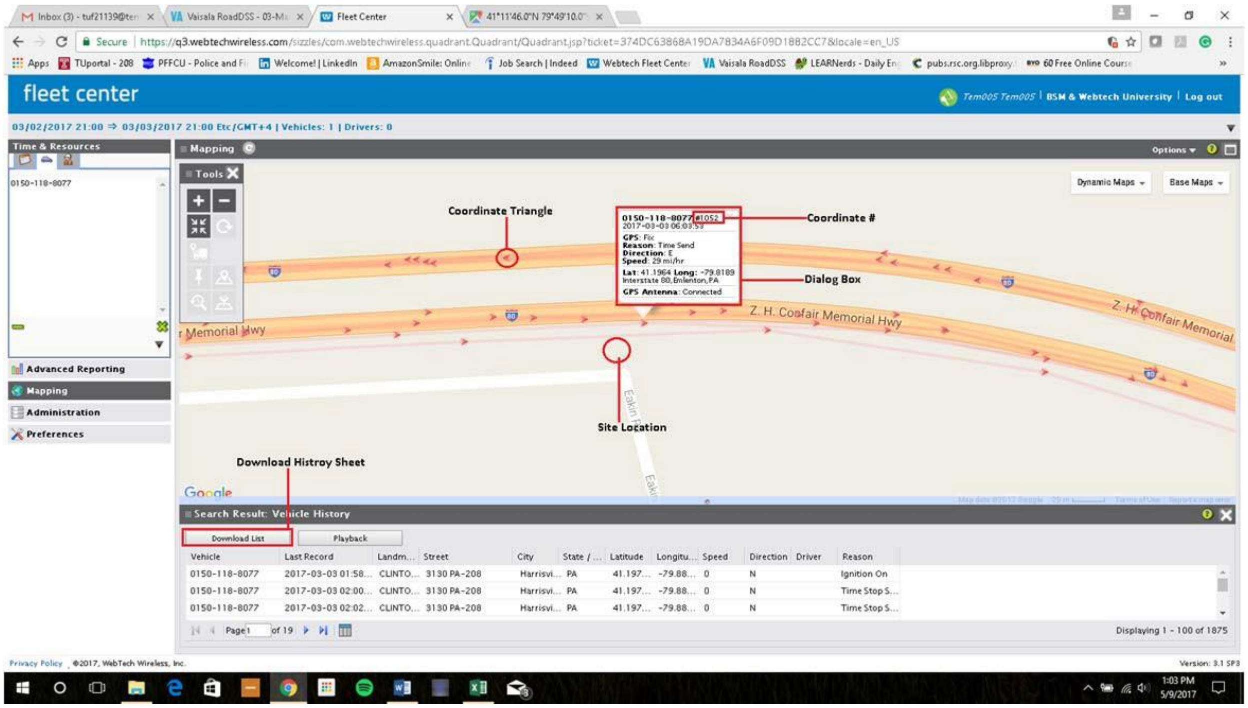


i. A trucks history will appear on the map in the form of colored triangles connected by lines of the same color. In order to get the proper coordinates, the map should be focused on the RWIS stations coordinates.

   i. If the road being examined has separated lanes then the user will note which side of the road the RWIS station is focused on. The side of the road that is the focus is the side of the road that the coordinate triangles are collected. If the road is not separated then all points, in both directions, should be collected.

   ii. The information to collect from each **coordinate triangle** can be accessed by left clicking on the triangle. When the **dialog box** appears over the triangle the **Coordinate #** is to be recorded. The **coordinate #** will correlate to a number found in the trucks history excel sheet.

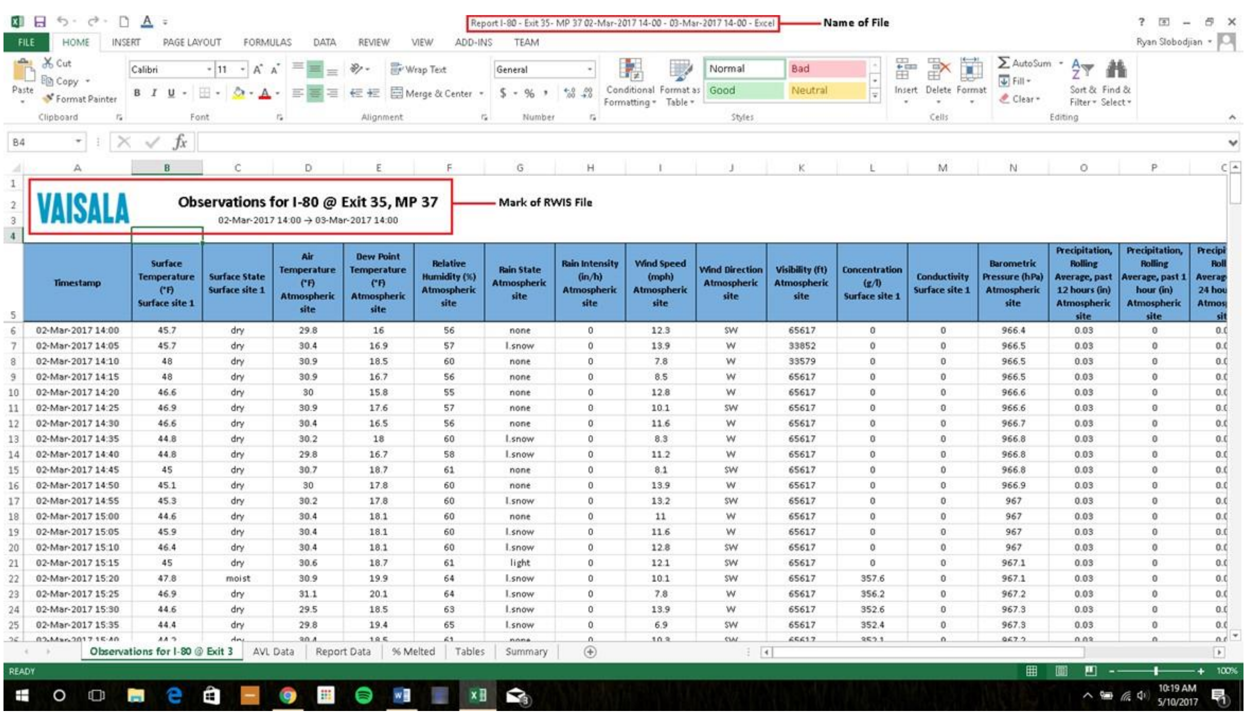
   iii. After recording all of the **coordinate #**’s that correlate with a passing of the site, the user will download the trucks history excel sheet and save it to their computer. The history sheet can be downloaded by clicking the **download list button**.



j. Once all of the truck coordinate #'s and truck history excel sheets have been collected it is time for the user to populate the RWIS station excel sheets with the data obtained.

1. Populating the RWIS Excel Sheets with Data –

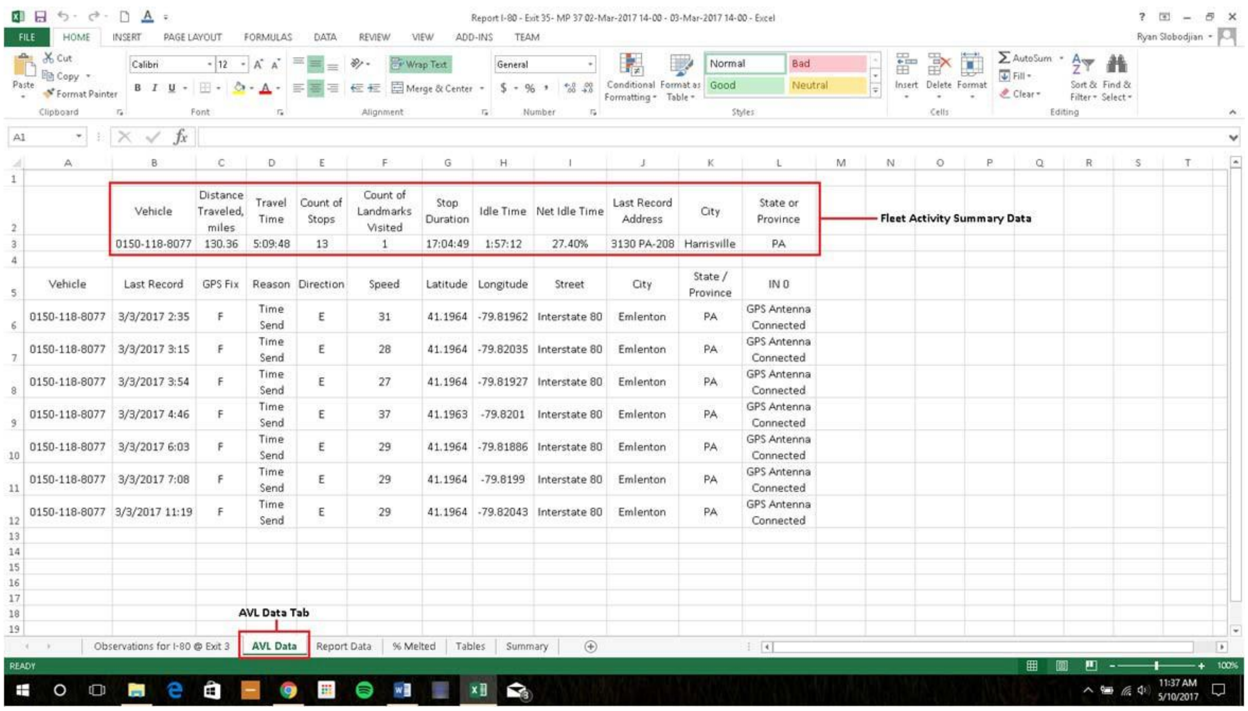
   a. The user should first open the RWIS Excel sheet that contains the station's data. The excel sheet will have a file name of "**Report – Station – Day1 – Month1 – Year – Day2 – Month2 – Year**".



b. In the excel file, there will be 6 tabs, 5 of those tabs will have to be made and populated by the user. The excel files are **Observations for Station X**, **AVL Data**, **Report Data**, **% Melted**, **Tables**, and **Summary**. The **Observations for Station X** tab will already have data in it from RWIS.

c. **AVL Data Tab**: The **AVL Data Tab** consist of all of the salt truck activity that happened the day of the winter storm event at the RWIS site. The following steps detail how to populate the tab.

   i. Step 1: Obtain each vehicle travel data by accessing it from **AVL "Fleet Center"**. The data can be found by clicking the **Advanced Reporting Tab**, then clicking **Fleet Activity Summary**. The summary that appears should be copied and pasted into the RWIS excel sheet.

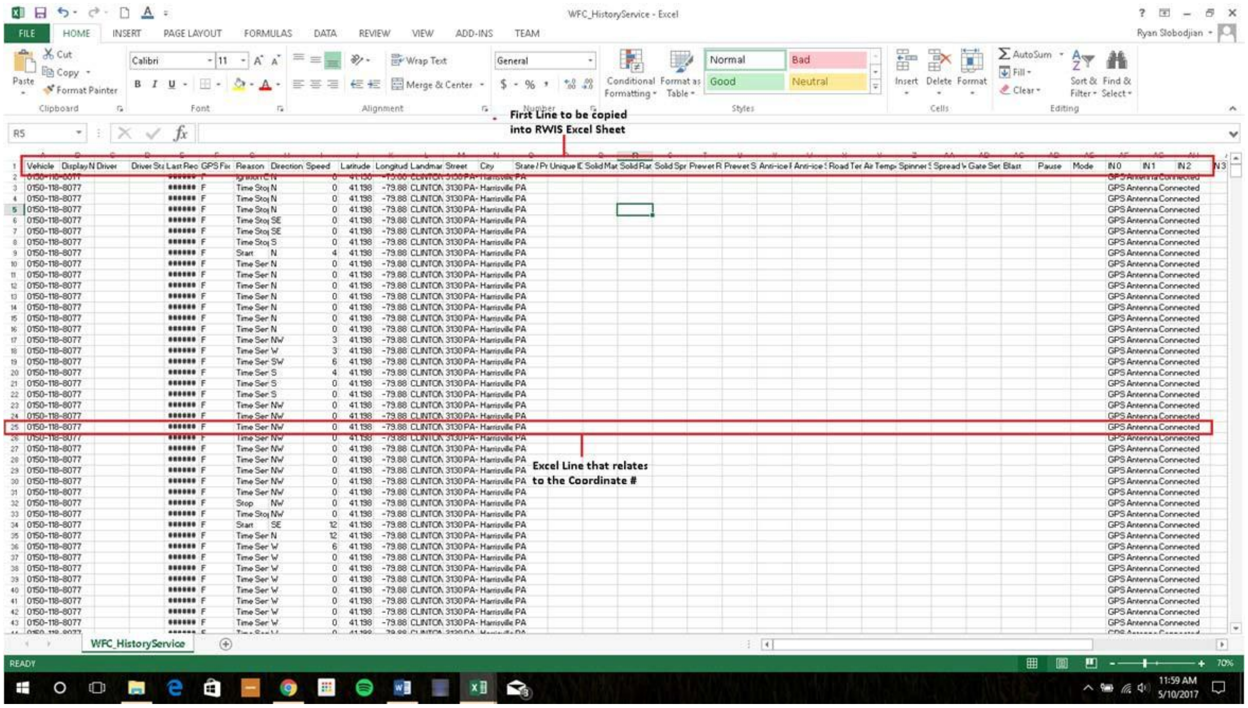


Vehicle	Distance Traveled, miles	Travel Time	Count of Stops	Count of Landmarks Visited	Stop Duration	Idle Time	Net Idle Time	Last Record Address	City	State or Province
0150-118-8077	130.36	5:09:48	13	1	17:04:49	1:57:12	27.40%	3130 PA-208	Harrisville	PA

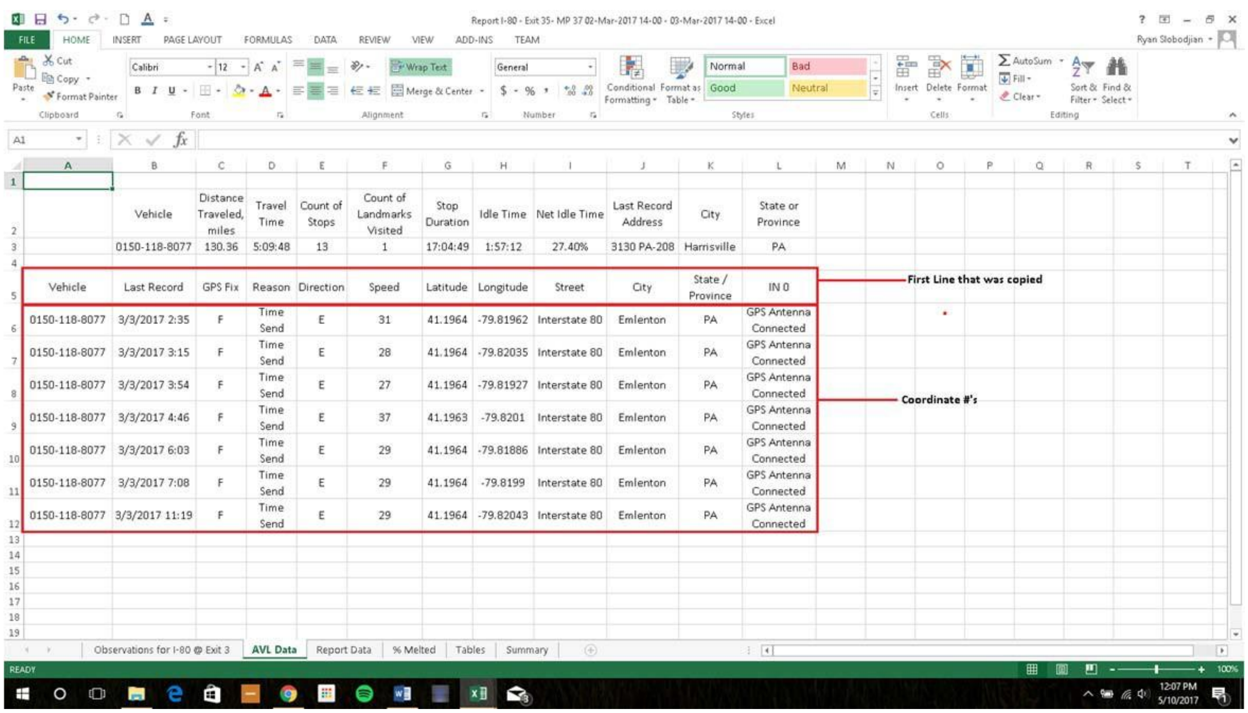
Vehicle	Last Record	GPS Fix	Reason	Direction	Speed	Latitude	Longitude	Street	City	State / Province	IN 0
0150-118-8077	3/3/2017 2:35	F	Time Send	E	31	41.1964	-79.81962	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 3:15	F	Time Send	E	28	41.1964	-79.82035	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 3:54	F	Time Send	E	27	41.1964	-79.81927	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 4:46	F	Time Send	E	37	41.1963	-79.8201	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 6:03	F	Time Send	E	29	41.1964	-79.81886	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 7:08	F	Time Send	E	29	41.1964	-79.8199	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 11:19	F	Time Send	E	29	41.1964	-79.82043	Interstate 80	Emlenton	PA	GPS Antenna Connected

   ii. Step 2: The user will now input the data that corresponds to truck passes at the RWIS site. This data can be found in the truck history excel files that were downloaded from AVL in prior steps. The user will open the file that correlates to the truck working at the site. Then the first line from the history will be copied into the RWIS excel sheet. After that, the **coordinate #'s**, that were previously collected, will be used to find the data in the history excel sheet that relates to a truck passing the site.

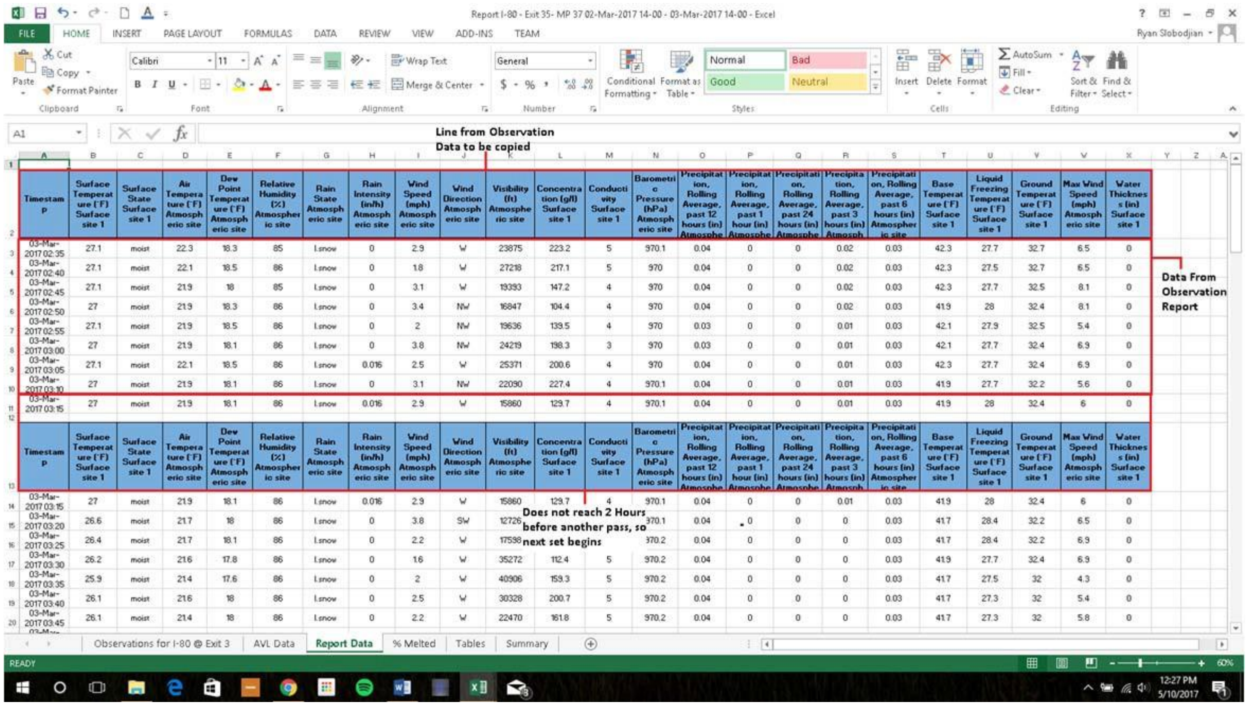
      1. **Coordinate #'s** in the history excel sheet will be that **#+1**, this is due to the first line in the excel sheet being used to identify data.
      2. In the photo below the example **coordinate #** is **24**, so the excel line that should be copied into the RWIS excel sheet should be **25**.



3. The data from the **Truck History Excel File** will be copied into the **AVL Data Tab** in the following format:



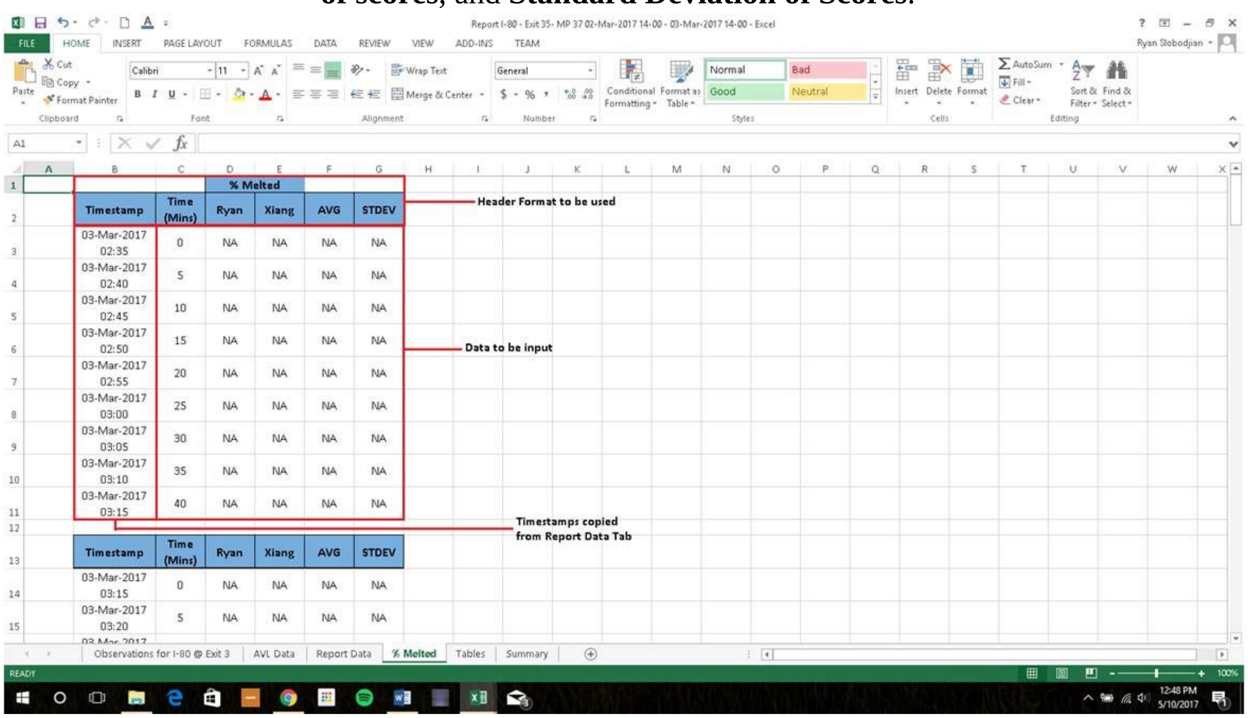
d. **Report Data Tab**: The **Report Data Tab** consist of the data from the **Observations for Station X Tab** that is collected from each pass the truck makes, up for 2 hours after. If another truck, or the same truck, passes the site again before 2 hours has passed then data will be collected up to that pass. The data will be organized similarly to the photo below:



Timestamp	Surface Temperature (°F) Surface site 1	Surface State Surface site 1	Air Temperature (°F) Atmospheric site	Dew Point Temperature (°F) Atmospheric site	Relative Humidity (%) Atmospheric site	Rain State Atmospheric site	Rain Intensity (in/h) Atmospheric site	Wind Speed (mph) Atmospheric site	Wind Direction Atmospheric site	Visibility (ft) Atmospheric site	Concentration (g/l) Surface site 1	Conductivity Surface site 1	Barometric Pressure (hPa) Atmospheric site	Precipitation, Rolling Average, past 12 hours (in) Atmosphe	Precipitation, Rolling Average, past 1 hour (in) Atmosphe	Precipitation, Rolling Average, past 24 hours (in) Atmosphe	Precipitation, Rolling Average, past 3 hours (in) Atmosph	Precipitation, Rolling Average, past 6 hours (in) Atmospheric site	Base Temperature (°F) Surface site 1	Liquid Freezing Temperature (°F) Surface site 1	Ground Temperature (°F) Surface site 1	Max Wind Speed (mph) Atmospheric site	Water Thickness (in) Surface site 1
03-Mar-2017 02:35	27.1	moist	22.3	18.3	85	l.snow	0	2.9	W	23875	223.2	5	970.1	0.04	0	0	0.02	0.03	42.3	27.7	32.7	6.5	0
03-Mar-2017 02:40	27.1	moist	22.1	18.5	86	l.snow	0	1.8	W	27218	217.1	5	970	0.04	0	0	0.02	0.03	42.3	27.5	32.7	6.5	0
03-Mar-2017 02:45	27.1	moist	21.9	18	85	l.snow	0	3.1	W	19393	147.2	4	970	0.04	0	0	0.02	0.03	42.3	27.7	32.5	8.1	0
03-Mar-2017 02:50	27	moist	21.9	18.3	86	l.snow	0	3.4	NW	16847	104.4	4	970	0.04	0	0	0.02	0.03	41.9	28	32.4	8.1	0
03-Mar-2017 02:55	27.1	moist	21.9	18.5	86	l.snow	0	2	NW	19636	139.5	4	970	0.03	0	0	0.01	0.03	42.1	27.9	32.5	5.4	0
03-Mar-2017 03:00	27	moist	21.9	18.1	86	l.snow	0	3.8	NW	24219	198.3	3	970	0.03	0	0	0.01	0.03	42.1	27.7	32.4	6.9	0
03-Mar-2017 03:05	27.1	moist	22.1	18.5	86	l.snow	0.016	2.5	W	25371	200.6	4	970	0.04	0	0	0.01	0.03	42.3	27.7	32.4	6.9	0
03-Mar-2017 03:10	27	moist	21.9	18.1	86	l.snow	0	3.1	NW	22090	227.4	4	970.1	0.04	0	0	0.01	0.03	41.9	27.7	32.2	5.6	0
03-Mar-2017 03:15	27	moist	21.9	18.1	86	l.snow	0.016	2.9	W	15860	129.7	4	970.1	0.04	0	0	0.01	0.03	41.9	28	32.4	6	0
Timestamp	Surface Temperature (°F) Surface site 1	Surface State Surface site 1	Air Temperature (°F) Atmospheric site	Dew Point Temperature (°F) Atmospheric site	Relative Humidity (%) Atmospheric site	Rain State Atmospheric site	Rain Intensity (in/h) Atmospheric site	Wind Speed (mph) Atmospheric site	Wind Direction Atmospheric site	Visibility (ft) Atmospheric site	Concentration (g/l) Surface site 1	Conductivity Surface site 1	Barometric Pressure (hPa) Atmospheric site	Precipitation, Rolling Average, past 12 hours (in) Atmosphe	Precipitation, Rolling Average, past 1 hour (in) Atmosphe	Precipitation, Rolling Average, past 24 hours (in) Atmosphe	Precipitation, Rolling Average, past 3 hours (in) Atmosph	Precipitation, Rolling Average, past 6 hours (in) Atmospheric site	Base Temperature (°F) Surface site 1	Liquid Freezing Temperature (°F) Surface site 1	Ground Temperature (°F) Surface site 1	Max Wind Speed (mph) Atmospheric site	Water Thickness (in) Surface site 1
03-Mar-2017 03:15	27	moist	21.9	18.1	86	l.snow	0.016	2.9	W	15860	129.7	4	970.1	0.04	0	0	0.01	0.03	41.9	28	32.4	6	0
03-Mar-2017 03:20	26.6	moist	21.7	18	86	l.snow	0	3.8	SW	12726	[illegible]	[illegible]	970.1	0.04	0	0	0	0.03	41.7	28.4	32.2	6.5	0
03-Mar-2017 03:25	26.4	moist	21.7	18.1	86	l.snow	0	2.2	W	17598	[illegible]	[illegible]	970.2	0.04	0	0	0	0.03	41.7	28.4	32.2	6.9	0
03-Mar-2017 03:30	26.2	moist	21.6	17.8	86	l.snow	0	1.6	W	35272	112.4	5	970.2	0.04	0	0	0	0.03	41.9	27.7	32.4	6.9	0
03-Mar-2017 03:35	25.9	moist	21.4	17.6	86	l.snow	0	2	W	40906	159.3	5	970.2	0.04	0	0	0	0.03	41.7	27.5	32	4.3	0
03-Mar-2017 03:40	26.1	moist	21.6	18	86	l.snow	0	2.5	W	30328	200.7	5	970.2	0.04	0	0	0	0.03	41.7	27.3	32	5.4	0
03-Mar-2017 03:45	26.1	moist	21.4	18	86	l.snow	0	2.2	W	22470	161.8	5	970.2	0.04	0	0	0	0.03	41.7	27.3	32	5.8	0

e. **% Melted Tab**: The **% Melted Tab** is where the researchers will input their scores of the photos collected from RWIS. The tab will follow the format in the photo below:

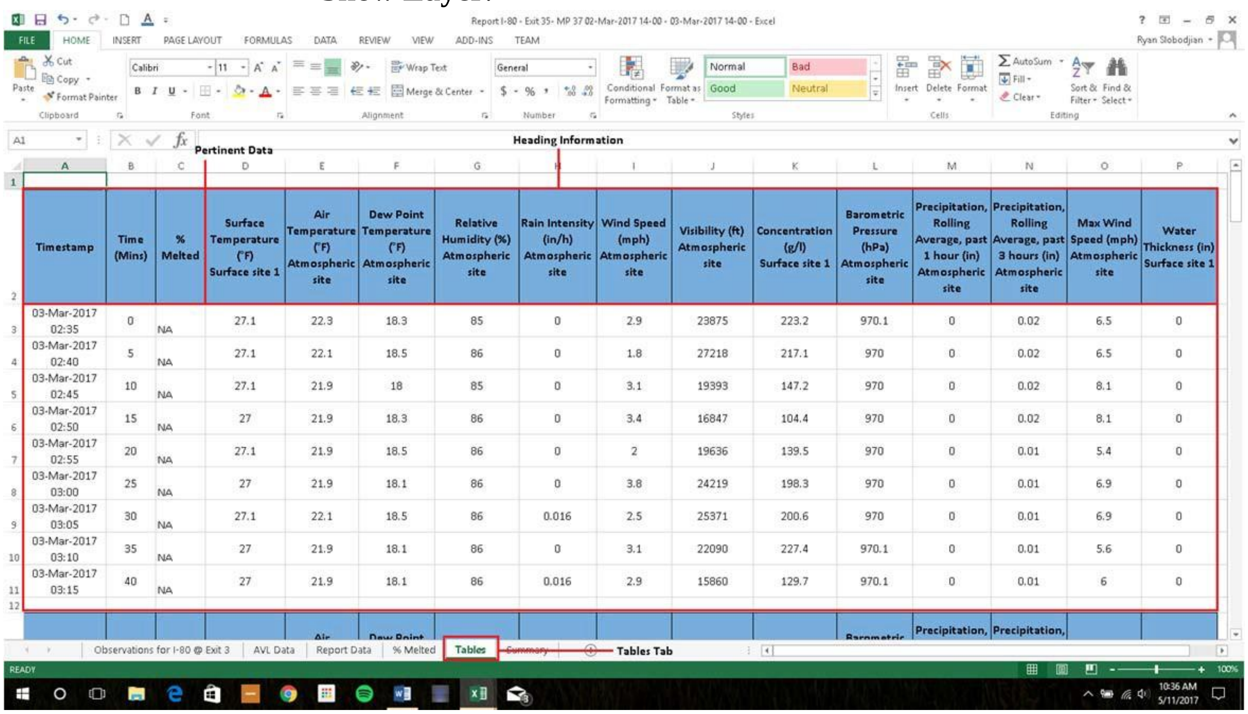
   i. Data to be input consist of **Timestamp**, **Time**, **Researchers Scores**, **Average of scores**, and **Standard Deviation of Scores**.



Timestamp	Time (Mins)	% Melted Ryan	Xiang	AVG	STDEV
03-Mar-2017 02:35	0	NA	NA	NA	NA
03-Mar-2017 02:40	5	NA	NA	NA	NA
03-Mar-2017 02:45	10	NA	NA	NA	NA
03-Mar-2017 02:50	15	NA	NA	NA	NA
03-Mar-2017 02:55	20	NA	NA	NA	NA
03-Mar-2017 03:00	25	NA	NA	NA	NA
03-Mar-2017 03:05	30	NA	NA	NA	NA
03-Mar-2017 03:10	35	NA	NA	NA	NA
03-Mar-2017 03:15	40	NA	NA	NA	NA
Timestamp	Time (Mins)	Ryan	Xiang	AVG	STDEV
03-Mar-2017 03:15	0	NA	NA	NA	NA
03-Mar-2017 03:20	5	NA	NA	NA	NA

f. **Tables Tab**: The **Tables Tab** consist of all of the pertinent information from all of the previous tabs. Its format is exactly the same as the **Report Data Tab** but with less of the extra information. The information included in the **Tables Tab** is as follows: **Timestamp**, **Time**, **% Melted**, **Surface Temp**, **Air Temp**, **Dew Temp**, **Relative Humidity**, **Rain Intensity**, **Wind Speed**, **Visibility**, **Concentration**[i], **Barometric Pressure**, **Precipitation Rolling Average 1 Hour**, **Precipitation Rolling Average 3 Hours**, **Max Wind Speed**, **Water Thickness**[i]**.**

   i. **Concentration** and **Water Thickness** are only measured at some of the RWIS Sites. At other sites, they will be exchanged for **Level of Grip**, **Ice Layer,** and **Snow Layer**.



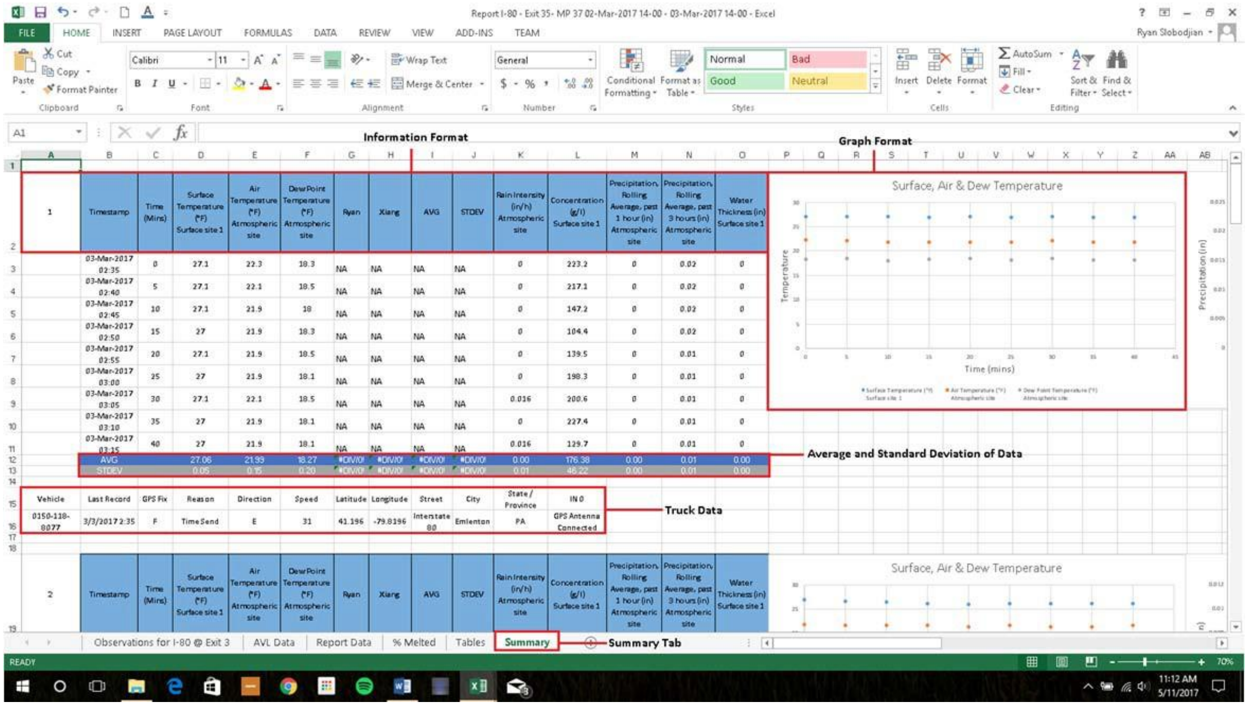
Timestamp	Time (Mins)	% Melted	Surface Temperature (°F) Surface site 1	Air Temperature (°F) Atmospheric site	Dew Point Temperature (°F) Atmospheric site	Relative Humidity (%) Atmospheric site	Rain Intensity (in/h) Atmospheric site	Wind Speed (mph) Atmospheric site	Visibility (ft) Atmospheric site	Concentration (g/l) Surface site 1	Barometric Pressure (hPa) Atmospheric site	Precipitation, Rolling Average, past 1 hour (in) Atmospheric site	Precipitation, Rolling Average, past 3 hours (in) Atmospheric site	Max Wind Speed (mph) Atmospheric site	Water Thickness (in) Surface site 1
03-Mar-2017 02:35	0	NA	27.1	22.3	18.3	85	0	2.9	23875	223.2	970.1	0	0.02	6.5	0
03-Mar-2017 02:40	5	NA	27.1	22.1	18.5	86	0	1.8	27218	217.1	970	0	0.02	6.5	0
03-Mar-2017 02:45	10	NA	27.1	21.9	18	85	0	3.1	19393	147.2	970	0	0.02	8.1	0
03-Mar-2017 02:50	15	NA	27	21.9	18.3	86	0	3.4	16847	104.4	970	0	0.02	8.1	0
03-Mar-2017 02:55	20	NA	27.1	21.9	18.5	86	0	2	19636	139.5	970	0	0.01	5.4	0
03-Mar-2017 03:00	25	NA	27	21.9	18.1	86	0	3.8	24219	198.3	970	0	0.01	6.9	0
03-Mar-2017 03:05	30	NA	27.1	22.1	18.5	86	0.016	2.5	25371	200.6	970	0	0.01	6.9	0
03-Mar-2017 03:10	35	NA	27	21.9	18.1	86	0	3.1	22090	227.4	970.1	0	0.01	5.6	0
03-Mar-2017 03:15	40	NA	27	21.9	18.1	86	0.016	2.9	15860	129.7	970.1	0	0.01	6	0

g. **Summary Tab**: In the **Summary Tab** the user will input the important information from the **Table Tab** and create graphs displaying the information. The information consists of **Timestamp**, **Time**, **Surface Temp**, **Air Temp**, **Dew Temp**, **Researchers Visual Scores**, **Average of Visual Scores**, **Standard Deviation of Visual Scores**, **Rain Intensity**, **Concentration**[i], **Precipitation Rolling Average 1 Hour**, **Precipitation Rolling Average 3 Hours** and **Water Thickness**[i]**.**

   i. **Concentration** and **Water Thickness** are only measured at some of the RWIS Sites. At other sites, they will be exchanged for **Level of Grip**, **Ice Layer,** and **Snow Layer**.

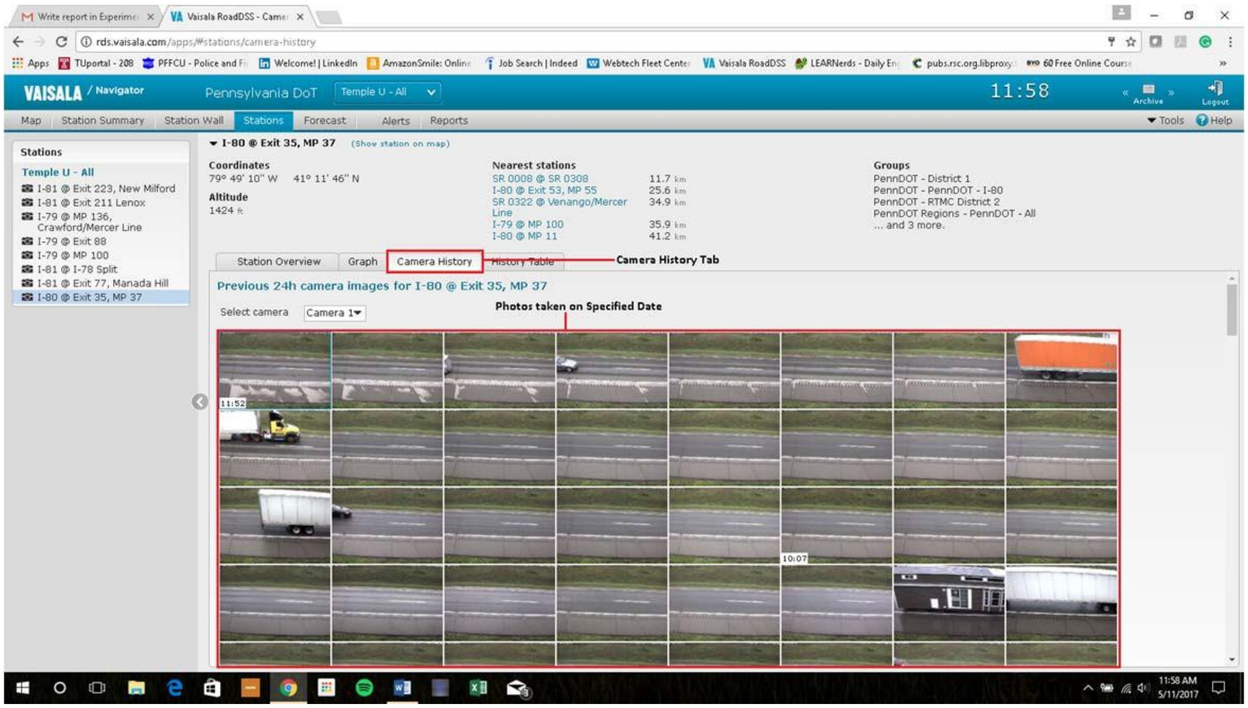
   ii. The **Surface Temp**, **Air Temp** and **Dew Temp** will be combined in one graph. The **Precipitation Rolling Average 1 Hour** and the **Precipitation Rolling Average 3 Hours** are to be combined into one graph as well. All other data will have its own graph to represent it.

   iii. Averages and Standard Deviations of all data will be included below the data, below that the data's truck information will be displayed as well.



1. Collecting Photos From RWIS –
    a. Go back to Section 1: **RWIS Data Collection** and then follow the instructions in that section to **Step d**. After completing **Step d**, click on the **Camera History Tab**. In this tab, the user will see all of the photos taken at the site over a 24 hour period, photos are taken every 5 minutes.

i. If the user attempts to collect photos to long after the storm event it is possible that RWIS will take the photos off the site, and the photos will be unavailable. It is recommended that the user collects the photos from RWIS before a month of time, since the storm event, has passed.



b. The user should now record, either in an excel sheet or notebook, the timelines to collect photos.

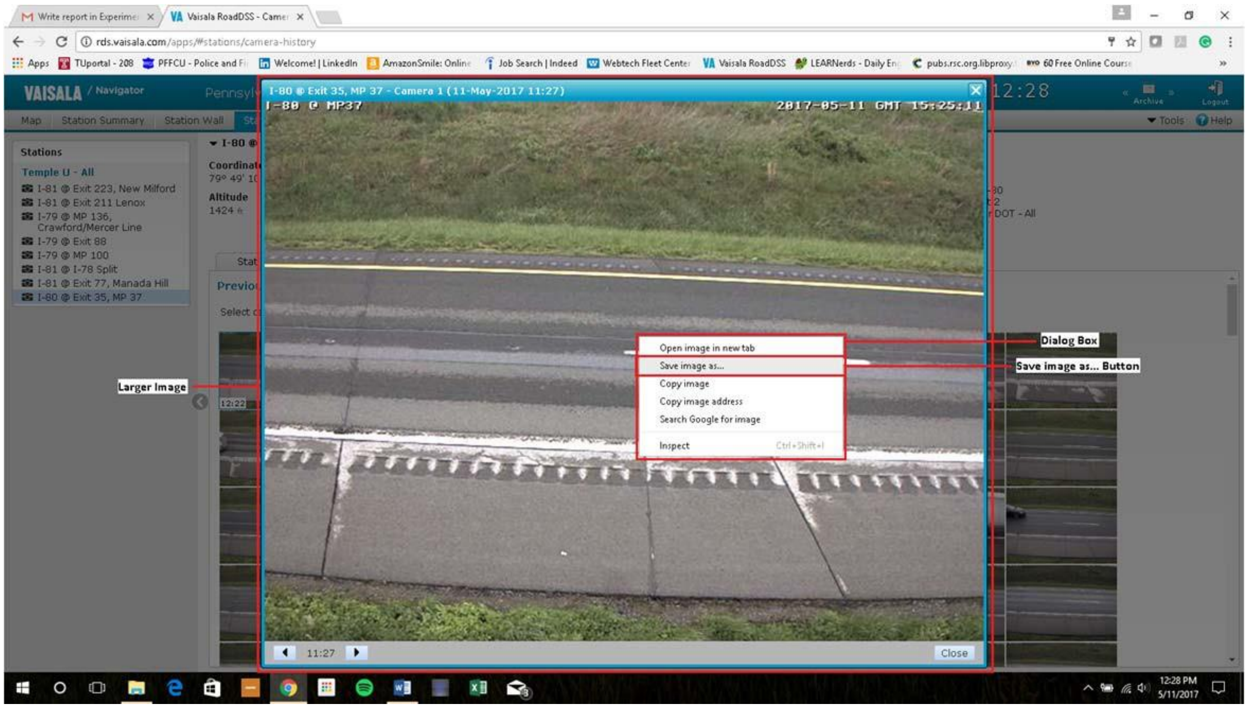
c. With the timelines known, the user will start downloading the photos from RWIS using the following method:

i. Left-click of the needed photo, this will bring a large image of the photo up. Then right-click on the photo to bring up a **dialog menu**, in this menu the user will click "**Save image as…"** The user will then save the image to their computer.

ii. When saving the image the following naming format will be used, **Time – Date – Station**. Ex. **07-35 03-03-17 I-80 Exit 35**.

iii. This Process will be done for each image needed.

iv. The user will not need to save any images that are blurry or are taken at night. These photos will be marked as "**NA**" in the **% Melted Tab** of the RWIS Excel Sheet.



d. Notes –

i. All computer programs and actions were using with Windows Operating System and Chrome Internet Browser. Using a different type of operating system (Mac, Linux) or a different web browser may provide different results, need extra steps or different commands.

