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Long-Term & Short-Term Measures of Roadway Snow and Ice Control Performance

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Executive Summary

Roadway snow and ice control (RSIC) serves a vital public safety function and reduces the economic losses caused by winter weather. The effectiveness and efficiency of the RSIC response requires that managers have access to meaningful performance measures that accurately capture the roadway conditions throughout the network. Performance measurement metrics provide a baseline for evaluating agency operations and improve agency transparency. Effective long-term performance measures can provide quality assurance of staff productivity, equipment allocation, and process evaluation. Effective short-term performance measurement can provide quality control for real-time productivity improvement and efficient resource use.

The primary performance measures for RSIC programs by state DOTs are 1) operating speed recovery time and 2) time to achieve bare pavement. There is a continued need for objective, outcome-based performance metrics for RSIC operations. The overall goal of this project was to develop new performance measures intended to improve the performance of RSIC activities by the VTrans fleet and a plan for how they could be implemented full-scale. Two specific objectives were planned by the research team at the University of Vermont Transportation Research Center to achieve this goal:

- Develop a long-term, seasonal "time-to-normal" measure utilizing readily available speed data
- Pilot-test a short-term measure utilizing imagery data collected and processed in real-time to compare roadway conditions in front of, and behind, an active RSIC vehicle

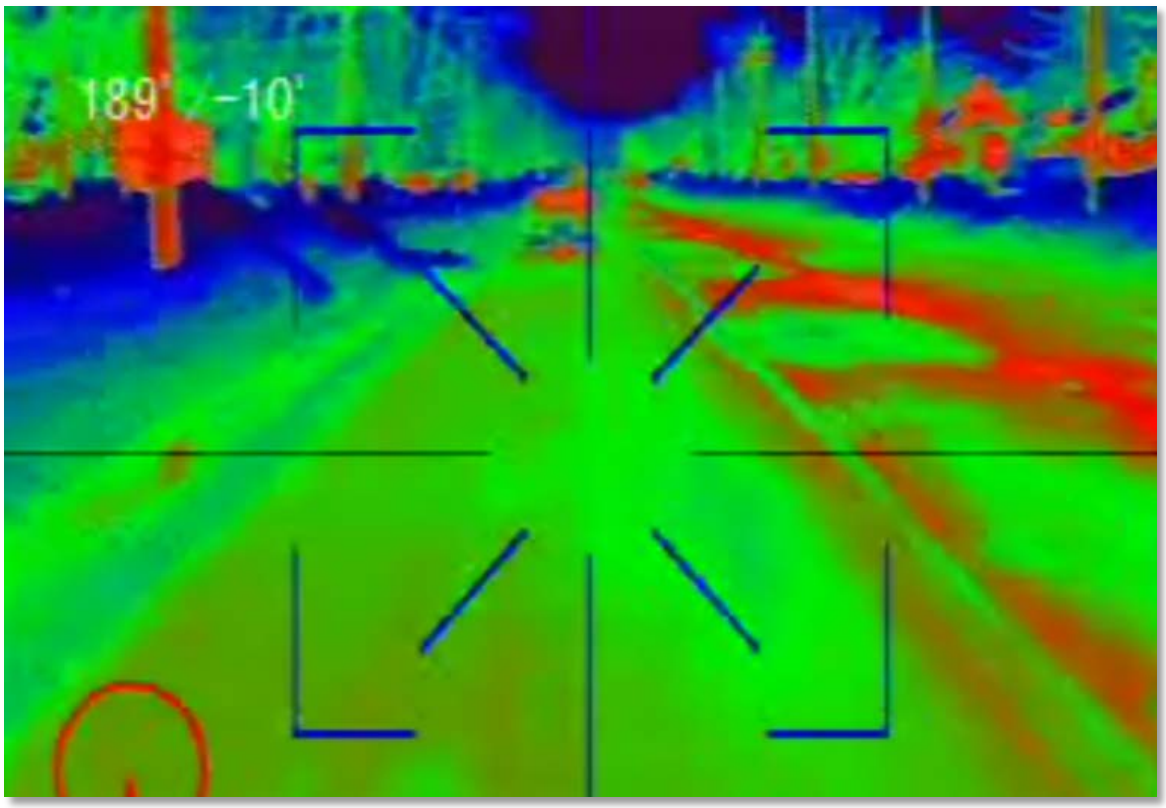
In this study, a new long-term performance measure, the Average Distribution Deviation (ADD), was developed to measure changes in the distribution of vehicle speeds after winter weather events. Measuring the recovery time for the entire distribution of vehicle speeds, rather than the recovery of a single measure like the mean speed, provides a more comprehensive assessment of RSIC performance. A thermal imaging video system was pilot-tested as a short-term measure of RSIC performance. These two long- and short-term RSIC performance measures provide distinct and complimentary assessments of RSIC operations. The long-term ADD performance metric can be used to measure the time to complete RSIC operations on a storm-by-storm or seasonal basis, while the short-term, video-based performance measure is designed to provide near instantaneous

feedback that can be used to inform the rate of application of chemicals by, and routing of, snow and ice control vehicles.

Data Collection and Data Gathering

For this project, thermal imagery was collected in grayscale, with whiter pixels representing warmer areas and blacker pixels representing colder areas. For the data collection process, two cameras were mounted on a VTrans plow truck. Test imagery was collected in the winter of 2013-2014 and complete video imagery using the full installation was collected for five complete RSIC dispatches on I-89 during February and March of 2015 and then again during February and March of 2016. Over 12 hours of thermal imagery was collected during the winters of 2014, 2015, and 2016.

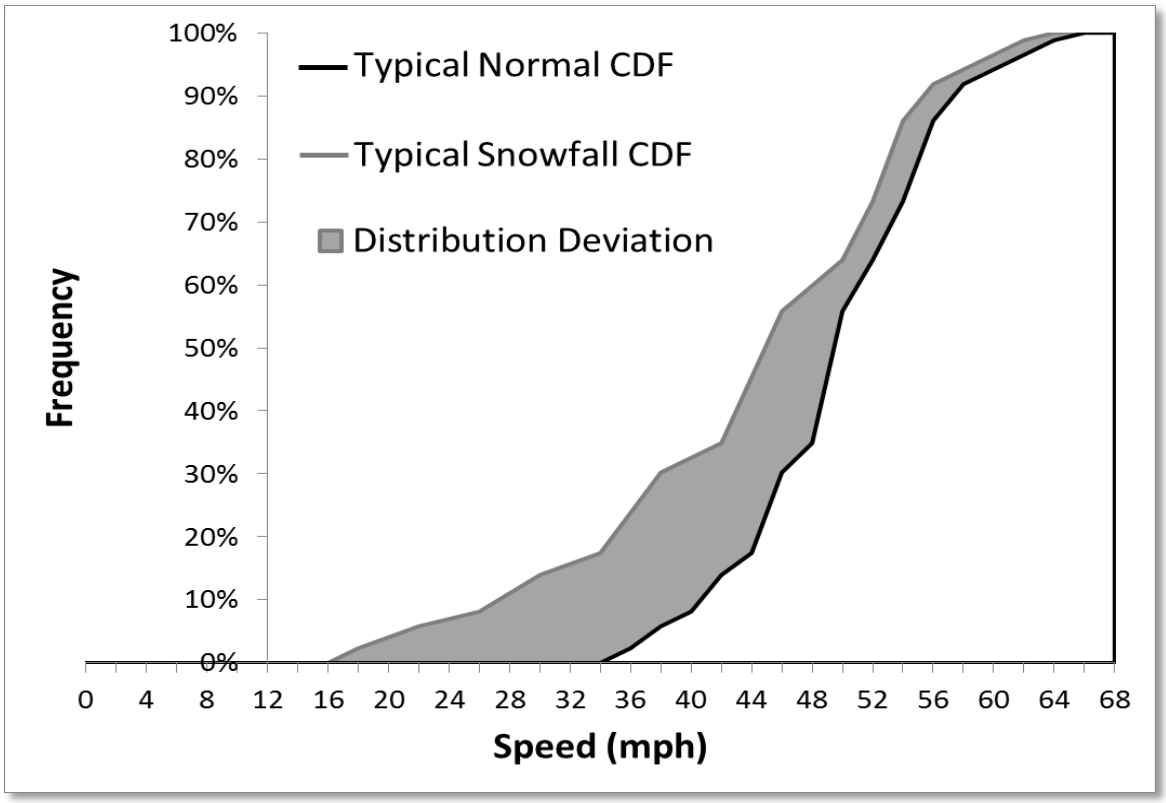
This recording was unaffected by low light conditions or resolution, even low-resolution images clearly indicate differences in temperature on a roadway with minor snow cover (green), bare pavement (orange), and snow-covered shoulders (blue):



Speed data from two weigh-in-motion (WIM) stations were coupled with weather data from proximate National Oceanic and Atmospheric Administration weather stations. Speed data were gathered (downloaded) for normal, snow-free weekday and weekend days to calculate ADD threshold values and for significant winter storm events at both the I-89 and US-4 WIM stations. A total of ten normal, snow-free days were selected for baseline ADD calculations – 3 weekdays and 3 weekend-days for I-89 and 4 weekdays for US-4. Speed data were also collected for one major, multi-day winter storm event for each of I-89 and US-4. Three additional days of speed data were collected for I-89, corresponding to single-day, low-snowfall events, with snow accumulations of between 0.6 and 1.5 inches.

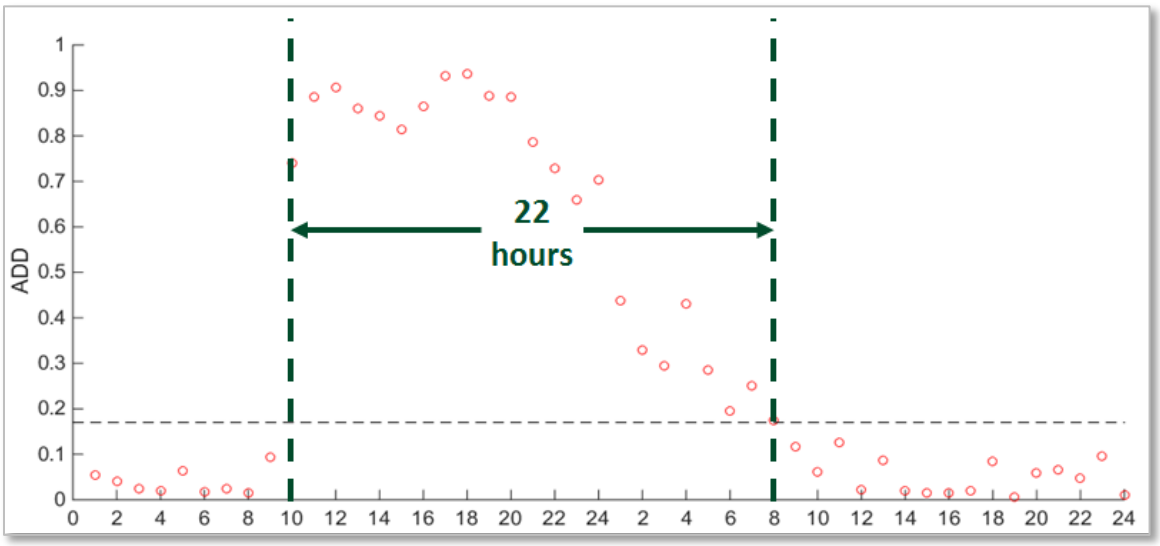
Methodology and Results

The ADD is based on the understanding that changes in the distribution of vehicle speeds during winter weather events is substantially greater than it is under normal operating conditions. The "distribution deviation" is the area between the cumulative distributions of hourly speed data on two separate days:



Two sets of ADD calculations are required to use the ADD as a RSIC performance metric. The first calculation is used to determine a threshold for baseline snow-free conditions that reflects the expected, day-to-day variability in traffic speed distributions. The second calculation compares the day with the winter storm under evaluation and the most recent baseline, snow-free day – values which exceed the baseline threshold indicate a disruption to normal traffic flow.

