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Leveraging Telematics for Winter Operations Performance Measures and Tactical Adjustment

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Abstract

The Indiana Department of Transportation (INDOT) maintains 29,000 lane miles of roadway and operates a fleet of nearly 1100 snowplows and spends upwards of $60 million annually on winter maintenance operations. Since winter weather varies considerably, allocation of snow removal and deicing resources are highly decentralized to facilitate agile response. Historically, real-time two-way radio communication with drivers has been the primary monitoring system, but with 6 districts, 29 subdistricts, and over one hundred units it does not scale well for systematic data collection. Emerging technology such as real-time truck telematics, hi-resolution NOAA data, dash camera imagery, and crowdsourced traffic speeds can now be fused into dashboards. These real-time dashboards can be used for systematic monitoring and allocation of resources during critical weather events. This paper reports on dashboards used during the 2020-2021 winter season derived from that data. Nearly 13 million location records and 11 million dash camera images were collected from telematics onboard 1105 trucks. Peak impact of nearly 1570 congested miles and 610 trucks deployed was observed for a winter storm on February 15th, 2021 chosen for further analysis. In addition to tactical adjustments of resources during storms, this system-wide collection of resources allows agencies to monitor multiple seasons and make long-term strategic asset allocation decisions. Also, from a public information perspective, these resources were found to be very useful to agencies that interface with the media (and social media) during large storms to provide real-time visual updates on conditions throughout the state from pre-treatment, through cleanup.

Keywords

Connected Vehicle Data, Telematics, Winter Operations, Snowplows, Weather

1. Introduction

Winter weather maintenance operations are estimated to cost approximately $2.3 billion annually in the United States thus reinforcing the critical need for state agencies to be able to easily and effectively track performance measures for financial accountability [1]. There are over 1.2 million weather related crashes annually in the United States [2], and an estimated 24 percent of these occur on snowy, slushy, or icy pavement conditions [3]. Reducing the overall impact of winter weather on mobility as well as driver safety is an important focus for transportation agencies [4] [5]. Previous studies have shown that snowy or slushy pavement reduces traffic speeds between 30 to 40 percent [6]. While state Departments of Transportation (DOT's) utilize approximately 20 percent of their maintenance budget on winter weather operations, often agencies do not have quantifiable mobility and safety impacts of the storm [2]. The adversity of winter weather introduces an additional challenge to develop performance measures due to a variety of road types, storms, and traffic conditions that may vary from event to event. Time to recovery from event, travel time reliability during an event, system efficiency, and level of customer/motorist satisfaction are some of the most commonly used performance measures [7].

2. Performance Measures

Performance metrics provide agencies with measures to evaluate the amount of effort required when planning for a winter event, which in turn helps them better manage costs. Pavement condition, storm impact and severity, frequency of accidents, visibility, reduction in traffic speeds and travel time delays are some of the winter operations performance metrics that have been proposed by researchers in the past [8] [9] [10] [11]. However, tracking these performance measures in real-time may be difficult without a centralized repository of traffic speeds, weather data and road conditions. The winter operations field continues to gravitate towards performance metrics that utilize traffic, weather and road condition data sets for a more holistic view of storm impacts. This information can provide a comprehensive real-time view of snow and ice control operations during a storm.

3. Automatic Vehicle Location Systems

Automatic Vehicle Location (AVL) systems were first implemented in public transportation for fleet management. As the technology evolved, the systems have been deployed on commercial fleets, emergency and security vehicles, and continue to be implemented on different agency vehicles [12]. AVL systems have the ability to enable stakeholders to gain real-time access to operational data thus helping them in the planning and resource allocation process. A precursor study of a limited fleet of Indiana Department of Transportation (INDOT) snowplows equipped with onboard MARWIS sensors broadcasting road condition data allowed the agency to track pavement friction values for a real-time look at travel conditions during a snowstorm [13]. To enhance and better understand real-time conditions of their roadway network INDOT equipped their nearly 1100 strong snowplow fleet with telematics devices and utilized the information obtained from them to assist in data-driven winter operations decision-making. Tracking as well as quantifying the performance of snow and ice control operations is a significant deliverable for stakeholders. This in turn has the potential to aid agencies and contractors as they strive for improved customer satisfaction and reducing systemwide mobility as well as safety impacts.

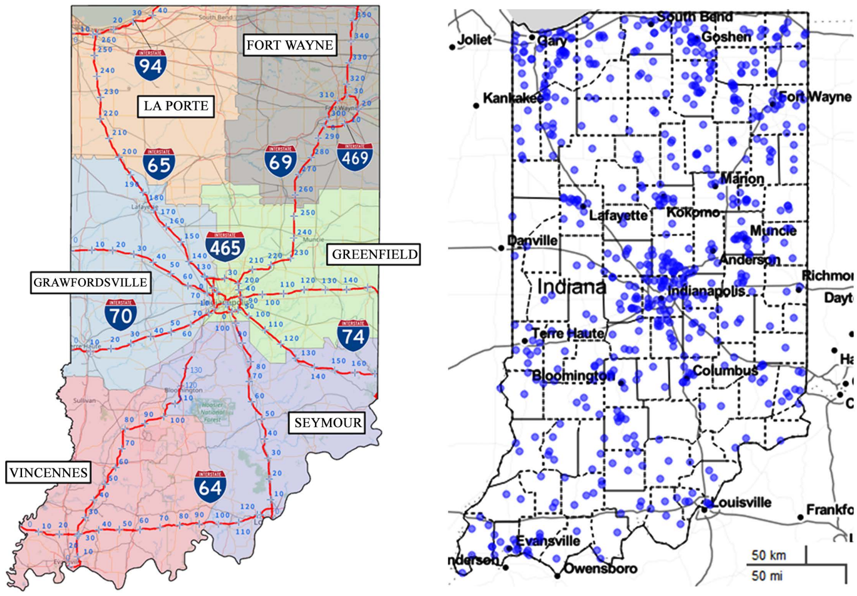
4. Objective and Paper Structure

The objective of this paper is to describe the integration of NOAA and NSSL weather data, connected vehicle speed data, and winter operation fleet telematics data to develop performance measure dashboards. The paper is organized along the following objectives:

- Introduce the concept of using connected vehicle speeds to characterize winter roadway conditions and verify the same using adjacent roadside cameras.
- Demonstrate how those connected vehicle speeds can be integrated into a system wide map showing roadways speeds, weather conditions, and location of statewide fleet.
- Demonstrate how connected vehicle data and winter operation fleet vehicle telematics can be fused into district level summaries for system level monitoring.
- Demonstrate how connected vehicle data, weather conditions and winter operations fleet telematics data can be fused to develop detailed operational dashboards for Interstates corridors and individual snow plow routes.
- Demonstrate how the combination of the above reports can be used to develop after action reports that can be used to engage diverse stakeholders and provide agile adjustment of winter operation strategies.

