Calculating Plow Cycle Times from Automatic Vehicle Location Data

Final Report

CLEAR ROADS

research for winter highway maintenance

AECOM

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February 2024

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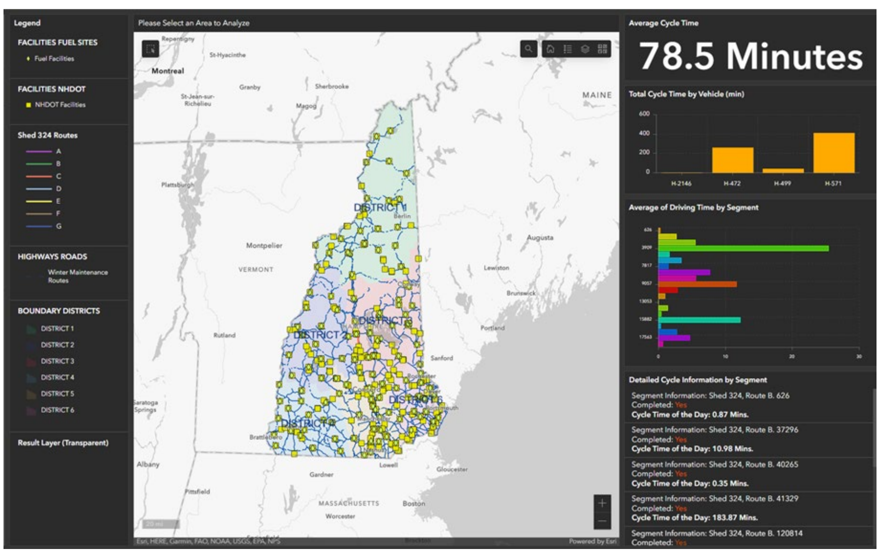

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16. Abstract
Winter weather events can yield low visibility and/or lower the coefficient of friction on the road surface resulting in vehicular crashes or congestion. Transportation agencies are tasked with maintaining safe and reliable roadways for the traveling public which includes combating these snow and ice events. The traveling public's demand for a high level of service (LOS) on roadways continues to increase, even during winter events when significant impacts on travel may occur. It is essential to consider plow and treatment cycle times as agencies work to improve LOS, travel safety, and reliability during snow and ice events. Cycle times can vary significantly depending on a variety of factors, including road type, lane miles, weather, road conditions, traffic volume and more.

This report develops a methodology for calculating plow cycle times that considers various factors that impact cycle times. The methodology was then used to create a framework for a visualization tool that agencies could format with their own electronic data to make real-time operational decisions and conduct better-informed post-storm analyses. By developing a visualization tool based on the methodology, agencies will have the ability to track snowplows in real time and make operational adjustments as needed to maximize efficiency. Additionally, agencies will have greater insight for post-storm analyses, performance evaluations, route optimization strategies and resource allocation efforts while leveraging data they likely already collect during the course of their routine winter maintenance activities.

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Table of Contents

List of Figures

List of Tables

Executive Summary

The traveling public's demand for a high level of service on roadways continues to increase, even during winter events when significant impacts on travel may occur. However, transportation agencies' winter maintenance budgets do not correlate with the increasing public demand and expectations. Therefore, transportation agencies must identify and rely on innovative solutions and best practices to plan, implement, manage, and evaluate cost-effective winter maintenance operations and strategies to increase snow and ice control efficiency and performance within the confines of budgetary constraints.

It is essential to consider plow and treatment cycle times as agencies work to improve levels of service (LOS), travel safety, and reliability during snow and ice events. Cycle time is the time it takes a snowplow to complete a single cycle to service an area or a route under various conditions. Cycle time is dependent on a number of variables, including resource availability, snowplow equipment capacity, roadway characteristics, traffic characteristics, and environmental factors. Many of those variables cannot be controlled and constantly evolve throughout a winter event. This makes the calculation and prediction of cycle times a challenging task.

Technology continues to evolve, and access to enhanced data makes it possible to develop and refine data-driven solutions for optimizing plow/treatment cycle time based on specific scenarios. Enhanced datasets, such as automatic vehicle location (AVL) data from snowplows, can benefit agencies through the development of standardized methodologies for streamlining data entry and calculating snowplow cycle times.

This report presents a methodology for calculating plow and treatment cycle times using data that are readily available for many transportation agencies. In addition, this report introduces a framework for a map-based online visualization tool and dashboards that are developed using the cycle time calculation methodology. By applying the methodology and developing a tool to visualize the cycle time data, agencies will have the ability to track snowplows in real time and make operational adjustments as needed to maximize efficiency. Additionally, agencies will have greater insight into post-storm analyses, performance evaluations, route optimization strategies, and resource allocation efforts while leveraging data they likely already collect during the course of their routine winter maintenance activities.

This report provides a review of the current state of the practice in calculating plow and treatment cycle times as well as routing winter maintenance vehicles. It also summarizes responses to a survey conducted with public agencies that gathered information regarding agencies' use of cycle times to support winter maintenance operations.

To help frame the benefits of a real-time cycle time visualization tool and dashboards, eight user stories were built based on hypothetical scenarios. The user stories describe the challenges agencies may face and convey the benefits of a real-time visualization tool and dashboards in improving winter maintenance operations and, in turn, safety and mobility for the traveling public. Scenarios of the user stories range from heavy traffic congestion during a major snow event, to reduced fleet availability, to post-storm analysis for plow route modifications.

The report discusses the variables that impact cycle times and presents the logic and methodology for calculating cycle times. In addition to required variables, it further provides information on desired variables that may enhance the accuracy of the calculation outputs. The variables accounted for in the methodology include snowplow location data (i.e., latitude, longitude, dates, and timestamps), treatment material spreader status (i.e., on or off), truck identification number, roadway segment spatial data (including start and end points, and segments between turnaround and crossover points), number of lanes or roadway widths, and weather data (including precipitation and amount, wind speed and direction, and temperature). Sources of the data are also discussed, including agencies' AVL data from snowplows, snowplow equipment databases, roadway asset databases, National Weather Service, third-party weather data providers, and agencies' road weather information systems.

The developed cycle time calculation methodology has a high degree of flexibility to account for variations of variables, as agencies may not have all the relevant variables readily available. The methodology accounts for basic location data of the snowplows and can integrate treatment sensor data for more accurate outputs. It accounts for road segment spatial data, which allows for the tool to account for using different equipment treating the route at the same time.

A functional tool framework for calculating and viewing cycle times was also developed based on the methodology. The framework aims to facilitate efficient data utilization and accessibility across the organization by integrating various data sources and formats. The purpose of the framework is to provide information to allow agencies to develop a visualization tool and dashboards based on their choice of software and data hosting platforms that are most suitable for their organization. The framework outlines a high-level architecture of the tool, data requirements, a database design, data conversion processes, Application Programming Interface (API) connections, and a storage option plan for archiving historical data. It also includes recommendations for suitable visualization and dashboard platforms, hosting options, use cases and workflows for the visualization tool, a visualization design diagram, and a roadmap for development and testing stages.

An implementation plan was created for agencies to follow when developing a plow/treatment cycle time tool based on the framework. The implementation plan lays out ideal environments for the tool development and deployment. The plan also provides strategies and steps to mitigate potential issues agencies may encounter during the tool development, such as the availability of data and choices of GIS platform.

1. Introduction

In cold regions, inclement weather includes precipitation mixing with cold temperatures (ambient and surface) which can cause snow and ice events. Winter weather events can yield low visibility and/or lower the coefficient of friction on the road surface resulting in vehicular crashes or congestion. Transportation agencies are tasked with maintaining safe and reliable roadways for the traveling public which includes combating these snow and ice events.

The traveling public's demand for a high level of service (LOS) on roadways continues to increase, even during winter events when significant impacts on travel may occur. However, transportation agencies' winter maintenance budgets do not correlate with the increasing public demand and expectations. Therefore, transportation agencies must identify and rely on innovative solutions and best practices to plan, implement, manage, and evaluate cost-effective winter maintenance operations and strategies to increase snow and ice control efficiency and performance within the confines of budgetary constraints.

It is essential to consider plow and treatment cycle times as agencies work to improve LOS, travel safety, and reliability during snow and ice events. **Cycle time** is the time it takes a snowplow to complete a single cycle to service a site, an area, or a route under various conditions. Cycle times can vary significantly depending on a variety of factors, including road type, lane miles, weather, road conditions, traffic volume, and more. By developing a methodology for this calculation and an online tool to visualize the data, agencies will have the ability to track snowplows in real time and make operational adjustments as needed to maximize efficiency. Additionally, agencies will have greater insight into post-storm analyses, performance evaluations, route optimization strategies, and resource allocation efforts while leveraging data they likely already collect during the course of their routine winter maintenance activities.

1.1 Background

To help transportation agencies with winter maintenance programs quickly and easily calculate the time it takes a snowplow to complete a cycle under various conditions, the Clear Roads research program initiated this project (Clear Roads Project 21-06: Calculating Plow Cycle Times from Automatic Vehicle Location Data). The goal of this project was to develop a methodology for calculating plow cycle times that considers various factors that impact cycle times. The methodology would then be used to create a framework for a visualization tool that agencies could format with their electronic data to make real-time operational decisions and conduct better-informed post-storm analyses.

This project included the following objectives:

- Gather and review the current state of the practice of the use for Automatic Vehicle Location (AVL) data, calculation of plow cycle times, routing winter maintenance vehicles (including specialty equipment such as tow-behind trailers), and other related topics.
- Identify relative variables that will influence plow cycle times.

- Build a hypothetical scenario and a user story showing the challenges and benefits of an online tool for determining and viewing plow cycle times.
- Develop a methodology for determining plow cycle times.
- Use the methodology to develop a framework for a map-based online visualization tool to assist transportation agencies with real-time decision-making and post-storm analysis.
- Develop an implementation plan for deploying an online visualization tool.

The purpose of this report is to provide transportation agencies with winter maintenance programs and a practical methodology for calculating plow cycle times under various conditions. This report also provides a framework for developing and implementing a visualization tool using the methodology. Transportation agencies can follow the framework and the accompanying implementation plan to develop, design, and implement a visualization tool suitable for their needs and software environments.

This report is organized into the following sections:

1. **Introduction:** This section provides the background and purpose of the project, the structure of the report, and the methodology used for the research.
2. **Literature Review:** This section summarizes relevant literature, current practices, and best practices in using real-time data for calculating plow cycle times.
3. **Agency Survey and AVL Data Gathering:** This section presents a summary of responses from transportation agencies to a survey conducted for this research. It also presents samples of AVL data that support the research team to gain an understanding of available variables from the data.
4. **User Stories:** This section presents eight user stories to convey the use cases and benefits of a real-time cycle time visualization tool.
5. **Variables, Methodology, and Case Study:** This section presents the variables required to calculate plow cycle times and a methodology for calculating cycle times. It also presents a hypothetical case study to illustrate the use of the methodology.
6. **Visualization Tool Framework:** This section describes a framework for developing a visualization tool to measure, view, and analyze plow cycle times. It includes an analysis of data requirements, database design, data conversion processes, data storage options, tool platform and hosting options, and a roadmap for tool development and testing. This section also showcases a sample visualization tool design.
7. **Tool Implementation Plan:** This section presents an implementation plan for transportation agencies to follow when developing a plow cycle time visualization tool.

1.2 Research Methodology

The research team utilized the following methodology to complete the project.

Literature Review

The research team first completed a review of relevant literature and studies. The review focused on how AVL data were used by agencies for calculating and reporting plow cycle times, and what factors agencies considered when determining plow cycle times. This foundational understanding was essential in the development of the operational scenarios, determining the variables and methodology for calculating plow cycle times, and developing the tool framework.

Survey

A survey was distributed to multiple state and local agencies in September 2022 to gather basic, high-level information regarding each agency's collection and use of AVL data for calculating plow cycle times. The survey focused on variables and performance measures agencies considered or used in calculating plow cycle times, other variables outside of AVL data considered or used, sources of other variables, and challenges agencies faced in calculating and monitoring cycle times.

Sample AVL Data Gathering

In addition to the survey, sample AVL data outputs from selected agencies were gathered and reviewed. These outputs represent variables that were available with AVL solutions. The information provided the research team indications as to what variables and data might need to come from other sources for developing the cycle time calculation methodology. These outputs helped shape the overall cycle time calculation methodology and tool framework.

User Story Development

Based on the data gathered, the research team developed hypothetical operational scenarios to show the potential challenges in calculating accurate cycle times as well as the benefits of integrating a cycle time tool into winter maintenance operations.

Variables Identification and Methodology Development

A proper methodology must use the appropriate variables. Each variable may have a different impact on the plow cycle time. The speed at which a truck can effectively apply a treatment to the roadways and truck capacity can have a direct impact on plow cycle times. The number of lane-miles per truck can also impact treatment times. Therefore, with a limited number of winter maintenance fleet vehicles and/or operators, the lane-miles each truck is responsible for may increase, causing each cycle to be longer. The roadway configuration, surrounding terrain, traffic, and type of weather being received can impact the truck's treatment speed. The research team reviewed each of the variables that could impact cycle times, documented them, and developed a methodology for calculating cycle times. The methodology was designed to provide performance measures that would be beneficial to transportation agencies.

Visualization Tool Framework Development

Upon the development of the methodology, the research team developed a framework that outlines the requirements of a map-based visualization tool. The framework considered the potential for various AVL data outputs and presented an integration path for the tool design concept. The framework defined the data requirements, database design, data conversion processes, API connections, use cases, workflows, and historical data storage options. It also recommended a suitable dashboard platform and hosting options and a roadmap for development and testing stages.

The research team followed the framework and developed a baseline tool to demonstrate the tool's functionalities. The baseline tool output included calculating plow cycle time for a user-selected route, along with the ability to conduct historical analyses.

Tool Implementation Plan

An implementation plan was developed for agencies to follow when developing a plow cycle time tool based on the framework. The implementation plan presented ideal environments for deployment, strategies, and steps to mitigate potential issues agencies may encounter during tool development and implementation.

2. Literature Review

This section provides a summary of the current practice and best practices in utilizing real-time data for calculating plow/treatment cycle times. The list of literature reviewed included documents recommended by the Clear Roads project subcommittee and additional literature identified by the research team. The research team conducted a literature search and reviewed agency publications, conference papers, presentations and proceedings, and professional and trade journals.

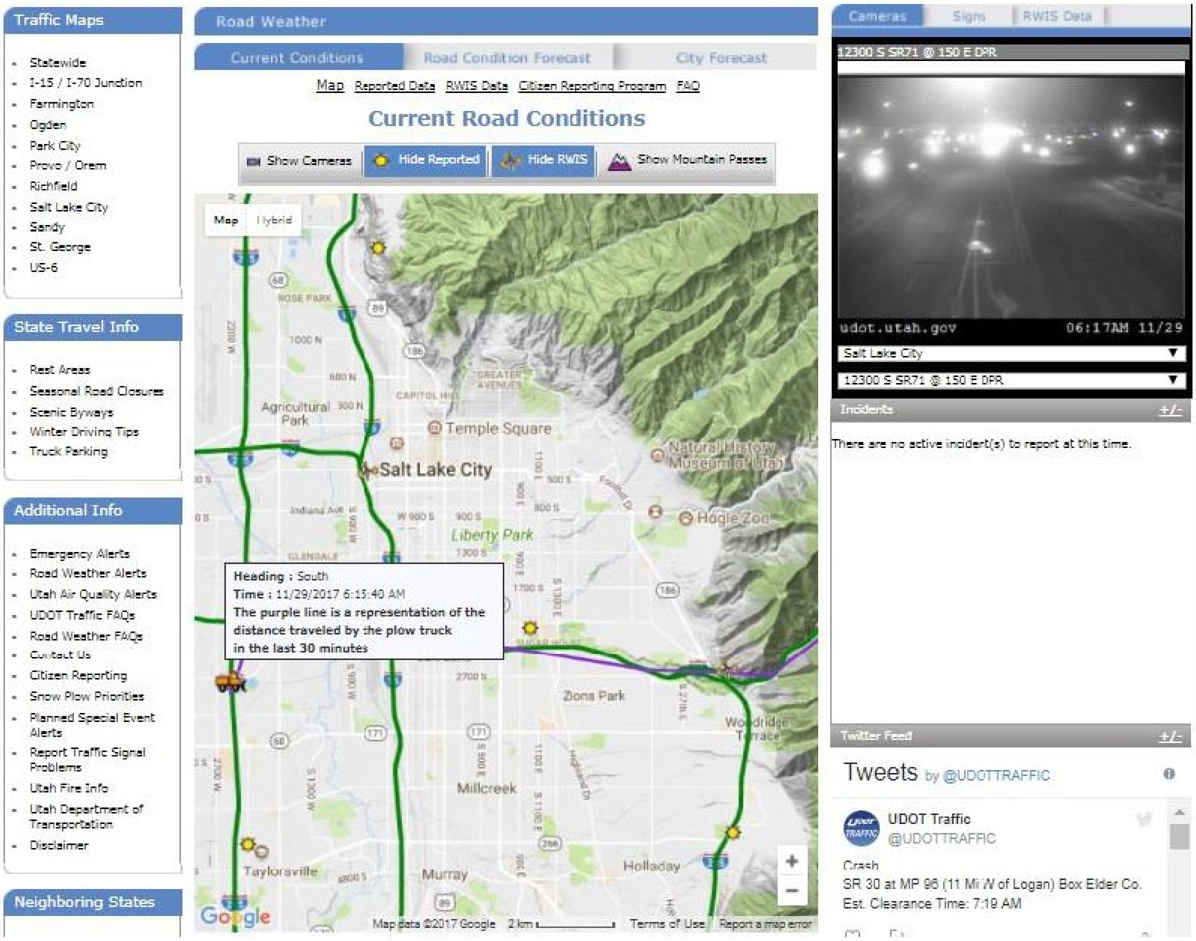
Utilization of AVL/GPS Technology: Case Studies (Lee & Nelson, 2018)

This report describes the use of AVL and global positioning systems (GPS) by transportation agencies to monitor vehicle locations and the operational status of equipment for winter road maintenance operations. The AVL/GPS system is to provide automatic vehicle location tracking for dispatchers and maintenance supervisors. In addition, AVL/GPS systems can provide vehicle maintenance technicians with valuable information about vehicle diagnosis. AVL/GPS systems can also be integrated with existing vehicle components used for snowplow operations such as spreader controllers and plow blades to provide reports to maintenance supervisors on material and plow usage applied by snowplow operators.

Six detailed case studies with state Departments of Transportation (DOTs) (Utah, Washington State, Michigan, Wisconsin, Nebraska, and Colorado) were conducted for this study. These case studies involved in-depth conversations with DOT staff involved in AVL/GPS system planning, procurement, implementation, management, and operations. The key results and lessons learned from the case studies are outlined in this final report. The case studies can be used as a guide to help state DOTs implement and use different AVL/GPS applications based on their unique geographic characteristics, organizational settings, winter maintenance requirements, and technical capabilities. Organizations can leverage the lessons learned from the case studies for launching, accelerating, replacing, and upgrading AVL/GPS for their winter maintenance operations.

Figure 1 shows the vehicle location on the Utah DOT traffic information webpage. Also, the vehicle can be tracked via mobile application. Based on the Utah DOT case study, an important lesson learned is the ability to track the locations of winter maintenance vehicles which provides enhanced resource sharing and allocation, as well as inter-regional coordination. AVL data supports monitoring and management of winter maintenance performance. Integrating AVL data with road weather information systems (RWIS) data and other real-time road condition information improves situational awareness and facilitates improved winter maintenance practices. Combined with UDOT cameras, real-time road condition information helps verify and confirm pavement conditions. Another example of lessons learned is that making vehicle location data and related performance metrics available to the public increases public confidence in winter maintenance operations.

