Dashboards for Real-time Monitoring of Winter Operations Activities and After-action Assessment

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ABSTRACT
The Indiana Department of Transportation (INDOT) operates a fleet of nearly 1100 snowplows and spends up to $60M annually on snow removal and de-icing as part of their winter operation maintenance activities. Systematically allocating resources and optimizing material application rates can potentially save revenue that can be reallocated for other roadway maintenance operations. Modern snowplows are beginning to be equipped with a variety of Mobile Road Weather Information Sensors (MARWIS) which can provide a host of analytical data characterizing on-the-ground conditions during periods of wintry precipitation. Traffic speeds fused with road conditions and precipitation data from weather stations provide a uniquely detailed look at the progression of a winter event and the performance of the fleet. This research uses a combination of traffic speeds, MARWIS and North American Land Data Assimilation System (NLDAS) data to develop real-time dashboards characterizing the impact of precipitation and pavement surface temperature on mobility. Twenty heavy snow events were identified for the state of Indiana from November 2018 through April 2019. Two particular instances, that impacted 182 miles and 231 miles of interstate at their peaks occurred in January and March, respectively, and were used as a case study for this paper. The dashboards proposed in this paper may prove to be particularly useful for agencies in tracking fleet activity through a winter storm, helping in resource allocation and scheduling and forecasting resource needs.

Keywords: mobility, winter operations, weather, performance metrics, resource allocation

BACKGROUND

Winter weather events have a significantly adverse impact on mobility (Day *et al.*, 2016). On average, there are over 5.8 million crashes in the United States every year, of which approximately 21% are weather-related, and resulting in 418,000 injuries and 5,000 fatalities (Federal Highway Administration, 2018). In 2017 alone, there were a total of 34,247 fatal crashes in the United States, of which 836 were in the state of Indiana (Federal Highway Administration, 2019). Winter weather operations can account for approximately 20 percent of a state Department of Transportation's (DOT) maintenance budget and state and local agencies annually spend upwards of 2.3 billion dollars on snow and ice control operations(Federal Highway Administration, 2018).

Tracking and quantifying the performance of snow and ice control operations is a fairly significant deliverable for agencies and contractors as they strive for improved customer satisfaction. A number of performance measures have been in use worldwide and there is no single widely accepted measure that applies to a variety of road types, storms and traffic conditions. Recovery from event, travel reliability during event, system efficiency and level of customer satisfaction are some of the proposed performance measures in *Performance Measures in Snow and Ice Control Operations* (Gopalakrishna *et al.*, 2019). Performance metrics prove helpful to agencies in providing guidance with regard to the amount of effort required when planning ahead for a winter event, which in turn helps them better manage costs.

Level of service (LOS) standards have been used to qualitatively gauge winter operations performance in the past. Pavement condition, storm impact, storm severity, accident frequencies, visibility, traffic speed reduction and travel delays are a few examples of winter operations performance metrics that have previously been proposed (Carmichael *et al.*, 2004; Usman, Fu and Miranda-Moreno, 2010; McCullouch, Partridge and Noureldin, 2013; Bandara, 2015). Congestion tickers (referred to as traffic tickers henceforth) have been developed that provide a data archive of real-time and historical congestion on interstate roadways in the state of Indiana (McNamara, 2016). There is a growing consensus in the winter operations field that traffic, weather and road condition data sets should be integrated to provide a comprehensive real-time view of snow and ice control operations during a storm. This has been the primary driving force behind this research.

STUDY MOTIVATION AND SCOPE

Inclement weather can significantly impact traffic operations, reducing efficiencies of state maintenance vehicles and creating unsafe driving conditions for the public. Advances in the sensors currently deployed to detect roadway conditions provide traffic management agencies with a unique opportunity to anticipate, control and plan ahead to better manage roadways in times of inclement weather. Proactive planning for weather events based on weather forecasts and impact assessment as well as the real-time monitoring of the resources are an important deliverable for agencies.

This study leverages traffic condition, road condition, weather data and geo-location of fleets to develop dashboards for real-time monitoring of winter operations activities and after-action assessment. The dashboards have the potential to provide agencies with a unified look at traffic, weather and pavement conditions in a single interface, thus making resource allocation and scheduling significantly more streamlined when operating off of a unified data source.

IDENTIFYING WINTER STORMS AND THEIR IMPACTS FOR 2018/19 SEASON

TABLE 1 enumerates 20 snow events in the state of Indiana over the period of November 3, 2018 through April 30, 2019. These events were shortlisted based on a value of maximum wintry precipitation (greater than 2mm/day) from the North American Land Data Assimilation System (NLDAS) weather stations across the state. TABLE 1 depicts the maximum miles operating below 45 mph, observable mobility impact and total mile-hours of congestion across interstate roadways in the state for these events. The storms were further classified as having an observable impact if the maximum miles operating below 45 mph on an event date were over 100 miles. In many cases, these winter events had no significant impact due to a combination of pre-treatment of the roads, precipitation rates low enough that winter maintenance crews could maintain clear roads or pavement temperatures remaining above 32F. Of the 20 events, 8 storms had a significant impact on Interstate mobility. Two of the events that were identified for further analysis in this paper were moderate winter storms that occurred on January 12 and March 30, 2019.