5. Study Location

INDOT divides its operations in Indiana over six regions termed districts as shown in **Figure 1(a)**, namely Crawfordsville, Fort Wayne, Greenfield, La Porte, Seymour and Vincennes. The analysis in the sections to follow is generally grouped by these regions. Additionally, access to weather data from nearly 590 unique Global Historical Climatology Network (GHCN) stations is available around the state as depicted by each of the stations shown in blue in **Figure 1(b)**.



(a) (b)

Figure 1. Indiana interstates, district boundaries and weather stations. (a) Indiana interstate system and INDOT districts; (b) 590 Unique Global Historical Climatology Network (GHCN) stations across Indiana.

6. Data Description

6.1. Telematics Data

Installation of telematics devices was initiated fleetwide in INDOT snowplows in the fall of 2020. Figure 2 shows a sample of the installed telematics equipment on a snowplow truck. Callout *i* represents the cellular antenna, callout *ii* the dash camera on the vehicle, callout *iii* the AVL interface tablet and callout *iv* shows the AVL processor which is located behind the passenger seat. The AVL system provides data at 60-second frequency and includes vehicle geolocation, controller spreader rates, salt totals, dash camera images, and vehicle data including odometer readings, engine hours, fuel usage and several other instrument cluster attributes. Nearly 13 million location records and 11 million dash camera images were collected from the telematics onboard 1105 INDOT snowplow trucks. The AVL interface tablet shows the salt application, dash camera, vehicle location, and the current local radar to the operator. Additionally, the operator could provide current roadway conditions including visibility, precipitation type, wind speed, and current accumulation status, all through the tablet interface thus giving an agency the ability to maintain a unified database of ground conditions as a storm progresses without dependence on traditional two-way radio communication.

A statewide map of sample snowplow bread crumb trails plotted using snowplow locations obtained from onboard telematics is shown in Figure 3 which illustrates the broad spatial coverage of INDOT's snowplow fleet on interstates and state routes. Major locations have been called out on the map for geographical context.

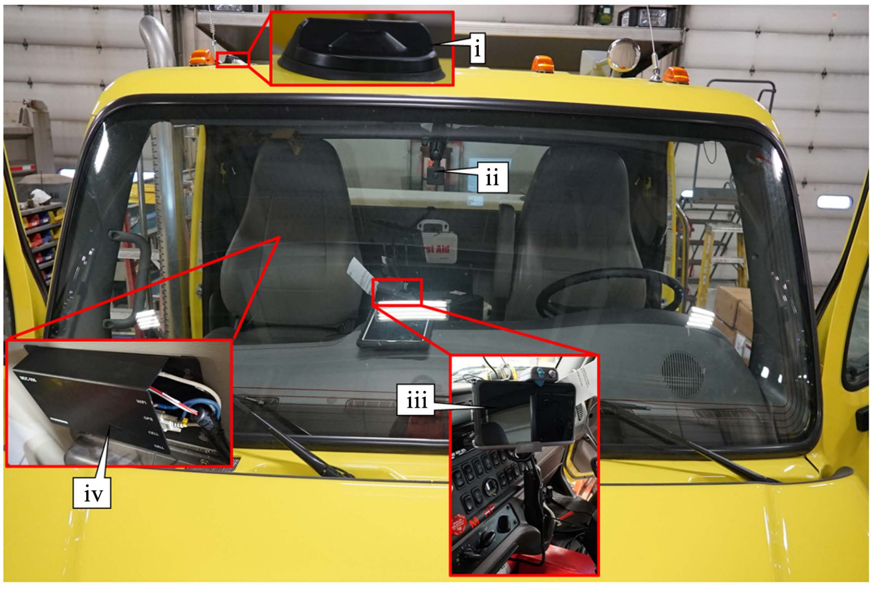


Figure 2. Telematics Equipment onboard INDOT snowplow truck.

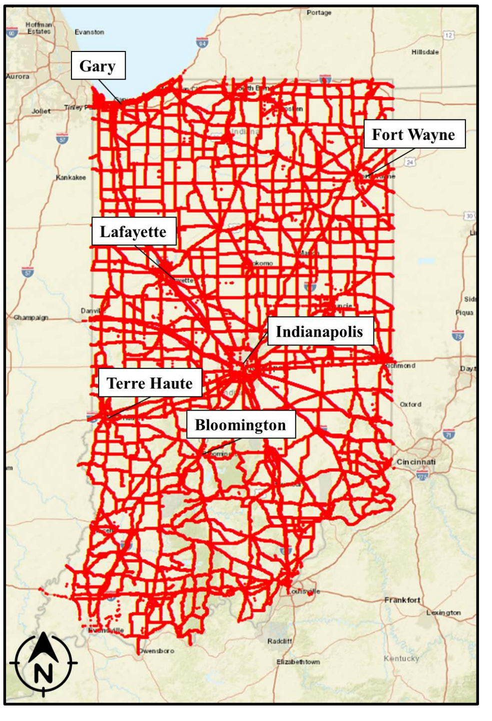


Figure 3. Statewide coverage of snowplow fleet.

6.2. Connected Vehicle Data

Connected vehicle speed data is obtained at 1-minute frequency for roughly every 0.1-mile linear referenced segment on Indiana Interstates from a third-party crowd sourced data provider.

6.3. Weather Data

Doppler reflectivity values are obtained from the National Severe Storms Laboratory's (NSSL) multi-radar multi-sensor system (MRMS) every 2 minutes. Doppler reflectivity values are colorized by their intensity as well as the type of precipitation. A red, green and yellow color scale is used for rain events while a blue scale is used for snow events. An example of the MRMS data is shown by the visualizations depicting the onset of the snowstorm in **Figure 5**.