CONTRACT NO. 4400011166
TEM WO 005
DELIVERABLE 3.2 FINAL REPORT TO INCLUDE DEICER PERFORMANCE DURING REAL-TIME ROADWAY TESTING

JANUARY 30, 2018

SUMMARY

In this part of the study, on-road real-time field tests were conducted to evaluate the deicer performance on several RWIS observation sites (eight sites were used during the winter 2016-2017 and five sites were used during the winter 2017-2018[1]).

During the winter 2016-2017, four deicers (AquaSalina, Beet Heet, Green Blast, and Magic Minus Zero) were evaluated via paired experiments including each the treatment site (treated with the product tested) and a reference site (treated by the reference product, Rock Salt), thus necessitating eight sites in total. The selected sites were site I-80 @ Exit 35 MP 37 for AquaSalina and site I-79 @ MP 136 Crawford/Mercer Line for the reference (Rock Salt); site I-79 @ Exit 88 for Beet Heet and I-79 @ MP 100 for the reference; site I-81 @ Exit 223 New Milford for Green Blast and site I-80 @ Exit 211 Lenox for the reference; and site I-81 @ Exit 77, Manada Hill for Magic Minus Zero and site I-81 @ Exit 223 New Milford for the reference (Table 2.1). The primary performance indicator for the deicers was the snow melted percentage derived from the photographs taken by on-sites cameras. Additional tentative indicators were the grip level and salt concentration – some sites were equipped with grip level sensors and some with salt concentration sensors. Data collected over the winter 2016-2017 revealed that few events allowed the use of photographs because many storms occurred in the dark or because poor visibility or technical issues. The salt concentration level fluctuated widely and did not correlate well enough with the snow melted percentage. On the other hand, the grip level was identified as a more robust indicator as it correlated well with the snow melted percentage and snow layer. However, only three sites (I-79 @ MP 136 Crawford/Mercer Line – Rock Salt, I-81 @ Exit 223 New Milford – Green Blast, and I-80 @ Exit 211 Lenox – Rock Salt) were equipped with grip level sensors, preventing to perform the complete statistical analysis and product ranking based on the 2016-2017 data.

During the winter 2017-2018, the same four deicers were evaluated using five sites (one site for each of the four products tested, AquaSalina, Beet Heet, Green Blast, Magic Minus Zero, and one site for the reference, Rock Salt). All sites were equipped with grip level sensors, as the grip level was estimated to be a more convenient and consistent performance indicator than the snow melted percentage or salt concentration (see above). Because the ranking method required introducing all data from all sites and all storm events into *one* single statistical model, it was decided that only one reference site (Rock Salt) would be sufficient. The selected sites were site SR 322 W/B - Venango-Mercer Co. Line for AquaSalina, site I-78 WB @ MM27 Berk Co. for Magic Minus Zero, site I-81 @ Exit 223 New Milford for Green Blast, site I-79 N/B @ Exit 60 Carfton Allegheny Co. for Beet Heet, and site I-80 @ MP 11 Mercer Co. for the reference, Rock Salt (Table 2.2). Data at these sites were collected during November and December 2017. Data collection ended on December 31, 2017 in order to proceed with data analysis and the estimation of deicer ranking. Three to six significant storm events were collected at each of these sites. Due to technical issues independent of the Team's responsibility, only data of one storm event were collected for Green Blast and not data were collected for Beet Heet. Also, at the time this report was prepared, the Team did not have the truck information for the Magic Minus Zero and Rock Salt sites

[1] No data were collected beyond December 2017. We still refer the second winter as 2017-2018.

Winter 2016 – 2017

Site I-80 @ Exit 35 MP 37 – AquaSalina

There were five useable snow events at site I-80 @ Exit 35 MP 37 (24-hour time window at one site is considered one snow event). At this site, the underground sensor recorded the salt concentration. The salt concentration and precipitation rolling average past 1 hour (referred to as precipitation hereafter) generally had an opposite trend. For all the snow events on Jan-05, Jan-31, Feb-08, Feb-09, and Mar-13 2017, the salt concentration decreased when there was snow precipitation and the deicer was applied. At the same time, the surface snow melted percentage recovered to 100% (i.e., no surface snow) within 30 min. Therefore, the deicer application was clearly effective at removing the surface snow. The deicer performance did not seem to be well reflected by the salt concentration. In many cases, it was too dark to collect on-road real-time images from the RWIS system, preventing to obtain snow melted percentage data.

Site I-79 @ MP 136 Crawford/Mercer Line – Reference (Rock Salt) for AquaSalina Rock Salt was applied at this site. The four snow events were recorded: 08-Feb-2017 19:00–09-Feb-2017 19:00, 09-Feb-2017 19:00–10-Feb-2017 19:00, 12-Feb-2017 19:00–13-Feb-2017 19:00, and 28-Jan-2017 20:00–29-Jan-2017 20:00. At this site, the underground sensor recorded the grip level. During all snow events, the grip level remained at high value (~0.8) when there was no precipitation. When there was precipitation, the grip levels decreased dramatically. The grip level was closely related to precipitation. After deicer application, the melted percentage increased significantly to 100% within about 60-90 min. It was noted that the grip level and melted percentage showed very similar trends, which indicates that the grip level can be considered as a potentially indicator of the snow condition and deicer performance.

Site I-79 @ Exit 88 – Beet Heet

There were five snow events at site I-79 @ Exit 88: Feb 08, 2017, Feb 12, 2017, Feb 15, 2017, Jan 30, 2017, and Jan 31, 2017. The underground sensor recorded the salt concentration. Generally, when the precipitation increased, the salt concentration decreased. After deicer applications, the melted percentage increased to 100%, which indicated that the deicer application was effective. Again, the snow condition was not well reflected by the salt concentration.

Site I-79 @ MP 100 – Reference (Rock Salt) for Beet Heet

There was only one usable snow event at this site: Feb 08, 2017. The underground sensor recorded the salt concentration. The salt concentration and precipitation had opposite trends. After precipitation and deicer application, the snow melted percentage recovered to 100% within about 25 min. The salt concentration fluctuations did not appear to be explained by any environmental factor or winter maintenance strategy.

Site I-81 @ Exit 223 New Milford – Green Blast & Site I-81 @ Exit 211 Lenox – Reference (Rock Salt)

There was only one snow event at site I-81 @ Exit 223 New Milford and the reference site, I-81 @ Exit 211 Lenox: Feb 08, 2017. However, Green Blast was applied at both sites. The underground sensors recorded the grip level. There was clear trend showing that when the precipitation increased (e.g., from 0.0 to 0.2 in.), the grip level decreased (e.g., from 0.8 to 0.4). This provides some evidence that the grip level and precipitation have a good correlation.

Site I-81 @ Exit 77 Manada Hill – Magic Minus Zero & Site I-81 @ Exit 223 New Milford – Reference (Rock Salt)

There was only one snow event at site I-81 @ Exit 77 Manada Hill: Feb 08, 2017, and none at the reference site, I-81@ Exit 223 New Milford. The underground sensor recorded the salt concentration. Although the precipitation was heavy at some point, the salt concentration recovered to a high level shortly after the precipitation ceased, showing that the deicer application was effective. The grip level and snow melted percentage showed similar trends, which provides further evidence that the grip level can be a good indicator of the snow conditions on the road.

Correlation Matrices at Grip Level Sites

We computed correlation matrices for the three grip level sites (I-79 @ MP 136 Crawford/Mercer Line – Rock Salt, I-81 @ Exit 223 New Milford – Green Blast, and I- 80 @ Exit 211 Lenox – Rock Salt) because the grip level appeared to be the indicator of choice for assessing the snow condition on the road and deicer performance. The correlation matrix analyses showed that at the Rock Salt site – but not at the Green Blast sites, the surface temperature correlated well the air temperature. Besides, significant correlations were observed at both sites between the significant variables with respect to the snow condition: the grip level, snow layer, and snow melted percentage (the latter being only available for the Rock Salt site). In addition, a good correlation was observed between the grip level and precipitation at the Green Blast sites. Both the grip level and snow layer appear then to be very reliable indicators of the snow condition on the road and, therefore, the deicing performance.

In summary, at sites equipped with grip level sensors, the grip level decreased quickly when there was precipitation, but it recovered after deicer applications. Also, after deicer applications, the melted percentages increased to 100% within a short period of time, which means that the deicers were efficient. At sites equipped with salt concentration sensors, the salt concentration and precipitation show a generally opposite trend.
However, the salt concentration level fluctuated over a wide range for reasons that are unknown. Because few events allowed obtaining the snow melted percentage and because the salt concentration fluctuated widely, the grip level was identified as a more robust indicator of the snow condition and deicer performance.

Winter 2017 – 2018

Site SR 322 WB Venango-Mercer Co. Line – AquaSalina

Six snow events were recorded at this site: Nov-19 12:00 to Nov 20 12:00, Dec-11 12:00 to Dec 12 12:00, Dec-12 12:00 to Dec 13 12:00, Dec-13 12:00 to Dec 14 12:00, Dec-15 12:00 to Dec 16 12:00, and Dec-24 12:00 to Dec 25 12:00. For all six snow events, the grip level data was obtained from the RWIS system. The snow melted percentage was obtained from the RWIS photographs for four events. The correlation matrix analysis between all recorded variables shows that the primary performance indicator, the grip level, correlated well other 'significant' variables with respect to the snow condition on the road: the snow layer, precipitation 1-hour, and snow melted percentage. The surface and air temperature were highly correlated but did not correlate significantly other significant variables. Other variables recorded by the system show low correlation with the grip level, snow layer, precipitation, or snow melted percentage. Both the grip level and snow layer appears to be good indicators of the road condition and, therefore, the deicing performance. Application of AquaSalina resulted in a sharp increase of the grip level and/or snow melted percentage, although the effect of the application was much less apparent when heavy precipitation was ongoing.

Site I-79 NB @ Exit 60 Carfton Allegheny Co. – Beet Heet
No data were recorded at the RWIS site in winter 2017-2018.

Site I-81 @ Exit 223 New Milford – Green Blast
Only one snow event was recorded at this site: Dec-13 12:00 to Dec 14 12:00. The correlation matrix showed that the grip level during this storm correlated well with the snow layer and snow melted percentage. This indicates again that both the grip level and snow layer are good indicators of road condition and deicer performance. The snow layer showed a low correlation with the precipitation and melted percentage. Unlike what was observed at other sites, the absence of good correlation between the four significant variables appears to be the limited data available at this site. The application of Green Blast generally resulted in a significant increase of the grip level and snow melted percentage, except when heavy precipitation was ongoing.

Site I-78 WB @ MM 27 Berk Co. – Magic Minus Zero
Four snow events were recorded at this site: Dec-13 12:00 to Dec 14 12:00, Dec-15 12:00 to Dec 16 12:00, Dec-22 12:00 to Dec 23 12:00, and Dec-24 12:00 to Dec 25 12:00.
The correlations matrix shows that the grip level correlated well with other significant variables: snow layer, precipitation 1-hour, and snow melted percentage. The graphical analysis also indicated that both the grip level and snow layer are good indicators of the road condition and, therefore, of the deicing performance. The effect of the application of Magic Minus Zero was not discussed as no truck information was not available at the time this report was prepared.

Site I-80 @ MP 11 Mercer County – Rock Salt
Five snow events were recorded at this site: Dec-12 12:00 to Dec 13 12:00, Dec-13 12:00 to Dec 14 12:00, Dec-15 12:00 to Dec 16 12:00, Dec-28 12:00 to Dec 29 12:00, and Dec-2912:00 to Dec 30 12:00. According to correlations matrix analysis, the grip level only correlated with the snow layer. However, graphical analyses of the profile of the significant variables revealed that during two storm events, there were discrepancies in the data recorded by the sensors (e.g., precipitation not associated with snow layer, grip level, and snow melted percentage). Removing these two storms from the data set resulted in good correlation between the four significant variables. The effect of the application of Rock Salt was not discussed as no truck information was not available at the time this report was prepared.

In summary, the correlation matrix analyses showed that at all sites, the surface temperature correlated very well the air temperature. Besides significant correlations were observed at most sites between the significant variables with respect to the snow condition, i.e., the primary indicator of the snow condition, the grip level, and other variables expected to be related to snow on the road: the snow level, precipitation 1-hour, and snow melted percentage. Overall, both the grip level and snow layer appear to be very reliable indicators of the snow condition of the road and, therefore, the deicing performance. The profile of significant variables during selected storms showed again a strong correlation between the precipitation 1-hour, snow layer, grip level, and snow melted percentage. After deicer application, we generally observed a rapid increase of the grip level and snow melted percentage, which reflected the efficiency of the deicer product applied. However, in some cases, the application did not result in significant recovery of the grip level and snow melted percentage, which may be caused by ongoing snow precipitation.

1. INTRODUCTION

In Task 1.2 and 1.3, the six deicer products (i.e., AquaSalina, Beet Heet, Green Blast, Salt Brine, Rock Salt, and Magic Minus Zero) were tested in parking lot tests. During parking lot tests, several external variables were evaluated, including deicer type, application rate and sample time. However, various environmental variables have not been taken into consideration, such as precipitation level, grip level, surface temperature, etc. Therefore, in this part of the study, on-road real-time field tests were conducted to evaluate the deicers performance at several RWIS observation sites.

In the winter 2016-2017, four pairs of sites were used for each deicer including one site for the product being tested and one site for the reference (Rock Salt): Site I-80 @ Exit 35 MP 37 for AquaSalina and site I-79 @ MP 136 Crawford/Mercer Line for the reference; site I-79 @ Exit 88 for Beet Heet and I-79 @ MP 100 for the reference; site I- 81 @ Exit 223 New Milford for Green Blast and site I-80 @ Exit 211 Lenox for the reference; and site I-81 @ Exit 77 Manada Hill for Magic Minus Zero and site I-81 @ Exit 223 New Milford for the reference. The field tests incorporated real world conditions, including variable weather (information collected from the RWIS system) and real application conditions (information collected from the AVL system). After careful data collection and data analysis, we were able to provide some suggestions about how to collect field data, conduct data analysis, perform evaluation of the deicers, and assess the effectiveness of RWIS system, AVL system, and field operations. However, comparison among the deicers performances was not feasible because there are only a limited number of field data available.

In the winter 2017-2018, five sites equipped with grip level sensors were used – one site for each deicer product being tested and one for the reference, Rock Salt. The selected sites were site SR 322 W/B - Venango-Mercer Co. Line for AquaSalina, site I-79 N/B @ Exit 60 Carfton Allegheny Co. for Beet Heet, site I-81 @ Exit 223 New Milford for Green Blast, site I-78 WB @ MM27 Berk Co. for Magic Minus Zero, and site I-80 @ MP 11 Mercer Co. for the reference, Rock Salt. Data at these sites were collected during November and December 2017. The Team stopped data collection on December 31st to work on data analysis, statistical analysis, and estimation of deicer ranking (Task 4). Data were analyzed and discussed based on correlation matrices and the graphical plots of the different variables recorded by the RWIS and AVL systems.

2. EXPERIMENTAL METHODS

The data collection can be divided into two parts: RWIS data collection and AVL data collection. The detailed, specific procedure to collect data from RWIS and AVL can be found in **Appendix I**.

The RWIS or road weather information system (http://rds.vaisala.com/apps/) continuously tracks and stores the following data for each site (they are some difference in the parameters recorded depending on sites): surface temperature (°F); surface state (dry or wet); air temperature (°F); dew point temperature (°F); level of grip; water layer (in.), ice layer (in.); snow layer (in.); relative humidity (%); rain state atmospheric site; rain intensity (in/h); wind speed (mph); wind direction; visibility (ft); salt concentration (g/l); grip levels; water thickness; liquid freezing temperature; ground temperature; base temperature; barometric pressure (hPa); precipitation rolling average past 12 hours; precipitation rolling average past 1 hour; precipitation rolling average past 24 hours; precipitation rolling average past 3 hours; precipitation rolling average past 6 hours; ground temperature (°F); water thickness (in.), rain on/off atmospheric, and camera shots of the road condition.

The AVL or automated vehicle location system https://q3.webtechwireless.com/wtw/jsp/QSecurity/login.jsp) gives the following deicer information: solid material, solid rate, solid application time, solid spread, prewet rate, prewet spread, anti-ice rate, and anti-ice spread.

For both the winter 2016-2017 and winter 2017-2018 data, preliminary analysis suggested that the environmental variables susceptible to be indicative of the road conditions and deicer field performances were the temperature (surface and air) and the precipitation. Therefore, the Results & Discussion section considered only these variables. Among all the precipitation variables, we decided to focus on the 'Precipitation Rolling Average Past 1 Hour' because it appeared the closest to the real-time data and it will be referred to as 'precipitation' hereafter. In addition, three variables representative of the road conditions were discussed when available: the grip level, salt concentration, snow layer, and snow melted percentage (derived from the on-site automated cameras).

Table 2.1 List of the eight sites (four pairs, each with a reference site) used for on-road real-time field tests in the winter 2016-2017

Number	Site name	Deicers	District
1	I-80 @ Exit 35, MP 37	AquaSalina	1
	I-79 @ MP 136 Crawford/Mercer Line	Rock Salt (reference)	1
2	I-79 @ Exit 88	Beet Heet	10
	I-79 @ MP 100	Rock Salt (reference)	10
3	I-81 @ Exit 223 New Milford	Green Blast	4
	I-80 @ Exit 211 Lenox	Rock Salt (reference)	4
4	I-81 @ Exit 77 Manada Hill	Magic Minus Zero	8
	I-81 @ Exit 223 New Milford	Rock Salt (reference)	8

Table 2.2 List of the five sites (four sites for deicer products and one site for reference) used for on-road real-time field tests in the winter 2017-2018

Number	Site name	Deicers	District
1	SR 322 WB Venango/Mercer Co. Line	AquaSalina	1
2	I 79 NB @ Exit 60 Carfton Allegheny Co	Beet Heet	11
3	I-81 @ Exit 223 New Milford	Green Blast	4
4	I-78 WB @ MM27 Berk. Co	Magic Minus Zero	5
5	I-80 @ MP11 Mercer County	Rock Salt (reference)	1

With the field images obtained from RWIS, the snow melted percentage scores were visually assigned by two different researchers. The final melted percentages were the average of the two scores. When the Temple team assigned the scores, the visual score criteria shown in Figure 2.1 were used to standardize the scoring process.

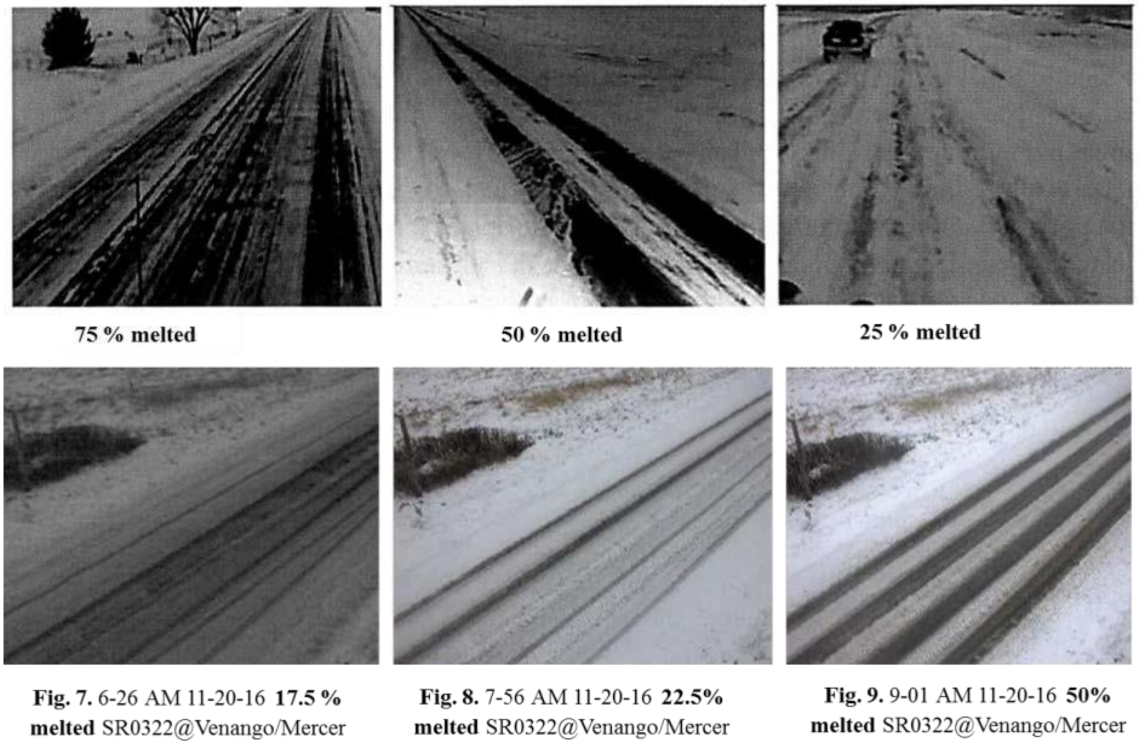


Figure 2.1 Standard images of visual scores during on-road real-time field tests.

A total of 55 snow events have been collected based on the weather history on the RWIS website from December 2016 to December 2017. During the field tests conducted from December 2016 to March 2017, 36 snow events have been collected from RWIS website (Table 2.3). During the field tests conducted from November 2017 to December 2017, 19 snow events have been collected from the RWIS website (Table 2.4). However, some snow events were not analyzed in this report because some data were missing, such as truck information, camera images, and/or road melted conditions.

Table 2.3 and 2.4 summarize all the snow events monitored and useful snow events at the RWIS sites during the winter 2016-2017 and 2017-2018 respectively.

Table 2.3 All snow events and useful snow events list of eight RWIS sites in the winter 2016- 2017

Site Name	Deicers	Sensor	Snow Events	Useful Events[2]	Melted %[3]
I-80@ Exit 35 MP 37	AquaSalina	Salt conc.	12	5	2
I-79 @ MP 136 Crawford/Mercer Line	Rock Salt	Grip level	8	4	2
I-79 @ Exit 88	Beet Heet	Salt conc.	7	4	1
I-79 @ MP 100	Rock Salt	Salt conc.	2	1	1
I-81 @ Exit 223 New Milford	Green Blast	Grip level	3	1	0
I-80 @ Exit 211 Lenox	Rock Salt	Grip level	3	1	0
I-81 @ Exit 77 Manada Hill	Magic Minus Zero	Salt conc.	1	1	0
I-81 @ I-78 Split	Rock Salt	Salt conc.	0	0	0

Table 2.4 All snow events and useful snow events list of eight RWIS sites in the winter 2017- 2018

Site Name	Deicers	Snow events	Useful Events	Melted %
SR 322 WB Venango/Mercer Co. Line	AquaSalina	6	6	4
I-78 WB@ MM27 Berk. Co.	Magic Minus Zero	4	0	2
I 79 NB @ Exit 60 Carfton Allegheny Co.	Beet Heet	3	0	3
I-81 @ Exit 223 New Milford	Green Blast	1	1	1
I-80 @ MP 11 Mercer County	Rock Salt (reference)	5	5	4

[2] Useful events are the events for which data from RWIS and AVL system are available.

[3] These are events in which the snow melted percentage was recorded from the onsite cameras.

3. RESULTS & DISCUSSION

3.1. Winter 2016-2017

This section is a reduced and polished version of the Results & Discussion section presented in Task 3.1 Interim Report.

3.1.1. AquaSalina (I-80 @ Exit 35 MP 37) & Reference Site (I-79 @ MP136 Crawford/Mercer Line)

Site I-80 @ Exit 35 MP 37 – AquaSalina

There were 5 events at this site (24 hour at one site is considered one snow event): 05- Jan-2017 16:00–06-Jan-2017 17:00; 31-Jan-2017 01:00–01-Feb-2017 01:00; 08-Feb- 2017 14:00–09-Feb-2017 14:00; 09-Feb-2017 17:00–10-Feb-2017 17:00; and 13-Mar-2017 20:00–14-Mar-2017 20:00. In the following section, representative snow events were discussed individually.

Jan-05-2017

One truck passed 17 times during 24 hours from 12:00 Jan-05 2017 to 12:00 Jan-06 2017. The solid application rates (unit: lb/lane-mile) of each truck passing are marked on the top of each application in Figure 3.1.1.

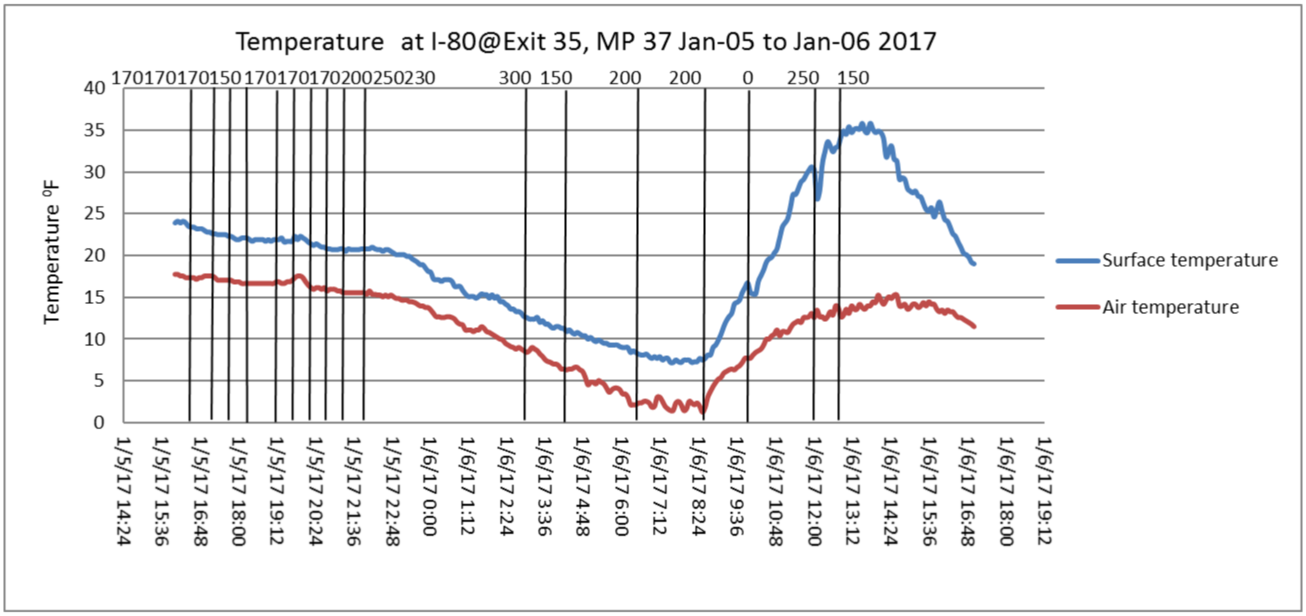


Figure 3.1.1 Temperature (surface temperature and air temperature) during 24 hours from 05- Jan-2017 16:00 to 06-Jan-2017 17:00 at site I-80 @ Exit 35 MP 37. Vertical solid lines indicate the times of deicer application, with the deicer application rates in lb/ lane-mile indicated immediately above the lines.

Figure 3.1.1 shows that the surface temperature and air temperature have similar trends during 24 hours. Around 2:00 pm the temperatures were the highest, and 6:00-8:00 am had the lowest temperature. The highest surface temperature reached around 35 ^{0}F, while the lowest surface temperature was around 7 ^{0}F.

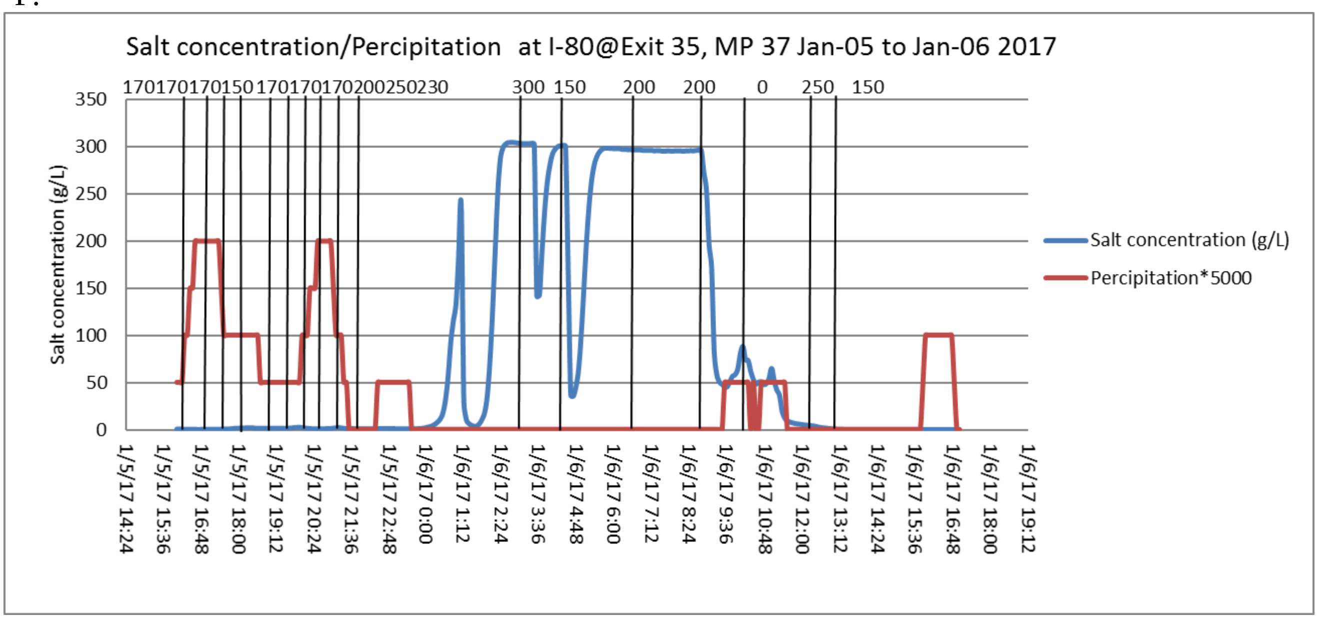


Figure 3.1.2 Salt concentration (g/L) and precipitation (in.) during 24 hours from 05-Jan-2017 1600 to 06-Jan-2017 1700 at site I-80 @ Exit 35 MP 37. Note that the precipitation values were multiplied by 5000 so they can be plotted on the same figure, for direct comparison purposes.

Figure 3.1.2 shows that when the precipitation increased during the whole event, the salt concentration decreased accordingly. Between 15:36 and 21:36, there was heavy continuous snow precipitation, during the same time, the truck passed by the site many times and salt concentration remained at zero. After snow stopped at about 0:00, the salt concentration started to increase sharply to almost 250 g/L within about 30 min. The salt concentration remains around 300 g/L when there was no precipitation, but decreased to < 50 g/L as soon as snow started again at 19:36. At this site, no photos could be collected for this event because RWIS did not have them online or the camera was not functioning.

Jan-31-2017

Two trucks passed the site 19 times during 24 hours from 31-Jan-2017 01:00 to 01-Feb- 2017 01:00 (truck 0150-425-8077 and truck 0150-118-8077). The prewetting rate was 10 gal/ton for all the applications during this event. The temperature in this case ranged from 22 ^{0}F (around 00:00 to 2:00 am Jan-31-2017) to 36 ^{0}F (around 13:00 to 14:00 Jan-31-2017), as shown in Figure 3.1.3.

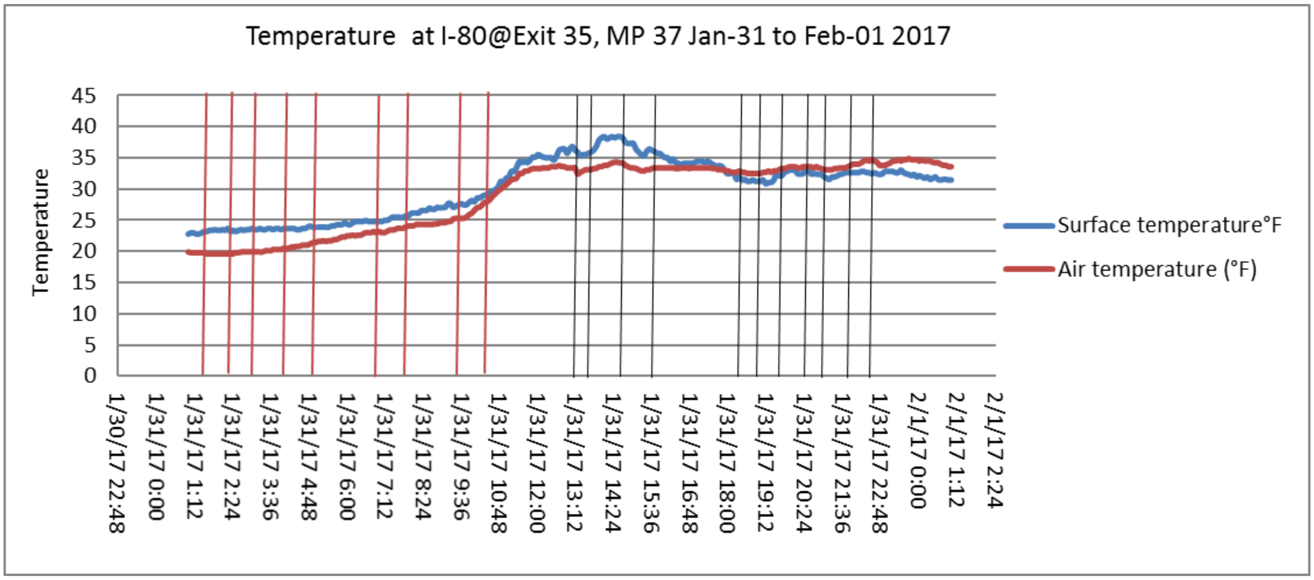


Figure 3.1.3 Surface temperature and air temperature during 24 hours from 31-Jan-2017 1600 to 01-Feb-2017 1700 at site I-80@ Exit 35, MP 37. The vertical lines have two colors, indicating two different trucks.

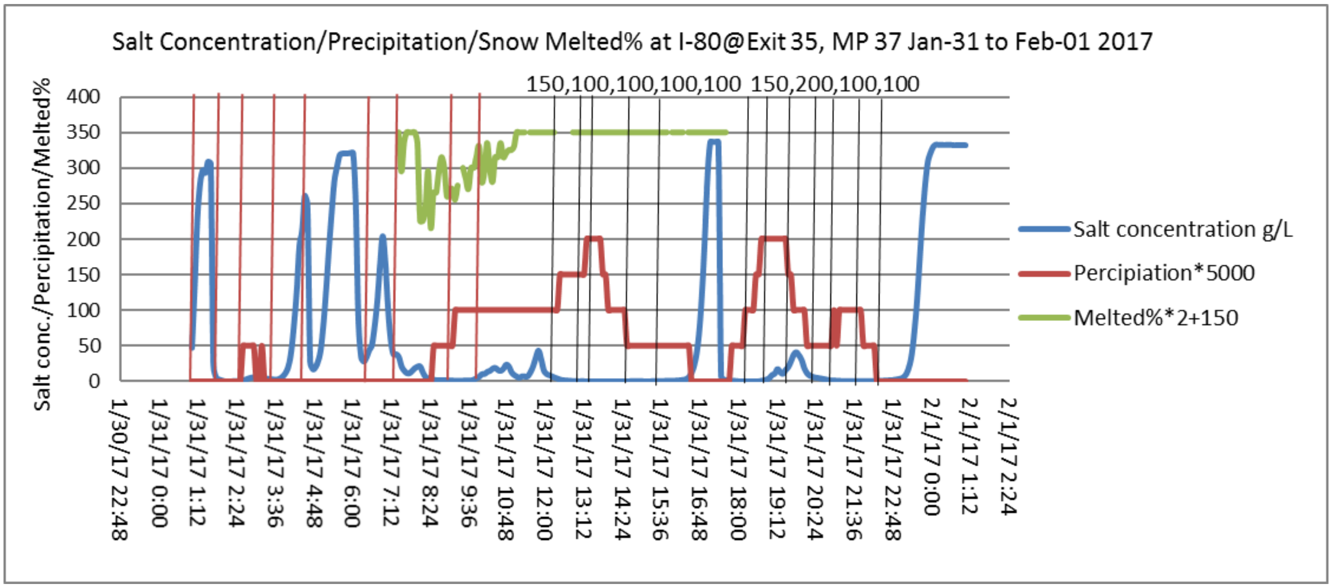


Figure 3.1.4 Salt concentration (g/L), precipitation, and snow melted percentage variables during 24 hours from 31-Jan-2017 16:00 to 01-Feb-2017 17:00 at site I-80 @ Exit 35 MP 37.
Precipitation was multiplied by 5000 and melted percentage was multiplied by 2 plus 150 in order to get a comparable level in the figure, so the reading of 350 is equivalent to 100% melted.

Figure 3.1.4 shows that the salt concentration and precipitation have an opposite trend during the 24 hours, similar to what was observed in Figure 3.1.2. For example, from 3:36 am Jan-31-2017 to 8:24 am Jan-31-2017, there was no precipitation, and then the salt concentration increased significantly during the same time period. After around 8:30 in the morning, there was a precipitation from 0.02 in. to 0.04 in. on the ground, and the salt concentration remained at lower levels from 0 to 40 g/L. The same phenomenon was observed from time 18:00 Jan-31, 2017 to 22:48 Jan-31, 2017. Therefore, it seems that as long as there is precipitation, the salt concentration is at a low level, no matter how much deicer has been applied to the road, so it remains unknown whether the salt concentration is an effective parameter to evaluate deicer performance.

On the other hand, around 8:24 am, there was snow precipitation, as a result, the melted percentage decreased and showed some fluctuations. Note that the photos taken priors to 8:24 am were too dark to assign reliable scores. After several passages of the trucks, the melted percentage increased effectively and then remained at a stable level of 100% from 12:00 to 15:30, despite the fact that there was constant precipitation during the period. Therefore, the deicer application was clearly effective in removing surface snow. However, that performance does not seem to be reflected in the measured salt concentrations.

<u>Feb-08-2017</u>
One truck passed though the site 12 times during 24 hours from 12:00 Jan-31 2017 to 12:00 Feb-01 2017 (truck 0150-425-8077). The following section discusses the surface temperature and air temperature and salt concentration/ precipitation variables from 12:00 Jan-31 2017 to 12:00 Feb-01 2017.

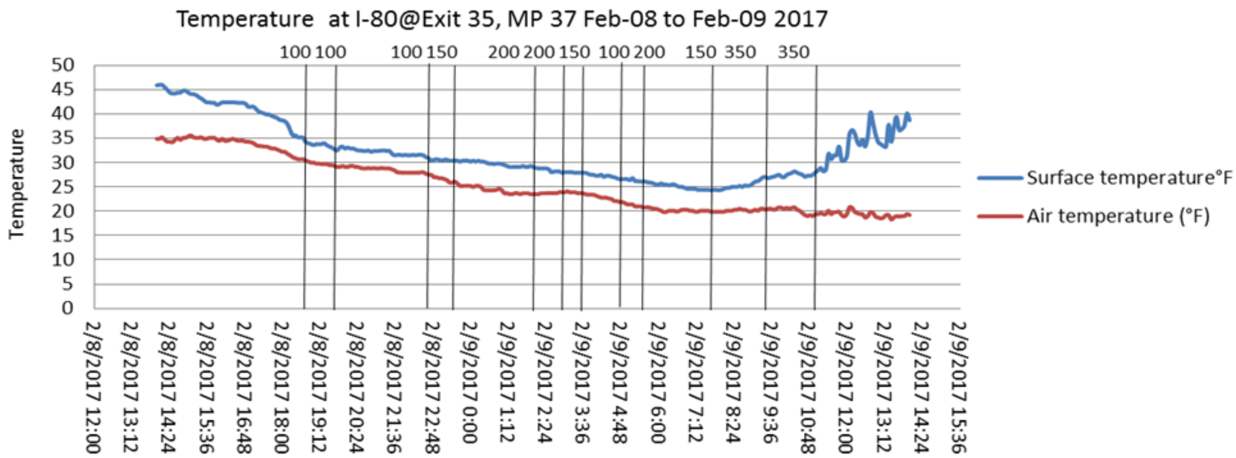


Figure 3.1.5 Surface temperature and air temperature during 24 hours from Feb 08, 2017 1600 to Feb 09, 2017 1700 at site I-80 @ Exit 35 MP 37.

As can be seen from Figure 3.1.5, the surface temperature remained between around 25 ^{0}F to 45 ^{0}F, while the air temperature remained between 20 ^{0}F to 35 ^{0}F during the same time period. Generally, the surface temperature and air temperature have a similar trend. Similar patterns have been observed for all other snow events at this and other sites, and the relationship between these two variables will not be discussed further.

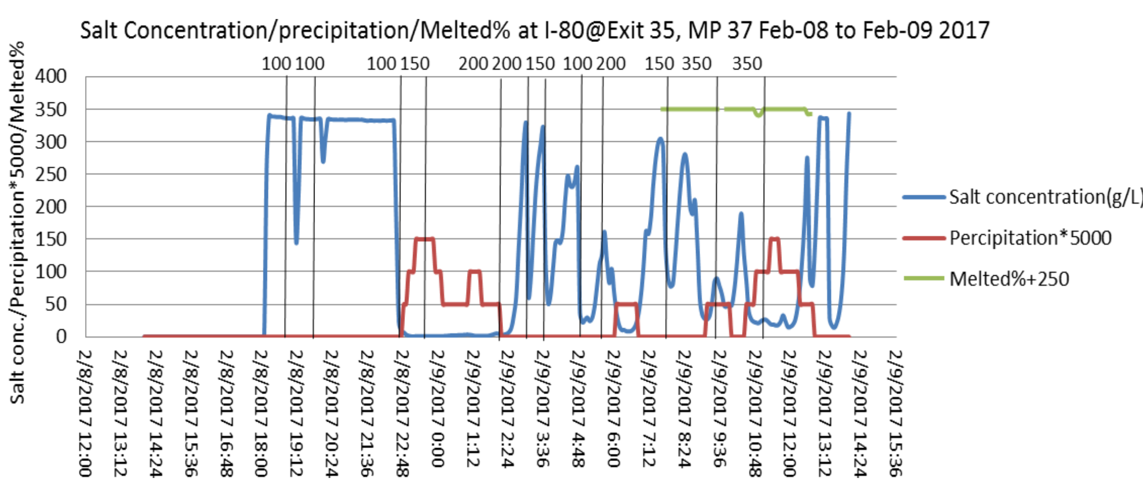


Figure 3.1.6 Salt concentration (g/L), precipitation and snow melted percentage variables during 24 hours from Feb 08, 2017 1600 to Feb 09, 2017 1700 at site I-80@ Exit 35, MP 37.
Precipitation was multiplied by 5000, melted percentages were added 250 in order to get a comparable level in the figure.

As can be seen from Figure 3.1.6, the salt concentration variable has a trend opposite to that of precipitation. The phenomenon is similar to the events we have discussed above. The precipitation for this event was between zero and 0.03 in.. There was a lot of precipitation from 22:48 on Feb 08, 2017 to 2:24 am on Feb 09, 2017. During this time, it was too dark to collect on-road real-time images from the RWIS system. However, there was another heavy precipitation from 9:00 am to 13:00 on Feb 08,

2017. In this time period, we could download useful RWIS images and gave visual scores. The results indicate that the melted percentage remained at 100% from 7:30 to 11:30 in the morning even during snow precipitation, indicating the deicer application was very effective.

However, within the same time period, the salt concentration changed wildly between < 25 g/L and 250 g/L, again leading us to question the usefulness of this parameter in accessing deicer performance.

Feb-09-2017

One truck passed the site 2 times during 24 hours from 12-00 Feb-09 2017 to 12-00 Feb- 10 2017.

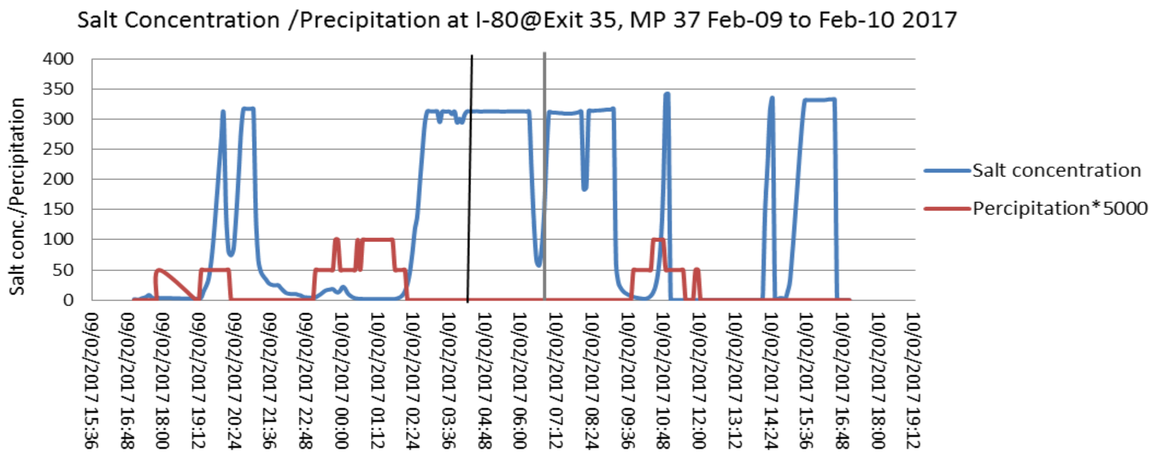


Figure 3.1.7 Salt concentration (g/L), precipitation variables during 24 hours from Feb 09, 2017 1500 to Feb 10, 2017 2000 at site I-80 @ Exit 35 MP 37. Precipitation was multiplied by 5000 in order to get a comparable level.