TABLE 1 Total Mile-Hours of Congestion across all Interstates in Indiana on days with maximum wintry precipitation greater than 2.0 mm

Event	**Date**	**Maximum Miles < 45 mph**	**Observable Mobility Impact (>100 miles)**	**Total Mile-Hours of Congestion**
(i)	11/14/2018	84.37	-	627.0
(ii)	11/15/2018	70.63	-	683.7
(iii)	11/19/2018	51.70	-	360.4
(iv)	12/25/2018	27.93	-	345.5
(v)	1/11/2019	78.40	-	351.7
(vi)	1/12/2019	181.55	✓	1943.7
(vii)	1/13/2019	126.54	✓	845.6
(viii)	1/19/2019	695.75	✓	3707.5
(ix)	1/28/2019	171.24	✓	1009.2
(x)	2/6/2019	53.83	-	383.8
(xi)	2/10/2019	174.16	✓	872.0
(xii)	2/12/2019	141.43	✓	1277.0
(xiii)	2/17/2019	83.58	-	487.0
(xiv)	2/19/2019	45.84	-	312.7
(xv)	2/20/2019	155.16	✓	832.4
(xvi)	3/30/2019	231.08	✓	1164.1
(xvii)	4/14/2019	61.19	-	972.5
(xviii)	4/20/2019	46.24	-	641.0
(xix)	4/27/2019	70.48	-	726.8
(xx)	4/28/2019	65.17	-	756.7

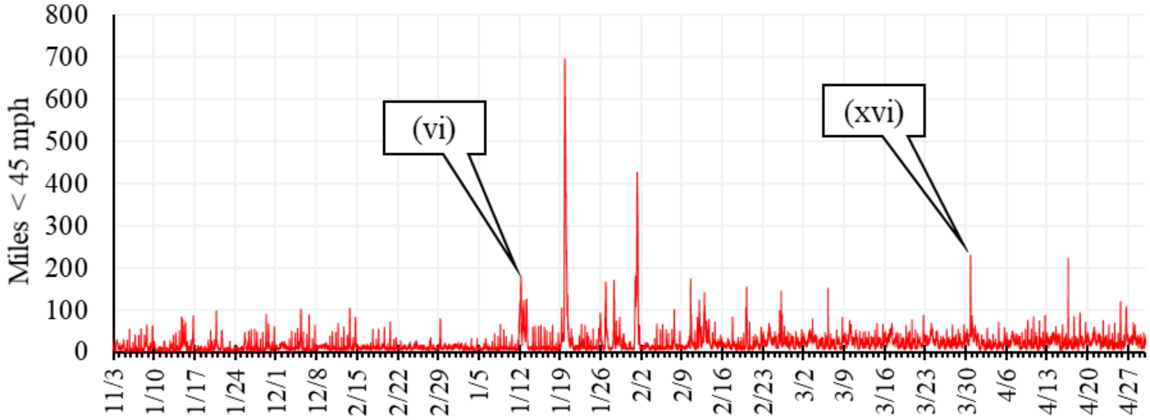
Figure 1a, Figure 1b and Figure 1c are reproductions of the Indiana traffic ticker (Day *et al.*, 2016) on a 6-month and 3-day scale. The Traffic Ticker was developed as a means of helping agencies and maintenance staff get a concise look at how many miles of interstate operated below the performance threshold of 45 mph. In this case, it helps visualize and highlight the statewide impact of a winter storm and observe its differential from congestion on a day with zero to low precipitation. The ticker was developed using commercially available crowdsourced probe vehicle speeds. These speeds are obtained on a minute-by-minute basis from aggregation of individual vehicle speeds determined from timestamped positions of GPS-enabled devices, including fleet telematics and cellular phones. For this study, segment definitions from the data provider are used, each approximately 1 mile in length. Speeds on these segments were later aggregated by 15-minute periods (to reduce minute-by-minute fluctuation of speed) with the median speed in this period used to classify the segment as being congested or not congested for a 15-minute block of time.

Figure 1a depicts miles of Interstate operating below 45 mph across the state of Indiana for the entire winter season with dates ranging from November 3, 2018 to April 30, 2019. The callouts (vi) and (xvi) directly correspond to entries in TABLE 1 for the two aforementioned storms. Figure 1b and Figure 1c specifically highlight miles of congestion across the 6 districts in Indiana for the two snow events that are being sampled in this paper. Congested miles or congested conditions in these graphics and in the text that follows are defined as lengths of interstate roadway that are operating below a speed threshold of 45 miles per hour. This threshold has previously been used in the 2015 Indiana Mobility Report (Brennan *et al.*, 2013; Day *et al.*, 2016). Total Mile-Hours of Congestion for the entries in TABLE 1 were computed using Equation 1 (Mekker, 2018).

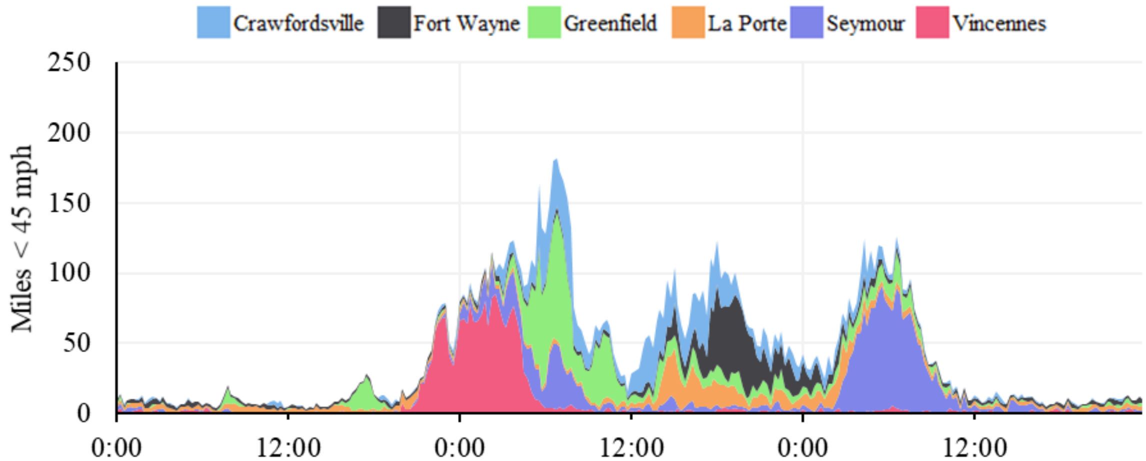
$$\boldsymbol{MH_{<45} = \sum_{i=1}^{n}(L_i \; X \; t_i)} \quad \textbf{(1)}$$

where,
$MH_{<45}$ = total mile-hours of congestion
n = total number of segments in a stretch of interstate
L_i = length of segment i in miles
t_i = duration of time in hours for which segment i was congested