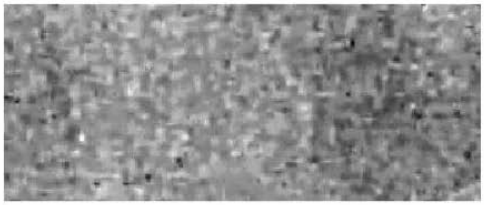
Baseline ADD values were calculated separately for both I-89 and US-4 since typical traffic flows may vary from roadway to roadway. However, the calculated thresholds were similar enough (0.17 and 0.18, respectively) that this separation may not be necessary in the future. Time-to-normal, then, is calculated as the elapsed time from the onset of the winter storm (when the snow-day ADD begins to exceed the threshold) to the time when normal mobility conditions have been restored (the snow-day ADD falls back under the threshold):

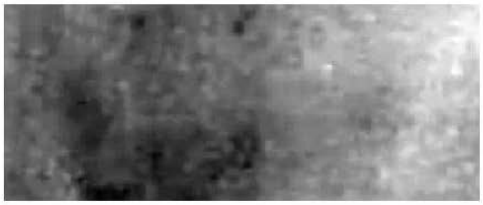


The time-to-normal for this storm on February 25th and 26th, 2011 was 22 hours, as calculated using the ADD approach.

To analyze the thermal video, an image comparison tool was developed in MATLAB®. The tool imports thermal video recordings and extracts still images at a specified sample rate. For this project, comparison images were extracted at 1-second intervals. A small lag time was introduced between the extraction of still images from the front and rear videos so that the pairs of images capture the same segment of roadway. The temperature difference between the two images is calculated on a pixel-by-pixel basis based on the relative difference in grayscale within a specified analysis zone. Each pixel is associated

with a value between 0 and 100, where 0 is a black pixel, 100 is a white pixel, and all values in between represent different shades of gray. The following output for a single second of analysis shows the difference between the front (left) and rear (right) thermal images to be 7.3:





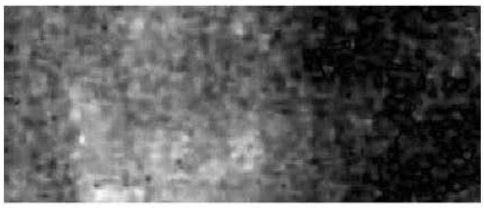


Fig. 1 - Average Intensity: 53.0 Standard Deviation: 1.5
Fig. 2 - Average Intensity: 46.5 Standard Deviation: 4.8

Average Difference: 7.3
Standard Deviation: 4.6

Conclusions

This project provided the first successful demonstration of a short-term performance measurement system for RSIC using real-time thermal-imaging of the pavement surface in front of, and behind, the RSIC vehicle. A computational script was developed and applied in MATLAB® to output the average difference in temperature between these surfaces, as measured by the grayscale image on a second-by-second basis with the thermal imaging system. This demonstration has the potential to become an effective real-time performance measurement system to allow RSIC operators and supervisors to make "on-the-spot" adjustments to optimize the effectiveness of their efforts.

The use of the ADD approach to calculating a time-to-normal for RSIC operations shows considerable promise as a long-term measure for grading RSIC performance by storm and by season. It can measure the real-world effectiveness of RSIC operations using speed data that are routinely collected by VTrans. For limited-access highways, baseline snow-free ADD values showed considerable stability across days of the week and time of day, making the determination of a threshold relatively straightforward. The stability of these threshold values and the sharp increase in ADD values during known winter storm events suggest that the ADD approach is an effective way to measure "time-to-normal" after the onset of a winter storm and consequent dispatch of RSIC vehicles.

1 Introduction

Winter maintenance operations are among the highest-profile activity of the Vermont Agency of Transportation (VTrans, 2011a), and it can account for more than 10% of the Agency's entire annual budget. District roadway snow and ice control (RSIC) operations are limited by the resources available for winter maintenance operations. Due to these resource limitations, winter maintenance resources must be deployed as efficiently as possible.

Maintaining safe, passable roadways minimizes weather-related traffic accidents and ensures access to hospitals, grocery stores, employment centers and other essential destinations. RSIC, therefore, serves a vital public safety function and reduces the economic losses caused by winter weather. The most appropriate RSIC activity varies from storm-to-storm and maximizing the effectiveness and efficiency of the response requires that managers have access to objective performance measures that accurately capture the roadway conditions throughout the network. With improvements in geographic information system (GIS) and information technology (IT) systems, detailed, link-by-link performance measures reflecting actual road surface conditions are achievable, potentially improving public safety and increasing the efficiency of RSIC operations.

Current performance metrics include material application rates, vehicle speeds, surface conditions, storm data, and plowing frequency (VTrans, 2011b). Of these, only vehicle speeds and surface conditions provide objective, direct metrics of the performance of RSIC operations. Material application rates and plowing frequency are input metrics that do not capture the effectiveness of RSIC operations directly. These measures can be valuable for determining the efficiency of RSIC operations but only when used in conjunction with outcome-based metrics. In fact, safe reductions in the use of de-icing and friction-controlling materials may be one of the ultimate goals of an effective RSIC program. Therefore, more effective, outcome-based metrics are needed.

Based on this need, VTrans awarded a project entitled "Identifying Performance-Based Measures for Winter Maintenance Practices" in the 2011-2012 research cycle of its Research Advisory Council (RAC). The objectives of this research initiative included summarizing RSIC performance measures in other states, identifying current winter-maintenance practices in Vermont, and gathering data needed to

establish a catalog of available performance metrics. During the Resource Management focus group convened in June 2012, participants from various divisions at the Agency stressed that a continuation of this project, aimed at recommending a specific set of performance metrics for Vermont and designing an implementation plan for the selected metrics, was of utmost importance (Colgrove, 2012).

Performance measurement is an important strategy for improving operational effectiveness and efficiency. Performance measurement metrics provide a baseline for evaluating agency operations and improving agency transparency. Since the late 1990s, state DOTs and other transportation agencies have placed an increasing focus on performance measurement (TRB, 2001) a trend that accelerated with the passage of the Moving Ahead for Progress in the 21st Century Act (MAP-21) (FHWA, 2015). The most recent transportation bill, FAST Act, continued to exhibit strong support for performance measurement and data collection by state DOTs.

A key challenge for performance measurement is to identify metrics that accurately reflect the objectives of the operation being evaluated. Ideally metrics should be easily understood, make use of existing data sources, and avoid opportunities for subjectivity or bias. Effective long-term performance measures can provide quality assurance for staff productivity, equipment allocation, and process evaluation. Effective short-term performance measurement can provide quality control for real-time productivity improvement and efficient use of resources.

Common outcome-oriented measures for RSIC operations include time-to-normal, friction measurements, and public surveys. Time-to-normal statistics measure the elapsed time between the start or end of a winter weather event and the return to road surface conditions that support normal traffic flow. These statistics are often self-reported and the assessment of “normal” can be subjective. Customer surveys are important for any public agency, but often collect only generalities about statewide and winter-long service and are generally not considered a suitable basis for performance measurement (TRB, 2001). Friction measurements use equipment to make objective estimates of the real-time friction of the road surface. Indirect friction methods include acoustic methods, which attempt to use noise to measure friction, and optical methods, which use imagery to measure friction. The most common type of imagery used for this purpose is infrared (Jonsson,et. al., 2015). Direct friction measurement methods are also available, but are limited to equipment located within the RSIC vehicle.

The primary performance measures for RSIC programs by state DOTs are 1) operating speed recovery time and 2) time to achieve bare pavement (VTrans, 2011b). These measures are both based on "time-to-normal" concepts. The primary sources of data for RSIC performance measurement are real-time speed data and field visual inspection or imagery-enhanced visual inspection of the road surface. Visual performance measurement is common, but is generally a subjective assessment made by RSIC operators and their supervisors. Automated methods for analyzing roadway images are being researched but are not yet widely implemented (Jonsson,et. al., 2015; Linton and Fu, 2015). There is a continued need for objective outcome-based performance metrics for RSIC operations.

The overall goal of this project was to improve the performance of RSIC activities by the VTrans fleet by developing new performance measures and a plan for how they could be implemented full-scale. Two specific objectives were planned by the research team at the University of Vermont Transportation Research Center (UVM TRC) to achieve this goal:

- Develop a long-term, seasonal "time-to-normal" measure utilizing readily available speed data
- Pilot-test a short-term measure utilizing imagery data collected and processed in real-time to compare roadway conditions in front of, and behind, an active RSIC vehicle

In this study, a new long-term performance measure, the Average Distribution Deviation (ADD), was developed to objectively measure the time-to-normal after a winter weather event. The ADD assesses the full cumulative speed distribution of all traffic, rather than a simplified measure of traffic speed like the mean. It is calculated by taking the difference in the hourly cumulative speed distribution at the same location for the same hour of the day on two separate days. Calculating the ADD for snow-free days establishes a baseline for day-to-day variability in traffic speed distributions under normal operating conditions. This baseline ADD is then used as a threshold to compare the ADD values recorded during and after a winter storm event to determine precisely when the speed distribution has been returned to normal. We illustrate the ADD growth and recovery for winter storm events on Interstate 89 (I-89) and U.S. Route 4 (US-4) in Vermont.

The ADD approach has considerable potential as a performance metric for RSIC operations because it captures the overall objective of RSIC operations – returning the highway system to normal operating

conditions and maximizing mobility. In addition, the ADD approach is easily understood and utilizes data that are routinely collected by state DOTs.

A thermal infrared video system was pilot-tested as a short-term measure of RSIC performance. Thermal video imagery captures long-wavelength infrared radiation (typically defined as radiation with wavelengths between 8 and 13 micrometers) that is invisible to the human eye and converts it into a visual representation of surface temperature. Thermal imagery is well suited to recording RSIC operations because it can be used to record the temperature differences between bare pavement and pavement that is covered by snow or ice whenever there is a temperature differential between the pavement and the covering precipitation. It also functions well in nighttime and low light situations, which are commonly encountered during RSIC operations.