Figure 3.1.7 shows the salt concentration (g/L) and precipitation variables during 24 hours from Feb 09, 2017 15:00 to Feb 10, 2017 20:00 at the site. As in the discussion above, the salt concentration and precipitation have an opposite trend.

Mar-13-2017

Four trucks passed the site 10 times during 24 hours from 12:00 March-13, 2017 to 12:00 March-14, 2017 (trucks 0150-425-8077, 0150-118-8077, 0150-206-8087, and 0150-352-5077). When the trucks passed by the RWIS site with deicer applications, the salt concentration generally decreased, while when the precipitation increased from 12:00 to 16:00 on March-14-2017, the salt concentration decreased significantly (Figure 3.1.8).

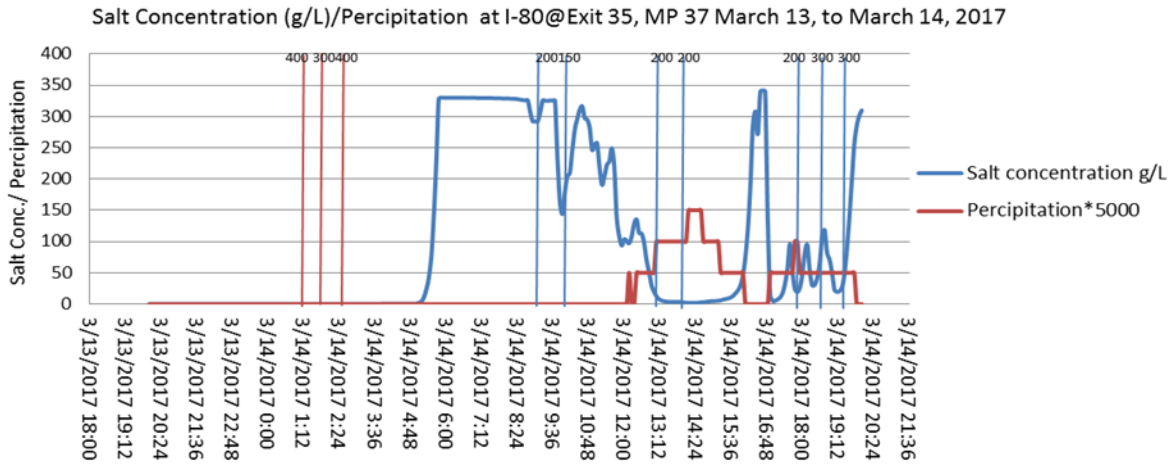


Figure 3.1.8 Salt concentration (g/L), precipitation variables during 24 hours from March 13, 2017 1800 to March 14, 2017 2200 at site I-80 @ Exit 35 MP 37. Precipitation was multiplied by 5000 in order to get a comparable level in the figure.

Site I-79 @ MP 136 Crawford/Mercer Line – Reference for AquaSalina

Site I-79 @ MP 136 Crawford/Mercer Line in this research was chosen as the reference site for the deicer AquaSalina. The four snow events for this site are as follows: 08-Feb- 2017 19:00 –09-Feb-2017 19:00; 09-Feb-2017 19:00–10-Feb-2017 19:00; 12-Feb-2017 19:00–13-Feb-2017 19:00; and 28-Jan-2017 20:00–29-Jan-2017 20:00. Each 24-hour period is considered as one snow event in the following discussion. The above snow events were discussed in the following section separately.

Jan-28-2017

Seven Trucks passed the site I-79 @ MP 136 Crawford/Mercer Line 62 times during 24 hours from 28-Jan-2017 20:00 to 29-Jan-2017 20:00 (trucks 0140-256-8087, 0140-465-8087, 0140-335-8087, 0140-085-8077, 0110-493-8077, 0110-094-8077 and 0110-070-5090).

The figure below shows the temperature variables during 24 hours from 28-Jan-2017 20- 00 to 29-Jan-2017 20-00. The solid application rates are marked on the top of each application. The units of the application rates are lb/lane-mile. The different trucks are marked with different colors.

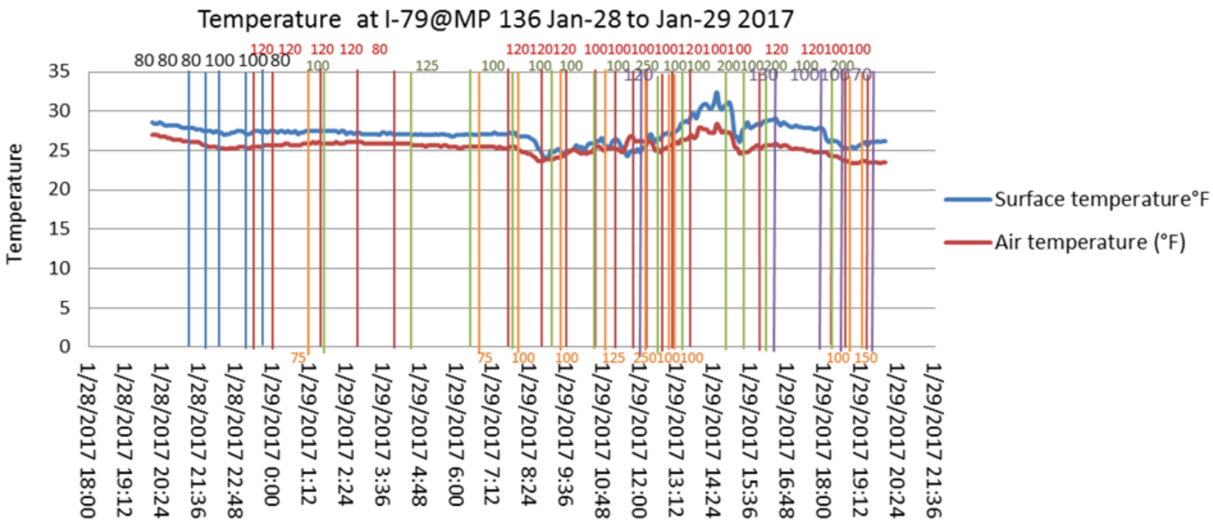


Figure 3.1.9 Surface temperature and air temperature during 24 hours from 28-Jan-2017 20-00 to 29-Jan-2017 20-00 at site I-79 @ MP 136 Crawford/Mercer Line.

From Figure 3.1.9 we can see that the surface temperature remained between 24 ^{0}F to 33 ^{0}F, while the air temperature remained between 24 ^{0}F to 27 ^{0}F during the whole 24 hours. The highest temperatures, both surface and air temperature, were observed at around 14:00 in the afternoon, while the lowest temperatures were in the morning, around 8:00 am.

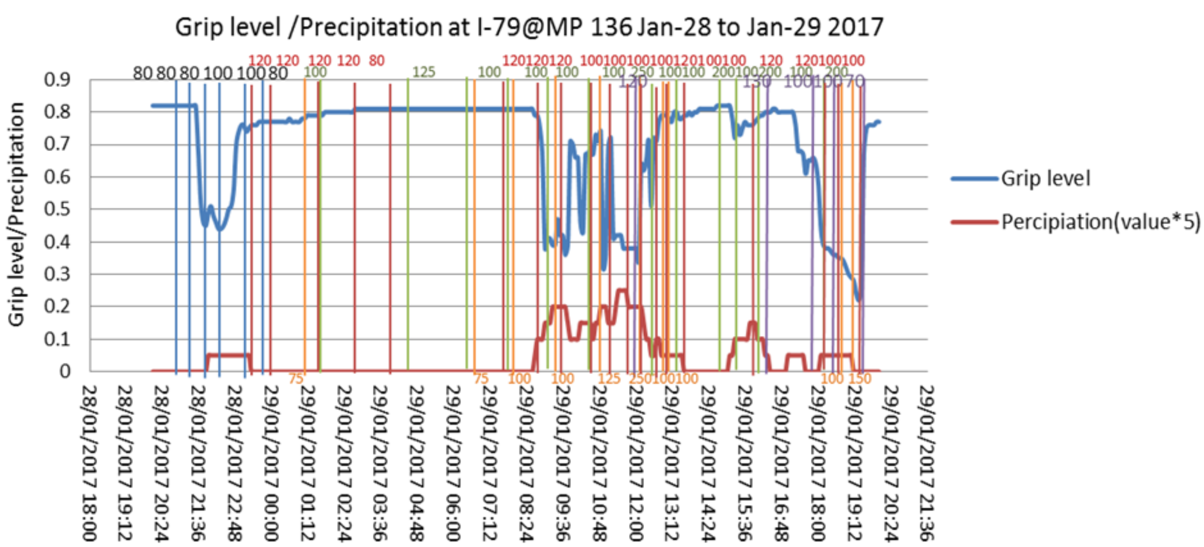


Figure 3.1.10 Grip level and precipitation (multiplied by 5) variables during 24 hours from 28- Jan-2017 20-00 to 29-Jan-2017 20-00 at site I-79 @ MP 136 Crawford/Mercer Line.

Figure 3.1.10 shows that there were several precipitation events during the whole 24 hours. For example, from 21:36 Jan-28-2017 to 23:00 Jan-28-2017, there was 0.01 in. precipitation, from 8:24 am to 13:20 Jan 29, 2017, there was a lot of precipitation (0.01~0.05 in.), also from 14:30 Jan 29, 2017 to 19:12 Jan 29, 2017, there was continuous precipitation with a maximum of 0.03 in. Accordingly, the grip levels during these time periods decreased dramatically (from > 0.8 to 0.25–0.45). However, when there was no precipitation, the grip level kept at a high value of 0.8 (levels above 0.7 can be considered a safe road according to the RWIS system), meaning that the deicer application effectively restored surface grip levels. Therefore, we can conclude that the grip level values are closely related with the precipitation status during the entire snow events.

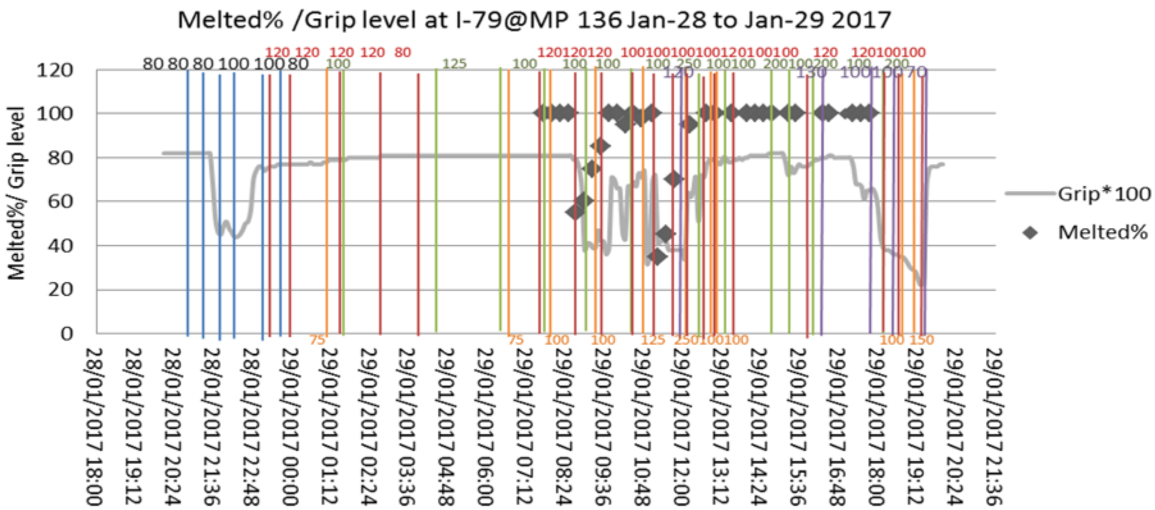


Figure 3.1.11 Melted percentage and grip level variables during 24 hours from 28-Jan-2017 20- 00 to 29-Jan-2017 20-00 at site I-79 @ MP 136 Crawford/Mercer Line.

Figure 3.1.11 shows that prior to 8:30 am on Jan 29, 2017, there was no precipitation and the melted percentage remained at 100%. From 8:30 am, precipitation began to accumulate then the melted percentage decreased to around 50% within 60 min. When deicers were applied, the melted percentage increased significantly to 100% within about 60-90 min (from 8:44 am ~55% melted percentage to 9:44 am 100% melted, from 11:14 am ~35% melted to 12:44 pm 100% melted). It is obvious that the melted percentage has a close relationship with the grip level. For instance, in the image for 8:44 Jan 28, 2017, the melted percentage decreased dramatically probably due to the heavy precipitation, at the same time, the grip level decreased from 0.8 to 0.38. After several deicer applications by different trucks with various application rates, the melted percentage increased within one hour, and then the grip level increased from 0.38 to around 0.75 accordingly. Then when, the snow precipitation increased again at 11:14 Jan 28, 2017, the melted percentage decreased to around 35% and the grip level decreased to around 0.37. Therefore, we can reach the conclusion that the grip level variable and the snow melted percentage followed a comparable trend. This is a very promising finding because the grip levels are readily available from RWIS, while collecting melted percentage is a labor and time intensive process. It remained to be tested whether the grip level can be an effective indicator of deicer field performance in additional snow events.

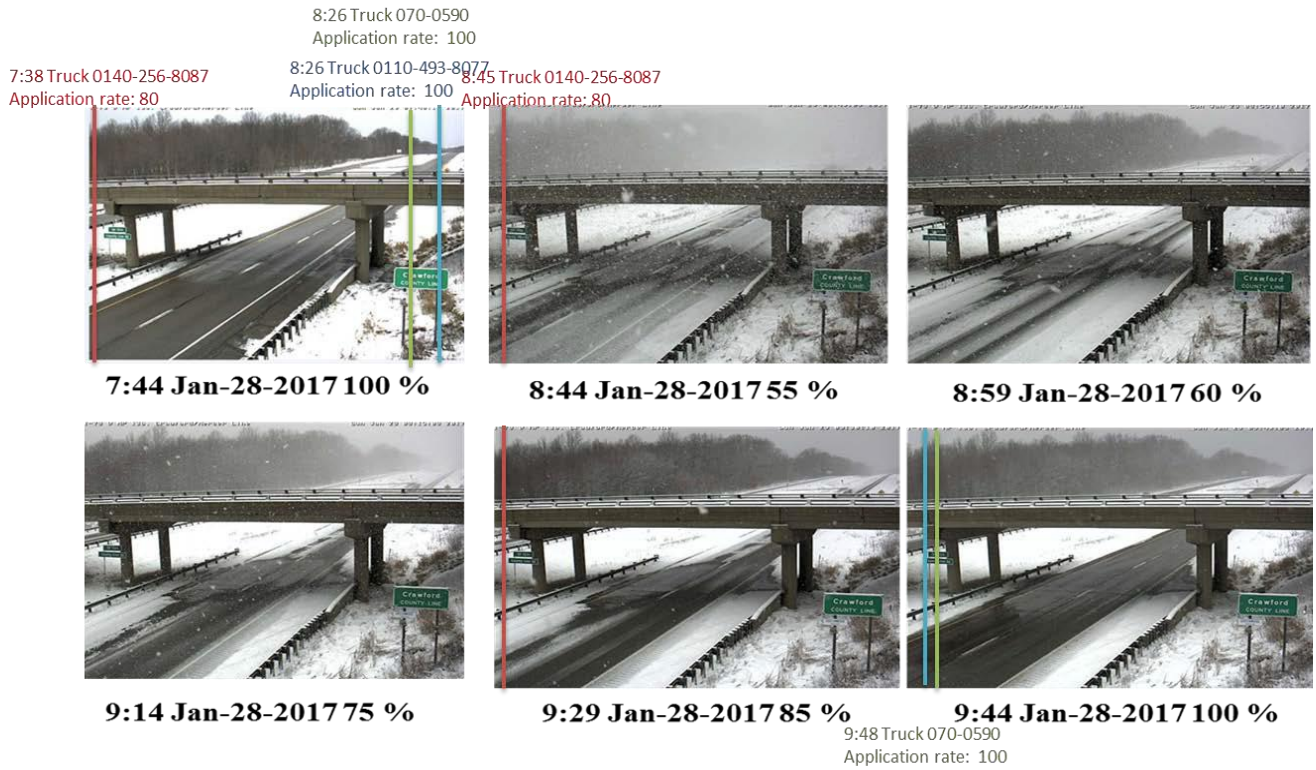


Figure 3.1.12 Photos downloaded from RWIS site I-79 @ MP 136 Crawford/Mercer Line. Time: 7:44 am Jan 28, 2017 to 9:44 Jan 28, 2017. The snow melted percentage scores were assigned by two different researchers and given an average value.

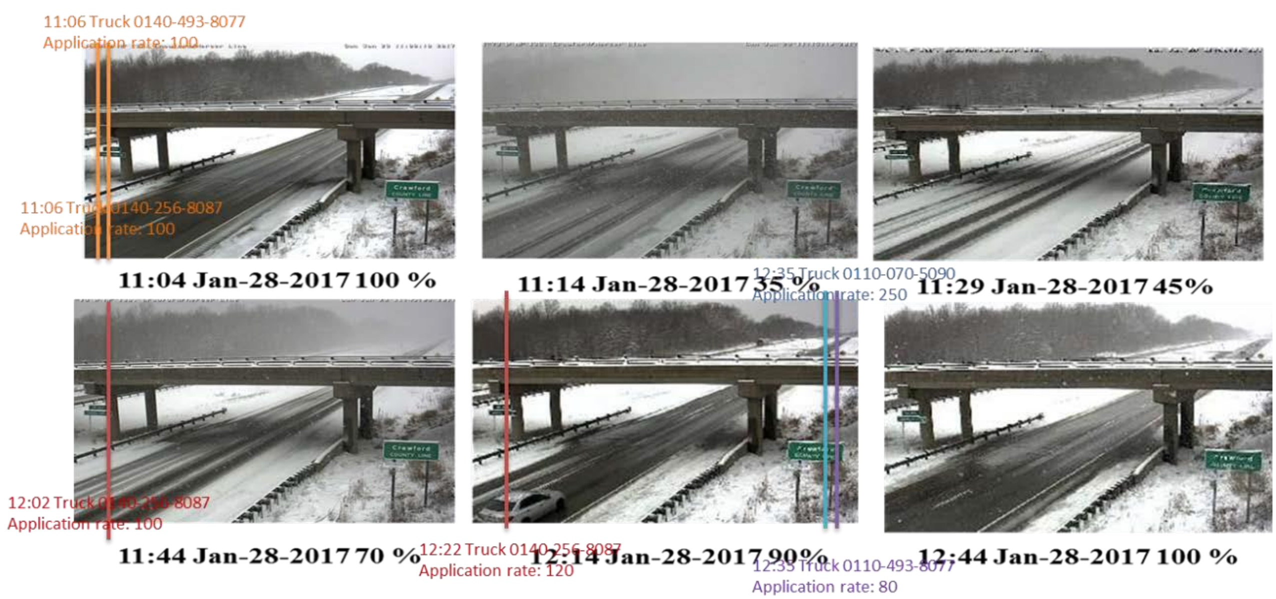


Figure 3.1.13 Photos downloaded from RWIS site I-79 @ MP 136 Crawford/Mercer Line. Time: 11:04 am Jan 28, 2017 to 12:44 Jan 28, 2017. The snow Melted percentage scores were assigned by two different researchers and given an average value.

<u>Feb-08-2017</u>

Five trucks passed the site 29 times during 24 hours from 12:00 March-13, 2017 to 12:00 March-14, 2017 (truck numbers 0110-493-8077; 0140-213-2072; 0110-552-8077; 0140-256-8087 and 0110-070-5090).

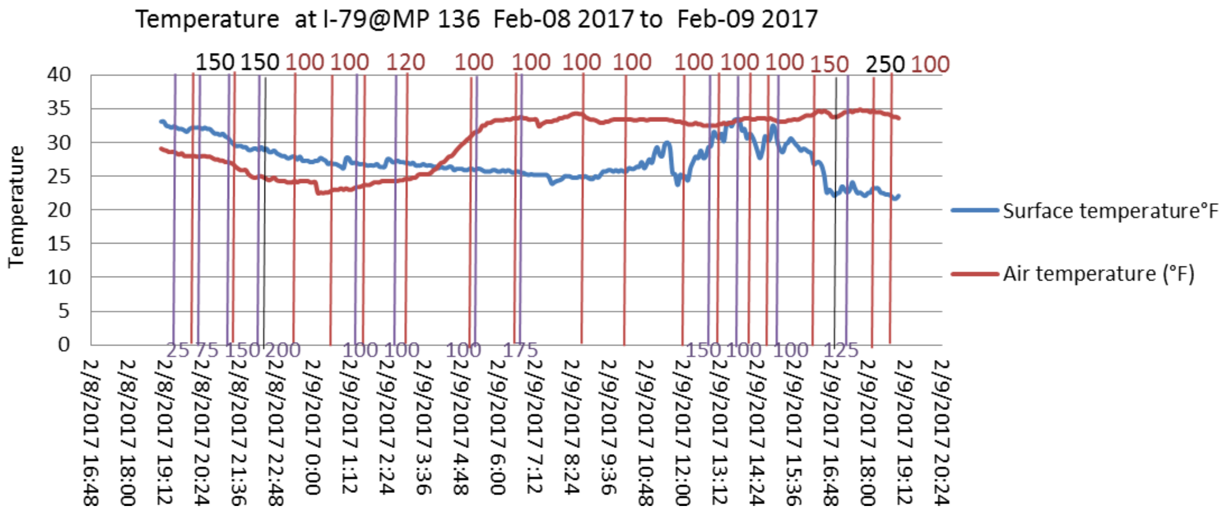


Figure 3.1.14 Surface temperature and air temperature\ during 24 hours from Feb 08, 2017 16:00 to Feb 09, 2017 21:00 at site I-79 @ MP 136 Crawford/Mercer Line.

Figure 3.1.14 shows that the air temperature varies from 22 ^{0}F to 34 ^{0}F, while the surface temperature varies from 23 ^{0}F to 34 ^{0}F, which was similar to air temperature.

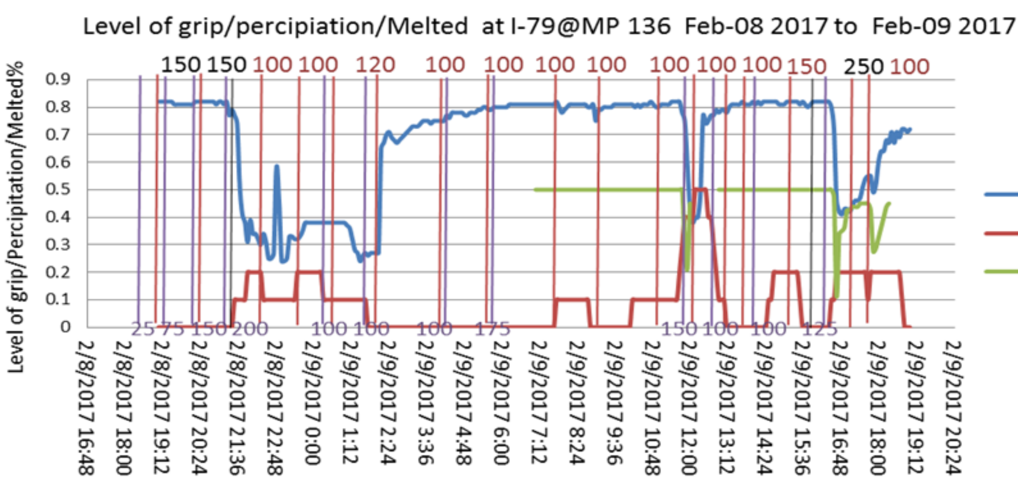


Figure 3.1.15 Grip levels/precipitation/snow melted percentage variables during 24 hours from Feb 08, 2017 16-00 to Feb 09, 2017 21-00 at site I-79 @ MP 136 Crawford/Mercer Line.

Figure 3.1.15 shows that the grip level and precipitation data have opposite trends. For example, from 21:30 Feb 08, 2017 to 1:30 Feb 09, 2017; from 10:00 Feb 09, 2017 to 15:36 Feb 09, 2017 and from 16:48 Feb 09, 2017 to 19:12 Feb 09, 2017, there was snow precipitation of 0-0.02 ,0-0.05 and 0-0.02 in., respectively, as a result, the grip level decreased significantly from 0.8 to 0.25, 0.38, 0.42, respectively. The RWIS photos provided images from 7:00 am to 19:30 Feb 09, 2017. At 11:54 Feb 09, 2017, the snow melted percentage decreased to 42.5%. At 11:59 Feb 09, 2017, it recovered to about 90% within only 10 min despite the relatively heavy snow precipitation, indicating the effectiveness of deicer applications. At 16:39 Feb 09, 2017, the snow melted percentage decreased to about 22.5%, after it had been snowing for some time. After two deicer applications, the melted percentage increased again to 90% at 17:24 Feb 09, 2017. Within the same time periods, the grip levels changed accordingly. Therefore, the grip level can be considered as a potential indicator of the snow melted percentages and deicer performance.

Figures 3.1.16 and 3.1.17 below show the photos downloaded from RWIS site I-79 @ MP 136 Crawford/Mercer Line from 16:29 Feb 08, 2017 to 17:24 Feb 08, 2017 and from 11:44 Feb 08, 2017 to 11:59 Feb 08, 2017.

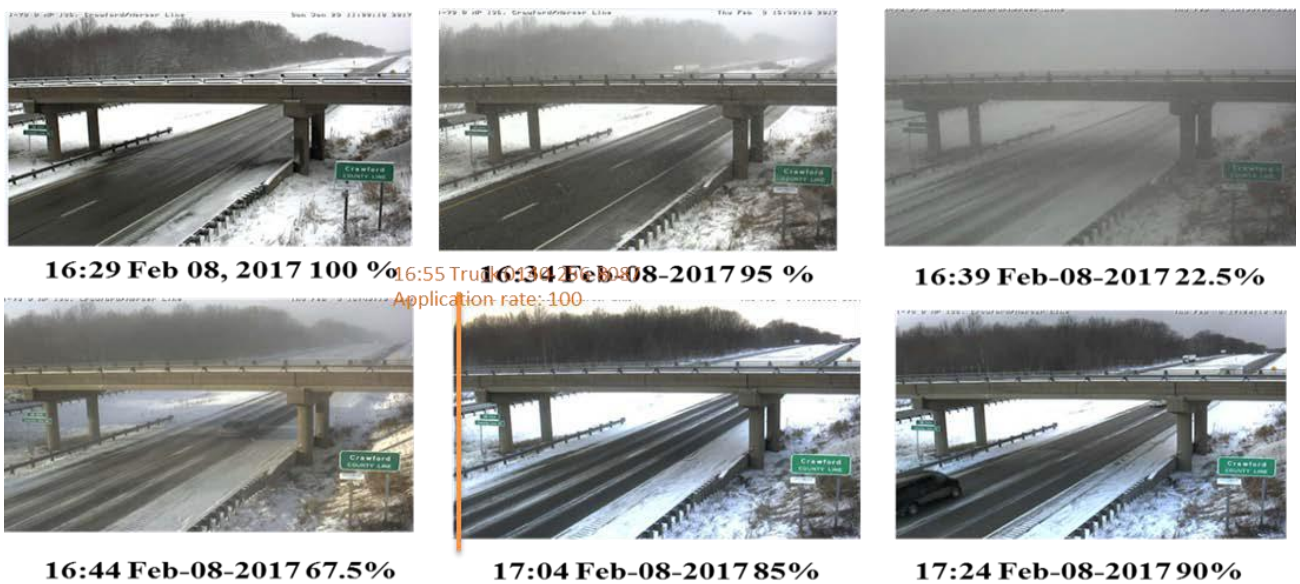


Figure 3.1.16 Photos downloaded from RWIS site I-79 @ MP 136 Crawford/Mercer Line. Time from 16:29 Feb 08, 2017 to 17:24 Feb 08, 2017. The snow melted percentage scores were assigned by two different researchers and given an average value.

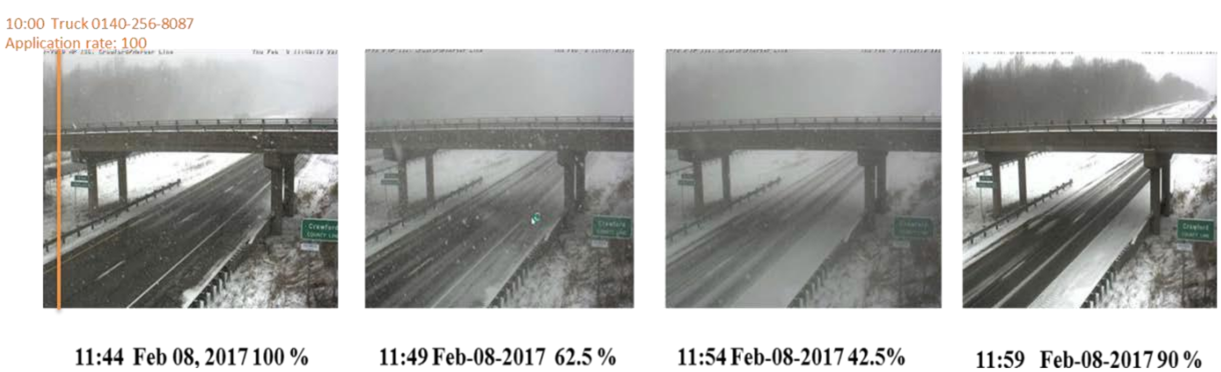


Figure 3.1.17 Photos downloaded from RWIS site I-79 @ MP 136 Crawford/Mercer Line. Time from 11:44 Feb 08, 2017 to 11:59 Feb 08, 2017. The snow melted percentage scores were assigned by two different researchers and given an average value.

<u>Feb-09-2017</u>

Six trucks passed site I-79@ MP136, Crawford/Mercer Line, 18 times during 24 hours from 12-00 Feb

09, 2017 to 12-00 Feb 10, 2017. There was precipitation around 0.1 in. from 2:30 to 6:00 am (Figure 3.1.18). After the trucks passed by the site, the grip levels increased effectively to around 0.8, which indicated again that the deicer applications were very effective. No RWIS photos were available.

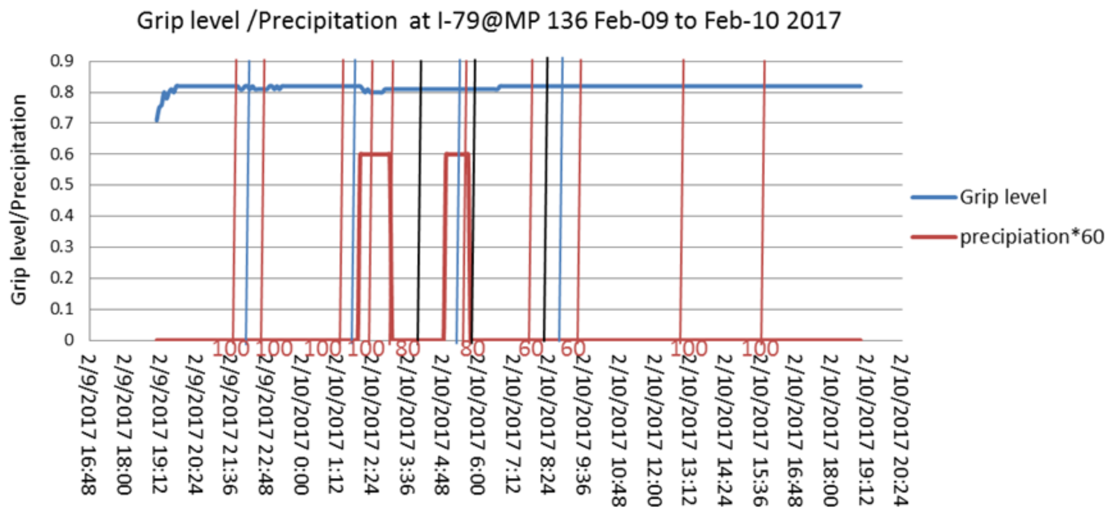


Figure 3.2.18 Grip levels/precipitation variables during 24 hours from Feb 09, 2017 16-00 to Feb 10, 2017 21-00 at site I-79 @ MP 136 Crawford/Mercer Line.

<u>Feb-12-2017</u>

One truck passed site I-79 @ MP 136 Crawford/Mercer Line 29 times during 24 hours from 12:00 March-13, 2017 to 12:00 March-14, 2017. Figure 3.1.19 shows that when the precipitation increased, the grip level deceased significantly. After the deicers were applied from around 21:30 pm to 8:30 am, the grip level increased and then remained at high value, although there was some precipitation from 0:00 to 6:00 am (above 0.7 in.). That indicated again that the deicer applications were very effective.

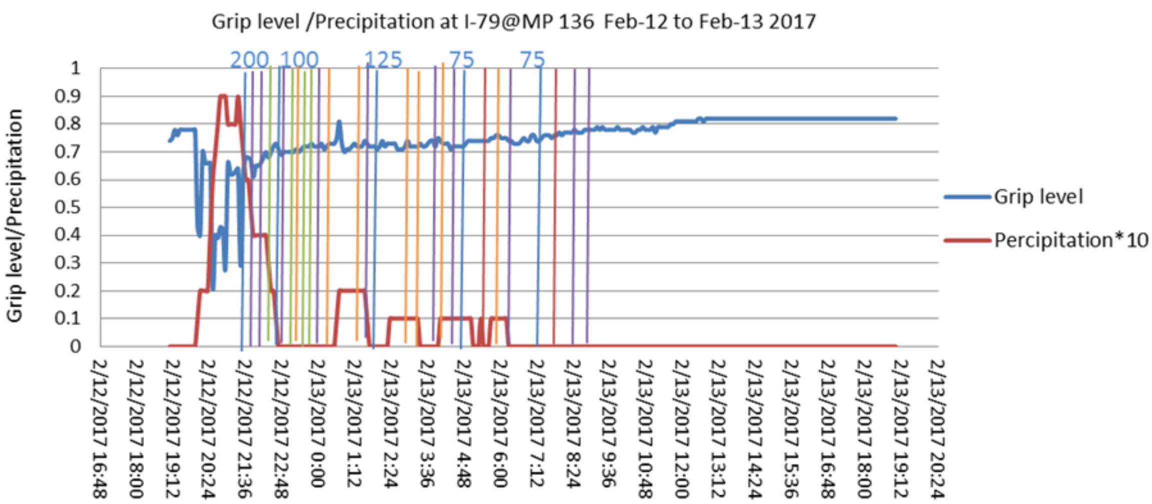
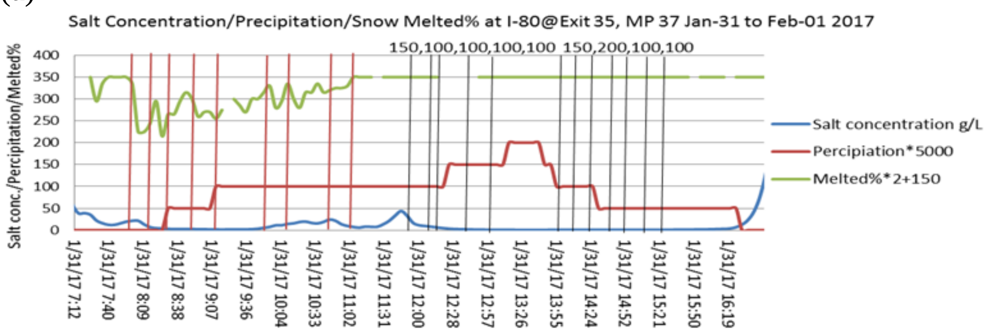


Figure 3.1.19 Grip levels/precipitation variables during 24 hours from Feb 12, 2017 16-00 to Feb 13, 2017 21-00 at site I-79 @ MP 136 Crawford/Mercer Line.

Comparison between AquaSalina and Rock Salt

The snow events on Jan 31, 2017 and Jan 29, 2017 are compared below at the site for AquaSalina (I-80 @ Exit 35 MP 37) and its reference site (I-79 @ MP 136 Crawford/Mercer Line). We chose these two events because there was limited image collection during other time periods and because we have limited data collected for the other three deicers (Beet Heet, Green Blast and Magic Minus Zero).

(a)



(b)

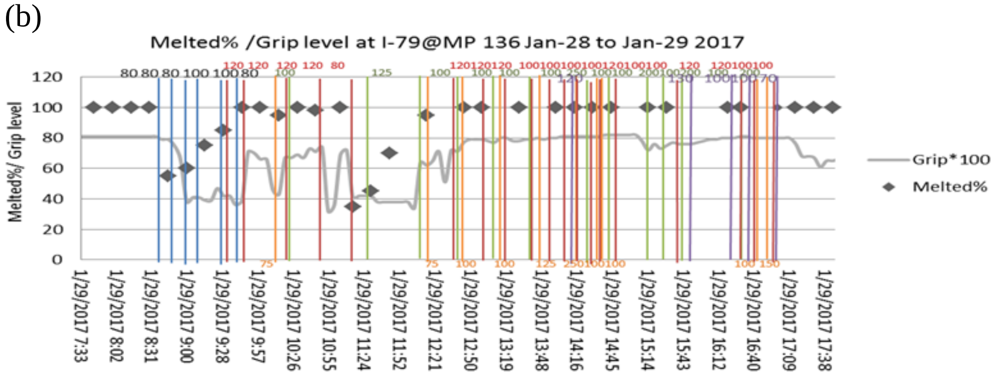


Figure 3.1.20 Comparison of I-80 @ Exit 35 MP 37 (a) with its reference site I-79 @ MP 136 Crawford/Mercer Line (b).

At the site I-80 @ Exit 35 MP 37 (Figure 3.1.20a), the snow melted percentage decreased to 72.5% from 100% (at around 7:25 to 7:30 am), and then recovered to 100% at 7:40 am, within only 10 minutes. The second available image data during this snow event began at 7:55 am. The melted percentage deceased from 100% to 37% within 15 minutes (from 7:55 am to 8:10 am), then the melted percentage increased to 82.5% within 35 min. During this period, there was a lot of precipitation which made the melted percentage remained at around 52.5% to 75%. During this time period, truck 0150-425-8077 applied AquaSalina 9 times (around 7:00-11:00 am Jan-28, 2017). Then Truck 0150-118-8077 applied AquaSalina 9 times (around 11:00-17:00 am Jan-28, 2017). The melted percentage remained at 100% although there was precipitation between 0.02 in. and 0.04 in.

For comparison, at the reference site I-79 @ MP 136, Crawford/Mercer Line, images were available from 7:44 am to 9:44 am, and from 9:59 am to 12:44 am on Jan-29-2017. From 8:29 to 8:44, the melted percentage decreased to 55% because of the precipitation, then recovered to 100% at 9:44 am within 60 minutes. For the second time, the melted percentage decreased to 35% at 11:14, then recovered to 100% at 12:44 within 90 minutes (Figure 3.1.20b). The precipitation was 0.02 in. to 0.05 in. from 8:24 to 13:00 on Jan 29, 2017.

The weather information at these two sites is shown in Table 3.1.1 below. The precipitation between the sites was similar (0.02-0.04 in. for I-80 @ Exit 35 MP 37 and 0.02-0.05 in. for I-79 @ MP 136

Crawford/Mercer Line) and the surface and air temperature were similar as well. The applicate rates were also comparable between these two events: The application rates at site I-80@ Exit 35 MP 37 were from 100 to 120 lb/lane mile, while the application rates at site I-79 @ MP 136 were from 100 to 150 lb/lane mile. Therefore, from the obtained limited data so far, it seems that the recovery times were shorter when AquaSalina was applied. Note that this observation is only based on one event. A number of events should be recorded and analyzed before a firm conclusion can be reached. For more quantitatively comparison about deicer AquaSalina and other deicers (e.g., Beet Heet, Green Blast and Magic Minus Zero), we need to collect additional data and conduct further data analysis in the winter of 2017-2018.

Table 3.1.1 Representative weather information between sites I-80@ Exit 35, MP 37 and its reference site I-79 @ MP 136, Crawford/Mercer Line

Site	Deicer	Date	Precipitation (in.)	Truck passing	Surface temp.	Air temp.
I-80 @ Exit 35 MP 37	Aqua Salir	Jan-31-2017	0.02-0.04	9 times (7:00-13:00)	25.7-32.9	24.1-28.5
I-79 @ MP 136 Crawford/Mercer Line	Rock Salt	Jan-28-2017	0.02-0.05	16 times (7:00-13:00)	2 4.1-31.1	24.8-26.2

3.1.2. Beet Heet (Site I-79 @ Exit 88) & Reference Site (I-79 @ MP 100)

Site I-79 @ Exit 88 – Beet Heet

For site I-79@Exit 88, the snow events recorded were 08-Feb-2017 19:00 to 09-Feb-2017 19:00 I-79 Exit 88; 12-Feb-2017 11:00 to 13-Feb-2017 11:00 I-79 Exit 88; 15-Feb-2017 17:00 to 16-Feb-2017 17:00 I-79 Exit 88; 31-Jan-2017 01:00 to 01-Feb-2017 01:00 I-79 Exit 88; 30-Jan-2017 17:00 to 31-Jan-2017 17:00 I-79 MP100. In the following section, the snow events are discussed separately.

Feb 08, 2017

This site is equipped with the sensor for the salt concentration instead of the grip level. Figure 3.1.21 shows that the air temperature and surface temperature have a similar trend. The temperatures are in the range of 21 ^{0}F to 44 ^{0}F.

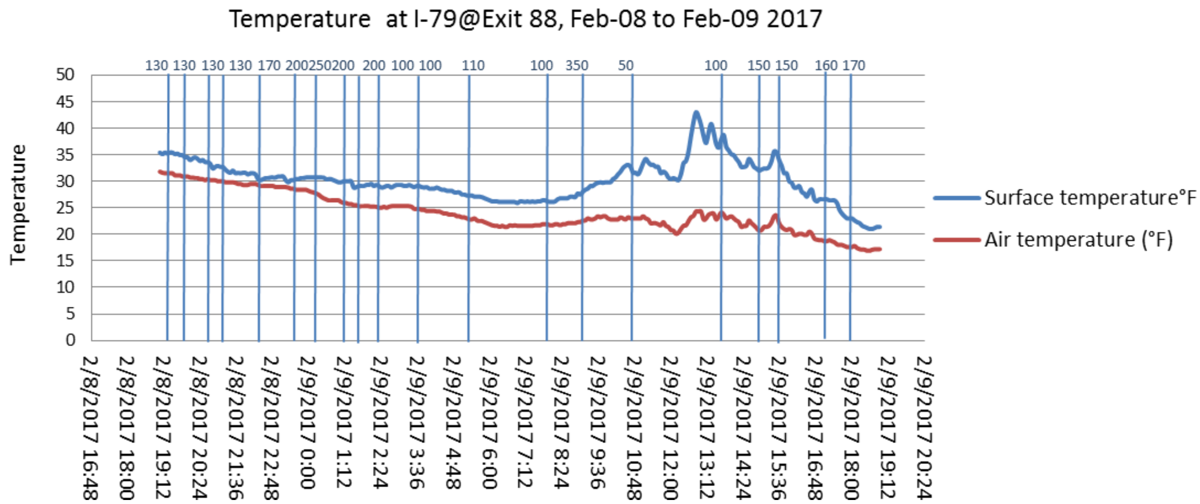


Figure 3.1.21 Surface temperature and air temperature during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at site I-79 @ Exit 88.

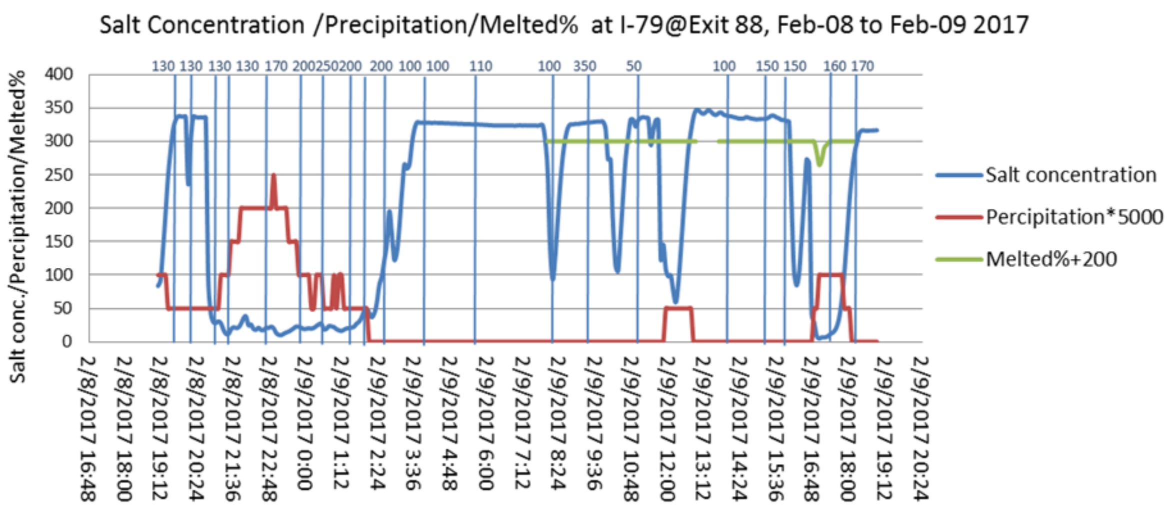


Figure 3.1.22 Salt concentration (g/L), precipitation and melted percentage variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at site I-79 @ Exit 88.