One of the main benefits the Michigan DOT (MDOT) has gained with the AVL/GPS system is the ability to track snowplow vehicles' speed and location. In this way, MDOT is able to review how effective their roadway maintenance activities are and identify segments/areas that need improvement for future operations. MDOT also uses the system data to determine what speed is optimal for spreading salt, brine, sand, and other de-icing chemicals to reduce plow cycle times.



Reference: (Lee & Nelson, 2018)

Figure 1. PC-Based Image from UDOT Traffic Information Webpage with Snowplow Locations

Wisconsin DOT had the advantage of having an AVL/GPS system when routes were reconfigured. This allowed Wisconsin DOT to increase the total lane-miles each truck was responsible for maintaining based on an optimization project. As a result, they were able to save about $85,000 per route annually. Brown County saved $1.2M in 2018 in equipment costs, as route optimization effectively absorbed 165 new lane miles and eliminated the need to expand the fleet. Dane County was able to remove four trucks from its fleet after a second round of optimization. Material usage and fuel consumption were reduced with the integration of the AVL/GPS system.

Colorado DOT reported that among the major benefits of using the AVL/GPS system is increased situational awareness of how staff respond to winter storms. The system had a positive impact on driver behaviors, such as promoting speed compliance and minimizing improper use of the equipment. Overall, this allowed the agency to decrease plow cycle times in the state of Colorado.

One lesson learned from the Nebraska DOT case study is the importance of being aware of how the DOT wants to use the AVL/GPS system. This will affect the requirements and specifications for the system in order to meet the winter maintenance staff needs. Pilot projects help identify problems that might occur during the implementation process on a smaller, manageable scale before a full fleet deployment.

Key recommendations offered in this report include focusing on planning and decision making, such as identifying an agency's needs and objectives for the AVL/GPS system; procurement, such as using a systems engineering approach in the system requirements development; system implementation, where the agency arranges an installation schedule to reduce impacts to winter maintenance operations; data collection and utilization (e.g., considering sharing vehicle location with the public); and operations and maintenance.

This study helped the research team determine how the AVL/GPS data were used at several DOTs, which would lead into the development of a real-time tool for plow cycle times.

Leveraging Road Weather Data for Performance Management Dashboards and Reports (U.S. Department of Transportation Federal Highway Administration, 2020)

This fact sheet explains the data management tools that use road weather data from mobile and connected vehicle (CV) technologies to improve existing performance metrics and the way organizations manage the performance of road weather operations and maintenance activities.

Performance management allows agencies to better direct investments and measure progress using the data. Additionally, it allows agencies to make operational adjustments to improve performance. By adopting performance management principles, agencies can better implement weather-sensitive management strategies to increase efficiency. Agencies can use performance metrics to evaluate the benefits of new practices or processes, justify funding, and improve public understanding.

Many agencies are collecting data that can be used for road weather performance measurements. Agencies can obtain weather data from RWIS, National Weather Service (NWS), road condition reports, and purchases of salt and supplies for winter maintenance.

One example of how proper performance measures can assist with operations is the average annual percentage of time roadways are cleared of snow and ice during winter storms, provided by the Idaho Transportation Department Control Panel, compares with the goal of maintaining at least 73 percent unhindered mobility.

Minnesota DOT (MnDOT) uses a performance dashboard to provide information on the percentage frequency of meeting their 70 percent bare lane target, a traffic volume-based number of hours for highways during the winter season. The dashboard also reports actual salt usage, actual and optimal salt usage, and weather severity index (WSI) for each season. MnDOT releases this information as part of its annual transportation scorecard and performance report.

Wisconsin DOT Annual Winter Maintenance Report and Mobility, Accountability, Preservation, Safety, Service (MAPSS) Program includes several measures for each winter to compare year-to-year performance, including information on weather conditions, material cost and quantity, hours of operation, average crew response time, and assets. In addition, the MAPSS Performance Improvement Report includes an annual measure of mobility for the winter response. It monitors WSI and the percentage of time that bare-wet condition targets are met after a winter weather event for roads that are maintained 24 hours a day and 18 hours a day. After the storm ends, these roads are targeted to be cleared within 4 and 6 hours, respectively, or 70 percent of the time.

Road weather performance metrics developed from data collected from mobile and CV sources can vary in complexity depending on the quality of data available and the sources used to collect the data. Agencies can publish calculated performance metrics for internal use or public consumption to see a year-over-year agency costs comparison and performance in road weather operations, and to highlight improvements and justify additional investment.

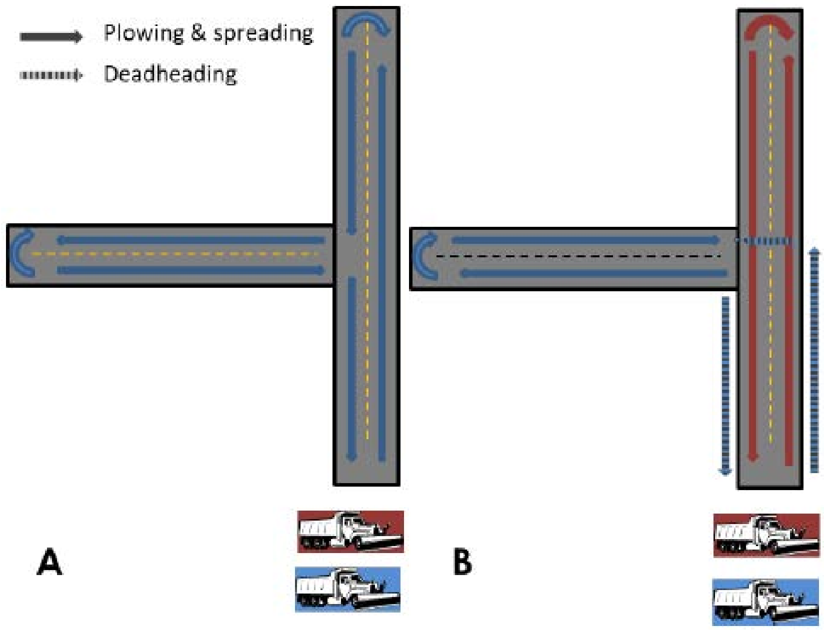
This report allowed the research team to compare the data management tools with CV technologies that improve existing performance metrics and obtain more information to generate a plow cycle time tool.

Synthesis of Technical Requirements and Considerations for Automated Snowplow Route Optimization (Dowds & Sullivan, Synthesis of Technical Requirements and Considerations for Automated Snowplow Route Optimization, 2021)

According to interviews conducted with DOT staff in this study, there are two types of challenges that prevent route optimization results from being implemented. First, there can be technical or operational issues with the final optimized routes make them unsafe or infeasible to implement. Second, there can be institutional barriers to change that prevent optimized routes that are safe and technically feasible from being implemented. These challenges can be mitigated with improvements to the process of soliciting, selecting, and managing the route optimization software or service provider. This study provides DOTs with the necessary tools to make these improvements.

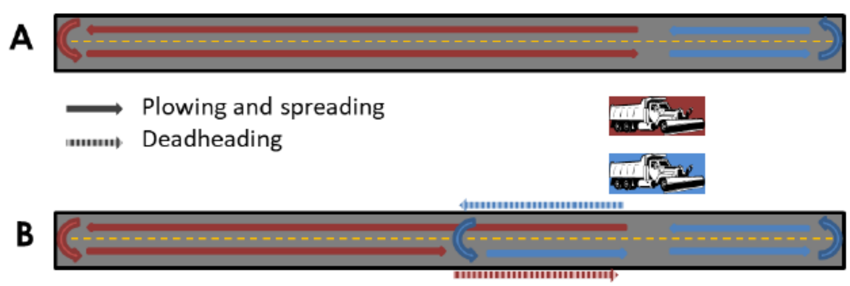
The study shows how to perform a route optimization project based on the needs of the agency which include cost minimization and service time minimization. In both scenarios (A and B) in Figure 2, a single garage that has two trucks (one red and one blue) maintains the road network. In scenario A, a single vehicle performs winter maintenance within the maximum cycle time threshold. Thus, only one of the winter maintenance vehicles is used, eliminating all deadhead and route overlap. It was ensured that the lowest possible vehicle operating time and travel mileage. In scenario B, both trucks create some deadheading as the blue vehicle travels to and from the section of road it serves; however, it results in the fastest possible winter maintenance for all road sections.

In Figure 3, the road network cannot be exceeded by a single truck within the cycle time threshold so both trucks are routed for the cost and service time minimizing optimizations. As seen in Figure 3, the cost-minimizing scenario removes all route overlap to minimize the total mileage of trucks. On the other hand, the service time minimization scenario enlarges vehicle miles traveled to provide winter maintenance service to all road segments faster. It should be noted that the locations of winter maintenance facilities (garages and salt sheds) are one of the determinants of optimal routes for winter maintenance activities. Facilities that are relatively evenly distributed throughout the road network tend to encourage more equal route lengths and reduce deadhead.



Reference: (Dowds & Sullivan, Synthesis of Technical Requirements and Considerations for Automated Snowplow Route Optimization, 2021)

Figure 2. Routes Optimized for A) Cost Minimization and B) Service Time Minimization, Example #1



Reference: (Dowds & Sullivan, Synthesis of Technical Requirements and Considerations for Automated Snowplow Route Optimization, 2021)

Figure 3. Routes Optimized for A) Cost Minimization and B) Service Time Minimization, Example #2

It is important to note that original snowplow routes have evolved throughout history, and the agencies are trying to shorten the cycle times by optimizing the routes. Some agencies reported that route optimization allowed them to have a massive increase in terms of efficiency and fuel savings while reducing the route numbers.

North Dakota DOT's optimization project aimed to accomplish the cycle times according to DOT's six-stage winter maintenance level of service policy by combining routes and removing some vehicles.

Snowplow operators were given draft routes and were asked to test the routes in maintenance vehicles to ensure routes were safe and viable. Some changes to the initial routes were necessary, such as setting turnaround points, considering rest areas, and turnouts that were not in the original network. Compared to the current implementation, the optimization decreased the number of routes from 354 to 327, reduced single loop plowing time by 23%, and total mileage by 8%.

The Colorado DOT optimization project aims to create a dynamic (not seasonal) optimization process that can be used in real-time to change and reroute winter maintenance vehicles in response to actual, current weather and traffic conditions. The baseline routes are designed to create relatively equalized route lengths, with a maximum cycle time of one hour for Category 1 highways and a maximum cycle time of two hours for Category 2 highways. During the optimization pilot, several lessons learned were: (1) it is time-consuming to install systems that will connect all weather and traffic data flows to the optimization tool (through APIs), (2) it is important to train and demonstrate the benefits of the system to operators, and (3) the relatively simple road network in the pilot area can be used to improve existing route efficiency and test the effectiveness of the system in more complex road networks.

Iowa DOT had an optimization project that minimizes vehicle hours traveled when meeting cycle time targets. However, the routes produced for this project needed to be manually changed, and limitations were placed on the modeling before implementation. Some operational issues would need to be adjusted for the routes to make them viable, and changing the routes was not straightforward. Additionally, baseline route data from AVL had some quality issues that made it difficult to compare the new routes with existing implementations.

This study allowed the research team to see the limitations of routing software and examine the challenges, such as AVL data quality issues, that hinder the implementation of route optimization results. Though the methodology and the tool to be developed by the research team would not perform route optimization, it might be ideal to use the proposed plow cycling calculation methodology and tool to test, validate, and monitor potential optimized routes by minimizing the cost and service time.

Integration of Advanced Technologies into Winter Operations Decisions (Minge, Gallagher, & Curd, 2020)

This report summarizes the state-of-the-practice in implementing advanced technologies in winter road maintenance operations. The project included a literature search, survey, and follow-up interviews with key stakeholders. The survey aimed to define the level of technology used by roadway maintenance agencies to support their winter maintenance program. While emerging technologies such as Automated Vehicles (AV), CV, 5G communication, and machine learning were considered, they are not currently deployed at most agencies. Typically, most agencies utilize cellular communication over 3G, 4G, or LTE networks as a means of communication to field equipment to transmit data.

Recommendations on integrating technologies into winter operations decisions for winter maintenance agencies were made. One of these recommendations was Connected and Automated Vehicle (CAV) Systems. CV systems involve communication and transmission of data either between two vehicles or between a vehicle and another stationary device. AV systems include vehicles that move and operate with minimal or no input from drivers. AV technology is still in its infancy in winter maintenance; however, several projects involving automatic airport runway sweepers were identified in the report.

Road conditions can be observed in the field with weather sensor technology. RWIS systems collect weather and pavement condition information without needing extensive deployments of roadside infrastructure. Installation of such sensors on snowplows provides agencies with improved data collection capabilities, helping with real-time decisions for maintenance operations. It can be said that these sensors are generally accurate and effective. However, while vehicle-mounted sensors are superior at detecting pavement temperature and the presence of moisture on the pavement, these sensors tend to have difficulty distinguishing between snow and ice and are unable to determine the depth of water in the pavement.

Camera systems that monitor plow and spreader operations, driver assistance technologies such as collision warning, and automated salt spreading can be given as an example of driver assistance systems. The most popular system on winter maintenance trucks is camera systems that include rear-view, spreader, and plow monitoring cameras with a dash-mounted display for the driver. These camera systems have been found helpful based on feedback from the operators.

Video analytics uses video cameras and artificial intelligence (AI) systems to systematically collect data, such as road conditions from fixed or vehicle-mounted cameras. In general, parameters such as visibility, precipitation and road surface conditions can be obtained from a video stream. However, this system is only preferred where RWIS equipment is not available and reliable, and where there is high communications bandwidth (> 1 Mbit/s), which is required for these systems.

There are two communications systems for winter maintenance vehicles: mobile communication and fixed (roadside) systems. Mobile communication is a system used in vehicles while a fixed system uses fiber optic or wireless communications located at a stable infrastructure. Cellular data systems are widely used and are expected to be the dominant communications system for mobile and roadside devices for winter maintenance. The cellular system is evolving with the spread of 5G technology, which offers the promise of higher bandwidth, and more flexible connectivity. Also, Low Earth Orbit (LEO) satellite systems are getting more popular. LEO is to make high-bandwidth connections to remote, fixed systems much cheaper and more accessible.

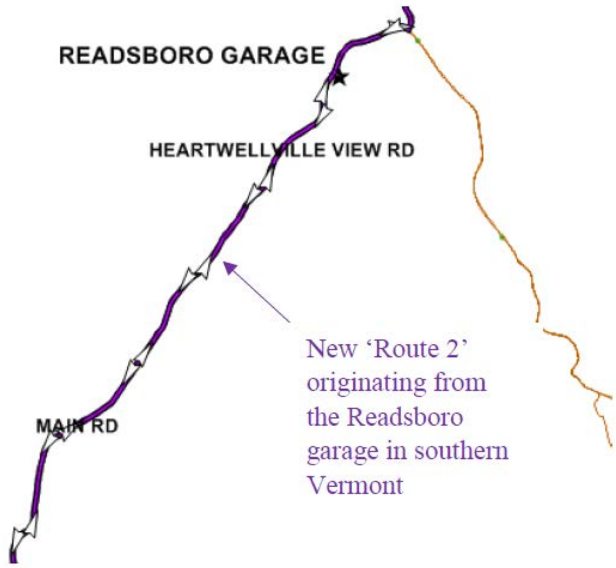
ArcGIS and Tableau software can input winter maintenance data to create easy-to-understand data visualizations. Maps showing high-traffic areas can be given as an example and these kinds of visualizations are important for effectively presenting conditions and data to the public. The winter maintenance data produces large and continuous data streams because of the variety of data sources used. This often requires large amounts of computing power to process effectively. Thus, these large datasets can be used to identify patterns or trends that can help predict future events or improve services.

Driver assistance technologies, camera, and communications systems such as cellular, and CV/AV discussed in this report allow agencies to observe road and weather conditions and collect the data. By using these data, agencies can be able to reduce plow cycle times of their current snowplow routes.

Identifying Best Practices for Snowplow Route Optimization (Dowds, Sullivan, Novak, & Scott, 2016)

This study provides an overview of computerized route optimization processes and explains how to make route improvements. Well-designed snowplow routes allow roads to be treated faster and more cost-efficiently, thus more effective snow and ice control services can be provided to the traveling public. To achieve the benefits of well-designed snowplow routes, advanced computerized tools are required. In addition, deadheading, route overlap and other inefficiencies can be reduced or eliminated with these tools. There are two different types of computerized tools: route review and route optimization. Route review tools display available routes. It also facilitates manual route revisions by visualizing a route and tracking mileage and cycle time. Route optimization tools, on the other hand, can create new routes using mathematical algorithms. Multiple route optimization projects have reported 5% to 10% reductions in route length, with reductions of up to 50% in one case. Even if there is a small gain in efficiency, this will allow DOTs and local agencies to save significant money given the high cost of snow and ice control operations. A wide variety of route lengths can be indicative of route improvement opportunities and AVL/GPS systems, smartphones and driver reports can collect route length data.

An important step in the route optimization process is determining which software to use. A similar set of inputs are required by all route optimization software. Therefore, choosing the software is usually based on the project team's expertise or ensuring the software is compatible with other agency projects and existing licenses. These inputs are generally locations of garages and other salt storage depots, an inventory of the winter maintenance vehicle fleet, a base routing network, and critical agency winter maintenance policies. Establishing the basic routing network for route optimization is one of the important steps in the optimization process and may require significant changes to the original source data. Once the data are ready, the software can be run to provide the new route map and turn-by-turn directions as shown in Figure 4. It is important to test the route under non-winter weather conditions to ensure there are no obstacles that may arise during the winter months.



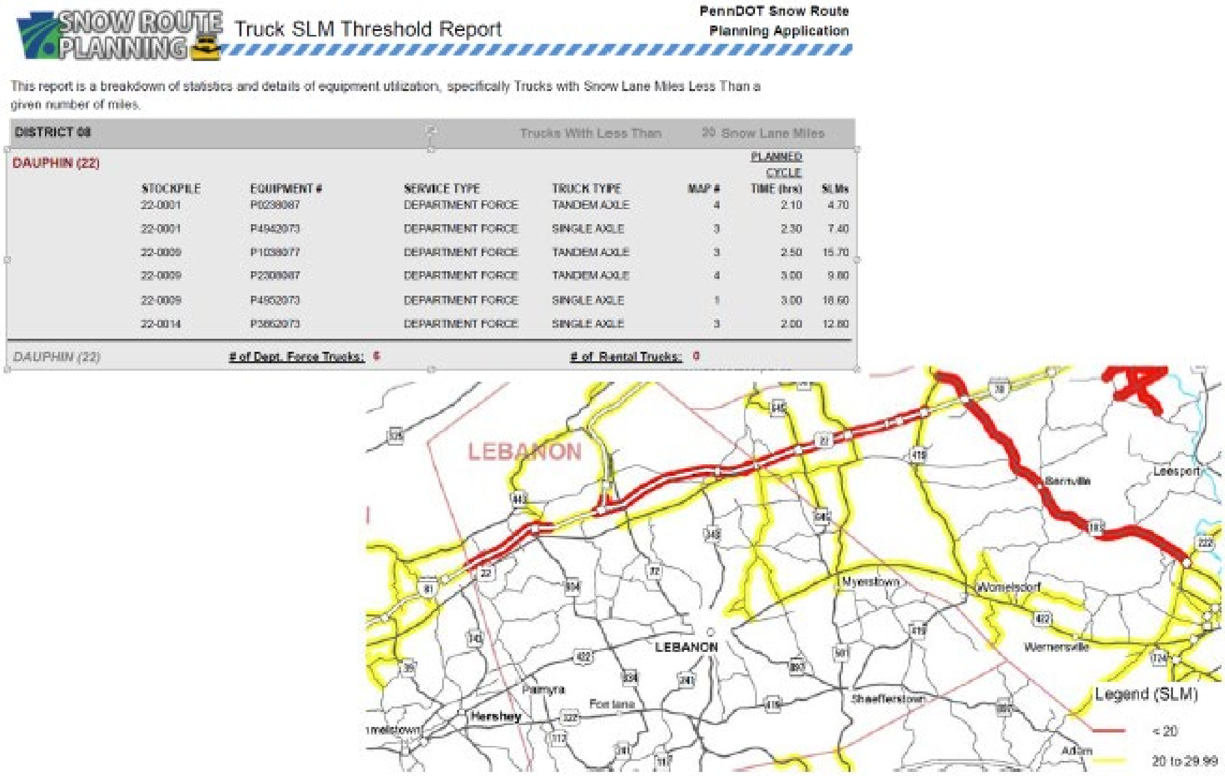
Route Direction for 'Route 2'
Total Distance: **26.4** Miles

1.	Start North West on **Garage Driveway**	326 ft	(0.1 mi)
2.	Turn Left onto **HEARTWELLVILLE VIEW RD**	4.2 mi	(4.2 mi)
3.	Turn Right onto **MAIN RD**	1.4 mi	(5.6 mi)
4.	Continue on **MAIN RD**	2.7 mi	(7 mi)

Reference: (Dowds, Sullivan, Novak, & Scott, 2016)

Figure 4. Examples of Visual and Turn-by-turn Route Optimization Outputs.

