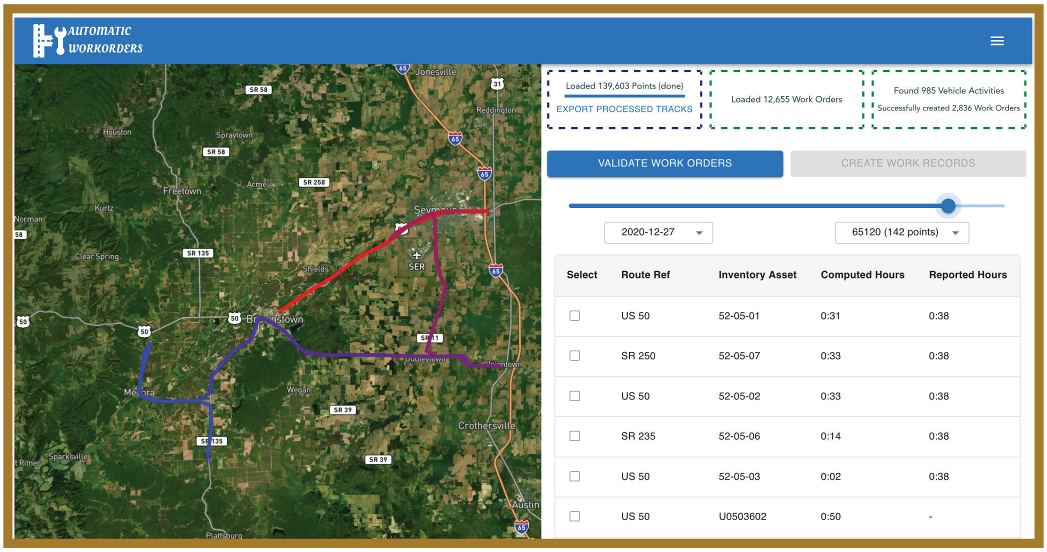
**JOINT TRANSPORTATION
RESEARCH PROGRAM**
INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Automated Record Keeping for Maintenance Operations via Tracking of Maintenance Vehicles Using Telematics Tracks



Loaded 139,603 Points (done)

Loaded 12,655 Work Orders

Found 985 Vehicle Activities

Successfully created 2,836 Work Orders

2020-12-27

65120 (142 points)

Select	Route Ref	Inventory Asset	Computed Hours	Reported Hours
☐	US 50	52-05-01	0:31	0:38
☐	SR 250	52-05-07	0:33	0:38
☐	US 50	52-05-02	0:33	0:38
☐	SR 235	52-05-06	0:14	0:38
☐	US 50	52-05-03	0:02	0:38
☐	US 50	U0503602	0:50	-

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JOINT TRANSPORTATION RESEARCH PROGRAM

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16. Abstract

Efficient and accurate record-keeping for maintenance vehicle operations is essential for optimizing resources, improving accountability, and enhancing decision-making for transportation agencies. The Indiana Department of Transportation (INDOT) sought an automated system to verify and improve work order records using telematics-based vehicle tracking. This study developed and evaluated a system that leverages GPS data from INDOT's Data Warehouse to automate work order verification, track vehicle movements, and enhance data accuracy for winter highway maintenance operations.

The system integrates GPS tracking, automated data processing, and visualization tools to address key challenges such as data standardization, GPS accuracy, and time resolution. Results indicate that minute-level GPS sampling is insufficient for work order automation, and higher-resolution second-level tracking is recommended. A web-based application was developed to provide managers with scalable, privacy-focused tools for visualizing and validating maintenance activities.

Key findings include the successful automation of work order verification, the development of a standardized GPS-to-road location conversion methodology, and the identification of operational challenges such as data transmission gaps in rural areas. The study recommends increasing GPS data resolution, implementing standardized data processing frameworks, enhancing work order recording methods with precise start and end times, and expanding the system to other maintenance operations such as asphalt patching and roadside mowing.

This research provides a scalable framework for automating maintenance record-keeping, emphasizing the importance of data accuracy, standardization, and enhanced GPS tracking to improve operational efficiency in transportation management.

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EXECUTIVE SUMMARY

Motivation

Efficient and accurate record-keeping for maintenance vehicle operations is crucial for optimizing resources, improving accountability, and enhancing decision-making in transportation agencies. The Indiana Department of Transportation (INDOT) sought an automated system to verify and improve work order records using GPS data. The project aimed to address inconsistencies in current record-keeping and leverage telematics for enhanced efficiency in winter highway operations.

Study

This study developed an automated work order verification system utilizing GPS-based tracking of maintenance vehicles. By leveraging GPS data from INDOT's Data Warehouse, the system was designed to accurately verify work orders, track vehicle movements, and enhance the precision of recorded data. Additionally, the study examined key challenges in work order automation, including data standardization, GPS accuracy, the need for higher time-resolution tracking, and the development of user-friendly visualizations to support intuitive decision-making for operators and managers.

The key objectives and contributions of this study included:

1. *Automating work order verification* by leveraging GPS data to improve accuracy and efficiency.
2. *Standardizing road naming conventions and GPS-to-road location conversion methodologies* to ensure data consistency and interoperability.
3. *Developing advanced tools for data processing and visualization* to support intuitive analysis and decision-making.
4. *Evaluating the feasibility of work order automation* with existing GPS data, identifying challenges, and proposing solutions for scalability and implementation.

Results

The key deliverables and findings of this study included:

1. *Fully Automated Work Order Verification*: The developed system successfully automated the verification of work orders for winter highway operations by matching vehicle GPS tracks with recorded work orders. This reduced manual verification efforts and improved accuracy.
2. *Data Standardization and Road Mapping*: A method was developed to standardize road naming conventions and establish a robust converter between INDOT's Reference Post System and GPS coordinates, enhancing consistency.
3. *Time Resolution Matters*: The study found that minute-level GPS tracking was insufficient for accurate work order automation. A higher resolution (second-level tracking) was recommended to capture precise vehicle activity.
4. *Web-Based Application for Data Access*: A scalable and privacy-focused web application was developed to allow managers to efficiently access, visualize, and validate work orders using GPS records.
5. *Operational Insights*: The study highlighted key operational challenges, including the digital divide affecting real-time GPS data transmission in rural areas and the necessity of integrating start and end times in work orders.

Recommendations

The key recommendations of this study included:

1. *Improve GPS Data Collection Frequency*: To enhance accuracy, increasing GPS data resolution to second-level logging is recommended.
2. *Implement a Standardized Data Processing Framework*: A uniform system for road naming, mile markers, and GPS conversions should be adopted to prevent ambiguities.
3. *Enhance Work Order Recording Methods*: Including start and end times in work orders will improve automation capabilities.
4. *Expand Web App Functionalities*: Integrating additional features for different maintenance operations (e.g., snowplowing, patrolling) will increase system adaptability.
5. *Optimize Data Transmission Strategies*: Implementing data caching and delayed uploads when network connectivity is limited can mitigate the impact of rural digital divide issues.
6. *Further Research and Development*: Additional work should be conducted to refine algorithms for multivehicle operations and GPS-based detection methods.

This study provides a foundational approach to automating maintenance vehicle record-keeping, offering a scalable solution that can be expanded for broader transportation applications. The findings emphasize the importance of data accuracy, standardization, and enhanced GPS tracking for improved operational efficiency.

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1. PROJECT OVERVIEW

1.1 Introduction

The Indiana Department of Transportation (INDOT), in collaboration with Parsons, is deploying telematics devices across its fleet vehicles. These devices integrate vehicle sensor data from Controller Area Network (CAN) bus and other sources with GPS positioning and time tracking, enabling the generation of detailed, real-time records of vehicle activity. This project explores the potential of leveraging this technology to enhance the management of winter operations, particularly snow and ice removal, by automating work order verification and generation. By providing automated, precise, and high-resolution records of vehicle movements, this work order automation system has the potential to streamline operations, improve decision-making, and enhance fleet management efficiency. Moreover, its applications extend far beyond winter operations, offering valuable insights for asphalt patching, mowing, herbicide application, and other maintenance activities.

Previous proof-of-concept studies have demonstrated the benefits of automated tracking using specialized temporary devices on pavement patching vehicles (Zhang et al., 2015) and mowing tractors (Mathew et al., 2018). Now, with telematics devices being permanently installed across most of INDOT's fleet, there is a unique opportunity to analyze this new data stream to automate work order verification, generate actionable management insights, and develop intuitive visualizations and dashboards that support data-driven decision-making across INDOT operations.

A critical, yet often overlooked, benefit of telematics-based sensing and data integration is its ability to automate record-keeping, significantly improving planning, review processes, and historical data analysis. Currently, work order records for many maintenance operations are manually collected, lacking spatial precision and temporal accuracy. Even for routine tasks like patrolling and snow and ice removal, relying on manual logs presents logistical challenges, limiting INDOT's ability to conduct comprehensive data analysis and make informed, data-driven decisions. Automating work order records can significantly enhance fleet management, operational efficiency, and performance evaluation while reducing administrative workload.

This automation approach is equally valuable for more complex maintenance operations. For example, in asphalt pothole patching, existing records estimate material usage over an entire workday, covering long roadway segments. However, actual patching work is highly localized, meaning that current aggregated records fail to capture the precise distribution of maintenance activities. With automated, high-resolution records collected over time, maintenance engineers will have access to web-based tools that provide actionable insights, allowing INDOT to better prioritize resurfacing and reconstruction efforts.

To ensure successful implementation, these advancements must be designed to integrate seamlessly into existing workflows without adding additional administrative burdens to crew chiefs and managers. Therefore, the development of fully or semi-automated maintenance record-keeping and reporting systems is a key objective of this initiative, enabling INDOT to maximize efficiency, improve accountability, and optimize resource allocation across its entire fleet and maintenance operations.

1.2 Prior Work

1.2.1 Pavement Patching

Zhang et al. (2015) proposed an algorithm for classifying vehicle activities in systems where multiple operators-and-vehicles work together to accomplish outdoor tasks. The classifier was a simple rule-based expert system, tuned for an application in farming and an application in transportation. The transportation application was prototyped on INDOT vehicles and used nothing more than vehicle GPS tracks and speeds to produce an estimate of asphalt patching effort with relatively high spatial resolution (on the order of 10 meters). The farming application used GPS tracks of harvesters, tractor-pulled grain carts, and semi-trucks to classify harvest activities (e.g., what, when, and where) for metadata record automation. The system was later used to calibrate standard yield monitors and to create records that would allow mapping weighed and graded truckloads to regions of the harvested field (Zhang et al., 2020). This is a major part of a product traceability system.

One part of the harvest classification expert system was adapted for pavement patching zone recognition for INDOT. Pavement patching (Figure 1.1) plays an important role in road maintenance, but with the records currently available from INDOT, it is hard to track the patched areas and monitor the maintenance performance (National Academies of Sciences, Engineering, and Medicine, 2014). At its simplest, the expert system classifies road points covered by a patching crew by thresholding the speeds and times with which the crew and vehicles move through a zone where patching could occur. Other functions the expert system must accomplish are to classify the activity is patching, using information about the types of vehicles involved and very coarse information about the segment where patching could be happening. A test was run using data collected for one pavement "cold" patching trip on Indiana State Road 49.

1.2.2 Roadside Mowing

A recently completed JTRP project used commercially available GPS logger-telematics devices to study the productivity of INDOT's roadside mowing (Mathew et al., 2018). Mowing activities are usually reported by daily work orders, and it is difficult to obtain quantitative information characterizing the utilization and productivity of the mowing operations. The project used the data to track the daily activity of seven mowers in the Fort Wayne district. Weather data from the National Oceanic and Atmospheric Administration (NOAA) was also captured to estimate the weather-related delays. The main study dataset covered a one-month period during which the mowers collectively traveled a total of approximately 1,170 miles while mowing an area of nearly 1,800 acres. See Figure 1.2 for installation images.

Figure 1.1 Road Patching With a Patching Truck [From Local Government & Municipal Knowledge Base by Mildura Rural City Council CC BY-SA 3.0].