Figure 3.1.22 shows that, generally, when the precipitation level increased, the salt concentration decreased accordingly. On the other hand, the snow melted percentage remained 100% from 8:30 am Feb 09, 2017 to 18:00 Feb 09, 2017, which indicated the deicer applications were effective, which was again not reflected by the recorded salt concentrations.

Feb 12, 2017

Three trucks passed at the site I-79 @ Exit 88 11 times in 24 hours (Figure 3.1.23).

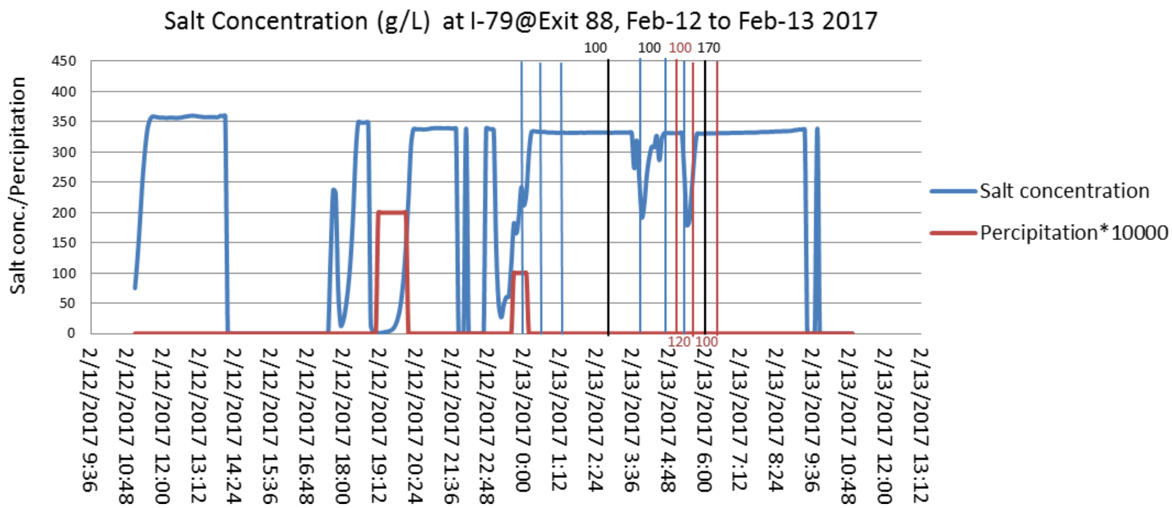


Figure 3.1.23 Salt concentration and precipitation during 24 hours from 12-Feb-2017 16:00 to 13-Feb-2017 17:00 at site I-79 @ Exit 88.

From Figure 3.1.23, we can conclude that the salt concentration remained stable when the deicer Beet Heet was applied. However, the salt concentration had fluctuations to some degree. The reason is unknown.

Feb 15, 2017

Seven trucks passed the site I-79 @ Exit 88 11 times during 24 hours (truck numbers 1020-535-8077; 1020-281-8077; 1020-451-8087; 1020-534-8077; 1020-108-8087; 1020-108-8087; and 1020-496-8077) (Figure 3.1.24).

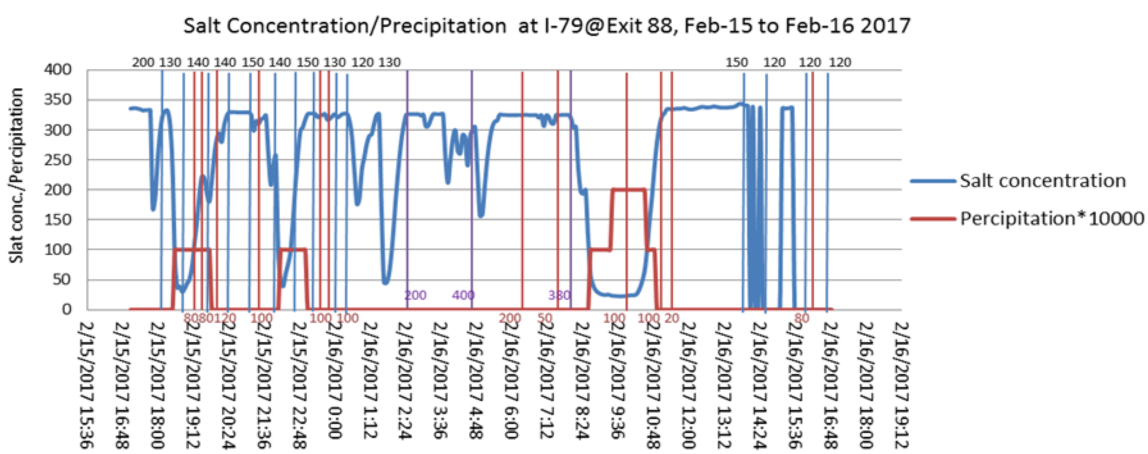


Figure 3.1.24 Salt concentration and precipitation during 24 hours from 15-Feb-2017 16:00 to 16-Feb-2017 17:00 at site I-79 @ Exit 88.

As it can be seen from Figure 3.1.24, there were many fluctuations in the salt concentration when the deicer Beet Heet was applied. It shows the same trend as AquaSalina on Jan-05-2017, Jan-31-2017, and Feb-08-2017: when the precipitation increased, the salt concentration decreased significantly. However, when there was no precipitation, the salt concentration also widely fluctuated. Therefore, we can reach the conclusion that the salt concentration was related with the precipitation, but that unknown factors might influence the salt concentration at the same time.

Jan 30 & Jan 31, 2017

Figure 3.1.25 and 3.1.26 show the salt concentration and precipitation variables during 24 hours from 31-Jan-2017 1600 to 01-Feb-2017 1700 and from Jan-30-2017 1600 to 31- Jan-2017 1700 at site I-79 @ Exit 88. We can reach the same conclusion as from the previous snow events: the salt concentration has an opposite trend with the precipitation in general. When there was no precipitation on the RWIS site, the salt concentration remained at a relatively high value.

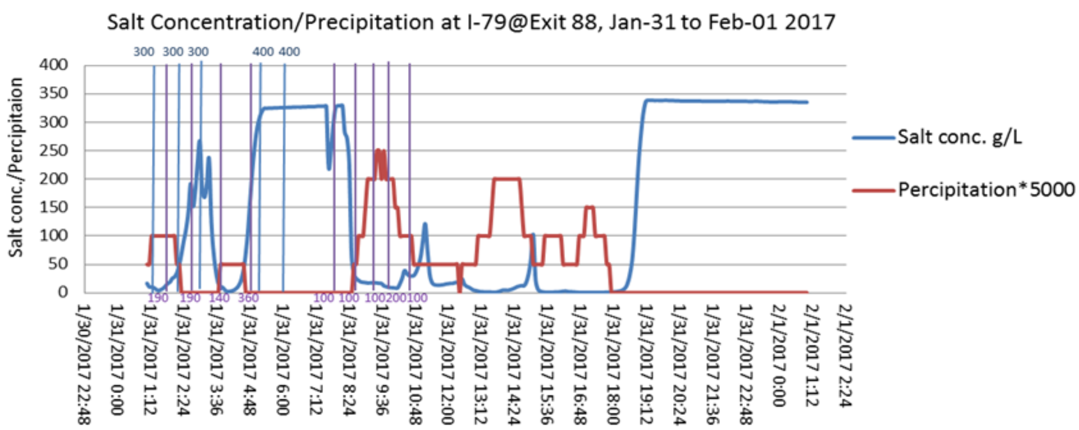


Figure 3.1.25 Salt concentration and precipitation variables during 24 hours from 31-Jan-2017 16:00 to 01-Feb-2017 17:00 at site I-79 @ Exit 88.

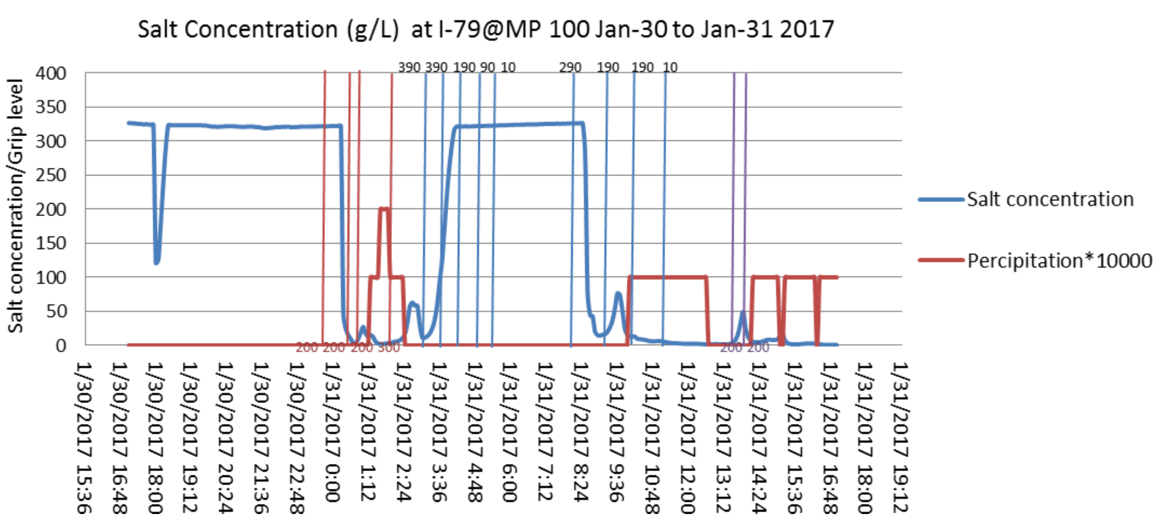


Figure 3.2.26 Salt concentration and precipitation during 24 hours from Jan-30-2017 1600 to 31- Jan-2017 1700 at site I-79 @ Exit 88.

Site I-79 @ MP 100 – Reference site for Beet Heet

At this site, the reference deicer Rock Salt was applied for comparison with Beet Heet. Only one usable snow event was recorded at this site.

Feb 08, 2017

During this event, there was one truck passage during 24 hours from Feb-08-2017 1600 to Feb-09-2017 1700. The surface temperature and air temperature) for this event are shown in Figure 3.1.27. The surface temperature was around 25 to 38 ^{0}F.

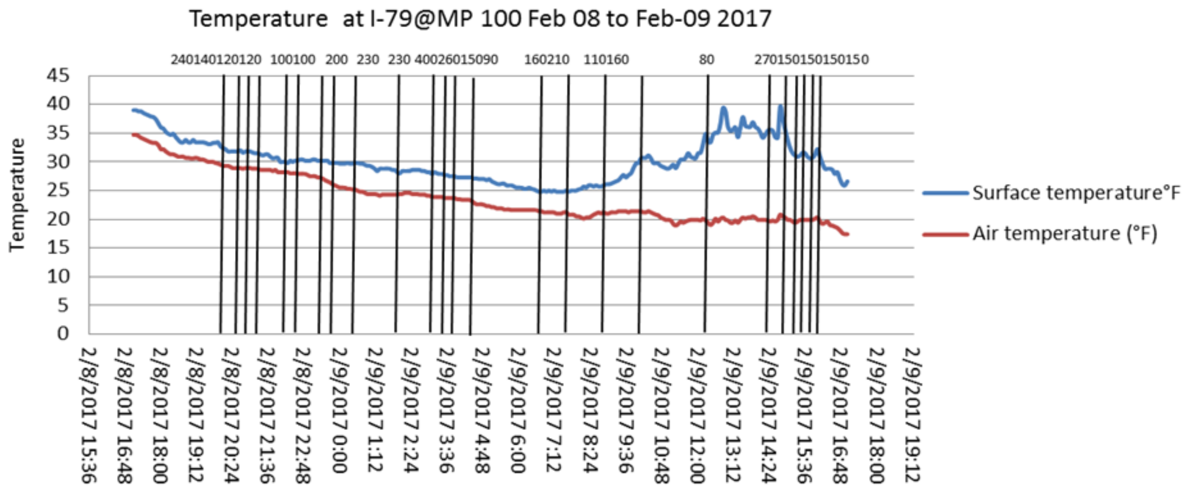


Figure 3.1.27 Surface temperature and air temperature during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at site I-79 @ MP 100.

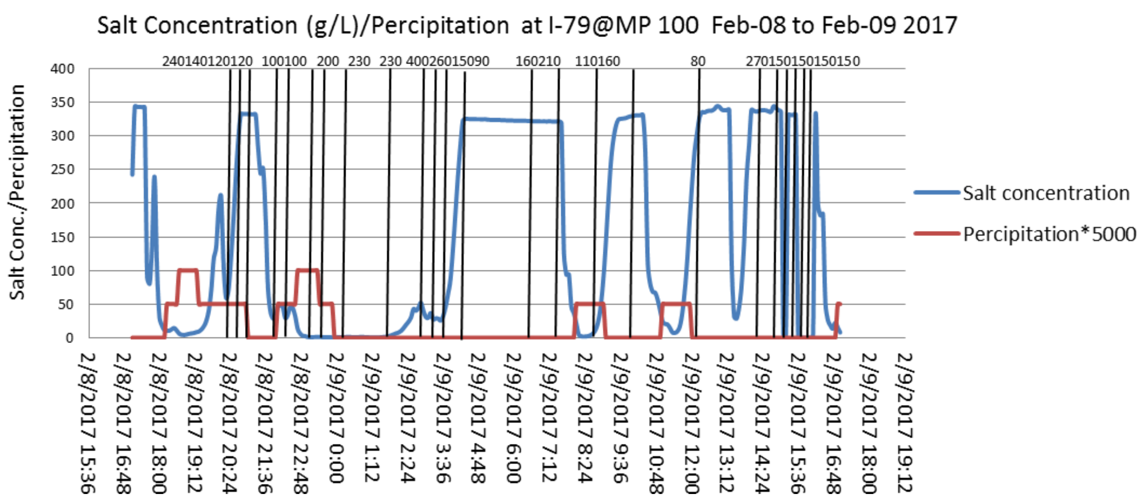


Figure 3.1.28 Salt concentration and precipitations during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at site I-79 @ MP 100.

As can be seen in Figure 3.1.28, the precipitation increased from 18:00 to 20:00 Feb 08, 2017, from 21:30 Feb 08, 2017 to 00:00 Feb 09, 2017, from 8:00 to 9:00 Feb 09, 2017, and from 11:00 to 12:00 Feb 09, 2017 (precipitation 0.02, 0.02, 0.01, and 0.01 in., respectively). During the same time period, the salt concentration decreased significantlyto nearly 0 g/L (initial salt concentration was above 300 g/L). This indicates the deicer applications were very effective at increasing the salt concentration.

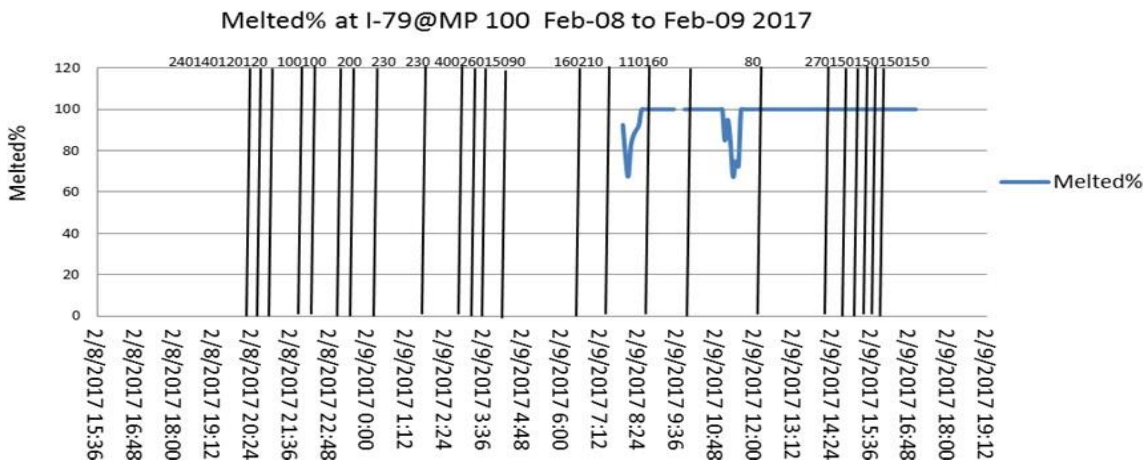


Figure 3.1.29 Snow melted percentage during 24 hours from 08-Feb-2017 16:00 to 09- Feb-2017 17:00 at site I-79 @ MP 100.

Figure 3.1.29 shows that, after the deicer, was applied, the melted percentage recovered to 100% effectively within around 25 min, and remained at this level until the next precipitation started.

3.1.3. Green Blast (I-81 @ Exit 223 New Milford) & Reference Site (I-81 @ Exit 211 Lenox)

<u>Feb 08, 2017</u>

Site I-81 @ Exit 223 New Milford was used for testing Green Blast, and the reference site I-81 @ Exit 211 Lenox was originally for Rock Salt. For this pair of sites in 2017, there was not much snow. The only snow event recorded was on Feb 08, 2017. Three trucks passed the site I-81@ Exit 223 9 times in the 24-hour time window. During this only usable snow event recorded at these sites, Green Blast was applied to both sites.

Figure 3.1.30 shows temperature (surface temperature and air temperature) variables during 24 hours from 08-Feb-2017 1600 to 09-Feb-2017 1700 at I-81 @ Exit 223 New Milford. In this case the surface temperature is relatively higher than the air temperature. The surface temperature was from 25 to 40 ^{0}F, and the air temperature was from 13 to 34 ^{0}F.

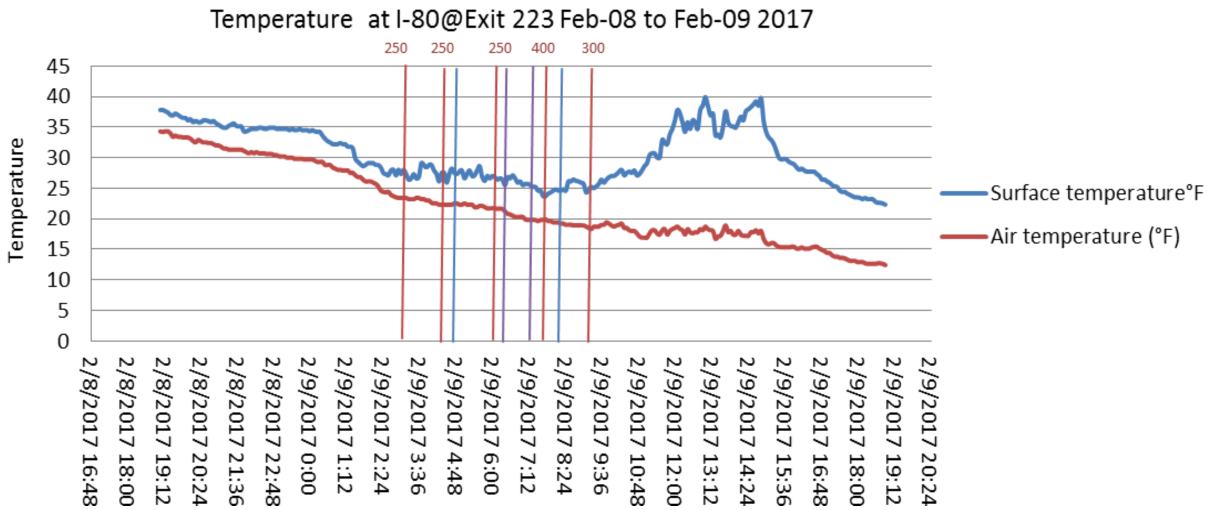


Figure 3.1.30 Surface temperature and air temperature during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at I-81 @ Exit 223 New Milford.

Site I-81 @ Exit 223 New Milford equipped with sensors for the grip level. Figure 3.1.31 shows that when the precipitation increased, the grip level decreased significantly.
Therefore, this is strong evidence that the grip level and precipitation have a good correlation. On the other hand, after several deicer applications, the grip level recovered to 0.72-0.81.

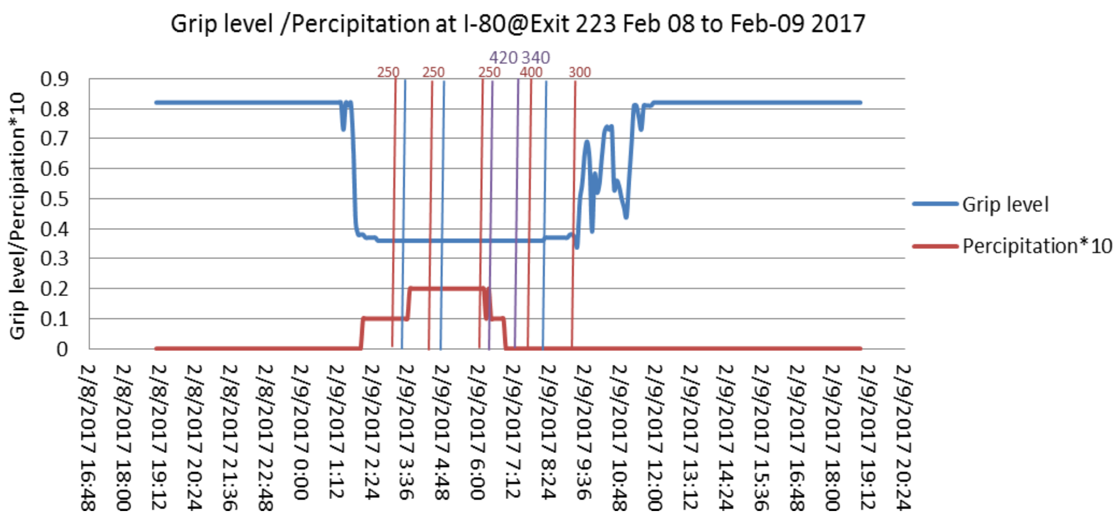


Figure 3.1.31 Grip level and precipitation during 24 hours from 08-Feb-2017 16:00 to 09-Feb- 2017 17:00 at I-81 @ Exit 223 New Milford.

On Feb 08, 2017, the reference site was spread with Green Blast instead of Rock Salt. Figure 3.1.32 shows the temperature (surface temperature and air temperature) variables during 24 hours from 08-Feb-2017 16:00 to 09-Feb-2017 17:00 at I-81 @ Exit 223 New Milford. The surface temperature was from 25 to 28 ^{0}F, and the air temperature was from 14 to 36 ^{0}F.

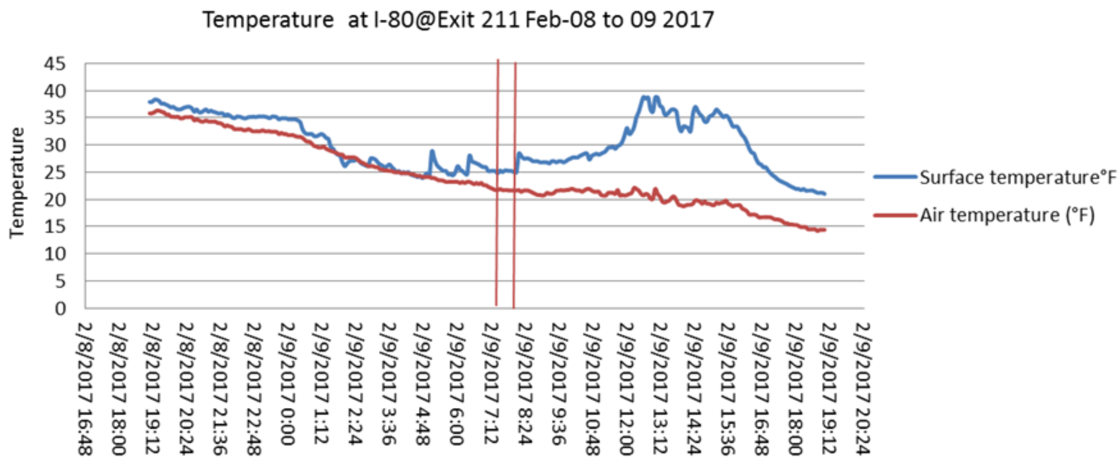


Figure 3.1.32 Surface temperature and air temperature during 24 hours from 08-Feb- 2017 1600 to 09-Feb-2017 1700 at I-80 @ Exit 211 New Milford.

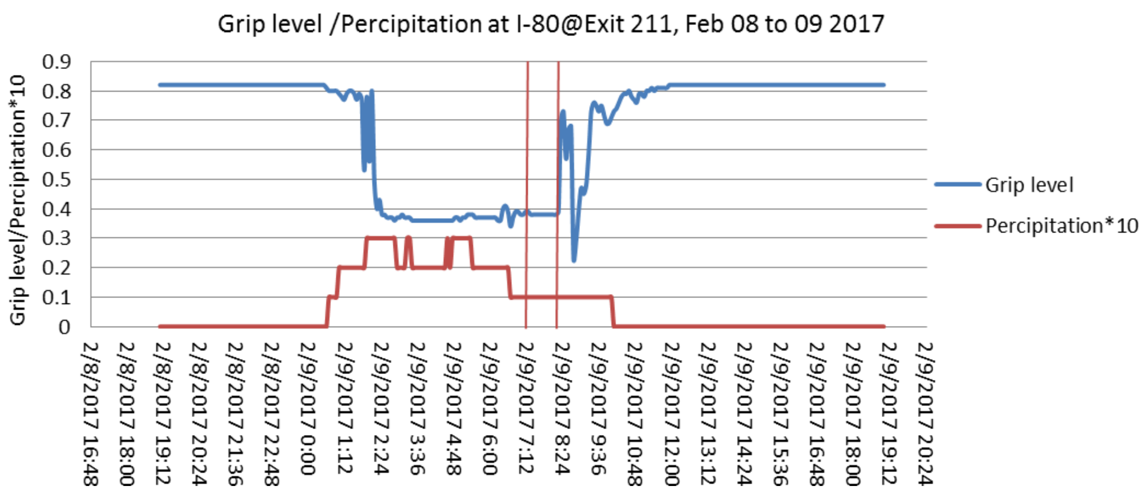


Figure 3.1.33 Surface temperature and air temperature during 24 hours from 08-Feb- 2017 1600 to 09-Feb-2017 1700 at I-81 @ Exit 223 New Milford.

Figure 3.1.33 shows again that when the precipitation increased, the grip level decreased significantly. We only observed two truck passages for this snow event, but it is likely that there were other trucks operating, but not tracked by the AVL system.

3.1.4. Magic Minus Zero (I-81 @ Exit 77 Manada Hill) & Reference Site (I-81 @ I-78 Split)

Feb 08, 2017

Only one snow event was recorded on site I-81 @ Exit 77 Manada Hill on Feb 08, 2017. Two trucks passed the site I-81 @ Exit 77, 32 times in 24 hours. Figure 3.1.34 shows that the surface temperature was from 28 to 49 ^{0}F, and the air temperature was from 22 to 45 ^{0}F.

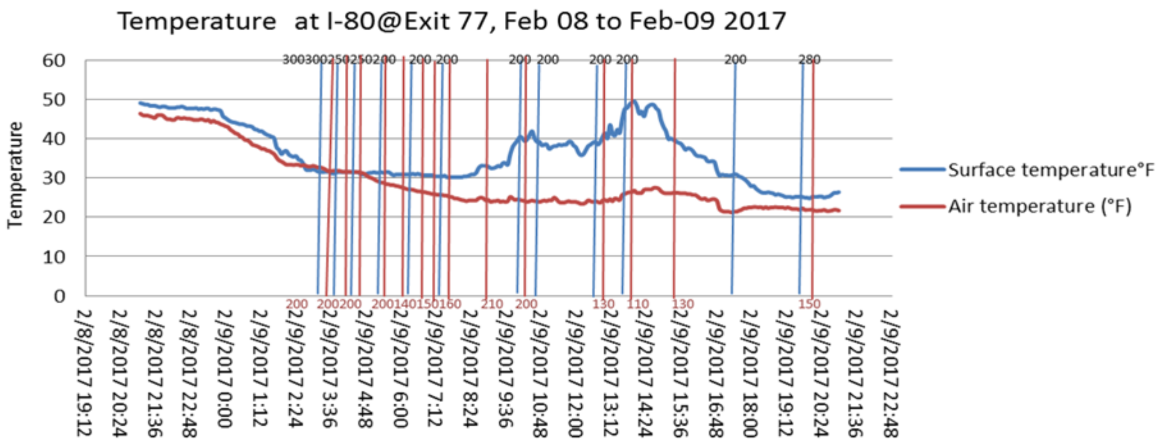


Figure 3.1.34 Surface temperature and air temperature during 24 hours from 08-Feb- 2017 16:00 to 09-Feb-2017 17:00 at I-80 @ Exit 211 New Milford.

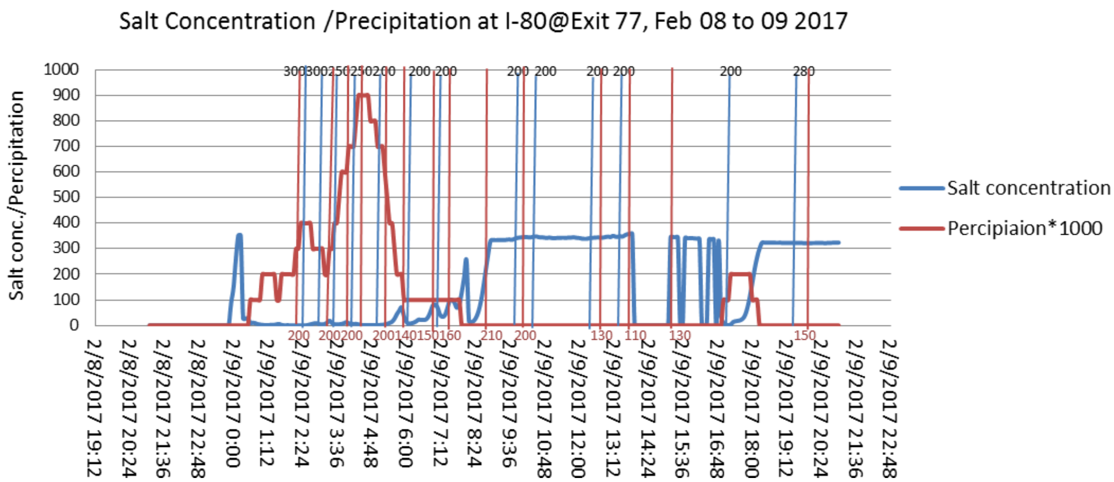


Figure 3.1.35 Salt concentration and precipitation variables during 24 hours from 08- Feb-2017 16:00 to 09-Feb-2017 17:00 at I-80 @ Exit 77.

For this event, the precipitation was heavy, with a value of 0.9 in (Figure 3.1.35). The salt concentration was between 0-350 g/L. There were 3 trucks passages at this site (truck numbers 0850-547-8077, 0850-389-8077 and 0850-324-8077). They passed this site 30 times within 24 hours. Although the precipitation was heavy from 1:12 to 8:00 am on Feb 09, 2017, the salt concentration recovered to a high level at around 9:00. This means the frequent deicer applications were very effective.

3.1.5. Correlation Matrices at Grip Level Sites

In order to understand better the relationships between the different variables, we computed correlations matrices including all environmental variables recorded by the RWIS system plus the snow melted percentage derived from the photographs at the three sites equipped with grip level sensors (I-79 @ MP 136 Crawford/Mercer Line – Rock Salt, I-81 @ Exit 223 New Milford – Green Blast, and I-80 @ Exit 211 Lenox – Green Blast). Because only few data included the snow melted percentages, correlation matrices were computed on the whole set of data (i.e., without removing data without snow melted percentage entries, as it was performed for winter 2017-2018 data).

Table 3.1.2 shows the correlation matrix for all the four storms recorded at the Rock Salt site, I-79 @

MP 136 Crawford/Mercer Line. As at all other sites, the surface temperature correlated well the air temperature. However, the surface temperature did not correlate will with any other significant variables. The grip level did not correlate well with the precipitation 1-hour, but correlated well with the snow layer and snow melted percentage. The snow layer also showed a low correlation with the precipitation and a relatively good correlation with the melted percentage. The precipitation was also relatively well correlated with the melted percentage.

Table 3.1.2 Correlation matrix including all variables recorded during all storms by the RWIS system and the snow melted percentage at site I-79 @ MP 136 Crawford/Mercer Line (Rock Salt). Good correlations (r ≥ 6.0) between snow-significant variables are highlighted in green, less significant correlations between snow-significant variables (r < 6.0) are highlighted in red

	Surf T	**Air T**	**Dew P**	**Grip**	**Ice**	**Snow**	**Rel Hum**	**Wind Sp**	**Barom**	**Prec 1 h**	**W Sp Max**	**Melted**
Surf T		0.735	0.375	0.058	-0.010	-0.062	-0.281	0.309	-0.171	-0.003	0.271	0.449
Air T	0.735		0.796	-0.142	0.084	0.074	0.082	0.128	-0.459	0.116	0.162	0.104
Dew Pt	0.375	0.796		-0.418	0.248	0.296	0.666	-0.080	-0.680	0.363	-0.009	-0.175
Grip	0.058	-0.142	-0.418		-0.631	-0.871	-0.541	0.027	0.351	-0.520	0.012	0.693
Ice	-0.010	0.084	0.248	-0.631		0.537	0.324	-0.100	-0.250	0.215	-0.124	0.039
Snow	-0.062	0.074	0.296	-0.871	0.537		0.422	-0.146	-0.309	0.369	-0.146	-0.591
Rel Hum	-0.281	0.082	0.666	-0.541	0.324	0.422		-0.289	-0.566	0.481	-0.218	-0.421
Wind Sp	0.309	0.128	-0.080	0.027	-0.100	-0.146	-0.289		0.288	0.179	0.861	0.155
Barom	-0.171	-0.459	-0.680	0.351	-0.250	-0.309	-0.566	0.288		-0.201	0.244	-0.083
Prec 1 h	-0.003	0.116	0.363	-0.520	0.215	0.369	0.481	0.179	-0.201		0.209	-0.581
W Sp Max	0.271	0.162	-0.009	0.012	-0.124	-0.146	-0.218	0.861	0.244	0.209		0.112
Melted	0.449	0.104	-0.175	0.693	0.039	-0.591	-0.421	0.155	-0.083	-0.581	0.112	

Table 3.1.3 shows the correlation matrix for all the storms recorded at the Green Blast sites, I-81 @ Exit 223 New Milford and I-80 @ Exit 211 Lenox (the latter received Green Blast although it was originally designed to receive the reference Rock Salt). Unlike other sites, the surface temperature did not correlate well the air temperature. The grip level correlated well with the snow layer and precipitation 1-hour. No photographs were recorded, so not data were obtained for the snow melted percentage. The snow layer also showed a good correlation with the precipitation 1-hour.

Table 3.1.3 Correlation matrix including all variables recorded during all storms by the RWIS system at site I-81 @ Exit 223 New Milford and I-80 @ Exit 211 Lenox (Green Blast). Good correlations (r ≥ 6.0) between snow-significant variables are highlighted in green, less significant correlations between snow-significant variables (r < 6.0) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Prec 1 h	W Sp Max
Surf T		0.540	0.134	0.585	-0.135	-0.481	-0.395	0.095	-0.417	0.040
Air T	0.540		0.854	0.104	-0.094	-0.076	0.346	-0.628	0.084	-0.725
Dew Pt	0.134	0.854		-0.374	0.012	0.326	0.783	-0.795	0.421	-0.888
Grip	0.585	0.104	-0.374		-0.124	-0.868	-0.817	0.302	-0.685	0.334
Ice	-0.135	-0.094	0.012	-0.124		-0.029	0.126	-0.026	-0.020	-0.011
Snow	-0.481	-0.076	0.326	-0.868	-0.029		0.702	-0.245	0.608	-0.286
Rel Hum	-0.395	0.346	0.783	-0.817	0.126	0.702		-0.667	0.684	-0.725
Wind Sp	0.095	-0.628	-0.795	0.302	-0.026	-0.245	-0.667		-0.313	0.886
Prec 1 h	-0.417	0.084	0.421	-0.685	-0.020	0.608	0.684	-0.313		-0.394
W Sp Max	0.040	-0.725	-0.888	0.334	-0.011	-0.286	-0.725	0.886	-0.394	

3.2. Winter 2017-2018

The storm events recorded and data collected were summarized for each site/deicer product. Correlation matrices were computed to understand the overall relationships between all the variables recorded by the RWIS system. Then, only a few representative storm events per site were described with more detail. Essentially, the five variables expected to be representative of the snow conditions (slightly different than for winter 2016-2017 because all sites were equipped with grip level sensors): surface temperature, grip level, snow layer , precipitation 1-hour, and snow melted percentage, were discussed.

3.2.1. Site SR 322 W/B, Venango-Mercer Co. Line – AquaSalina

Six snow events were recorded at this site: Nov-19 12:00 to Nov 20 12:00, Dec-11 12:00 to Dec 12 12:00, Dec-12 12:00 to Dec 13 12:00, Dec-13 12:00 to Dec 14 12:00, Dec-15 12:00 to Dec 16 12:00, and Dec-24 12:00 to Dec 25 12:00. In the following sections, we analyzed the relationships between the most significant variables recorded for all storm events at the AquaSalina site (correlation matrices). Then a representative storm was studied in more details, which included the graphical analysis of the most significant variables and their changes with the precipitation and application of deicer products.

AquaSalina was used as it, according to the manufacturer recommendation, and applied together with antiskid product in the ratio of 67/33 volume/volume.

<u>All Storms Events</u>
In order to understand better the relationships between the different variables, we computed correlations matrices including all environmental variables recorded by the RWIS system plus the snow melted percentage derived from the photographs. Table 3.2.1 shows the correlation matrix for all the six storms recorded at the AquaSalina site. The following discussion focused on the 'significant' variables with respect to the snow and road conditions: the surface temperature, grip level, snow layer, precipitation 1-hour, and snow melted percentage. As at all other sites, the surface temperature correlated well the air temperature. However, the surface temperature did not correlate well with any other significant variables. The grip level did not correlate well with the precipitation 1-hour, but correlated well with the

snow layer and snow melted percentage. The snow layer also showed a low correlation with the precipitation and a good correlation with the melted percentage. The precipitation was well correlated with the melted percentage.

Table 3.2.1 Correlation matrix including all variables recorded during all storms by the RWIS system and the snow melted percentage at site SR 322 W/B, Venango-Mercer Co. Line (AquaSalina). Good correlations (r ≥ 6.0) between snow-significant variables are highlighted in green, less significant correlations between snow-significant variables (r < 6.0) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted%
Surf T		0.886	0.657	0.372	0.069	-0.296	-0.368	-0.131	0.454	-0.179	-0.266	-0.114	-0.152	0.406
Air T	0.886		0.875	0.254	0.138	-0.212	-0.156	-0.155	0.434	-0.118	-0.313	-0.127	-0.183	0.233
Dew Pt	0.657	0.875		-0.052	0.190	0.038	0.340	-0.219	0.217	0.148	-0.324	-0.179	-0.250	-0.009
Grip	0.372	0.254	-0.052		-0.306	-0.756	-0.632	-0.071	0.310	-0.581	-0.154	-0.068	-0.071	0.692
Ice	0.069	0.138	0.190	-0.306		0.037	0.114	0.057	0.053	-0.003	0.114	0.050	0.061	-0.010
Snow	-0.296	-0.212	0.038	-0.756	0.037		0.528	-0.104	-0.466	0.561	-0.125	-0.093	-0.120	-0.755
Rel Hum	-0.368	-0.156	0.340	-0.632	0.114	0.528		-0.160	-0.426	0.565	-0.049	-0.131	-0.168	-0.569
Wind Sp	-0.131	-0.155	-0.219	-0.071	0.057	-0.104	-0.160		0.345	0.051	0.526	0.881	0.940	-0.243
Barom	0.454	0.434	0.217	0.310	0.053	-0.466	-0.426	0.345		-0.259	0.194	0.338	0.343	0.109
Prec 1 h	-0.179	-0.118	0.148	-0.581	-0.003	0.561	0.565	0.051	-0.259		0.008	0.054	0.049	-0.677
Wind Dir	-0.266	-0.313	-0.324	-0.154	0.114	-0.125	-0.049	0.526	0.194	0.008		0.463	0.556	-0.182
Wind Spd	-0.114	-0.127	-0.179	-0.068	0.050	-0.093	-0.131	0.881	0.338	0.054	0.463		0.839	-0.233
Max W Spd	-0.152	-0.183	-0.250	-0.071	0.061	-0.120	-0.168	0.940	0.343	0.049	0.556	0.839		-0.257
Melted%	0.406	0.233	-0.009	0.692	-0.010	-0.755	-0.569	-0.243	0.109	-0.677	-0.182	-0.233	-0.257	

In an attempt to improve the correlations, we removed data with flat trend, i.e., snow layer at zero (Table 3.2.2) and data with no snow melted percentage entries (Table 3.2.3).

When we removed all data points with the snow layer at zero (Table 3.2.2), we did not obtain better correlations – actually the opposite: only the precipitation correlated with the snow melted percentage.

Table 3.2.2 Correlation matrix including variables recorded during all storms by the RWIS system and the snow melted percentage at site SR 322 W/B, Venango-Mercer Co. Line (AquaSalina). Data with the snow layer at zero were removed. Good correlations (r ≥ 6.0) between snow-significant variables are highlighted in green, less significant correlations between snow-significant variables (r < 6.0) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted%
Surf T		0.964	0.920	-0.336	0.441	-0.244	0.351	0.068	0.293	0.139	0.181	0.073	0.055	0.154
Air T	0.964		0.950	-0.335	0.437	-0.201	0.352	0.031	0.305	0.112	0.188	0.041	0.017	0.189
Dew Pt	0.920	0.950		-0.329	0.321	-0.053	0.625	-0.142	0.095	0.258	0.095	-0.114	-0.164	-0.043
Grip	-0.336	-0.335	-0.329		-0.399	-0.301	-0.157	0.076	-0.003	-0.104	0.125	0.049	0.102	0.304
Ice	0.441	0.437	0.321	-0.399		-0.266	-0.122	0.079	0.203	-0.225	0.135	0.068	0.087	0.304
Snow	-0.244	-0.201	-0.053	-0.301	-0.266		0.349	-0.342	-0.594	0.279	-0.520	-0.305	-0.376	-0.489
Rel Hum	0.351	0.352	0.625	-0.157	-0.122	0.349		-0.518	-0.491	0.491	-0.186	-0.457	-0.547	-0.456
Wind Sp	0.068	0.031	-0.142	0.076	0.079	-0.342	-0.518		0.644	-0.033	0.337	0.878	0.948	-0.109
Barom	0.293	0.305	0.095	-0.003	0.203	-0.594	-0.491	0.644		-0.158	0.451	0.611	0.642	-0.057
Prec 1 h	0.139	0.112	0.258	-0.104	-0.225	0.279	0.491	-0.033	-0.158		-0.208	-0.020	-0.032	-0.632
Wind Dir	0.181	0.188	0.095	0.125	0.135	-0.520	-0.186	0.337	0.451	-0.208		0.281	0.354	0.120
Wind Spd	0.073	0.041	-0.114	0.049	0.068	-0.305	-0.457	0.878	0.611	-0.020	0.281		0.840	-0.141
Max W Spd	0.055	0.017	-0.164	0.102	0.087	-0.376	-0.547	0.948	0.642	-0.032	0.354	0.840		-0.075
Melted%	0.154	0.189	-0.043	0.304	0.304	-0.489	-0.456	-0.109	-0.057	-0.632	0.120	-0.141	-0.075	

When we removed all data points without snow melted percentage entries (Table 3.2.3), we obtained better correlations between the variables of interest: the grip level correlated with the snow layer, precipitation, and snow melted percentage, the snow layer correlated with the snow melted percentage (and to a lesser extent with the precipitation), and the precipitation correlated with the snow melted percentage. On the other hand, the surface temperature did not correlate any other significant variables.

Table 3.2.3 Correlation matrix including variables recorded during all storms by the RWIS system and the snow melted percentage at site SR 322 W/B, Venango-Mercer Co. Line (AquaSalina). Data without snow melted percentage values were removed. Good correlations ($r \geq 6.0$) between snow-significant variables are highlighted in green, less significant correlations between snow-significant variables ($r < 6.0$) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted%
Surf T		0.895	0.729	0.522	0.061	-0.377	-0.191	-0.335	0.329	-0.331	-0.569	-0.295	-0.354	0.406
Air T	0.895		0.918	0.274	0.187	-0.148	0.048	-0.425	0.362	-0.224	-0.605	-0.371	-0.433	0.233
Dew Pt	0.729	0.918		0.008	0.314	0.076	0.440	-0.379	0.255	0.005	-0.587	-0.328	-0.379	-0.009
Grip	0.522	0.274	0.008		-0.276	-0.866	-0.618	-0.349	0.126	-0.608	-0.334	-0.315	-0.377	0.692
Ice	0.061	0.187	0.314	-0.276		0.159	0.392	0.003	-0.262	0.022	0.114	-0.022	0.012	-0.010
Snow	-0.377	-0.148	0.076	-0.866	0.159		0.545	0.327	-0.028	0.577	0.174	0.317	0.335	-0.755
Rel Hum	-0.191	0.048	0.440	-0.618	0.392	0.545		0.011	-0.187	0.532	-0.088	0.018	0.031	-0.569
Wind Sp	-0.335	-0.425	-0.379	-0.349	0.003	0.327	0.011		0.055	0.434	0.570	0.868	0.928	-0.243
Barom	0.329	0.362	0.255	0.126	-0.262	-0.028	-0.187	0.055		-0.028	-0.281	0.129	0.012	0.109
Prec 1 h	-0.331	-0.224	0.005	-0.608	0.022	0.577	0.532	0.434	-0.028		0.269	0.402	0.448	-0.677
Wind Dir	-0.569	-0.605	-0.587	-0.334	0.114	0.174	-0.088	0.570	-0.281	0.269		0.474	0.614	-0.182
Wind Spd	-0.295	-0.371	-0.328	-0.315	-0.022	0.317	0.018	0.868	0.129	0.402	0.474		0.811	-0.233
Max W Spd	-0.354	-0.433	-0.379	-0.377	0.012	0.335	0.031	0.928	0.012	0.448	0.614	0.811		-0.257
Melted%	0.406	0.233	-0.009	0.692	-0.010	-0.755	-0.569	-0.243	0.109	-0.677	-0.182	-0.233	-0.257	

Further analyses will then include the variables that seem to be more significant in terms of road conditions: grip level, snow layer, precipitation 1-hour and snow melted percentage.