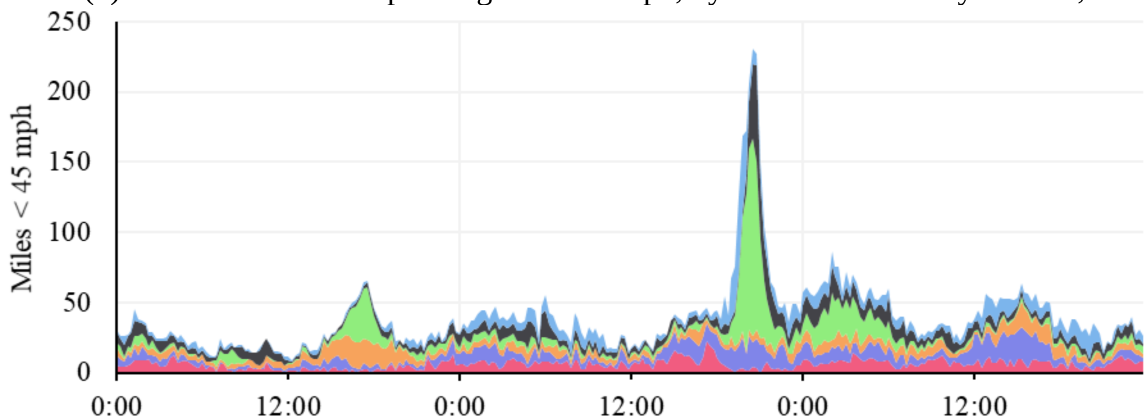
For the winter storm of January 11-13, 2019, it is observed from Figure 1b that peak congestion involved approximately 182 congested miles at 6:30 AM on January 12, 2019. Similarly, peak congestion for the winter storm of March 29-31, 2019 was reached at 8:30 PM on March 30, 2019 with about 231 miles congested across 6 districts. Statewide mile-hours of congestion values reached as high as nearly 1943 mile-hours for January 12 and about 1164 mile-hours of congestion for March 30, 2019.



(a) Miles of Indiana Interstates operating below 45mph for 2018/19 Winter Season



(b) Miles of Interstate operating below 45mph, by district for January 11 – 13, 2019



(c) Miles of Interstate operating below 45mph, by district for January March 29 – 31, 2019

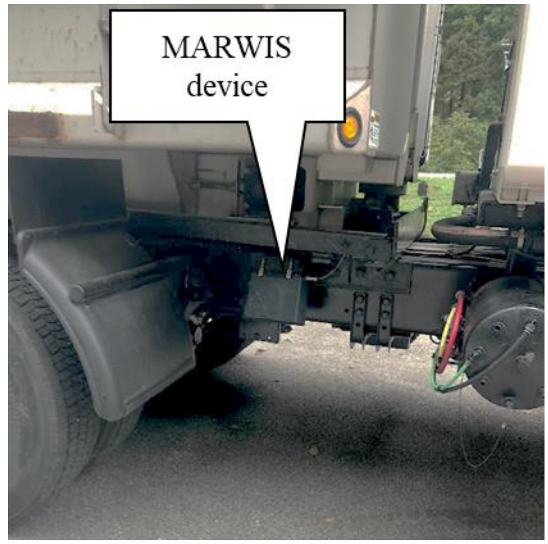
Figure 1 INDOT Interstate Traffic Tickers