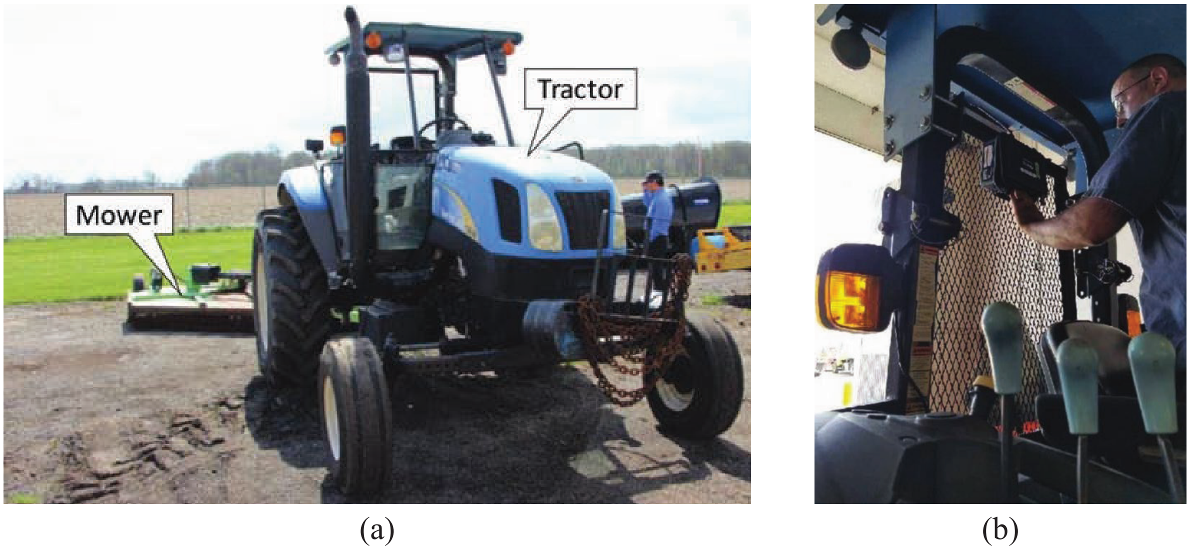
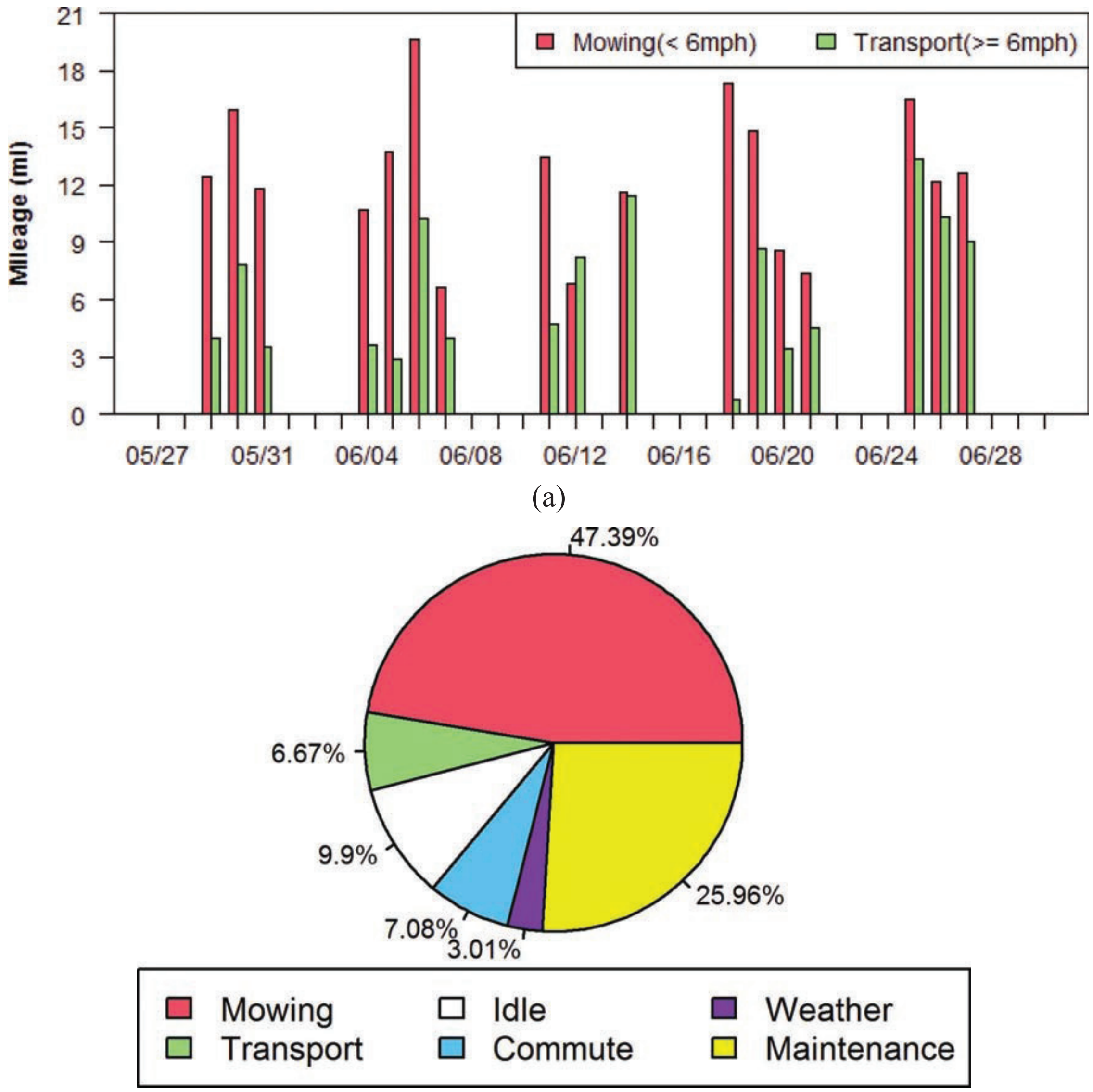


Figure 1.2 GPS Telematics Equipment Installation. (a) Tractor With 15-Ft Width Mower. (b) GPS Unit Installation Behind Operator Seat in the Tractor.

Approximately 450,000 data points were collected from the seven mowers over the season's first cycle of mowing operations from May 29 to June 30, 2018. Commercial GPS trackers provided time-stamped location data at a frequency of 5-second intervals. The built-in accelerometers also ensured that the devices only recorded data when the mowers were in motion. The data was stored in a Microsoft SQL database and analyzed using R.

The mower work hours were classified into four bins: 1) crew commute, 2) equipment transport between locations, 3) mowing, and 4) downtime. A very simple classification algorithm was used—mowing crew activities associated with speeds less than 6 mph were assumed to be mowing. Furthermore, downtime was further classified into delays due to maintenance, customary breaks, and weather-related events. Some of the result



(a)

(b)

Figure 1.3 Sample of the Mowing Operations Analysis Produced. (a) Transport vs. Mowing Mileage for One of the Mowers. (b) Allocation of Work Hours Across the Seven Machines During the Study Period.

graphs are shown in Figure 1.3 and considerably more detail is contained in the report.

On an average 9.5-hr workday approximately 50% of the time was spent on mowing. Other activities such as crew commute and equipment transport accounted for 7% each, whereas customary breaks, such as lunch breaks, accounted for 10%. Weather delay was minimal with nearly 3%. Downtime due to maintenance was estimated to be around 26%. These results highlight the promise of such data to identify opportunities for enhancing management practices and resource allocations of roadside mowing operations. Detailed maintenance reporting systems could also provide better insights into the downtime. But the work reported in the mowing project used very simple and largely non-autonomous classification to analyze the resulting data. In order to roll the lessons learned as a general tool, two requirements must be met: First, the GPS data must be gathered automatically and over a very large percentage of the fleet, and, second, the analytics and report creation need to be autonomous to not overburden maintenance crew supervisors and managers.

1.2.3 JTRP Intelligent Snowplow Project

This completed JTRP project explored data-driven methodologies and analytical tools to enhance decision-making for statewide winter operations deployment and management (Mahlberg et al., 2021). The project team successfully integrated telematics from 1,100 snowplow trucks into real-time dashboards, enabling comprehensive visualization of snowplow trajectories. These dashboards overlay time-space diagrams of general traffic, ambient traffic speeds, weather maps, and dashcam snapshots from snowplow trucks, offering a holistic view of winter storm operations.

The dashboards developed are designed to support operational managers in analyzing storm impacts, optimizing truck deployment, and improving response efficiency. Additionally, the system enables automated generation of after-action winter storm reports, providing agencies with data-driven insights for decision-making, performance evaluation, and training.

For the current proposal, the primary contribution of the "Intelligent Snowplow" project lies in its debugging and API development efforts, which were essential for ingesting GPS data from a fleet of thousands of vehicles. Furthermore, the prototypes for dashboards and report generation serve as a foundation for future advancements in automated record-keeping systems, streamlining data collection and enhancing operational efficiency.

1.3 Work Order Automation for Winter Operations

Efficient and accurate record-keeping for maintenance vehicle operations is essential for optimizing resource allocation, improving accountability, and enhancing data-driven decision-making in transportation agencies. This research addresses the need for automating record-keeping by integrating sensor-telematics systems with existing work management systems. A focused study was conducted on winter operations to develop and validate an automated system for work order verification and generation, specifically for patrolling and snow and ice removal.

INDOT sought to implement an automated system that utilizes GPS data to verify and enhance work order records. The primary objective was to assess how telematics could optimize maintenance operations by automating vehicle tracking and data collection. To maximize the practical impact of the resulting tools on INDOT's management practices, we adopted a research-driven approach to tool development (Section 2). Algorithms were designed to fully automate work order verification and partially automate work order generation, improving both accuracy and efficiency. To support these efforts, we delivered two complementary software solutions: a MATLAB-based implementation, accessible via OneDrive, for statewide comprehensive analysis (Section 3), and a web application designed for interactive supervision and near-real-time logistics management at the district level (Section 0).

The project addressed inconsistencies in current record-keeping practices and demonstrated how telematics integration can improve accuracy and operational oversight. One of the key findings was the necessity of higher GPS sampling resolution, as the current minute-level sampling rate was found to be insufficient for precise analysis. A second-level GPS sampling rate is strongly recommended to achieve the required level of accuracy and granularity. Additionally, local data caching is recommended to mitigate the impact of connectivity limitations in rural areas, where stable telecommunications infrastructure is not always available for real-time data transmission.

Standardization is another critical factor in improving work order automation. Establishing a uniform system for road naming, mile markers, and GPS conversions is necessary to prevent data inconsistencies and ambiguities. Additionally, automating the capture of driver activity, particularly the exact start and end times of maintenance tasks, remains a key challenge and a near-term priority for advancing work order automation.

Effective visualization is essential for making the automated system user-friendly and operationally valuable. Developing tailored visualizations for different maintenance activities ensures that insights are easily interpretable and actionable. Properly implemented algorithms can significantly enhance the scalability of the work order automation system, enabling its expansion to other maintenance operations beyond winter services. The feasibility of an interactive web application that operates entirely on the user's side without requiring data uploads has been successfully demonstrated. This approach ensures high security and privacy by processing data locally rather than transmitting sensitive information to cloud-based systems.

By addressing these challenges and implementing these recommendations, INDOT can significantly enhance the accuracy, efficiency, and scalability of its maintenance record-keeping processes, paving the way for a more data-driven and automated fleet management system.

2. RESEARCH-DRIVEN TOOL DEVELOPMENT FOR WORK ORDER AUTOMATION

In the United States, more than 70% of roads are located in regions prone to snow and ice, similar to conditions in Indiana (Federal Highway Administration, 2023). Snow and ice on roads significantly slow traffic and pose serious safety risks to drivers (Federal Highway Administration, 2023). Recognizing this critical impact, INDOT prioritizes snow and ice removal as its top operational focus during winter months (Zhang et al., 2024). This massive effort involves more than 1,000 snowplows, nearly 2,000 employees, and more than 29,000 lane miles of roads (INDOT, 2022). Managing such an extensive fleet is inherently challenging, particularly due to the manual nature of current tracking and reporting processes (INDOT, 2023). Work records for these vehicles are manually generated, a process that is time-consuming and lacks the granularity required for detailed analysis, especially given the urgency of winter operations (INDOT, 2023).

The manual process places a significant administrative burden on managers, particularly during severe storm events. For example, a district manager overseeing dozens of vehicles may be required to generate hundreds or even thousands of work order entries each week during peak snow seasons. These records are essential because they directly impact driver payroll, procurement of treatment materials, and planning for future road improvements. Since drivers work long hours during storms, timely and accurate payroll processing is critical; however, delays caused by manual record-keeping can lead to dissatisfaction among drivers and operational inefficiencies. Additionally, from the managers' perspective, creating these records is a necessary but low-value task that diverts attention from higher-priority responsibilities such as strategic planning, resource allocation, and real-time problem-solving during storms. Automating the work order process would alleviate this burden, reduce errors, and allow managers to focus on more critical operational decisions.

Extensive research has explored logistics automation and decision-making using telematics data derived from satellite navigation technologies (Ghaffarpasand et al., 2022). Applications include recognizing human activities (Wang et al., 2021), monitoring agricultural vehicles (Wang et al., 2023; Zhang et al., 2020), and route planning for self-driving cars (Kinable et al., 2016). However, much of this research is limited to small-scale, short-term studies and lacks the longitudinal analysis required for comprehensive fleet management (Goel, 2008). Collecting telematics data for an entire fleet over a large geographic area, particularly in rural regions like Indiana, presents significant challenges. As a result, studies often focus on a few vehicles or limited objectives (Goel, 2008; Wang et al., 2023; Zhang et al., 2020), neglecting large-scale trend and pattern analyses. Winter road maintenance introduces unique complexities, as vehicles repeatedly traverse the same routes—unlike the single-trip scenarios typically studied (Kinable et al., 2016; Milford et al., 2019; Wang et al., 2023; Zhang et al., 2020). Visualizing these repeated movements and integrating them into meaningful work records is particularly challenging.

A complicating factor in fleet telematics analysis for INDOT is its reliance on a linear reference system that uses road names and mileposts rather than GPS coordinates (Zhang et al., 2024). Converting GPS data from telematics trackers into this linear reference system is non-trivial, requiring sophisticated mapping algorithms to accurately align GPS coordinates with road segments and mileposts. This process must account for anomalies such as GPS drift, road curvature, and varying segment lengths. Additionally, telematics data analysis is highly application-specific, necessitating tailored algorithms for each use case (Wang et al., 2023; Zhang et al., 2017). Even within INDOT's operations, tasks such as asphalt patching (Zhang et al., 2015) and mowing (Mathew et al., 2018) require distinct data collection and analysis methodologies.

To address these challenges, this study proposes a solution that automates the work recording process for winter maintenance operations, leveraging telematics data from INDOT's extensive fleet. The study utilizes a large-scale GPS dataset obtained from the INDOT Data Warehouse, containing 5,115,844 data points from 1,051 vehicles during the winter season from December 2, 2020, to April 30, 2021. This dataset includes 50,829 vehicle tracks covering the entire state of Indiana. Sampling statistics indicate that the smallest interval between adjacent GPS points is 1 minute, with 34% of intervals at exactly 1 minute and 14% extending beyond 5 minutes. The sheer volume and complexity of this dataset make manual inspection and analysis infeasible (Zhang et al., 2024).

The proposed automated work order system consists of two key components: a MATLAB-based research tool (Zhang et al., 2024) and an in-browser web application (Naman et al, 2025). Together, these tools enhance GPS track analysis and visualization, significantly improving winter maintenance operations for INDOT.

The MATLAB tool serves as a research and development platform, focusing on algorithm optimization and data processing methodologies. MATLAB's robust environment supports flexible experimentation and testing, enabling the refinement of algorithms before implementation in the web application. This tool is crucial for exploring advanced data processing techniques, optimizing GPS data interpretation, and developing analytical features tailored to winter road maintenance.