In 2012, Pennsylvania DOT (PennDOT) decided to improve their data needs, such as winter maintenance fleet, vehicle routing and material usage. A custom GIS-based tool was developed by DOT's external contract. The tool would track winter maintenance data and create a new route map. In the end, this tool was able to reduce the time required to create the snowplow route maps from two weeks to two days. Also, route visualizations were significantly improved as shown in Figure 5. By integrating the program more closely with AVL systems, PennDOT can verify that the routes in the Snow Route Planning Application tool accurately reflect snow and ice control activities occurring at the site. Monitoring material application rates with the AVL and the Snow Route Planning Application tool can provide improvements in material application consistency and reduce annual material costs.



SNOW ROUTE PLANNING Truck SLM Threshold Report

PennDOT Snow Route Planning Application

This report is a breakdown of statistics and details of equipment utilization, specifically Trucks with Snow Lane Miles Less Than a given number of miles.

DISTRICT 08 — Trucks With Less Than 20 Snow Lane Miles

DAUPHIN (22)

STOCKPILE	EQUIPMENT #	SERVICE TYPE	TRUCK TYPE	MAP #	PLANNED CYCLE TIME (hrs)	SLMs
22-0001	P0238087	DEPARTMENT FORCE	TANDEM AXLE	4	2.10	4.70
22-0001	P4942073	DEPARTMENT FORCE	SINGLE AXLE	3	2.30	7.40
22-0009	P1038077	DEPARTMENT FORCE	TANDEM AXLE	3	2.50	15.70
22-0009	P2308087	DEPARTMENT FORCE	TANDEM AXLE	4	3.00	9.80
22-0009	P4952073	DEPARTMENT FORCE	SINGLE AXLE	1	3.00	18.60
22-0014	P3862073	DEPARTMENT FORCE	SINGLE AXLE	3	2.00	12.80

DAUPHIN (22) # of Dept. Force Trucks: 6 # of Rental Trucks: 0

Reference: (Dowds, Sullivan, Novak, & Scott, 2016)

Figure 5. Tabular and Visual Reports from the Snow Route Planning Application.

Iowa DOT conducted a project in 2015 in which all of its winter maintenance vehicles were equipped with new-generation AVL/GPS systems. Thus, the DOT would be able to collect the real-time location of each vehicle and collect additional data on the time, length, and material used along each route with this system. Using the AVL/GPS system may allow DOT to reduce material usage and evaluate service gaps. Also, this system could collect some of the engine diagnostic data, so preventative maintenance may be done that may keep more of the fleet on the roadway during an event.

Successful route optimization projects need close collaboration between experienced winter maintenance professionals and the individuals conducting the route optimization. This is because the people who run the route optimization may not completely understand all the operational constraints that affect snowplowing, such as the restrictions on where vehicles can turn around safely or size constraints that prevent certain vehicles from servicing narrow roads. Successful route optimization often requires the inclusion of individual lanes in the road network separately. Also, it is important to avoid impractical routes that could be caused by not including highway crossover and turnaround locations.

This study shows how some agencies have leveraged route review and optimization tools for improvements to provide more effective snow and ice control service by minimizing the cost and delivering faster service. Eliminating deadheading and route overlap allows agencies to improve plow cycle times.

Optimal Allocation of Vehicles to Bus Routes Using Automatically Collected Data and Simulation Modelling (Sanchez-Martinez, Koutsopoulos, & Wilson, 2016)

This paper develops a framework for maximizing service performance on a range of high-frequency bus routes and addresses the issue of assigning vehicles to bus network routes given their planned headways and overall fleet size constraints. It illustrates the feasibility and potential benefits of the approach through a case study that involves morning peak service on nine bus routes in Boston, MA.

The dispatching discipline used at terminals and the set of strategies used to regulate headways can be given as an example of factors – in control of the operator that affects service performance. Infrastructure, congestion, and demand for service are considered fixed in the short term. On the other hand, scheduled cycle time is in control of management at the service planning stage. Longer cycle times result in longer recovery times at terminals, thus facilitating the regular dispatch of vehicles. Running time variability can be managed by increasing the cycle times in the service planning stage.

Increasing fleet size or headway or a combination of both results in greater cycle time. Increasing headway while not changing fleet size will increase cycle time without any operating cost however, at the same time it will decrease the service passenger capacity, so vehicles will be more crowded and waiting times will increase. While the planned cycle time has increased, waiting times at stops will increase and become more volatile, so the net effect may be lower quality of service if the number of passengers is high. When passenger numbers are relatively low and the operator has difficulty dispatching vehicles at regular intervals, the additional recovery time provided by an increased headway can improve service reliability.

An alternative way to increase cycle times is to increase fleet size while keeping target headway constant. Even though this increases operational costs, it adds slack to running times while not affecting waiting times. Headway regularity can be improved by having the operator use the additional resources so that waiting times decrease and loads from vehicle-to-vehicle balance. Balanced loads can reduce running time variability through less variable dwell times. The extra slack then can be used at the terminals to improve dispatching regularity and hold or slow down vehicles to maintain regular headways.

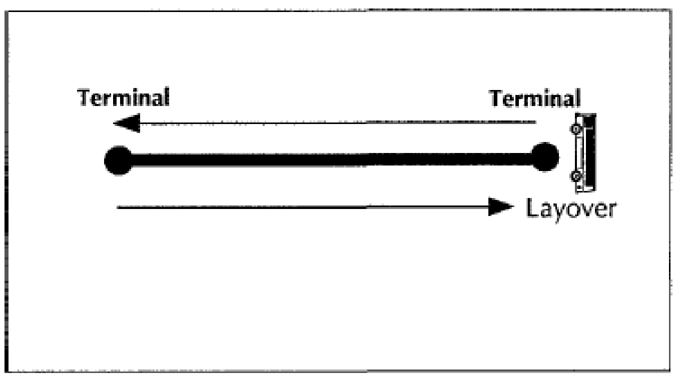
This study shows the ways to increase cycle times to leverage longer recovery times at bus terminals which allow the operators to dispatch vehicles regularly. Although increasing headway results in greater cycle time, it may not the best approach since this approach will decrease the service passenger capacity. Increasing fleet size only will increase the operational cost but it may be a better approach since the service passenger capacity will not decrease.

Transit Scheduling: Basic and Advanced Manuals (Pine, Niemeyer, & Chisholm, 1998)

This transit planning guide includes modern training techniques for bus and light rail transit scheduling. The manual consists of two sections: a basic treatment and an advanced section. The findings show that the content and design of the guide effectively and efficiently meet the need for practical, structured, and documented transit scheduling training materials applicable to both transit and non-transit participants with varying degrees of transit experience and need.

The manual explains route structure as where the vehicle travels on a route during the service day is, to a great degree, related to the interconnectedness of the service network. Three areas of route structure that are most influenced by service standards and policies are route cycle times, route configurations, and interlining. Cycle time is important for several reasons, including playing a role in the formula used to determine the number of vehicles required to provide a given level of service on a route.

Cycle time, as shown in Figure 6, is the time it takes to drive a round trip on a route, plus the time it takes for the operator and/or the vehicle to take a break before starting on another trip. Typical service standards seek to maximize the length of the route design per cycle time while providing for the minimum allowable layover/recovery time. Maximizing route length per cycle time makes the most efficient use of equipment and workforce. However, other considerations such as headway and rush hour/non-rush hour considerations make this optimization difficult to achieve because these considerations may need additional layover/recovery time beyond the minimum allowed.



Reference: (Pine, Niemeyer, & Chisholm, 1998)

Figure 6. Cycle time illustration

Minimum cycle time is the number of minutes scheduled for the vehicle to make a round trip, including a minimum layover/recovery time as set by employment contract or agency policy. Per the Route 32 example, the minimum layover/recovery time is 10% of the round-trip time. However, maintaining a constant 30-minute policy-based headway for Route 32 will result in a cycle time other than the minimum cycle time for the vehicles operating that route. On Route 32, vehicles will have to layover/recover longer than the minimum 10% agency requirement. Otherwise, they would leave the layover point too early and arrive at the stops along the route earlier than the schedule indicates. The resulting cycle time required to maintain the 30-minute headways is referred to as available cycle time. To operate the 30-minute headway on Route 32, the formula below is used to determine the number of vehicles needed:

 # Vehicles = Cycle time / Desired Headway

Given the minimum layover/recovery time for Route 32 of 10% of the round-trip time, the number of vehicles needed can be calculated as follows:

Minimum Cycle Time = (Round Trip Time + Min. Layover/Recovery)

= (72 + (10% x 72))

= (72 + 7.2)

(7.2 is rounded to the next whole number 8)

= 72 + 8

= 80

Desired Headway = 30 minutes

Vehicles $= \frac{80}{30}$ = **2.67**

The number of vehicles needed would be rounded up to three (3) since it is impossible to operate 2.67 vehicles which means the cycle time would have to be updated if the 30-minute headway remained constant. Using the equation (*# Vehicles = Cycle time / Desired Headway*), 3 = Cycle time / 30 min, the available cycle time would be found as 90 min. With a round trip time of 72 minutes, 18 minutes of layover/recovery time per round trip is required to maintain the 30-minute headway, while 3 vehicles are utilized.

This manual illustrates the importance of cycle time by pointing out the differences between minimum cycle time and available cycle time. Layover/recovery time, the number of minutes that the operator and/or vehicle would need to take a break before starting on another trip was also considered. These concepts could be applied in the calculations used in the development of a dashboard, though winter operation cycle times require multiple passes on one roadway.

Additional Studies

Route Optimization report (Schneider, Miller, & Holik, 2016) demonstrates optimizing ice and snow routes for the agency's snowplow trucks when eliminating county border restrictions. Digitizing base routes, placing GPS recorders in snowplow trucks, and collecting data regarding actual cycle times are within the scope of the study. By determining the maximum cycle time, it is aimed to place the trucks in garages according to their needs. Thus, the agency maintains the required roads efficiently and economically. In addition, the Route Optimization Model (ROM) is used to analyze new equipment technology and new operational considerations, such as adding a wing plow or a hopper that can treat multiple lanes in one pass for faster treatment.

According to the Long-Term & Short-Term Measures of Roadway Snow and Ice Control (RSIC) Performance report (Sullivan, Dowds, Scott, & Novak, 2016), the Average Distribution Deviation (ADD), a new long-term performance measure, was developed to measure changes in the distribution of vehicle speeds after winter weather events to improve the performance of roadway snow and ice control activities. A short-term performance measure, a thermal imaging video system was pilot tested. The short-term, video-based performance measure is designed to provide near-instantaneous feedback that can be used to notify the rate of application of chemicals by, and routing of, snow and ice control vehicles. On the other hand, the long-term ADD performance metric can be used to measure the time to complete RSIC operations on a storm-by-storm or seasonal basis.

Iowa DOT Office of Maintenance Snowplow Optimization report (Dong, Zhang, & Yang, 2020) uses an optimization-based approach to minimize the deadhead distance and meet service expectations. It aimed to design the optimal snowplow routes under the existing configurations without changing the warehouse responsibility areas and the fleets managed by various warehouses. Additionally, the report discusses allowing snowplow trucks to reload at warehouses or reloading stations outside their warehouses when designing warehouse responsibilities and routes.

Snow Removal Performance Metrics report (Xu, et al., 2017) analyzes performance measures of snow and ice maintenance operations, their temporal evolution and effectiveness, costs of analyzing the performance data, and communication methods inside the agency to identify effective performance metrics for snow and ice maintenance operations. This report also evaluates existing snow/ice removal performance metrics and data to measure service levels, compare service across regions, and validate budget allocations.

3. Agency Survey and AVL Data Gathering

This section summarizes the responses received from a survey on the use of cycle time data for plowing and/or treating operations within winter maintenance operations by transportation agencies. The survey was designed to gather basic, high-level information regarding each agency's use of cycle times to support winter maintenance operations, as well as detailed information on the sources used to collect and track cycle time data.

In addition, sample AVL data outputs from selected agencies were gathered and reviewed. These outputs presented variables that were available with AVL solutions. They also provided indications as to what variables and data might need to be obtained from other sources. These outputs helped shape the overall cycle time calculation methodology and tool framework.

3.1 Agency Survey

The survey was developed by AECOM and reviewed by the Clear Roads project subcommittee before being distributed to various agencies on September 26, 2022. The survey was made available in an online format and was distributed through the following channels:

- Snow and Ice listserv maintained by the University of Iowa
- Clear Roads members
- International agencies through the Norwegian Public Roads Administration and other Nordic countries, including Denmark, Norway, Sweden and Finland

A total of 24 agency responses were received. Table 1 presents a listing of agencies who responded to the survey that have AVL/GPS systems for winter maintenance operations. Table 2 presents a listing of agencies that responded to the survey without AVL/GPS systems.

Table 1. Survey Respondents with AVL/GPS Systems

Agency	Name
Arizona DOT	Kevin Duby
Colorado DOT	Jamie Yount
Idaho Transportation Department	Steve Spoor
Illinois DOT	Laura Shanley
Maryland DOT State Highway Administration	Joshua Stonesifer
Massachusetts DOT	Mark A Goldstein
Minnesota DOT	Joe Huneke
New Hampshire DOT	David Gray
Ohio DOT	Scott Lucas
Pennsylvania DOT	Bill Jennueh
Utah DOT	Rhett Arnell
Vermont Agency of Transportation	Todd C Law
Wisconsin DOT	Mike Adams
City of Farmington Hills, MI	Bryan Pickworth
City of Golden Valley, MN	Tim Kieffer

Agency	Name
City of West Des Moines Public Services, IA	Bret Hodne
Crow Wing County, MN	Jory Danielson
East End Crossing Partners	Phillip Anderle
Norwegian Public Roads Administration, Norway	Bård Nonstad and Øystein Larsen

Table 2. Survey Respondents without AVL/GPS Systems

Agency	Name
Kansas DOT	Clay Adams
Montana DOT	Douglas McBroom
North Dakota DOT [1]	Mike Kisse
Wyoming DOT	Cliff Spoonemore
City of Keller, TX	Kelly Howell

[1] Agency is in the process of deploying AVL/GPS on winter maintenance vehicles or equipment.

3.2 Summary of Survey Responses

The survey consisted of 20 questions. A question-by-question summary of the responses received from the responding agencies is presented below. Each agency's responses to the survey are provided in the appendix of this report for further reference.

Question 1. Do you currently use an Automatic Vehicle Location / Global Positioning System (AVL/GPS) system for winter maintenance operations?

Yes	No	No but in the process of deploying	No Response
19	4	1	2

Question 2. What performance measures are used to determine level of service (LOS) for winter maintenance operations?

Performance Measures	Total Agencies
Cycle time	5
Average distribution deviation (changes in the distribution of vehicle speeds after event)	2
Operating speed recovery time	9
Time to achieve bare pavement	9
Time to return to a reasonable near-normal road condition	11
Length of road closures	4
Crash reduction	5
Public satisfaction	8
Other (please specify)	6

Performance Measures	Total Agencies
Visual to see what is working etc., Residents feedback, etc.	1
LOS is time committed to the route. Monitoring speed recovery time, but it is antidotal.	1
All performance measures are helpful in determining if LOS are being maintained	1
Road Condition Rating	1
Mobility defined as water present on pavement with temperatures below freezing.	1
Working on speed recovery but do not currently have a measure.	1

Question 3. Do you use AVL data to track cycle times?

Yes	No	No response
6	18	2

If yes – please explain the process and/or performance measures that are monitored for cycle times:

Agency	Process/Performance Measures for Cycle Times
Massachusetts DOT	We encourage our 140+ depots' Timekeepers to consider their snowfighting equipment's cycle time in light of the current rate of precipitation. It is an excellent way to attain a level of comfort with one's depot's LOS during an event
Pennsylvania DOT	AVL tracks the vehicle from stockpile to another stockpile, would be considered a trip.
Wisconsin DOT	We try but it's extremely difficult. We need to know cycle times to make MDSS more effective, but really haven't found a good way to track them.
City of Farmington Hills, MI	Not currently, but could be an interesting subject to measure
City of West Des Moines Public Services, IA	We examine the data after each storm to see what the cycle times were for each route
Crow Wing County, MN	Our goal is to have priority 1 roads within 6 hours after the event ends, priority 2 within 8 hours, and priority 3s within 10 hours of the event ends. We also want to have all operators back to their shop within 15 minutes of each other for route equity.
East End Crossing Partners	By contract we are required to cycle the route every 2 hours. Our route traversal time is approximately 1 hour and 25 minutes leaving 35 minutes for reloading and bio breaks for a total of 2-hour cycle time.
Norwegian Public Roads Administration, Norway	AVL data gives necessary information to control the required cycle times.

Question 4. Does your AVL system data provide you with cycle time measures?

Yes	No	Not Applicable	No Response
8	12	4	2

Question 5. Does your agency use AVL data to validate your current route maps/data?

Yes	No	Not Applicable	No Response
7	15	2	2

Question 6. What variable(s) from your AVL system data are most helpful for measuring the performance of winter maintenance operations?

Variables from AVL/GPS Data	Total Agencies
Breadcrumb trails of where the trucks treated recently	15
Historical locations	12
Plow up/down	11
Recovery speeds/rate	2
Route treatment status (cycle time)	6
Salt/material application rates	18
Salt/material totals for an event	15
Truck speed	16
Weather details	8
Other (please specify):	5
Looking at pavement and friction data as events change	1
Not Applicable	1
We have a new system being installed this year, so unsure of new capabilities.	1
Spinner Speeds, truck speeds, material pre-wet applications	1
Photo	1

Question 7. Is your AVL raw data readily available for internal staff access? (i.e., stored in-house or API available to hook into)

Yes	No	Not Applicable	No Response
19	1	3	3

Question 8. Besides AVL data, are there other data sources used to track cycle times, including manually tracking such as weather data (from RWIS, mobile RWIS, NWS, etc.), route data?

Yes	No	Not Applicable	No Response
10	12	1	3

If yes, please describe the other data sources:

Agency	Other Data Sources
Arizona DOT	We can use RWIS
Idaho Transportation Department	RWIS
Maryland DOT-SHA	RWIS, MARWIS
Massachusetts DOT	Our depot timekeepers are always on top of cycle times. They know when they send our batteries and ramp trucks, etc.
Pennsylvania DOT	NWS, Accuweather, RWIS tracks Weather Data
Utah DOT	RWIS, Traffic Operations Center (Cameras, Sensors, etc.)
City of Farmington Hills, MI	We plan on piloting another tool through plow opps to give some feedback to our team.
City of Golden Valley, MN	road and weather station.
Crow Wing County, MN	RWIS to forecast pavement temps and weather conditions to adjust routes and material.
East End Crossing Partners	MDSS from DTN

Question 9. What other infrastructure assets are commonly used by your agency during winter events?