ROAD CONDITION AND FLEET LOCATION DATA

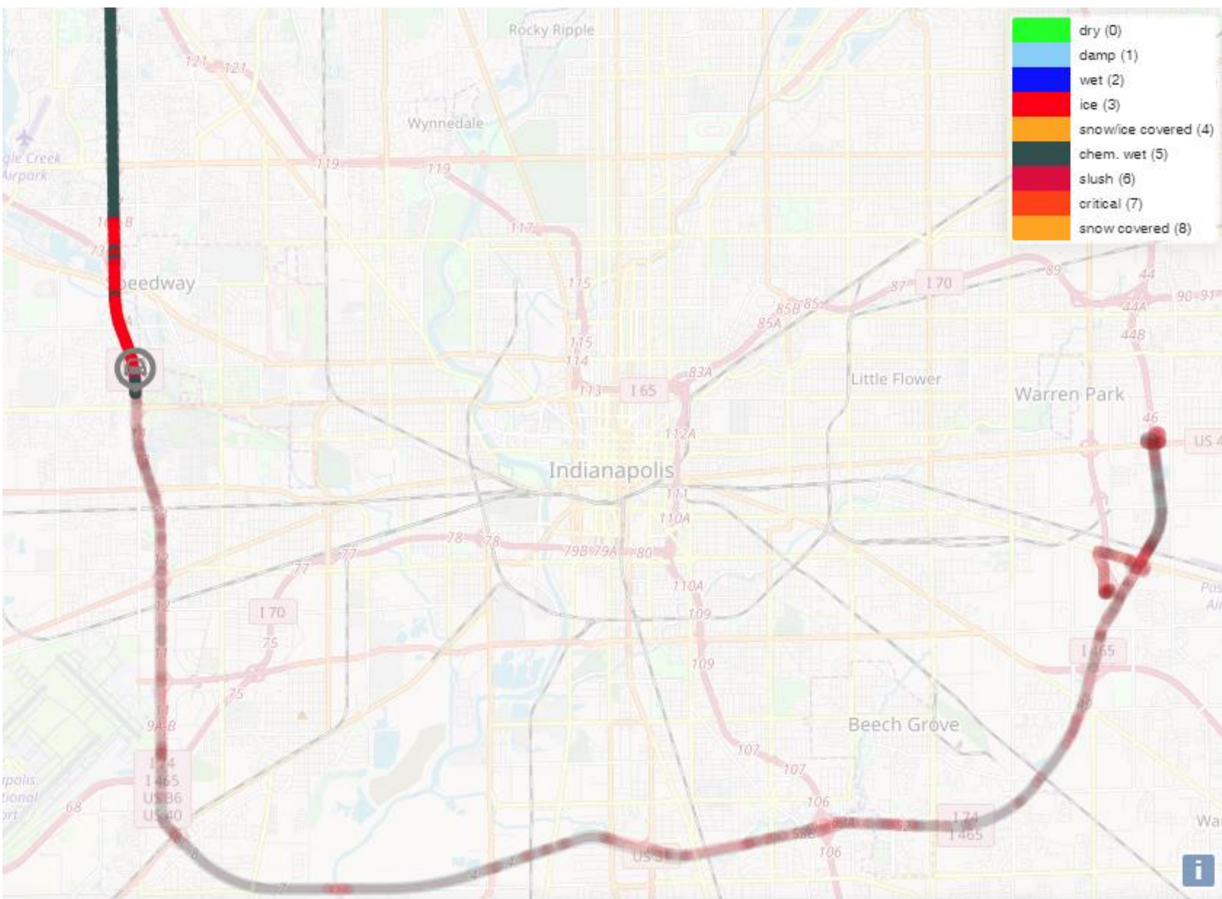
The Indiana Department of Transportation (INDOT) currently operates 14 snow plow trucks outfitted with the Mobile Advanced Road Weather Information System (MARWIS) sensor (Figure 2a and Figure 2b). The sensors collect geo-location data including latitude, longitude and altitude along with speeds and heading. In addition, they estimate road condition from the measured parameters, which includes dew point, surface temperature, friction, ice percent, relative humidity and water film height. The data coming in from these trucks at 5-second frequency constitutes an important data set that is a significant bellwether of pavement friction conditions.

Figure 2c illustrates a sample view of a commercially available dashboard that shows the activity of a snow plow truck with its trajectory color coded by the road condition. Data shows stretches of I-465 being in icy or chemically wet conditions during the winter storm on January 12, 2019. While the two storms that are presented in the sections to follow showed a moderate impact on mobility, they were chosen due to the near complete coverage of MARWIS data available from snow plows on those dates. Additionally, the contrast in the winter weather maintenance strategy for these dates made them ideal candidates for this research.

(a) INDOT Snowplow



(b) Mounted MARWIS sensor



(c) Web dashboard showing truck's location on I-465 and road condition on January 12,2019 from MARWIS

Figure 2 MARWIS sensor and road condition data

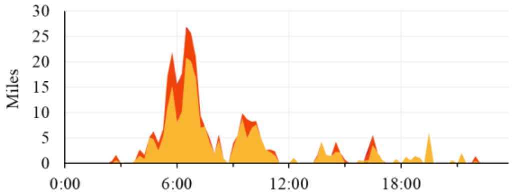
SPEED PROFILE HEAT MAPS DASHBOARD WITH ROAD CONDITIONS

Figure 3a and Figure 3b show traffic ticker views for the 53 mile section of I-465, color coded by speed on 12 January, 2019. The heat maps in Figure 3c and Figure 3d show traffic speeds spatially along the 53 mile section of I-465 in 15 minute intervals throughout the day for both the inner loop (clockwise) and outer loop (counter clockwise). The horizontal black lines on the heat maps indicate mile-marker locations where INDOT TrafficWise cameras have been positioned and real-time images from the same can be obtained when hovering over these camera lines.

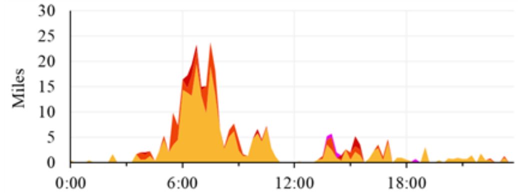
Moderate congestion can clearly be seen in both directions of travel in the stretch of 4 AM through 11 AM. Figure 3a and Figure 3b show vehicle speeds from data obtained through the traffic ticker for the 53-mile stretch of I-465 in both directions of travel and also highlight the same period of congestion as observed on the heat maps in Figure 3c and Figure 3d. The outer loop showed a peak congestion of nearly 27 miles at 6:30 AM, while the inner loop showed roughly 24 congested miles at 7:30 AM.

Figure 3e and Figure 3f shows the same traffic speed heat maps as in Figure 3c and Figure 3d but with an added overlay of geo-location trajectories from the snowplows color coded by the road friction value recorded on the MARWIS sensors from Figure 2c. The friction values are seen to be decreasing as the storm sets in, and after multiple passes of the snowplow trucks the friction eventually improves to an acceptable level by the evening of the same day. INDOT snow plows in this case began pre-treating before the onset of the snow storm in the early hours of January 12. They continued treating and plowing the road all through the storm and only halted when wintry precipitation had completely stopped. Although these heat maps have been created as an after-action tool by superimposing the MARWIS trajectories, they could easily be implemented in real-time as well.