<u>Dec-24 12:00 to Dec 25 12:00</u>

Analysis of the data showed a typical pattern that will be globally retrieved at other sites and during other storms.

First and as shown in all correlation analyses performed, the surface and air temperature were highly correlated (Figure 3.2.1). Because of this observation and because the surface temperature is expected to reflects better the road conditions, we will not include the air temperature in further discussions. In the case of this storm, we observed a relationship between surface temperature and snow layer and precipitation (especially apparent after 3:00), likely reflecting the cooling of the surface when it becomes covered with snow.

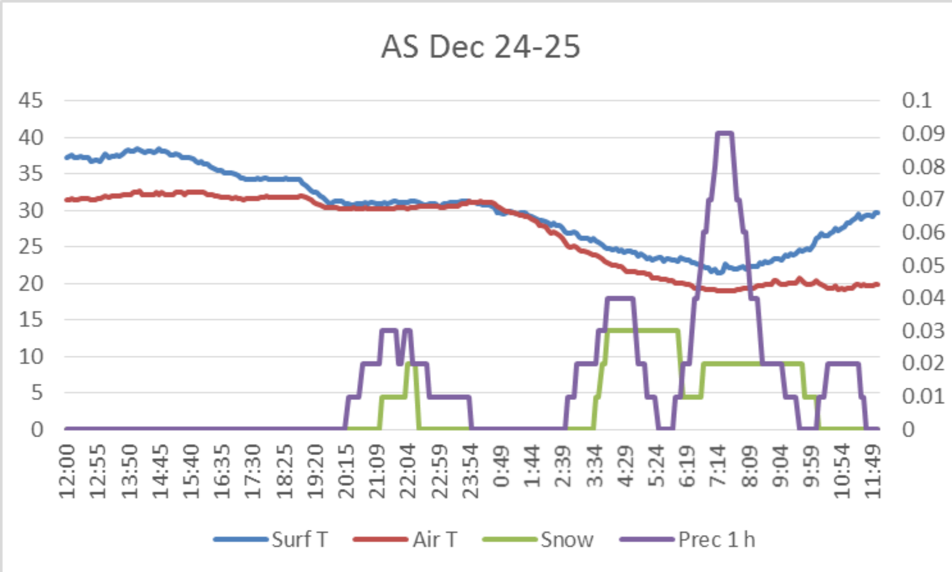


Figure 3.2.1 Surface temperature, air temperature, snow layer, and precipitation 1-hour at site SR 322 W/B, Venango-Mercer Co. Line (AquaSalina) on Dec-24 12:00 to Dec 25 12:00.
Temperatures are on the left axis (°F), snow layer and precipitation (in.) are on the right axis.

The variables that are included in the graphical representations of the storms include the grip level, snow melted percentage, snow layer, and precipitation 1-hour (Figure 3.2.2). We observed that the grip level decreased before (first snow event: 20:00-24:00) or shortly after (second snow event: 3:00-11:00) the onset of the snow precipitation, which was in turn followed by an increase of the snow layer. We also observed that the snow layer on the road did not correlate as well as anticipated the precipitation 1-hour, which may be explained by snow packing or other local effects. This therefore indicates that both the grip level and snow layer are good indicator of the road condition and, therefore, of the deicing performance.

Figure 3.2.2 also shows the effect of the application of deicer on the road condition, as represented by the grip level and snow melted percentage. For both snow events shown, the 1st truck passage of the 1st event (Dec 24 19:50) and the two 1st truck passages of the 2nd event (Dec 25, 6:05 & 6:15) did not have a significant effect on the grip level (the snow melted percentage was not recorded at that time because of darkness), presumably because of ongoing precipitation. The 2nd and 3rd truck passage during the 1st event (Dec 24 22:17 & 22:25), occurring when the precipitation was decreasing, resulted in a sharp increase of the grip level. The 3rd truck passage during the 2nd event (Dec 25 8:25), also occurring when the precipitation was decreasing, resulted in a sharp increase of the snow melted percentage. The corresponding increase of the grip level occurred with a 2- hour delay.

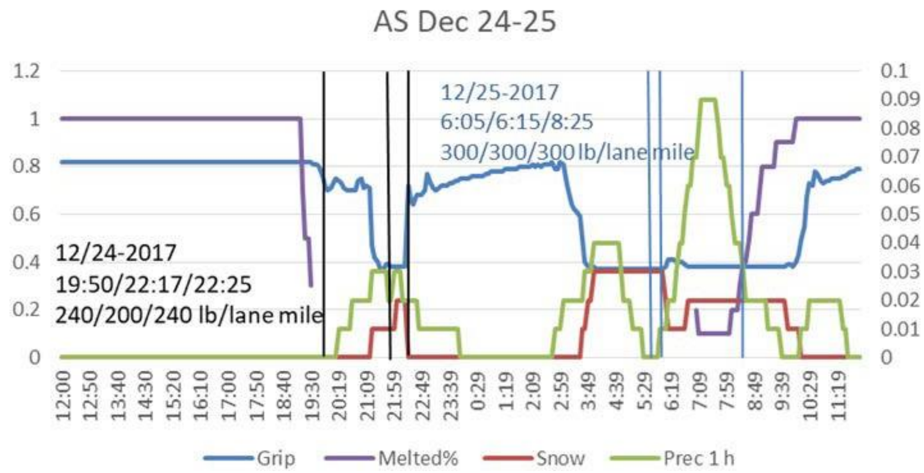


Figure 3.2.2 Grip level, snow melted percentage, snow layer, and precipitation 1-hour at site SR 322 W/B, Venango-Mercer Co. Line (AquaSalina) on Dec-24 12:00 to Dec 25. Grip level (arbitrary units) and snow melted percentage (in.) are on the left axis, snow layer and precipitation 1-hour (in.) are on the right axis. Vertical lines show the truck passages labelled with the passage time and the deicer spread rate (lb/mile line).

3.2.3. Site I-79 N/B @ Exit 60 Carfton Allegheny Co. – Beet Heet

No data were recorded for the Beet Heet site.

3.2.4. Site I-81 @ Exit 223, New Milford – Green Blast

Due to technical problem beyond the Team's responsibility, data could only be collected at this site prior to December 15. Therefore, only one snow event was recorded: Dec-13 12:00 to Dec 14 12:00.

In the following sections, we analyzed the relationships between the most snow- significant variables recorded at the Green Blast site (correlation matrices). The storm was then studied in more details, which included the graphical analysis of the most significant variables and their changes with the precipitation and application of deicer products.

Green Blast was prepared according to the manufacturer recommendation by mixing with salt brine in the ratio of 1:4 volume/volume. The liquid mix was then applied together with an antiskid product in the ratio of 50:33 volume/volume.

<u>Dec-13 12:00 to Dec 14 12:00</u>
As for the prior site, correlations matrices including all environmental variables recorded by the RWIS system plus the snow melted percentage were computed. Table 3.2.4 shows the correlation matrix for the only storm recorded at the Green Blast site. We focused on the significant variables with respect to snow and road conditions: the surface temperature, grip level, snow layer, precipitation 1-hour, and snow melted percentage. As in other storms, the surface temperature correlated well the air temperature. The grip level did not correlate well with the surface temperature and precipitation 1-hour, but correlated well with the snow layer and snow melted percentage. The snow layer also showed a low correlation with the precipitation and melted percentage. No correlation could be calculated between the precipitation 1-hour and snow melted percentage.

Table 3.2.4 Correlation matrix including all variables recorded during all storms by the RWIS system and the snow melted percentage at site I-81 @ Exit 223, New Milford (Green Blast). Good correlations (r ≥ 6.0) between snow-significant variables are highlighted in green, less significant correlations between snow-significant variables (r < 6.0) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted
Surf T		0.874	-0.503	0.409		-0.291	-0.613	0.833	0.236	-0.178	0.408	0.772	0.849	0.282
Air T	0.874		-0.697	0.512		-0.346	-0.795	0.847	0.233	-0.222	0.516	0.781	0.874	0.164
Dew Pt	-0.503	-0.697		-0.721		0.556	0.985	-0.625	-0.131	0.302	-0.505	-0.574	-0.623	0.028
Grip	0.409	0.512	-0.721			-0.822	-0.746	0.530	0.634	-0.387	0.507	0.470	0.583	0.640
Ice														
Snow	-0.291	-0.346	0.556	-0.822			0.566	-0.399	-0.546	0.323	-0.370	-0.362	-0.464	-0.556
Rel Hum	-0.613	-0.795	0.985	-0.746		0.566		-0.695	-0.210	0.310	-0.536	-0.639	-0.705	-0.053
Wind Sp	0.833	0.847	-0.625	0.530		-0.399	-0.695		0.323	-0.230	0.606	0.888	0.935	0.342
Barom	0.236	0.233	-0.131	0.634		-0.546	-0.210	0.323		-0.242	0.413	0.249	0.395	0.784
Prec 1 h	-0.178	-0.222	0.302	-0.387		0.323	0.310	-0.230	-0.242		-0.279	-0.216	-0.257	
Wind Dir	0.408	0.516	-0.505	0.507		-0.370	-0.536	0.606	0.413	-0.279		0.630	0.603	0.413
Wind Spd	0.772	0.781	-0.574	0.470		-0.362	-0.639	0.888	0.249	-0.216	0.630		0.862	0.285
Max W Sp	0.849	0.874	-0.623	0.583		-0.464	-0.705	0.935	0.395	-0.257	0.603	0.862		0.423
Melted	0.282	0.164	0.028	0.640		-0.556	-0.053	0.342	0.784		0.413	0.285	0.423	

As in the prior analysis, we removed data with 'flat' trend, i.e., snow layer at zero (Table 3.2.5) and data without snow melted percentage entries (Table 3.2.6).

In the case of this storm, removing all data points snow layer at zero (Table 3.2.5) did not improve correlations between the variables of interest: significant correlations were only observed between the surface temperature and snow melted percentage, and between the grip level and snow layer.

Table 3.2.5 Correlation matrix including variables recorded during all storms by the RWIS system and the snow melted percentage at site I-81 @ Exit 223, New Milford (Green Blast). Data with the snow layer at zero were removed. Good correlations (r ≥ 6.0) between snow-significant variables are highlighted in green, less significant correlations between snow-significant variables (r < 6.0) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted
Surf T		0.485	0.282	-0.123		0.101	-0.041	-0.561	-0.804	0.024	-0.529	-0.538	-0.517	-0.775
Air T	0.485		0.928	-0.366		0.283	0.682	-0.161	-0.581	-0.039	-0.030	-0.166	-0.128	-0.756
Dew Pt	0.282	0.928		-0.314		0.257	0.869	-0.059	-0.495	-0.098	0.118	-0.047	-0.040	-0.450
Grip	-0.123	-0.366	-0.314			-0.600	-0.244	0.003	0.186	-0.010	0.028	0.155	0.081	0.276
Ice														
Snow	0.101	0.283	0.257	-0.600			0.262	0.004	-0.298	0.023	0.023	-0.120	-0.183	-0.192
Rel Hum	-0.041	0.682	0.869	-0.244		0.262		0.088	-0.272	-0.199	0.310	0.126	0.061	0.453
Wind Sp	-0.561	-0.161	-0.059	0.003		0.004	0.088		0.475	-0.052	0.574	0.693	0.666	0.407
Barom	-0.804	-0.581	-0.495	0.186		-0.298	-0.272	0.475		0.076	0.401	0.466	0.480	0.739
Prec 1 h	0.024	-0.039	-0.098	-0.010		0.023	-0.199	-0.052	0.076		-0.212	-0.160	-0.089	
Wind Dir	-0.529	-0.030	0.118	0.028		0.023	0.310	0.574	0.401	-0.212		0.815	0.518	0.465
Wind Spd	-0.538	-0.166	-0.047	0.155		-0.120	0.126	0.693	0.466	-0.160	0.815		0.568	0.415
Max W Sp	-0.517	-0.128	-0.040	0.081		-0.183	0.061	0.666	0.480	-0.089	0.518	0.568		0.466
Melted	-0.775	-0.756	-0.450	0.276		-0.192	0.453	0.407	0.739		0.465	0.415	0.466	

When we removed all data points without snow melted percentage entries (Table 3.2.6), we obtained slightly better correlations between the variables of interest: the grip level correlated well with the snow layer and snow melted percentage, the snow layer correlated marginally with the snow melted percentage (r = -0.56). No correlations could be calculated with the precipitation 1-hour as the variable was at zero for all time points. The surface temperature did not correlate with any other variables.

Table 3.2.6 Correlation matrix including variables recorded during all storms by the RWIS system and the snow melted percentage at site I-81 @ Exit 223, New Milford (Green Blast). Data without snow melted percentage values were removed. Good correlations (r ≥ 6.0) between snow- significant variables are highlighted in green, less significant correlations between snow- significant variables (r < 6.0) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hu	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted
Surf T		0.858	-0.527	0.462		-0.313	-0.644	0.824	0.143		0.409	0.748	0.850	0.282
Air T	0.858		-0.777	0.626		-0.415	-0.875	0.835	0.140		0.534	0.754	0.877	0.164
Dew Pt	-0.527	-0.777		-0.627		0.457	0.981	-0.672	0.119		-0.519	-0.602	-0.662	0.028
Grip	0.462	0.626	-0.627			-0.811	-0.680	0.620	0.582		0.619	0.527	0.672	0.640
Ice														
Snow	-0.313	-0.415	0.457	-0.811			0.485	-0.445	-0.490		-0.446	-0.382	-0.497	-0.556
Rel Hum	-0.644	-0.875	0.981	-0.680		0.485		-0.743	0.005		-0.559	-0.666	-0.749	-0.053
Wind Sp	0.824	0.835	-0.672	0.620		-0.445	-0.743		0.184		0.613	0.867	0.926	0.342
Barom	0.143	0.140	0.119	0.582		-0.490	0.005	0.184			0.363	0.108	0.261	0.784
Prec 1 h														
Wind Dir	0.409	0.534	-0.519	0.619		-0.446	-0.559	0.613	0.363			0.611	0.604	0.413
Wind Spd	0.748	0.754	-0.602	0.527		-0.382	-0.666	0.867	0.108		0.611		0.838	0.285
Max W Sp	0.850	0.877	-0.662	0.672		-0.497	-0.749	0.926	0.261		0.604	0.838		0.423
Melted	0.282	0.164	0.028	0.640		-0.556	-0.053	0.342	0.784		0.413	0.285	0.423	

Unlike at the AquaSalina site, we did observed a clear relationship between the surface temperature, snow layer, and precipitation, which confirms the correlation analyses showing a limited relationship between the temperature and snow coverage (Figure 3.2.3).

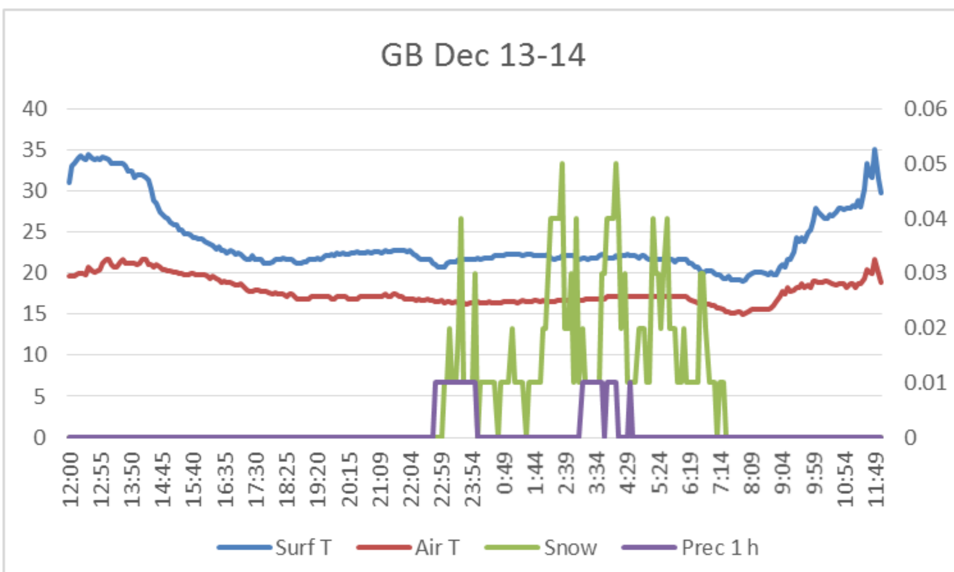


Figure 3.2.3 Surface temperature, air temperature, snow layer, and precipitation 1-hour at site I- 81 @ Exit 223, New Milford (Green Blast) on Dec-13 12:00 to Dec 14 12:00. Temperatures are on the left axis (°F), snow layer and precipitation (in.) are on the right axis.

The variables that were included in the graphical representations of the storms include the grip level, snow melted percentage, snow layer, and precipitation 1-hour (Figure 3.2.4). We observe that the grip level decreased immediately after the onset of the snow precipitation, in turn followed by an increase of the snow layer. Again, the snow layer on the road did not correlate as well as anticipated with the precipitation. In fact, and unlike what was observed at the prior sites, the snow layer exceeded the level of precipitation, which again may be explained by snow packing, blowing, or other local effects. These observations again indicates that both the grip level and snow layer are good indicators of the road condition and, therefore, of the deicing performance.

Figure 3.2.4 also shows the effect of the application of Green Blast on the road conditions, as represented by the grip lave and snow melted percentage. No precipitation of snow was recorded prior or shortly before the 1st truck passage (15:10) and no effect is therefore visible on the grip level and snow melted percentage. The 2nd deicer application occurred at the beginning of the precipitation and did not seem to have a significant effect on the reduced grip level, presumably because of ongoing precipitation. The 3rd (5:30) and 4th (7:53) applications resulted in a significant increase of the grip level and snow melted percentage. The last application (9:29) occurred after the storm and did not have a visible effect on the grip level and snow melted percentage.

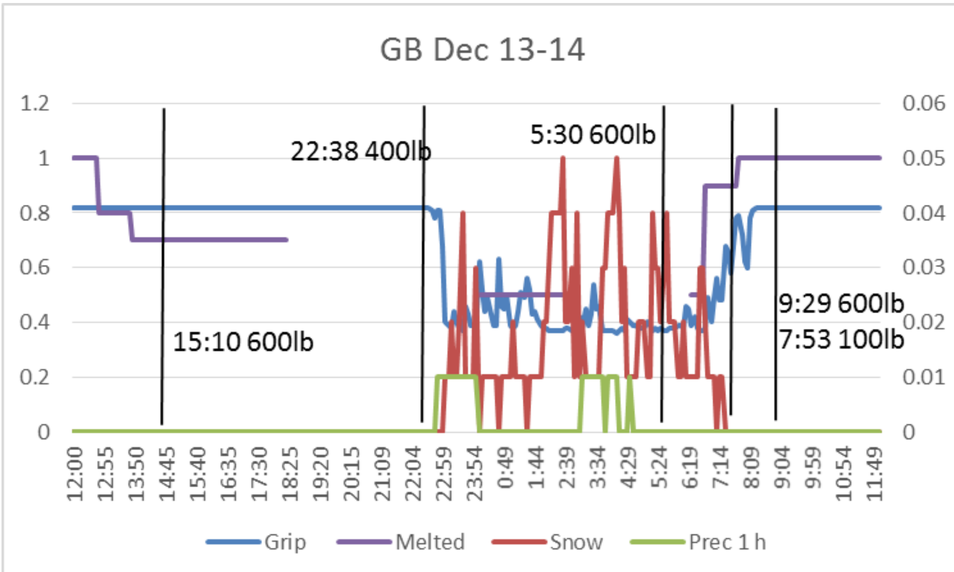


Figure 3.2.4 Grip level, snow melted percentage, snow layer, and precipitation 1-hour site I-81 @ Exit 223, New Milford (Green Blast) on Dec-13 12:00 to Dec 14. Grip level (arbitrary units) and snow melted percentage (in.) are on the left axis, snow layer and precipitation 1-hour (in.) are on the right axis.

3.2.4. Site I-78 WB @ MM27 Berk Co. – Magic Minus Zero

Four snow events were recorded at this site: Dec-13 12:00 to Dec 14 12:00, Dec-15 12:00 to Dec 16 12:00, Dec-22 12:00 to Dec 23 12:00, and Dec-24 12:00 to Dec 25 12:00. In the following sections, we analyzed the relationships between the most significant variables recorded for all storm events at the Magic Minus Zero site (correlation matrices). Then a representative storm was studied in more details, which includes the graphical analysis of the most significant variables and their changes with the precipitation and application of deicer products. At the time this report was prepared, the Team did not have the truck information for the Magic Minus Zero site.

<u>All Storm Events</u>

As for the prior sites, the correlations matrices including all environmental variables recorded by the

RWIS system plus the snow melted percentage were computed. Table 3.2.7 shows the correlation matrix for all the four storms recorded at the Magic Minus Zero site. We focused on the significant variables with respect to snow and road conditions: the surface temperature, grip level, snow layer, precipitation 1-hour, and snow melted percentage. As for other storms, the surface temperature correlated well the air temperature. The grip level did not correlate well with the surface temperature, snow layer, and precipitation 1-hour, but correlated well with the snow melted percentage. The snow layer also showed a low correlation with the precipitation, but a good correlation with the melted percentage. The precipitation 1-hour was well correlated with the melted percentage.

Table 3.2.7 Correlation matrix including all variables recorded during all storms by the RWIS system and the snow melted percentage at site I-78 WB @ MM27 Berk Co. (Magic Minus Zero). Good correlations (r ≥ 6.0) between snow-significant variables are highlighted in green, less significant correlations between snow-significant variables (r < 6.0) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted
Surf T		0.918	0.546	0.161	-0.008	0.166	-0.345	0.163	0.418	0.163	-0.218	0.148	0.176	0.551
Air T	0.918		0.777	0.134	0.006	0.230	-0.283	-0.003	0.508	0.241	-0.314	-0.010	-0.002	0.767
Dew Pt	0.546	0.777		-0.114	0.026	0.254	0.017	-0.353	0.351	0.465	-0.487	-0.339	-0.369	-0.509
Grip	0.161	0.134	-0.114		-0.024	-0.009	-0.180	0.201	0.162	-0.444	0.107	0.190	0.213	0.890
Ice	-0.008	0.006	0.026	-0.024		0.070	-0.050	-0.014	-0.009	0.020	-0.027	-0.012	-0.022	
Snow	0.166	0.230	0.254	-0.009	0.070		-0.864	0.212	0.022	-0.084	0.026	0.189	0.179	-0.822
Rel Hum	-0.345	-0.283	0.017	-0.180	-0.050	-0.864		-0.395	-0.105	0.300	-0.173	-0.362	-0.380	-0.648
Wind Sp	0.163	-0.003	-0.353	0.201	-0.014	0.212	-0.395		-0.158	-0.122	0.522	0.942	0.966	0.589
Barom	0.418	0.508	0.351	0.162	-0.009	0.022	-0.105	-0.158		-0.089	-0.240	-0.149	-0.149	-0.352
Prec 1 h	0.163	0.241	0.465	-0.444	0.020	-0.084	0.300	-0.122	-0.089		-0.244	-0.111	-0.132	-0.909
Wind Dir	-0.218	-0.314	-0.487	0.107	-0.027	0.026	-0.173	0.522	-0.240	-0.244		0.519	0.510	0.427
Wind Spd	0.148	-0.010	-0.339	0.190	-0.012	0.189	-0.362	0.942	-0.149	-0.111	0.519		0.917	0.552
Max W Spd	0.176	-0.002	-0.369	0.213	-0.022	0.179	-0.380	0.966	-0.149	-0.132	0.510	0.917		0.655
Melted	0.551	0.767	-0.509	0.890		-0.822	-0.648	0.589	-0.352	-0.909	0.427	0.552	0.655	

As in the prior analysis, we removed data with 'flat' trend, i.e., snow layer at zero (Table 3.2.8) and data without snow melted percentage entries (Table 3.2.9).

When we removed all data points with the snow layer at zero (Table 3.2.8), we obtained somehow better correlations: the surface temperature correlated well with the grip level and precipitation, the grip level correlated well with the snow layer and precipitation, and the precipitation correlated well with the snow melted percentage.

Table 3.2.8 Correlation matrix including variables recorded during all storms by the RWIS system and the snow melted percentage at site I-78 WB @ MM27 Berk Co. (Magic Minus Zero). Data with the snow layer at zero were removed. Good correlations (r ≥ 6.0) between snow- significant variables are highlighted in green, less significant correlations between snow- significant variables (r < 6.0) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted
Surf T		0.826	-0.048	0.675	-0.037	0.169	-0.590	0.156	0.765	-0.604	-0.135	0.136	0.198	-0.156
Air T	0.826		0.385	0.828	-0.005	0.571	-0.858	0.090	0.587	-0.646	-0.178	0.070	0.093	0.182
Dew Pt	-0.048	0.385		0.186	0.057	0.769	-0.531	-0.594	-0.225	-0.019	-0.350	-0.567	-0.639	-0.091
Grip	0.675	0.828	0.186		-0.010	0.628	-0.866	0.431	0.402	-0.773	0.139	0.402	0.432	0.458
Ice	-0.037	-0.005	0.057	-0.010		0.060	-0.032	-0.037	-0.027	0.064	-0.060	-0.033	-0.047	
Snow	0.169	0.571	0.769	0.628	0.060		-0.875	-0.067	-0.137	-0.376	-0.013	-0.064	-0.106	-0.281
Rel Hum	-0.590	-0.858	-0.531	-0.866	-0.032	-0.875		-0.105	-0.285	0.626	0.040	-0.095	-0.100	-0.417
Wind Sp	0.156	0.090	-0.594	0.431	-0.037	-0.067	-0.105		0.069	-0.384	0.619	0.947	0.975	0.032
Barom	0.765	0.587	-0.225	0.402	-0.027	-0.137	-0.285	0.069		-0.423	-0.319	0.055	0.118	0.262
Prec 1 h	-0.604	-0.646	-0.019	-0.773	0.064	-0.376	0.626	-0.384	-0.423		-0.264	-0.364	-0.401	-0.820
Wind Dir	-0.135	-0.178	-0.350	0.139	-0.060	-0.013	0.040	0.619	-0.319	-0.264		0.606	0.591	-0.132

Wind Spd	0.136	0.070	-0.567	0.402	-0.033	-0.064	-0.095	0.947	0.055	-0.364	0.606		0.930	0.092
Max W Spd	0.198	0.093	-0.639	0.432	-0.047	-0.106	-0.100	0.975	0.118	-0.401	0.591	0.930		0.568
Melted	-0.156	0.182	-0.091	0.458		-0.281	-0.417	0.032	0.262	-0.820	-0.132	0.092	0.568	

When we removed all data points without snow melted percentage entries (Table 3.2.9), we obtained even better correlations between the variables of interest: the grip level correlated well with the snow layer, precipitation, and snow melted percentage, the snow layer correlated well with the precipitation and snow melted percentage, and the precipitation correlated well with the snow melted percentage. On the other hand, the surface temperature did not correlate with any other variables.

Table 3.2.9 Correlation matrix including variables recorded during all storms by the RWIS system and the snow melted percentage at site I-78 WB @ MM27 Berk Co. (Magic Minus Zero). Data without snow melted percentage values were removed. Good correlations ($r \geq 6.0$) between snow-significant variables are highlighted in green, less significant correlations between snow- significant variables ($r < 6.0$) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted
Surf T		0.822	-0.768	0.482		-0.406	-0.834	0.834	-0.333	-0.393	0.329	0.797	0.831	0.551
Air T	0.822		-0.606	0.700		-0.597	-0.772	0.788	-0.486	-0.595	0.433	0.750	0.849	0.767
Dew Pt	-0.768	-0.606		-0.465		0.393	0.968	-0.585	0.176	0.389	-0.239	-0.549	-0.575	-0.509
Grip	0.482	0.700	-0.465			-0.924	-0.602	0.480	-0.346	-0.824	0.385	0.447	0.525	0.890
Ice														
Snow	-0.406	-0.597	0.393	-0.924			0.511	-0.417	0.299	0.763	-0.369	-0.385	-0.457	-0.822
Rel Hum	-0.834	-0.772	0.968	-0.602		0.511		-0.679	0.238	0.506	-0.316	-0.638	-0.694	-0.648
Wind Sp	0.834	0.788	-0.585	0.480		-0.417	-0.679		-0.410	-0.403	0.468	0.925	0.951	0.589
Barom	-0.333	-0.486	0.176	-0.346		0.299	0.238	-0.410		0.218	-0.251	-0.379	-0.420	-0.352
Prec 1 h	-0.393	-0.595	0.389	-0.824		0.763	0.506	-0.403	0.218		-0.319	-0.381	-0.468	-0.909
Wind Dir	0.329	0.433	-0.239	0.385		-0.369	-0.316	0.468	-0.251	-0.319		0.459	0.475	0.427
Wind Spd	0.797	0.750	-0.549	0.447		-0.385	-0.638	0.925	-0.379	-0.381	0.459		0.892	0.552
Max W Spd	0.831	0.849	-0.575	0.525		-0.457	-0.694	0.951	-0.420	-0.468	0.475	0.892		0.655
Melted	0.551	0.767	-0.509	0.890		-0.822	-0.648	0.589	-0.352	-0.909	0.427	0.552	0.655	

<u>Dec-13 12:00 to Dec 14 12:00</u>

Analysis of the data showed a typical pattern that was globally retrieved at other sites and during other storms.

Again, we did not observe a clear relationship between surface temperature and snow layer and precipitation, which confirms the correlation analyses showing limited relationship between temperature and snow coverage (Figure 3.2.5).

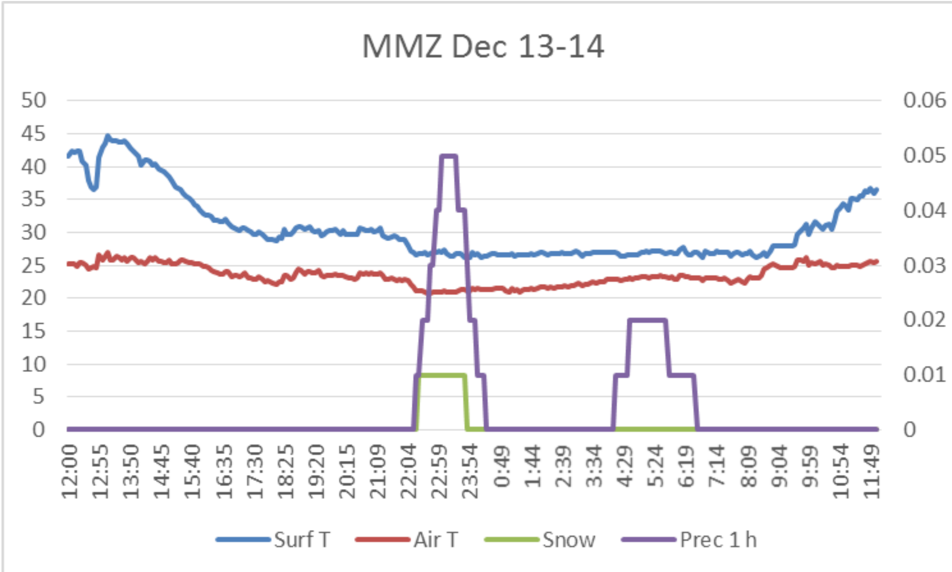


Figure 3.2.5 Surface temperature, air temperature, snow layer, and precipitation 1-hour at site I- 78 WB @ MM27 Berk Co. (Magic Minus Zero) on Dec-13 12:00 to Dec 14 12:00. Temperatures are on the left axis (°F), snow layer and precipitation (in.) are on the right axis.

The variables that are included in the graphical representations of the storms include the grip level, snow melted percentage, snow layer, and precipitation 1-hour (Figure 3.2.6). We observed that the grip level decreased immediately after the onset of the snow precipitation, in turn followed by an increase of the snow layer, which was observed only for the first snowfall of the storm (22:00-24:00), no snow accumulation was recorded during the second snowfall (4:00-6:00). Again, the snow layer on the road did not correlate as well as anticipated with the precipitation, which may be explained by snow packing or by local effects. These observations indicate that both the grip level and snow layer are good indicators of the road condition and, therefore, of the deicing performance.

Because not truck information was available to the Team for the Magic Minus Zero site at the time this report was written, analysis of the effect of deicers on road conditions could not be performed.

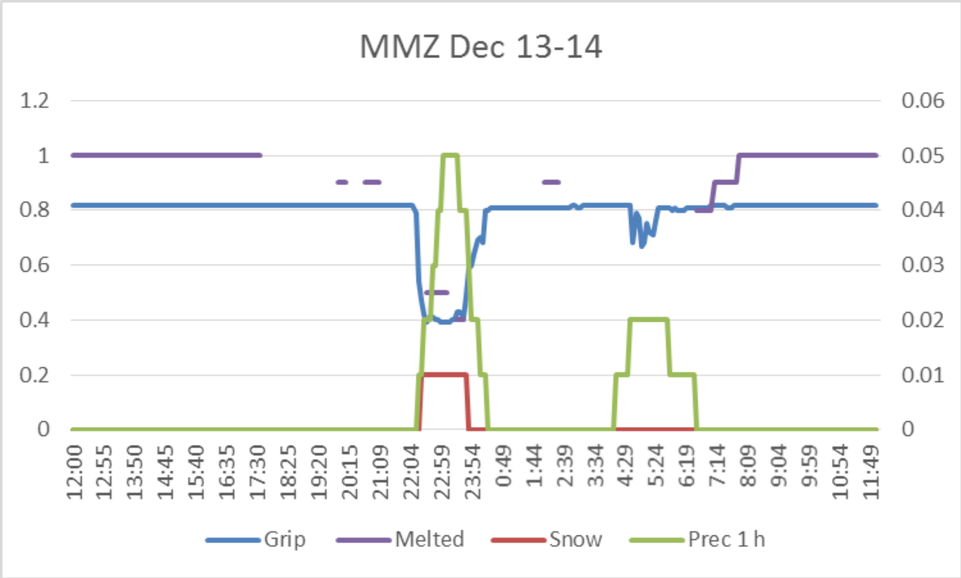


Figure 3.2.6 Grip level, snow melted percentage, snow layer, and precipitation 1-hour at site I-78 WB @ MM27 Berk Co. (Magic Minus Zero) on Dec-13 12:00 to Dec 14. Grip level (arbitrary units) and snow melted percentage (in.) are on the left axis, snow layer and precipitation 1-hour (in.) are on the right axis.

3.2.5. Site I-80 @ MP 11 Mercer Co. – Reference Rock Salt.

Five snow events were recorded at this site: Dec-12 12:00 to Dec 13 12:00; Dec-13 12:00 to Dec 14 12:00; Dec-15 12:00 to Dec 16 12:00; Dec-28 12:00 to Dec 29 12:00; Dec-2912:00 to Dec 30 12:00. In the following sections, we analyzed the relationships between the most snow-significant variables recorded for all storm events at the Rock Salt site (correlation matrices). Then a representative storm was studied in more details, this includes the graphical analysis of the most significant variables. At the time this report was prepared, the Team did not have the truck information for the Rock Salt site.

<u>All storm events</u>

As for the prior sites, the correlations matrices including all environmental variables recorded by the RWIS system plus the snow melted percentage were computed. Table 3.2.10 shows the correlation matrix for the only storm recorded at the Rock Salt (reference) site. We focused on the significant variables with respect to snow and road conditions: the surface temperature, grip level, snow layer, precipitation 1-hour, and snow melted percentage.

As in other storms, the surface temperature correlated well the air temperature. The grip level did not correlate well with the surface temperature, precipitation 1-hour, and snow melted percentage, but, as at other sites, correlated well with the snow layer. The snow layer also showed a low correlation with the precipitation and melted percentage. The precipitation 1-hour did not correlate well with the melted percentage.

Table 3.2.10 Correlation matrix including all variables recorded during all storms by the RWIS system and the snow melted percentage at site I-80 @ MP 11 Mercer Co. (Reference Rock Salt). Good correlations (r ≥ 6.0) between snow-significant variables are highlighted in green, less significant correlations between snow-significant variables (r < 6.0) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted
Surf T		0.893	0.597	0.368	-0.095	-0.227	-0.385	0.343	-0.484	0.028	0.208	0.281	0.481	0.179
Air T	0.893		0.834	0.249	-0.044	-0.121	-0.144	0.174	-0.463	0.044	0.121	0.138	0.319	0.101
Dew Pt	0.597	0.834		-0.147	0.128	0.230	0.423	0.020	-0.573	0.174	0.019	0.003	0.065	-0.110
Grip	0.368	0.249	-0.147		-0.382	-0.839	-0.700	0.124	0.275	-0.284	0.065	0.108	0.297	0.285
Ice	-0.095	-0.044	0.128	-0.382		0.132	0.315	-0.059	-0.134	-0.102	0.148	-0.043	-0.058	-0.051
Snow	-0.227	-0.121	0.230	-0.839	0.132		0.642	-0.134	-0.375	0.431	-0.132	-0.113	-0.310	-0.304
Rel Hum	-0.385	-0.144	0.423	-0.700	0.315	0.642		-0.246	-0.292	0.257	-0.159	-0.215	-0.405	-0.389
Wind Sp	0.343	0.174	0.020	0.124	-0.059	-0.134	-0.246		-0.442	0.139	0.398	0.728	0.817	0.085
Barom	-0.484	-0.463	-0.573	0.275	-0.134	-0.375	-0.292	-0.442		-0.276	-0.190	-0.347	-0.402	0.215
Prec 1 h	0.028	0.044	0.174	-0.284	-0.102	0.431	0.257	0.139	-0.276		0.039	0.105	0.044	-0.008
Wind Dir	0.208	0.121	0.019	0.065	0.148	-0.132	-0.159	0.398	-0.190	0.039		0.470	0.408	0.165
Wind Spd	0.281	0.138	0.003	0.108	-0.043	-0.113	-0.215	0.728	-0.347	0.105	0.470		0.654	0.074
Max W Sp	0.481	0.319	0.065	0.297	-0.058	-0.310	-0.405	0.817	-0.402	0.044	0.408	0.654		0.141
Melted	0.179	0.101	-0.110	0.285	-0.051	-0.304	-0.389	0.085	0.215	-0.008	0.165	0.074	0.141	

As in the prior analysis, we removed data with 'flat' trend, i.e., snow layer at zero (Table 3.2.11) and data without snow melted percentage entries (Table 3.2.12).

In the case of this storm, removing all data points the snow layer at zero (Table 3.2.11) did not improve correlations between the variables of interest: in fact, no significant correlations were observed between any of the snow-significant variables.

Table 3.2.11 Correlation matrix including variables recorded during all storms by the RWIS system and the snow melted percentage at site I-80 @ MP 11 Mercer Co. (Reference Rock Salt). Data with the snow layer at zero were removed. Good correlations (r ≥ 6.0) between snow- significant variables are highlighted in green, less significant correlations between snow- significant variables (r < 6.0) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted
Surf T		0.981	0.969	-0.244	0.288	0.361	0.631	0.248	-0.865	0.288	0.156	0.225	0.337	-0.557
Air T	0.981		0.982	-0.279	0.286	0.375	0.622	0.160	-0.822	0.254	0.121	0.154	0.270	-0.567
Dew Pt	0.969	0.982		-0.281	0.242	0.451	0.756	0.118	-0.853	0.306	0.108	0.123	0.194	-0.570
Grip	-0.244	-0.279	-0.281		-0.249	-0.175	-0.207	0.037	0.184	0.015	-0.107	0.003	0.023	0.090
Ice	0.288	0.286	0.242	-0.249		-0.350	0.024	0.014	-0.120	-0.303	0.314	0.012	0.158	-0.014
Snow	0.361	0.375	0.451	-0.175	-0.350		0.579	0.006	-0.559	0.409	-0.158	0.022	-0.128	
Rel Hum	0.631	0.622	0.756	-0.207	0.024	0.579		-0.074	-0.695	0.386	0.035	-0.028	-0.139	-0.206
Wind Sp	0.248	0.160	0.118	0.037	0.014	0.006	-0.074		-0.368	0.351	0.350	0.807	0.852	-0.314
Barom	-0.865	-0.822	-0.853	0.184	-0.120	-0.559	-0.695	-0.368		-0.378	-0.125	-0.320	-0.339	0.434
Prec 1 h	0.288	0.254	0.306	0.015	-0.303	0.409	0.386	0.351	-0.378		0.019	0.304	0.267	-0.534
Wind Dir	0.156	0.121	0.108	-0.107	0.314	-0.158	0.035	0.350	-0.125	0.019		0.426	0.370	-0.224
Wind Spd	0.225	0.154	0.123	0.003	0.012	0.022	-0.028	0.807	-0.320	0.304	0.426		0.703	-0.222
Max W Sp	0.337	0.270	0.194	0.023	0.158	-0.128	-0.139	0.852	-0.339	0.267	0.370	0.703		-0.439
Melted	-0.557	-0.567	-0.570	0.090	-0.014		-0.206	-0.314	0.434	-0.534	-0.224	-0.222	-0.439	

When we removed all data points without snow melted percentage entries (Table 3.2.12), we obtained a significant correlation between the grip level and snow layer. No other significant correlations were observed between any other variables.

Table 3.2.12 Correlation matrix including variables recorded during all storms by the RWIS system and the snow melted percentage at site I-80 @ MP 11 Mercer Co. (Reference Rock Salt). Data without snow melted percentage values were removed. Good correlations (r ≥ 6.0) between snow-significant variables are highlighted in green, less significant correlations between snow- significant variables (r < 6.0) are highlighted in red

	Surf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted
Surf T		0.899	0.602	0.468	-0.386	-0.388	-0.491	0.267	-0.511	0.102	-0.018	0.175	0.428	0.179
Air T	0.899		0.852	0.319	-0.276	-0.261	-0.205	0.146	-0.504	0.082	-0.036	0.109	0.336	0.101
Dew Pt	0.602	0.852		0.036	-0.034	-0.024	0.336	0.048	-0.524	0.016	-0.115	0.030	0.150	-0.110
Grip	0.468	0.319	0.036		-0.605	-0.878	-0.530	0.087	0.052	0.010	0.034	0.060	0.180	0.285
Ice	-0.386	-0.276	-0.034	-0.605		0.462	0.458	-0.053	-0.073	-0.118	0.100	0.004	-0.097	-0.051
Snow	-0.388	-0.261	-0.024	-0.878	0.462		0.449	-0.126	-0.026	0.040	-0.065	-0.088	-0.174	-0.304
Rel Hum	-0.491	-0.205	0.336	-0.530	0.458	0.449		-0.181	-0.092	-0.116	-0.153	-0.141	-0.331	-0.389
Wind Sp	0.267	0.146	0.048	0.087	-0.053	-0.126	-0.181		-0.336	0.128	0.212	0.562	0.650	0.085
Barom	-0.511	-0.504	-0.524	0.052	-0.073	-0.026	-0.092	-0.336		-0.052	0.035	-0.221	-0.339	0.215
Prec 1 h	0.102	0.082	0.016	0.010	-0.118	0.040	-0.116	0.128	-0.052		0.232	0.086	0.256	-0.008
Wind Dir	-0.018	-0.036	-0.115	0.034	0.100	-0.065	-0.153	0.212	0.035	0.232		0.340	0.242	0.165
Wind Spd	0.175	0.109	0.030	0.060	0.004	-0.088	-0.141	0.562	-0.221	0.086	0.340		0.485	0.074
Max W Sp	0.428	0.336	0.150	0.180	-0.097	-0.174	-0.331	0.650	-0.339	0.256	0.242	0.485		0.141
Melted	0.179	0.101	-0.110	0.285	-0.051	-0.304	-0.389	0.085	0.215	-0.008	0.165	0.074	0.141	

Dec-13 12:00 to Dec 14 12:00

Analysis of the data showed a typical pattern that was globally retrieved at other sites and during other storms.

Unlike at the AquaSalina site, we again did not observe a clear relationship between surface temperature and snow layer and precipitation, which confirms the correlation analyses showing limited relationship between temperature and snow coverage (Figure 3.2.7).

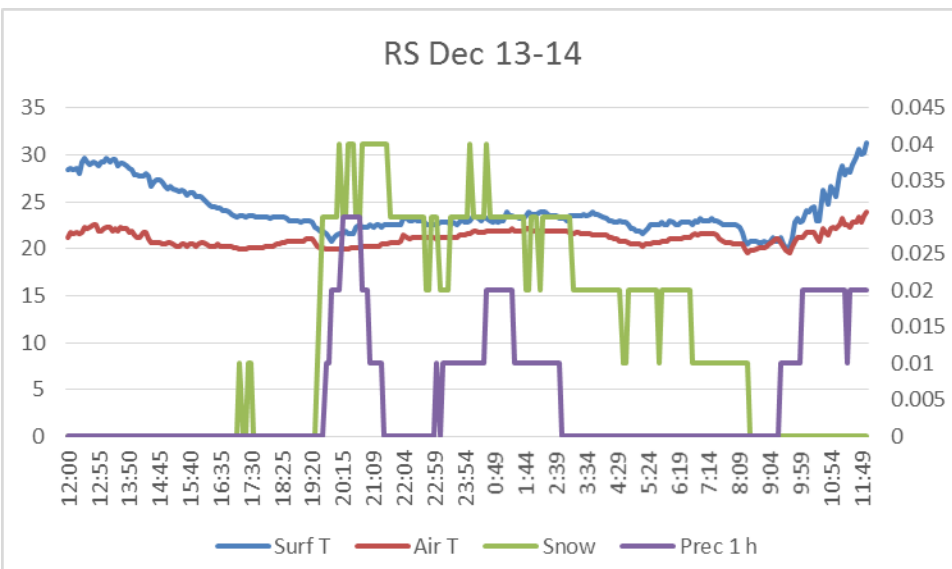


Figure 3.2.7 Surface temperature, air temperature, snow layer, and precipitation 1-hour at site I- 80 @ MP 11 Mercer Co. (Reference Rock Salt) on Dec-13 12:00 to Dec 14 12:00. Temperatures are on the left axis (°F), snow layer and precipitation (in.) are on the right axis.