Other Assets Used	Total Agencies
Dashcams	8
Dynamic message signs	15
Mobile RWIS	8
RWIS	22
Traffic cameras	20
Variable speed limit signs	7
Other (please specify):	3
We have one RWIS available to us through MDOT, we are installing more cameras at our city facilities as well have two mainline trucks setup with Vaisalas MD-3 to help support decisions.	1

Other Assets Used	Total Agencies
Not true variable speed limit signs, but I-90 VMSs display lowered speed (from 65 MPH to 40 MPH) for applicable stretches	1
Friction measurements	1
None	1

Question 10. How do you calculate cycle times?

Vendor Solution(s)	In-house Tool(s)	Not Currently Calculating Cycle Times	No Response
0	9	15	2

If your agency uses either vendor provided solution(s) or in-house tool(s) to calculate cycle times, please use the space below to indicate the vendor solution(s) and/or in-house tool(s) used:

Agency	Vendor Solution(s) / In-house Tool(s) Used
Massachusetts DOT	Our Depot timekeepers are instrumental in determining how long a treatment cycle takes. Commuter traffic is the biggest exacerbating factor for cycle times. If cycle times increase too much, more equipment may be assigned to certain routes to ensure that levels of service are maintained adequately
Minnesota DOT	Cycle time are determined by the Operations supervisors and inputted into our MDSS modeling. The System does not automatically determine or calculate cycle times. MDSS has the manual inputs and bases recommendations from that data.
Norwegian Public Roads Administration, Norway	Climate, AADT, Road type and importance, accidents, topography.
Vermont Agency of Transportation	We did a route optimization with University of Vermont, TRC a few years ago. Our managers also review the cycle times for the 25 trucks in our fleet that perform winter maintenance.
Wisconsin DOT	Each county is doing it however they want. Not an effective method whatsoever.
City of West Des Moines Public Services, IA	Time for completion of route based on AVL data. Storm conditions are also taken into consideration.
Crow Wing County, MN	Precise and inhouse spreadsheets.

Question 11. Does your agency track plow up or plow down?

Yes	No	Not Applicable	No Response
12	12	0	2

Question 12. Please rank the following variables based on impact to cycle time (with 1 being the highest impact and 11 being the lowest impact).

Agency	Variables										
	Type of storm event (severity)	**Type of treatment**	**Road geometry**	**Surround-ing terrain**	**Capacity of truck**	**Number operational trucks**	**Available staffing to operate trucks**	**Distance/ time to refill material**	**Long-term construction**	**Incident clearance**	**Peak hour traffic**
Idaho Transportation Department	1	2	5	9	6	3	4	7	10	11	8
Illinois DOT	1	6	11	7	8	4	3	2	10	9	5
Maryland DOT-SHA	1	2	9	8	3	4	5	11	10	7	6
Massachusetts DOT	2	7	6	8	11	3	4	10	9	5	1
Minnesota DOT	0	4	0	0	1	2	0	3	10	9	5
New Hampshire DOT	1	4	7	6	5	2	3	8	9	10	11
North Dakota DOT	7	6	5	8	4	1	2	3	11	10	9
Norwegian Public Roads Administration, Norway	1	2	4	6	11	5	10	3	9	8	7
Ohio DOT	2	11	4	5	6	8	7	9	10	3	1
Pennsylvania DOT	2	3	11	6	10	5	4	8	9	1	7
Utah DOT	1	2	4	5	8	6	7	9	11	10	3
Vermont Agency of Transportation	4	7	9	10	3	8	5	1	11	6	2
Wisconsin DOT	7	4	6	10	1	2	3	5	11	9	8
Wyoming DOT	0	0	8	0	3	0	9	0	0	0	0

Agency	Variables										
	Type of storm event (severity)	**Type of treatment**	**Road geometry**	**Surround-ing terrain**	**Capacity of truck**	**Number operational trucks**	**Available staffing to operate trucks**	**Distance/ time to refill material**	**Long-term construction**	**Incident clearance**	**Peak hour traffic**
City of Farmington Hills, MI	0	10	0	0	7	0	0	6	5	8	9
City of Golden Valley, MN	1	9	3	4	8	6	7	5	11	10	2
City of Keller, TX	1	4	2	3	5	6	7	8	11	10	9
City of West Des Moines Public Services, IA	0	0	0	0	3	0	0	9	0	10	2
Colorado DOT	2	9	10	11	7	4	3	6	8	5	1
Crow Wing County, MN	1	6	8	7	9	4	2	10	11	5	3
East End Crossing Partners	3	8	10	11	9	1	2	7	6	5	4

Question 13. Do different routes have higher LOS for cycle times?

Yes	No	Not Applicable	No Response
17	1	6	2

If yes, please briefly explain:

Agency	Explanation
Arizona DOT	Although we do not really track cycle times at this time, we do primarily focus our routes based on ADT, typically focusing on interstates first. we have priority routes 1-5. 1 being interstates, 5 being seasonal closure points.
Idaho Transportation Department	Interstates have a higher LOS than non-interstates.
Illinois DOT	Some routes are longer than others. Distance from yards.
Maryland DOT-SHA	Our Interstates have a higher priority, there for shorten loops to ensure more frequent coverage.
Massachusetts DOT	Mainlines require more equipment to achieve a LOS that can be achieved on a secondary route with less equipment. Lots of variables dictate LOS though. Traffic can help work the salt into the snow, but can ultimately slow down treatment vehicles, resulting in poor LOS.
Minnesota DOT	Higher volume roads typically are shorter and have shorter cycle times than rural longer routes.
North Dakota DOT	Higher LOS routes have shorter cycle times.
Norwegian Public Roads Administration, Norway	We have five winter maintenance classes for road, and three classes for pedestrian and cycling areas.
Ohio DOT	We have a higher level of service on our priority route.
Pennsylvania DOT	Main Priority routes have higher LOS
Utah DOT	Interstates > Major Routes > Minor Routes
Vermont Agency of Transportation	Our level of service hasn't had much effect on cycle times, but during the nighttime operations, we reduce staffing and extend routes, which impacts LOS.
City of Golden Valley, MN	We have a main collector route where two trucks run in tandem. The route's cycle time is less than other routes.
City of West Des Moines Public Services, IA	We have arterial routes, collector routes and residential street routes. All have varying level of LOS expectations.
Crow Wing County, MN	All of our roads are prioritized by ADT or major connections between state roads.
East End Crossing Partners	Mainline freeway is higher priority than feeder routes and ramps

Question 14. What other performance measures (besides cycle time) or enhancements are desirable for understanding the live progress of winter maintenance operations?

Agency	Other Desired Performance Measures / Enhancements
Arizona DOT	We focus on the use of AVL and material usage overall. Cycle times are recognized as important, as is LOS. We have chosen to focus on materials, plow speeds, deployment etc. With these improvements, our hope is to enhance operations all the while reducing cost and salt usage overall.
Colorado DOT	Real-time information of what the material spreader is putting on the road
Illinois DOT	Time to bare/acceptable. Friction/grip. Traffic speeds.
Maryland DOT-SHA	return to "Normal" speed
Massachusetts DOT	We are paying more attention to maintaining grip levels instead of treatments based on temporal rhythms. We are also studying time to recover to normal speeds following the end of precipitation while considering total precipitation and over what length period it fell.
Minnesota DOT	Return to bare lane times (by MnDOT criteria)
North Dakota DOT	bread crumb of which roads have been treated, storm severity, precipitation type and rate, application type and rate. Possibly staffing and number of trucks available
Ohio DOT	Road friction recovery.
Vermont Agency of Transportation	Looking into Grip measures, cost versus storm severity and time to normal speed.
City of Farmington Hills, MI	Timing of event compared to rush hour times.
City of Golden Valley, MN	How fast the road surface recovers.
City of Keller, TX	Driver report of route completed
City of West Des Moines Public Services, IA	Time to achieve LOS goals. Time to complete routes/zones
Crow Wing County, MN	Material usage specific to each event along with road temps
East End Crossing Partners	effectiveness maintenance efforts to maintain serviceability of the roadway during winter precipitation.
Norwegian Public Roads Administration, Norway	Average speed, friction measurements, residual snow after plowing.

Question 15. Does your agency currently use dashboard and/or map-based tools to monitor/present cycle time information?

Yes	No	Not Applicable	No Response
3	18	3	2

Question 16. What dashboarding platform does your agency prefer, if any?

Preferred Dashboarding Platforms	Total Agencies
Power BI	5
Tableau	2
ArcGIS or AGOL (ArcGIS Online)	9
Not Sure/Unknown	6
Other (please specify)	4
tied into or AVL provider SKYHAWK	1
Compass Com	1
PreCise	1
Vendor specific web interface	1

Question 17. What are some challenges you face or foresee facing with calculating cycle times?

Agency	Challenges with Calculating Cycle Times
Arizona DOT	We need to understand the overall benefit, but some challenges would be staff, plow vehicles, SSI, type of storm and traffic
Colorado DOT	Developing a methodology to calculate cycle times on multi lane roads when we have many different trucks operating
Idaho Transportation Department	Inconsistent routes.
Illinois DOT	Routes may change due to staffing issues. Having the flexibility to change/calculate if routes are tweaked.
Maryland DOT-SHA	Hardware issues
Massachusetts DOT	If we have sufficient equipment and are not caught in commuting traffic, none of our routes are too long to make plow cycle times the be-all, end-all. We want our material spreaders to maintain low speeds and not rush to make a cycle time benchmark. If we're doing our jobs correctly and not bogged down by roadway impingements (accidents ahead, etc.), cycle times are usually acceptable. We also have folks monitoring roadway conditions while not directly involved in treatments. They help us determine if cycle times are too long to keep up with the rate of precipitation. The hardest part is maintaining cycle times that are short enough to leave the route in safe travel condition until the next pass. It's desirable to leave enough time for the drivers to get a break
Minnesota DOT	Information from each event is different, and normalizing the information based on storm severity, truck availability, to name a couple.
North Dakota DOT	Equipping entire fleet with AVL to get good coverage of data collection and accuracy
Ohio DOT	We do not calculate it at this time.
Utah DOT	Accuracy from GPS; Road Geometry (# of lanes); Number of passes per roadway section
Wisconsin DOT	Gathering the data, classifying the storm severity.

Agency	Challenges with Calculating Cycle Times
City of Farmington Hills, MI	See what our AVL provides on the current reports
City of Golden Valley, MN	Time of day, severity of storm, and number of operational trucks.
City of West Des Moines Public Services, IA	Conditions are always variable. Staff proficiency also varies.
Crow Wing County, MN	Type of event dictates the outcome.
East End Crossing Partners	Equipment breakdowns, materials supplies, staffing shortages.

Question 18. What practical advice can be offered to others interested in considering cycle time to improve LOS through increased safety and reliability during snow and ice events?

Agency	Practical Advice for Considering Calculating Cycle Times
Arizona DOT	N/A
Colorado DOT	I think our ability to put equipment on the road might be the most important aspect of S&I operations with current labor issues and traffic impacts
Illinois DOT	IDOT is not currently implementing cycle times so unable to answer.
Massachusetts DOT	Get out ahead of the commute and utilize RWIS (grip levels) and ITS cameras to ensure that traffic is flowing, and roads are in safe condition relative to the rate and type of precipitation. Never be back on your heels because that's when you rush and don't administer treatments as well.
North Dakota DOT	Adhering to LOS standards in place. Tracking progress and accountability. Getting public to agree with LOS standards for their area
Ohio DOT	If you want to increase cycle time, shorten the route distance.
Utah DOT	Set clear and definable goals and start small.
City of Farmington Hills, MI	It's worth looking into based on lane miles per route, where your maintenance yard is located in your area, etc.
City of West Des Moines Public Services, IA	Cycle time is critical when considering LOS levels. It impacts plowing and road conditions, deicer effectiveness, and several other aspects.
Crow Wing County, MN	Level of priority
East End Crossing Partners	Route optimization
Norwegian Public Roads Administration, Norway	It is hard to consider all the factors that can appear in a real situation.

Question 19. May we contact you with follow-up questions?

Yes	No	No response
22	2	2

3.3 AVL Sample Data

Requests for sample AVL data were sent to 19 selected agencies upon reviewing responses from the survey described in Section 3.2. Sample data sets were received from Colorado DOT, Ohio DOT, and Massachusetts DOT. In addition, to gain an understanding of available variables from AVL solutions, these sample data sets assisted with addressing any data cleanup within the tool framework. They also allowed the research team to identify options for using specific information/metrics based on an agency's unique data being collected. Sample AVL data sets collected are included in Appendix B.

Colorado DOT also provided a link to their API which provided information on how to pull data, what data fields were available, and the data format. The API Information was available at: [Data Feed | Geotab Developers](). Below is a sample of the API data format, which is the raw data pulled from the AVL system that may feed directly into a plow cycle dashboard or tool.


```
Done:  - Object { ... }
          - data:  Array[260]
             - 0:  Object
                  dateTime:  "2022-10-31T12:00:14.000Z"
                - device:  Object
                     id:  "b21C"
                  id:  "b75341A"
                  latitude:  35.9456253
                  longitude:  -78.5441818
                  speed:  81
             + 1:  Object
             + 2:  Object


Done:  - Object { ... }
          + data:  Array[260]
            toVersion:  "000000000075351d"
```


Figure 7. Sample API Data Format

4. User Stories

The purpose of this section is to build hypothetical scenarios via user stories to show the challenges and benefits of a real-time cycle time tool/dashboard. These user stories were based on the information gathered from current practices in the calculation and applications of cycle times discovered in the literature search and from the agency survey. Key findings from other agencies discovered in the literature search and the survey were:

- Commuter traffic is the biggest factor that affects cycle time (Massachusetts DOT)
- Cycle times are determined by Operational Supervisors and used in Maintenance Decision Support System (MDSS) (Minnesota DOT)
- Storm conditions are considered when reviewing AVL data for cycle time (City of West Des Moines Public Services)
- 70% of survey participants stated that they have different cycle times targets or goals based on the classification of the route
- The survey showed that the top five variables affecting cycle times as reported by transportation agencies were:
    1. Type of Storms
    2. Number of Operational Trucks
    3. Available Staff to Operate Trucks
    4. Peak Hour Traffic
    5. Type of Treatment

Based on these observations, eight user stories were developed to show how a real-time tool for cycle times may benefit the transportation agency's winter operations and ultimately increase safety and mobility for the traveling public.

The eight user stories are:

- User Story 1: Heavy Traffic Congestion During a Major Snow Event
- User Story 2: Reduced Fleet Size Due to Availability Issues
- User Story 3: A Snow Event with Extreme Temperatures
- User Story 4: Mountainous Terrain (Planning and Calibrating Routes)
- User Story 5: Traffic Operation Center
- User Story 6: Post Storm Analysis – Route Modifications
- User Story 7: Post Storm Analysis for Disaster-Level Readiness
- User Story 8: Enhanced MDSS Recommendations

The eight user stories are presented on the following pages.

User Story 1: Heavy Traffic Congestion During a Major Snow Event
Story
The weather forecast showed that there was a high chance for a major winter storm event to hit Wayne County and the surrounding counties in 24 hours. The forecast showed that Wayne County would be receiving more intense weather than the surrounding counties, and that the storm would accumulate between 6 and 8 inches of snow within Wayne County within approximately 6 hours, averaging an inch per hour. For this area, this amount of accumulation and intensity would classify this event as a "severe" or "heavy" snow and ice event. The state DOT is responsible for the main interstate running through these counties, as well as other state and US routes. This DOT agency categorized each road they maintain according to their priority level based on functional class and traffic volume, with the interstates being the highest priority. The routes for the highest priority are predetermined to have a 90-minutes cycle time on an average winter weather event. Around 3 a.m., the snow started to fall. Once the plows started hitting the roads, the winter maintenance manager started to monitor the data they get from the truck's AVL system within a Cycle Time Dashboard, which provides information on the average cycle time (in real-time) for any given route. It was very beneficial to be able to monitor how long the cycle time was taking to treat on their routes since there were multiple high-priority routes within the agency's road network. The manager was able to see that the cycle time was longer along the interstate routes than what the agency desired. Lower priority roads were even worse, the cycle times were way above the target. When the County Manager notices that the average interstate cycle time was estimated to be 120 minutes and the knowledge that the afternoon commuter traffic was starting to increase, the Manager knew this cycle time would continue to increase with the risk of the plow getting blocked by traffic and the increased potential for incidents solely based on volume and weather. Therefore, the manager took actions to attempt to mitigate this increase. The manager communicated with the surrounding County managers to see if their cycle times were near or below the target. The county west of Wayne County was not experiencing such a severe storm and their cycle times were below the target. The managers worked to shift resources east along the interstate to allow Wayne County to bring their cycle time back to a reasonable measure. In addition, the manager was able to alert the traveling public about the condition of the route using dynamic message signs and social media. This helped to make the public aware that both high and low-priority routes were having such a low level of service, so that the public could reduce travel until other agencies' equipment and personnel arrived on site. Altogether, being able to track the cycle time allowed the agency to lower the possibility of a crash and avoid any congestion that could have occurred on this route that had a heavy snow event.
Assumptions
▶ The fleet is equipped with an AVL system ▶ 6 to 8 inches is a "heavy" storm event for this agency ▶ There were available resources in nearby garages that the agency could utilize ▶ Uses different cycle times based on the type of route
Scenario Outcome and Comments
▶ Were able to get the interstate routes closer to the desired cycle time and keep the public traveling safer ▶ Best practices for shifting and sharing resources
Operational Systems
▶ AVL System ▶ Cycle Time Real-time Tracking Dashboard/Tool ▶ RWIS system to monitor the weather

User Story 2: Reduced Fleet Size Due to Availability Issues
Story
It was mid-way through the winter season and there have been frequent and severe winter events. At this point, there were several trucks in need of mechanical work mostly hydraulic line issues. In addition to a reduced fleet, two of the four mechanics (2 per shift at this garage) were out with COVID. Therefore, at this point in the season, this garage was operating with 70% of the fleet and 50% of their mechanics. The weather data showed that the service area for the garage would receive 20 to 30 inches of snow over the next two days, which could cause a “severe” or “heavy” weather effect since the 3 trucks would not be in the service. Once the snow started, the manager was monitoring the cycle time information from the Cycle Time Dashboard and noticed that the cycle times were around 240 minutes for the 3 routes with the lowest priority. The routes for the lowest priority are predetermined to have a 120-minute cycle time on an average winter weather event. Cycle times for these 3 routes were doubled due to the reduced resources available. Though these are the lower priority routes, there is still a need to serve the public to the best of their ability. The snowfall severity was at the same level across the nearby garages, so shifting or borrowing trucks was not an option at this point; however, sharing mechanics could be an option to help get trucks back on the road. With the cycle time data available, the manager was able to justify this mitigation strategy. Before the next shift was scheduled to arrive, the manager of the garage was able to work with the manager at the garage east of them to have one of their mechanics report to the garage. Additionally, the manager was able to work with the agency’s communication department to use the real-time cycle time information to alert the traveling public before the morning commuters left via social media, the agency’s public-facing website, and relationships with local media. This would help to manage traveler expectations. With an additional mechanic, the two mechanics were able to get 2 more trucks up and running mid-way through the event. The extra operators were able to assist with loading trucks, making brine, and helping the mechanics when capable while waiting for the trucks to be operational. Once these were deployed, the manager was able to monitor the cycle time and saw that it was improving. The next shift did not require any other mechanics to shift garages.
Assumptions
▶ The fleet is equipped with an AVL system ▶ Communication with the public was approved and conducted by the proper department ▶ There were available resources in nearby garages that the agency could utilize ▶ Uses different cycle times based on the type of route
Scenario Outcome and Comments
▶ Traveler expectation ▶ Reliable information ▶ Justification for non-standard practices of sharing mechanics
Operational System
▶ AVL System ▶ Cycle Time Real-time Tracking Dashboard/Tool ▶ Social media and dissemination mechanisms

User Story 3: A Snow Event with Extreme Temperatures

Story

By the middle of winter, the pavement temperatures have been as low as 18°F. The local weather data reported that a strong cold front was moving in and over the next few days, it was estimated that the pavement temperature would be approximately 10°F or lower during the week across the northern part of the State. Additionally, during this time, there was a snow event in the forecast. The agency typically chemically treats with sodium chloride (NaCl) in rock form and brine. However, brine is not useful below 15°F. Furthermore, since it's 77% water, it can freeze and should not be used in these conditions. Therefore, the agency switched to a low-temperature deicer material that would help keep the surface friction reasonable. This decision was supported by the Maintenance Decision Support System (MDSS). Through experience, they knew that the low-temperature deicer would not last as long on the roadways as brine normally would. Therefore, all routes, regardless of priority, have to have a 90-minute cycle time if they want to keep the roads running at the highest LOS possible with this chemical treatment. The cycle time needs to be monitored closely to meet this new requirement.