This report contains a description of the methodological background for RSIC performance measurement and a review of the research literature (Section 2), a description of the data collected and gathered for use in the project (Section 3), a description of the methods used to analyze that data, (Section 4), a summary of the results achieved with these methods (Section 5), and the conclusions of the study along with a discussion of the implementation plan (Section 6).

2 Background and Literature Review

According to the "Identifying Performance-Based Measures for Winter Maintenance Practices" project, the primary performance measures for RSIC programs in northern states are (1) operating speed recovery time, and (2) time to achieve bare pavement. Maryland, New York, and Wisconsin use a combination of these measurements to evaluate RSIC operations (VTrans, 2011b). VTrans' current performance standards require a visual judgment of a road surface with "bare pavement" or "1/3 bare pavement" (see Figure 1). This type of visual performance measure is common among northern state DOTs, but is limited by its subjectivity and lack of automation. The primary sources of data for RSIC performance measurement are speed data and visual inspection or imagery of the road surface.

During the literature review, particular attention was paid to the proceedings of the International Conference on Winter Maintenance and Surface Transportation Weather (TRB, 2012). One of the conference papers included in that publication proposed a prototype model to predict the speed reduction that should occur from a given storm, and then measure RSIC performance in relation to that target speed (Greenfield et. al., 2012). Several other research projects have studied the impact of weather on vehicle speeds, showing predictable reductions of between 8 mph (Knapp et. al., 2000) and 19 mph (Kyte et. al., 2001). Qiu and Nixon (2009) developed a simple equation to estimate average free-flow traffic speed drop as a result of a winter storm with typical RSIC measures implemented. However, few studies have focused on the development of a comprehensive, objective method of measuring the performance of RSIC activities.

Developing a speed-based, time-to-normal metric requires a method for quantifying "normal" traffic speeds so that deviations from normal can be identified. Prior research has used average speed to assess whether or not traffic operations have returned to normal, assuming that average speeds within 10 mph of historical norms indicates recovery (Sharifi et. al., 2014). While mean speed or percentile speed thresholds are appealing as performance metrics because they are easily understood and calculated, they do not provide information about the full distribution of vehicle speeds and may indicate a return to normal operating conditions even when the overall distribution of vehicle speeds differs from that seen during non-storm periods. Additionally, average vehicle speeds can mask driving behavior at unusually high or low speeds during winter weather. These driving behaviors may be an indication of unsafe operation or abnormal road surface characteristics,

both of which are a concern for time-to-normal measurement. Since trips canceled prior to or during a storm may result in fewer trips later in the day (e.g., a canceled morning commute often results in a canceled evening commute), vehicle volumes may remain low even after RSIC operations have successfully returned the roadways to safe operating conditions. Lower traffic volumes increase the risk that the mean traffic speed will be unduly influenced by outlier observations.

Very little research has been conducted on the use of roadway imagery for RSIC performance measurement. However, the recurring need to make the determination of when "bare pavement" has been achieved speaks to the need for an imagery-based method. To this end, agencies often make use of a "spotter" who traverses the agencies' roads in a non-RSIC vehicle and makes "on the spot" visual determinations of progress toward bare pavement.

A few researchers have attempted to automate this process and incorporate more objectivity by using images captured in the spotters' sight path. Linton and Fu (2015) are pursuing a research track that captures visual imagery from a smartphone mounted on the spotters' dashboard and outputs an objective assessment of the progress toward bare pavement. However, the procedure's reliance on the contrast between white snow and black pavement makes it vulnerable to unusual contrast situations, as when a bare road appears white from the presence of dissolved salt. For reasons like this one, the method is not yet ready for full-scale implementation. Purely visual methods also lack the ability to assess the presence of "black ice", or an ice-covered road that is otherwise bare (free of snow, slush, or accumulated precipitation).

A research team from Sweden and Norway (Jonsson et. al., 2015) addressed the shortcomings of the visual imagery based methods by focusing on near-infrared images from stationary imaging systems in Gevsjön, Sweden and Teveldalen, Norway. A model was developed using a k-nearest neighbors (KNN) classification method on individual pixels and trained to recognize pavement that is dry, wet, icy, or snowy. One of the most significant findings of this research was to demonstrate that visual images alone will frequently classify the road surface incorrectly, so infrared imagery is needed. Nonetheless, misclassifications are still relatively common with this model as, for example, a snow-covered road was classified as "icy" 18% of the time and as "wet" 4% of the time.

3 Description of the Data

Both short- and long-term RSIC performance measures provide valuable information to shape the RSIC operations. Short term performance metrics that provide instantaneous or near real-time information that can be used to adjust the rate of application of chemicals by, and routing of, snow and ice control vehicles. Data for these metrics must be collected and analyzed in real-time. Long term metrics can be used to measure the season-long performance of an agency's RSIC operations and the data for these metric can be archived and analyzed after the fact.

3.1 Speed Data Gathering

VTrans collects continuous speed data at a number of facilities located along the state highway system including RWIS (road weather information system) and WIM (weigh-in-motion) stations. RWIS stations would be an ideal source of data for developing a time-to-normal RSIC performance metric since both speed and weather data are collected concurrently at the same location. This is especially important in a state like Vermont where the topography frequently drives highly localized variations in winter precipitation. Unfortunately, due to server limitations and instrument problems, RWIS data for winter storms were unavailable during the data gathering phase of this project. For this reason, speed data from two WIM stations were coupled with weather data from proximate National Oceanic and Atmospheric Administration (NOAA) weather stations.

WIM stations are used primarily for monitoring loads on the roadway by heavy-duty vehicles and enforcing load limits but some WIM devices also collect complete traffic measurement and classification data for all vehicles classes. In 2011, VTrans operated six WIM stations that recorded vehicle speeds for all vehicle classes, including stations along I-89, US-4 (both 4-lane divided highways with limited access) and four two-lane state highways. The individual vehicle classifications and speeds recorded by these WIM stations are aggregated for each lane on an hourly basis. The aggregated data are binned in 10-mph increments for vehicles traveling between 1 and 51 mph and in 5-mph increments for vehicles traveling between 51 and 81 mph. All vehicles traveling in excess of 81 mph are included in an 81+ mph bin.

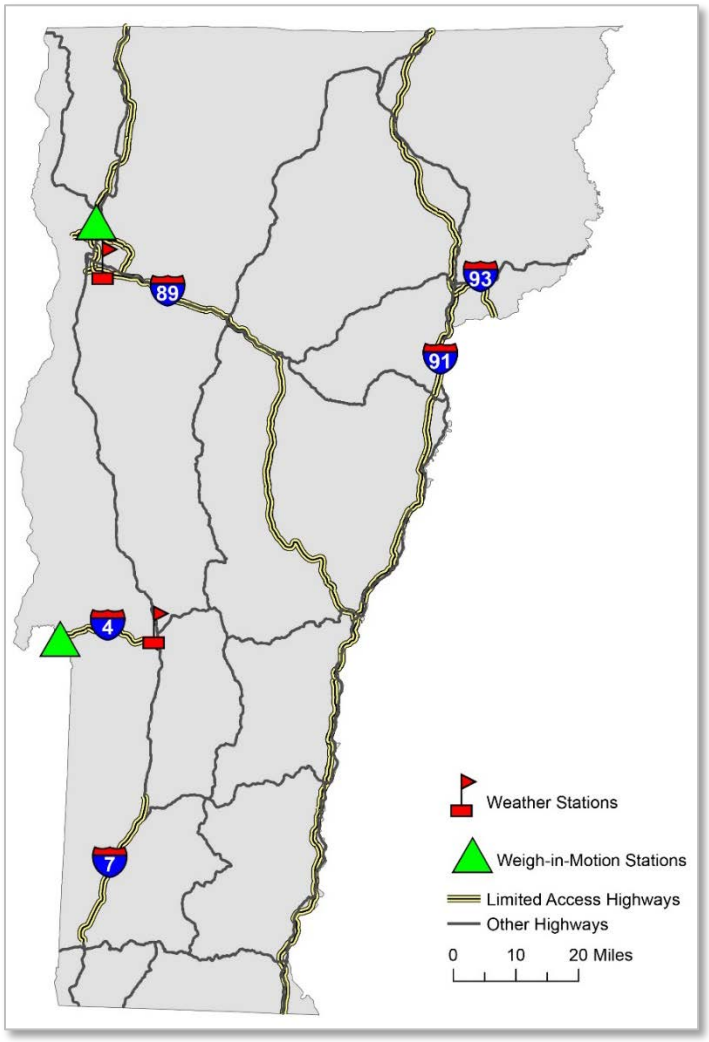


Figure 1 Weigh-In-Motion Stations and Weather Stations Used in this Study

Speed data was downloaded for normal (snow-free) weekday and weekend days to calculate ADD threshold values and for significant winter storm events at both the I-89 and US-4 WIM stations. A total of 10 normal, snow-free days were selected for baseline ADD calculations – three weekdays and three weekend-days for I-89 and four weekdays for US-4. All of the selected baseline days were preceded by at least one day without any precipitation to avoid ongoing traffic disruptions from a recent winter weather event. Nonetheless, one of these days exhibited a bimodal speed distribution that was dissimilar from the speed distributions seen on other snow-free days. Traffic flow on this day was assumed to be impacted by an unrecorded weather or traffic incident and was discarded from the baseline dataset. Speed data was also collected for one major, multi-day winter storm event for each of I-89 and US-4. Three additional days of speed data were collected for I-89, corresponding to single-day, low-snowfall events, with snow accumulations of between 0.6 and 1.5 inches.

The location of the WIM and weather stations used in this study are shown in Figure 1. The WIM station on I-89 in northwestern Vermont is located approximately 11 kilometers northwest of the NOAA weather station at the Burlington International Airport. The WIM station on US- 4 in west-central Vermont is approximately 25 kilometers west of the NOAA weather station in Rutland Vermont. Weather data was

obtained from the NOAA Daily Summaries and the Winter Event database. The NOAA Daily Summary data includes records of total daily snowfall and total precipitation. In addition, the Winter Event database provides estimates of storm start times for significant winter storm events. Daily Summaries were downloaded from the two weather stations in Burlington and Rutland for use in this project.

Figure 2 provides a 3-D visualization of the speed data obtained from the WIM station on I-89 during two 48-hour periods – February 11 and 12, 2011 and February 25 and 26, 2011.