7. Using Connected Vehicle Speeds to Characterize Winter Roadway Conditions with ITS Cameras

Using roadside Intelligent Transportation System (ITS) cameras and connected vehicle speeds, an integrated view of winter roadway conditions can be obtained. An example of the same is shown in **Figure 4**. A representative image of a roadside ITS camera mounted on a tower can be seen in **Figure 4(a)**.

Spatiotemporal heatmaps using connected vehicle data were developed to easily visualize vehicle speeds by linear referenced 0.1-mile segments on interstate roadways. The concept of these heatmaps has been extensively used in past research to visualize congested conditions [13] [14] [15]. The horizontal axis on the speed profile heatmaps represents time of day while the vertical axis represents mile marker location along the interstate. For the interstate 465 (I-465) beltway around Indianapolis, a 53-mile stretch is shown for both directions of travel, Inner Loop (IL) and Outer Loop (OL) in **Figure 4(b)**.

Callouts numbered ii through vii on the I-465 speed profile heatmap indicate instances at which ITS camera images have been obtained for the inner loop direction of travel on February 15th and 16th, 2021. They have been shown individually in **Figure 4(c)** through h along with a white arrowhead pointing to the direction of travel. **Figure 4(c)**, **Figure 4(d)** and **Figure 4(e)** show nearly clear roadway conditions preceding the winter storm, followed by snowy conditions as the storm encompasses the roadway in f ang g, followed by clear conditions once again in h once the storm has abated. The ITS camera utilized for the above imagery is situated in the vicinity of mile marker 3.2 on I-465.

8. Integrating Connected Vehicle Speeds, Weather Data and Location of Snowplow Fleet on System Wide Map

Weather data obtained from the National Severe Storms Laboratory's (NSSL) multi-radar multi-sensor system (MRMS) every 2 minutes provides accurate depictions of high-impact weather events such as snowstorms by combining multiple data streams. **Figure 5** shows an integrated map view of this weather data (doppler reflectivity), coupled with interstate traffic speeds as well as snowplow truck locations indicated by solid blue circles. This view of road conditions presents a unified look at interstate mobility with respect to the deployment status of the snowplow fleet as well as prevailing weather conditions. This view is also valuable in advance of the storm to visualize pre-treatment activities.

The dashboard visualizations that are shown in **Figures 5(a)-(d)** cover a nearly 19-hour period beginning 8:30 AM on Sunday February 14 and ending 3:50 AM

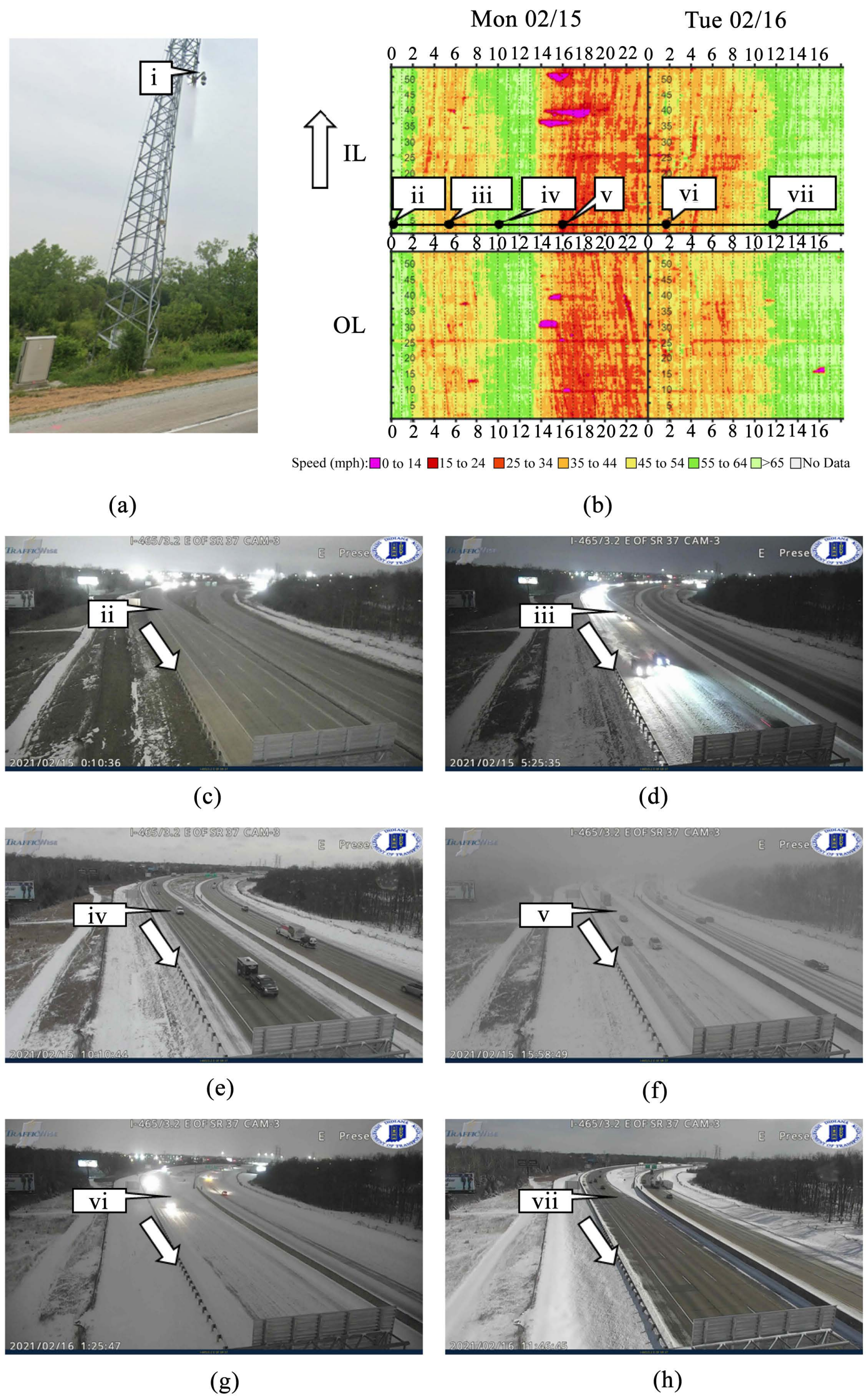


Figure 4. Feb 14-Feb 16, 2021 winter storm, I-465 speed profile Heatmaps and images. (a) Interstate camera tower; (b) I-465 Speed Profile Heatmap; (c) Feb 15th, 12:10 AM; (d) Feb 15th, 5:25 AM; (e) Feb 15th, 10:10 AM; (f) Feb 15th, 3:58 PM; (g) Feb 16th, 1:25 AM; (h) Feb 16th, 11:46 AM.