The web application, in contrast, processes GPS data to verify existing work records, generate new work records with start and end times tied to specific road segments, and provide detailed visualizations of vehicle activity. This browser-based tool is designed for practical use by INDOT managers and operators, automating and streamlining the record-keeping process in a user-friendly manner.

This approach offers multiple operational benefits:

1. *Reduced Administrative Burden*: The web application automates work recording, reducing manual data entry and allowing managers to focus on higher-value tasks.
2. *Enhanced Accuracy and Detail in Work Records*: Both tools contribute to generating detailed, segment-level work records with consistent timestamps, capturing nuanced data across vehicle movements.
3. *Research-Driven Optimization and Development*: The MATLAB tool enables in-depth research, allowing for testing and refinement of algorithms that are later implemented in the web application.
4. *Improved Cost Analysis and Planning:* The segment-based tracking provided by both tools supports precise cost evaluations and data-driven decision-making for future maintenance and resource allocation.
5. *User-Friendly and Secure Design:* The web application operates locally, ensuring data privacy without requiring cloud storage.
6. *Bridging Research and Practical Application*: By integrating the MATLAB research tool with the practical web application, this solution bridges advanced research with real-world operations, enhancing INDOT's ability to leverage data insights.

This comprehensive approach not only automates work recording but also provides a robust platform for continuous improvement, enabling INDOT to benefit from both immediate operational efficiencies and ongoing research-driven advancements.

3. RESEARCH ON WORK ORDER AUTOMATION USING MATLAB

In this section, we demonstrate the effectiveness of automating telematics data collection and processing procedures for key winter operations of INDOT, significantly reducing the time and effort invested by engineers and managers in record-keeping (Zhang et al., 2024).

We collaborated with INDOT to access and analyze telematics data from their fleet, including GPS tracks acquired through the Automatic Vehicle Location program (INDOT, 2021). Using historical work orders exported from the INDOT Management Information Systems as a reference, we developed a suite of MATLAB-based algorithms to automate the verification of work orders, aiming to improve both the accuracy and efficiency of this process.

3.1 Statewide GPS Dataset for Winter Road Maintenance

The GPS data for this project were obtained from the INDOT Data Warehouse, covering winter maintenance operations during the 2020–2021 season, specifically from December 2, 2020, to April 30, 2021. As illustrated in Figure 3.1, the dataset comprises 5,115,844 point entries across 50,829 tracks from a fleet of 1,051 vehicles operating statewide. Sampling analysis reveals that 34% of the recorded points were captured at precise 1-minute intervals, while 14% had sampling gaps exceeding 5 minutes. The extensive scale of this dataset, with its high-frequency tracking and multiple overlapping tracks, presents significant challenges for manual verification, underscoring the necessity for automated analytical approaches.

3.2 Reference Work Orders

To benchmark our analysis, we obtained work orders from INDOT for the same timeframe (Figure 3.2), which serve as a reference for the GPS-based automation. Key fields from the work orders include Resource Type, Management Unit, and Resource Name, which are derived from associated vehicle information. Each work order (identified by WO#) may contain multiple entries, reflecting different maintenance routes and shifts. The work zones are represented by start and end mile markers on specified road segments, following INDOT's linear reference system (Zhang et al., 2015). Each entry also records the cumulative work hours for the associated task, allowing us to quantify workload effectively.

3.3 Algorithm for Automated Work Order Verification

Our approach to automating work order verification is structured into three main components: *preprocessors*, *postprocessors*, and the *core processing* module.

3.3.1 Preprocessing Components

The *preprocessors* are responsible for preparing raw GPS and work order data for analysis. This includes:

- *Data Cleaner*: Cleans and filters raw data from both GPS and work orders. It also converts INDOT timestamps into a format that is compatible with MATLAB for further processing.
- *Work Order Parser*: Extracts historical activity records from the work order data, creating a structured dataset that serves as a baseline for verification.

3.3.2 Core Processing Module

At the core of our algorithm is a two-step process that assigns geographic and operational context to the GPS data:

- *GPS to Mile Marker Converter*: This module associates GPS points with specific road segments by assigning *road name* and *mile marker* labels, using publicly available datasets of highway mile markers (Business Information and Technology Systems, 2012) and street centerlines (Indiana Geographic Information Office, 2020). This step is crucial for aligning GPS data with INDOT's linear reference system.
- *Vehicle Work Order Entry Generator*: Utilizing the preprocessed GPS data and vehicle lists, this module categorizes GPS points as either *working* or *not working*. Points are grouped into reference activity records based on spatial and temporal continuity, forming a dataset of work order entries that align with real-world operations.

3.3.3 Postprocessing Components

The *postprocessors* evaluate the accuracy and quality of the generated work order records:

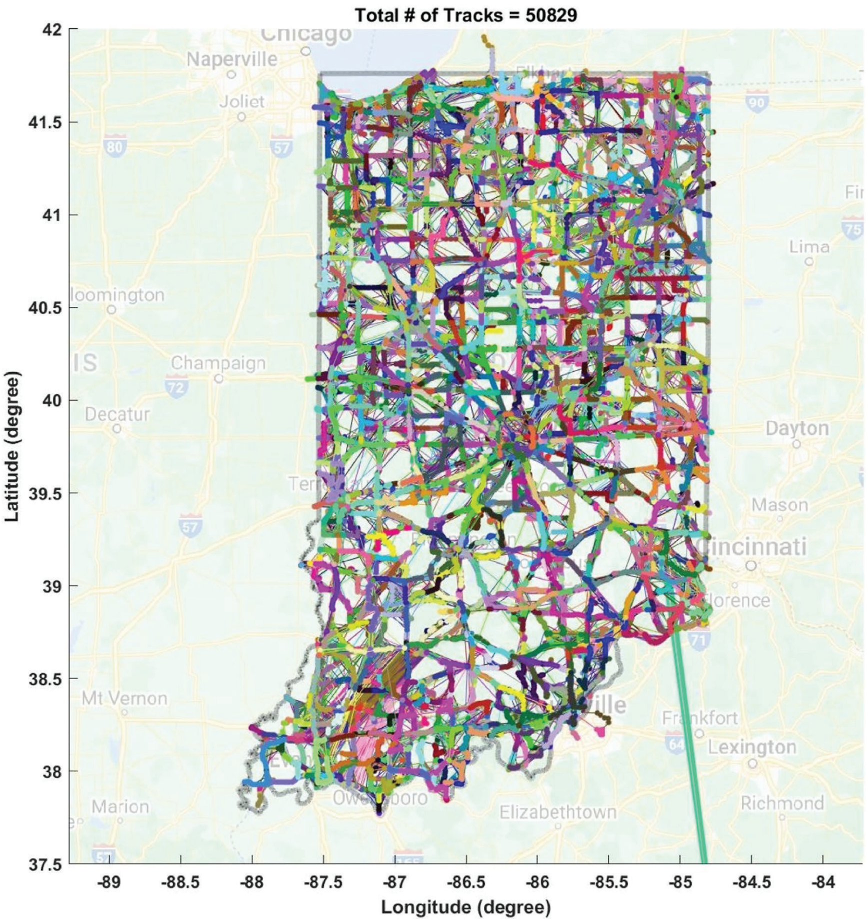
- *Work Order Verifier*: Compares algorithm-generated records against INDOT's original work orders, generating a verification report that highlights discrepancies and areas for improvement.
- *Visualization Tools*: These include *work zone maps* that overlay GPS records on road maps to visually indicate work zones and *workload overviews* that present workload data in both temporal and spatial formats for user inspection.

This framework provides a fully automated solution for processing, verifying, and visualizing work orders based on GPS data, significantly reducing the manual workload for INDOT personnel. By integrating pre- and postprocessing steps with sophisticated core algorithms, we deliver a high level of accuracy and granularity in the generated work order records, allowing for enhanced planning and resource allocation across winter road maintenance operations.

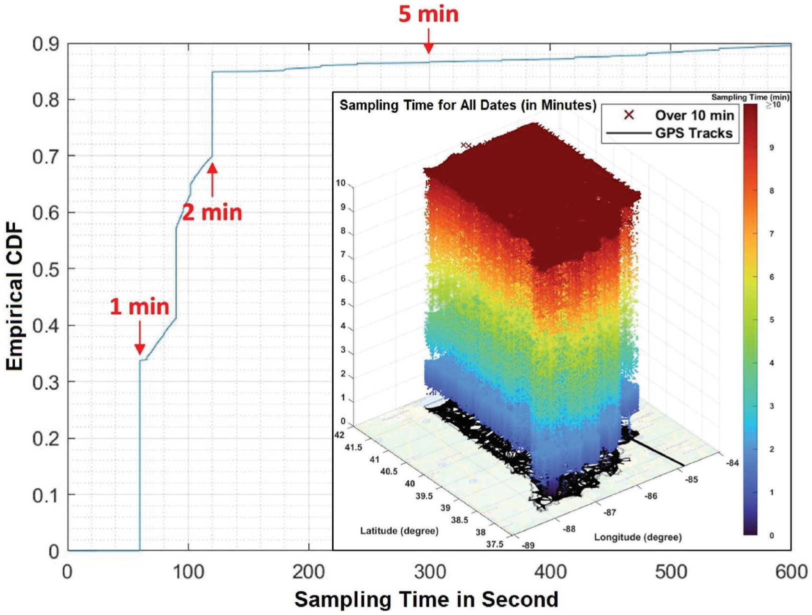
3.4 Workload Visualizations

Building on the algorithms and insights developed using the MATLAB-based research tool, we present three workload visualizations that illustrate the potential of automated work order generation and verification. These case studies demonstrate how our methods enhance INDOT's current manual record-keeping system by providing more detailed and accurate workload visualizations.

Our visualizations, particularly the workload overview, leverage data from the GPS to mile marker converter and vehicle work order entry generator modules described earlier. These case studies highlight the practical benefits of integrating automated data analysis into winter road maintenance workflows.

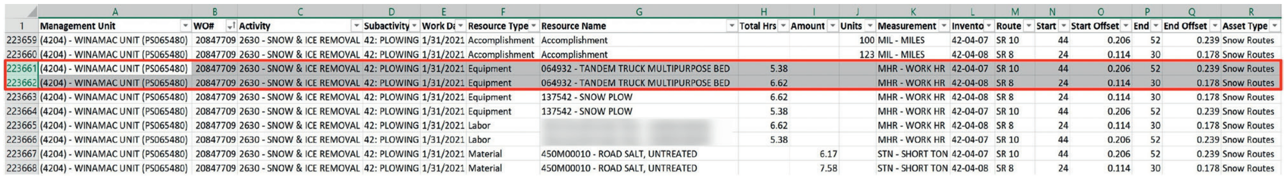


(a) All GPS Tracks (Colored by Track).



(b) Empirical Cumulative Distribution Function (CDF) for Sampling Time.

Figure 3.1 Overview of GPS Dataset for Winter Season 12/2/2020 to 4/30/2021.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	Management Unit	WO#	Activity	Subactivity	Work Da	Resource Type	Resource Name	Total Hrs	Amount	Units	Measurement	Invento	Route	Start	Start Offset	End	End Offset	Asset Type
223659	(4204) - WINAMAC UNIT (PS065480)	20847709	2630 - SNOW & ICE REMOVAL	42: PLOWING	1/31/2021	Accomplishment	Accomplishment			100	MIL - MILES	42-04-07	SR 10	44	0.206	52	0.239	Snow Routes
223660	(4204) - WINAMAC UNIT (PS065480)	20847709	2630 - SNOW & ICE REMOVAL	42: PLOWING	1/31/2021	Accomplishment	Accomplishment			123	MIL - MILES	42-04-08	SR 8	24	0.114	30	0.178	Snow Routes
223661	(4204) - WINAMAC UNIT (PS065480)	20847709	2630 - SNOW & ICE REMOVAL	42: PLOWING	1/31/2021	Equipment	064932 - TANDEM TRUCK MULTIPURPOSE BED	5.38			MHR - WORK HR	42-04-07	SR 10	44	0.206	52	0.239	Snow Routes
223662	(4204) - WINAMAC UNIT (PS065480)	20847709	2630 - SNOW & ICE REMOVAL	42: PLOWING	1/31/2021	Equipment	064932 - TANDEM TRUCK MULTIPURPOSE BED	6.62			MHR - WORK HR	42-04-08	SR 8	24	0.114	30	0.178	Snow Routes
223663	(4204) - WINAMAC UNIT (PS065480)	20847709	2630 - SNOW & ICE REMOVAL	42: PLOWING	1/31/2021	Equipment	137542 - SNOW PLOW	6.62			MHR - WORK HR	42-04-08	SR 8	24	0.114	30	0.178	Snow Routes
223664	(4204) - WINAMAC UNIT (PS065480)	20847709	2630 - SNOW & ICE REMOVAL	42: PLOWING	1/31/2021	Equipment	137542 - SNOW PLOW	5.38			MHR - WORK HR	42-04-07	SR 10	44	0.206	52	0.239	Snow Routes
223665	(4204) - WINAMAC UNIT (PS065480)	20847709	2630 - SNOW & ICE REMOVAL	42: PLOWING	1/31/2021	Labor	[redacted]	6.62			MHR - WORK HR	42-04-08	SR 8	24	0.114	30	0.178	Snow Routes
223666	(4204) - WINAMAC UNIT (PS065480)	20847709	2630 - SNOW & ICE REMOVAL	42: PLOWING	1/31/2021	Labor	[redacted]	5.38			MHR - WORK HR	42-04-07	SR 10	44	0.206	52	0.239	Snow Routes
223667	(4204) - WINAMAC UNIT (PS065480)	20847709	2630 - SNOW & ICE REMOVAL	42: PLOWING	1/31/2021	Material	450M00010 - ROAD SALT, UNTREATED		6.17		STN - SHORT TON	42-04-07	SR 10	44	0.206	52	0.239	Snow Routes
223668	(4204) - WINAMAC UNIT (PS065480)	20847709	2630 - SNOW & ICE REMOVAL	42: PLOWING	1/31/2021	Material	450M00010 - ROAD SALT, UNTREATED		7.58		STN - SHORT TON	42-04-08	SR 8	24	0.114	30	0.178	Snow Routes

Figure 3.2 Example Work Order Records. Note That There May Be Multiple Entries for the Same Vehicle on the Same Day, as Highlighted by the Red Rectangle.