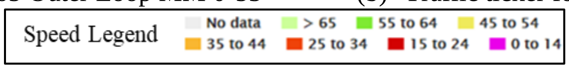
These road condition parameters coupled with traffic speeds present an accurate and localized view of the impact of a winter storm on mobility on a particular stretch of roadway and help agencies in the decision-making process. The data in Figure 3a,Figure 3c and Figure 3e corresponds to the I-465 outer loop while Figure 3b, Figure 3d and Figure 3f correspond to the I-465 inner loop. For example, callout i in Figure 3f, corresponds to a truck travelling from mile marker 0 to mile 20 around 2 AM. This particular trajectory is mostly green, indicating good friction. The subsequent trajectory (Figure 3f, callout ii) occurs around 4 AM and shows a significant amount of red, indicating extremely bad friction and one can see the speed profile heat map shows traffic slowing significantly.

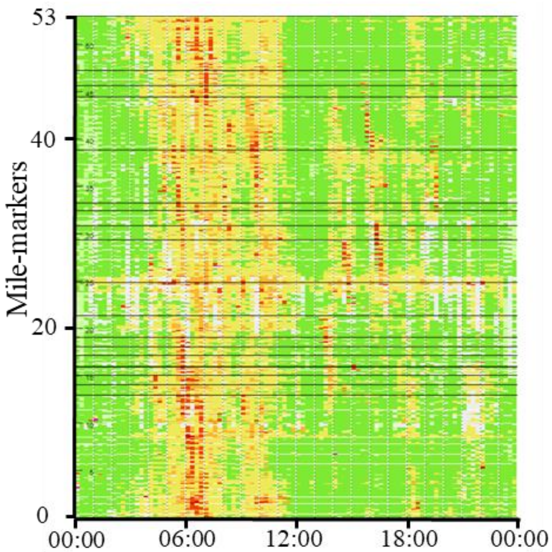


(a) Traffic ticker for I-465 Outer Loop MM 0-53

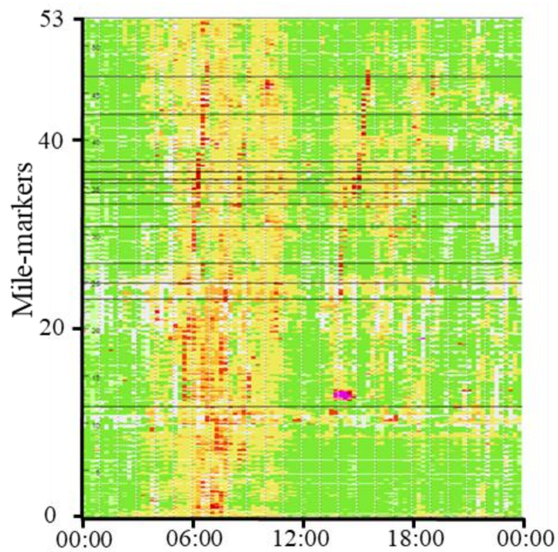


(b) Traffic ticker for I-465 Inner Loop MM 0-53

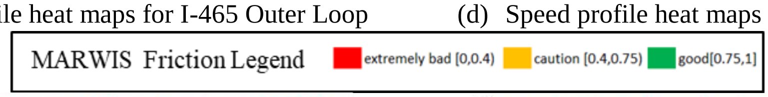


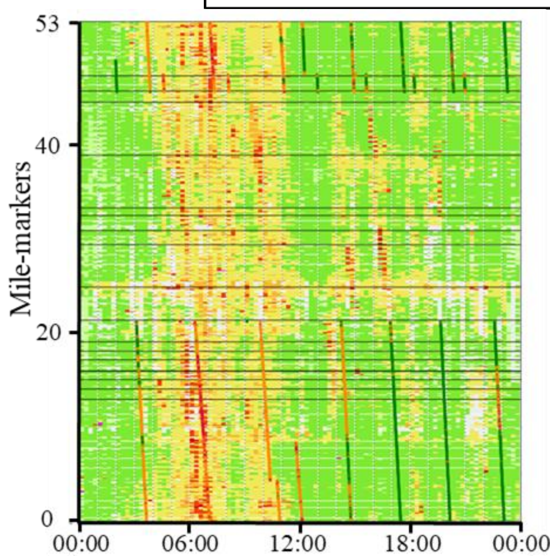


(c) Speed profile heat maps for I-465 Outer Loop

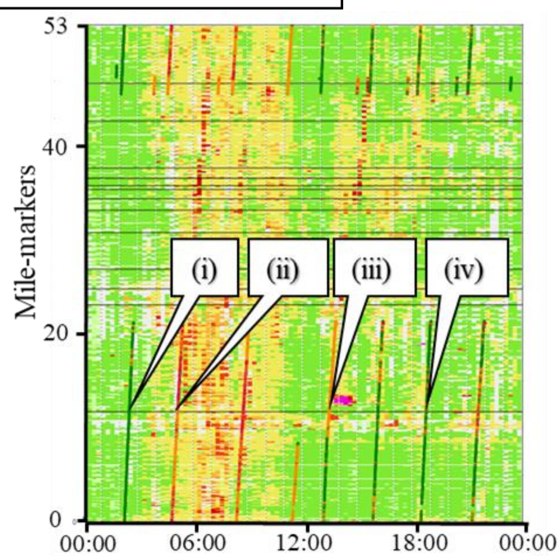


(d) Speed profile heat maps for I-465 Inner Loop





(e) Speed profile heat maps for I-465 Outer Loop with MARWIS friction trajectories



(f) Speed profile heat maps for I-465 Inner Loop with MARWIS friction trajectories