The variables that are included in the graphical representations of the storms include the grip level, snow melted percentage, snow layer, and precipitation 1-hour (Figure 3.2.8). As at other sites, we observe that the grip level decreased immediately after the onset of the snow precipitation, in turn followed by an increase of the snow layer. In the case of this storm, the snow layer correlated very well with the precipitation, except by the end of the storm (9:00-12:00), when a precipitation event was not associated with any increase of snow layer or decrease of grip level and snow melted percentage. Again, the snow layer generally exceeded the level of precipitation, which may be explained by snow packing, blowing, or other local effects. These observations again indicates that both the grip level and snow layer are good indicators of the road condition and, therefore, of the deicing performance.

Because not truck information was available to the Team for the Rock Salt site at the time this report was written, analysis of the effect of Rock Salt on the road conditions could net be performed.

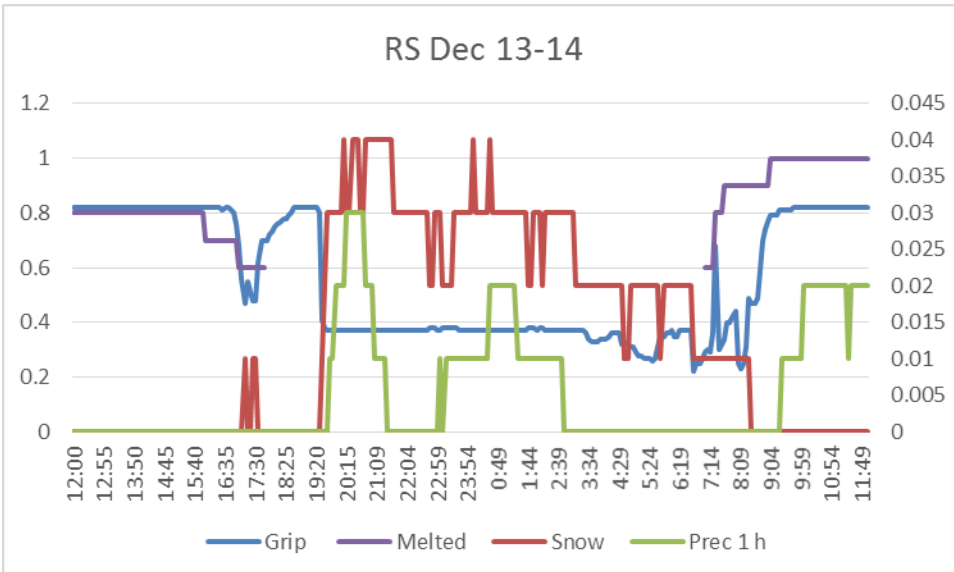


Figure 3.2.8 Grip level, snow melted percentage, snow layer, and precipitation 1-hour site I-80 @ MP 11 Mercer Co. (Reference Rock Salt) on Dec-13 12:00 to Dec 14. Grip level (arbitrary units) and snow melted percentage (in.) are on the left axis, snow layer and precipitation 1-hour (in.) are on the right axis.

<u>Low correlation between significant variables</u>

The low correlation observed between the grip level, precipitation, and snow melted percentage (Table 3.2.12) may be explained by some discrepancies noted in the data recorded by the sensors. During the storm in Dec 13-14, we noticed that precipitation was not associated with any increase of snow layer and decrease of grip level or snow melted percentage (Figure 3.2.8). On the contrary, during the storm in Dec 28-29, an increase of snow layer associated with decrease of the grip level was not associated with any precipitation (Figure 3.2.9).

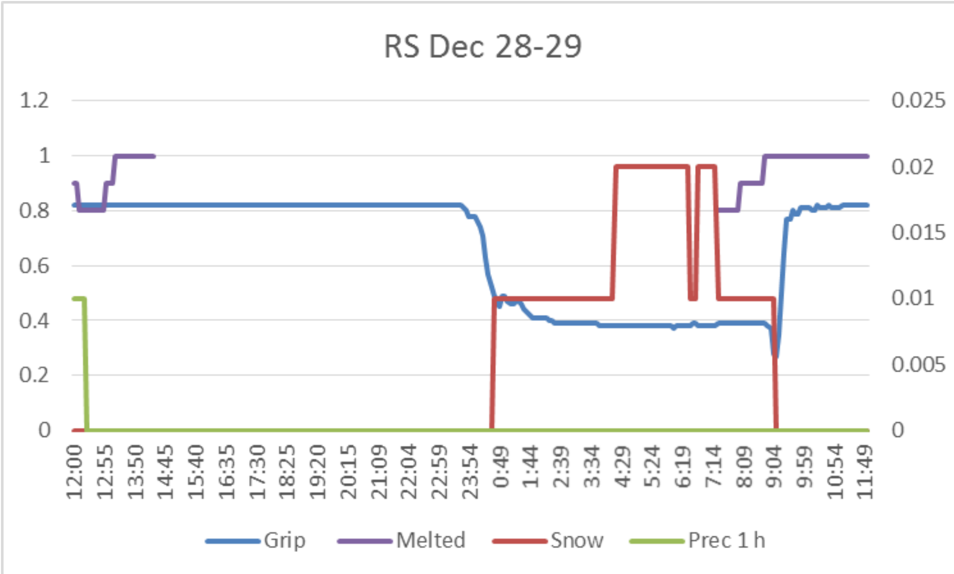


Figure 3.2.9 Grip level, snow melted percentage, snow layer, and precipitation 1-hour site I-80 @ MP 11 Mercer Co. (Reference Rock Salt) on Dec-28 12:00 to Dec 29. Grip level (arbitrary units) and snow melted percentage (in.) are on the left axis, snow layer and precipitation 1-hour (in.) are on the right axis.

Removing these two storms from the data set resulted in a clear improvement of the correlation between the significant variables. As at other sites where data were recorded, Table 3.2.13 shows now a good correlation between the grip level, snow layer, precipitation, and snow melted percentage.

Table 3.2.13 Correlation matrix including variables recorded during the storms in Dec 12-13 and Dec 15-16 by the RWIS system and the snow melted percentage at site I-80 @ MP 11 Mercer Co. (Reference Rock Salt). Data without snow melted percentage values were removed. Good correlations (r ≥ 6.0) between snow-significant variables are highlighted in green, less significant correlations between snow-significant variables (r < 6.0) are highlighted in red

	Suf T	Air T	Dew Pt	Grip	Ice	Snow	Rel Hum	Wind Sp	Barom	Prec 1 h	Wind Dir	Wind Spd	Max W Spd	Melted
Suf T		0.640	0.126	0.420	-0.219	-0.389	-0.405	-0.311	0.286	-0.347	-0.171	-0.144	-0.477	0.698
Air T	0.640		0.801	0.233	-0.090	-0.243	0.311	-0.362	0.832	-0.245	-0.179	-0.248	-0.429	0.268
Dew Pt	0.126	0.801		-0.062	-0.040	0.039	0.817	-0.319	0.885	0.074	-0.167	-0.276	-0.345	-0.161
Grip	0.420	0.233	-0.062		-0.582	-0.992	-0.331	-0.246	0.072	-0.749	-0.140	-0.082	-0.411	0.725
Ice	-0.219	-0.090	-0.040	-0.582		0.525	0.014	0.295	-0.012	-0.025	0.087	0.065	0.244	-0.445
Snow	-0.389	-0.243	0.039	-0.992	0.525		0.304	0.224	-0.105	0.799	0.149	0.088	0.402	-0.690
Rel Hum	-0.405	0.311	0.817	-0.331	0.014	0.304		-0.169	0.606	0.370	-0.110	-0.210	-0.143	-0.516
Wind Sp	-0.311	-0.362	-0.319	-0.246	0.295	0.224	-0.169		-0.299	0.103	0.195	0.409	0.489	-0.228
Barom	0.286	0.832	0.885	0.072	-0.012	-0.105	0.606	-0.299		-0.130	-0.213	-0.302	-0.388	-0.034
Prec 1 h	-0.347	-0.245	0.074	-0.749	-0.025	0.799	0.370	0.103	-0.130		0.127	0.058	0.291	-0.565
Wind Dir	-0.171	-0.179	-0.167	-0.140	0.087	0.149	-0.110	0.195	-0.213	0.127		0.349	0.257	-0.157
Wind Spd	-0.144	-0.248	-0.276	-0.082	0.065	0.088	-0.210	0.409	-0.302	0.058	0.349		0.374	-0.047
Max W Spd	-0.477	-0.429	-0.345	-0.411	0.244	0.402	-0.143	0.489	-0.388	0.291	0.257	0.374		-0.332
Melted	0.698	0.268	-0.161	0.725	-0.445	-0.690	-0.516	-0.228	-0.034	-0.565	-0.157	-0.047	-0.332	

4. CONCLUSIONS

4.1 Winter 2016-2017

At all sites, the surface temperature and air temperature have parallel trends. In the morning, the temperature was the lowest, while in the afternoon, it was the highest.

At the sites equipped with salt concentration sensors (site I-80 @ Exit 35 MP 37 for AquaSalina, site I-79 @ Exit 88 for Beet Heet, sire I-79 @ MP 100 for the Beet Heet reference, site I-81 @ Exit 77 Manada Hill for Magic Minus Zero, and site I-81 @ Exit 223 New Milford for the Magic Minus Zero reference), we observed that the salt concentration and precipitation have a generally opposite trend. On the other hand, the salt concentration varied widely for unknown reasons, which may prevent it to be used a good indicator of the snow on the road and the deicer performances.

At the sites equipped with grip level sensors (site I-79 @ MP 136 Crawford/Mercer Line for the AquaSalina reference, site I-81 @ Exit 223 New Milford for Green Blast, and site I-80 @ Exit 211 Lenox for the Green Blast reference), we observed that both the grip level and snow melted percentage decreased rapidly during precipitation, but recovered after each deicer applications, showing the effectiveness of deicer application. The grip level correlated well with both the precipitation and snow melted percentage during the snow events. This leads us to recommend the use of the grip level instead of salt concentration as indicator of the snow on the road and deicer performance.

The snow melted percentage, although a reliable indicator of the road conditions, could not be recorded during several snow events. Indeed, the photo recording was impaired by many factors, such as the light conditions and blurry images, limiting the quantity of usable data collected during the storm events.

The limitation of the snow melted percentage as road condition and deicer performance indicator as well as the high variability of the salt concentration led the Team to adopt another road condition indicator, the grip level, – and choose other sites equipped with grip level sensors – for data collection in the winter 2017-2018. The grip level showed a good correlation with the melted percentage and we expect that the melted percentage may be advantageously replaced by the grip level for data collection in the winter 2016- 2017.

4.2 Winter 2017-2018

The data analysis was conducted in two steps. First we pooled all data from all storms for each site and computed the correlations matrices including all environmental and parametric variables recorded by the RWIS system as well as the snow melted percentage derived from the photographs. In a second step, we analyzed with more details the profile of significant variables with respect to the road conditions and the effect of deicer spreading for one representative storm per site (when deicer application data were available).

The correlation matrices showed more significant relationships when the data without snow melted percentage entries were removed from the analysis. These corrected matrices were used as a basis for the discussion. At all sites, the surface temperature correlated very well the air temperature. Besides significant correlations were observed at all sites between the primary indicator of the snow condition, i.e., the grip level, and other variables expected to be related to the snow on the road: the snow level, precipitation 1- hour, and snow melted percentage. Although the surface temperature is expected to be an important variable affecting the snow layer and snow persistence on the road, it did not correlate well any other *snow-significant variables*. Poor correlations were generally observed between these snow-significant variables and other variables recorded by the RWIS system, e.g., dew point, barometric pressure, wind conditions, water and ice layers, etc. This therefore indicates that both the grip level and snow layer are good indicators of the road condition and, therefore, the deicers performance.

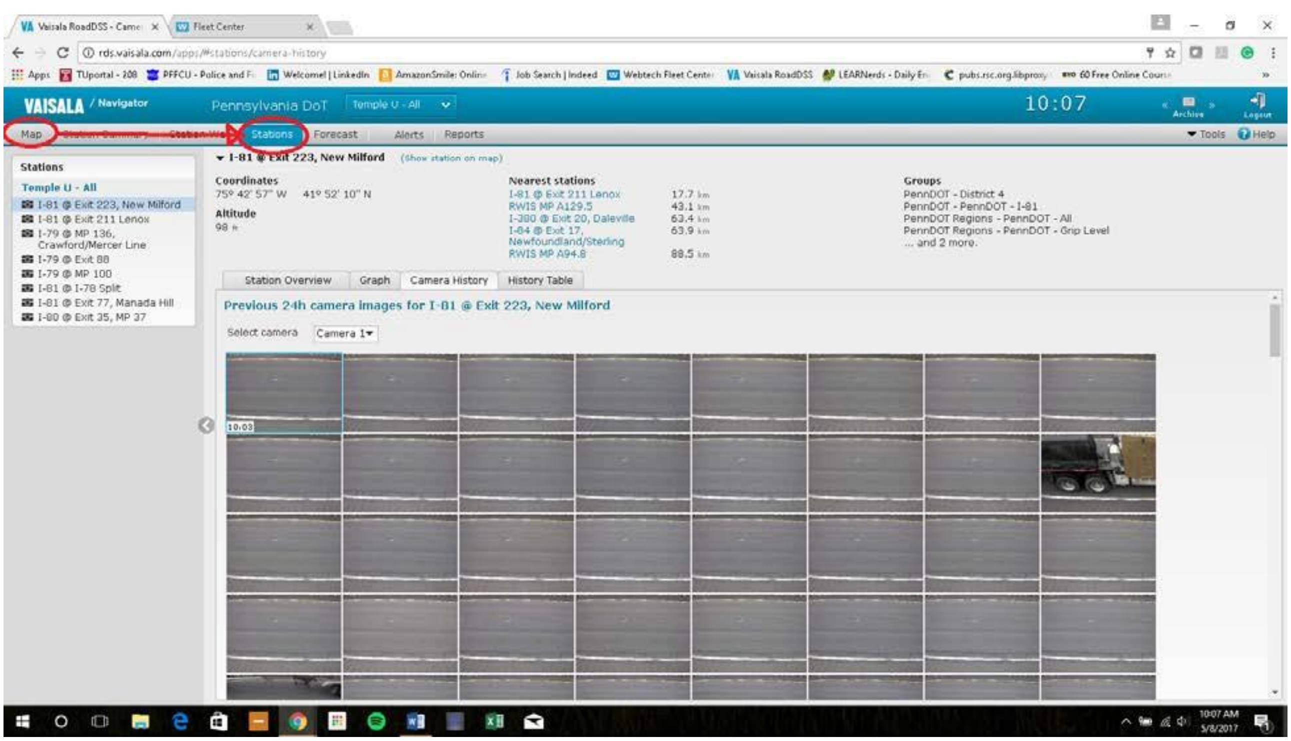
The profile of significant variables was then analyzed for selected storms at each site in relation with the deicer application. Generally speaking, a strong relationship was observed between the air and surface temperature, but no clear correlation was observed between the surface temperature and other snow-significant variables. We also observed a relationship between the precipitation 1-hour, snow layer, grip level, and snow melted percentage: the precipitation was associated with an increase of the snow layer and decrease of the grip level and snow melted percentage. After deicer application, we sometimes did not observe significant changes in the grip level/or and snow melted percentage, which was especially apparent when the precipitation was continuing. In other cases, we observed a rapid increase of the grip level and snow melted percentage, which then reflected the efficiency of the deicer product applied.

APPENDIX I

Procedure to collect data from RWIS and AVL

Part Two: Experimental Methods –

1. RWIS Data Collection –
    a. Log in to **RWIS** using the provided Username and Password.
    b. From the **Home: Map Tab**, left click on the **Stations Tab** and select the site that is being observed.

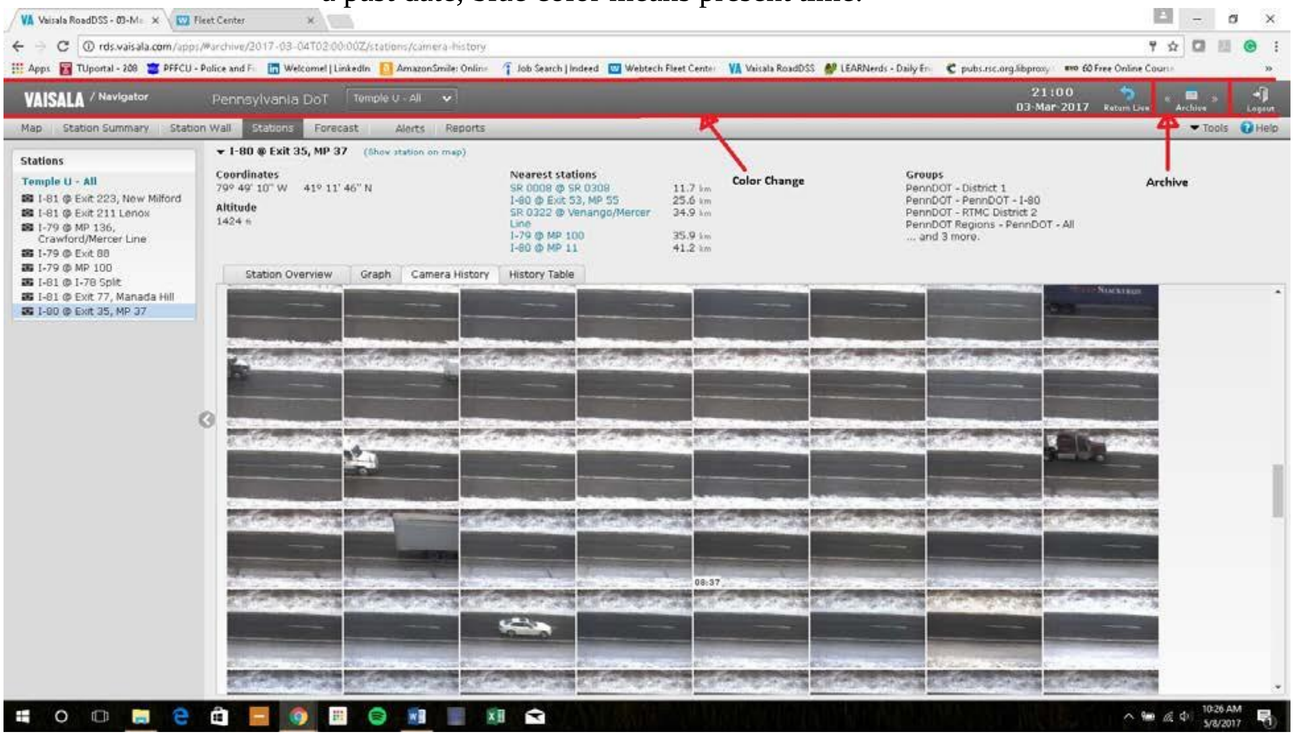


i. Sites can be found in the **Stations** menu on the left side of the screen.

c. After selecting a site, change the date on the RWIS site to the date of the observed winter storm event.

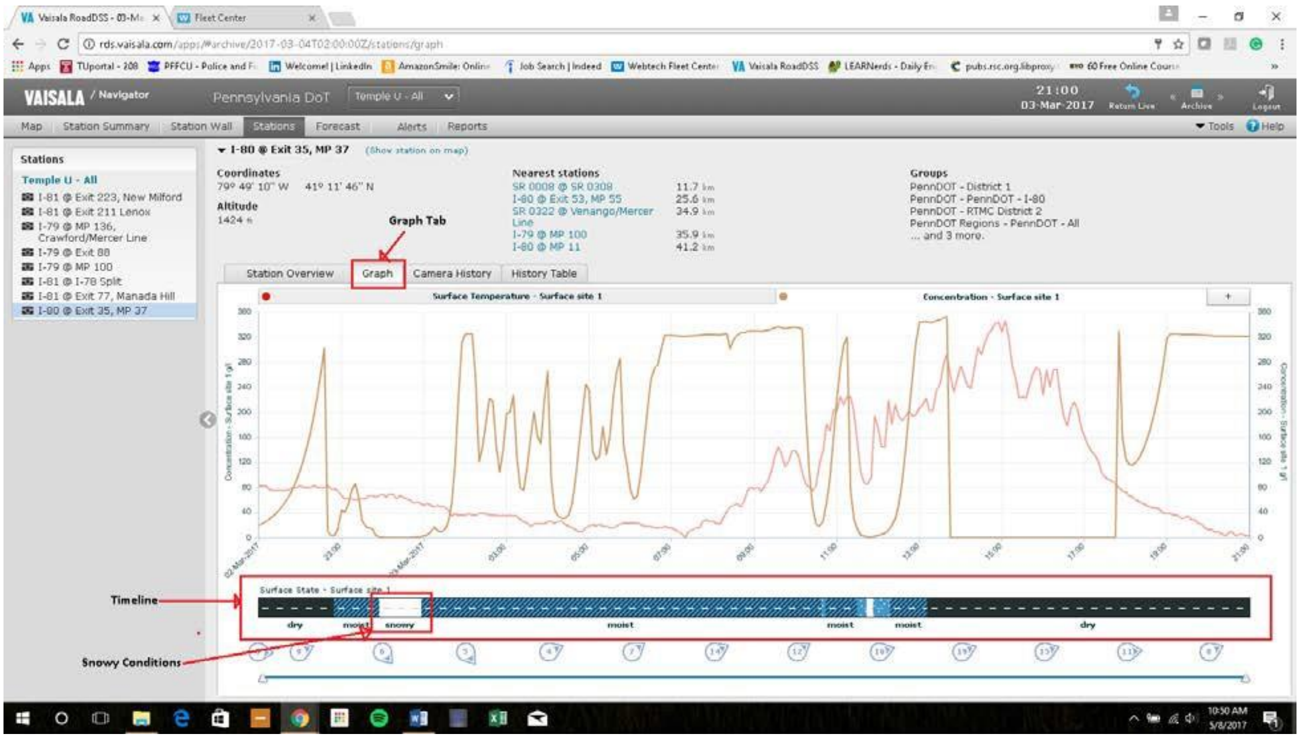
i. Dates can be changed by selecting the **Archive Calendar Symbol** in the top right of the screen.

ii. The blue bar on the top of the screen will change color to gray when looking at a past date, blue color means present time.



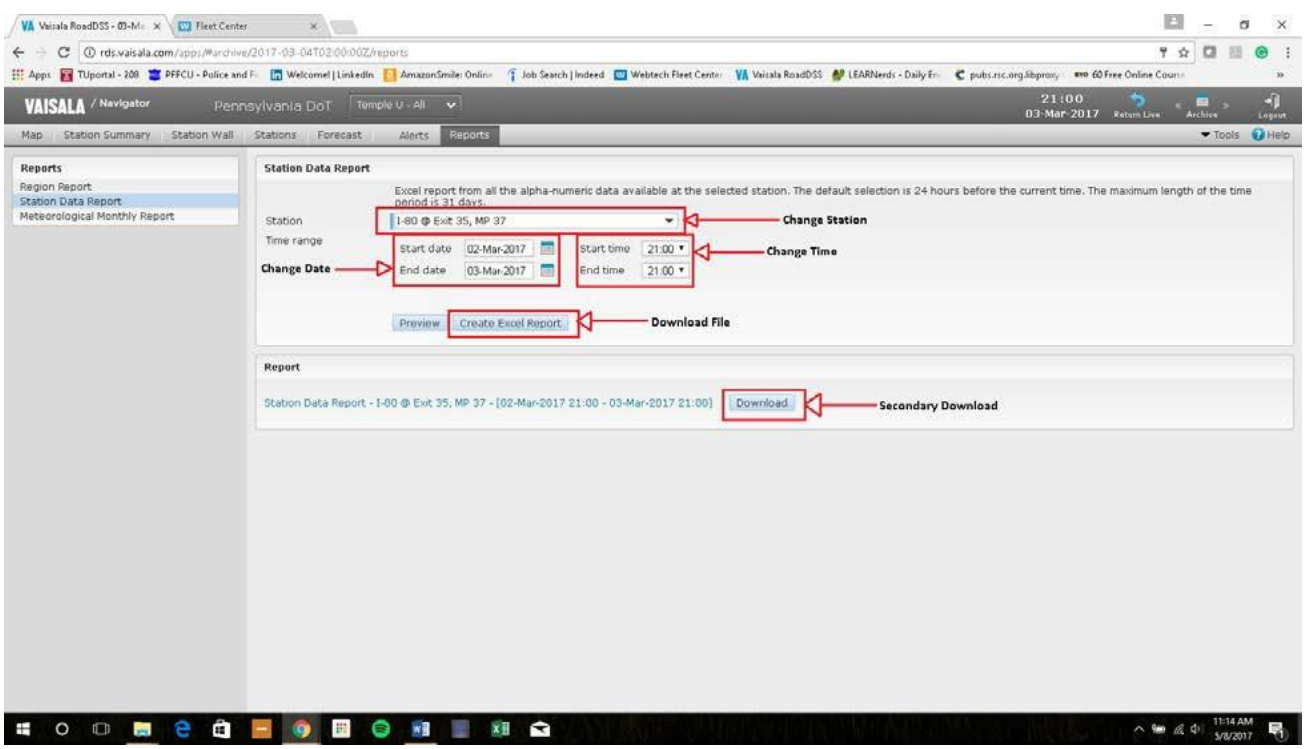
d. While in the **Station Tab** select the **Graph Tab** below the station data. Observe the timeline below and adjust the time with the **Archive** button.

i. The time should be adjusted to 1 hour before "snowy" conditions are seen, or 1 hour before a salt truck passes a point.



e. Next, select the **Reports Tab**, change the station to the one being observed and change the timeline to the one being used. Then left click

Create Excel Report, the download of the excel file should start automatically, but if it does not click the **Download Button** that appears.



f. Once the excel file is saved to the user's computer open up the **AVL "Fleet Center"** website.

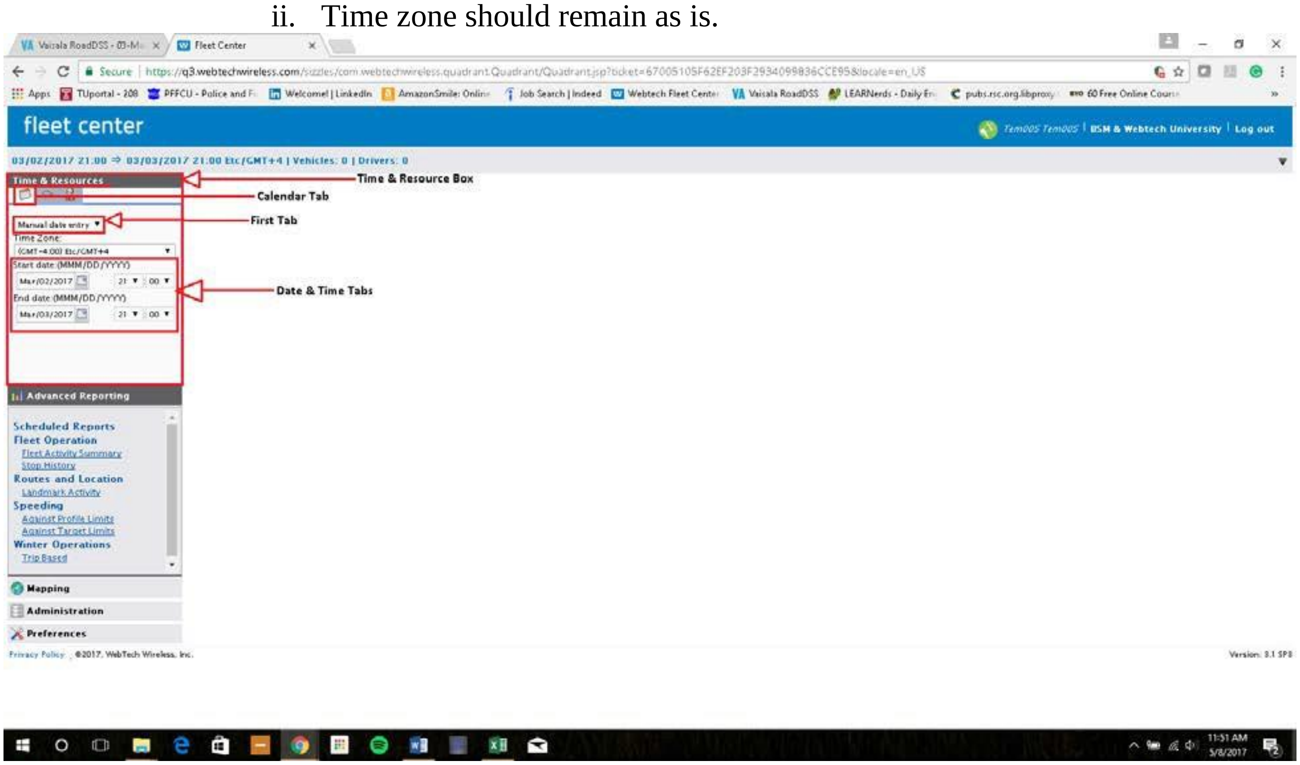
2. AVL Data Collection –

   a. Log into **AVL "Fleet Center"** using the provided Username and Password.

   b. When Fleet Center first opens look for the **Time & Resources Box**. In that box, there will be a **Calendar Tab** which will allow the user to change the dates to the specified dates and times. In the **Calendar Tab** change the first tab to **Manual Data Entry**, new tabs should appear to let the user change the **time zone**, **start date**, **end date** and **time**.

      i. Start Date, End date and the times should be changed to the same dates and times as the RWIS Excel File that was previously downloaded.

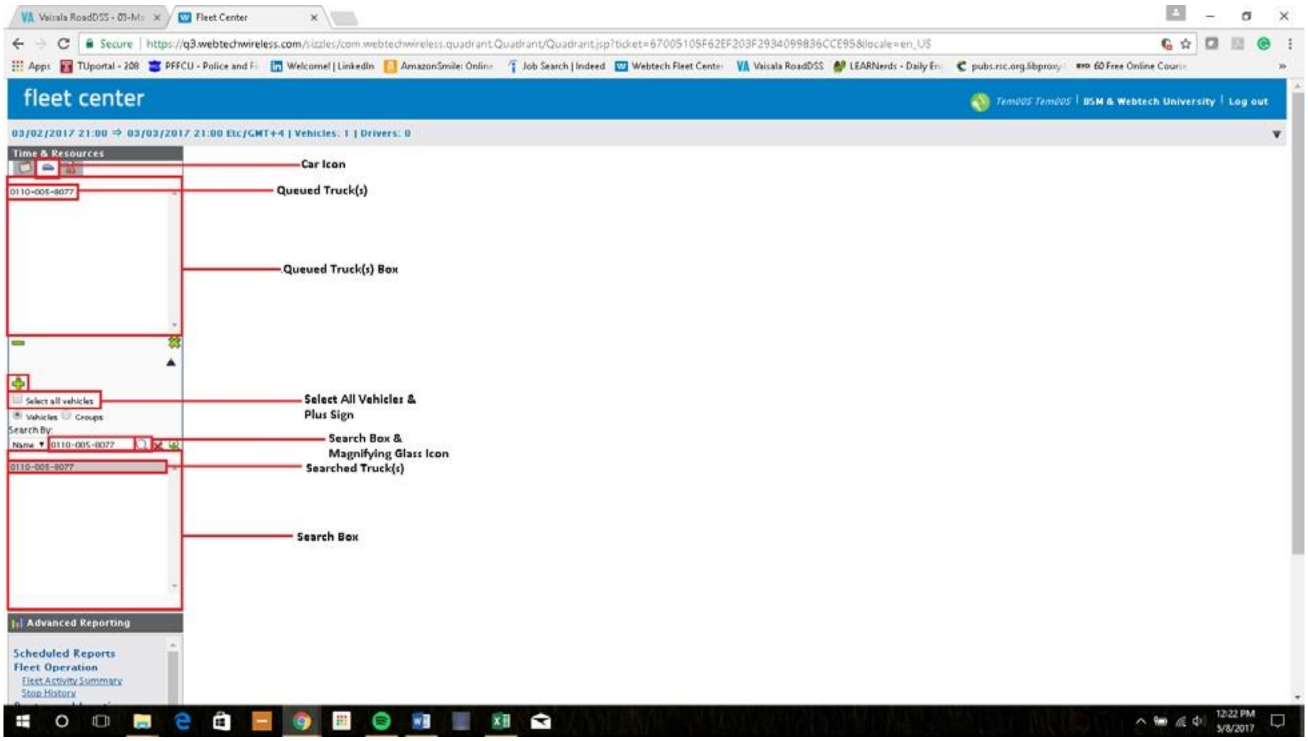
      ii. Time zone should remain as is.



   c. After selecting the proper time and date, select the next tab with the **Car Icon**. In this tab, the user will be selecting the trucks that are present at the site during the time period.

      i. If the truck number is already known, the truck number can be typed into the search box in the **Car Tab**. Then click the **Magnifying Glass Icon** to search for the truck. Once the search is complete double click the truck number that appears to add it to the box above. If a second truck is needed, click the drop down tab and repeat the steps above for the second truck.

      ii. If the trucks present at the site are unknown. Click the check box designated **Select All Vehicle**, then click the **Green Plus Sign** above the check box. This will add all known trucks to the box above.



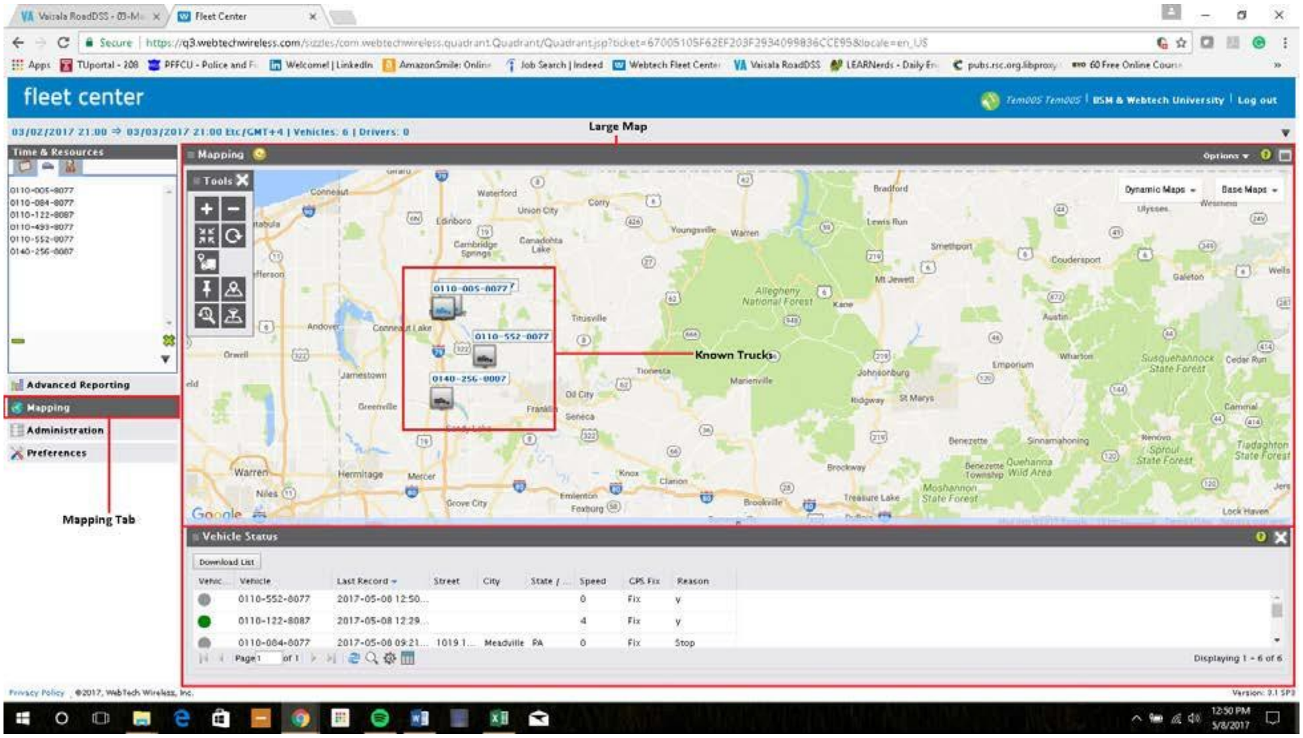
d. Once all of the trucks needed have been added to the queue, click on the **Mapping Tab** found on the left side of the screen. In the **Mapping Tab,** the user will find a **large map of the earth** on the top and a **vehicle status bar** underneath. The user will be using this tab to find the trucks' locations and see the routes taken during the winter storm event.

i. If the trucks in the **queue trucks box** were known then the map will automatically zoom in to encompass all of the known trucks.

ii. If the trucks were unknown, the user will have to zoom in on the area at which the RWIS station is found.

1. To find the location of the RWIS station go to RWIS site, find the station and take the coordinates of the station from the station's information. They will be marked **Coordinates**.

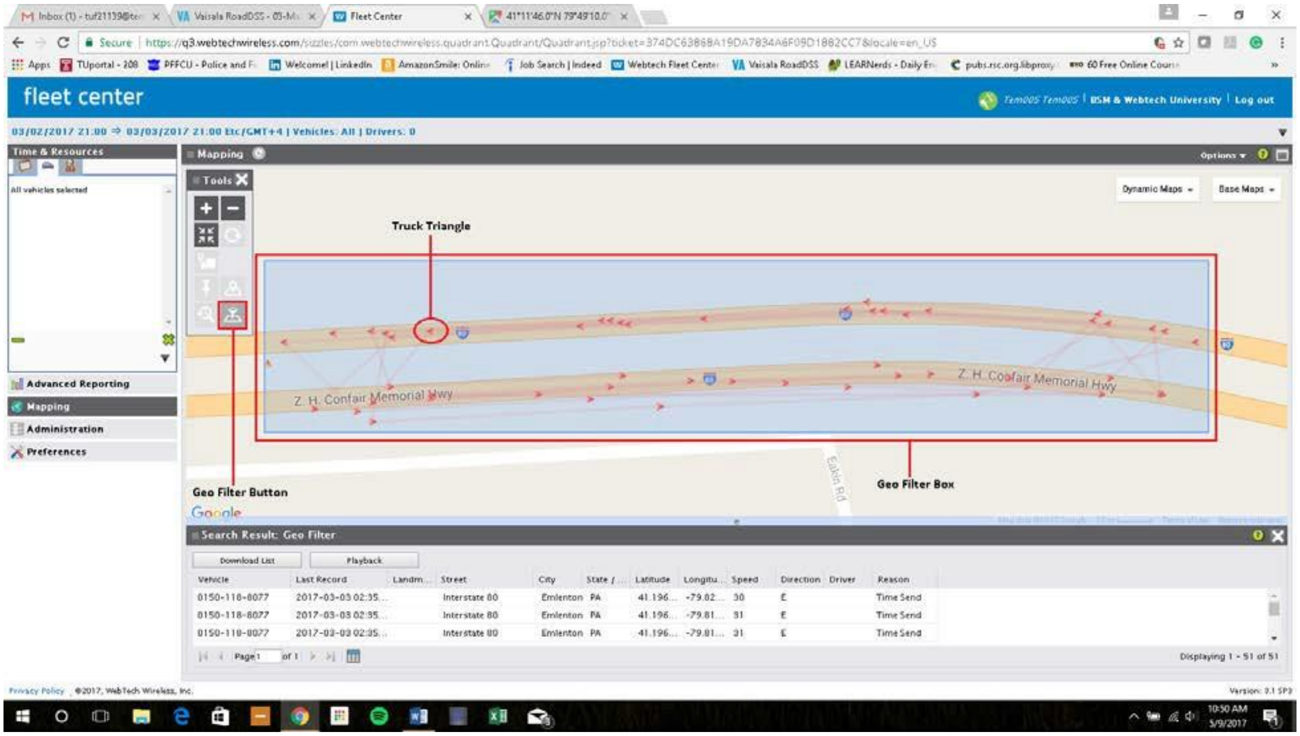
2. Copy the coordinates into google maps and the station's location will appear. Then find that location on the AVL map.



e. If the trucks are unknown: **All vehicles** will be selected in the **queue box**, and all of the vehicles will appear on the map. The user will then find the location of the site through the method above. Once the site has been found the user will use the **Geo Filter** command to search for all know trucks that pass the site.

   i. Since the **Geo Filter** command is searching through all known trucks it may take some time to finish its search.

   ii. When the search has completed trucks coordinates will appear inside the **Geo Filter** box in the form of colored triangles. Different colored triangles indicated different trucks, while the direction of the triangle indicates the direction of the truck.

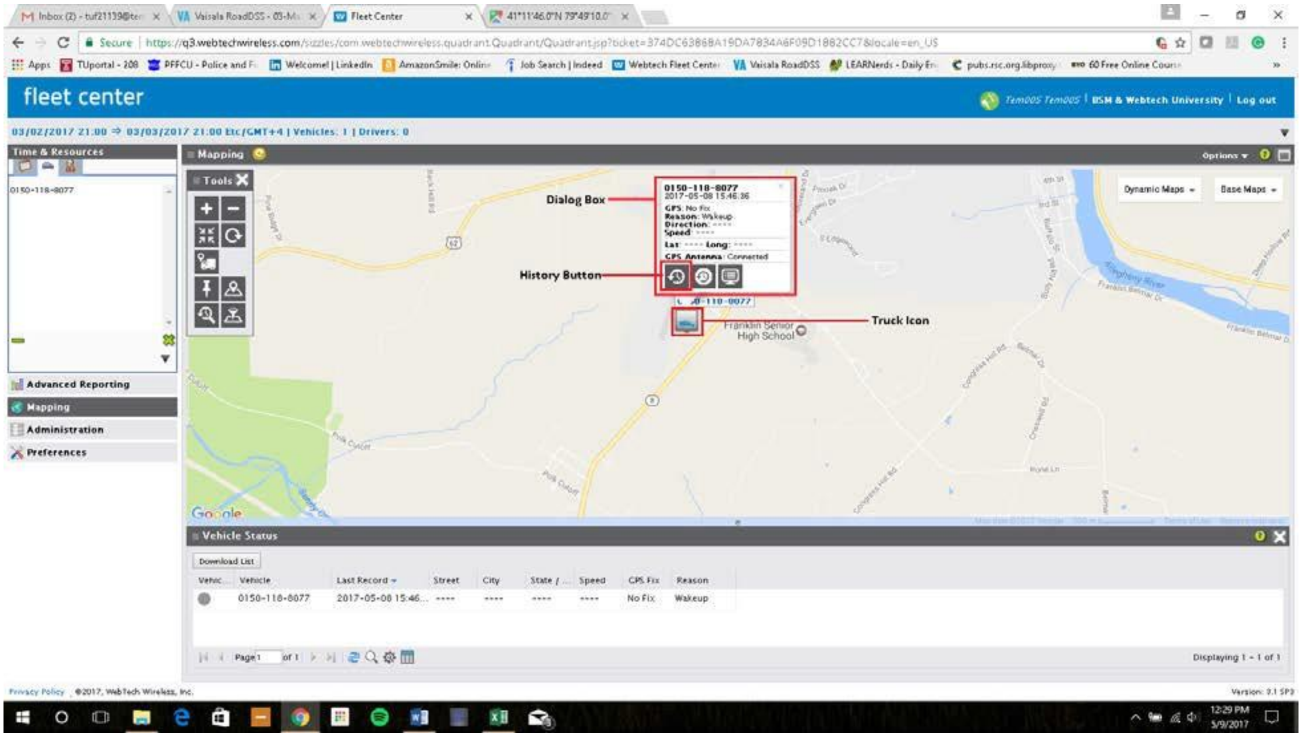


f. After finding all of the trucks that pass the site through **Geo Filter**, the user will use an excel sheet or a notepad to record all of the truck numbers that pass the site.

g. Once all of the trucks have been recorded the user will go back to **Step C** and input all of the found trucks into the queue box and remove the **All Vehicles Selected** option. Then follow the "known trucks" instructions up to **Step D**.

h. With all the known trucks on the map, the user will now select a **truck icon** and access its history. This is done by left clicking on a truck which will make a **dialog box** appear above the truck. In this dialog box, the **History Button** will be selected to get the trucks history.

   i. When the history button is selected it may take a moment for the history to load.