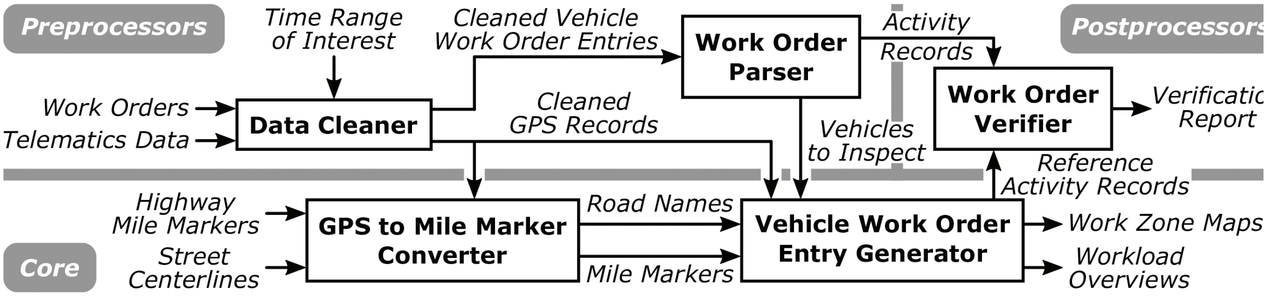


Figure 3.3 Block Diagram for Automated Work Order Verification (Zhang, 2023).

3.4.1 Single-Road Patrolling

This case, as illustrated in Figure 3.4, involves a vehicle patrolling a single road over the course of a day. The GPS tracks for this activity are visualized in multiple formats. The traditional map-based visualization reveals the limitations of overlapping tracks, especially when sampling intervals vary from 1 minute to tens of minutes. To address this, we enhance the visualization with dotted lines representing general movement between GPS points when precise route details are unavailable. Tracks are also styled to age gracefully, with older paths becoming wider and more transparent to prevent obscuring recent data.

The 3D visualization extends the traditional map view by adding a temporal dimension, enabling users to trace vehicle movements over time. While this method works well for single-road cases, it can become visually complex in multiroad scenarios.

The workload overview introduces a novel visualization approach: plotting mile markers against time to represent the vehicle's activity along a linear reference system. Color coding distinguishes between active work (colored rectangles) and non-working periods (grey). This visualization provides additional insights such as cumulative mileage, which is absent from traditional work orders, adding value for fleet managers.

3.4.2 Single-Road Snow and Ice Removal

In this example, a snowplow clears a single road during a work shift, as shown in Figure 3.5. Similar to the single-road patrolling case, the activity is visualized using traditional maps, 3D plots, and workload overviews.

The workload overview reveals that the snowplow operated for approximately 7.9 hr along I-69 on January 31, 2021, closely matching the reported time of 8 hr. This demonstrates the algorithm's precision in calculating operational hours and highlights its ability to supplement manual records with additional context.

3.4.3 Multiroad Snow and Ice Removal

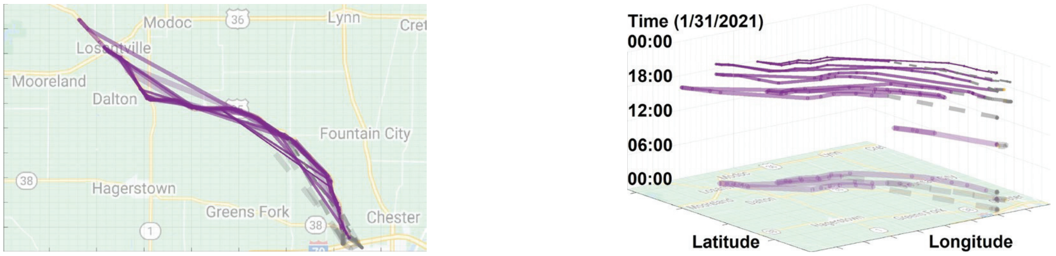
This complex example (Figure 3.6) involves a vehicle working across multiple roads. Traditional map visualizations and 3D plots reveal the interleaved nature of the activity but can be challenging to interpret.

The workload overview provides a clearer picture by summarizing work hours and mileage for each road segment. This enhanced granularity, made possible by the algorithm's ability to identify and classify small activity segments, is not present in traditional work orders. By offering detailed insights into multiroad operations, this visualization method enables managers to identify inefficiencies and optimize resource allocation.

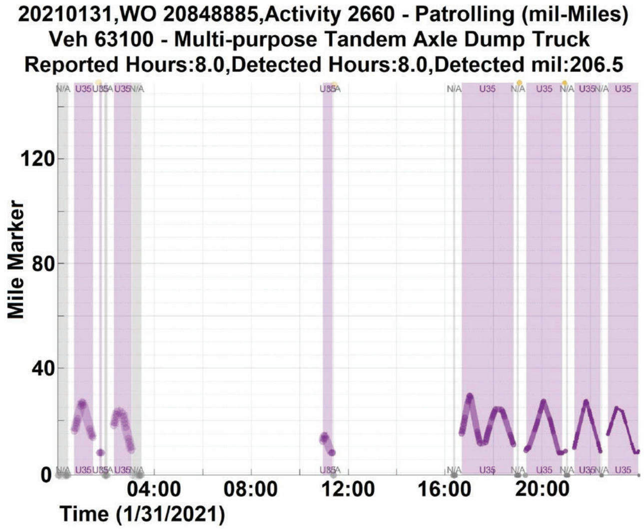
In summary, our visualization techniques offer comprehensive and detailed analyses of winter road maintenance operations, automating and enhancing work order verification and generation procedures. The workload overview proves to be a powerful tool, providing insights beyond the capabilities of traditional manual record-keeping systems.

3.5 Proof-of-Concept Programs for State-Level Work Order Automation

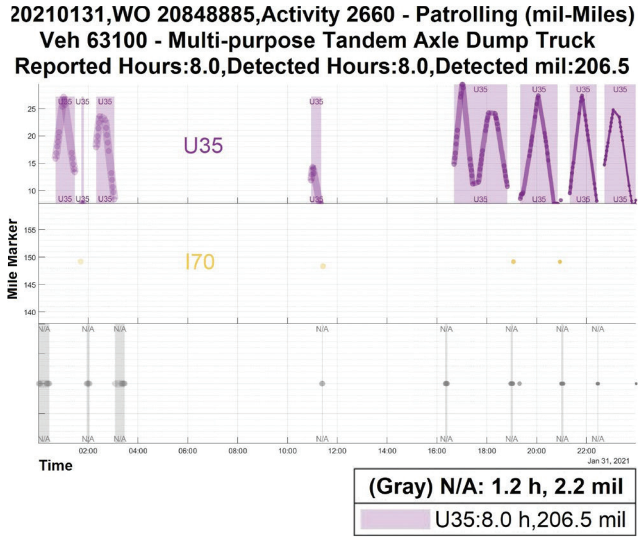
To showcase the full automation of work order verification, we developed a MATLAB program (Zhang, 2023). The screenshot in Figure 3.7, depicts the program processing data from 1/31/2021 covering the entire state of Indiana. The results include analysis plots for all work orders, providing an option



(a) Tracks on Map. (b) 3D Visualization With Time.

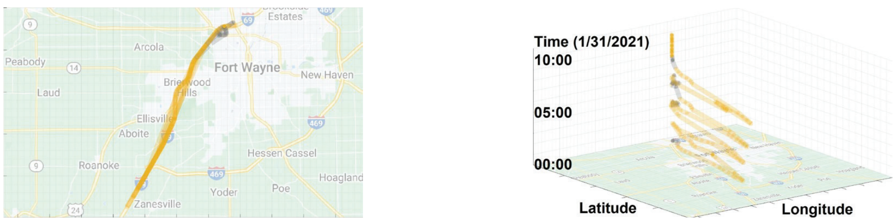


(c) Workload Overview With One Visualization Section.

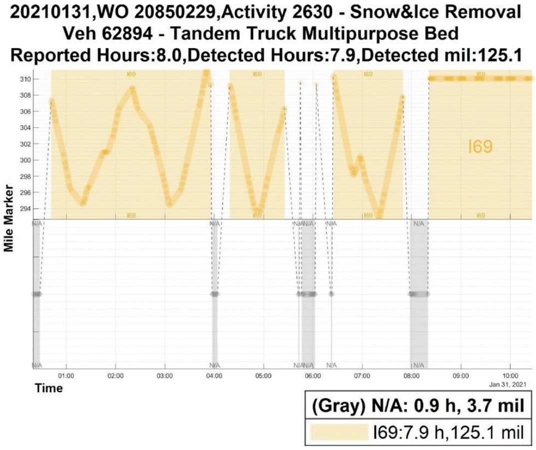


(d) Improved Workload Overview With Multiple Sections.

Figure 3.4 A Vehicle Patrolling One Road Over One Day. Each Subfigure Highlights Different Visualization Approaches. Tracks on the Map (a) Provide Spatial Context, While 3D Visualization (b) Adds a Temporal Dimension. Workload Overviews (c) and (d) Summarize Operational Details by Road Segment and Time, With the Improved Version Offering Greater Clarity for Multisection Scenarios.

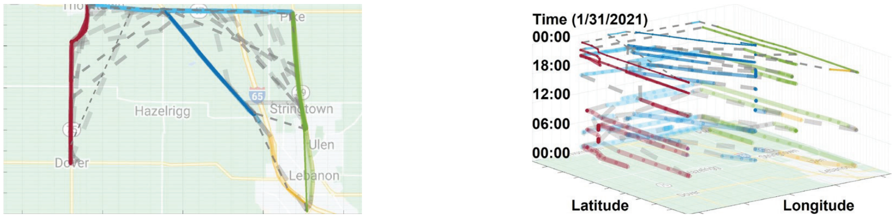


(a) Tracks on Map. (b) 3D Visualization With Time.

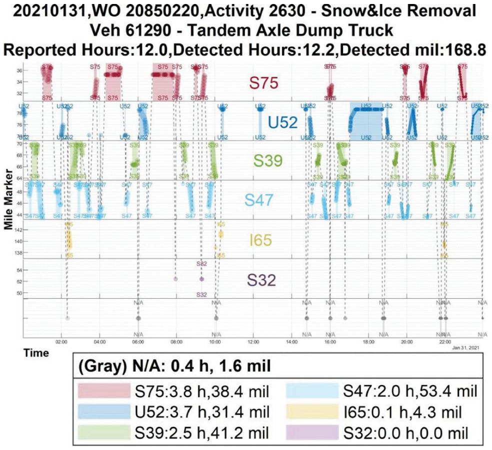

20210131,WO 20850229,Activity 2630 - Snow&Ice Removal
Veh 62894 - Tandem Truck Multipurpose Bed
Reported Hours:8.0,Detected Hours:7.9,Detected mil:125.1

(c) Workload Overview.

Figure 3.5 A Snowplow Clearing One Road in One Day. Tracks on the Map (a) Provide Spatial Context, While 3D Visualization (b) Incorporates Temporal Information. The Workload Overview (c) Summarizes Operations, Detailing the Cumulative Duration and Mileage of Activity Along the Road Segment of Interest.



(a) Tracks on Map. (b) 3D Visualization With Time.

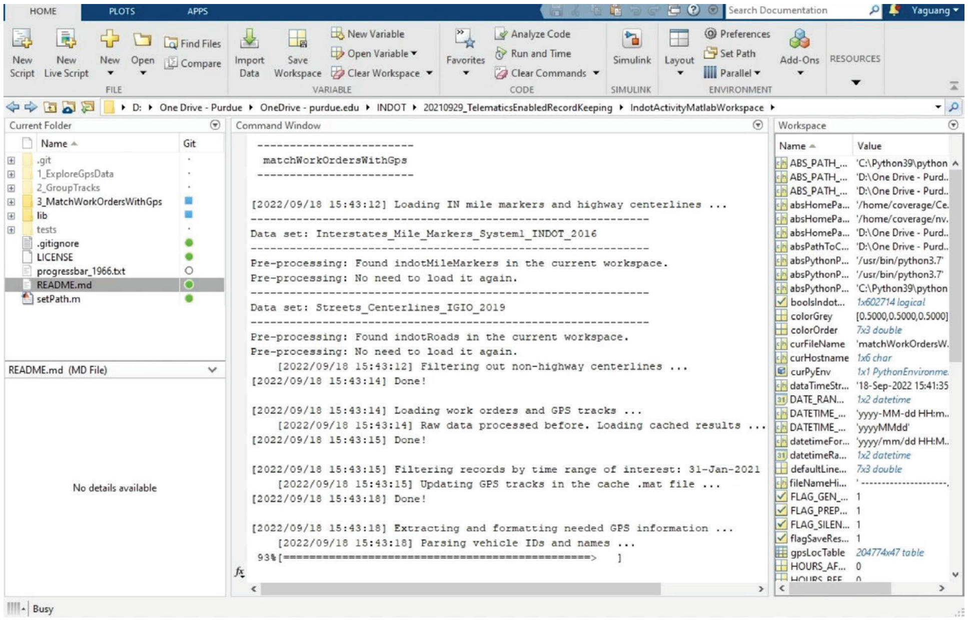

20210131,WO 20850220,Activity 2630 - Snow&Ice Removal
Veh 61290 - Tandem Axle Dump Truck
Reported Hours:12.0,Detected Hours:12.2,Detected mil:168.8

(c) Workload Overview.

Figure 3.6 A Snowplow Conducting Multiroad Clearing Operations Over a Single Day. The Mapped Tracks (a) Offer Spatial Context, While the 3D Visualization (b) Integrates Temporal Dynamics, Illustrating Movement Patterns Over Time. The Workload Overview (c) Provides a Comprehensive Summary of Operations, Detailing the Cumulative Duration and Mileage of Activity Across Various Road Segments.

for manual inspection by operators or managers. Moreover, the program computes matching scores between the recorded work hours in existing work orders and those extracted by our algorithms. The verification report, shown in Figure 3.7b, displays these scores and other crucial extracted information, with a 100% score indicating a perfect match. Work orders with lower scores may necessitate further attention.