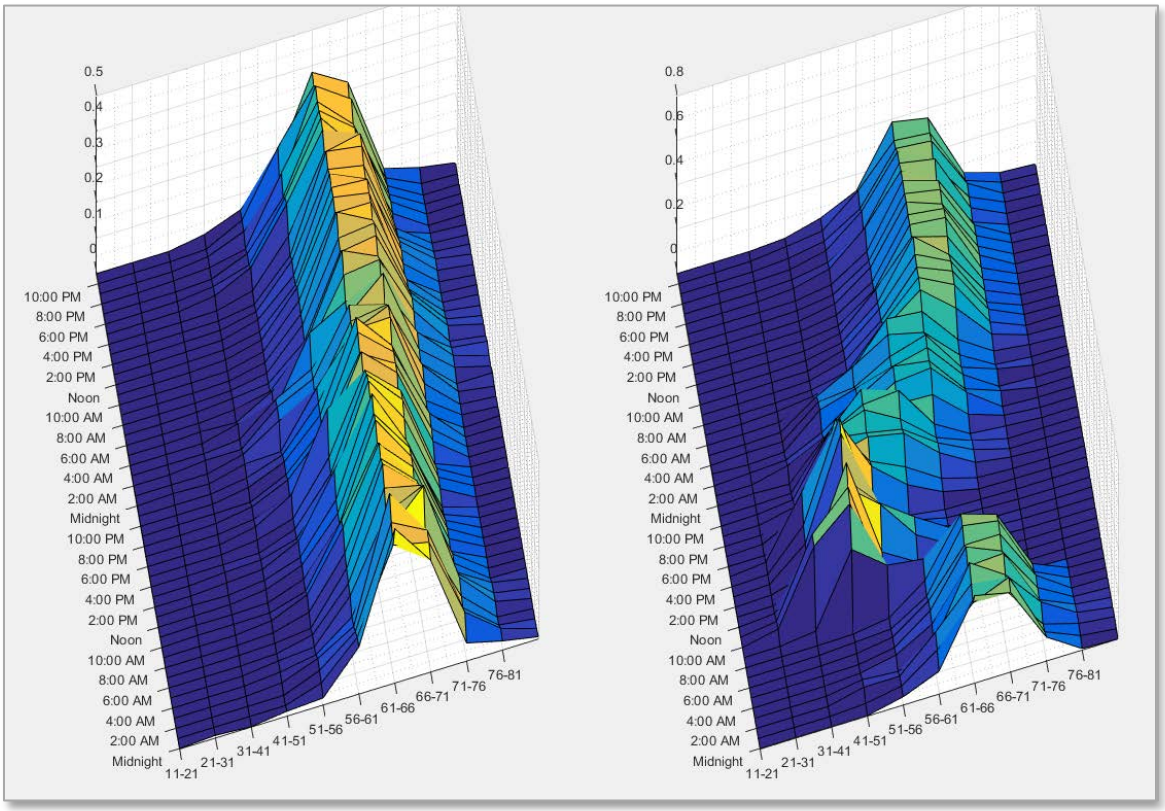


Figure 2 Example Speed Distributions on I-89 for 2 Days Without Snowfall (left) and 2 Days With Snowfall (right)

In each panel, the z-axis depicts the proportion of total traffic in each speed bin (shown on the x-axis) for each hour of the day (shown on the y-axis). The 48-hour period in the left panel shows the distribution of traffic speeds for two snow-free days. The surface is remarkably consistent both across hours in the day and between days. The only notable change in the speed distribution occurs during the very early hours of Saturday morning.

The 48-hour period in the panel to the right, in contrast, includes a major winter storm event that began at about 10:00 AM the morning of

February 25th with total snow accumulation equaling 9.6 inches and traffic impacts that lasted well into Saturday morning even though there was no additional snowfall on Saturday.

3.2 Thermal Imagery Data Collection

The thermal infrared imagery used in this project was collected using video cameras manufactured by FLIR that include both thermal infrared and visible light recording capacity. The cameras are sold by Sierra Pacific Innovations Corp for use in marine safety and security surveillance (Figure 3). The primary intended use for this device is to quickly locate a human body in water, but is also intended for locating a human body in other types of concealment, as by law enforcement. The cameras capture thermal infrared radiation with wavelengths between 8 and 12 microns at a 640 x 480 resolution. The camera can swivel 360° and tilt up to 90°. It will operate in temperatures from -13°F to 140°F.

Figure 3 Thermal / Visible Video Camera Used for this Project

Thermal infrared radiation captured by the camera is converted into a color gradient and produced as a streaming video image. For this project, thermal imagery was collected in grayscale, with whiter pixels representing warmer areas and blacker pixels representing colder areas. To maximize contrast in the video image, the camera dynamically adjusts the grayscale relative to the temperature range in the field of view, a process we call “normalization.” Thus, when recording an area with a relatively small temperature range, the resulting image will feature a larger range of grayscale than it would if an absolute temperature range was used with white at 140°F and black at -13°F. This feature is helpful in the context of RSIC performance measurement since road and precipitation temperatures can be very similar during winter weather events.

For the data collection process, two cameras were mounted on a VTrans plow truck. The route covered by the plow truck outfitted with the camera equipment included I-89 between Exits 11 and 12 in the District 5 service territory. The route includes the exit ramps at both interchanges and utilizes the median turnarounds south of Exit 11 and north of Exit 12. The forward-facing camera was attached to the roof of the cab using a magnetic mount supplied by the manufacturer. The rear-facing camera was attached to the right edge of the dump body, using a custom mounting bracket made for the purpose. Both cameras were positioned as close to the edge of the truck as possible to minimize obstruction by the truck itself. Thermal video from both cameras was recorded on a multi-channel DVR device.

Test imagery was collected in the winter of 2013-2014 and complete video imagery using the full installation was collected for five complete RSIC dispatches on I-89 during February and March of 2015 and then again during February and March of 2016. Unfortunately, due to unusually low precipitation levels in the winters of 2014-2015 and 2015-2016, full data collection was limited to relatively minor winter weather events. Over 12 hours of thermal imagery was collected during this period to support short-term measurement of RSIC performance in front of and behind an RSIC test vehicle. For this pilot testing, the data was stored and analyzed off line but the resulting method is designed to be applicable in real-time, allowing plow truck drivers or supervisors to make adjustments during a storm or even during a single pass.

Figure 4 Thermal (top) and Visible (bottom) Imagery in Low-Light, Pre-Dawn Conditions

Since the camera records thermal infrared radiation, the recordings are unaffected by low light conditions, which is important since RSIC operations often take place during pre-dawn hours. Figure 4 shows a thermal (top) and visible light (bottom) image of I-89 shortly after 5:00 AM on March 2, 2016. The thermal image shows contrast on the road surface, including tire tracks where the pavement is bare (darker), while the visible light image only reveals the lights from other vehicles in the background but no indication of the road's surface condition.

Thermal imagery is capable of discerning temperature variations in the road surface that are indicative of snow and ice cover on the pavement. Initial test imagery illustrated in Figure 5 showed that even low-resolution images clearly indicate differences in temperature on a roadway with minor snow cover (green), bare pavement (orange), and snow-covered shoulders (blue).

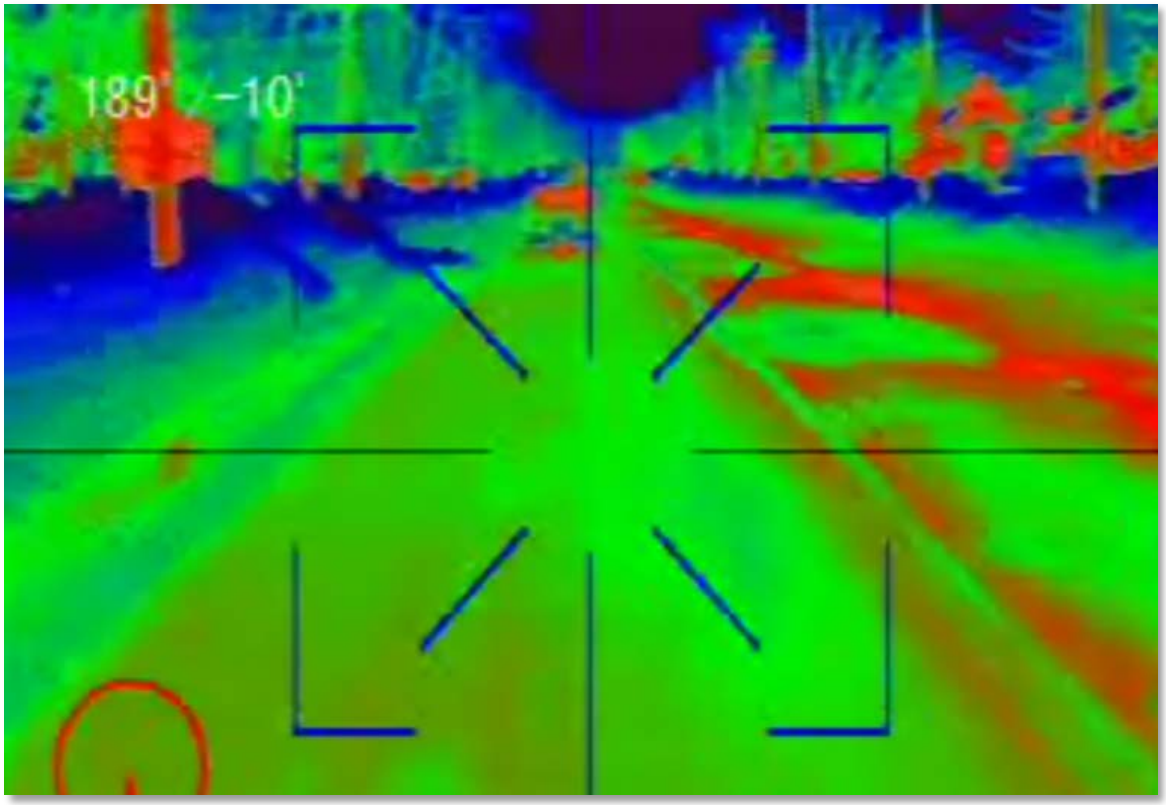


Figure 5 Test Imagery of Roadway with Minor Snow Cover (Green), Bare Pavement (Orange) and Snow-Covered Shoulders (Blue)

By mounting two thermal video cameras on a plow truck, one forward-facing and one backward-facing, differences in the temperature of the road surface created by the RSIC vehicle pass can be quantified and feedback provided to plow truck operators as a short-term measure of RSIC effectiveness. With this information, it may be possible for operators or supervisors to make real-time adjustments that maximize the resulting temperature difference.

4 Methodology

4.1 Long-Term Performance Measure Methodology

The ADD measure was derived to assess time-to-normal based on the full speed distribution. This approach was used since traffic flows with very different speed distributions may have the same mean traffic speed and therefore mean speed will not always be a good indicator of "normal" traffic flow.

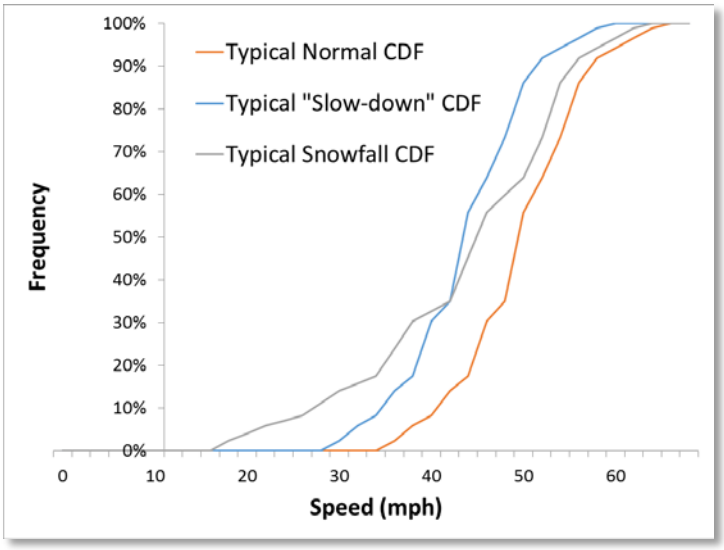


Figure 7 Typical CDFs for Roadway Speeds

Figure 6 provides an example of a typical cumulative distribution function (CDF) curve for roadway speeds, along with the typical deflection of the curve during snowfall. As shown in the figure, the deflection of the CDF during snowfall is slightly different than it is for a typical slowdown, as from traffic congestion. The "distribution deviation" is calculated as the area between the CDFs of an hourly speed distribution for a roadway under "normal" snow-free conditions and conditions of reduced travel speed and/or capacity from the precipitation and accumulation (Figure 7).