on the morning of Monday February 15, 2021. These visualizations clearly show the progression of the winter storm as well as how snowplow deployment ramps up as the storm gradually begins to engulf the state. While around 73 trucks were seen active at 8:30 AM on February 14, deployment quickly ramped up to 456

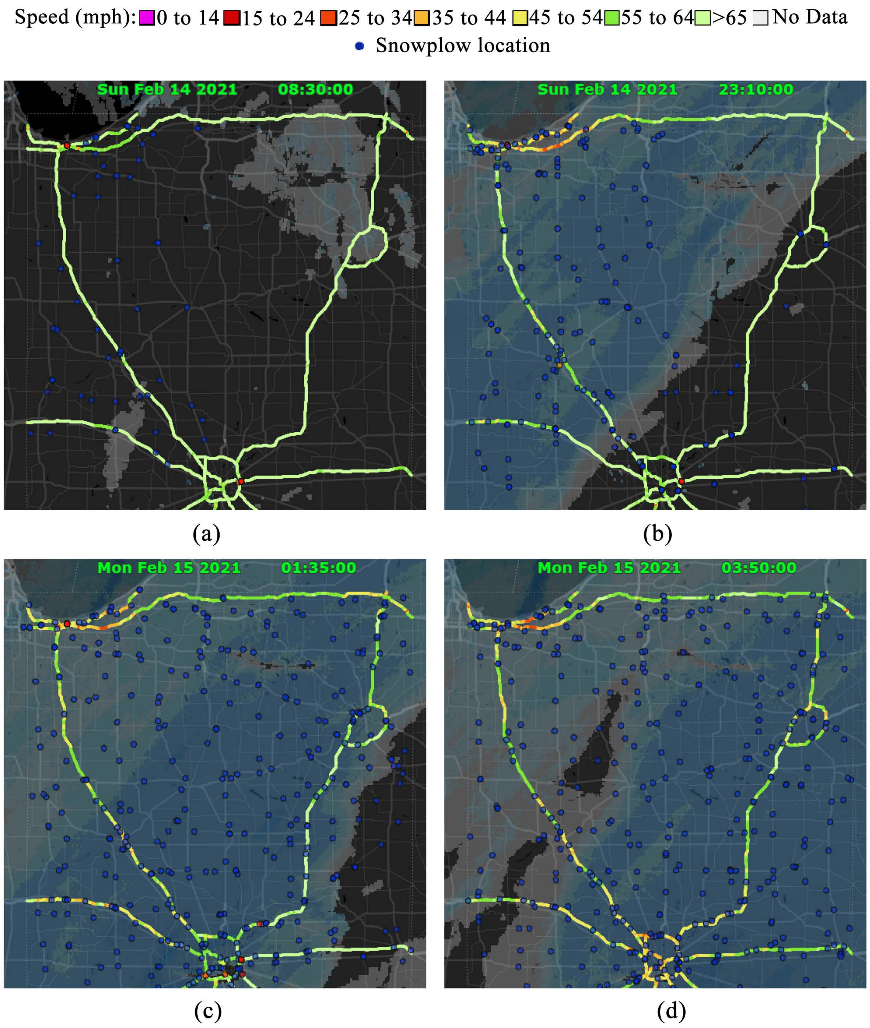


Figure 5. Snowplow Fleet deployment status for Feb 14-16, 2021 winter storm. (a) 8:30 AM, Sun Feb 14, 2021; (b) 11:10 PM, Sun Feb 14, 2021; (c) 1:35 AM, Mon Feb 15, 2021; (d) 3:50 AM, Mon Feb 15, 2021.

trucks statewide by 11:10 PM, 624 trucks by 1:35 AM on the morning of February 15. This peak deployment of snowplow trucks was sustained for an extended period of time.

9. Integrated District-Level Summaries for System Wide Monitoring

Utilizing daily snowfall totals from the NOAA GHCN stations around the state of Indiana, a bar and line representation of the maximum daily snowfall and mean daily snowfall values (across all stations in the state) was created and has been shown in Figure 6(a). Indiana observed non-zero maximum snowfall on at least 76 days out of the 181 days in the analysis period. Among them, the winter storms of February 15 and February 1, 2021 stand out as those with the two highest maximum and mean daily snowfall values for the entire winter season of November 2020 to April 2021 pointed to by callout i on Figure 6(a).