Around 10 a.m., the snow started to fall and pavement temperatures were nearing 11°F. Once the trucks started treatment, the manager started monitoring the Cycle Time Dashboard. The garages within this region were prepared for this change in cycle time, and all routes were meeting the 90-minute goal.

As the storm progressed, the manager reviewed the Cycle Time Dashboard and noticed two of the interstate routes started to fall behind due to incidents that occurred along their routes, causing the cycle time to increase outside the desired 90 minutes. Both these routes are along a 4-lane (2 lanes per direction) interstate. The manager radioed the operators of the two routes and suggested that they focus on treating the right lane of the roadway only for the next pass to allow travelers to safely enter and exit the interstate. This would allow for at least one lane to stay within the treatment material's life expectance and thus safer to travel. Once the trucks were back on track with their cycle times, they were able to get the other lanes treated and stay on the 90-minute cycle time target.

The operators have enough tasks while treating the roadway and do not need to add checking to see how close they are to the targeted cycle times. Therefore, having a source allowing managers to monitor current and projected cycle times helps real-time decision-making and improves operations efficiency.

Assumptions

- The fleet is equipped with an AVL system
- 10°F weather temperature with treatment lasting approximately 90 minutes

Scenario Outcome and Comments

- Better decision-making to maintain open roadways

Operational System

- AVL System
- Cycle Time Real-time Tracking Dashboard/Tool
- RWIS system to monitor the weather
- Maintenance Decision Support System

User Story 4: Mountainous Terrain (Planning and Calibrating Routes)
Story
Colorado experienced rapid population growth over the past years. The state transportation agency conducted a review of their current level of service of snowplow routes to investigate if adjustments on winter maintenance operations were needed. The agency also established a standard cycle time target of 90 minutes to all routes. With this goal, the agency conducted a route optimization project over the non-winter months to model new routes and determine the number of trucks required to complete all routes. Data from the Cycle Time Dashboard were used as inputs to the route optimization model. During the fall, the operators were trained on these routes and performed a dry run to check cycle times. The operators drove the routes on a dry day while the manager monitored the Cycle Time Dashboard and found that all the routes were at or lower than the desired cycle time target. The agency felt ready for the upcoming winter season. The winter season started with a few minor snowfall events, and the cycle time goal was met for all the routes. As the season progressed and the first moderate snowfall hit the area, the agency observed challenges in meeting the cycle time goal. As the snowfall intensified, the manager monitored the Cycle Time Dashboard and noticed that two of the routes were taking much longer to complete than planned. Both these routes were through mountainous terrain which caused operators to move slower due to road geometry and poor visibility during moderate/heavy snowfall. It appeared the route optimization model didn't adequately account for the impacts of varying conditions in the real-world situation. The manager documented and reported these real-world route times through the use of the Cycle Time Dashboard. The route optimization model was then calibrated using the data from the Cycle Time Dashboard. As the calibration process could not be completed within the current winter season, the operations continued with the set routes. With the resources available in the current season, the cycle time that could be achieved on routes through mountainous terrain was 110 minutes during heavier snowfall events. Once the season was over, the agency went through the cycle time data, event severity data, material dissipation rates, weather-related incident data, budget/cost, public satisfaction, and operation and mobility performance to investigate if a 110-minute cycle time was an acceptable target or if the benefit-cost justified adding more resources. Using these data points, the agency made a decision to procure more resources to enable them to meet the 90-minute cycle time goal. Additionally, more route books were built for various scenarios that might occur through the winter season, such as down one truck, down 2 trucks, etc. Managers would continue using the Cycle Time Dashboard to monitor operations and feed the data for calibrating the route optimization model as needed.
Assumptions
▶ The fleet is equipped with an AVL system ▶ Budget available for route optimization and more resources
Scenario Outcome and Comments
▶ Data for route optimization modeling ▶ Calibration of route optimization ▶ Realistic route cycle times ▶ Standardized expectations across all routes for all users

Operational System
▶ AVL System ▶ Cycle Time Real-time Tracking Dashboard/Tool ▶ Route Optimization Modeling

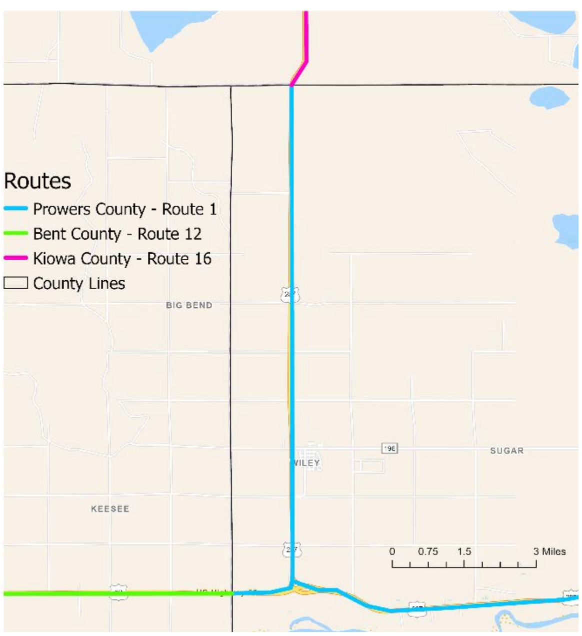
User Story 5: Traffic Operation Center
Story
The Traffic Operation Center (TOC) monitors the DOT's routes for congestion, incidents and road conditions and disseminates information to the public. The TOC uses social media, the agency's website (such as the 511 website), DMS assets, Waze, and the Integrated Public Alert & Warning System (iPAWS) to alert travelers of roadway conditions and disruption. The iPAWS application is the Federal Emergency Management Agency's (FEMA) national system for spatially alerting the public through mobile phones, radios, and television. During the winter season, the TOC works closely with roadway maintenance operations to help manage inclement weather events. Along with their typical work tasks, TOC operators will monitor the roadway travel times and the AVL data to alert operators via radios if they are approaching heavy congestion. At the start of the season, the maintenance operations provided the TOC with access to the newly deployed Cycle Time Dashboard to see if they find value. During the first major winter storm, all stakeholders were busy managing the roadways. One of the TOC operators noticed that there was a route with an estimated cycle time of 300 minutes. The operator communicated with the garage manager to see if this was correct and if they thought this would improve soon. The manager stated that the truck broke down and the other trucks nearby helped cover the route to the extent possible. However, it was expected the route would still be highly impacted for the remainder of the storm. The key personnel, including the communication department, were brought into the conversation and the group determined that, in addition to posting emergency alerts on the agency's website and social media, the TOC would initiate the iPAWS to alert the persons within that spatial zone that the roadways were not safe to travel and if there was an emergency, please contact the emergency services for assistance. The data from the Cycle Time Dashboard allowed the operations team to justify using the iPAWS to alert the public of a safety concern.
Assumptions
▶ TOC have capacity to review the Cycle Time Dashboard ▶ The fleet is equipped with an AVL system ▶ Communication with the public was approved and conducted by the proper department
Scenario Outcome and Comments
▶ Decision-making tool ▶ Increase awareness to the public of conditions to increase their safety
Operational System
▶ AVL System ▶ Cycle Time Real-time Tracking Dashboard/Tool ▶ iPAWS

User Story 6: Post Storm Analysis – Route Modifications

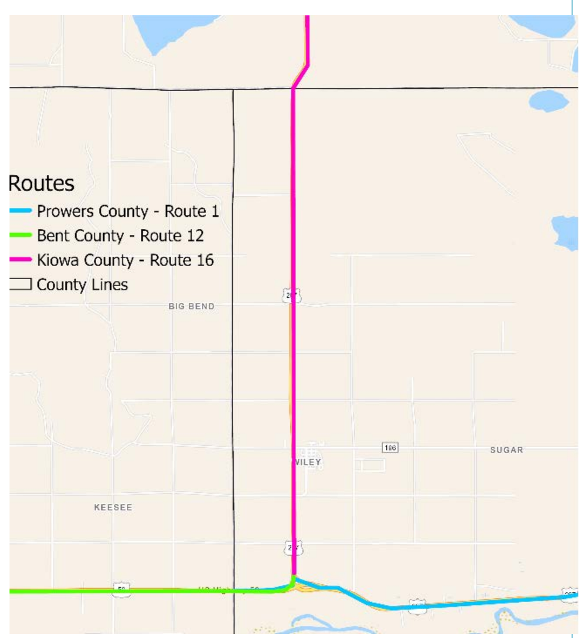
Story

After each winter event, when there is a break in the weather, the Prowers County managers review all the available data from the previous event. After one moderate snowfall event, the County Managers were checking the Cycle Time Dashboard to determine how the fleet performed by comparing the desired cycle times with the average cycle times realized. For a moderate event, anything within 10-mins of the desired 100-minute cycle time for a route is considered a successful event, based on that particular key performance indicator (KPI). All the routes are reviewed as an average cycle time for the entire route throughout the event (one average cycle time per route for the timeframe selected). Fifteen of the sixteen routes met the cycle time KPI target. For the route that did not meet the target, Route 1 of Prowers County, was reviewed further. The managers used the Cycle Time Dashboard to drill-down to smaller segments within the route to get a better understanding of the issues.

Upon review of the route segments, it was determined that northwest corner of the county had a segment of roadway that was the issue with the high cycle time. This was due to the deadhead to refill with chemical treatment material and the number of ramps at the interchange of US 287 and US 50. The County managers reached out to Bent and Kiowa County managers and asked if they could extend their routes to cover this corner of the county and the overlap helped with the interchange ramps. After the next winter event, the cycle times were checked on all these routes to see the impact of the changes. All routes met their targets, and the change was used the rest of the season. The maps below present the original routes (left) and the modifications (right).



Original Routes



Modified Routes

Assumptions

- Surrounding Counties, Bent and Kiowa, were able to assist without impact to their desired cycle time targets

- Deadhead to get to the nearest salt and material facility was too far for this route to meet the target

Scenario Outcome and Comments

- Were able to get the interstate routes closer to the desired cycle time and keep the public traveling safer

Operational System

- AVL System
- Cycle Time Tracking Dashboard

User Story 7: Post Storm Analysis for Disaster-Level Readiness

Story

After one severe winter, there were several agencies that made national news due to major incidents that left hundreds stranded, vehicle-pile ups, and several Injury-A crashes. One state agency in the same region as the agencies with these major events, decided to develop action plans for their disaster-level snow and ice events. Taking the lessons learned from other agencies, they wanted to develop Operational Condition (OpCon) which would use key performance index (KPI) for various measures to determine when a state of emergency should be triggered and roadways should be shut down.

The project team tasked with developing the action plans utilized available weather data to identify how the weather variables normalized by treatment information impacted travelers. Weather data included variables from hourly NOAA weather stations and RWIS sensor data. The treatment information included material types and rates (from the AVL system) along with cycle time (from the Cycle Time Dashboard). The impact to traveler variables looked at probe speed data, volume data, crash reports, and the incident logs from the Advance Transportation Management System (ATMS) collected from the Transportation Operation Center (TOC).

A linear regression model was built to determine which variables are most impactful to the level of service and safety of the traveling public. From these data points, the agency was able to build an OpCon to identify when conditions range from normal event to state-of-emergency (five category system) and the required actions within each category. The KPI used in the OpCon must be available in real or semi-real time in order to be effective for triggering the proper action plan. Due to the lack of cellular coverage in the mostly rural state, the agency utilizes their AVL system data historically. Each time the truck enters one of the agency's garages, the modem on the truck connects to the WiFi at the garage and automatically downloads the data to the proper server. In addition, the agency's OpCon relies on traffic data, TOC ATMS incident data, and weather data for all their KPIs. The Cycle Time Dashboard and AVL data collected in the previous year helped support the model and therefore, the KPI that was developed. After each snow and ice event, the project team is able to validate their current model with the new data and continue to fine-tune the KPI thresholds within the OpCon.

Assumptions

- The fleet is equipped with an AVL system with material information
- Weather and TOC ATMS variables can be monitored in real-time

Scenario Outcome and Comments

- Best practices for readiness and disaster-level snow and ice events

▶ Increase safety
Operational System
▶ AVL System ▶ Cycle Time Real-time Tracking Dashboard/Tool ▶ ATMS ▶ Modeling Software

User Story 8: Enhanced MDSS Recommendations
Story
Multiple agencies that were a part of the Federal Highway Administration's (FHWA) MDSS Pooled Fund program have started utilizing a Cycle Time Dashboard. Currently, the MDSS algorithm uses one cycle time variable for the routes within the system. Through using the data from the Cycle Time Dashboards, it was clear the cycle time ranges based on the time of day (peak vs off-peak), resources available, and weather severity. At a recent conference, these agencies began to discuss utilizing the cycle time data within the MDSS to continue to enhance the system for better recommendations. The agencies reached out to FHWA to work on another pooled fund program project to further enhance the MDSS by utilizing the Cycle Time Dashboard. One of the goals of the enhancement project is to include cycle time data based on time of day and weather severity, and the software will provide insight to expected cycle time if resources are not increased. The project moved forward and was successful in linking the Cycle Time Dashboard data into MDSS for better recommendations. These enhanced insights are beneficial for storm planning and communicating timeframes, as well as overall winter maintenance resource and budget planning.
Assumptions
▶ FHWA agrees to update MDSS ▶ Cycle time data are collected at agencies using MDSS ▶ Cycle time data will enhance recommendations
Scenario Outcome and Comments
▶ Better recommendations for MDSS
Operational System
▶ AVL System ▶ Cycle Time Real-time Tracking Dashboard/Tool ▶ MDSS

5. Variables, Methodology and Case Study

This section presents the variables required to calculate plow cycle times. Additionally, it provides information on desired variables that may enhance the accuracy of the calculation outputs. Along with the variables, this section presents the logic and methodology for calculating plow/treatment cycle times. In addition, a hypothetical case study is presented to illustrate the use of the methodology and default values to show how the methodology works and how each variable impacts the calculation and output.

5.1 Variables

Table 3 identifies the variables necessary to build a robust methodology for calculating plow cycle times. The table notes the variables that are desired, as well as optional for the calculation. The sources of the variables are also identified.

Table 3. Variables for Calculating Plow Cycle Times

Variable	Purpose	Source	Format
Latitude	North-South location of truck. To determine when truck is on a route	Truck AVL	Decimal Degree
Longitude	East-West location of truck. To determine when truck is on a route	Truck AVL	Decimal Degree
Date and Timestamp	To timestamp when a truck starts and ends on a route, the duration will be required for cycle time calculation	Truck AVL	MM/DD/YYYY HH:MM ZZZZ
Treatment Data (Optional)	If available, this will provide more accurate data of when treatment is occurring. Spreader On/Off, Plow activity, spinner speed, and other setting options that contribute to a change in a truck's treatment width are another option that may be included depending on the AVL data available.	Truck AVL	Binary (1,0)
Truck Identification Number	To determine the capacity of the truck while treating a road	Truck AVL	Text

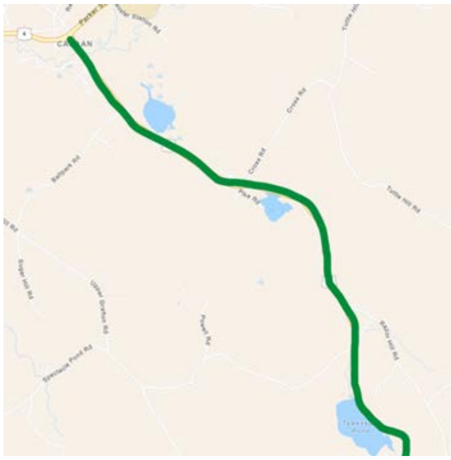
Variable	Purpose	Source	Format
Plow and/or Treatment Width	Based on the truck ID, the tool will determine how much of the roadway width was treated per pass. Each truck has a different treatment width based on size of plow(s) and chemical treatment spreading abilities.	Truck/Equipment Dataset	Decimal Number
Spatial Road Segment (ideally segmented between turnaround / cross over intersections)	To determine when the truck starts and ends on a road segment which will build into a route's plow cycle time	Spatial GIS Road Data	GIS Line
Snow and Ice Routes	Tool will be able to drill down to a road segment but should be able to drill up to provide insights by pre-determined routes as well.	Spatial GIS Road Data	GIS Line
Number of lanes or roadway width (or passes till considered complete, so if you count shoulders or median, include)	Within the road segment data, each segment should provide information on the require number of lanes or effective roadway width. If the DOT includes shoulder or median treatment, then the passes or extra width should be included.	Spatial GIS Road Data	Decimal Number within Road segment line
Weather Data – precipitation, wind and temperature (Optional)	To determine when an event has started. Also, may be used for cycle time vs storm severity analyses.	National Weather Service, Third-Party or RWIS	Decimal Number

A review of the sample AVL data gathered by the research team showed that all AVL data had the required fields with the exception of the Minnesota DOT (MnDOT) data. The MnDOT AVL data presented location by road name, but not latitude/longitude. The research team believed that the Latitude / longitude data was gathered by the MnDOT AVL vendor Ameritrak Fleet. All of the sample AVL data showed a data field for material spreader on/off variable; however, some were empty and might not be collected. The research team concluded that using the above variables to develop a methodology for calculating cycle times and a dashboard/tool was practical, advantageous and sustainable for winter maintenance agencies.

5.2 Cycle Time Calculation Methodology

Using the variables outlined above, a cycle time calculation methodology and its logic was developed and is presented on the next two pages.

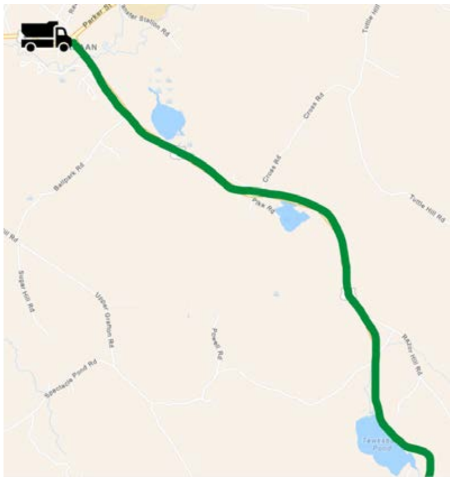
Route A – Snow and Ice Route



Step One: Identify that a truck has started on a segment of road via **latitude/longitude**. **Optional treatment data** - check if **spreader/sprayer is ON**, if TRUE, the following process that will occur when:

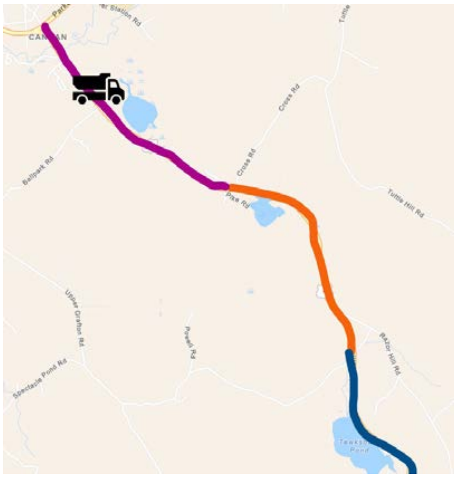
- Start **Date and Timestamp, t_{si}** for the Cycle
- Start **Date and Timestamp, t_{sij}** for the individual pass
- Based on **truck's ID** and **optional treatment data** - query **truck's plow and treatment width/Capacity, C_T**

where, *i* = road segment and *j* = individual pass along the road segment.