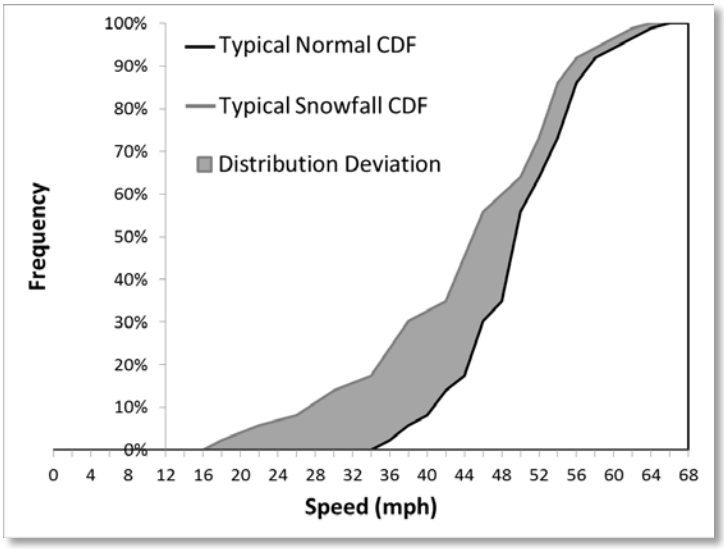


Figure 7 The Distribution Deviation

Using binned speed data requires that a series of deviation

differences be averaged across the distribution. The ADD is calculated by averaging the distribution deviation for the same time period, at the same site, on separate days. Because the vehicle speed data collected by the VTrans WIM stations are aggregated hourly into 12 speed bins, the ADD calculations described here are calculated at hourly intervals. That is, separate ADD values are calculated in hourly increments for speed data from the midnight to 1:00AM hour, through the 11:00 PM to midnight hour. The ADD for hour h can be calculated as:

$$\boldsymbol{ADD_h} = \left(\sum_{\boldsymbol{b=1}}^{\boldsymbol{B}} \left|\boldsymbol{P_{h,b,d_1}} - \boldsymbol{P_{h,b,d_2}}\right|\right) \Big/ \boldsymbol{B}$$

In this equation, $P_{h,b,d1}$ is the proportion of all traffic in hour h of day d_1 traveling at or below the maximum speed of bin b and $P_{h,b,d2}$ is the proportion of all traffic in hour h of day d_2 traveling at or below the maximum speed of bin b. The absolute value of the difference between the $P_{h,b,d1}$ and $P_{h,b,d2}$ is calculated for all bins B that include a least 5% of total traffic volume on both days but no more than 95% of the traffic on either day. This truncation is intended to reduce the impact of outliers during periods of low traffic volume. The deviations are calculated for each bin and then averaged by dividing by the numbers of bins, B.

The calculation process with binned data is illustrated conceptually in Figure 8 which shows the binned cumulative speed distributions on I-89 for the 6:00 AM to 7:00 hour for two Saturdays in February 2011. In this example, the deviation between the two distributions is calculated for the 51-56, 56-61, 61-66 and 66-71 mph bins. The ADD for this hour is simply the average of the absolute value of these deviations. With disaggregate data, distribution deviation could be calculated more precisely but the binned approach was necessary to accommodate the lack of availability of raw data from the WIM traffic data recorders.

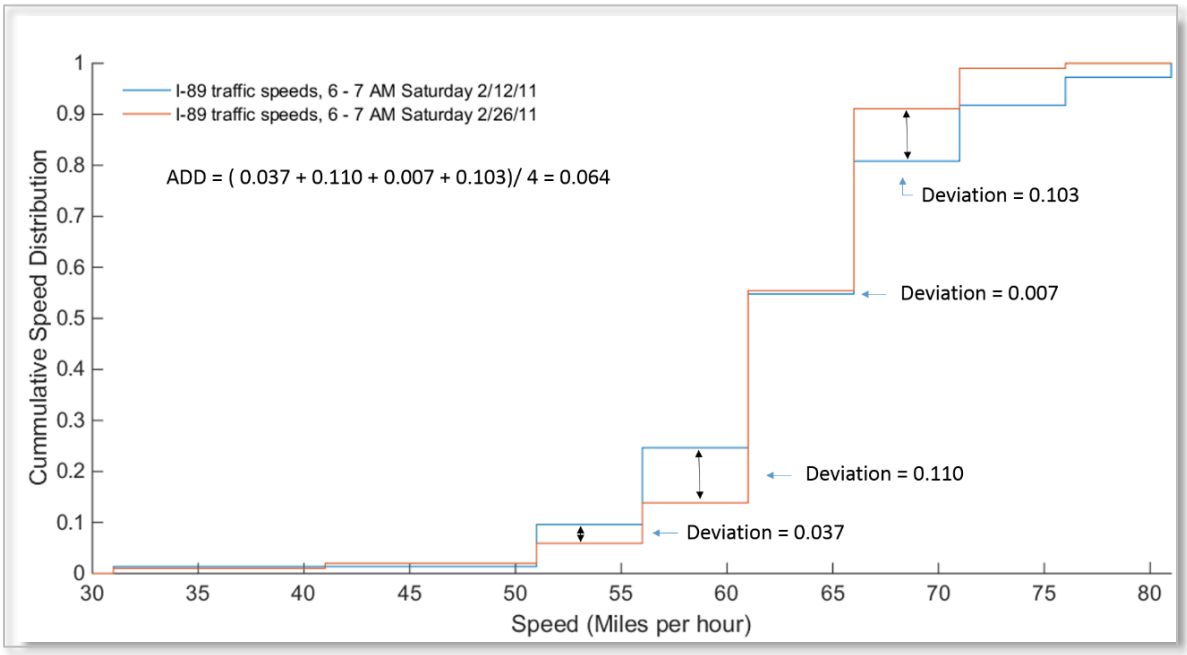


Figure 8 Graphical Illustration of ADD Calculation

Two sets of ADD calculations are required to use the ADD as a performance metric. The first calculation is used to determine a threshold for baseline, snow-free conditions that reflects normal, day-to-day variability in traffic speed distributions. The second calculation compares the day with the winter storm under evaluation and the most recent baseline, snow-free day – values which exceed the threshold indicate a disruption to normal traffic flow.

Baseline ADD values were calculated separately for both I-89 and US-4 since typical traffic flows are likely to vary among different roadways. In addition, to account for possible variations in speed distributions between weekdays and weekends, baseline ADD values were calculated separately for weekday-to-weekday, weekday-to-weekend and weekend-to-weekend pairs for I-89. Once all baseline ADD values were calculated for each site, the 95th percentile of the baseline ADDs was used as the threshold for normal operating conditions. The use of the 95th percentile baseline ADD is intended to exclude higher ADD values from overnight periods when low traffic volumes and routine anomalies overly impact the determination of normal traffic-flow variations. Time-to-normal, then, is calculated as the elapsed time from the onset of the winter storm (when the snow-day ADD begins to exceed the threshold) to the time when normal mobility conditions have been restored (the snow-day ADD falls back under the threshold).

4.2 Short-Term Performance Measure Methodology

To analyze the thermal video, an image comparison tool was developed in MATLAB® which imports the thermal video recordings and extracts still images at a specified sample rate. For this project, comparison images were extracted at one second intervals. A small lag time was introduced between the extraction of still images from the front and rear videos so that the pairs of images would capture the same segment of roadway. While the exact lag between front and rear images depends on the speed that the plow truck is traveling, and thus can vary slightly over the course of a route, using a two second lag appeared to work well enough for this project.

Since the field of view in the images is larger than the lane being serviced by the plow truck, the comparison of the front and rear facing images requires that the user specify an analysis zone on the road surface that excludes portions of the image outside the travel lanes where RSIC is not being performed. Analysis zones should be specified so that they are equidistant from the road shoulder and a similar distance in front of, and behind, the truck so that they are capturing the same road surface segment. Figure 9 shows an example of the analysis zones for the front and rear from a reconnaissance (no plowing or salting taking place) pass on February 16, 2016.

Figure 9 Analysis Zones for Front and Rear Images

Once the analysis zones are specified, the comparison tool extracts these segments of the images and flips the rear image vertically and horizontally so that it has the same orientation as the front image. Reorienting the rear image is necessary because the imagery captured by the rear facing camera shows the right shoulder on the left side of the image and the direction of travel is from the top of

the image toward the bottom of the image, both of which are the opposite of the image captured by the front facing camera. The original orientations of the front and rear images are illustrated in Figure 10.

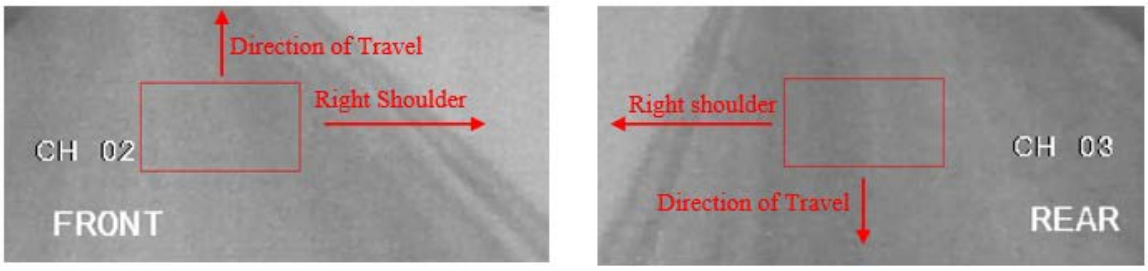


Figure 10 Orientation of Front and Rear Analysis Zones

After the analysis zones have been extracted and the rear image has been flipped, the difference in the grayscale intensity (a representation of temperature) between the two images is calculated on a pixel-by-pixel basis within the analysis zone. Each pixel is associated with a value between 0 and 100, where 0 is a black pixel, 100 is a white pixel, and all values in between represent different shades of gray. The difference between the front and rear image is reported as the average of the absolute value of the difference between each pixel:

$$\sum_{p=1}^{n} \left| f_p - r_p \right| / n$$

In this equation f_p is pixel p in the front image and r_p is the corresponding pixel in the rear image and n is the total number of pixels in each image.