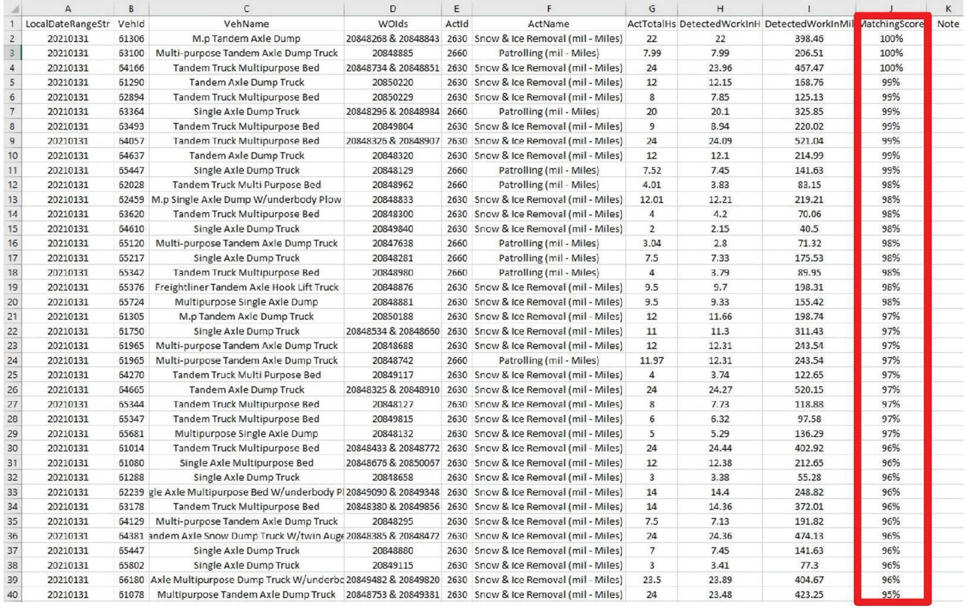
All results are accessible through the OneDrive web app, as illustrated in Figure 3.7c. This platform facilitates easy viewing, sorting, filtering, and sharing of results. Following this approach, we process INDOT data using powerful clusters at Purdue University. The results are seamlessly uploaded to OneDrive, facilitating effortless sharing with INDOT engineers for further investigation and analysis.



```
  ------------------------
   matchWorkOrdersWithGps
  ------------------------

[2022/09/18 15:43:12] Loading IN mile markers and highway centerlines ...
------------------------------------------------------------
Data set: Interstates_Mile_Markers_System1_INDOT_2016
------------------------------------------------------------
Pre-processing: Found indotMileMarkers in the current workspace.
Pre-processing: No need to load it again.
------------------------------------------------------------
Data set: Streets_Centerlines_IGIO_2019
------------------------------------------------------------
Pre-processing: Found indotRoads in the current workspace.
Pre-processing: No need to load it again.
    [2022/09/18 15:43:12] Filtering out non-highway centerlines ...
[2022/09/18 15:43:14] Done!

[2022/09/18 15:43:14] Loading work orders and GPS tracks ...
    [2022/09/18 15:43:14] Raw data processed before. Loading cached results ...
[2022/09/18 15:43:15] Done!

[2022/09/18 15:43:15] Filtering records by time range of interest: 31-Jan-2021
    [2022/09/18 15:43:15] Updating GPS tracks in the cache .mat file ...
[2022/09/18 15:43:18] Done!

[2022/09/18 15:43:18] Extracting and formatting needed GPS information ...
    [2022/09/18 15:43:18] Parsing vehicle IDs and names ...
 93%[=================================================>    ]
```

Name	Value
ABS_PATH_...	'C:\Python39\python
ABS_PATH_...	'D:\One Drive - Purd..
ABS_PATH_...	'D:\One Drive - Purd..
absHomePa...	'/home/coverage/Ce.
absHomePa...	'/home/coverage/nv.
absHomePa...	'D:\One Drive - Purd..
absPathToC...	'D:\One Drive - Purd..
absPythonP...	'/usr/bin/python3.7'
absPythonP...	'/usr/bin/python3.7'
absPythonP...	'C:\Python39\python
boolsIndot...	1x602714 logical
colorGrey	[0.5000,0.5000,0.5000]
colorOrder	7x3 double
curFileName	'matchWorkOrdersW.
curHostname	1x6 char
curPyEnv	1x1 PythonEnvironme.
dataTimeStr...	'18-Sep-2022 15:41:35
DATE_RAN...	1x2 datetime
DATETIME_...	'yyyy-MM-dd HH:m..
DATETIME_...	'yyyyMMdd'
datetimeFor...	'yyyy/mm/dd HH:M..
datetimeRa...	1x2 datetime
defaultLine...	7x3 double
fileNameHi...	' --------------------.
FLAG_GEN_...	1
FLAG_PREP...	1
FLAG_SILEN...	1
flagSaveRes...	1
gpsLocTable	204774x47 table
HOURS_AF...	0

(a) Screenshot of the Program.



	A	B	C	D	E	F	G	H	I	J	K
1	LocalDateRangeStr	VehId	VehName	WOIds	ActId	ActName	ActTotalHs	DetectedWorkInH	DetectedWorkInMil	MatchingScore	Note
2	20210131	61306	M.p Tandem Axle Dump	20848268 & 20848843	2630	Snow & Ice Removal (mil - Miles)	22	22	398.46	100%	
3	20210131	63100	Multi-purpose Tandem Axle Dump Truck	20848885	2660	Patrolling (mil - Miles)	7.99	7.99	206.51	100%	
4	20210131	64166	Tandem Truck Multipurpose Bed	20848734 & 20848851	2630	Snow & Ice Removal (mil - Miles)	24	23.96	467.47	100%	
5	20210131	61290	Tandem Axle Dump Truck	20850220	2630	Snow & Ice Removal (mil - Miles)	12	12.15	168.76	99%	
6	20210131	62894	Tandem Truck Multipurpose Bed	20850229	2630	Snow & Ice Removal (mil - Miles)	8	7.85	125.13	99%	
7	20210131	63364	Single Axle Dump Truck	20848296 & 20848984	2660	Patrolling (mil - Miles)	20	20.1	325.85	99%	
8	20210131	63493	Tandem Truck Multipurpose Bed	20849804	2630	Snow & Ice Removal (mil - Miles)	9	8.94	220.02	99%	
9	20210131	64057	Tandem Truck Multipurpose Bed	20848326 & 20848907	2630	Snow & Ice Removal (mil - Miles)	24	24.09	521.04	99%	
10	20210131	64637	Tandem Axle Dump Truck	20848320	2630	Snow & Ice Removal (mil - Miles)	12	12.1	214.99	99%	
11	20210131	65447	Single Axle Dump Truck	20848129	2660	Patrolling (mil - Miles)	7.52	7.45	141.63	99%	
12	20210131	62028	Tandem Truck Multi Purpose Bed	20848962	2660	Patrolling (mil - Miles)	4.01	3.83	83.15	98%	
13	20210131	62459	M.p Single Axle Dump W/underbody Plow	20848833	2630	Snow & Ice Removal (mil - Miles)	12.01	12.21	219.21	98%	
14	20210131	63620	Tandem Truck Multipurpose Bed	20848300	2630	Snow & Ice Removal (mil - Miles)	4	4.2	70.06	98%	
15	20210131	64610	Single Axle Dump Truck	20849840	2630	Snow & Ice Removal (mil - Miles)	2	2.15	40.5	98%	
16	20210131	65120	Multi-purpose Tandem Axle Dump Truck	20847638	2660	Patrolling (mil - Miles)	3.04	2.8	71.32	98%	
17	20210131	65217	Single Axle Dump Truck	20848281	2660	Patrolling (mil - Miles)	7.5	7.33	175.53	98%	
18	20210131	65342	Tandem Truck Multipurpose Bed	20848980	2660	Patrolling (mil - Miles)	4	3.79	89.95	98%	
19	20210131	65376	Freightliner Tandem Axle Hook Lift Truck	20848876	2630	Snow & Ice Removal (mil - Miles)	9.5	9.7	198.31	98%	
20	20210131	65724	Multipurpose Single Axle Dump	20848881	2630	Snow & Ice Removal (mil - Miles)	9.5	9.33	155.42	98%	
21	20210131	61305	M.p Tandem Axle Dump Truck	20850188	2630	Snow & Ice Removal (mil - Miles)	12	11.66	198.74	97%	
22	20210131	61750	Single Axle Dump Truck	20848534 & 20848660	2630	Snow & Ice Removal (mil - Miles)	11	11.3	311.43	97%	
23	20210131	61965	Multi-purpose Tandem Axle Dump Truck	20848688	2630	Snow & Ice Removal (mil - Miles)	12	12.31	243.54	97%	
24	20210131	61965	Multi-purpose Tandem Axle Dump Truck	20848742	2660	Patrolling (mil - Miles)	11.97	12.31	243.54	97%	
25	20210131	64270	Tandem Truck Multi Purpose Bed	20849117	2630	Snow & Ice Removal (mil - Miles)	4	3.74	122.65	97%	
26	20210131	64665	Tandem Axle Dump Truck	20848325 & 20848910	2630	Snow & Ice Removal (mil - Miles)	24	24.27	520.15	97%	
27	20210131	65344	Tandem Truck Multipurpose Bed	20848127	2630	Snow & Ice Removal (mil - Miles)	8	7.73	118.88	97%	
28	20210131	65347	Tandem Truck Multipurpose Bed	20849815	2630	Snow & Ice Removal (mil - Miles)	6	6.32	97.58	97%	
29	20210131	65681	Multipurpose Single Axle Dump	20848132	2630	Snow & Ice Removal (mil - Miles)	5	5.29	136.29	97%	
30	20210131	61014	Tandem Truck Multipurpose Bed	20848433 & 20848772	2630	Snow & Ice Removal (mil - Miles)	24	24.44	402.92	96%	
31	20210131	61080	Single Axle Multipurpose Bed	20848676 & 20850067	2630	Snow & Ice Removal (mil - Miles)	12	12.38	212.65	96%	
32	20210131	61288	Single Axle Dump Truck	20848658	2630	Snow & Ice Removal (mil - Miles)	3	3.38	55.28	96%	
33	20210131	62239	gle Axle Multipurpose Bed W/underbody Pl	20849090 & 20849348	2630	Snow & Ice Removal (mil - Miles)	14	14.4	248.82	96%	
34	20210131	63178	Tandem Truck Multipurpose Bed	20848380 & 20849856	2630	Snow & Ice Removal (mil - Miles)	14	14.36	372.01	96%	
35	20210131	64129	Multi-purpose Tandem Axle Dump Truck	20848295	2630	Snow & Ice Removal (mil - Miles)	7.5	7.13	191.82	96%	
36	20210131	64381	andem Axle Snow Dump Truck W/twin Auge	20848385 & 20848472	2630	Snow & Ice Removal (mil - Miles)	24	24.36	474.13	96%	
37	20210131	65447	Single Axle Dump Truck	20848880	2630	Snow & Ice Removal (mil - Miles)	7	7.45	141.63	96%	
38	20210131	65802	Single Axle Dump Truck	20849115	2630	Snow & Ice Removal (mil - Miles)	3	3.41	77.3	96%	
39	20210131	66180	Axle Multipurpose Dump Truck W/underbc	20849482 & 20849820	2630	Snow & Ice Removal (mil - Miles)	23.5	23.89	404.67	96%	
40	20210131	61078	Multipurpose Tandem Axle Dump Truck	20848753 & 20849381	2630	Snow & Ice Removal (mil - Miles)	24	23.48	423.25	95%	

(b) Example Work Order Verification Scoring Results.

Figure 3.7 MATLAB Program (Zhang, 2023) for Fully Automated Work Order Verification.

(c) Algorithm Outputs for 1/31/2021 Hosted on OneDrive.

Figure 3.7 Continued

4. WEB APPLICATION FOR GPS-BASED WORK ORDER AUTOMATION

Building on the insights and algorithms developed in MATLAB, we implemented a web-based application designed to automate work orders and streamline fleet management for winter operations (Ault & Naman, 2024a, 2024b). While the MATLAB tool serves as a research platform for algorithm development and optimization, this web application provides a practical, user-friendly interface for operational use by INDOT fleet managers and operators. In this section, we detail the web application's design, its core features, and the algorithms utilized to calculate operational metrics, such as snow operation time for specific vehicles on designated road segments.