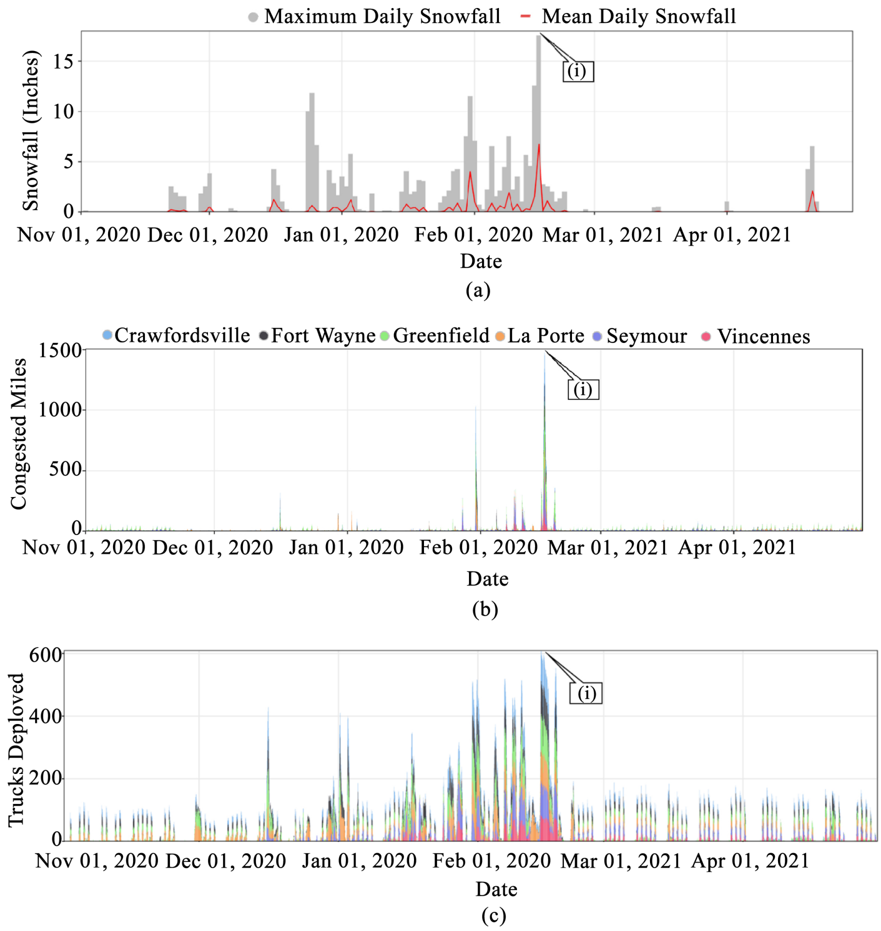


Figure 6. November 1, 2020-April 30, 2021 winter season. (a) Maximum and Mean Daily Snowfall Recorded in Indiana across GHCN stations; (b) Interstate Miles Operating Below 45 mph by District; (c) Snowplow Fleet Deployment Counts by Hour and District.

Subsequently a traffic ticker visualization (nominally a stacked area representation) of congested miles of interstate roadway categorized by the 6 INDOT districts was created for the entire winter season and has been illustrated in **Figure 6(b)**. Callout i on the same points to maximum congested miles that were observed statewide during the course of the February 15 winter storm. Congested miles are defined as miles of interstate roadway operating below 45 miles per hour, a threshold defined in existing literature and extensively used in past studies [5].

An additional visualization was created in **Figure 6(c)** that depicts hourly snowplow deployment counts over the course of the winter season with multiple visible peaks in the December 2020 to February 2021 period corresponding to major storms that demanded snowplow callouts. Callout i on the same similarly points to peak deployment of snowplows coinciding with the February 15 storm.

The above visualizations together provide stakeholders with district level summaries for system wide monitoring of weather, congestion and fleet deployment, all at once. The winter storm for the period of February 14-16, 2021 was thus picked for detailed analysis in the sections that follow.

10. Operational Dashboards for Interstate Corridors and Individual Snow Routes

Using the connected vehicle data earlier described, an interstate traffic ticker was created as a statewide visualization of congested miles of traffic in each district for the 3-day storm period. Peak congestion of about 1571 miles was observed at about 9:30 PM on February 15, 2021. A traffic ticker visualization for the February 14-16, 2021 winter storm has been shown in **Figure 7(a)**.

Geolocations obtained from each active snowplow truck operating above 10 mph (to discount trucks idling but not treating roadways) were cross-referenced with INDOT district boundaries to create an hourly count of active snowplow trucks over the period of this winter storm and a stacked bar representation of the same has been shown in **Figure 7(b)**. Peak deployment of 610 snowplow trucks was observed for the hour of 2 AM-3 AM on February 15, 2021 (**Figure 6(c)**, callout i). One can also see the baseline fleet usage during non-winter operations periods in late March and April in **Figure 6(c)**.

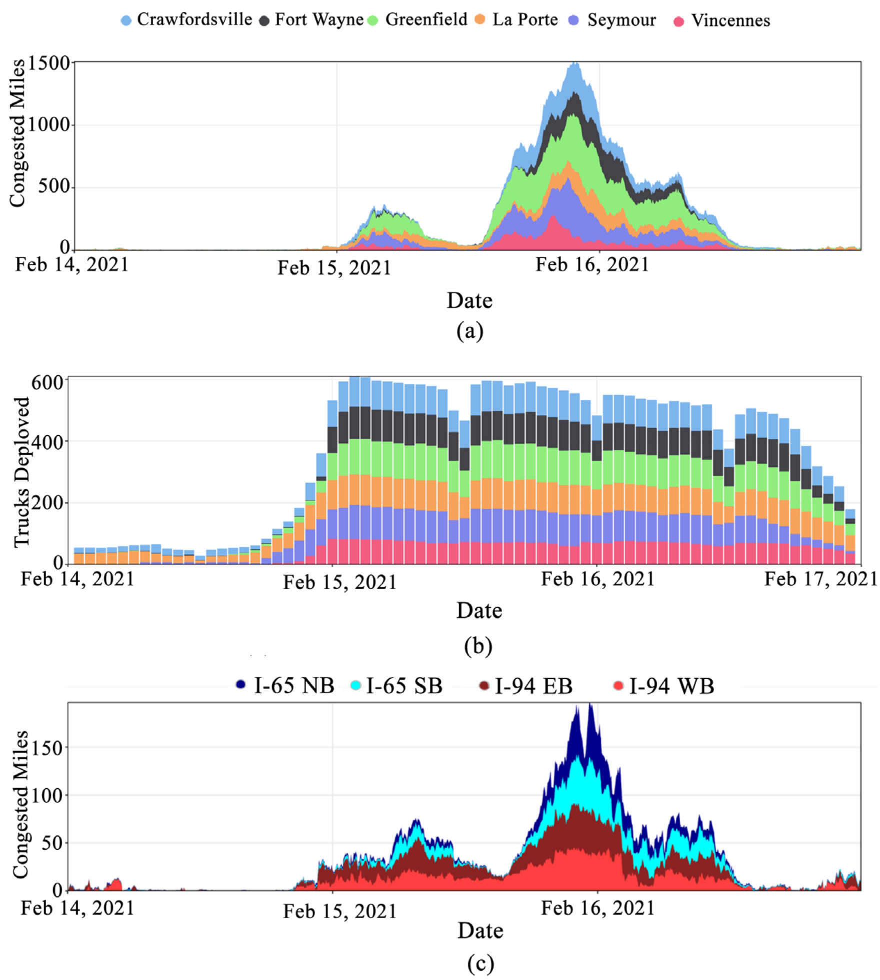


Figure 7. Feb 14-Feb 16, 2021 winter storm. (a) Impacted Miles of Interstate by District; (b) Hourly Truck Deployment Counts by District; (c) Impacted Miles by Interstate Route in La Porte District.