The difference between the front and rear images is also converted back into a grayscale image as visual feedback. If the road is covered in precipitation that is significantly warmer or colder than the road surface and the road surface is cleared or mostly cleared of precipitation in the rear image, the absolute value of the difference in images will be close to 100 and the image will be predominately light gray or white. On the other hand, if there is no change between the front and rear images, the difference for each pixel will be 0 and the resulting image will be predominately black.

5 Results

5.1 Long-Term Performance Measure Results

Summary statistics used in the determination of baseline ADD threshold values for I-89 and US-4 are provided in Table 1.

Table 1 Baseline ADD Values Calculated for I-89 and US-4

	Comparison Days	N	Mean	Std. Dev.	95th Percentile
I-89	Weekday – Weekday	144	0.07	0.06	0.21
	Weekend – Weekend	144	0.06	0.05	0.16
	Weekday – Weekend	432	0.07	0.05	0.17
	Any day – Any day	720	0.07	0.05	**0.17**
US-4	Weekday – Weekday	288	0.07	0.05	**0.18**

ADD values for I-89 were initially calculated separately for pairs of weekend-days and weekdays and then for all 15 combinations of 7 normal days. The resulting ADD values did not differ significantly from one another, so the team decided to use unrestricted pairings of normal snow-free days for the final ADD threshold calculation of 0.17. The baseline ADD for US-4 was calculated using only weekday-weekday pairings of snow-free days since this analysis did not include a weekend storm event impacting US-4. The calculations for US-4 resulted in a threshold value of 0.18, very similar to the any day-any day threshold for I-89.

ADD values for snow-free days on I-89 are shown in Figure 11. Weekday-weekday values are shown in blue, weekend-weekend values are in red and weekday-weekend ADD values in green. The 95th percentile threshold for the full dataset is shown with a dashed line.

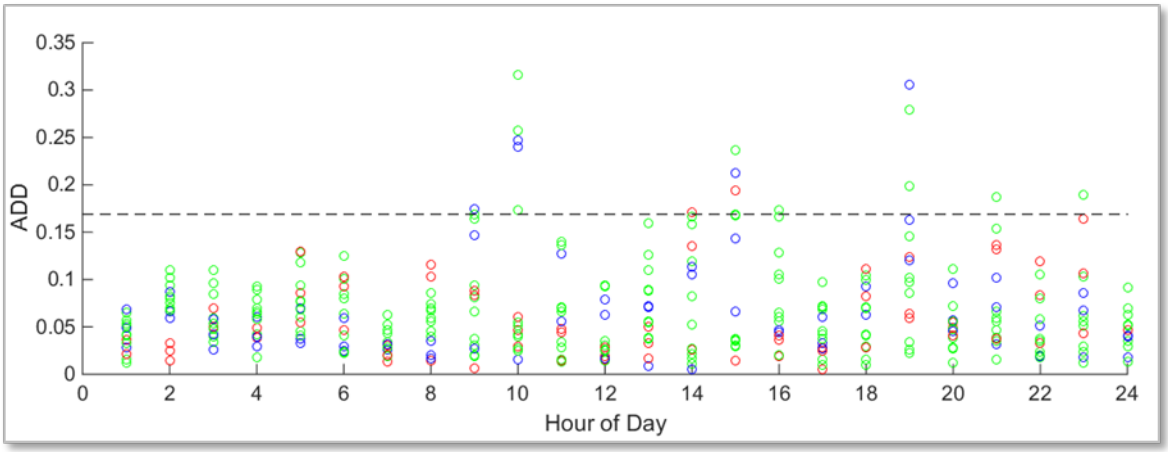


Figure 11 Baseline (Snow-Free) ADD Values for I-89 and the Selected Threshold

In Figure 12, baseline ADD values for US-4 are shown in blue and the 95th percentile threshold of 0.18 is shown with a dashed line.

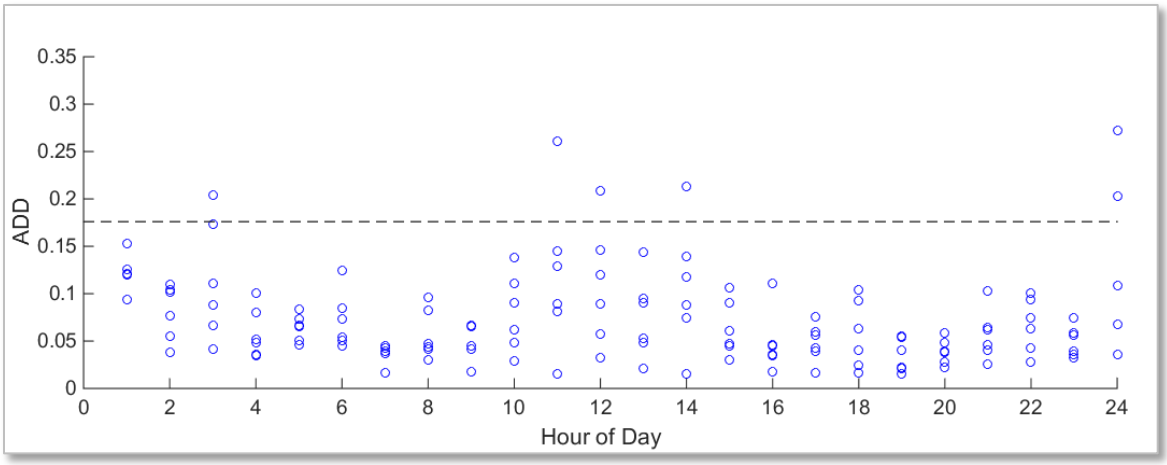


Figure 12 Baseline (Snow-Free) ADD Values for US-4 and the Selected Threshold

Figure 13 shows the ADD values calculated for US-4 for Monday, March 7th and Tuesday, March 8th, 2011. Snowfall accumulation on Monday totaled 7.8 inches with another 4.4 inches of accumulation on Tuesday.

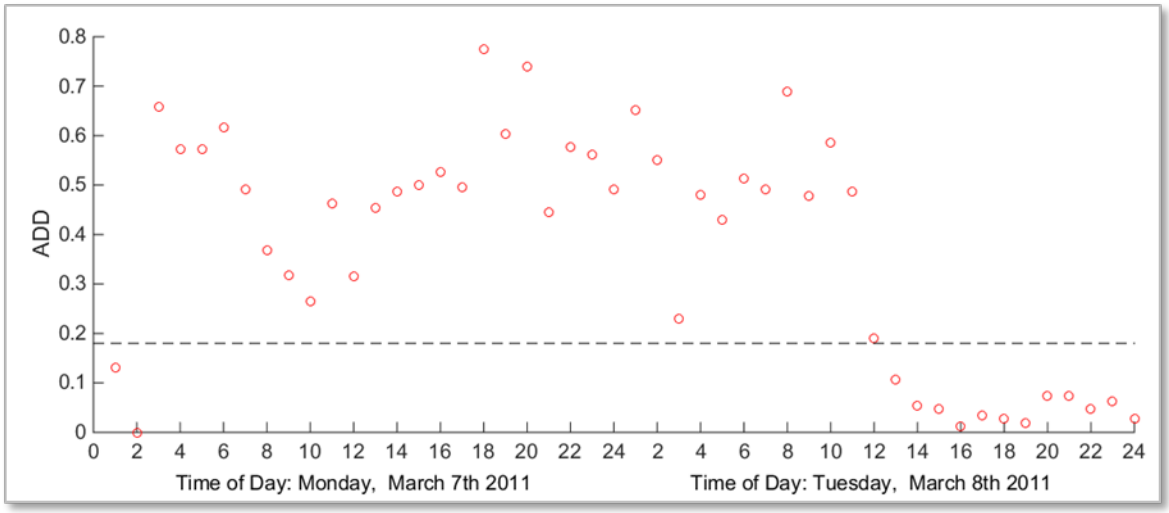


Figure 13 ADD Values for US-4 During 12-inch Snowfall Event in March 2011

Comparing the ADD values during this period with the ADD threshold for US-4 (again shown with a dashed line) shows a sudden and dramatic ADD spike starting at 3:00AM. ADD values remained above the threshold throughout the day Monday before recovering to below threshold levels slightly after noon on Tuesday.

Figure 14 shows the ADD values for a similarly large storm on I-89 on February 25th and 26th, 2011 which dropped about 10 inches of snow.

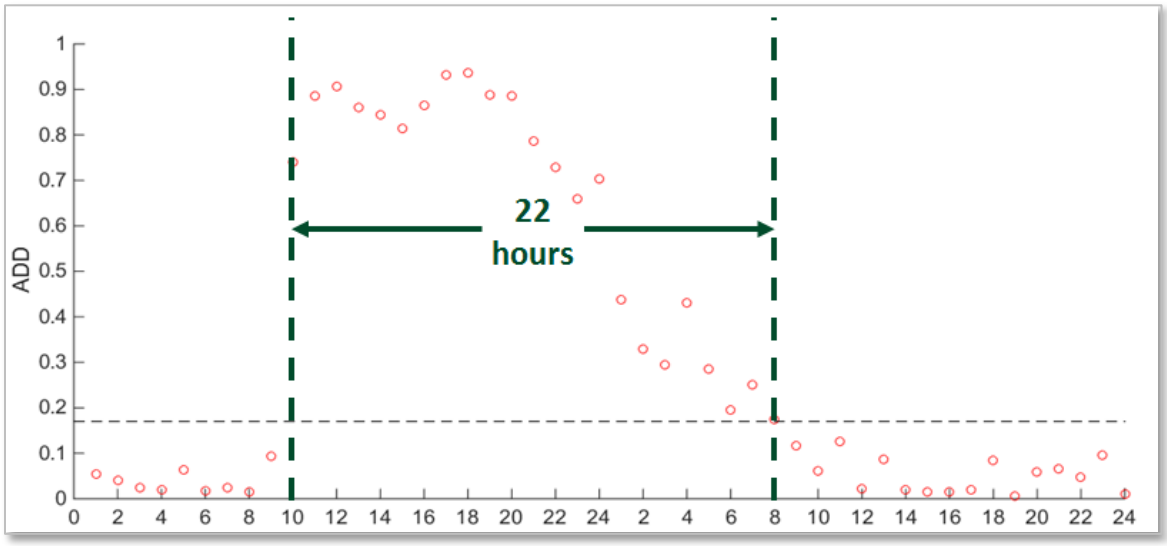


Figure 14 ADD Values for a 10-inch Snowfall Event on I-89 in February 2011

ADD values again show a large and abrupt jump when the storm first hits at approximately 10:00AM on the 25th. These values stay high though the duration of the storm before gradually returning to below the threshold on Saturday morning. The time-to-normal for this storm

is calculated as the elapsed time between the ADD exceeding the threshold and returning back to below the threshold. As shown in the figure, the time-to-normal for this storm was 22 hours, as calculated by the ADD approach.

Prior research has suggested that speeds within 5 or 10 mph of historical average speeds could be considered normal (Sharifi et. al., 2014). For I-89, this equates to a deviation in average speed of approximately 10%. Using this threshold, the time-to-normal was calculated using the average speed with an approach similar to the ADD approach. For comparison purposes, Figure 15 shows the ADD values (in red) and the deviations in average speed (in blue) on I-89 for the same February winter storm depicted in Figure 14. Both methods show the same storm start time but the average speed method shows a return to normal that occurs several hours before the ADD approach.