Step Two: Compare C_T to the road segment lane count or width, w_i to get a cycle ratio.

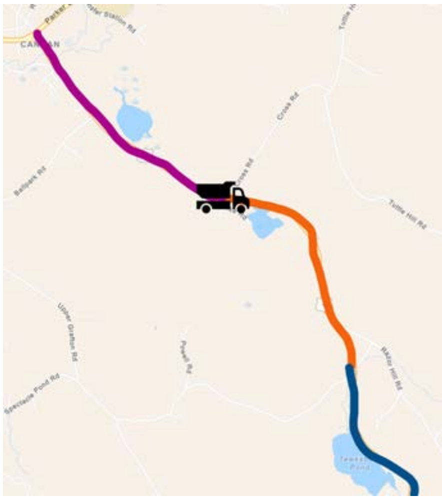
$$Cycle\ Ratio, \theta_j = \frac{C_T}{w_i}$$



Step Three: Calculate duration to treat an individual pass along the segment.

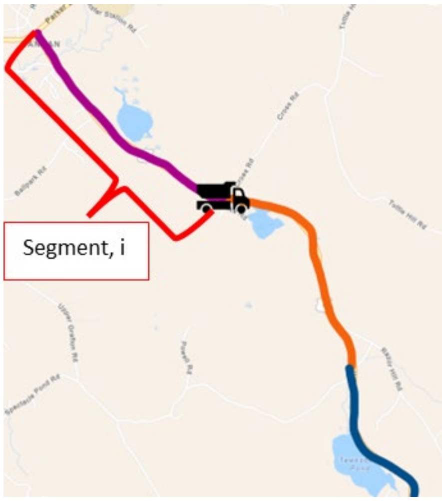
- **End Date and Timestamp, t_{eij}**

$$Duration, D_j = t_{eij} - t_{sij}$$



Step Four: Calculate Results

$$Total\ Duration\ to\ Clear\ Segment, T_i = \sum_{\theta_j}^{\theta_j => 1} D_j$$



When $\sum \theta_j = 1$; **End Date and Timestamp, t_{ei}** for Cycle

$$Cycle\ Time_i = t_{ei} - t_{si}$$

Step Five: Drill up to review multiple segment (total route) Cycle Time

$$Total\ Time\ to\ Clear\ Segment, T_{selected} = \sum T_i$$

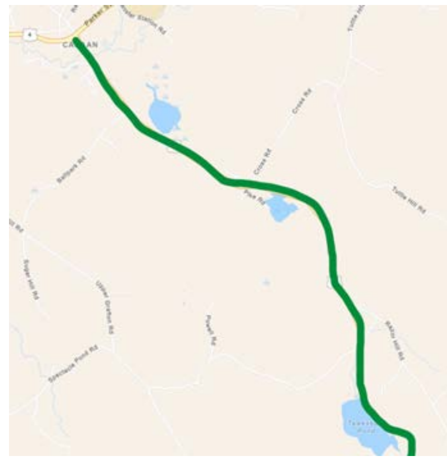
For Cycle Time

$$Cycle\ Time = Latest(t_{si}) - Earliest(t_{ei})$$

5.3 Case Study

A case study of applying the methodology on a hypothetical scenario is presented below. The hypothetical scenario involves a truck that is equipped with AVL going out to treat a roadway segment, Route A, which has three segments.

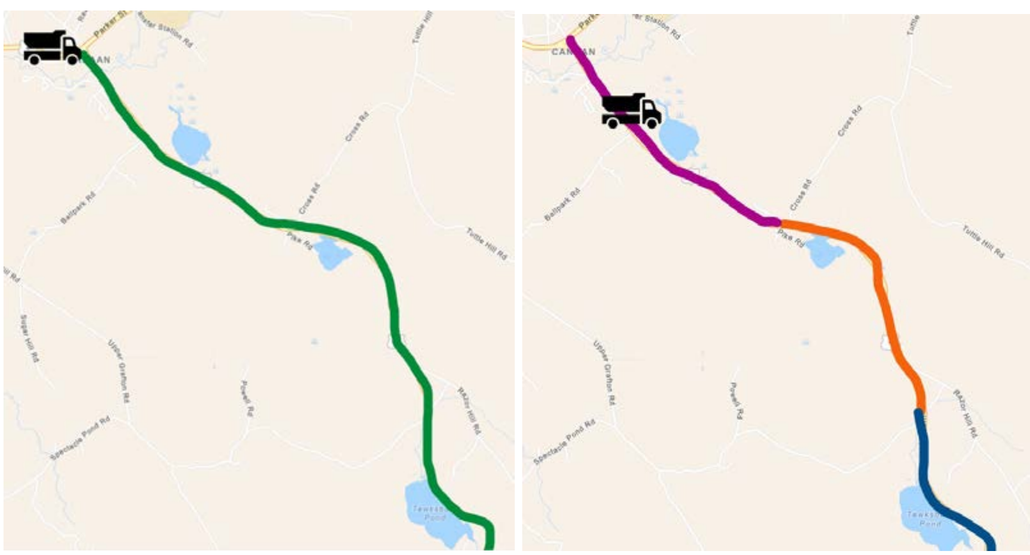
Route A – Snow and Ice Route



Roadway Segment Database

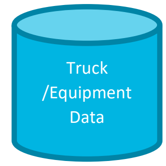
Road Segment (i)	Route	Width (ft)
XXX1	A	24
XXX2	A	24
XXX3	A	24
XXX4	B	36
… n^{th}	…n^{th}	…n^{th}

<u>Step 1</u> – Truck ID 1234 enters Road Segment XXX1 on 12/20/2023 at 2:30 a.m. Truck 1234 was not plowing, salting only with spinner at 2.



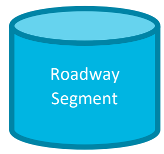
Truck / Equipment Database (C_T)

Truck ID	C_{T1} Width (ft) Plow = ON	C_{T2} Width (ft) Plow = OFF Salt = ON Spreader = 1	C_{T3} Width (ft) Plow = OFF Salt = ON Spreader = 2	C_{T4} Width (ft) Plow = OFF Salt = ON Spreader = 3
1234	12	12	14	18
2234	11	12	14	18
3334	12	12	14	18
… n^{th}	…n^{th}	…n^{th}	…n^{th}	…n^{th}



Roadway Segment Database

Road Segment (i)	Route	Width (ft)
XXX1	A	24
XXX2	A	24
XXX3	A	24
XXX4	B	36
… n^{th}	…n^{th}	…n^{th}



Start Date and Timestamp, $t_{start\ on\ Segment\ xxx1}$ for the Cycle = **12/20/2023 at 2:30 a.m.**

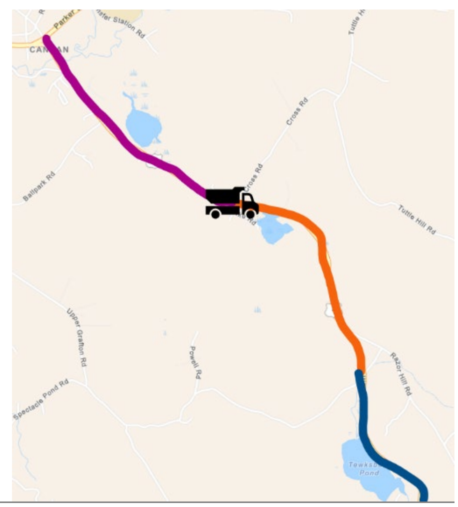
Start Date and Timestamp, $t_{start\ on\ Segment\ xxx1\ for\ first\ past}$ for the individual pass = **12/20/2023 at 2:30 a.m.**

$$Cycle\ Ratio, \theta_{xxx1} = \frac{C_T}{w_i} = \frac{14}{24} = 0.58$$

$$Check\ if \sum \theta_{xxx1} => 1 \quad \sum \theta_{xxx1} = 0.58\ therefore\ FALSE$$

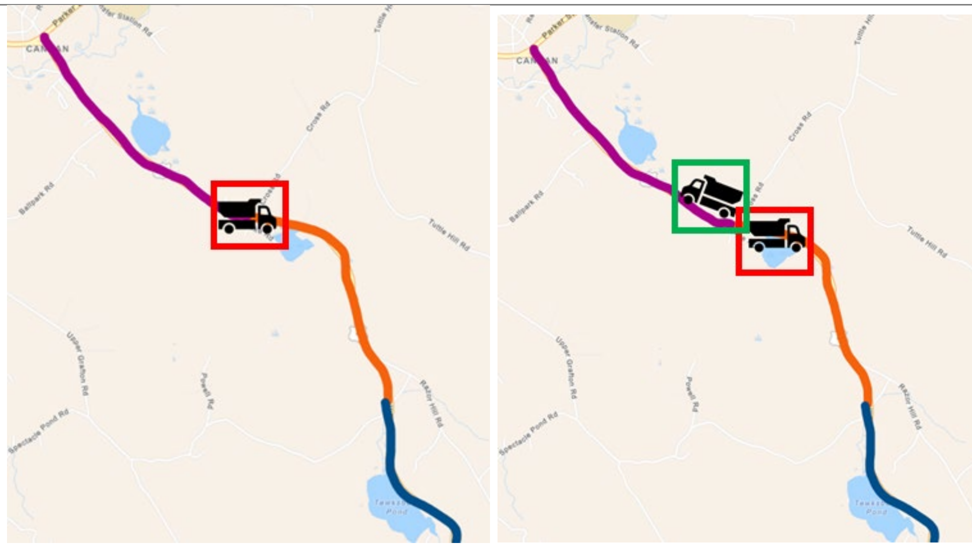
End Date and Timestamp, $t_{End\ on\ Segment\ xxx1\ for\ first\ past}$ for the individual pass = **12/20/2023 at 2:55 a.m.**

$$Duration, D_{Segment\ xxx1\ for\ first\ past} = 2{:}45\ AM - 2{:}30\ AM = 0.25\ hours$$



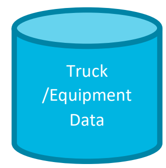
Step 2 – **Truck ID 1234 enters Road Segment XXX2 on 12/20/2023 at 2:55 a.m. Truck 1234 was not plowing, salting only with spinner at 2.**

Truck ID 2234 enters Road Segment XXX1 on 12/20/2023 at 2:55 a.m., was not plowing, salting only with spinner at 3.



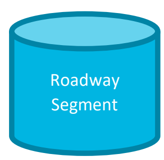
Truck / Equipment Database (C_T)

Truck ID	C_{T1} Width (ft) Plow = ON	C_{T2} Width (ft) Plow = OFF Salt = ON Spreader = 1	C_{T3} Width (ft) Plow = OFF Salt = ON Spreader = 2	C_{T4} Width (ft) Plow = OFF Salt = ON Spreader = 3
1234	12	12	14	18
2234	11	12	14	18
3334	12	12	14	18
… n^{th}	…n^{th}	…n^{th}	…n^{th}	…n^{th}



Roadway Segment Database

Road Segment (i)	Route	Width (ft)
XXX1	A	24
XXX2	A	24
XXX3	A	24
XXX4	B	36
… n^{th}	…n^{th}	…n^{th}



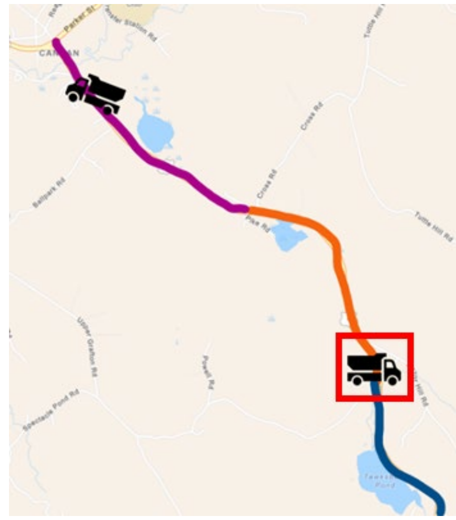
Start Date and Timestamp, $t_{start\ on\ Segment\ xxx2}$ for the Cycle = **12/20/2023 at 2:55 a.m.**

Start Date and Timestamp,
$t_{start\ on\ Segment\ xxx2\ for\ first\ past}$ for the individual pass =
12/20/2023 at 2:55 a.m.

End Date and Timestamp,
$t_{End\ on\ Segment\ xxx2\ for\ first\ past}$ for the individual pass =
12/20/2023 at 3:05 a.m.

$$Cycle\ Ratio, \theta_{xxx2\ frist\ pass} = \frac{C_T}{w_i} = \frac{14}{24} = 0.58$$

$$Duration, D_{Segment\ xxx2\ for\ first\ past} = 3{:}05\ AM - 2{:}55\ AM = 0.2\ hours$$



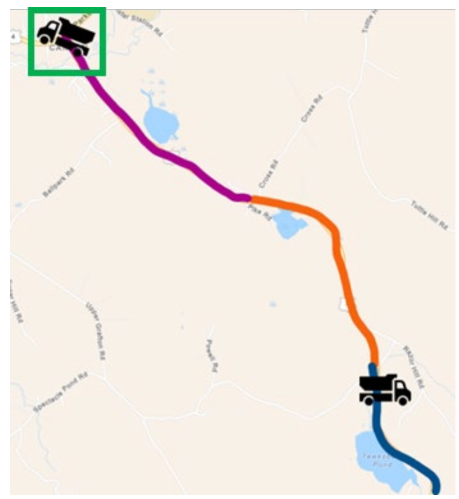
Start Date and Timestamp, $t_{start\ on\ Segment\ xxx1}$ for the Cycle = **12/20/2023 at 2:30 a.m.**

Start Date and Timestamp, $t_{start\ on\ Segment\ xxx1\ for\ Second\ past}$ for the individual pass = **12/20/2023 at 2:55 a.m.**

End Date and Timestamp, $t_{End\ on\ Segment\ xxx1\ for\ second\ past}$ for the individual pass = **12/20/2023 at 3:15 a.m.**

$$Duration, D_{Segment\ xxx1\ for\ first\ past} = 3{:}15\ AM - 2{:}55\ AM = 0.33\ hours$$

$$Cycle\ Ratio, \theta_{xxx1} = \frac{C_T}{w_i} = \frac{14}{24} = 0.58$$



Check if $\sum \theta_{xxx1} => 1$ $\sum \theta_{xxx1} = 0.58 + 0.58$ **therefore TRUE**

Reset θ_{xxx1} And Conduct Total Calculations

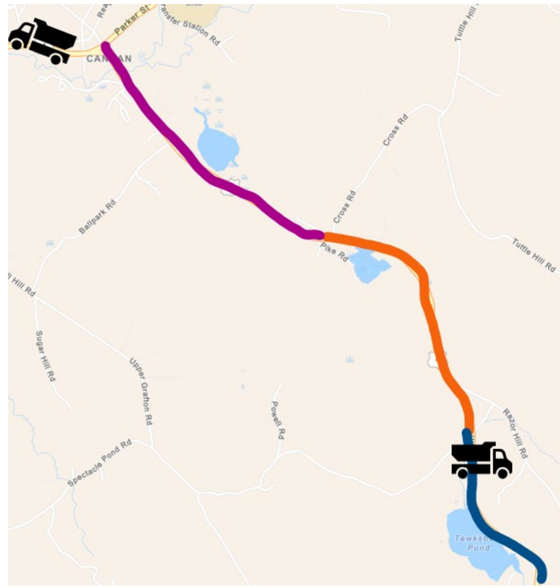
$$Total\ Duration\ to\ Clear\ Segment, T_{xxx1} = \sum_{\theta_j}^{\theta_j=>1} 0.33 + 0.25 = 0.58\ hrs$$

$$Cycle\ Time_{for\ segment\ xxx1} = 3{:}15\ AM - 2{:}30\ AM = 0.75\ hrs = 45\ mins$$

Notes: still need cycle time for Route A (not just segments)

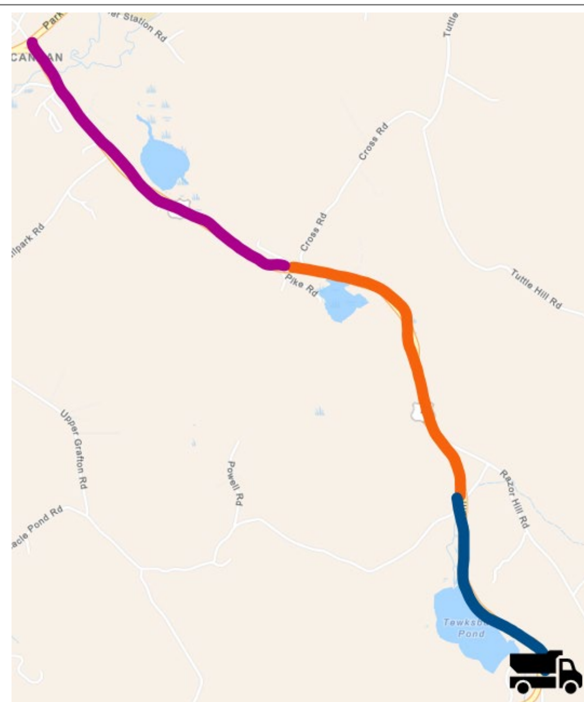
<u>Step 3</u> – Truck ID 1234 enters Road Segment XXX3 on 12/20/2023 at 3:15 a.m. Truck 1234 was not plowing, salting only with spinner at 3.

Calculations continue as shown above with spinner 3 data



Truck ID 1234 ended first pass and started second pass on Road Segment XXX3 on 12/20/2023 at 3:25 a.m. Truck 1234 was not plowing, salting only with spinner at 3.

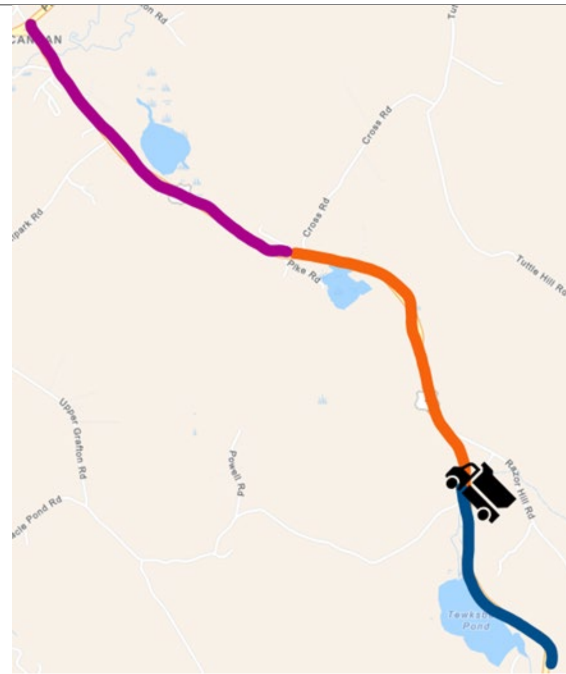
Calculations continue as shown above with spinner 3 data



Truck ID 1234 completed second pass on Road Segment XXX3 on 12/20/2023 at 3: 40 a.m. And started second pass on Road Segment XXX2.

$$\textit{Total Duration to Clear Segment}, T_{xxx3} = \sum_{\theta_j}^{\theta_j=>1} 0.16 + 0.25 = 0.42\ hrs$$

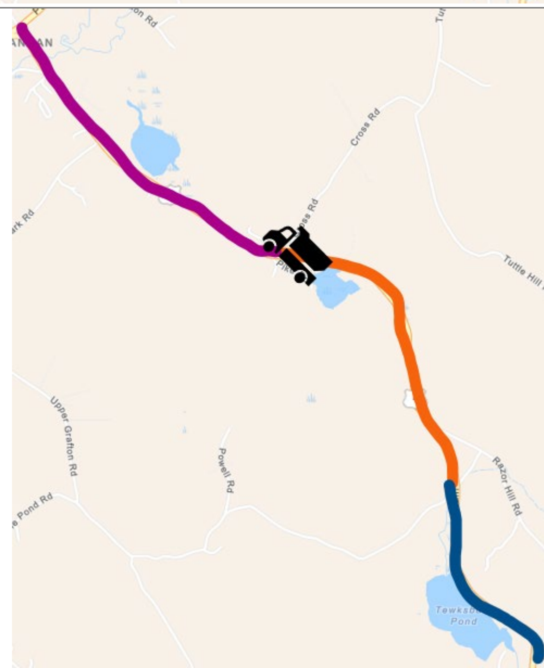
$$\textit{Cycle Time}_{\textit{for segment xxx3}} = 3{:}40\ AM - 3{:}15\ AM = 0.42\ hrs = 25\ mins$$



Truck ID 1234 completed second pass on Road Segment XXX2 on 12/20/2023 at 3: 55 a.m. Truck 1234 was not plowing, salting only with spinner at 3.

$$\textit{Total Time to Clear Segment}, T_{xxx2} = \sum_{\theta_j}^{\theta_j=>1} 0.2 + 0.25 = 0.45\ hrs$$

$$\textit{Cycle Time}_{\textit{for segment xxx3}} = 3{:}55\ AM - 2{:}55\ AM = 1\ hrs = 60\ mins$$



<u>Step 3</u> – Route Cycle Time

For Cycle Time of ROUTE A

$$\textit{Cycle Time} = \textit{Latest}(t_{si}) - \textit{Earliest}(t_{ei})$$

$$\textit{Cycle Time} = 3{:}55\ AM - 2{:}30\ AM = 1.42hr = 85\ mins$$

6. Visualization Tool Framework

This section outlines a comprehensive framework for developing a dashboard/tool to measure and analyze plow/treatment cycle times. The dashboard/tool is intended to provide a user-friendly interface for visualizing cycle time data, enabling effective decision-making and operational planning. The tool framework aims to facilitate efficient data utilization and accessibility across the organization by integrating various data sources and formats. This section includes an analysis of data requirements, a database design outlining data conversion processes, API connections, and a storage options plan for archiving historical data. It outlines recommendations for a suitable dashboard platform and hosting option, use cases and workflows for the tool, a visualization design diagram, and a roadmap for development and testing stages. The framework provides a resource for monitoring and optimizing plow operations, enabling data-driven decision-making, and enhancing overall operational efficiency.