4.1 Web Application

The initial interface of the web application, as depicted in Figure 4.1, is systematically divided into two primary sections: a map and a control panel. This dual-section design works well in allowing simultaneous access to both controls and map

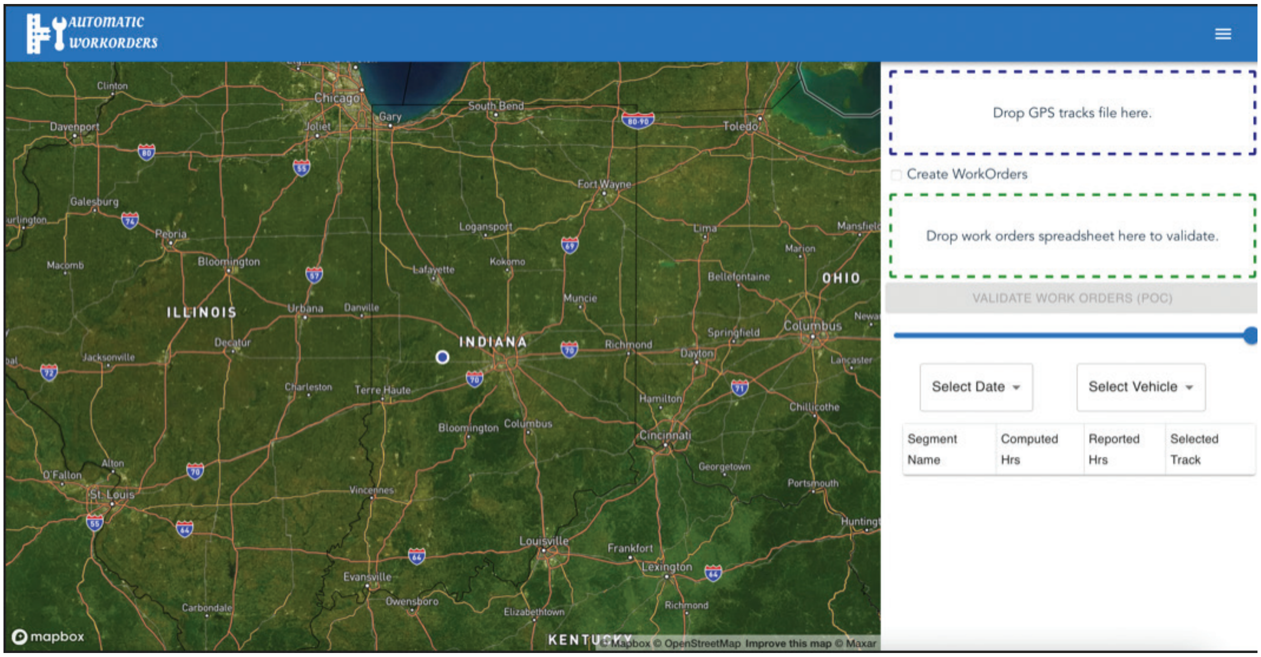


Figure 4.1 Initial View of the Web Application.

visualization on a laptop or desktop-sized, landscape-oriented screen which is the targeted use case.

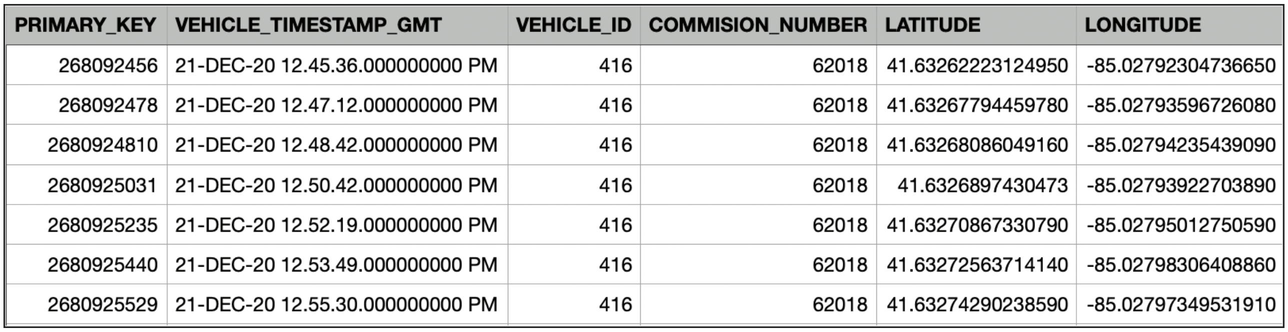
The map interface, powered by Mapbox, occupies the left and central portions of the screen. This dynamic and interactive feature provides a satellite view of Indiana, highlighting all major state highways and interstates, and delineating state boundaries. This helps users, particularly fleet managers and operators, to visualize their vehicles' locations and movements across the region. A prominent blue marker is displayed at the start location of a selected vehicle, allowing users to quickly identify the vehicle's initial position. This marker represents the vehicle's "current location" corresponding to the position of the time slider in the control panel, while a line element is drawn to represent the vehicle's historical path from the start of the day up to that synthetic "current" location. The line segment feature, which visually represents the vehicle's route on the chosen day, will be described and shown in detail later.

To the right of the map is the control panel, divided into several interactive sections designed to enhance the management and tracking of vehicle activities. The upper segment as seen in Figure 4.1 of this panel features two prominent file upload areas. The top box, outlined with a blue dashed border, is designated for uploading GPS track files. This feature allows users to input data directly from their fleet's GPS systems, ensuring accurate tracking and analysis of vehicle movements. Below this, a green dashed box is reserved for work order spreadsheets. Figure 4.2 and Figure 3.2 show examples of the GPS data and work order records that are used as input for the application, respectively. Upon uploading a valid work order spreadsheet, the *Validate Work Orders* button becomes active, initiating the validation process. After validation, you can download the validation report. An example of a validation report can be seen in Figure 4.3.

In the control panel, a checkbox labeled *Create Work Orders* allows users to initiate the creation of work orders directly from the interface by uploading a list of vehicle activities, thereby automating the tedious process of manually recording work activity for each covered road segment. The work order creation interface is shown in Figure 4.4. An example of vehicle activities used as input for work order creation can be seen in Figure 4.5. An example of created work orders can be seen in Figure 4.6.

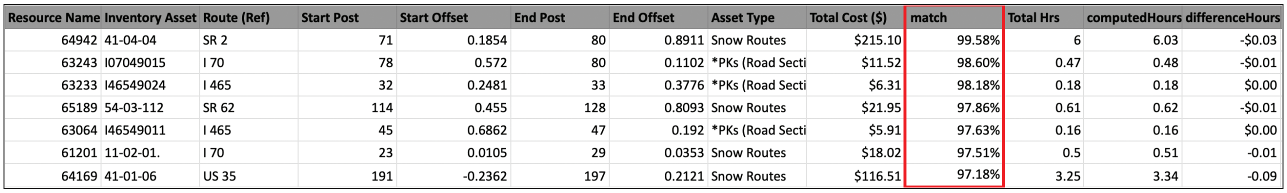
This application also extends its functionality through the inclusion of supplementary tools designed for targeted data selection and manipulation. These tools, as seen in the middle of the right panel in Figure 4.1, are in the form of drop-down menus labeled *Select Date* and *Select Vehicle*. They allow users to implement granular filters, enabling the visualization and analysis of data about specific dates or individual vehicles within the fleet. The tools become available when the checkbox *Create Work Orders* is disabled, allowing users to customize their interaction with the data as needed for work order verification. This feature proves particularly advantageous in facilitating historical data analysis and the focused tracking of specific vehicles. Once a desired vehicle ID and date are selected, the application leverages GPS data to generate a visual representation of the chosen vehicle's track.

Further customization options are facilitated by a horizontal slider positioned beneath the validation button. This slider, as seen in Figure 4.1, allows users to dynamically adjust the displayed timeframe, enabling the tracking of a particular vehicle's path through the use of animated lines. These lines are color-coded by time intervals, with red signifying past GPS data points and blue highlighting the most recently traversed location. This implementation injects a dynamic element into the application, empowering users to gain valuable insights into vehicle



PRIMARY_KEY	VEHICLE_TIMESTAMP_GMT	VEHICLE_ID	COMMISION_NUMBER	LATITUDE	LONGITUDE
268092456	21-DEC-20 12.45.36.000000000 PM	416	62018	41.63262223124950	-85.02792304736650
268092478	21-DEC-20 12.47.12.000000000 PM	416	62018	41.63267794459780	-85.02793596726080
2680924810	21-DEC-20 12.48.42.000000000 PM	416	62018	41.63268086049160	-85.02794235439090
2680925031	21-DEC-20 12.50.42.000000000 PM	416	62018	41.6326897430473	-85.02793922703890
2680925235	21-DEC-20 12.52.19.000000000 PM	416	62018	41.63270867330790	-85.02795012750590
2680925440	21-DEC-20 12.53.49.000000000 PM	416	62018	41.63272563714140	-85.02798306408860
2680925529	21-DEC-20 12.55.30.000000000 PM	416	62018	41.63274290238590	-85.02797349531910

Figure 4.2 Sample GPS Data.



Resource Name	Inventory Asset	Route (Ref)	Start Post	Start Offset	End Post	End Offset	Asset Type	Total Cost ($)	match	Total Hrs	computedHours	differenceHours
64942	41-04-04	SR 2	71	0.1854	80	0.8911	Snow Routes	$215.10	99.58%	6	6.03	-$0.03
63243	I07049015	I 70	78	0.572	80	0.1102	*PKs (Road Secti	$11.52	98.60%	0.47	0.48	-$0.01
63233	I46549024	I 465	32	0.2481	33	0.3776	*PKs (Road Secti	$6.31	98.18%	0.18	0.18	$0.00
65189	54-03-112	SR 62	114	0.455	128	0.8093	Snow Routes	$21.95	97.86%	0.61	0.62	-$0.01
63064	I46549011	I 465	45	0.6862	47	0.192	*PKs (Road Secti	$5.91	97.63%	0.16	0.16	$0.00
61201	11-02-01.	I 70	23	0.0105	29	0.0353	Snow Routes	$18.02	97.51%	0.5	0.51	-0.01
64169	41-01-06	US 35	191	-0.2362	197	0.2121	Snow Routes	$116.51	97.18%	3.25	3.34	-0.09

Figure 4.3 Sample Verification Report. The "Match" Column, Highlighted by The Red Rectangle, Indicates How Closely the Computed Time Aligns With the Reported Time.

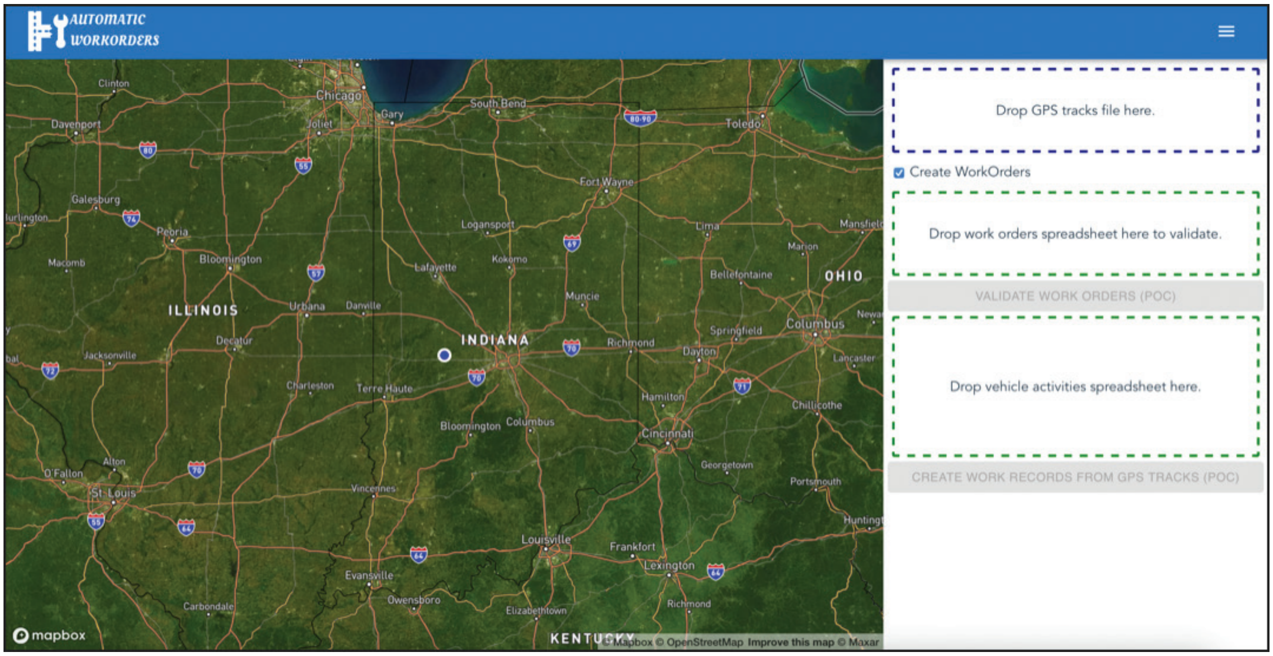
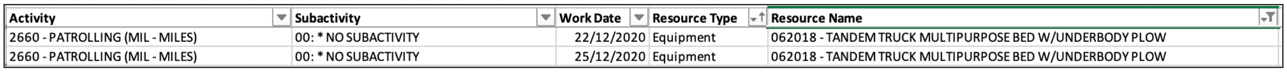
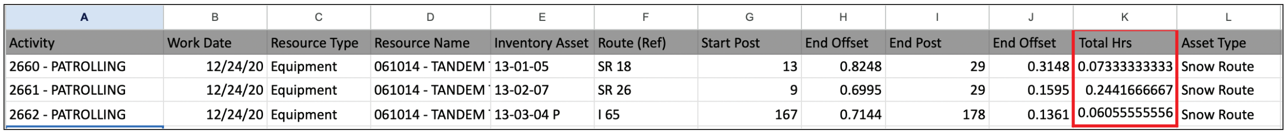


Figure 4.4 Work Order Creation Interface.



Activity	Subactivity	Work Date	Resource Type	Resource Name
2660 - PATROLLING (MIL - MILES)	00: * NO SUBACTIVITY	22/12/2020	Equipment	062018 - TANDEM TRUCK MULTIPURPOSE BED W/UNDERBODY PLOW
2660 - PATROLLING (MIL - MILES)	00: * NO SUBACTIVITY	25/12/2020	Equipment	062018 - TANDEM TRUCK MULTIPURPOSE BED W/UNDERBODY PLOW

Figure 4.5 Sample Vehicle Activity Data.