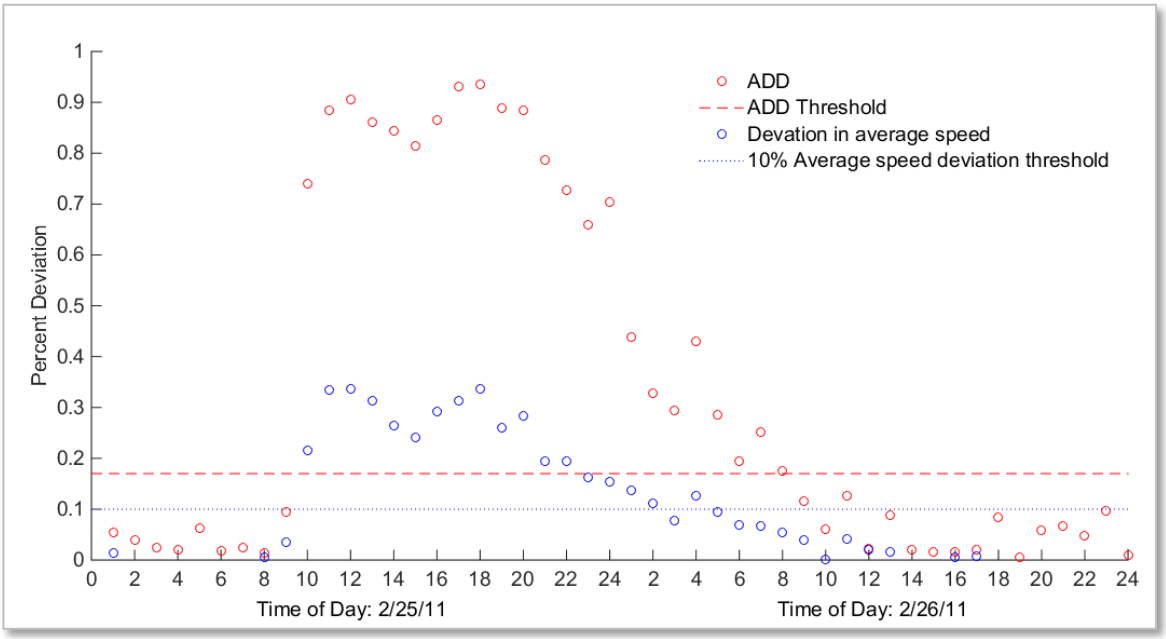


Figure 15 Comparison of ADD and Average Speed Approaches to Calculating Time-to-Normal

Figure 16 shows the impact of three smaller winter weather events on traffic speeds on I-89 using the ADD approach to calculate time-to-normal.

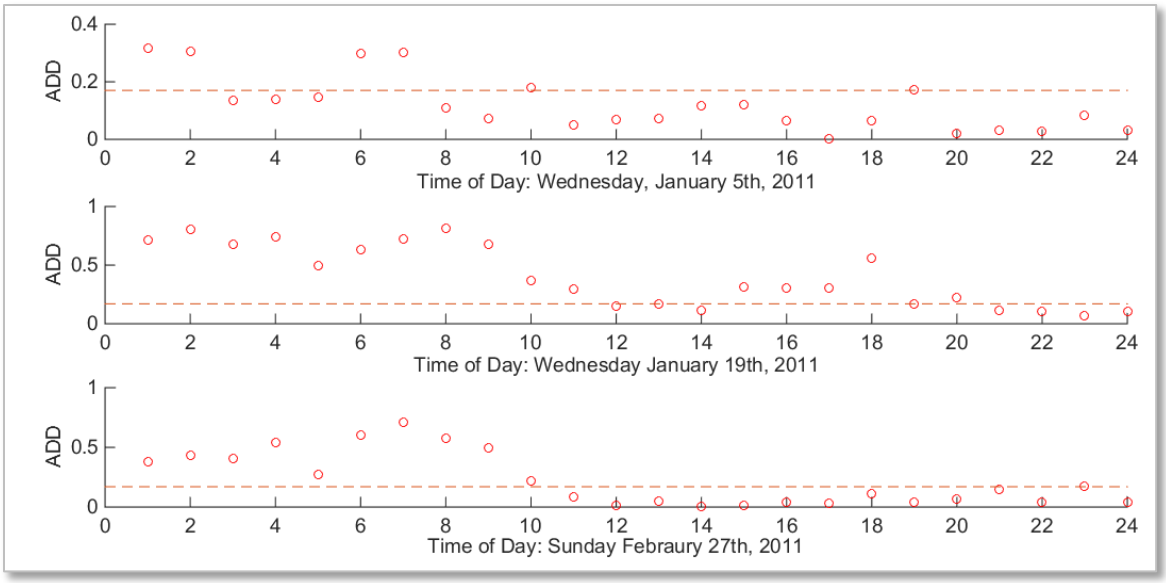


Figure 16 ADD Values for 3 Minor Snowfall Events (0.6, 1.3 and 1.5 inches of snowfall, respectively) in January & February 2011

The top panel shows a storm with 0.6 inches of snow accumulation, the middle panel 1.5 inches of accumulation, and the bottom panel 1.3 inches of accumulation. The effect of the minor snowfall in the top panel barely exceeded the threshold ADD, but two episodes of disruption each with a 2-hour time-to-normal are indicated. Both of the bottom two panels show early pre-dawn disruptions using the ADD approach. In each case, the time-to-normal roughly parallels the depth of snowfall recorded, with calculated values of 11 and 10 hours for the 1.5-inch and the 1.3-inch storm, respectively.

5.2 Short-Term Performance Measure Results

The MATLAB® comparison tool was successfully applied to an RSIC service run on February 16th, 2016, capturing the differences in road surface temperature created by a combination of plowing and salt spreading. The first pass of the route on this date started at 5:28AM as a reconnaissance pass, when the operator is not plowing or spreading salt, but is inspecting the roadway conditions to prepare for a service pass. The second pass began at 7:17AM and included plowing the right lane of travel in both directions. Table 2 shows the average difference between the front and rear images on the reconnaissance and plowing passes across 4 minutes (240 frames at one per second) of video.

Table 2 Image Comparison Summary Results

	Number of Frames Compared	Average Front/Back Difference	Standard Deviation
Reconnaissance Pass	239	6.6	2.5
Plowing Pass	239	14.5	6.1

As expected, the difference is considerably larger, in this case more than twice as large, for the plowing pass. A t-test of the mean difference for the reconnaissance and plowing passes shows a statistically significant difference at the p = .01 level.

Figure 17 shows a sample of the second-by-second output from the MATLAB® comparison tool for the plowing pass on February 16th.

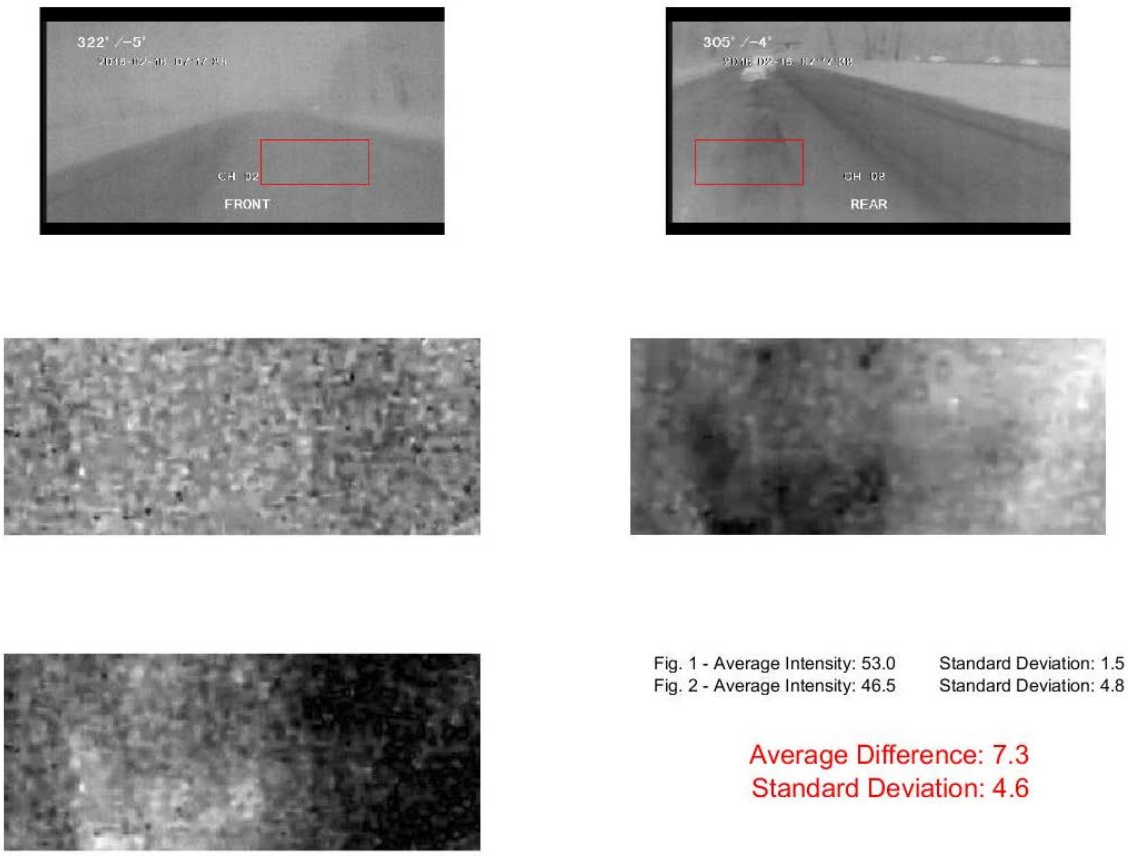


Figure 17 Example of Output from the Image Comparison Tool

The top row of the output shows the complete front and rear thermal images. The reported surface temperatures on I-89 at the time of the recording were 29.1°F and 30.0°F at 5:30AM and 7:15AM, respectively. At 7:15AM, the hourly rolling average precipitation was 3.2 mm and

the precipitation was warmer than the road surface. Consequently, bare pavement appears darker than precipitation-covered pavement in the test imagery. The middle row shows enlarged versions of the analysis zone from each image. The bottom row shows the grayscale image of the difference between the front and rear analysis zones and the average intensity of the front and rear images as well as the average difference between the two images. For this section of I-89, the left lane was plowed prior to the right lane and consequently appears darker than the right lane in the front image in Figure 17.

6 Conclusions, Challenges, and Implementation Plan

This project provided the first successful demonstration of a short-term performance measurement system for RSIC using real-time thermal-imaging of the pavement surface in front of, and behind, the RSIC vehicle. A computational script was developed and applied in MATLAB® to output the average difference in temperature between these surfaces, as measured by the grayscale image on a second-by-second basis with the thermal imaging system. This demonstration has the promise to become an effective real-time performance measurement system to allow RSIC operators and supervisors to make "on-the-spot" adjustments to optimize the effectiveness of their efforts.