6.1 Requirements

The cycle time tool is supported by several components or subsystems as shown in the high-level architecture (HLA) in Figure 8. The HLA helps understand the functional components of an overall system and the relationships between them, including components for data ingestion and data processing. Defining an HLA is a critical step in identifying software components and connections that must be developed to support the tool. The HLA flows from left to right, beginning with data inputs, which flow into data cleaning and formatting modules, followed by data processing, AI and Machine Learning (ML), and output modules. The functions of these modules are described in Table 4. Note that there are required paths (solid lines) and optional paths to enhance the tool (dashed lines) within Figure 8.

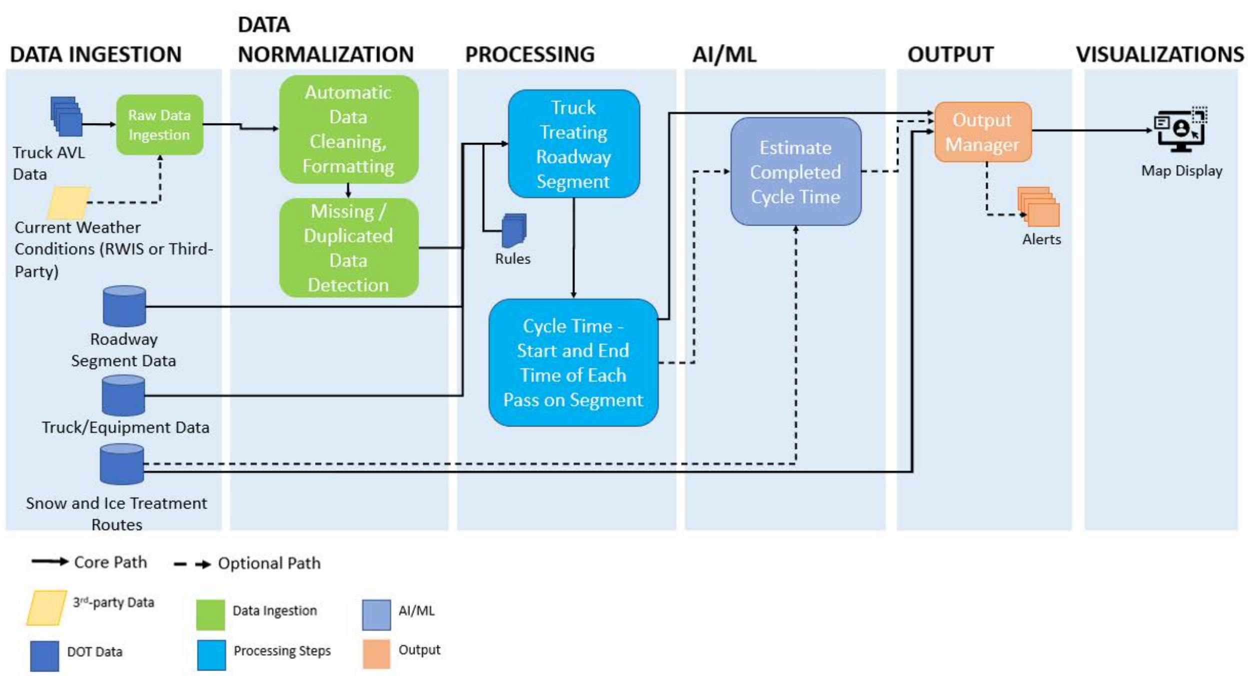


Figure 8. High-level Architecture of Cycle Time Tool

Table 4. Cycle Time Tool Module Descriptions

Module Name	Module Type	Description
Raw Data Ingestion	Data Ingestion Module	Device-specific data handler
Automatic Data Cleaning, Formatting	Data Normalization Module	Clean and format data
Missing/Duplicated Data Detection	Data Normalization Module	Detect duplicated or missing data
Rules - Action Threshold Comparison	Processing Module	Compare input data to threshold values to determine if a response is needed
Cycle Time - Start and End Time of Each Passing Segment	Processing Module	Calculate cycle time ratio based on results of the previous module while collecting time stamps, noting when a cycle is complete (the ratio is greater than or equal to one)
Truck Treating Roadway Segment	Processing Module	Pull proper treatment width based on the truck's treatment widths and compare to road segment width
(AI/ML) Estimate Completed Cycle Time	AI/ML Module	An AI/ML model trained to estimate the plow/treatment cycle time based on historical data ideally fused with weather data.
Output Manager	Output Module	Manage output type and content
Map Display	Visualizations	Plow/Treatment Cycle Time Tool/Dashboard

Data Ingestion and Normalization

This tool harnesses a combination of live and stored data to provide comprehensive insights. Live data encompasses real-time information sourced directly from the winter maintenance fleet's AVL system, allowing for immediate monitoring and analysis. Stored data refers to information stored in existing databases, comprising critical details like road segment specifics, truck profiles, and route data. Additionally, this tool offers the flexibility to integrate optional sources for enhanced accuracy and coverage such as weather data from environmental sensors or third-party weather services.

Stored data are assumed to have already been through a data cleaning, formatting, and validation process, so these data sources may bypass those steps. Therefore, these data types are treated differently in the HLA. Live data are assumed to be raw and are therefore ingested using source-specific ingestion modules, which then pass the data to automatic cleaning, formatting, and missing/duplicated detection processes within the tool development process. If the AVL data are already clean, this step might not be required. Missing and duplicated data are defined by a set of rules that may be customized based on the data source. Examples of missing or duplicated data for winter maintenance operations can range from missing route start times, duplicated route ids, or inconsistent route geometry. Rules can be implemented to set flags when these instances occur in a dataset to check for accuracy and quality.

The refined data is subsequently routed to the processing modules. While clean data can also be stored in an agency storage database, this step is omitted from the Cycle Time tool's HLA diagram for the sake of clarity.

Processing

Data are combined and analyzed within a process step that detects the maintenance activity of a truck on a winter operations route. To achieve this, basic rules and associations are employed. These rules consist of predefined criteria and conditions that serve as the foundation for decision-making within the system. For instance, a basic rule might specify that if a vehicle's GPS coordinates fall within the geographic boundaries of a designated winter maintenance route during a specific time frame, it is considered to be on that route.

Associations, on the other hand, establish connections between different data points or attributes. For example, associating GPS coordinates with a specific maintenance route allows the system to link a vehicle's location with a known route, enabling tracking and analysis.

The robustness of this processing step plays a vital role in enhancing the efficiency and accuracy of the tool/dashboard. By harnessing these fundamental rules and associations, the system can reliably discern the presence of trucks and ascertain treatment widths, providing invaluable insights for optimizing winter maintenance operations.

Once a truck's treatment is verified, its data are sent to the next processing module: the Cycle Time – Start and End Time of Each Pass on Segment. This is the module that will take time stamps for each pass and calculate the cycle time ratio. Once the cycle time ratio equals or exceeds 1, the cycle is considered complete, and the next loop will begin to accumulate the cycle time ratio till it equals or exceeds 1.

Once complete the module could go to the optional AI/ML modules or directly to the Output Manager.

AI/ML

An AI module may be developed for this tool. The module will use advanced techniques to estimate predictive cycle time based on historical data and/or conditions.

Output and Visualizations

This tool will output a spatial dashboard or user interface that will allow users to review cycle time results. The tool can allow routes to be reviewed as a whole or drill down to individual segments within a route.

6.2 Database Design

The Extract, Transform, Load (ETL) process, in the context of dashboard development for calculating plow/treatment cycle times, is a crucial methodology for efficiently gathering, transforming, and loading the necessary data into the dashboard system (Figure 9). This process ensures that the data essential for accurate cycle time calculations are effectively extracted from relevant sources, undergo appropriate transformations, and are loaded into the dashboard for visualization and analysis. To calculate plow/treatment cycle times, the ETL process encompasses the following key steps. First, data are extracted from diverse sources, including AVL systems, weather data providers, and other relevant databases. This extraction phase involves meticulous identification and retrieval of the required data elements, such as plow/treatment locations, timestamps, weather conditions, and any additional parameters pertinent to accurate cycle time calculations.

Subsequently, the extracted data undergo meticulous transformations to prepare it for cycle time calculations. These transformations may encompass data format conversions, thorough data cleansing and validation procedures, necessary calculations to derive cycle time metrics, data aggregation at desired intervals (e.g., minutes), and the application of any essential business rules or adjustments to ensure the accuracy of cycle time measurements. Finally, the transformed data are loaded into the dashboard system, where they are structured and organized within the dashboard's data model for seamless visualization and analysis. This loading process ensures that the transformed data are readily available within the dashboard, enabling real-time or historical cycle time calculations and providing users with comprehensive visualization capabilities.

The ETL process plays a pivotal role in the creation of a plow/treatment cycle time dashboard by enabling the research team to harness and integrate relevant data from disparate sources. For the proof-of-concept tool developed within this project, the team embarked on utilizing AVL data obtained from a Skyhawk system to model plow cycle times based on historical routes. The ETL process served as a foundational framework to transform raw data into a usable format for analysis and visualization.

The initial step of the ETL process involved extracting the AVL data from the Skyhawk system. This included gathering information such as vehicle locations, timestamps, and other pertinent data points associated with plowing/treating activities if possible. However, the extracted data required significant cleanup and refinement to ensure their quality and consistency. For instance, the coordinate values provided in the raw data needed to be split into latitude and longitude points for precise geospatial analysis. A similar process will apply to other AVL datasets, and the user will have to review the format of the data and determine the proper processing needed to get the data in a workable format for this tool. Also, the additional sensor data, such as material spreading system or plow position, will allow the tool to be more accurate. Without these data sets, the cycle time may still be calculated but more assumptions will be necessary. For example, if a truck only provides location information without specifying treatment activity, users will need to infer the treatment width used by the truck while operating on the road during an event. In cases where a truck supplies plow and material with AVL data, the system will employ conditional statements to establish if treatment is taking place and, if confirmed, identify the correct treatment width based on information retrieved from the equipment dataset.

Extraction from APIs

- Identify the APIs you need to retrieve data from. This could include RESTful APIs, SOAP APIs, GraphQL APIs, or other web services. Obtain the necessary API credentials (e.g., API keys, tokens) to access the data. Use API client libraries or HTTP requests (GET, POST, etc.) to extract data from the APIs. Many programming languages have libraries or frameworks that simplify working with APIs, such as requests in Python or libraries for specific APIs.

Data Transformation

- Once you've extracted data from the API, you may need to transform it to make it suitable for your target system.

Loading the Data

- After transformation, load the data into your target destination. This could be a database (e.g., SQL database, NoSQL database) or a data warehouse (e.g., Amazon Redshift, Google BigQuery). Ensure that the loading process is robust, supports incremental loads if needed, and handles any data consistency or integrity issues.

Automation and Scheduling

- Consider automating the ETL process by setting up scheduled jobs or triggers to periodically fetch and transform data from the APIs. This ensures that data are always up-to-date. Use ETL orchestration tools or job schedulers to manage and monitor the execution of ETL workflows.

Error Handling and Logging

- Implement error handling mechanisms to deal with issues that may arise during data extraction, transformation, or loading. Log errors and exceptions for troubleshooting and auditing purposes.

Security and Rate Limiting

- Ensure that the ETL process complies with security best practices. Protect API credentials and data during transmission and storage. Be aware of API rate limits and implement mechanisms to respect them to avoid being blocked or throttled by the API provider.

Monitoring and Alerts

- Set up monitoring for your ETL processes to track the performance, and configure alerts for any anomalies or failures.

Scalability and Performance

- Design ETL process to be scalable, especially if dealing with large volumes of data. Consider parallel processing or distributed ETL solutions as needed.

Documentation

- Document your ETL processes thoroughly, including API endpoints, data schemas, transformation rules, and any scheduled jobs or configurations. This documentation will be valuable for maintenance and troubleshooting.

Testing and Validation

- Rigorously test the ETL pipelines, including edge cases and error scenarios, to ensure data accuracy and reliability.

Figure 9. Extract, Transform, and Load Overview

The next crucial phase involved transforming the extracted data into a standardized and structured format that could be processed and analyzed. The research team undertook various data transformation operations, including data cleansing, normalization, and enrichment. By following these steps, any inconsistencies, errors, or missing values in the dataset were addressed, thus enhancing the accuracy and reliability of the subsequent analysis.

Furthermore, the research team delineated the necessary layers for the cycle time dashboard. These layers encompassed essential components such as road segment data, winter maintenance routes, and equipment information. Each layer provided distinct insights and contributed to a comprehensive understanding of the plow/treatment cycle process. The ETL process facilitated the extraction of relevant data for each layer, enabling that only the required information was included in the subsequent analysis and visualization stages.

The choice of ETL option is dependent on an agency's specific requirements, constraints, and preferences for data integration. Factors like data volume, complexity, budget, and the need for real-time processing will influence the decision. Additionally, factors like data security, data governance, and compliance requirements should be considered when choosing an ETL solution. The research team opted for an ETL tool option that allows for data integration with visualization capabilities. While Table 5 outlines different ETL options, it implicitly conveys valuable insights regarding their respective strengths and limitations. For instance, custom ETL scripts offer unparalleled flexibility but can be time-consuming and necessitate specialized development expertise. ETL tools, on the other hand, provide a user-friendly graphical interface but may entail a learning curve and potentially higher costs depending on the tool selected.

Table 5. Extract, Transform, and Load Options

ETL Options	Description	Pros	Cons
Custom ETL Scripts/Code	Writing custom scripts or code in programming languages like Python, Java, or Ruby to perform ETL tasks. This approach offers maximum flexibility but can be time-consuming and requires development expertise.	Maximum flexibility can be tailored to specific needs.	Time-consuming, and requires development expertise.
ETL Tools	There are many ETL tools available, both open-source and commercial, that provide a graphical interface for designing ETL workflows.	Provides a graphical interface, may have pre-built functionalities.	May have a learning curve, may be costlier depending on the tool.
Cloud-Based ETL Services	Many cloud providers offer ETL services that are fully managed and scalable.	Fully managed, scalable, often integrated with cloud platforms	Might involve ongoing costs, dependency on the cloud provider.

ETL Options	Description	Pros	Cons
Open-Source ETL Frameworks	Build ETL processes using open-source frameworks and libraries. These frameworks provide flexibility and can be customized as needed.	Flexible, customizable, and often community supported.	Required expertise, potential integration challenges.
Data Integration Platforms	Some platforms offer comprehensive data integration capabilities, including ETL, data transformation, and data quality.	Comprehensive solution, covers ETL, transformation, and quality,	Potentially higher cost, may be complex to implement.
Data Integration as a Service	There are SaaS solutions that provide ETL and data integration capabilities, often with pre-built connectors to popular data sources.	SaaS model, pre-built connectors for data sources.	Subscription based-cost, dependency on service-provider.
Serverless ETL	ETL processes using serverless computing platforms, which can be cost-effective and scalable.	Cost-effective, scalable, event-driven model.	May require adaptation to serverless paradigm, potential integration challenges.

Cloud-based ETL services offer scalability and full management but may involve ongoing expenses and a degree of dependency on the chosen cloud provider. Open-source ETL frameworks present a flexible and customizable solution yet may require expertise and potentially encounter integration challenges. Data integration platforms offer a comprehensive solution, encompassing ETL, transformation, and data quality, but may involve higher costs and complexity in implementation.

Data integration as a service follows a SaaS model, often with pre-built connectors, but is subscription-based and reliant on the service provider. Serverless ETL processes are cost-effective and scalable yet may require adaptation to a serverless paradigm and face potential integration challenges. Recognizing these implicit pros and cons is paramount in making an informed decision tailored to the specific needs and constraints of the agency.

In summary, the ETL process served as the foundation for the creation of a cycle time dashboard by extracting AVL data, transforming it into a standardized format, and loading the pertinent information for analysis. The ETL process included data cleanup, including splitting coordinate values, and facilitated the extraction of data layers crucial for understanding road segments, snow and ice routes, and equipment information.

The following sections aim to provide the Clear Roads Project Committee with the necessary variables to construct a dashboard/tool capable of determining plow/treatment cycle times. Furthermore, they present information regarding desired variables that could potentially enhance the functionality of the tool. In conjunction with the variables, the following sections provide an outline of the logical and methodological framework for the tool, ensuring accurate determination of cycle times. This cycle time tool will empower agencies to make more informed decisions about their fleet during active winter events and facilitate post-event performance evaluation.

Roadway Segment Data Geodatabase

The roadway segment database is an ESRI (Environmental Systems Research Institute) Geodatabase consisting of an LRS (Linear Reference System) polyline feature class. LRS features can locate points or lines along a route. More specifically, they contain x, y, and m values, where m is a value that represents the distance from the beginning of the line or a segment along the route. The polyline feature class will be segmented by turnaround points, cross-over points, or intersections along winter maintenance routes. Segments will also be attributed with route ID to calculate the total plow/treatment cycle time for a given pass.

Table 6 represents the Roadway Segment polyline feature class database architecture to satisfy calculation of plow/treatment cycle times. Note that the table does not include a source since this dataset will be pre-populated with the required data within the attributes. The table includes a column for suggested data type that must be selected when creating each attribute field. The available data types include Short (integer), Long (integer), Float (or single precision floating-point numbers), Double (or double-precision floating-point numbers), and Text. When selecting data types for each attribute consider the data needs such as whole numbers (Short or Long) and fractional numbers (Float and Double).