A	B	C	D	E	F	G	H	I	J	K	L
Activity	Work Date	Resource Type	Resource Name	Inventory Asset	Route (Ref)	Start Post	End Offset	End Post	End Offset	Total Hrs	Asset Type
2660 - PATROLLING	12/24/20	Equipment	061014 - TANDEM	13-01-05	SR 18	13	0.8248	29	0.3148	0.07333333333	Snow Route
2661 - PATROLLING	12/24/20	Equipment	061014 - TANDEM	13-02-07	SR 26	9	0.6995	29	0.1595	0.2441666667	Snow Route
2662 - PATROLLING	12/24/20	Equipment	061014 - TANDEM	13-03-04 P	I 65	167	0.7144	178	0.1361	0.06055555556	Snow Route

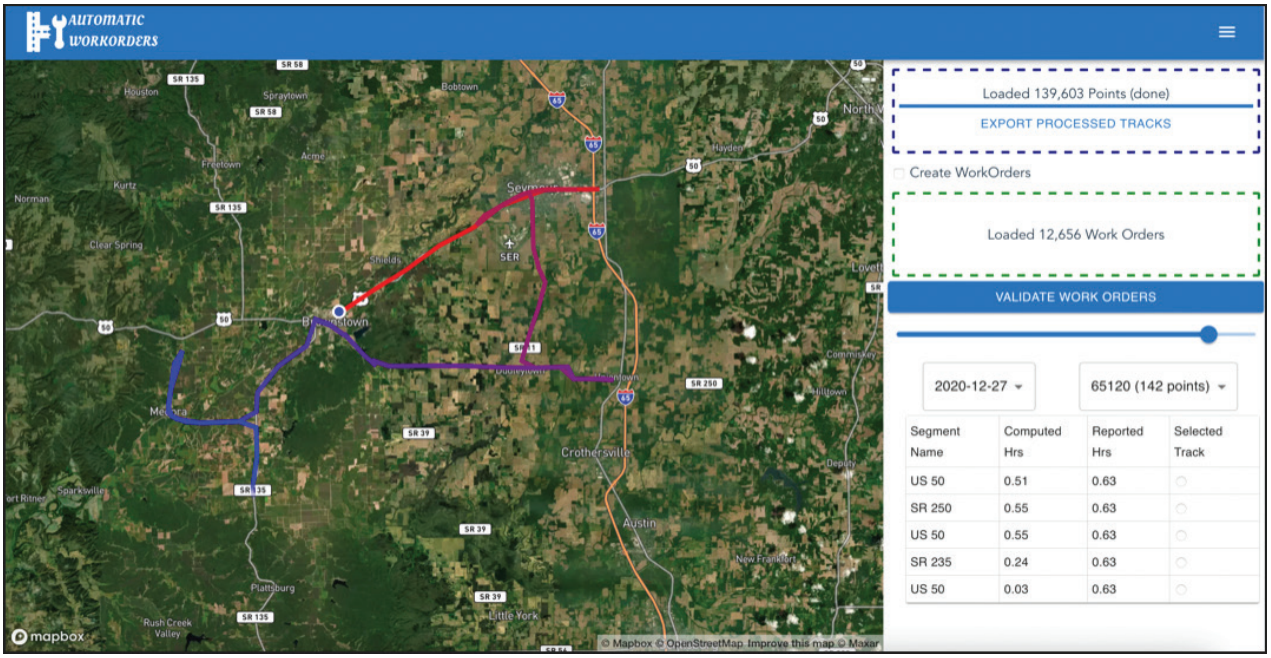
Figure 4.6 Sample Created Work Order Report. The *Total Hrs* Column, Highlighted by the Red Rectangle, Indicates the Computed Time for the Given Road Segment.

movements across the temporal dimension. A visual representation of a vehicle's tracked path can be found in Figure 4.7.

At the bottom of the control panel, there is a table, as seen in Figure 4.7, designed to show detailed information about the chosen vehicle's operations during work order verification. The table has columns labeled *Segment Name*, *Computed Hrs*, *Reported Hrs*, and *Selected Track*. These columns provide specific insights into the fleet's activities. *Segment Name* shows the specific road segment the vehicle traveled on that day. *Computed Hrs* and *Reported Hrs* provide a comparison between the exact time spent on each road segment, as calculated from the GPS data timestamps, and the time reported for those segments in the system records. This allows for accurate verification of reported times and identification of any discrepancies.

The *Selected Track* column contains radio buttons allowing users to focus on specific road segments rather than the entire route. By selecting a radio button, users can isolate and examine the details of a particular segment. This table provides a clear summary of the selected vehicle's activities, enabling managers to quickly assess performance, identify discrepancies, and make informed decisions to improve fleet operations. A working visual example of a specific segment the vehicle traveled, along with the table summarizing the fleet's activities for each road segment on the selected date, can be seen in Figure 4.8.

Overall, the application design allows for robust visualization of detailed paths over time, even when snow plows travel back and forth over the same road.



Loaded 139,603 Points (done)

☐ Create WorkOrders

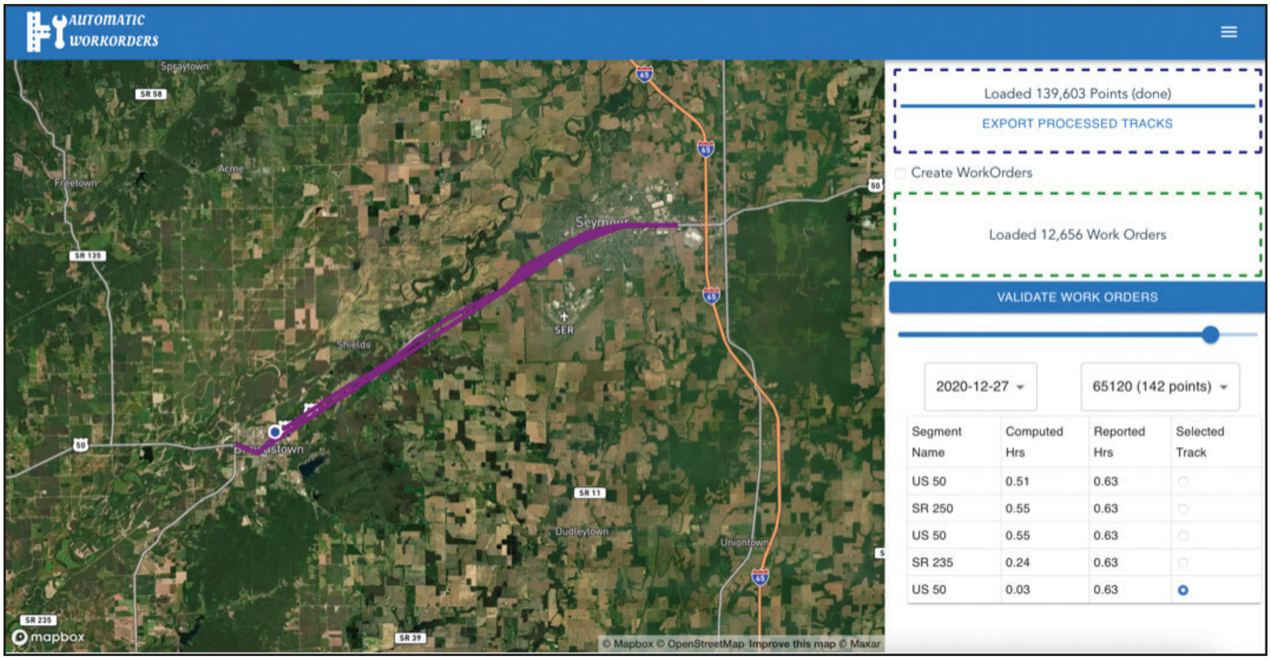
Loaded 12,656 Work Orders

2020-12-27

65120 (142 points)

Segment Name	Computed Hrs	Reported Hrs	Selected Track
US 50	0.51	0.63	○
SR 250	0.55	0.63	○
US 50	0.55	0.63	○
SR 235	0.24	0.63	○
US 50	0.03	0.63	○

Figure 4.7 Interface Displaying a Sample Case With the Vehicle's Path Traced From GPS Data.



Loaded 139,603 Points (done)

☐ Create WorkOrders

Loaded 12,656 Work Orders

2020-12-27

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Segment Name	Computed Hrs	Reported Hrs	Selected Track
US 50	0.51	0.63	○
SR 250	0.55	0.63	○
US 50	0.55	0.63	○
SR 235	0.24	0.63	○
US 50	0.03	0.63	●

Figure 4.8 Interface With a Working Example Case Illustrating the Specific Road Segment Path Traced by the Vehicle Using GPS Data.

4.2 Algorithm for Automated Work Order Verification

This section details the algorithms embedded in the web application to analyze GPS data and calculate the *Computed Hours* displayed in the summary table. Figure 4.9 provides a high-level view of the application's backend, showing how these algorithms process inputs to generate and display results.

The first part of the algorithm determines the most likely road the vehicle is on at each GPS point or decides if the vehicle is off the road. To handle the large number of points in the INDOT dataset efficiently, the algorithm uses geohashing (Niemeyer, 2008) to group nearby road segments together and then find the relevant group for each point. This process

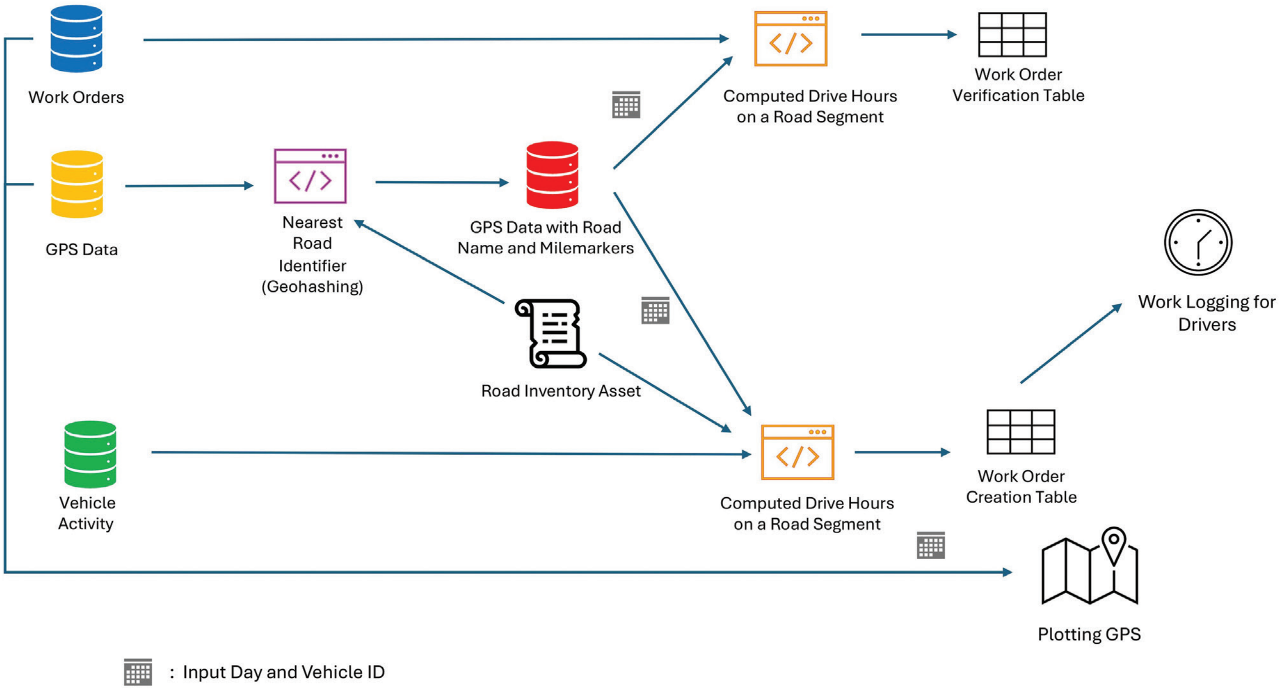

Figure 4.9 Overview of Backend Processing, Showing How Input Data Is Transformed by Algorithms to Generate Results in the Web Application.

is illustrated as the pink program in Figure 4.9. After identifying the roads and mile marker offsets for each GPS point, the second part of the algorithm calculates the *Computed Hours*, which represents the total time the vehicle was operating on each road segment that day. This step is shown as the orange program in Figure 4.9.

Before diving into the algorithm, we also define a few key terms that will be referenced in the following sections:

- Route Ref: This is the road name or reference identifier for the road segment.
- Road Type: This refers to the classification of the road, such as interstate, highway, state highway, etc.
- Mile Markers: These are numerical values representing specific locations along a road, typically indicating distance from a defined starting point.
- Start Post and End Post: These are the mile markers that denote the beginning and end of a road segment.
- Road Inventory Assets: These are the comprehensive collection of road segments used by INDOT to facilitate maintenance, planning, and operational efficiency.

4.2.1 Geohashing for Nearest Road Identification

For calculating *Computed Hours* for each road segment the vehicle traveled on that day, we first need to ensure that the current GPS point is on the mentioned road segment. Identifying the closest road to a GPS point is a complex problem due to the large number of roads and GPS points involved. Each GPS point must be compared to every road, requiring a vast number of distance calculations. This brute-force approach is slow and inefficient, as it involves looping through all roads for every single GPS point, resulting in a huge computational load. Additionally, handling the full road dataset in one go is impractical, especially in memory-limited environments like web browsers, because the data is too large to download and process efficiently.

Geohashing offers an elegant solution to this problem. It encodes geographic coordinates into short strings of letters and numbers, each representing a small rectangular area on a map, called a tile. By dividing the entire map into these smaller tiles, geohashing creates a spatial index that makes it much easier to manage and search the data (Niemeyer, 2008). Algorithm 1 (Figure 4.10 illustrates the pseudo-code implementation. When a GPS point needs to be processed, its geohash is calculated to determine which tile it falls into. Only the roads within this tile and its neighboring tiles need to be considered, drastically reducing the number of distance calculations required (Figure 4.10, lines 3–5).

This method not only speeds up the computation but also reduces the amount of data that needs to be downloaded to the browser at any one time. Instead of dealing with the entire road dataset, the algorithm can focus on a much smaller subset, making it feasible to run efficiently even in a web browser. This allows the spatially indexed set of road segments to be hosted entirely in GitHub Pages as small, simple files named by their geohash, eliminating the need for any external database or server. By limiting the search to a localized area, geohashing ensures that the process of finding the nearest road is both quick and resource-efficient (Figure 4.10, lines 6–13).