Figure 3 Speed profiles shown by heat maps and traffic ticker, along with overlaid MARWIS trajectories color coded by friction for I-465 MM 0-53 January 12, 2019

Figure 4 shows corresponding traffic camera images for callouts (i), (ii), (iii) and (iv) placed on Figure 3f. This traffic camera is situated at mile marker 11.7 on the I-465 Inner Loop and the images below show a clear progression of friction conditions from the onset of the storm through recovery to normal traffic and uncongested conditions following snowplow activity throughout the day. Starting out with good friction values during the first pass (Figure 4a) around 2:30AM, the friction worsened over the next couple of hours due to low overnight temperatures as well as reduced traffic activity as shown by Figure 4b. After nearly 6 passes, friction improved to an ideal range and Figure 4d illustrates the clear road conditions in support of the same. This shows ideal coverage of the interstate by snow plows resulting in recovery from the storm to ideal road conditions on the very same day in a span of a few hours.

(a) Good friction conditions at 2:16 AM corresponding to callout (i)

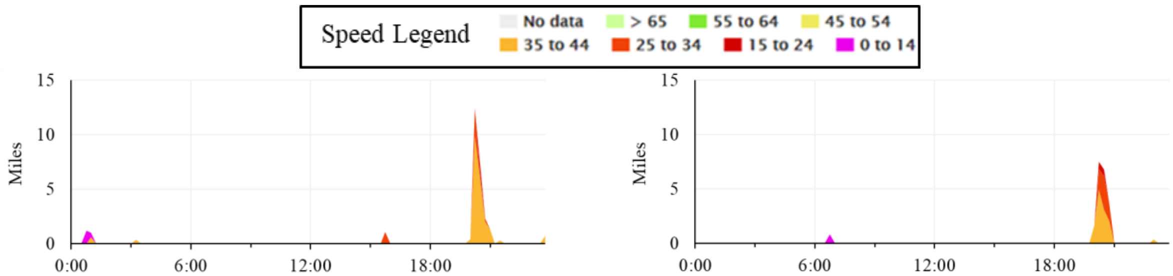
(b) Friction worsens with snow at 5:08 AM corresponding to callout (ii)

(c) Friction improving at 1:22 PM corresponding to callout (iii)

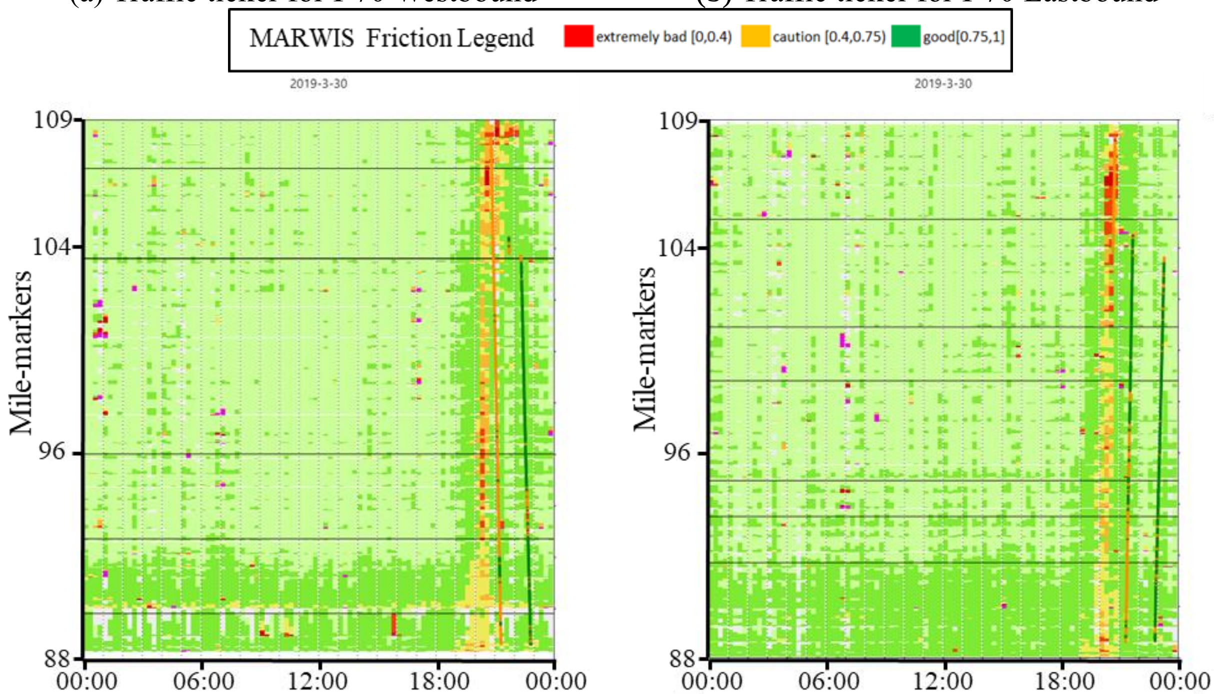
(d) Good friction conditions at 6:44 PM corresponding to callout (iv)

Figure 4 Traffic camera images showing roadway conditions from Figure 3f

Figure 5 shows a similar representation of speed profiles as shown in Figure 3, but for the winter storm of March 30, 2019 on interstate I-70 from mile marker 88 to 109. From the snow plow trajectory overlays it is evident that the fleet was late in catching up to the winter storm on March 30 and only started plowing and applying material when congestion on this stretch of roadway was at its peak value. To understand why the winter operation fleet was deployed after traffic speeds begin to deteriorate, it is important to consider the weather conditions that led to this storm.