The use of the ADD approach to calculating a time-to-normal for RSIC operations shows considerable promise as a long-term measure for grading RSIC performance by storm and by season. It can measure the real-world effectiveness of RSIC operations using speed data that are routinely collected by VTrans. For limited-access highways, baseline snow-free ADD values showed considerable stability across days of the week and time of day, making the determination of a threshold relatively straightforward. The stability of these threshold values and the sharp increase in ADD values during known winter storm events suggest that the ADD approach is an effective way to measure time-to-normal after the onset of a winter storm and consequent dispatch of RSIC vehicles.

The following two subsections are a discussion of the challenges that were encountered with each of these performance measurement systems that will need to be overcome before full-scale implementation can be considered. The final subsection is the initial draft of an Implementation Plan, outlining the next steps that need to be taken if full-scale implementation is planned.

6.1 Challenges and Opportunities for Speed Data Collection for Long-Term Performance Measurement

Since the data collection phase of this project, VTrans has contracted with Vaisala to maintain a web-portal for accessing RWIS data from Vermont. This portal includes binned speed data in 5-minute increments that can be easily downloaded. The greater stability of this data portal makes it feasible to use RWIS data for ADD calculations. Using this data would enable ADD calculations in smaller time

increments, allowing for greater precision in the metric. In addition, the weather data collected by the RWIS station would enable storm start and end times to be identified more accurately than with the NOAA data used in this project.

Calculating ADD values with disaggregated speed data would add minimal additional computation burden. The use of data that is at the resolution of the individual vehicle would enable deviations to be calculated at smaller speed intervals, and the ADD would capture more subtle deviations in the speed distributions. This benefit might be especially important for measuring RSIC performance during smaller winter events. Over the course of about 15 months in 2014 and 2015, UVM TRC staff made inquiries and attempts to coordinate the archiving of raw speed data ("event" data) collected from the RWIS and WIM stations in Vermont. However, at the end of these inquiries, it was still unclear how and where the data was being stored and archived, and what resources were needed to set up a regular transmission of the data to a server hosted by VTrans or UVM for use in research. Additional attempts to coordinate this archiving were outside the scope of this project.

6.2 Challenges with Data Collection for Short-Term Performance Measurement

While thermal video is well matched to RSIC evaluation, there are a number of challenges that make it difficult to consistently collect clear, unobstructed thermal imagery.

Automated analysis of truck-mounted thermal video is limited by the difficulty of consistently obtaining, clear, unobstructed imagery of the road surface. Active precipitation or even high moisture content in the air can reduce the clarity of the thermal imagery as infrared radiation reflects off of airborne water molecules. Consequently, the underlying infrared radiation from the road surface can be distorted. A similar challenge to the video collection process is the buildup of moisture, ice, and grime on the camera lens. As materials accumulate on the camera lens the image quality degrades significantly. Figure 18 shows images captured at 5:29 AM and 5:46 AM on February 16th that illustrate this problem.

Figure 18 Image Quality Degradation Caused by Buildup on the Camera Lens

The earlier image on the left is crisper, capturing temperature variations in exposed pavement, precipitation covered pavement, guardrails, and other surrounding features. The image at right is considerably less distinct and captures very little temperature variation in the roadway or surroundings.

The camera system used for this research utilizes an automated image-spectrum normalization which automatically adjusts the range of colors or shades on the image to maximize contrast. In the grayscale spectrum, white and black pixels represent the warmest and coolest sections of the image, respectively so that even small temperature differentials can be captured visually and the full scale from black to white is being constantly utilized.

Since this normalization process takes place independently for the front- and rear-facing cameras, however, when the temperature range in the front field of view is different than the range in the rear field of view, the grayscales are normalized differently and a comparison of the grayscale intensity of these images will not accurately reflect underlying temperature differences. This disparity is most common when passing vehicles are particularly close to either the rear- or front-facing camera and the camera is exposed to the intense heat from the vehicle engine. Figure 19 illustrates the grayscale normalization that occurs as a tractor trailer truck passes in the left lane.

Figure 19 Grayscale Normalization in Response to Passing Vehicles

When this large heat source is close to the camera, the temperature range in the image increases and the road surface is represented by a darker gray even though its absolute temperature has not changed. Drivers using these cameras as part of a real-time feedback system would need to be aware of this issue and to discount system results in this situation.

The segment of the rear image that is used for the temperature comparison can also be obstructed by a closely following vehicle – a common problem for RSIC vehicle operators. In this case, the comparison is temporarily compromised because the rear road surface is occluded, as shown in Figure 20.

Figure 20 Following Car Obstructing the Analysis Zone

Finally, the concept of using a vehicle mounted thermal camera systems to measure RSIC performance relies on the premise that plowing and salting have a relatively rapid impact on the temperature of the road surface. Since the de-icing function of salt takes time to take effect, the impact of salt application might better be measured of a longer time span. Since plowing immediately impact the precipitation cover on the road surface, it can more effectively be evaluated in real-time. However, in some instances, the temperature of the bare pavement may not be significantly different from the temperature of the snow or ice that is covering it. In these cases, the removal of precipitation from the road surface does not cause a measurable temperature change.

6.3 Implementation Plan

Implementation of performance measurement of RSIC in Vermont will require a minimization of subjectivity and bias that can only come with a high degree of automation. The performance measures that were developed and pilot tested in this project show great promise toward satisfying this requirement. The ADD approach is ready for validation

on limited-access highways and for pilot testing on two-lane state highways. The short-term video analysis approach faces more significant equipment challenges. Neither of the approaches is currently ready for full-scale implementation due to limitations in collection, storage, archiving, and transmission of the data required.

The following sections describe the steps that will eventually need to be taken in order to implement full-scale performance measurement for RSIC.

6.3.1 Video Equipment and Installation

In order to implement the short-term performance measurement system, two compact, combination visible / thermal imaging cameras are needed for each vehicle. These cameras must be securely installed over the cab and at the back edge of the dump body, with wireless streaming transmission to an image display within the cab. The forward-facing camera can be installed with the cameras integrated magnetic base, if one is available, but a specialized custom bracket will have to be constructed for the rear-facing installation. VTrans mechanical staff will likely be required to complete this installation. These cameras will both need to have the automatic grayscale normalization turned off and they will both also need a specialized housing to prevent build-up of ice and snow on the camera.

In order to capture the information gained from the method developed in this project in real time, the streaming video must be integrated with an onboard computer to run the MATLAB® (or other scripted) comparison tool and output the average front-to-back difference in temperature instantaneously or within a short time period of less than 10 seconds.

For vehicles outfitted with an onboard computer for processing automatic vehicle locator (AVL) data, it might be possible to make use of the AVL computer for logging streaming video and running the comparison tool. However, since the AVL system is a proprietary, vendor-administered system, it would likely require extensive intervention from the vendor to allow that to happen. A more cost-effective option might be to add a second on-board computer dedicated solely to processing the thermal imagery. The average front-to-back difference in temperature can then be used by the vehicle operator or an attendant to adjust salt application and timing of plowing passes during an RSIC dispatch.

As of the preparation of this report, current thermal camera technology does not meet these needs for a short-term performance measurement using thermal imagery.

6.3.2 Winter Storm Forecasting

Due to the way that each of the approaches developed in this project were designed to be implemented, it will not be necessary to have an accurate winter storm forecast to implement them. For long-term performance measurement, established measures of precipitation intensity and winter-storm severity can be used to identify a measurable winter weather event and develop the "time-to-normal" for each speed data collection station for that event. For the short-term performance measurement approach using the average temperature difference between the forward- and rearward-facing thermal cameras, the RSIC vehicle dispatch at the VTrans District level can serve as the benchmark for when performance measurement will take place.

6.3.3 Identification of the Onset and the End of a Winter Storm

The NOAA Storm Events Database now contains data for 48 different event types, including a "Winter Weather" event. A Winter Weather event could result from one or more winter precipitation types (snow, or blowing/drifting snow, or freezing rain/drizzle), on a widespread or localized basis. The following data are included in the database for each Winter Weather event:

- Beginning Time –Time when winter weather precipitation started to accumulate or the phenomena began.
- Ending Time – Time when the winter weather precipitation stopped accumulating or phenomena ended.

6.3.4 Selection of Stations to Analyze for Long-Term Performance

All of the WIM and RWIS stations can be used to measure RSIC performance for all Winter Weather events once proper storage and archiving of the raw "event" speed data is arranged.

Since access to raw "event" speed data is not yet possible, the scripted query for measuring RSIC performance after a Winter Weather event has not been developed. However, the development of this script will be relatively straightforward since a similar script has been developed in MATLAB® to develop the ADD approach.

6.3.5 ADD Validation and Roll Out

The ADD approach requires only current RWIS, WIM, and other speed data collectors for implementation. To validate the 95th percentile ADD thresholds used in this analysis, ADD "normal" assessments should be compared with existing visual inspection methods and the thresholds adjusted as necessary.

Additional analysis is needed to determine the effectiveness of ADD in more congested settings and for smaller, two-lane state highways, both of which may see greater baseline ADD variability due to reduced free-flowing traffic.

Ideally, raw speed data would be available for ADD-based evaluation, but this is not necessary for implementation. The Agency currently does not receive the "event" speed data in a raw form that is necessary for full-scale implementation. It is unclear what additional steps need to be taken to begin archiving raw speed data on a server that is available for research or performance measurement applications.

6.3.6 Approach to Grading Vermont's RSIC Performance by Storm

Winter weather severity will be a key component of a comprehensive algorithm for grading long-term RSIC performance by the VTrans fleet. "Time-to-normal" measures can be used to compare the Agency's effectiveness against efforts from other districts, or from similar storms earlier in the season, or in previous years. However, it will be critical to avoid comparisons across precipitation types (freezing rain, sleet, and snow) and between storms whose intensity and ambient weather conditions are not similar.

Within each precipitation category, efforts should be made to compare RSIC efforts for storms with similar:

- Ambient temperatures during and 24-hours prior to the storm,
- Hourly intensities for the duration of the storm
- Total accumulations
- Hourly traffic flows at the speed-data collection point

RSIC dispatches found to have excessive "time-to-normal" recovery times when compared to similar events should be investigated further at the District level - ancillary circumstances, like a vehicle crash, roadway damage, or unusually heavy traffic congestion may have adversely affected the recovery of normal traffic conditions.

6.3.7 Approach to Grading Vermont's RSIC Performance by Season

Seasonal comparisons may be more effective, since storm-specific intensities may be less likely to match than a season-wide intensity. The Midwestern Regional Climate Center publishes an Accumulated Winter Season Severity Index to quantify the overall intensity of the winter season for 52 locations across the continental U.S., including Vermont (Boustead et. al., 2015).

To compare RSIC performance in Vermont from one season to the next, all of the "time-to-normal" measures for all WIM and RWIS stations statewide can be summed to create an overall seasonal "time-to-normal", and this value can be considered qualitatively alongside the Accumulated Winter Season Severity Index for Vermont from year-to-year to assess improvements in overall RSIC for facilitating mobility in adverse winter weather.

7 References

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