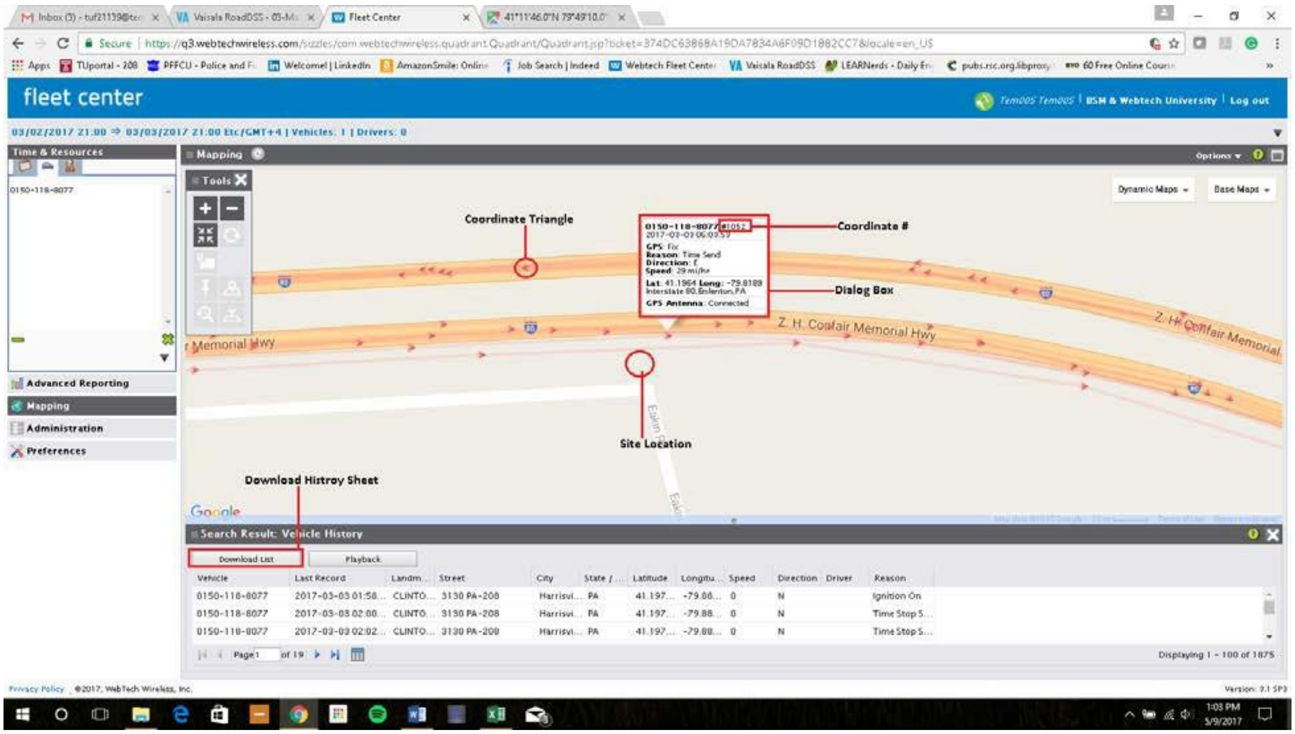


i. A trucks history will appear on the map in the form of colored triangles connected by lines of the same color. In order to get the proper coordinates, the map should be focused on the RWIS stations coordinates.

   i. If the road being examined has separated lanes then the user will note which side of the road the RWIS station is focused on. The side of the road that is the focus is the side of the road that the coordinate triangles are collected. If the road is not separated then all points, in both directions, should be collected.

   ii. The information to collect from each **coordinate triangle** can be accessed by left clicking on the triangle. When the **dialog box** appears over the triangle the **Coordinate #** is to be recorded. The **coordinate #** will correlate to a number found in the trucks history excel sheet.

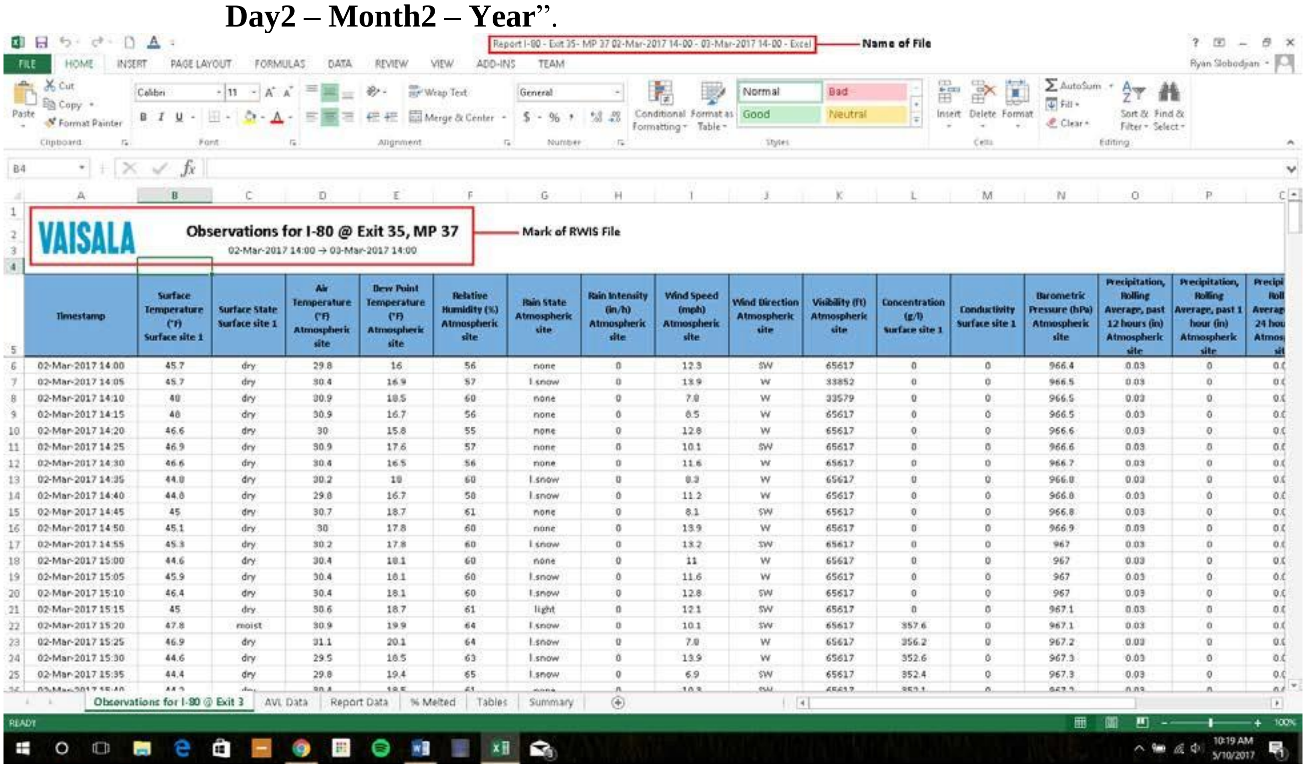
   iii. After recording all of the **coordinate #**’s that correlate with a passing of the site, the user will download the trucks history excel sheet and save it to their computer. The history sheet can be downloaded by clicking the **download list button**.



j. Once all of the truck coordinate #'s and truck history excel sheets have been collected it is time for the user to populate the RWIS station excel sheets with the data obtained.

1. Populating the RWIS Excel Sheets with Data –

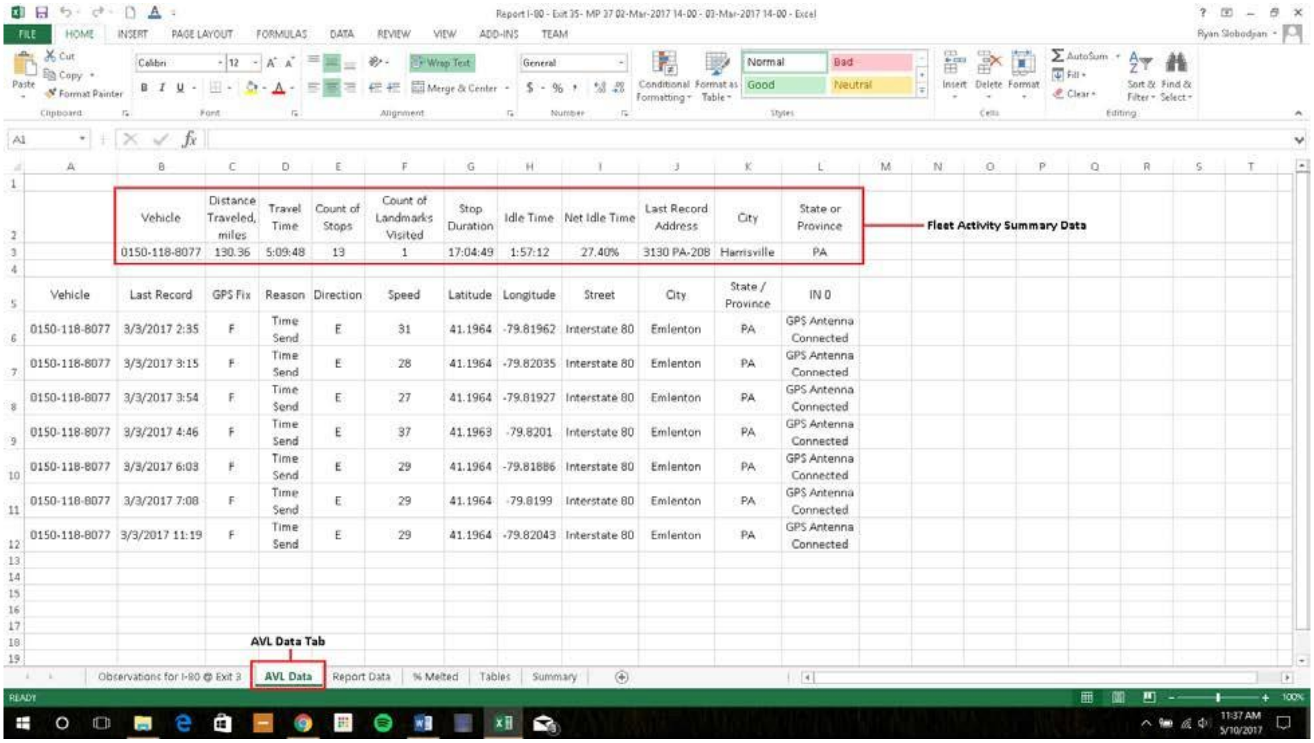
   a. The user should first open the RWIS Excel sheet that contains the station's data. The excel sheet will have a file name of "**Report – Station – Day1 – Month1 – Year – Day2 – Month2 – Year**".



b. In the excel file, there will be 6 tabs, 5 of those tabs will have to be made and populated by the user. The excel files are **Observations for Station X**, **AVL Data**, **Report Data**, **% Melted**, **Tables**, and **Summary**. The **Observations for Station X** tab will already have data in it from RWIS.

c. **AVL Data Tab**: The **AVL Data Tab** consist of all of the salt truck activity that happened the day of the winter storm event at the RWIS site. The following steps detail how to populate the tab.

    i. Step 1: Obtain each vehicle travel data by accessing it from **AVL "Fleet Center"**. The data can be found by clicking the **Advanced Reporting Tab**, then clicking **Fleet Activity Summary**. The summary that appears should be copied and pasted into the RWIS excel sheet.

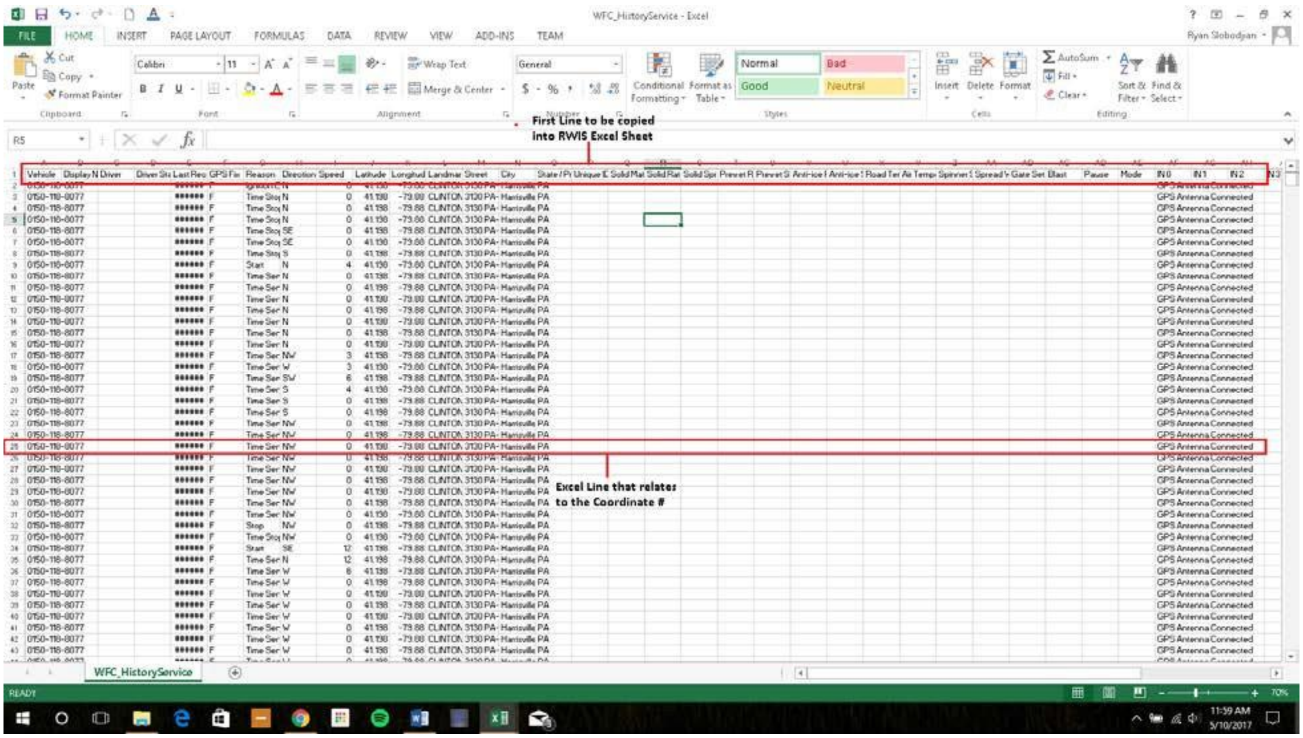


Vehicle	Distance Traveled, miles	Travel Time	Count of Stops	Count of Landmarks Visited	Stop Duration	Idle Time	Net Idle Time	Last Record Address	City	State or Province
0150-118-8077	130.36	5:09:48	13	1	17:04:49	1:57:12	27.40%	3130 PA-208	Harrisville	PA

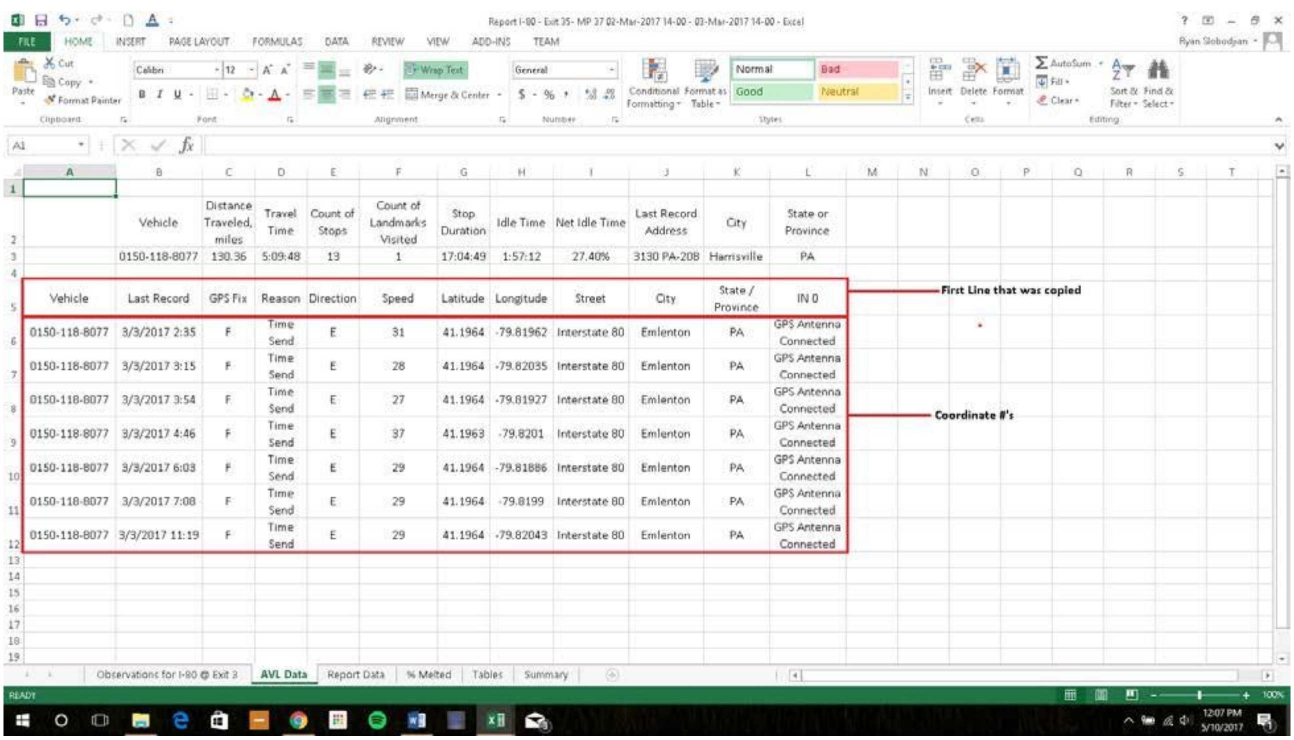
Vehicle	Last Record	GPS Fix	Reason	Direction	Speed	Latitude	Longitude	Street	City	State / Province	IN 0
0150-118-8077	3/3/2017 2:35	F	Time Send	E	31	41.1964	-79.81962	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 3:15	F	Time Send	E	28	41.1964	-79.82035	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 3:54	F	Time Send	E	27	41.1964	-79.81927	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 4:46	F	Time Send	E	37	41.1963	-79.8201	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 6:03	F	Time Send	E	29	41.1964	-79.81886	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 7:08	F	Time Send	E	29	41.1964	-79.8199	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 11:19	F	Time Send	E	29	41.1964	-79.82043	Interstate 80	Emlenton	PA	GPS Antenna Connected

ii. Step 2: The user will now input the data that corresponds to truck passes at the RWIS site. This data can be found in the truck history excel files that were downloaded from AVL in prior steps. The user will open the file that correlates to the truck working at the site. Then the first line from the history will be copied into the RWIS excel sheet. After that, the **coordinate #'s**, that were previously collected, will be used to find the data in the history excel sheet that relates to a truck passing the site.

1. **Coordinate #'s** in the history excel sheet will be that **#+1**, this is due to the first line in the excel sheet being used to identify data.
2. In the photo below the example **coordinate #** is **24**, so the excel line that should be copied into the RWIS excel sheet should be **25**.



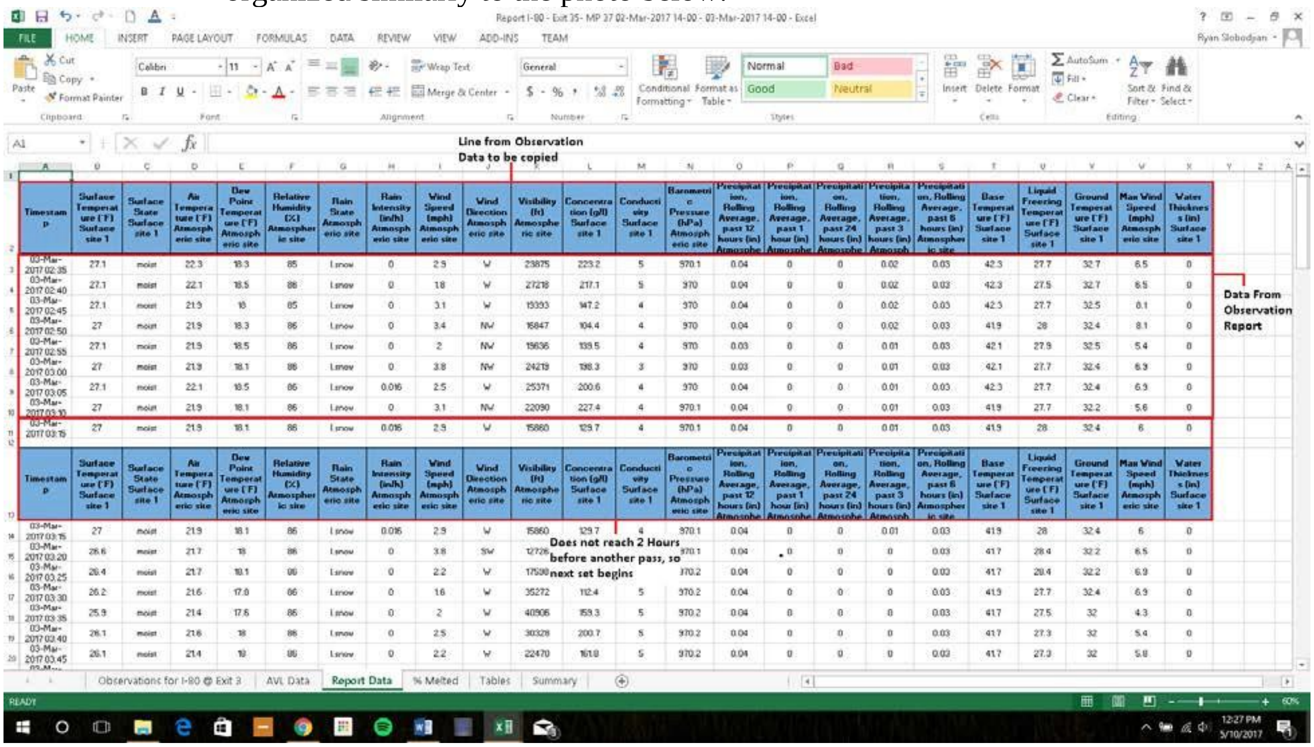
3. The data from the **Truck History Excel File** will be copied into the **AVL Data Tab** in the following format:



Vehicle	Distance Traveled, miles	Travel Time	Count of Stops	Count of Landmarks Visited	Stop Duration	Idle Time	Net Idle Time	Last Record Address	City	State or Province
0150-118-8077	130.36	5:09:48	13	1	17:04:49	1:57:12	27.40%	3130 PA-208	Harrisville	PA

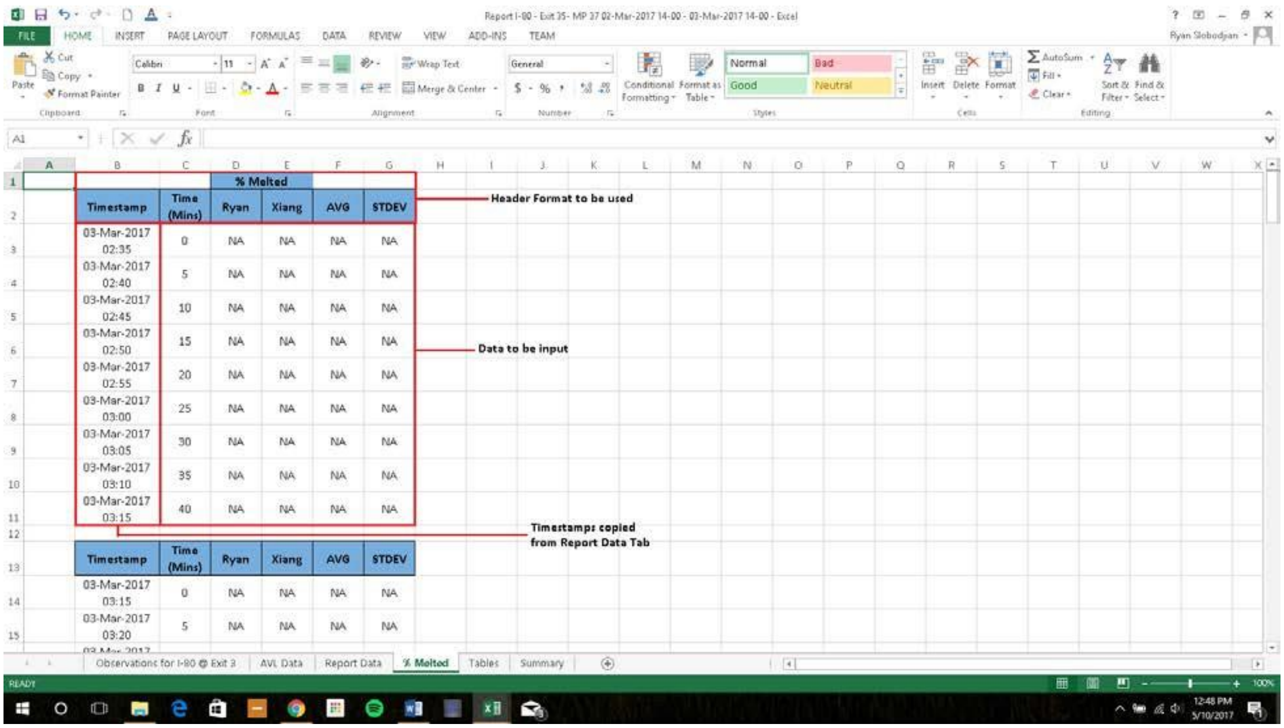
Vehicle	Last Record	GPS Fix	Reason	Direction	Speed	Latitude	Longitude	Street	City	State / Province	IN 0
0150-118-8077	3/3/2017 2:35	F	Time Send	E	31	41.1964	-79.81962	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 3:15	F	Time Send	E	28	41.1964	-79.82035	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 3:54	F	Time Send	E	27	41.1964	-79.81927	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 4:46	F	Time Send	E	37	41.1963	-79.8201	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 6:03	F	Time Send	E	29	41.1964	-79.81886	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 7:08	F	Time Send	E	29	41.1964	-79.8199	Interstate 80	Emlenton	PA	GPS Antenna Connected
0150-118-8077	3/3/2017 11:19	F	Time Send	E	29	41.1964	-79.82043	Interstate 80	Emlenton	PA	GPS Antenna Connected

d. **Report Data Tab**: The **Report Data Tab** consist of the data from the **Observations for Station X Tab** that is collected from each pass the truck makes, up for 2 hours after. If another truck, or the same truck, passes the site again before 2 hours has passed then data will be collected up to that pass. The data will be organized similarly to the photo below:



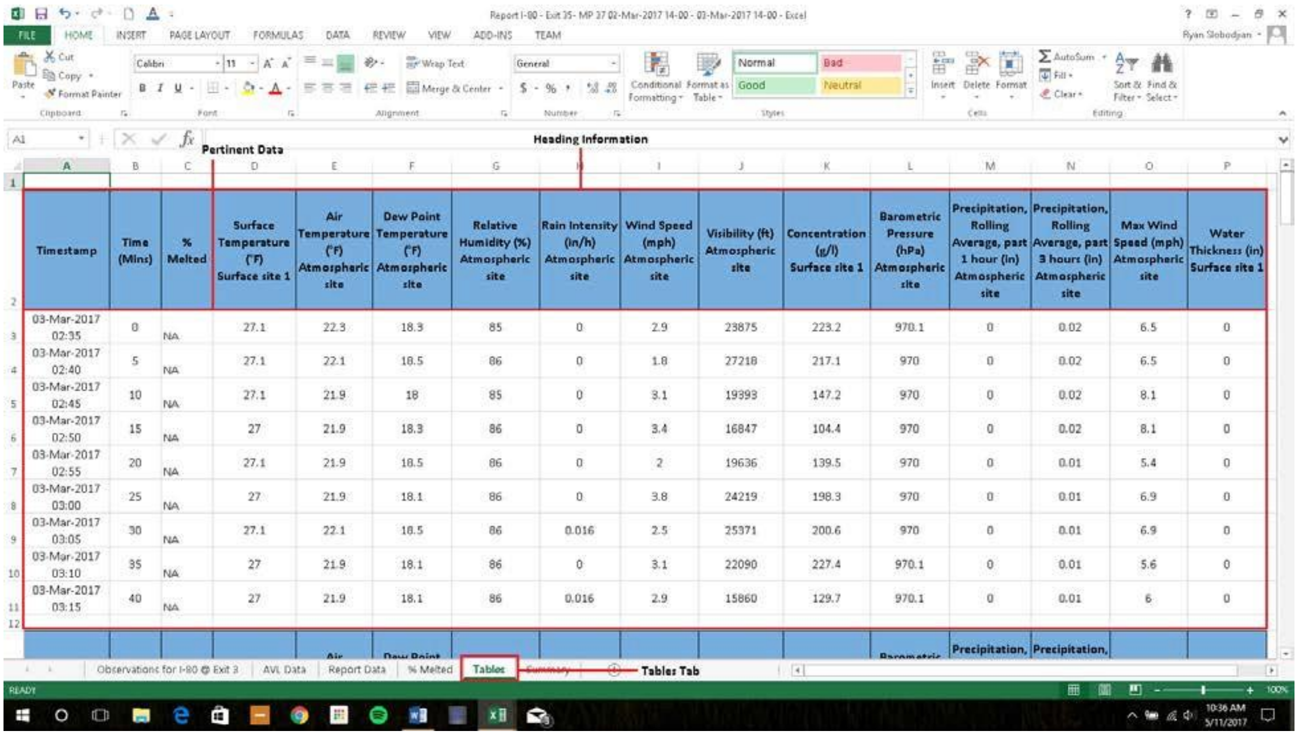
e. **% Melted Tab**: The **% Melted Tab** is where the researchers will input their scores of the photos collected from RWIS. The tab will follow the format in the photo below:

i. Data to be input consist of Timestamp, Time, Researchers Scores, Average of scores, and Standard Deviation of Scores.



f. **Tables Tab**: The **Tables Tab** consist of all of the pertinent information from all of the previous tabs. Its format is exactly the same as the **Report Data Tab** but with less of the extra information. The information included in the **Tables Tab** is as follows: **Timestamp**, **Time**, **% Melted**, **Surface Temp**, **Air Temp**, **Dew Temp**, **Relative Humidity**, **Rain Intensity**, **Wind Speed**, **Visibility**, **Concentration**[i], **Barometric Pressure**, **Precipitation Rolling Average 1 Hour**, **Precipitation Rolling Average 3 Hours**, **Max Wind Speed**, **Water Thickness**[i]**.**

i. **Concentration** and **Water Thickness** are only measured at some of the RWIS Sites. At other sites, they will be exchanged for **Level of Grip**, **Ice Layer,** and **Snow Layer**.



Timestamp	Time (Mins)	% Melted	Surface Temperature (°F) Surface site 1	Air Temperature (°F) Atmospheric site	Dew Point Temperature (°F) Atmospheric site	Relative Humidity (%) Atmospheric site	Rain Intensity (in/h) Atmospheric site	Wind Speed (mph) Atmospheric site	Visibility (ft) Atmospheric site	Concentration (g/l) Surface site 1	Barometric Pressure (hPa) Atmospheric site	Precipitation, Rolling Average, past 1 hour (in) Atmospheric site	Precipitation, Rolling Average, past 3 hours (in) Atmospheric site	Max Wind Speed (mph) Atmospheric site	Water Thickness (in) Surface site 1
03-Mar-2017 02:35	0	NA	27.1	22.3	18.3	85	0	2.9	23875	223.2	970.1	0	0.02	6.5	0
03-Mar-2017 02:40	5	NA	27.1	22.1	18.5	86	0	1.8	27218	217.1	970	0	0.02	6.5	0
03-Mar-2017 02:45	10	NA	27.1	21.9	18	85	0	3.1	19393	147.2	970	0	0.02	8.1	0
03-Mar-2017 02:50	15	NA	27	21.9	18.3	86	0	3.4	16847	104.4	970	0	0.02	8.1	0
03-Mar-2017 02:55	20	NA	27.1	21.9	18.5	86	0	2	19636	139.5	970	0	0.01	5.4	0
03-Mar-2017 03:00	25	NA	27	21.9	18.1	86	0	3.8	24219	198.3	970	0	0.01	6.9	0
03-Mar-2017 03:05	30	NA	27.1	22.1	18.5	86	0.016	2.5	25371	200.6	970	0	0.01	6.9	0
03-Mar-2017 03:10	35	NA	27	21.9	18.1	86	0	3.1	22090	227.4	970.1	0	0.01	5.6	0
03-Mar-2017 03:15	40	NA	27	21.9	18.1	86	0.016	2.9	15860	129.7	970.1	0	0.01	6	0

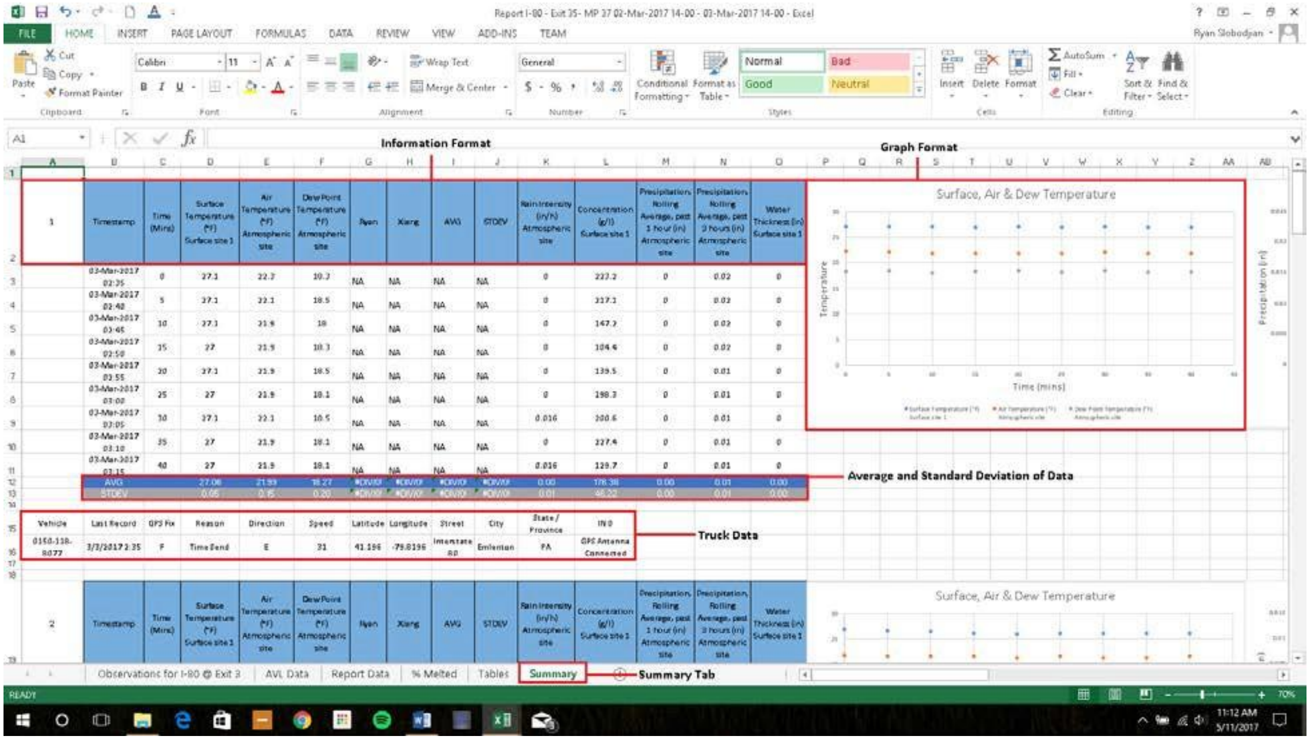
g. Summary Tab: In the **Summary Tab** the user will input the important information from the **Table Tab** and create graphs displaying the information. The information consists of **Timestamp**, **Time**, **Surface Temp**, **Air Temp**, **Dew Temp**, **Researchers Visual Scores**, **Average of Visual Scores**, **Standard Deviation of Visual Scores**, **Rain Intensity**, **Concentration**[i], **Precipitation Rolling Average 1 Hour**, **Precipitation Rolling Average 3 Hours** and **Water Thickness**[i]**.**

i. **Concentration** and **Water Thickness** are only measured at some of the RWIS Sites. At other sites, they will be exchanged for **Level of Grip**, **Ice Layer,** and **Snow Layer**.

ii. The **Surface Temp**, **Air Temp** and **Dew Temp** will be combined in one graph. The **Precipitation Rolling Average 1 Hour** and the **Precipitation Rolling Average 3 Hours** are to be combined into one graph as well. All other data will have its own graph to represent it.

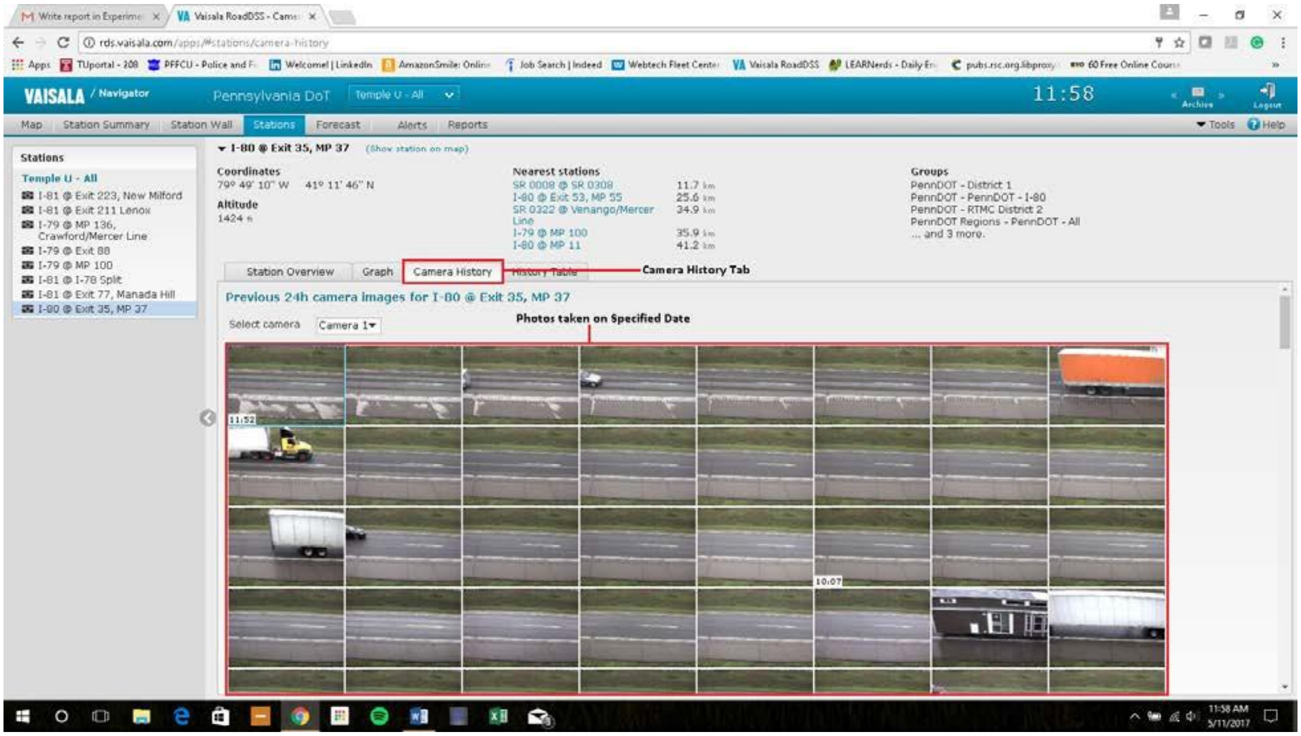
iii. Averages and Standard Deviations of all data will be included below the data, below that the data's truck information will be displayed as well.

1. Collecting Photos From RWIS –



   a. Go back to Section 1: **RWIS Data Collection** and then follow the instructions in that section to **Step d**. After completing **Step d**, click on the **Camera History Tab**. In this tab, the user will see all of the photos taken at the site over a 24 hour period, photos are taken every 5 minutes.

i. If the user attempts to collect photos to long after the storm event it is possible that RWIS will take the photos off the site, and the photos will be unavailable. It is recommended that the user collects the photos from RWIS before a month of time, since the storm event, has passed.



b. The user should now record, either in an excel sheet or notebook, the timelines to collect photos.

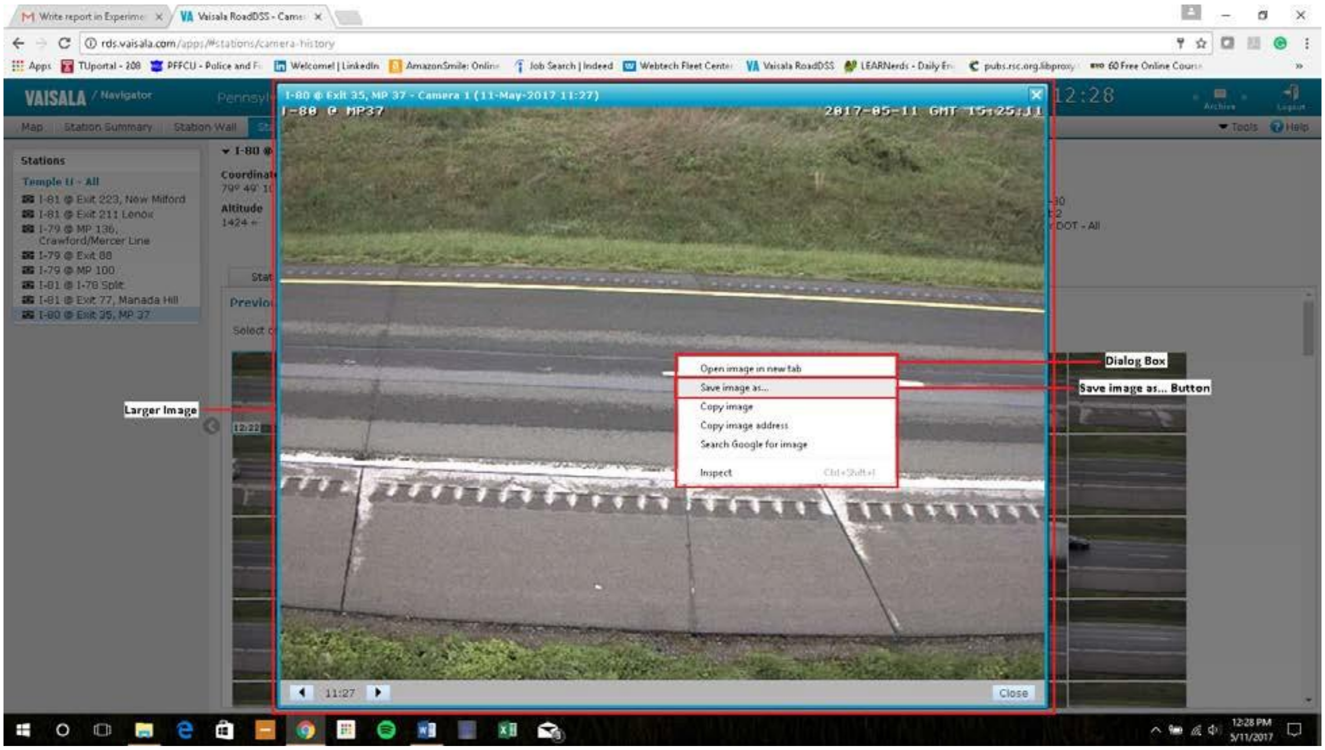
c. With the timelines known, the user will start downloading the photos from RWIS using the following method:

i. Left-click of the needed photo, this will bring a large image of the photo up. Then right-click on the photo to bring up a **dialog menu**, in this menu the user will click "**Save image as…"** The user will then save the image to their computer.

ii. When saving the image the following naming format will be used, **Time – Date – Station**. Ex. **07-35 03-03-17 I-80 Exit 35**.

iii. This Process will be done for each image needed.

iv. The user will not need to save any images that are blurry or are taken at night. These photos will be marked as "**NA**" in the **% Melted Tab** of the RWIS Excel Sheet.



d. Notes –

i. All computer programs and actions were using with Windows Operating System and Chrome Internet Browser. Using a different type of operating system (Mac, Linux) or a different web browser may provide different results, need extra steps or different commands.

CONTRACT NO. 4400011166
TEM WO 005
DELIVERABLE 4 REPORT TO INCLUDE PRODUCT STATISTICAL ANALYSIS AND RANKING APPROACHES FOR THE ON-ROAD REAL-TIME TEST

March 27, 2018

SUMMARY

The performances and cost analysis of four deicers products, i.e., Aqua Salina (AS), Beet Heet (BH), Green Blast (GB), Magic Minus Zero (MMZ), and the references, Rock Salt (RS) and/or Salt Brine (SB), were evaluated in this study.

The present report (Task 4) includes three major parts. (1) First the statistical analysis of the on-road test results (Task 3) was performed. (2) Then ranking of the deicer products as obtained from different tests – including laboratory (Phase I – TEM WO 003), parking lot tests (Phase II – Task 1) and on-road tests (Phase II – Task 3) – were compared and discussed. (3) Finally, a cost analysis was performed based on the results from the parking lot tests (Task 1). Laboratory tests (Phase I) were not used for the cost analysis as no statistical models were available. On-road tests (Task 3) were not used as well as only partial, qualitative, and mostly non-significant ranking was obtained from the available data.

Statistical Analysis of On-Road Tests. In previous on-road real-time tests conducted over the winter 2016-2017 and winter 2017-2018 (until December 31, 2017, referred to as winter 2017 hereafter), a large number of data were collected from the RWIS and AVL systems, and used to conduct a statistical analysis and ranking of the deicer products. During the two data collection campaigns, one site was used per deicer product (except during the winter 2016-2017, where four sites were used for the reference, Rock Salt). The multivariate linear regression method including all data from all storms and all deicers (i.e., all sites) was applied in order to build a model descriptive of the deicer performance (i.e., the snow condition on the road). Because two indicators were used for the deicer performance and because data from the winters 2016-2017 and 2017 could not be integrated into the same model due to differences in the application methods, four models were computed: (1) winter 2016-2017 data using the snow melted percentages as the performance indicator, (2) winter 2016-2017 data using the grip level as the performance indicator, (3) winter 2017 data using the snow melted percentage as the performance indicator, and (4) winter 2017 data using the grip level as the performance indicator. The statistical models include one dependent variable indicative of the snow condition on the road – either the grip level or the snow melted percentage, and a series of independent variables including categorical variables representing the deicer products. Because of various technical and operational issues, only limited or no data were collected for some deicer products, preventing the comparison among all five products. In addition, in several cases, the analysis could not determine a rank with statistical significance. Only partial comparison between deicers was obtained.

The **statistical analysis of winter 2016-2017 data using the grip level** as the performance

indicator included 1,439 observations, 14 variables (Deicer type, surface temperature, air temperature, dew point temperature, snow layer, relative humidity, barometric pressure, precipitation 1 hour, wind speed, max wind speed, solid rate, speed of deicer truck, deicer prewet rate, and deicer type), and only two deicer products, GB and RS. After removing the outliers, the adjusted R-squared for the model was 0.8522. The ranking analysis showed that there is no significant evidence showing that GB performs better than RS.

The **statistical analysis of winter 2016-2017 data using the snow melted percentage** as the performance indicator included 465 observations, 10 variables (Deicer type, surface temperature, dew point temperature, rain, relative humidity, barometric pressure, precipitation 1 hour, wind speed, and speed of deicer truck), and only three deicer products, AS, BH, and RS. After removing the outliers, the ranking analysis showed that AS and BH are similar. There exists moderate evidence showing that AS and BH may perform better than RS. The R-square is only 0.1637 and considered as low, making the statistical significance of the ranking questionable.