(a) Traffic ticker for I-70 Westbound (b) Traffic ticker for I-70 Eastbound



(c) Speed profile heat maps for I-70 WB with MARWIS friction trajectories (d) Speed profile heat maps for I-70 EB with MARWIS friction trajectories

Figure 5 Speed profiles shown by heat maps and traffic ticker, along with overlaid MARWIS trajectories color coded by friction for I-70 MM 88-109 March 30, 2019

INTEGRATION OF WEATHER DATA WITH ROAD CONDITIONS

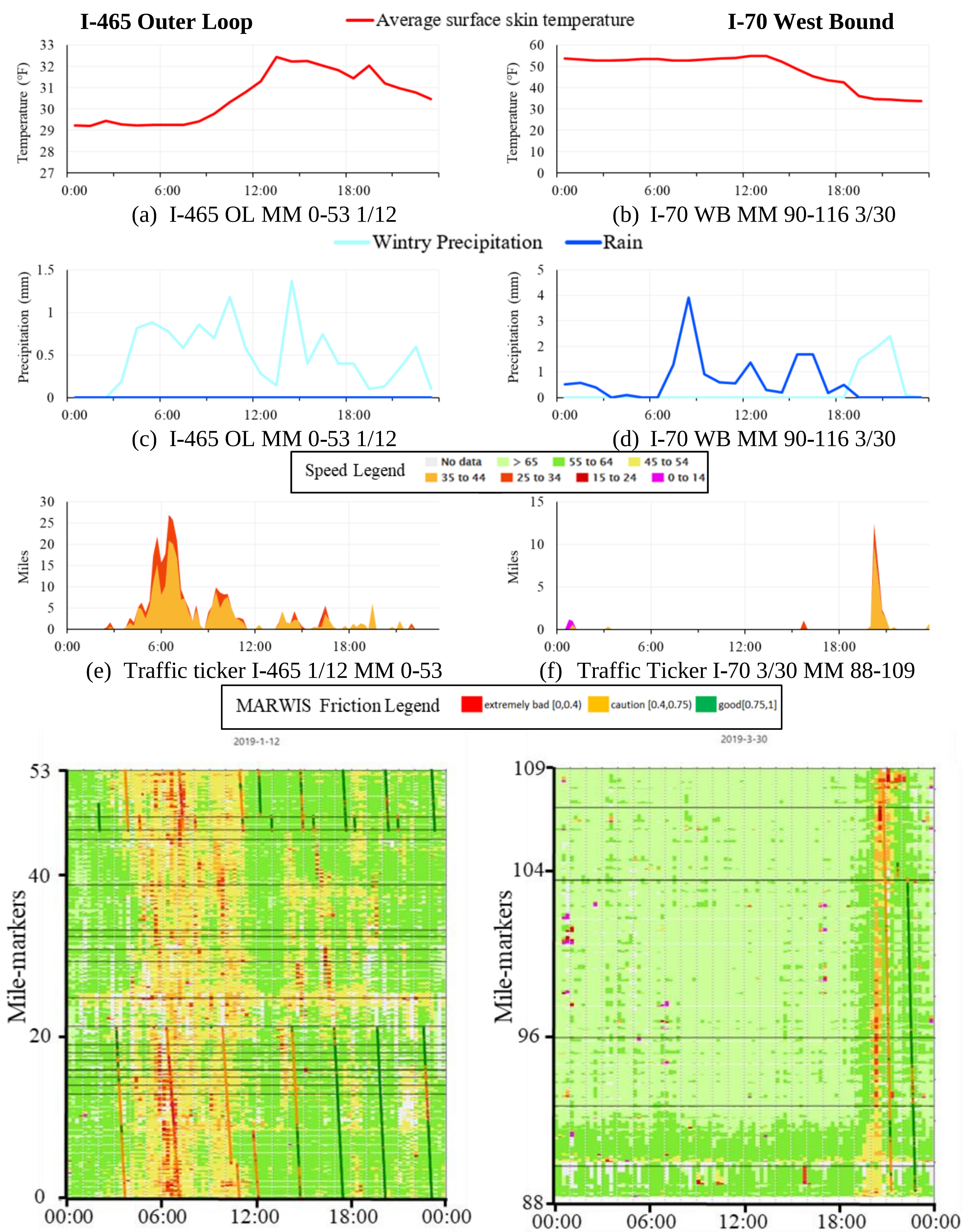
Improvements in weather prediction and forecasting models carry immense value for state agencies who can use these advances for efficient resource allocation, scheduling and maintaining roadways during heavy precipitation events. Studies have found precipitation rate to be one of the most important weather variables to have an effect on road safety (Koetse and Rietveld, 2009). Most studies do tend to indicate a positive relationship between precipitation and frequency of road accidents (Chung *et al.*, 2005).

Figure 6 offers a comprehensive look at traffic and weather data in a suite of dashboards to directly visualize how a sustained precipitation event followed by reduction in temperature impacted the road and traffic conditions. The graphics in Figure 6a, Figure 6c, Figure 6e and Figure 6g pertain to the January 12 storm on I-465 outer loop direction from Figure 3a, Figure 3c and Figure 3e. The plots in Figure 6b,Figure 6d,Figure 6f and Figure 6h correspond to the March 30 storm on I-70 west bound direction from Figure 5a and Figure 5c. Figure 6a, Figure 6b, Figure 6c and Figure 6d were plotted using data obtained from NLDAS sensors near the respective stretches of interstate. Figure 6a and Figure 6b depict the median average surface skin temperature on an hourly fidelity for the two winter storms. Figure 6c and Figure 6d depict the median amount of wintry precipitation in millimeters again on an hourly granularity for these two storms. The precipitation amount has been split into rain and wintry precipitation amounts to exactly pinpoint the onset of each snow storm.