Using a similar methodology as was used to develop the district wise traffic ticker, congestion in each district can further be broken down into its component interstate routes as well as by directions of travel. Thus, the La Porte district was chosen for further analysis and an interstate route ticker was developed for the two routes in the district, the north-south route I-65 and the east-west route I-94, shown in Figure 7(c). From the ticker, it can be seen that route I-94 saw peak congestion of nearly 100 miles on the night of February 15. As I-94 is only a 46-mile long route, the congested miles approaching 100 would indicate that a majority of the interstate was operating under 45 mph. This led to us choosing this route for an in-depth analysis of roadway conditions in the sections that follow.

11. Integrating Connected Vehicle Speeds, Snowplow Locations and Dash Camera Images into Operational Dashboards

Operational dashboards were created that integrate connected vehicle speeds, snowplow locations and snowplow dash camera images all into one unified interface. A sample view from such a dashboard has been illustrated in Figure 8 for interstate 94 (I-94) in the eastbound direction of travel (EB) for the three-day winter storm period of February 14-16, 2021. Figure 8(a) shows a bar plot representation of the hourly snowplow deployment counts for this roadway.

Using the available snowplow geolocations from onboard telematics devices, each snowplow waypoint could be linearly referenced to a 0.1-mile section of roadway and a snowplow's entire trajectory could thus be plotted. Figure 8(b) shows such a representation where spatiotemporal speed profile heatmaps are overlaid with snowplow trajectories (indicated by blue solid lines). Each particular instant where a dash camera image was captured by the snowplow is indicated by a solid grey circle layer on top of the snowplow trajectory. Owing to multiple snowplows covering this stretch of road over the course of the storm, obtaining a longitudinal slice of roadway conditions at the same location but at different times is possible. Callouts c through h (corresponding to Figures 8(c)-(h)) on Figure 8(b) indicate time instances from which snowplow dash camera images were sampled to obtain a brief view of the storm's progression over the three-day period. In order, Figures 8(c)-(h) indicate clear conditions preceding the storm (10:43 AM, Feb 14), wintry weather on the first night of the storm (4:28 AM, 8:04 AM and 10:49 AM, Feb 15) and post-storm roadway maintenance and snow removal activities (3:14 PM, Feb 16).

12. Agile Adjustment of Winter Operations Strategies

Figure 9 shows speed profile heatmaps and snowplow coverage with telematics locations and dash camera imagery for February 14-16, 2021 for I-94 in the westbound (WB) direction of travel.

Figure 9(a) shows hourly counts of snowplow truck deployments on the I-94 corridor in the westbound direction of travel. An accompanying speed profile

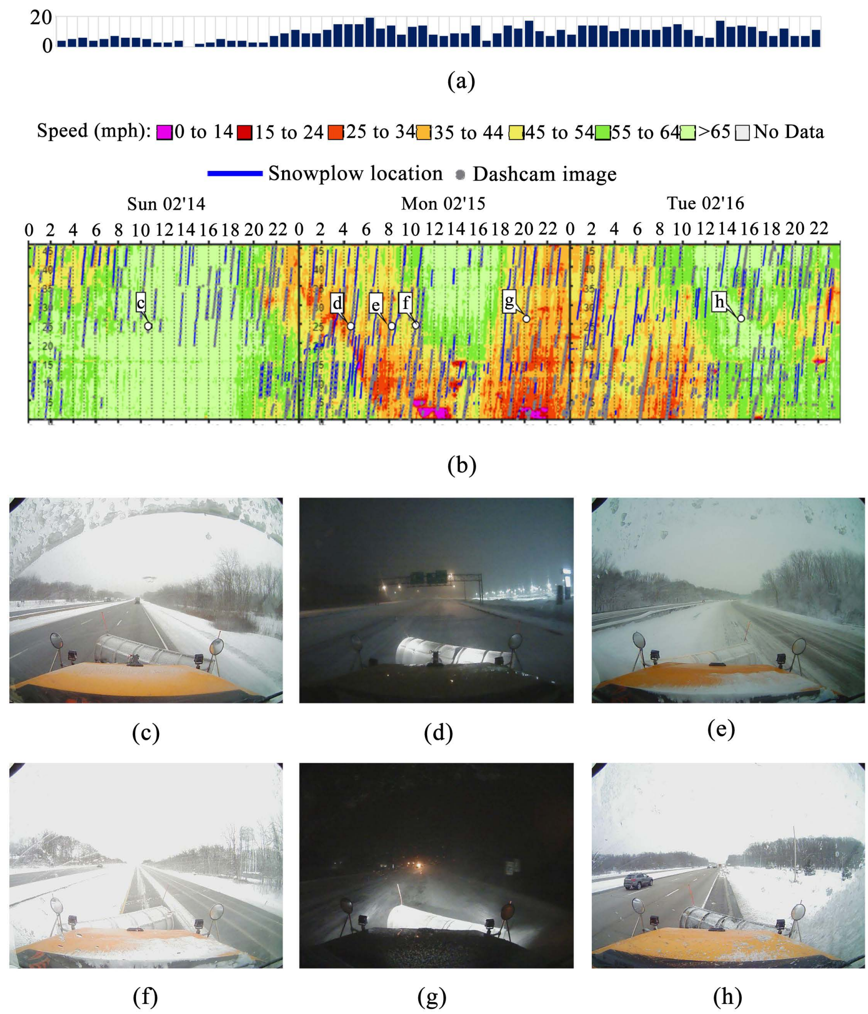
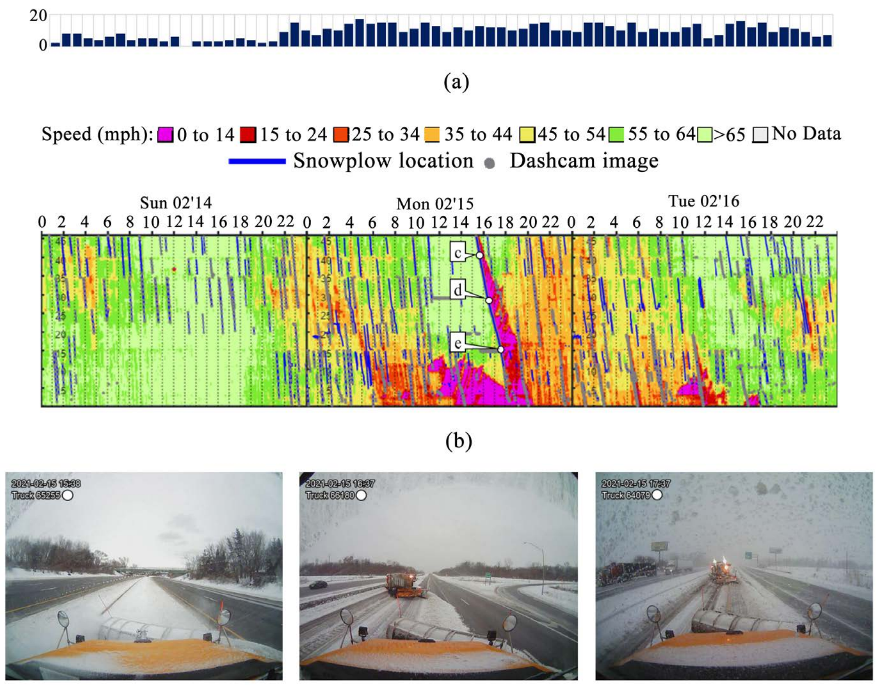