The algorithm also employs a hierarchical decision-making process to select the most appropriate road. Initially, it checks

Algorithm 1 Geohashing for Nearest Road Identification

```
function IdentifyRoads(GPSPoints, Roads)
    GeohashMap ← createGeohashMap(Roads)
    for each point in GPSPoints do
        currentGeohash ← computeGeohash(point)
        nearbyTiles ← getNearbyTiles(currentGeohash)
        candidateRoads ← retrieveRoads(GeohashMap, nearbyTiles)
        minDistance ← infinity
        closestRoad ← null
        for each road in candidateRoads do
            distance ← calculateDistance(point, road)
            if distance ¡ minDistance then
                minDistance ← distance
                closestRoad ← road
            end if
        end for
        selectedRoad ← null
        if isHintRoadValid(previousRoad, point) then
            selectedRoad ← previousRoad
        else if isCloseEnough(closestInterstate, point) then
            selectedRoad ← closestInterstate
        else if isCloseEnough(closestStateRoad, point) then
            selectedRoad ← closestStateRoad
        else if isCloseEnough(closestLocalRoad, point) then
            selectedRoad ← closestLocalRoad
        else
            selectedRoad ← OffRoad
        end if
        updatePreviousRoad(selectedRoad)
    end for
end function
```

Figure 4.10 Pseudo-Code for Algorithm 1 Illustrating Geohash-Based Nearest Road Identification.

if the previously identified road (what we call the *hint road*) is still valid for the current GPS point (Figure 4.10, line 16). If not, it prioritizes the nearest interstate roads, followed by state and local roads, based on their proximity (Figure 4.10, lines 17–23). If no road is sufficiently close, the point is classified as off-road. This structured approach ensures that the road identification process is deterministic, resilient to accidental jumps when a vehicle crosses other roads, and it favors selecting interstates and state highways where INDOT snowplowing typically occurs. This geohashing and distance algorithm allows fast identification of roads for a given GPS data point significantly improving the performance and practicality of GPS-based road identification.

4.2.2 Compute Seconds on Road Segment for Vehicle on Day

In this section, we describe the second algorithm that calculates the number of hours a vehicle was actively engaged in snow plowing and patrolling operations on *each specific road segment* listed in the work order records for a given day. This provides detailed data for the summary table, as shown in Figure 4.8.

The algorithm works by processing each GPS data point for a vehicle on the selected road segment from the work orders. It sums the valid driving durations between successive GPS points while ignoring periods when the vehicle is stationary or the data is unreliable. Algorithm 2 (Figure 4.11) presents the pseudo-code for this implementation.

The algorithm starts by taking the vehicle ID and day information along with a road segment as input and verifies the presence of a route reference, denoted as **Route Ref**, for the input segment **seg**. This route reference serves as the identifier for the specific road under consideration. If this reference is absent, it is impossible to determine the pertinent road segment, which leads to a return value of 0 seconds. This precautionary step ensures that the algorithm only processes segments with identifiable route information, thereby maintaining data integrity and avoiding erroneous calculations.

We then utilize the **roadNameToType** function to discern the road type and name from the route reference. This function is pivotal as it standardizes the identification of road types, such as interstate highways or local roads. By initializing the **startpost**

Algorithm 2 Compute Seconds on Road Segment for Vehicle on Day

```
function ComputeSecondsOnRoadSegmentForVehicleOnDay(seg, vehicleid, day)
    if Route Reference not present in seg then
        log(”No Route Ref”)
        return 0
    end if
    seg_road ← roadNameToType(seg.RouteRef)
    Initialize startpost, endpost, startoffset, endoffset
    if Start Post, End Post, Start Offset, and End Offset exist in seg then
        milemarkers ← fetchMileMarkersForRoad(road)
        if milemarkers is empty then
            return 0
        end if
        startpost ← find(milemarkers, seg.StartPost)
        endpost ← find(milemarkers, seg.EndPost)
        if startpost or endpost is empty then
            return 0
        end if
        Adjust startpost and endpost for offsets
    end if
    dt ← daytracks[day][vehicleid]
    if dt is empty then
        return 0
    end if
    computedSeconds ← 0
    for each (index, point) in dt.track do
        if point.road is empty or point.road ≠ seg_road then
            continue
        end if
        if startpost and endpost are defined then
            Validate point against startpost and endpost
        end if
        next_point ← dt.track[index + 1]
        duration ← min(next_point.time.unix() - point.time.unix(), 600)
        computedSeconds ← computedSeconds + duration
    end for
    computedHrs ← computedSeconds / 3600
    return computedHrs
end function
```

Figure 4.11 Pseudo-code for Algorithm 2 Illustrating the Computation of Driving Time on a Specified Road Segment by Aggregating Valid Durations Between Successive GPS Points.

and **endpost** variables along with their respective offsets, the algorithm sets the stage for accurate segment delineation.

Mile markers are indispensable for precise localization along a road. They provide exact reference points, facilitating accurate distance and time measurements. If either the start post or end post is missing, the algorithm logs this discrepancy and returns 0 seconds. This ensures that calculations are only performed when both mile markers are available, thus preventing inaccuracies due to incomplete data. To maintain logical consistency, the algorithm assesses and adjusts the start and end posts based on the presence of positive or negative offsets. For instance, a negative start offset necessitates adjusting the start post to the preceding mile marker, while a positive end offset requires adjusting the end post to the subsequent mile marker. These adjustments ensure that the segment boundaries are accurately defined, reflecting any offsets specified in the segment data.

The algorithm then iterates through each recorded GPS point in the vehicle’s track. These GPS points already have the nearest identifiable road precomputed using geohashing. For each point, it then verifies whether the point lies on the specified road segment. If the segment has defined start and end posts, it further validates the point's position relative to these posts and their offsets. If the point satisfies all these conditions, the algorithm calculates the duration to the next point by computing the time difference between the current and next points. This duration is capped at 10 minutes to handle potential long gaps in the data. The hard threshold of 10 minutes is chosen based on sampling statistics of GPS points in the dataset, where 14% of points have gaps that extend beyond 5 minutes. This helps in ensuring that any prolonged discontinuities do not skew the results. The calculated duration is then aggregated and returned as the final result, as well as exported as the application's output depending on the choice of verification and creation. An example of a verification case is shown in Figure 4.8, where the value is displayed in the summary table as well as the output reports in Figure 4.3 and Figure 4.6.

4.3 Potential Real-World Application

In this section, we discuss the real-world application of our system, providing examples that highlight its potential.

4.3.1 Time Granularity in Work Orders

A significant challenge in the telematics dataset is the lack of granularity in the start and end times for work orders (WOs). This limitation complicates the process of obtaining exact verification matches between the telematics data and the work orders. As shown in Table 4.1, the majority of work orders (21,655) in our dataset are confined to a single day. However, there are notable instances where work orders extend across multiple days.

The key issue is that each work order entry in our dataset has only one date, without a precise timestamp. For instance, one work order spans eight days, involving more than ten different vehicles, highlighting the challenges due to the absence of precise start and end times. Ideally, we need two timestamps (start and end) for each work order to enhance accuracy and clarity. This lack of temporal granularity leads to several implications:

- Verification Difficulty: Human-entered work orders may not use the same midnight-to-midnight convention as the algorithms, leading to difficult-to-detect errors in work order verification.
- Extended Work Orders: Work orders may extend beyond the recorded date, either starting earlier or ending later, leading to potential inaccuracies.
- Data Entry Errors: Manual entry can result in work orders spanning non-consecutive days or involving multiple vehicles.

TABLE 4.1
Distribution of Work Orders Across Multiple Days.

Days Spread	WO Count
1 day	21655
2 days	989
3 days	47
4 days	2
5 days	4
6 days	0
7 days	2
8 days	1

Integrating our system into the work order management process can effectively address these issues. Our automated system is capable of incorporating precise start and end timestamps when creating work records, significantly enhancing the accuracy and verification of work order records.

4.3.2 Calculation of Work Hours for Drivers

During storm events, drivers often work extended hours, and manually logging these hours becomes both a distraction and a significant burden. The manual process of recording work orders is time-consuming and prone to errors and delays. In severe snowstorms, the high volume of work orders can overwhelm manual systems, causing delays in processing drivers' salaries and resulting in dissatisfaction among drivers who rely on timely payment for their extended shifts. From a managerial perspective, manually creating work records is necessary but low-value, diverting time from strategic activities such as planning and resource allocation.

Our application simplifies this process by automating the recording of work hours. Instead of manually logging each entry, our system calculates the total work hours by summing the operational time of the given vehicle ID for the given day. This approach streamlines the process, reduces errors, and ensures accurate and timely reporting of work hours.

To translate vehicle total work hours into driver work hours, we require a means to identify which drivers are driving which vehicles. While we currently lack such a dataset, an exported spreadsheet of vehicle drive times can be easily annotated with driver information for cases where the same driver uses the same vehicle for the entire day.

4.3.3 Visualization of Overlapping Roads When Tracking Vehicles

Tracking vehicle movements accurately, especially during winter maintenance operations, often involves dealing with overlapping road segments. Vehicles may travel the same routes multiple times, making it challenging to distinguish between individual trips and visualize the exact paths taken. This complexity can lead to difficulties in analyzing data, understanding operational patterns, and ensuring accurate reporting.

Our application addresses these challenges with advanced visualization techniques designed to depict overlapping roads. The application traces the path of each vehicle using distinct temporally color-coded lines and user-driven animation via a time slider to represent different trips on overlapping road segments. This allows users to intuitively differentiate between multiple passes over the same road.

5. FUTURE WORK

This study has successfully demonstrated the feasibility of automating work order verification using GPS and telematics data for winter maintenance operations. However, several areas remain for refinement and expansion. One of the key next steps is addressing missing GPS records in rural areas. Limited connectivity can lead to data gaps that impact the accuracy of work order verification. Future work should explore local data caching solutions that store GPS records temporarily when network connectivity is lost and upload them once a stable connection is available. Opportunistic wireless communication between maintenance vehicles could also be investigated to relay GPS data in areas with weak cellular coverage. Additionally, the integration of low-power wide-area networks (LPWAN) such as LoRaWAN could be explored to enhance GPS data transmission in remote regions.

Another important improvement involves increasing the resolution of GPS data collection. The study found that minute-level tracking is insufficient for precise work order verification, particularly in scenarios requiring detailed vehicle movement analysis. Future systems should advocate for second-level GPS logging to enhance accuracy. Real-time GPS data processing, combined with CAN bus logging, could further improve work order automation by providing accurate odometer readings, tracking vehicle operational states, and detecting specific maintenance activities such as plow blade engagement.

The web-based application developed in this study provides an effective tool for work order verification and validation. A natural progression for future work is expanding its functionality to accommodate additional maintenance operations beyond winter services. Work order automation could be applied to pavement patching, roadside mowing, street sweeping, and vegetation control. Each of these activities presents unique challenges in terms of data collection and verification, but the core methodologies developed in this study—GPS-based road segment mapping, automated time tracking, and anomaly detection—can be adapted to other maintenance tasks. Applying these techniques to a broader range of INDOT maintenance activities would further improve efficiency, accuracy, and data-driven decision-making across the agency.

A follow-up project could explore the integration of machine learning techniques to enhance anomaly detection in work order verification. By analyzing historical work order data alongside GPS records, predictive models could identify inconsistencies, detect missing entries, and suggest corrections to human-entered work orders. AI-driven work order adjustments could refine the verification process, reducing manual interventions and improving overall system reliability.

Another potential direction is real-time vehicle tracking and fleet optimization. While the current system focuses on post-event verification, integrating live GPS data into a decision support system could enhance INDOT's ability to manage maintenance operations dynamically. A real-time dashboard could provide supervisors with instant insights into vehicle locations, road conditions, and work progress, enabling proactive decision-making during winter storms or emergency maintenance situations.

Standardizing work order recording practices is also an essential next step. Ensuring consistency in road naming conventions, mile marker references, and time-stamping methods would help improve the interoperability of automated verification systems. Establishing best practices for digital work order entry, including mandatory start and end times, would further enhance data accuracy and alignment with automated verification tools.

This study has laid the groundwork for automating maintenance record-keeping. Future research should build on this foundation by refining data processing methodologies, improving system accuracy, and expanding the scope of work order automation to a wider range of maintenance activities. Through these advancements, INDOT can continue to enhance operational efficiency, optimize resource allocation, and support data-driven decision-making across its maintenance fleet.

5.1 Results Summary

The key deliverables and findings of this study included:

1. *Fully Automated Work Order Verification*: The developed system successfully automated the verification of work orders for winter highway operations by matching vehicle GPS tracks with recorded work orders. This reduced manual verification efforts and improved accuracy.
2. *Data Standardization and Road Mapping*: A method was developed to standardize road naming conventions and establish a robust converter between INDOT's Reference Post System and GPS coordinates, enhancing consistency.
3. *Time Resolution Matters*: The study found that minute-level GPS tracking was insufficient for accurate work order automation. A higher resolution (second-level tracking) was recommended to capture precise vehicle activity.
4. *Web-Based Application for Data Access*: A scalable and privacy-focused web application was developed to allow managers to efficiently access, visualize, and validate work orders using GPS records.
5. *Operational Insights*: The study highlighted key operational challenges, including the digital divide affecting real-time GPS data transmission in rural areas and the necessity of integrating start and end times in work orders.

5.2 Recommendations

The key recommendations of this study included:

1. *Improve GPS Data Collection Frequency*: To enhance accuracy, increasing GPS data resolution to second-level logging is recommended.
2. *Implement a Standardized Data Processing Framework*: A uniform system for road naming, mile markers, and GPS conversions should be adopted to prevent ambiguities.
3. *Enhance Work Order Recording Methods*: Including start and end times in work orders will improve automation capabilities.
4. *Expand Web App Functionalities*: Integrating additional features for different maintenance operations (e.g., snowplowing, patrolling) will increase system adaptability.
5. *Optimize Data Transmission Strategies*: Implementing data caching and delayed uploads when network connectivity is limited can mitigate the impact of rural digital divide issues.
6. *Further Research and Development*: Additional work should be conducted to refine algorithms for multivehicle operations and GPS-based detection methods.

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About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at https://docs.lib.purdue.edu/jtrp/.

Further information about JTRP and its current research program is available at https://engineering.purdue.edu/JTRP.

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