Directly comparing Figure 6c and Figure 6g for the first winter storm, it is observed that the snow plows operated very much in tandem with the winter storm on January 12, 2019 and in fact had begun operating just as soon as wintry precipitation amounts were beginning to rise on I-465. They continued roadway maintenance activity throughout the day until the storm died out and wintry precipitation amounts were declining towards the end of the day, with a subsequent effect seen in better pavement friction values on I-465. Wintry precipitation first began between the hours of 2:00 AM and 3:00 AM on January 12, and the first pass of the snow plow on this route was also in the same time period thus showing good storm coverage by INDOT in this instance.

The same comparison for the March 30 storm shows that while wintry precipitation began between 6:00 PM and 7:00 PM, the snow plows were deployed around the 9:00 PM mark, at a time when wintry precipitation was at its peak value of 2.4 mm. Due to this, congestion had already significantly built up on I-70 as can be seen from Figure 6f and Figure 6h before the plowing and road treatment activity. During the March storm, the elevated temperatures and precipitation would have washed away any pre-treatment and the pavement temperature was not forecast to drop below freezing during the precipitation event. As seen in Figures 6b and Figure 6d, the sudden drop in temperatures resulted in the transition to wintry precipitation from rain. Such events are very difficult to forecast in advance. A more accurate forecast would have provided the opportunity for earlier coverage by the snow plow fleet that could potentially have alleviated some of the congestion that occurred which at its peak was nearly 15 congested miles on I-70 in a 21-mile stretch of road. It was also observed that the traffic ticker plots in Figure 6e and Figure 6f follow the same general trend as the wintry precipitation plots in Figure 6c and Figure 6d thus showing a direct impact of adverse weather conditions resulting in congested stretches of interstate.

Although weather forecasts will never be 100% accurate, dashboards such as these provide a framework for winter operations staff to monitor conditions, perform after action assessment, and provide improved feedback to forecast modeling colleagues.



(a) I-465 OL MM 0-53 1/12

(b) I-70 WB MM 90-116 3/30

(c) I-465 OL MM 0-53 1/12

(d) I-70 WB MM 90-116 3/30

(e) Traffic ticker I-465 1/12 MM 0-53

(f) Traffic Ticker I-70 3/30 MM 88-109

(g) MARWIS trajectories on heat maps for I-465 OL 1/12 MM 0-53

(h) MARWIS trajectories on heat maps for I-70 WB 3/30 MM 88-109

Figure 6 Traffic and Weather Data for 2 Winter Storms showing inflection points

SUMMARY

This study began with the identification of twenty winter storm events from November 2018 to April 2019 using NLDAS precipitation data. These storms were classified as being of observable mobility impact if the peak congested miles on the event days were over 100 miles (TABLE 1). Two storms with moderate observable impact, with a marked difference in statewide impact, as well as snow plow coverage were then explored in detail. The two cases highlighted situations wherein snow plows covered and treated roadways for a storm well in advance (Figure 3) as well as when snow plows lagged the storm by a couple hours (Figure 5) leading to delayed maintenance activity. A suite of dashboards was presented that compiled traffic, road condition and weather data all into one providing a unique solution for agencies towards real-time tracking for winter weather operations (Figure 6).

These web dashboards can clearly show the impact and efficiency of winter weather maintenance activity before, during and after a storm and can also prove as a medium for tracking an agency's snow plow fleet in real-time with the progression of a storm. Snow plows can provide data from on-board controllers (plowing and salting) as well as externally fitted mobile road weather devices. However, telemetry will be an important factor moving forward, as these data sets will help agencies and stakeholders to understand the changing on-the-ground conditions in real-time and optimize winter weather maintenance strategies. Less than ideal friction conditions can be detected from enhanced probe vehicle data including brake pressure, anti-lock brake (ABS) activation or traction control intervention and can be validated by the ground-truth MARWIS readings. With OEMs starting to capture these enhanced probe data (Li *et al.*, 2019), agencies and DOTs will have a complete picture of the road conditions without having to depend solely on weather forecast models.

Moving forward, these dashboards can also be used to quantify a number of performance metrics. The recovery from event performance metric can be computed with the help of the snow plow trajectories as they track pavement friction values in real-time and can exactly pinpoint the beginning and ending of an event based on the pavement friction value dipping below a certain pre-defined number. Safety is another performance metric that can be tracked using these dashboards, as linking a crash database to highlight crash events on the heat maps can be easily done, or speed profile minimums could be set that indicate a temporary road closure due to a crash. Apart from pavement friction, MARWIS devices offer a number of parameters in real-time, each of which could be used as a performance measure to gauge whether a stretch of roadway has recovered from a winter event.

Lastly, multi-variate Autoregressive Integrated Moving Average (ARIMA) forecasting models could be developed based on the three data sets observed in this paper – traffic (speeds), weather (surface skin temperature and precipitation amount) and MARWIS (trajectories, weather data) to be able to forecast traffic conditions on a winter event day and how they would be impacted by precipitation using historical data. This can prove to be an effective weather prediction tool for agencies which will eventually help them better allocate and schedule their resources in advance of a snow event leading to an overall improvement in winter weather mobility.

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AUTHOR CONTRIBUTION
The authors confirm contribution to the paper as follows: study conception and design: Darcy Bullock, Jeffrey Brooks, Howell Li; data collection: Jairaj Desai, Mingmin Liu, Woosung Kim; analysis and interpretation of results: Jairaj Desai, Woosung Kim, Jijo Mathew, Darcy Bullock; draft manuscript preparation: Jairaj Desai, Jijo Mathew, Howell Li, Darcy Bullock, Jeffrey Brooks. All authors reviewed the results and approved the final version of the manuscript.

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