Figure 8. Feb 14-Feb 16, 2021 winter storm, I-94 EB Speed Profile Heatmaps and Snowplow Coverage. (a) I-94 EB Hourly Snowplow Deployment Counts; (b) I-94 EB Speed Profile Heatmap with Overlaid Snowplow Trajectories; (c) Feb 14, 10:43 AM; (d) Feb 15, 4:28 AM; (e) Feb 15, 8:04 AM; (f) Feb 15, 10:49 AM; (g) Feb 15, 8:11 PM; (h) Feb 16, 3:14 PM.

heatmap for I-94 WB for the three-day period spanning February 14-16, 2021 is depicted in Figure 9(b).

While a longitudinal slice of roadway conditions was captured by the snowplow presence in Figure 8, a lateral slice of roadway conditions is captured by the heatmaps and dash camera images in Figure 9. Figures 9(b)-(e) capture a tandem plowing operation (windrowing) involving three snowplow trucks traversing the entire length of I-94 WB from MM 46 to MM 0. The leading and following trucks in the plowing platoon can be seen by the dash camera images shown in Figures 9(c)-(e).

It is visually decipherable from the heatmaps above that the multi truck snow removal activity conducted in the hours of 3 PM to 7 PM resulted in significant queuing of vehicles behind the platoon, indicated by the substantial purple patches (speeds of 0 to 14 miles per hour) on the heatmap in Figure 9(b). In fact, by the time the operation was nearing completion at about 1800 hrs, the



(c) (d) (e)

Figure 9. Feb 14-Feb 16, 2021 winter storm, I-94 WB Speed Profile Heatmaps and Snowplow Coverage (https://doi.org/10.4231/KVTF-W862). (a) I-94 WB Hourly Snowplow Deployment Counts; (b) I-94 WB Speed Profile Heatmap with Overlayed Snowplow Trajectories; (c) 3:38 PM, Truck 65255; (d) 4:37 PM, Truck 66180; (e) 5:37 PM, Truck 64079. (see **Appendix** for additional imagery on winter storms).

queue behind the trucks was almost 10 miles long.

However, with access to operational dashboards such as those presented in this study, a tactical redeployment of resources was made possible by reviewing the mobility impacts caused by this winter maintenance operation. Subsequently, when a similar operation was to be carried out following the conclusion of this winter storm, tandem plows were deployed in the early morning hours of about 1:30 AM-4:30 AM on February 19, 2021 to reduce the mobility impact on the traveling public. A speed profile heatmap with only connected vehicle speeds is shown in **Figure 10(a)** for the EB direction of travel to visualize and compare the minimal queues observed compared to those of February 15. Additionally, a corresponding heatmap is shown in **Figure 10(b)** with overlaid snowplow trajectories to show the tandem plow fleet traversing I-94 along with a lateral slice showing dash camera images of the operation (**Figures 10(e)-(g)**). The WB direction has also been shown in **Figure 10(c)** and **Figure 10(d)** for context showing the same tandem plow fleet returning after completion of the snow removal operation with non-existent queuing on the interstate.

While this is a specific example, it goes to show the scalable nature of these operational dashboards that make after action reviews of critical weather events feasible on a systemwide as well as a local level, and allow for tactical redeployment and resource allocation adjustments based on data-driven insights.