The **statistical analysis of winter 2017 data using the grip level** as the performance indicator included 2,005 observations, 12 variables (surface temperature, air temperature, dew point temperature, snow layer, relative humidity, barometric pressure, precipitation in 1 hour, wind speed, max wind speed, solid rate (deicer application rate), speed of deicer truck, and deicer type), and only three deicer products, AS, GB, and RS. After removing the outliers, the adjusted R-square for the model was 0.7166. The ranking analysis showed that there exists sufficient statistical evidence that GB performed better than AS, while AS is similar as RS.

The s**tatistical analysis of winter 2017 data using the snow melted percentage** as the performance indicator included 669 observations, 13 variables (surface temperature, air temperature, dew point temperature, snow layer, relative humidity, barometric pressure, precipitation in 1 hour, wind speed, wind spread, max wind speed, solid rate (deicer application rate), speed of deicer truck, and deicer type), and only three deicer products, AS, GB, and RS. After removing the outliers, the adjusted R-square for the model was 0.6519. RS is not shown statistically different than GB and AS. On the other hand, there exists moderate evidence that GB performs worse than AS (p-value = 0.0118).

Ranking of Deicer Products Based on All Tests. In order to summarize the results, we ranked the deicer products based on the numerical or comparative performances obtained from different tests conducted in Phase I (TEM WO 003) and II (TEM WO 005) of this project. A discrete score (from 1 – best – to 6 – worst) was assigned to each product under study and the reference products.

Integrating rankings from the different tests into a single indicator was not feasible primarily because the preparation methods of the products were different in each test, and secondary because there is no rationale for weighing the results from different test procedures. The ranking performances obtained from the lab test (Phase I), parking lots tests (Phase II), and on-road tests (Phase II), were presented in a summary table (see Section 3) and compared.

The parking lot tests using the PennDOT formulation[1] gave the following ranking BH ≈ GB ≈ MMZ > AS ≈ RS > SB. The test using the manufacturer formulation indicated that the 'liquid' deicers performed better with GB > AS, and that among 'solids deicers', RS performed better than the others, with an overall ranking as GB > AS > RS ≥ BH ≥ MMZ ≈ SB. When comparing the results from the laboratory tests (Phase I) and from the parking lot tests using the same manufacturer recommendations, there are some similarities: AS ranked first and BH ranked last (together with MMZ and SB). Little similarity was observed between the laboratory tests and the parking lot tests using PennDOT formulation, mainly because different ways of deicer preparation. Considering the significant results only, the road tests suggested that AS ≈ BH and GB > AS ≈ RS. The ranking GB > AS ≈ RS is consistent with the parking lots test results using PennDOT formulation.

Cost Analysis. Because of the different conditions under which the different tests were conducted and because of the absence of significant results in some cases, it was not possible to integrate the results of all tests to conduct the cost analysis. In addition, the lab tests (Phase I) were not included in the analysis as no statistical models were computed and/or are available. The skid resistance test did not show any significant differences between the products and was not considered. Finally, difficulties arose from the low statistical significance and partial ranking from the on-road tests, which were not considered either.

Performance data from both the parking lot tests and the costs of the products were used to perform the cost analysis. Using the manufacturer's recommended application rates and the price of the deicers provided by PennDOT, the cost difference between the deicer products and the reference, SB, was calculated by dividing the cost of the deicer (on a gallon-per-lane-mile basis) by that of SB, showing the following rank: BH (cost difference 10.4) > MMZ (cost difference 8.6) > GB (cost difference 7.4) > AS (cost difference 4.5) > SB (cost difference 1.0).

---

[1] See TEM WO 005 Task 1.2 Report for details of the formulation.

The melted percentages from the first parking lot test (using the manufacturer's recommendations) at different time points and for different application rates were used to calculate the differences in performance between the deicer products and the reference, SB. We conclude that AS is 4.5 times more expensive than SB, with performance 2.8 – 8.8 better. GB is 7.5 times more expensive than SB, with performance 3.3 – 12.4 times better. BH and MMZ are 10.4 and 8.6 times more expensive than SB, but their performances are not statistically different from SB.

The melted percentages from the second parking lot test (using PennDOT's recommendations) at different time points and an application rate of 500 lbs per lane mile were used to calculate the differences in performance between the deicer products and the reference, SB. The average differences across all time points were used to conduct the cost comparison. We conclude that

AS, BH, GB, and MMZ performed 20%, 51.3%, 66.7%, and 86.2% better than SB, respectively, although the cost differences by comparison to SB are 4.5, 10.4, 7.5 and 8.6 times, respectively.

1. INTRODUCTION

Deicing materials can protect the road safety. In the recent years, new deicer products have been developed. Beyond laboratory testing (performed in the Phase I of this study – TEM WO 003), it is necessary to evaluate the deicers performance in field tests, such as parking lot tests and on-road real-time tests (Phase II – TEM WO 005).

In Task 1, the deicer products were tested in parking lot tests, in which several external variables were evaluated, including deicer type, application rate and sample time. However, various environmental variables have not been taken into consideration, such as precipitation level, grip level, surface temperature, etc. Therefore, on-road real-time field tests were conducted (Task 3) to evaluate the deicers performance at several observation sites. As for the parking lot tests, the approach chosen was to include data collected into a multivariate regression model, including one dependent variable indicative of the snow condition on the road – either the grip level or the snow melted percentage, a series of independent variables, categorical variables representing the deicer product used, and the deicer application rate. After fitting the model, we conduct the pairwise comparison using Tukey's adjustment to rank the deicer products based on their snow melting performances.

Since the statistical analysis of the parking lot test results has already been performed (Task 1.4), the present report focuses primarily on the statistical analysis of the on-road tests performed and described in Task 3.1 and 3.2 Reports. Then ranking of the deicer products as obtained from different tests – including laboratory (Phase I – TEM WO 003), parking lot tests (Phase II – Task 1) and on-road tests (Phase II – Task 3) were compared. In addition, a cost analysis was performed based on the results from the parking lot tests (lab tests were not used as no statistical models were available, and on-road tests were not used as only partial, qualitative, and mostly non-significant ranking was obtained from the available data).

2. STATISTICAL ANALYSIS OF ON-ROAD TESTS

2.1 Data Collection

2.1.1 RWIS and AVL systems

All data used in the regression models were from both RWIS (Road Weather Information System, http://rds.vaisala.com/apps/) and AVL systems (Automatically vehicles control, https://q3.webtechwireless.com/wtw/jsp/QSecurity/login.jsp.). Deicer solid application rates, truck speeds, and prewet rates were collected from AVL website.

2.1.2 Data Collected

During the winter 2016-2017, four deicers (AquaSalina, Beet Heet, Green Blast, and Magic Minus Zero) were evaluated via paired experiments including each the treatment site (treated with the product tested) and a reference site (treated by the reference product, Rock Salt), thus necessitating eight sites in total (site I-80 @ Exit 35 MP 37 for AquaSalina and site I-79 @ MP 136 Crawford/Mercer Line for the reference (Rock Salt); site I-79 @ Exit 88 for Beet Heet and I-79 @ MP 100 for the reference; site I-81 @ Exit 223 New Milford for Green Blast and site I-80 @ Exit 211 Lenox for the reference; and site I-81 @ Exit 77, Manada Hill for Magic Minus Zero and site I-81 @ Exit 223 New Milford for the reference).

The primary performance indicator for the deicers was the snow melted percentage derived from the photographs taken by on-sites cameras. Additional tentative indicators were the grip level and salt concentration – some sites were equipped with grip level sensors and some with salt concentration sensors. Data collected over the winter 2016-2017 revealed that few events allowed the use of photographs because many storms occurred in the dark or because poor visibility or technical issues. The salt concentration level fluctuated widely and did not correlate well enough with the snow melted percentage. As a consequence, the grip level was identified as a more robust indicator as it correlated well with the snow melted percentage and snow layer.

During the winter 2017, the same four deicers were evaluated using five sites (one site for each of the four products tested, AquaSalina, Beet Heet, Green Blast, Magic Minus Zero, and one site for the reference, Rock Salt). All sites were equipped with grip level sensors. The selected sites were site SR 322 W/B - Venango-Mercer Co. Line for AquaSalina, site I-78 WB @ MM27 Berk Co. for Magic Minus Zero, site I-81 @ Exit 223 New Milford for Green Blast, site I-79 N/B @ Exit 60 Carfton Allegheny Co. for Beet Heet, and site I-80 @ MP 11 Mercer Co. for the reference, Rock Salt. Data at these sites were collected during November and December 2017.

Due to technical issues independent of the Team's responsibility, RWIS data from several storms were not available (i.e., data not recorded) or not useable (i.e., photographs taken by night). In addition, the truck information for some sites was not available (i.e., Magic Minus Zero in winter 2016-2017). Table 2.1 represents the list of the storms recorded at each site over the two data collection campaigns and the data that were collected. Table 2.2 summarizes the total number of snow event that were useable for statistical analysis and deicer ranking. Because two indicators of the deicer performance were used and because data from the winter 2016-2017 and 2017 could not be integrated into the same model due to differences in the application method, four models were computed: (1) winter 2016-2017 data using the snow melted percentage as performance indicator, (2) winter 2016-2017 data using the grip level as performance indicator, (3) winter 2017 data using the snow melted percentage as performance indicator, and (4) winter 2017 data using the grip level as performance indicator.

Table 2.1: Data collected over the winter 2016-2017 and 2017

Winter	Site	Description	District	Deicer	Sensor	Total events	Usable events	With snow melted %	With grip level
2016-2017	Site	Site I-80@ Exit 35 MP 37	1	AquaSalina	Salt	12	5	**2**	**0**
	Site	I-79 @ MP 136	1	Rock Salt	Grip level	8	4	**2**	**4**
	Site	I-79 @ Exit 88	10	BEET HEET	Salt	7	4	**1**	**0**
	Site	I-79 @ MP 100	10	Rock Salt	Salt	2	1	**0**	**0**
	Site	I-81 @ Exit 223 New Milford	4	Green Blast	Grip level	3	1	**0**	**1**
	Site	I-80 @ Exit 211 Lenox	4	Rock Salt	Grip level	3	1	**0**	**1**
	Site	I-81 @ Exit 77 Manada Hill	8	Magic Minus	Salt	1	1	**0**	**0**
	Site	I-81 @ Exit 223 New Milford	8	Rock Salt	Salt	0	0	**0**	**0**
2017-2018	Site	SR 322 WB - Venango-Mercer	1	Aqua Salina	Grip level	6	5	**4**	**5**
	Site	I-79 NB @ Exit 60 Carfton	11	BEET HEET	Grip level	3	0	**0**	**0**
	Site	I-81 @ Exit 223 New Milford	4	Green Blast	Grip level	1	1	**1**	**1**
	Site	I-78 WB@ MM27 Berk Co	5	Magic Minus	Grip level	4	0	**2**	**0**
	Site	I-80 MP@11 Mercer County	1	Rock Salt	Grip level	5	5	**4**	**5**

Table 2.2: Useable data for statistical analysis and deicer ranking

Deicer performance indicator	Deicer	2016-2017	2017	Total
Snow melted percentage	**AS**	2	4	6
	BH	1	0	1
	GB	0	1	1
	MMZ	0	0	0
	RS Ref	2	4	6
Grip level	**AS**	0	5	5
	BH	0	0	0
	GB	1	1	2
	MMZ	0	0	0
	RS Ref	5	5	10

2.1.3 Processing Photographs

The snow melted percentage data were derived from the photographs obtained from the RWIS system. Snow melted percentage scores were visually assigned by two different researchers independently. The final melted percentages are the average of the two scores. The visual score criteria utilized are shown in Figure 2.1.

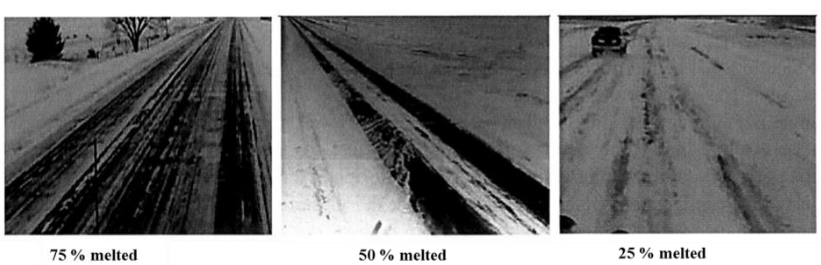


Figure 2.1: Standard images of visual scores during on-road real-time field tests.

2.2 Statistical Data Analysis

2.2.1 Statistical Software & General Description

All the statistical analysis was based on a professional statistical analysis software R®. R (version 3.3.3) is a free software environment for statistical computing and graphics (https://www.r-project.org/). R provides a wide variety of statistical (e.g., linear and nonlinear modeling, classical statistical tests, time- series analysis, classification, clustering) and graphical techniques, and it is highly extensible.

We used the linear multiple regression models to predict the performance of various deicers. In particular, we use the linear regression models to study the relationship between a scalar dependent variable Y (in our case the grip level and the snow melted percentage) and one or more explanatory or independent variables X (e.g., variables recorded by the RWIS system, such as surface temperature, humidity, and snow layer).

2.2.2 Formatting Data in R

All the data in Excel worksheet were converted into CSV format (comma delimited) and then imported into R.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	SurfT	AirT	DewPt	Grip	Snow	RelHum	Barom	Prec1h	WindSp	WindDir	WindSpd	MaxWSpd	SolidR	TruckS	Prewet	Deicer
2	30.90	30.40	28.90	0.76	0.00	95.00	960.90	0.00	3.80	155.00	1.20	8.50	300.00	21.00	15.00	AS
3	31.30	30.40	29.10	0.72	0.00	96.00	960.80	0.00	2.50	121.00	0.90	8.50	300.00	21.00	15.00	AS
4	31.30	30.40	29.30	0.70	0.00	96.00	960.70	0.00	2.90	135.00	1.40	6.00	300.00	21.00	15.00	AS
5	31.30	30.20	29.30	0.71	0.00	97.00	960.60	0.00	2.50	150.00	1.10	5.10	300.00	21.00	15.00	AS
6	31.30	30.20	29.50	0.73	0.00	97.00	960.50	0.00	2.20	148.00	0.70	4.70	300.00	21.00	15.00	AS
7	30.90	30.20	29.50	0.75	0.00	97.00	960.40	0.00	2.20	144.00	1.60	3.80	300.00	21.00	15.00	AS
8	30.90	30.20	29.50	0.74	0.00	98.00	960.30	0.01	2.20	153.00	0.80	5.40	300.00	21.00	15.00	AS
9	30.70	30.20	29.50	0.73	0.00	98.00	960.20	0.01	3.40	152.00	1.70	5.40	300.00	21.00	15.00	AS
10	30.70	30.40	29.70	0.71	0.00	98.00	960.00	0.01	2.20	156.00	1.40	5.10	300.00	21.00	15.00	AS
11	30.90	30.20	29.70	0.70	0.00	98.00	959.80	0.01	1.80	142.00	0.80	4.30	300.00	21.00	15.00	AS

Figure 2.2: Examples to show the formatting process in R.

2.2.3 Model Construction

The linear regression model was fitted using R among all the deicers, the rock salt (RS) was set as the reference deicer. We fitted the linear model using the ordinary least square (OLS) approach.

2.2.5 Outlier Detection

An outlier is an observation which is distant from other observations, due to variability in the measurement or experimental error. An outlier can cause problems in statistical analysis. In the analysis, we identify those observations with the corresponding standardized residues being larger than 3 or less than -3 as outliers and remove them to improve the model fit.

2.2.6 Variables Selection

With a large number of independent variables, we apply the bi-directional stepwise regression to choose the candidate model. The criteria to keep/kill a variable is the Bayesian Information Criteria (BIC). This is done using the R package *MASS*.

2.2.7 Ranking the Deicers

After fitting the model, we run the pairwise comparison of all the deicers using Tukey's adjustment for the multiplicity. This is done using the function glht() from the R package: *multcomp*.

2.3 Results & Discussion

Because two indicators of the deicer performance were used and because data from the winter 2016-2017 and 2017 could not be integrated into the same model due to differences in the application method, four models were fitted separated for the data: (1) winter 2016-2017 data using the grip level as the performance indicator, (2) winter 2016-2017 data using the snow melted percentage as the performance indicator, (3) winter 2017 data using the grip level as the performance indicator, and (4) winter 2017 data using the snow melted percentage as the performance indicator.

2.3.1 Winter 2016-2017 Data Using the Grip Level as the Performance Indicator

The regression analysis was run using the grip level as the dependent variable and a set of independent variables, including surface temperature, air temperature, dew point temperature, water layer, ice layer, snow layer, relative humidity, barometric pressure, precipitation in 1 hour, wind speed, max wind speed, solid rate (deicer application rate), speed of deicer truck, and deicer type (categorical variables). The total sample size is 1,439. After removing data with missing entries, the sample size for the data analysis is 1,438. The model suggested by using the stepwise regression is:

Grip level ~ deicer type + surface temperature + air temperature + dew point temperature + water layer + ice layer + snow layer + relative humidity + precipitation in 1 hour + max wind speed + speed of deicer truck

After fitting the model, we calculate the standardized residuals. Out of 1,438 samples, the magnitude of the standardized residuals of 28 of them is greater than 3 and they were marked as outliers. After removing them, we have the following output of the model:

Table 2.3.1 List of independent variables coefficients and their statistical significance

	Estimate	Std. Error	t value	Pr(>|t|)	Sig.
(Intercept)	2.05E+00	1.85E-01	11.106	< 2e-16	***
DeicerRS	-6.51E-03	8.10E-03	-0.803	0.421988	
SurfT	3.58E-03	7.51E-04	4.772	2.01E-06	***
AirT	-3.58E-02	5.97E-03	-6	2.51E-09	***
DewPt	3.45E-02	6.08E-03	5.676	1.68E-08	***
Water	1.40E+00	4.12E-01	3.398	0.000699	***
Ice	-2.50E+01	7.94E-01	-31.43	< 2e-16	***
Snow	-7.42E+00	1.91E-01	-38.815	< 2e-16	***
RelHum	-1.33E-02	1.94E-03	-6.842	1.16E-11	***
Prec1h	-1.98E+00	1.81E-01	-10.972	< 2e-16	***
MaxWSpd	-2.99E-03	3.18E-04	-9.395	< 2e-16	***
TruckS	-1.12E-03	3.18E-04	-3.53	0.000429	***

Note: 'Estimate' is the estimated value of the parameter in the model; 'Std. Error' is the standard error of the parameter; 't value' is the result of the t-test testing the significance of the parameter listed; 'Pr(>|t|)' is the *p*-value for that t-test (the proportion of the t distribution at that df which is greater than the absolute value of t statistic); Significant *** means *p*-value = 0-0.001; Significant ** means *p*-value = 0.001-0.01; Significant * means *p*-value = 0.01-0.05; DewPt = dew point temperature; SurfT = surface temperature; Ice = ice layer; Snow = snow layer; water= water layer; AirT = air temperature; Prec 1h = precipitation in 1 hour; MaxWspd = max wind spread; RelHum = relative humidity; TruckS = truck speed; RS = Rock Salt.

In this model, residual standard error is 0.06089 on 1396 degrees of freedom. The multiple R-square is 0.8522 and the Adjusted R-square is 0.8522. The F-statistic is 738.6 with 11 and 1396 degrees of freedom, resulting in an extremely small p-value (p-value < 2.2e-16).

Table 2.3.2 The model fitting equations. Y = model calculated response variable

Deicer	Model Equation
GB	y=2.05+3.58E-03×SurfaceT-3.58E-02×AirT+3.45E-02×Dewpt+1.4×water-2.5×ice-7.42×snow-1.33E-02×RelHum-1.98×Pre1h-2.99E-03×MaxWindSpd-1.12E-03×TruckSpeed
RS	y=2.043+3.58E-03×SurfaceT-3.58E-02×AirT+3.45E-02×Dewpt+1.4×water-2.5×ice-7.42×snow-1.33E-02×RelHum-1.98×Pre1h-2.99E-03×MaxWindSpd-1.12E-03×TruckSpeed

When running the pair-wise comparison with Tukey’s adjustment, we have the following table:

Table 2.3.3 Tukey pairwise comparison results of each deicer

Linear Hypotheses: Esti	mated Std.	Error t va	lue Pr (	>|t|) Sig
GB - RS - 0.00	65 0.008	1 - 0.8	03 0.4	22

Based on this comparison, there is no evidence showing that GB and RS perform differently.

2.3.2 Winter 2016-2017 Data Using the Snow Melted Percentage as the Performance Indicator

In this analysis, the response variable is the melted percentage and the independent variables include: surface temperature, dew point temperature, relative humidity, rain, visibility, pressure, precipitation in 1 hour, wind speed, solid rate (deicer application rate), speed of deicer truck, and deicer type (categorical variables). The total sample size is 465. There are no missing entries.

The model suggested by the stepwise regression is:

Snow melted percentage ~ deicer type + surface temperature + relative humidity + visibility

After removing 12 outliers, identified by the standardized residuals, the following table provides the key quantities regarding the coefficients:

Table 2.3.4 List of independent variables coefficients and their statistical significance

	Estimate	Std. Err	t value	Pr(>|t|)	Sig
(Intercept)	9.04E+01	1.80E+00	50.115	< 2e-16	***
DeicerBH	-5.716E-02	7.351E-01	-0.078	.9381	
DeicerRS	-1.503E+00	6.366E-01	-2.361	0.0187	*
SurfT	3.397E-01	5.167E-02	6.576	1.35E-10	***
Visibility	7.205E-06	1.251E-05	.576	0.5650	***
RelHum	-1.847E-02	8.557E-03	-2.159	0.0314	*

When running the pair-wise comparison using Tukey's method, we have the following summary table:

Table 2.3.5 The model fitting equations. Y = model calculated response variable

Deicer	Model Equation
AS	y=9.04E+01+3.397E-01×SurfaceT+7.205E-06×Visibility-1.847E-02×RelHum
BH	y=-5.716E-02+3.397E-01×SurfaceT+7.205E-06×Visibility-1.847E-02×RelHum
RS	y=-1.503E+00+3.397E-01×SurfaceT+7.205E-06×Visibility-1.847E-02×RelHum

Table 2.3.6 Tukey pairwise comparison results of each deicer

	Estimate	Std. Error	t value	Pr(>|t|)	Sig
BH-AS	-0.057	0.735	-0.078	0.9966	
RS-AS	-1.503	0.6366	-2.361	0.0478	*
RS-BH	-1.446	0.55	-2.626	0.0236	*

From these p-values, we can see that BH and AS are similar. There exists moderate evidence showing that these AS and BH are better than RS. But we have to admit that this model is a poor fit for the data. The R-square of this model is only 0.1637. Additionally, the p-values are in the range between 0.02 and 0.05, not as significant (< 0.01) as needed.

2.3.3 Winter 2017-2018 Data Using the Grip Level as the Performance Indicator

The regression analysis was run using the grip level as the dependent variable and a set of independent variables, including surface temperature, air temperature, dew point temperature, snow layer, relative humidity, barometric pressure, precipitation in 1 hour, wind speed, max wind speed, solid rate (deicer application rate), speed of deicer truck, and deicer type (categorical variables). The sample size is 2,005 with no missing entries.

The model suggested by the stepwise regression is:

Grip level ~ surface temperature+ air temperature+ dew point temperature+ snow layer+ relative humidity+ barometric pressure+ precipitation in 1 hour+ wind speed+ solid rate+ speed of deicer truck + deicer type

After removing 24 outliers, the R-square of the model is 0.7166 and the following table is the coefficient for the model fit:

Table 2.3.7 List of independent variables coefficient and their statistical significance

	Estimate	Std. Error	t value	Pr(>|t|)	Sig
(Intercept)	6.53E+00	6.57E-01	9.94	< 2e-16	***
DeicerGB	5.46E-02	1.23E-02	4.422	1.03E-05	***
DeicerRS	-2.16E-03	8.95E-03	-0.242	0.809082	
SurfT	3.64E-03	1.09E-03	3.338	0.000861	***
AirT	-5.89E-02	7.53E-03	-7.828	8.02E-15	***
DewPt	6.24E-02	7.63E-03	8.174	5.28E-16	***
Snow	-8.04E+00	2.71E-01	-29.717	< 2e-16	***
RelHum	-2.66E-02	2.45E-03	-10.877	< 2e-16	***
Barom	-3.52E-03	6.07E-04	-5.797	7.85E-09	***
Prec1h	7.36E-01	2.27E-01	3.251	0.00117	**
WindSp	-8.48E-03	8.85E-04	-9.583	< 2e-16	***
SolidR	-3.54E-04	2.52E-05	-14.028	< 2e-16	***
TruckS	-1.63E-04	4.84E-05	-3.373	0.000759	***

The residual standard error is 0.1085 on 1960 degrees of freedom (8 observations deleted due to meaninglessness). Multiple R-square is 0.7166; Adjusted R-square is 0.7149; F-statistic is 413 with degrees of freedom as 12 and 1960. The resultant p-value is p-value < 2.2e-16.

Table 2.3.8 The model fitting equations. Y = model calculated response variable

Deicer	Model Equation
AS	y=6.53+3.64E-03×SurfaceT-5.89E-02×AirT+6.24E-02×Dewp -8.04×snow – 2.66E-02×RelHum – 3.52E-03×Barom+7.36E-01×Pre1h-8.48E-03×windSpeed-3.54E-04×Solid R-1.63E-04×TruckSpeed
GB	y=6.4754+3.64E-03×SurfaceT-5.89E-02×AirT+6.24E-02×Dewp -8.04×snow – 2.66E-02×RelHum – 3.52E-03×Barom+7.36E-01×Pre1h-8.48E-03×windSpeed-3.54E-04×Solid R-1.63E-04×TruckSpeed
RS	y=6.5273+3.64E-03×SurfaceT-5.89E-02×AirT+6.24E-02×Dewp -8.04×snow – 2.66E-02×RelHum – 3.52E-03×Barom+7.36E-01×Pre1h-8.48E-03×windSpeed-3.54E-04×Solid R-1.63E-04×TruckSpeed

When running the pairwise comparison, we have the following table:

Table 2.3.9 Tukey pairwise comparison results of each deicer

	Estimate	Std. Error	t value	Pr(>|t|)	Sig
GB - AS	0.054594	0.012345	4.422	<1e-04	***
RS - AS	-0.002161	0.008945	-0.242	0.968	
RS - GB	-0.056755	0.013333	-4.257	<1e-04	***

Based on the pairwise comparison with Tukey's adjustment, there exists sufficient statistical evidence showing that GB performed better than AS and RS, although AS is not significantly different than RS.

2.3.4 Winter 2017-2018 Data Using the Snow Melted Percentage as the Performance Indicator

The regression analysis was run using the snow melted percentage as the dependent variable and a set of independent variables, including surface temperature, air temperature, dew point temperature, snow layer, relative humidity, barometric pressure, precipitation in 1 hour, wind speed, wind spread, max wind speed, solid rate (deicer application rate), speed of deicer truck, and deicer type (categorical variables). The total sample size is 669.

The model suggested by the stepwise regression is:

Snow melted percentage ~ surface temperature+ air temperature+ dew point temperature+ snow layer+ relative humidity+ barometric pressure+ precipitation in 1 hour+ solid rate+ speed of deicer truck+ deicer type

After removing 19 outliers, the R-square is 0.6567 and the following table summarizes all the coefficients:

Table 2.3.10 List of independent variables coefficients and their statistical significance

	Estimate	Std. Error	t value	Pr(>|t|)	Sig.

(Intercept)	5.06E+00	5.68E-01	8.894	< 2e-16	***
DeicerGB	-5.32E-02	1.86E-02	-2.862	0.00435	**
DeicerRS	-1.19E-02	1.74E-02	-0.684	0.49412	
SurfT	1.31E-02	2.68E-03	4.878	1.35E-06	***
AirT	-1.40E-01	1.75E-02	-8.004	5.78E-15	***
DewPt	1.33E-01	1.84E-02	7.206	1.64E-12	***
Snow	-1.09E+01	9.36E-01	-11.691	< 2e-16	***
RelHum	-4.39E-02	5.95E-03	-7.37	5.33E-13	***
Prec1h	-5.00E+00	4.37E-01	-11.446	< 2e-16	***
SolidR	-2.26E-04	4.90E-05	-4.61	4.88E-06	***

The residual standard error is 0.1289 on 634 degrees of freedom (6 observations deleted due to missingness). Multiple R-squared is 0.6567; adjusted R-square is 0.6519; F-statistic is 134.8 on 9 and 634 DF, p-value: < 2.2e-16.

Table 2.3.11 The model fitting equations. Y = model calculated response variable

Deicer	Model Equation
AS	y=5.06+1.31E-02×SurfaceT-1.4E-01×AirT+1.33E-01×Dewp -1.09E+01×snow-4.39E-02×RelHum -5.00E+00×Pre1h-2.26E-04×Solid R
GB	y=5.0068+1.31E-02×SurfaceT-1.4E-01×AirT+1.33E-01×Dewp -1.09E+01×snow-4.39E-02×RelHum -5.00E+00×Pre1h-2.26E-04×Solid R
RS	y=5.0431+1.31E-02×SurfaceT-1.4E-01×AirT+1.33E-01×Dewp -1.09E+01×snow-4.39E-02×RelHum -5.00E+00×Pre1h-2.26E-04×Solid R

When running the pairwise comparison, we have the following table:

Table 2.3.12 Tukey pairwise comparison results of each deicer

	Estimate	Std. Error	t value	Pr(>|t|)	Sig
GB - AS	-0.05321	0.01859	-2.862	0.0118	*
RS - AS	-0.01189	0.01739	-0.684	0.7688	
RS - GB	0.04132	0.02297	1.799	0.1668	

Based on this analysis on the available data, RS is not statistically different than either GB and AS. The results shown that RS is slightly better than GB and slightly worse than AS, however, none of the difference is significant. On the other hand, there exists moderate evidence that AS performs better than GB (p-value = 0.0118).

3. RANKING OF DEICER PRODUCTS BASED ON ALL TESTS

In order to summarize the results, we ranked all the deicer products based on the numerical or comparative performances obtained from different tests: a discrete numeric score from 1 (best performance) to 6 (worse performance) was assigned to each product and the references.

Table 1 shows the ranking obtained from all performance tests conducted in Phase I (TEM WO 003) and II (TEM WO 005) of this project. Results from environmental and ecotoxicology testing performed in Phase I are not included as they did not show significant differences between the deicer products and because of the difficulty to weigh these rankings together with the performance rankings.

Table 3.1 Deicer product ranking in different tests performed (rank values range from 1–best to 6–worse)

		AS	BH	GB	MMZ	SB	RS
Laboratory tests	De-icing	1	6	3	2	4	4
	Anti-freezing	1	6	2	3	4	4
Parking lot tests - visual rankin	g						
Manufacturer formulation							
Image J	Solid		2		2	2	1
	Liquid	2		1			
Visual scores	Solid		1		3	3	1
	Liquid	2		1			
PennDOT formulation		4	1	1	1	6	4
Parking lot tests - statistical analysis							
Manufacturer formulation		1	4	1	4	4	3
PennDOT formulation		4	1	1	1	6	4
Skid resistance tests		N/A					
On-road real-time tests	Winter I - grip level	1					1
	Winter I - snow	1	1				2(1)
	Winter II - grip level	2		1			2
	Winter II - snow	1		2(1)			1-2

(1) Moderate evidence.

Integrating ranking from different tests into a single indicator was not feasible primarily because the preparation methods of the products were different in each test. We however discussed the ranking performances obtained from the lab test (Phase I) and the parking lots tests (Phase II). The skid resistance test (Phase II) did not show any significant difference between the deicer products and was not considered. Similarly, difficulties arose from the low statistical significance and partial ranking from the on-road tests (Phase II), which were not considered.

The parking lot tests provided several rankings depending on the preparation and analysis method. The test using the PennDOT formulation gave consistent results with both analysis methods (visual scores and statistical models) with a ranking BH ≈ GB ≈ MMZ > AS ≈ RS >

SB. Considering results from both analytical methods, the test using the manufacturer formulation indicated that the 'liquid' deicers performed better with GB > AS, and that among the 'solids deicers', RS performed better than the others, with an overall ranking of GB > AS > RS ≥ BH ≥ MMZ ≈ SB. When comparing the results from the laboratory tests (Phase I – TEM WO 003) with those from the parking lot tests, both using manufacturer recommendations for deicer preparation, statistical analysis showed some similarities: AS ranked first and BH ranked last (together with MMZ and SB) in both tests. On the other hand, little similarity was observed between the laboratory tests and the parking lot tests using PennDOT formulation, which is not surprising considering the difference in product preparation. Results from the road tests gave partial ranking with limitation related to the statistical significance. Considering only significant results from all three models, the analysis indicates that AS ≈ BH and GB > AS ≈ RS. The ranking GB > AS ≈ RS is consistent with the parking lots test results using PennDOT formulation.

4. COST ANALYSIS

Because of different conditions under which the different tests were conducted and because of the absence of significant results in some cases, it was not possible to integrate the results of all tests to conduct the cost analysis.

The lab tests (Phase I – TEM WO 003) were not included in the analysis as no statistical models were computed and/or are available. The skid resistance test did not show any significant differences between the deicer products and was not considered either. Similarly, difficulties arose from the low statistical significance and partial ranking from the on-road tests, which were not considered.

Performance data from each parking lot tests and the costs of the products were used to perform the cost analysis.

Table 4.1 shows the application rates of different deicers according to manufacturers' recommendations for the novel deicers and based on Gerbino-Bevins (2011) for SB.

Table 4.1 Recommended application rates for all deicers.

Deicer	Application	Recommended Rates
AS	De-icing and anti-icing	35-70 gal/LM

	Pre-wetting	8-10 gal/ton
GB	20% to salt brine	
BH	Deicing (mix with SB 50:50 in V)	35-45 gal/LM
	Anti-icing (mix with SB 50:50 in V)	15-25 gal/LM
	Pre-wetting	5 gal/ton
	Pre-wetting (cut with brine)	7 gal/ton
MMZ	Pre-wetting	6-8 gal/ton
SB	De-icing	20-80 gal/LM

Based on the recommended application rates and the price of each deicer as provided by PennDOT (March 2018), we selected three representative rates for de-icing, two for anti-icing, and three for pre- wetting, and calculated the deicer costs at these respective rates (Table 4.2). Note that the costs listed here only reflect the costs of the deicer material, without including the cost of the labor, equipment, rock salt, and fuel needed to apply the deicers.

The cost difference between the deicers products under study and SB was then calculated by dividing the cost of the deicer by that of SB, e.g., for AS: \$0.72 divided by \$0.16 giving 4.5, meaning that AS is 4.5 times more expensive than RS on per gallon basis. These cost differences will be used below to conduct cost comparison. This comparison shows that based on manufacturer recommendations, the costs of deicer products on a per gallon basis rank as BH (most expensive) > MMZ > GB > AS > SB (least expensive).

Table 4.2 Cost of all deicers at different application rates.

		De-icing, cost/mile			**Anti-icing, cost/mile**		**Pre-wet, cost/100 lbs**			**Cost diff.**
Deicer	**\$ per gallon**	35 gal/LM	50 gal/LM	70 gal/LM	15 gal/L M	25 gal/LM	5 gal/to n	8 gal/to n	10 gal/ton	
SB	\$0.16	\$5.60	\$8.00	\$11.20	\$2.40	\$4.00	\$0.04	\$1.40	\$2.00	1.0
AS	\$0.72	\$25.20	\$36.00	\$50.40	\$10.80	\$18.00	\$0.18	\$6.30	\$9.00	4.5
BH	\$1.66	\$58.10	\$83.00	\$116.20	\$24.90	\$41.50	\$0.42	\$14.53	\$20.75	10.4
GB	\$1.20	\$42.00	\$60.00	\$84.00	\$18.00	\$30.00	\$0.30	\$10.50	\$15.00	7.5
MMZ	\$1.38	\$48.30	\$69.00	\$96.60	\$20.70	\$34.50	\$0.35	\$12.08	\$17.25	8.6

4.1 First Parking Lot Test

The statistical analysis in Task 1.4 (using the manufacturer recommendations) concluded that GB ≈ AS > RS > BH ≈ MMZ ≈ SB. Based on Table 3 in Task 1.4 (see Task 1.5 Report), we can calculate the melted percentage at any given time and application rate (example shown in

Table 4.1.1 for SB). Note that the Box-Cox transformation has to be applied to convert the model calculated response variable $\hat{y}$ to the corresponding melted percentage.

Table 4.1.1 Estimated melted percentages of SB at different times and application rates (lbs per lane mile) based on the models in Table 3 in Task 1.4.

Time (min)/Rate lbs/LM	100	200	350	500	700
10	0.16	0.35	0.58	0.77	0.99
20	0.13	0.33	0.60	0.84	1.12
30	0.10	0.31	0.62	0.91	1.25
40	0.08	0.29	0.64	0.98	1.40
50	0.06	0.27	0.67	1.06	1.55
60	0.04	0.26	0.69	1.14	1.72
75	0.02	0.23	0.72	1.26	1.99

Based on the calculated melted percentages, the difference in performance between the novel deicers and SB was then calculated based on the following equation:

Difference = [(melted % of deicer – melted % of SB)/melted % of SB] *100 (1)

where melted percentages are at the same time and application rate, respectively.

Using equation (1), we can obtain the differences in AS vs. SB (Table 4.1.2) and GB vs. SB (Table 4.1.3). For example, at 10 min with the application rate of 100 lbs/LM, AS melted 302% more (~3 times more) snow than SB (Table 4.1.2). Since no statistically significant difference was observed between BH, MMZ and SB, no further calculation was conducted for BH and MMZ. Note that it was continuously snowing during the test such that at lower application rates (100 and 200 lbs per lane mile), the observed melted percentages decreased after 40 min for 100 lbs/LM and after 60 min for 200 lbs/LM (Table 4.1.1). To avoid miss-interpretation of the data, these numbers are excluded from further analysis, as shown in Tables 4.1.2 and 4.1.3.

Table 4.1.2 Increase in melted percentage as calculated based on equation 1 when AS was applied as the deicer as compared to SB at 10 – 60 min with the application rates of 100, 200, 350, 500, and 700 lbs per lane mile. These rates corresponded to 44.4, 88.9, 155.6, 222.2 and 311.1 gal per lane mile for AS (details in Task 1.4 Report).

Time (min)/Rate lbs/LM	100	200	350	500	700
10	302%	289%	282%	278%	275%
20	524%	407%	354%	330%	311%
30	875%	554%	433%	383%	347%
40	-	736%	520%	438%	383%
50	-	-	614%	495%	418%
60	-	-	716%	554%	452%

Table 4.1.3 Increase in melted percentage as calculated based on equation 1 when GB was applied at the deicer as compared to SB at 10 – 60 min with the application rates of 100, 200, 350, 500 and 700 lbs per lane mile. These rates corresponded to 33.3, 66.7, 116.7, 166.7, and 233.3 gal per lane mile for GB (details in Task 1.4 Report).

Time (min)/Rate lbs/LM	100	200	350	500	700
10	330%	387%	420%	438%	452%
20	585%	561%	549%	543%	538%
30	996%	783%	694%	656%	627%
40	-	1064%	858%	775%	717%
50	-	-	1040%	902%	809%
60	-	-	1241%	1034%	901%

As shown in Table 4.1.2 and 4.1.3 and summarized in Table 4.1.4, AS melted between 2.8 and 8.8 times more snow than SB at different times and application rates, while GB melted between 3.3 and 12.4 times more snow than SB. Larger differences were observed at longer times and higher application rates.

Based on these data, we can conclude that AS is 4.5 times more expensive than SB, but its performance is 2.8 – 8.8 times better; GB is 7.5 times more expensive than SB, but its performance is 3.3 – 12.4 times better. BH and MMZ are 10.4 and 8.6 times more expensive than SB, but their performances are not statistically different from SB.

Table 4.1.4 Cost analysis based on the 1st Parking lot test data.

	Cost difference	Performance difference
SB	1	0
AS	4.5	2.8 – 8.8
BH	10.4	Not significant
GB	7.5	3.3 – 12.4
MMZ	8.6	Not significant

4.2 Second Parking Lot Test

The statistical analysis in Task 1.4 (using the PennDOT recommendations) concluded that BH ≈

GB ≈ MMZ > RS ≈ AS > SB. Based on Table 4 in Task 1.4, we can calculate the melted percentage at any given time, as shown in Table 6.2.7. Note the application rate was fixed at 500 lbs per lane mile in this test. Equation (1) was then applied to calculate differences in melted percentage between the novel deicers and SB, as shown in Table 6.2.8.

Table 6.2.7. Estimated melted percentages at different times based on the models in Table 4 in Task 1.4.

Time (min)	10	20	30	40	50	60	75
SB	3.24	3.40	3.56	3.72	3.88	4.04	4.28
AS	3.98	4.14	4.3	4.46	4.62	4.78	5.02
BH	5.14	5.30	5.46	5.62	5.78	5.94	6.18
GB	5.71	5.87	6.03	6.19	6.35	6.51	6.75
MMZ	6.43	6.59	6.75	6.91	7.07	7.23	7.47

Table 6.2.8. Increase in melted percentage of the deicers (calculated based on equation 1) as compared to SB at 10 – 75 min with the application rate of 500 lbs per lane mile.

Time (min)	10 min	20 min	30 min	40 min	50 min	60 min	75 min
SB	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AS	22.8%	21.8%	20.8%	19.9%	19.1%	18.3%	17.3%
BH	58.6%	55.9%	53.4%	51.1%	49.0%	47.0%	44.4%
GB	76.2%	72.6%	69.4%	66.4%	63.7%	61.1%	57.7%
MMZ	98.5%	93.8%	89.6%	85.8%	82.2%	79.0%	74.5%

For each deicer, rather similar differences were observed at all time points. Therefore, we used the average differences across all time points to conduct the cost comparison, as shown in Table 6.2.9. We can then conclude that, on average, AS, BH, GB, and MMZ performed 20%, 51.3%, 66.7%, and 86.2% better than SB, respectively, in melting snow between time zero and 75 min, while they are 4.5, 10.4, 7.5 and 8.6 times more expensive than SB using the same application rate.

Table 6.2.9. Cost analysis based on the 2nd parking lot test data.

	Cost difference	Performance difference
SB	1	0
AS	4.5	20.0 ± 2.0%
BH	10.4	51.3 ± 5.0%
GB	7.5	66.7 ± 6.5%
MMZ	8.6	86.2 ± 8.4%

Reference

Gerbino-Bevins, B. M. 2011, “Performance rating of de-icing chemicals for winter operations”, Master’s thesis, Department of Civil Engineering, University of Nebraska.

5. CONCLUSIONS

In this study, the performances and cost analysis of four deicers products, i.e., Aqua Salina (AS), Beet Heet (BH), Green Blast (GB), Magic Minus Zero (MMZ), and the references, Rock Salt (RS) and/or Salt Brine (SB) were evaluated through parking lot tests (Task 1) and on-road tests (Task 3). In the prior phase of the project, the performances of the products were evaluated through laboratory tests (Phase I – TEM WO 003). The parking lot tests considered two performances indicators, the snow melted percentage and skid resistance. The skid resistance test (Task 1.3) results did not show significant differences between the deicer products and were not usable.

The integration of the ranking results from different tests into a single indicator was not feasible because different formulations and application rates were used in the various tests (e.g., using manufacturer's or PennDOT's recommendations, addition of anti-skid agent or not, etc.). Nevertheless, the rankings from the different tests were compared and discussed. The laboratory tests (Phase I) provided the following ranking: AS > GB ≈ MMZ > SB ≈ RS > BH. On the other hand, the parking lot tests using the PennDOT's formulation gave the following ranking: BH ≈ GB ≈ MMZ > AS ≈ RS > SB, while the parking lot test using the manufacturer's recommendations provided an overall ranking that can be summarized as GB > AS > RS ≥ BH ≥ MMZ ≈ SB. The second parking lot test therefore shows little consistency with the laboratory tests. Considering only the significant results, the road tests suggested that AS ≈ BH and GB > AS ≈ RS. The ranking GB > AS ≈ RS is consistent with the parking lots test using PennDOT's formulation. Ranking deicer products based on these tests gave relatively inconsistent results, primarily because of the different formulations and application rates used.

Because of different conditions under which the different tests were conducted and the absence of significant results and/or complete results in some cases (e.g., on-road tests), it was not possible to integrate the results of all tests to conduct cost analysis. The lab tests (Phase I) were not included in the analysis as no statistical models were computed and/or are available. Difficulties arose from the low statistical significance and partial ranking from the on-road tests (Phase II), which were not considered either.

Only the performance data from both parking lot tests were therefore used to perform the cost analysis. Using the manufacturer's recommended application rates and the price of the deicers provided by PennDOT, the cost difference between the deicer products under study and SB was calculated showing the following ranking (on a gallon-per-lane-mile basis): BH (cost difference 10.4) > MMZ (cost difference 8.6) > GB (cost difference 7.4) > AS (cost difference 4.5) > SB (cost difference 1.0).

Results from the first parking lot test (using the manufacturer's recommendations) were used to calculate the differences in performance between the deicers product under study and the reference, SB. It can be concluded that the performance of AS was 2.8 – 8.8 better than SB (AS was 4.5 times more expensive), performance of GB was 3.3 – 12.4 times better than SB (GB was 7.5 times more expensive), the performances of BH and MMZ were not statistically different from

SB (BH and MMZ were 10.4 and 8.6 times more expensive, respectively).

Results from the second parking lot test (using PennDOT's recommendations) were also used to calculate the differences in performance. It can be concluded that AS, BH, GB, and MMZ performed 20%, 51.3%, 66.7%, and 86.2% better than SB, respectively, although the cost differences by comparison to SB were 4.5, 10.4, 7.5 and 8.6 times, respectively.