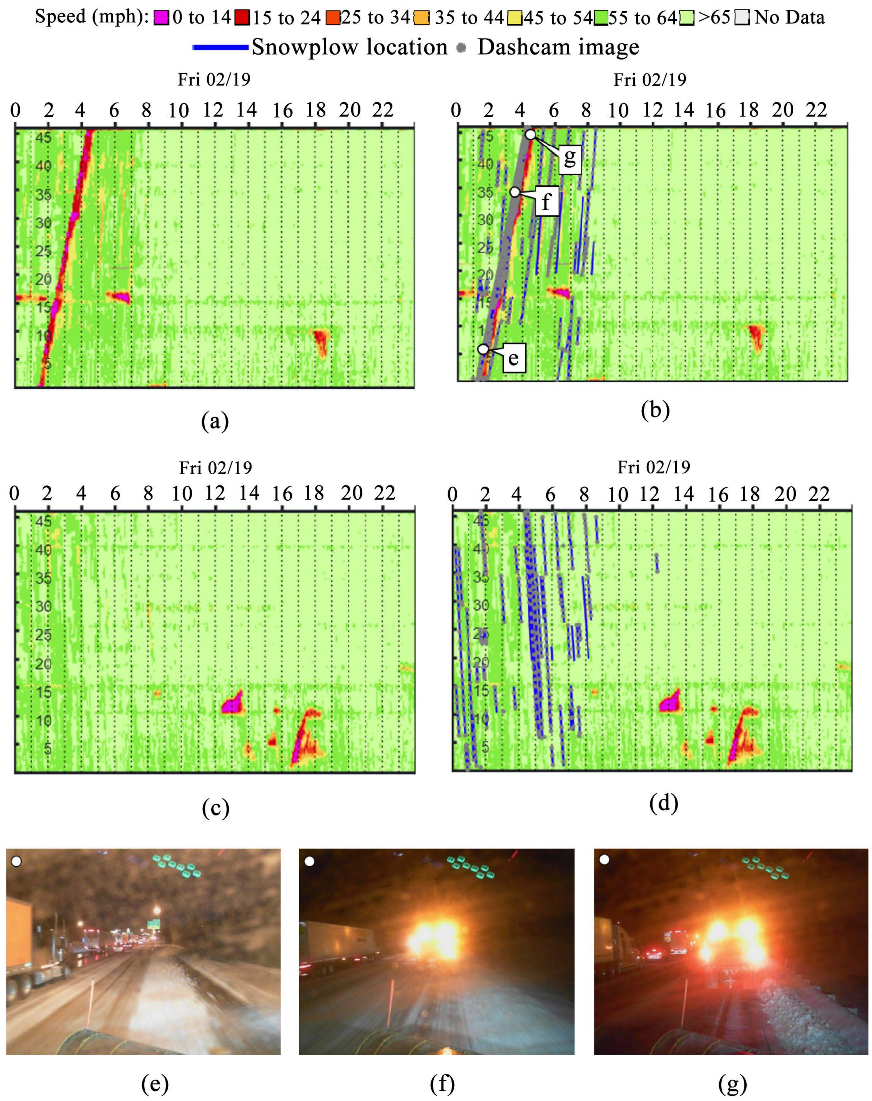


Figure 10. Feb 19, 2021 I-94 Speed Profile Heatmaps and Snowplow Telematics Showing Post-Storm Maintenance. (a) I-94 EB Speed Profile Heatmap; (b) I-94 EB Speed Profile Heatmap with snowplow trajectories; (c) I-94 WB Speed Profile Heatmap; (d) I-94 WB Speed Profile Heatmap with snowplow trajectories; (e) 1:43 AM, Truck 64382; (f) 3:49 AM, Truck 64382; (g) 4:12 AM, Truck 64382.

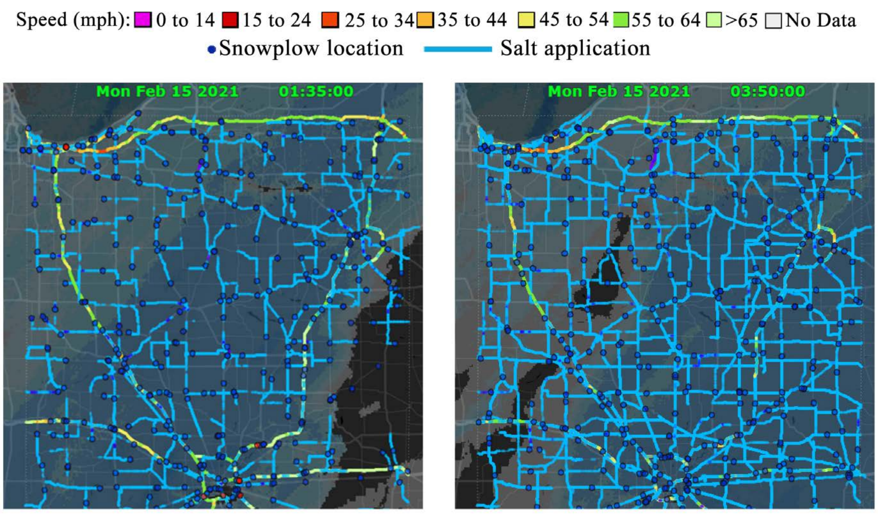
13. Conclusions

This study used daily weather data obtained from 590 unique GHCN weather stations across the state of Indiana for the period of November 1, 2020, to April 30, 2021, to obtain daily maximum and average snowfall values for the state. The case study presented in this paper was the largest and most impactful snowstorm of the season, occurring during the period February 14th-16th, 2021.

Using onboard telematics devices installed on INDOT snowplow trucks, truck geolocation and speeds could be retrieved for snowplow trucks in the state over the course of the winter season. Integrated visualizations with weather and traffic speeds prove valuable in seeing the onset of a storm and the fleetwide reaction of maintenance activity. One of the heaviest impacted interstate roadways I-94 was selected for further study. Speed profile heatmaps with overlaid snowplow truck trajectories and supporting dash camera imagery provide insights into a storm's progression both temporally as well as spatially. Speed profile heatmaps on I-94 depict daytime windrowing activity which led to substantial queuing and travel time delays. However, a review of these mobility impacts allowed better planning and redeployment on subsequent days resulting in minimal queuing as a result of the corresponding windrowing activity. Access to these integrated dashboards holds promise for winter maintenance stakeholders in helping the decision-making process with real-time feedback available from ground telematics.

14. Future Scope

Telematics data has additional capability to provide information on material application rates, plow position and many other attributes in addition to the ones analyzed in this study. An example of the material application rate can be observed in Figure 11 as the February 14th-16th, 2021 storm progresses through the state. Future research will involve an in-depth spatial and temporal analysis of material application and treatment zones in preparation for a winter storm event in conjunction with its impacts on mobility. Additionally, an after-action review of past maintenance and material application activity, along with a quantifiable relationship drawn between road treatment, mobility and safety will heavily inform future decisions.



(a) (b)

Figure 11. Snowplow fleet deployment and material application for Feb 14-16, 2021 Winter Storm. (a) 1:35 AM, Mon Feb 15, 2021; (b) 3:50 AM, Mon Feb 15, 2021.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Title	Link
February 15th, 2021 Winter Storm Activity	https://doi.org/10.4231/R3XJ-0875
February 10th, 2021 Winter Storm Activity	https://doi.org/10.4231/RR0D-C529
February 08th, 2021 Winter Storm Activity	https://doi.org/10.4231/VXZQ-9G72
December 16th, 2021 Winter Storm Activity	https://doi.org/10.4231/7DSJ-1475
February 08th, 2021 Tandem Plow Activities	https://doi.org/10.4231/A0BA-P609
February 06th, 2021 Tow Plow Activities	https://doi.org/10.4231/8KER-F373
February 15th, 2021 Windrow Activities	https://doi.org/10.4231/KVTF-W862
Integrated Connected Vehicle and INDOT Snowplow 63678 Telematics Feed from February 15-16th, 2021 Winter Storm	https://doi.org/10.4231/D8XT-JS45
Integrated Connected Vehicle and INDOT Snowplow 63550 Telematics Feed from February 15-16th, 2021 Winter Storm	https://doi.org/10.4231/V572-YX70
Integrated Connected Vehicle Data and INDOT Traffic Camera Feed from February 15-16, 2021, Winter Storm	https://doi.org/10.4231/SFMN-R881