Table 6. Roadway Segment Geodatabase Sample

Attribute Field	Purpose	Data Type
Route_ID	Represents a given route or pass.	Text
Segment_ID	Represents an individual segment.	Text or Long
Segment_Lanes	The number of lanes of a given segment which will be used in the cycle time calculation.	Short
Segment_Width	The width of a given segment that will be used in the cycle time calculation.	Float
Segment_Shoulder	(Optional) The width could be provided if shoulder exists. It is recommended that the agency add this dimension to the Segment_Width attribution field.	Float
Segment_Median	(Optional) The width could be provided if median exists. It is recommended that the agency add this dimension to the Segment_Width attribution field.	Float
From_DFO	DFO (Distance from Origin). Contains values for each segment from the DFO based on the Linear Reference System.	Double

Attribute Field	Purpose	Data Type
To_DFO	DFO (Distance from Origin). Contains values for each segment to the DFO based on the Linear Reference System.	Double
Start_Latitude	First vertices representing the beginning of the segment. Lat/Long can potentially be used for determining when a vehicle begins or ends a given segment.	Double
Start_Longitude	First vertices representing the beginning of the segment. Lat/Long can potentially be used for determining when a vehicle begins or ends a given segment.	Double
End_Latitude	Last vertices of the ending of the segment. Lat/Long can potentially be used for determining when a vehicle begins or ends a given segment.	Double
End_Longitude	Last vertices representing the ending of the segment. Lat/Long can potentially be used for determining when a vehicle begins or ends a given segment.	Double
Len_Miles	This attribute is added to store the length in miles of each line feature.	Double

Truck/Equipment Data Geodatabase

The Truck/Equipment Data will contain the truck ID and treatment width. Additional fields based on treatment type may be developed. Treatment width may be different based on material settings and plow positions. If AVL has these data points, additional fields for specific settings can be developed for the process to pull when specific conditions are met.

Table 7. Truck/Equipment Data Geodatabase

Variable	Purpose	Data Type
Truck Identification Number	To determine the capacity of the truck while treating a road	Text
Plow and/or Treatment Width	Based on the truck ID, the tool will determine how much of the roadway width was treated per pass. Each truck has a different treatment width based on size of plow(s) and chemical treatment spreading abilities.	Decimal Number

Snow and Ice Treatment Routes Geodatabase

The Snow and Ice Treatment Routes Geodatabase will include a polyline feature class like the one found in the Roadway Segment Geodatabase. This polyline feature class will be used for the overall cycle time calculation of a route (not a segmented route). The schema of this dataset will be smaller than that of the Roadway Segment but will still include Route_ID, DFO fields, and Len_Miles as variables. The attributes included, in conjunction with those of the previously mentioned Geodatabase, allow for the calculation of the total amount of time to clear a route. This will allow for filtering/drilling down functions on an interactive tool.

Table 8. Snow and Ice Treatment Routes Geodatabase

Attribute Field	Purpose	Data Type
Route_ID	Represents a given route or pass.	Text
From_DFO	DFO (Distance from Origin). Contains values for each segment from the DFO based on the Linear Reference System.	Double
To_DFO	DFO (Distance from Origin). Contains values for each segment to the DFO based on the Linear Reference System.	Double
Start_Latitude	First vertices representing the beginning of the segment. Lat/Long can potentially be used for determining when a vehicle begins or ends a given segment.	Double
Start_Longitude	First vertices representing the beginning of the segment. Lat/Long can potentially be used for determining when a vehicle begins or ends a given segment.	Double
End_Latitude	The last vertices of the ending of the segment. Lat/Long can potentially be used for determining when a vehicle begins or ends a given segment.	Double
End_Longitude	The last vertices represent the ending of the segment. Lat/Long can potentially be used for determining when a vehicle begins or ends a given segment.	Double
Len_Miles	This attribute is added to store the length in miles of each line feature.	Double

Overall, the Snow and Ice Treatment Routes Geodatabase is a valuable dataset for managing winter weather conditions and ensuring the safety and mobility of the public. By providing detailed and up-to-date information about treatment routes, plow cycles, and weather conditions, the dashboard/tool enables more effective and transparent decision-making and improves the overall efficiency and effectiveness of winter maintenance operations.

AVL Data

The AVL data is an ESRI Geodatabase containing a point feature class that will store data populated by the AVL data services, spatially joined data from the Roadway Segment Geodatabase.

There are several different types of AVL systems used by transportation agencies to monitor vehicle locations and the operational status of equipment for winter maintenance operations. An AVL system provides automatic vehicle location tracking for dispatchers and maintenance supervisors. In addition, when integrated with vehicle health monitoring systems, AVL systems can provide vehicle maintenance technicians with valuable information about vehicle diagnosis. AVL systems can also be integrated with existing vehicle components used for snowplow operations such as spreader controllers and plow positions to provide reports to maintenance supervisors on material and plow usage applied by snowplow operators.

ESRI offers two platforms for AVL systems: Geo Event and Velocity. Both can incorporate real-time data through APIs but are potentially costly for DOTs. The advantage is that they are equipped with processes that are formatted for a point feature class in a geodatabase.

Another potentially more affordable, option is to create a custom system that incorporates Microsoft Azure and AGOL (ArcGIS Online). The real-time data could be processed within the Azure database and then appended to the cycle time process.

To compute Cycle Times, spatial joins at the given intervals received by an AVL system would be conducted between the Truck/Equipment point feature class with the Roadway Segment polyline feature class.

Table 9. AVL Data

Variable	Purpose	Format
Latitude	North-South location of the truck. To determine when the truck is on a route	Decimal Degree
Longitude	East-West location of the truck. To determine when the truck is on a route	Decimal Degree
Date and Timestamp	To timestamp when a truck starts and ends on a route, the duration will be required for cycle time calculation	MM/DD/YYYY HH:MM ZZZZ
Treatment Data (Optional)	If available, this will provide more accurate data of when treatment is occurring. Spreader On/Off, Plow activity, spinner speed, and other setting options that contribute to a change in a truck's treatment width are another option that may be included depending on the AVL data available.	Binary (1,0)
Truck Identification Number	To determine the capacity of the truck while treating a road	Text

Weather Data – Optional Enhancement

It may be ideal to integrate weather information and/or index for severity. This will allow for the users to determine the impact of the weather on cycle time. The weather information data will be similar to data presented in the table below. The date and time will link to treatment/cycle time activity and the segment or route data will link the proper weather data to the proper service area.

Table 10. Weather Data

Variable	Purpose	Format
Latitude	North-South location of weather station.	Decimal Degree
Longitude	East-West location of weather station.	Decimal Degree
Segment_ID/Route_ID	Link weather data to segments or Route	Text
Date and Timestamp	To timestamp for weather conditions	MM/DD/YYYY HH:MM ZZZZ
Weather Data – precipitation, wind, and temperature (Optional)	To determine when an event has started. Also, may be used for cycle time vs storm severity analyses.	Decimal Number

6.3 Storage Options

Selecting the most suitable data storage option depends on several factors. Here are some key considerations to help select the right data storage option:

Data Volume and Size: Begin by carefully evaluating the magnitude of data that requires storage. It's imperative to recognize that various storage solutions cater to different scales. While some are proficient in handling small to medium-sized datasets, others outperform when it comes to managing large-scale data. For instance, AVL data tends to possess a larger volume compared to equipment or route data.

Data Structure and Format: Delve into a detailed analysis of the data's underlying structure and format. This step is pivotal in selecting a storage option that seamlessly accommodates the data's specific format, ensuring optimal efficiency.

Data Access Patterns: Gain a comprehensive understanding of how the data will be accessed. Different storage systems are intricately designed and optimized for distinct access patterns. This knowledge is foundational in making an informed choice.

Scalability Requirements: Anticipate future growth and consider scalability needs. The selected data storage solution should possess the capacity to gracefully accommodate expansion over time. Cloud-based storage solutions, in particular, often present a straightforward path to scalability.

Performance Requirements: Gauge the performance demands of the application or analytics. Certain databases are finely tuned for swift, low-latency, high-throughput transactions, while others shine in handling intricate analytical queries.

Consistency and ACID (Atomicity, Consistency, Isolation, Durability) Compliance: Determine whether stringent data consistency and robust transaction support are essential. In such cases, databases that provide ACID compliance should be prioritized. Conversely, NoSQL databases often emphasize flexibility and scalability over absolute consistency.

Data Security and Compliance: Ensure that the chosen data storage solution aligns seamlessly with security and regulatory compliance requirements. This encompasses critical aspects such as encryption, access controls, and compliance with standards like GDPR, HIPAA, or other pertinent regulations.

Budget: Prudently factor in budget considerations. Certain data storage solutions may entail substantial upfront costs, ongoing operational expenses, or cloud storage charges. It is imperative to evaluate the total cost of ownership (TCO) in a comprehensive manner.

Integration with Existing Systems: If there are existing systems or applications in place, carefully consider how well the chosen data storage option integrates with them. Compatibility plays a pivotal role in ensuring smooth data transfer and system architecture.

Data Lifecycle Management: Devise a meticulous plan for data retention, archiving, and purging. Some storage solutions come equipped with built-in features that facilitate effective data lifecycle management.

Backup and Disaster Recovery: Establish a robust strategy for safeguarding data through backup and disaster recovery measures. Many cloud-based storage options offer integrated features for these critical functions.

Community and Support: Give due consideration to the availability of a supportive community or reliable support channels for the chosen data storage technology. This resource can prove invaluable for troubleshooting and staying ahead of best practices. It's a cornerstone of a sustainable and effective data storage strategy.

Common data storage options include:

- Relational Databases: Suitable for structured data and transactions. Examples include MySQL, PostgreSQL, Oracle, and SQL Server.
- NoSQL Databases: Offer flexibility for semi-structured and unstructured data. Types include document-oriented (MongoDB), key-value (Redis), column-family (Cassandra), and graph databases (Neo4j).
- Data Warehouses: Designed for analytical queries and aggregations. Examples include Amazon Redshift, Google BigQuery, and Snowflake.
- Cloud Storage: Provides scalable, cost-effective storage solutions like Amazon S3, Google Cloud Storage, and Azure Blob Storage.
- File Systems: For storing unstructured data like files and documents. Examples include NFS, CIFS, and distributed file systems like HDFS.
- In-Memory Databases: Offer extremely fast read and write access by storing data in RAM. Examples include Redis and Apache Ignite.
- Object Stores: Great for storing large volumes of unstructured data. Examples include Amazon S3, Google Cloud Storage, and Azure Blob Storage.

Ultimately, the data storage option decision depends on specific requirements. It's often a good idea to consult with data architects and engineers who can help tailor the choice to the agency's needs. For a comprehensive Cycle Time dashboard tool encompassing Road Segment, Routes, Truck/Equipment, AVL, and an optional Weather dataset, it is recommended to have a combination of storage options to best accommodate the diverse nature of the data:

1. **Relational Database (e.g., PostgreSQL or MySQL):** This would serve as the backbone of the storage system. A relational database is excellent for structured data and transactions, making it suitable for Road Segment, Routes, Truck/Equipment, and AVL data. The relational model helps maintain relationships between different entities, providing a structured foundation.
2. **NoSQL Database (e.g., MongoDB):** Given the optional Weather dataset, which may contain semi-structured or unstructured data, incorporating a NoSQL database can provide the necessary flexibility. MongoDB, for instance, excels in handling diverse data types and can seamlessly integrate with structured data.
3. **Cloud-Based Storage (e.g., Amazon S3):** Utilizing cloud storage options like Amazon S3 for storing large binary objects such as images, videos, or any other media associated with the Cycle Time dashboard can be advantageous. It provides scalable and cost-effective storage solutions for unstructured data.
4. **In-Memory Database (e.g., Redis):** Consider integrating an in-memory database for caching frequently accessed data or for scenarios requiring extremely fast read and write access. This can enhance the real-time performance of the dashboard, especially when dealing with AVL data.
5. **Data Warehousing (e.g., Amazon Redshift):** If a need for complex analytical queries on large volumes of data is anticipated, a data warehouse solution like Amazon Redshift could be beneficial. It's designed for high-performance analytics and aggregations.

Regardless of the chosen storage options, implementing a robust backup and disaster recovery strategy is essential to safeguard against data loss or system failures. This could involve automated backup routines, versioning, and regular testing of recovery procedures. It is a good practice to verify that all chosen storage options meet the security and compliance requirements pertinent to the data being stored. This includes encryption, access controls, and adherence to any industry-specific or governmental regulations. By implementing this multi-tiered storage approach, agencies will be able to leverage the strengths of each solution to effectively handle the diverse datasets in the Cycle Time dashboard tool. It provides a scalable and flexible foundation to support current needs and future expansion.

6.4 Tool Platform and Hosting

Table 11 provides a summary of the platform and hosting options for this tool.

Table 11. Platform and Hosting Options

Hosting Platform	Power BI	Tableau	ESRI	QlikView	Google Data Studio
Data Visualization	✓	✓	✓	✓	✓
Mapping & Spatial Analysis	✗	✗	✓	✗	✗
Data Source Types	Various (CSV, Excel, SQL)	Various (files, databases, cloud)	Geospatial data formats, GIS databases	Various (files, databases, cloud)	Various (Google Sheets, BigQuery, etc.)
Integration Capabilities	Good integration with Microsoft products, REST APIs, SDKs	Connectors, APIs, third-party integrations	Integration with ArcGIS Online, ArcGIS Enterprise	APIs, connectors, and custom integrations	Integration with Google products, connectors
Collaboration & Sharing	Collaboration features, sharing with Power BI Pro license	Collaboration features with Tableau Creator license	Collaboration features with ArcGIS Online	Collaboration features, sharing capabilities	Collaboration features, sharing capabilities
Cost	Varies based on licensing plan (e.g., Power BI Pro, Premium)	Varies based on licensing plan (e.g., Creator, Explorer)	Varies based on licensing plan (e.g., ArcGIS Online, Enterprise)	Varies based on licensing plan	Free for basic usage, additional costs for advanced features
System Requirements	Internet connectivity, compatible web browser	Internet connectivity, compatible web browser	Internet connectivity, compatible web browser	Internet connectivity, compatible web browser	Internet connectivity, compatible web browser

Agencies can select any platform that will allow the methodology to be programmed and provide the performance measures and outputs in the desired visual format. Based on the resources the research team had available, the team opted to use ESRI as the hosting platform for the demo dashboard/tool designed to calculate plow/treatment cycle times. While ESRI may not offer the same level of data visualization and interactive dashboarding capabilities as Power BI or Tableau, it excels in mapping and spatial analysis functionalities, which are critical for winter maintenance scenarios. The ability to integrate with ESRI's ArcGIS Online and ArcGIS Enterprise provides extensive geospatial data support, allowing for accurate representation of plow routes and assessment of cycle times. Additionally, ESRI offers collaboration features through ArcGIS Online, enabling the research team to work together efficiently on analyzing and improving plow cycle times. While ESRI's licensing costs may vary based on the selected plan, the investment in ESRI's platform is justified by its robust GIS capabilities, making it an excellent choice for winter maintenance analysis and planning.

6.5 Development and Testing

To create an effective and user-friendly tool/dashboard, the development and testing process was divided into three key stages. The first stage, Wireframe/Mockup, focused on visualizing the tool/dashboard's layout and presenting the data and methodology in a visual format. This stage served as an opportunity for the project subcommittee to review and provide feedback on the proposed design. Additionally, the final tool platform and hosting options were determined during this stage to ensure optimal performance and accessibility.

Following the approval of the Wireframe/Mockup, the development process advanced to the Alpha Development stage. The development team incorporated the feedback received during the previous stage and ensured that the tool/dashboard met all the specified requirements. The project subcommittee's inputs and guidance were instrumental in refining the functionality and usability of the tool/dashboard. Once all the comments and issues from the Alpha phase were addressed, the development process entered the final stage: Beta Development. In this phase, the tool/dashboard application was finalized, and accompanying documentation for administration and user support was prepared. Rigorous user testing was also conducted during this stage. The purpose of this testing was to verify that the tool/dashboard not only met the agency's user requirements but also performed as intended in real-world scenarios. This thorough testing ensured that the final tool/dashboard was ready for deployment and effectively supporting the needs of the intended users.

Wireframe / Mockup Stage

The Cycle Time Dashboard shown in Figure 10 boasts a thoughtfully crafted layout, optimized for intuitive navigation. The tool was carefully curated with a design and visualization scheme that balances aesthetics with functionality. The dashboard embraces a dark color scheme, providing a sleek backdrop that places emphasis on the informative elements. The map adopts a light gray palette, offering a subdued canvas for data representation. This unobtrusive background allows routes to be symbolized with distinct colors, ensuring clear differentiation and easy identification. Crucially, color is strategically employed to enhance user experience. The Legend, Map, and Bar Graphs are the focal points for color utilization. The Legend serves as a visual guide, employing colors to represent Facilities, Routes, Roads, and other key elements. This aids users in quick interpretation and reference. Its design prioritizes user-friendly functionality, ensuring that users can effortlessly access and interpret critical information.

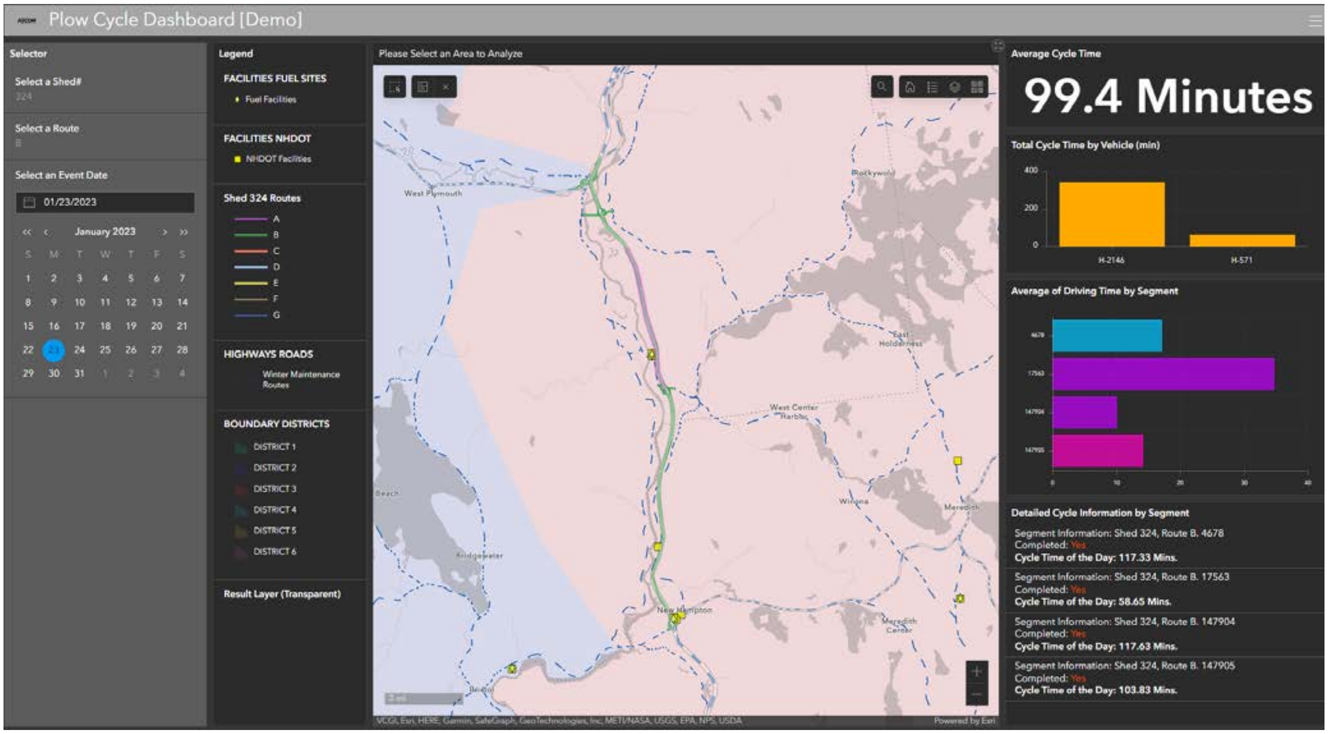


Figure 10. Plow Cycle Times Dashboard Interface

The dashboard's layout strategically positions key elements such as the Selector, Legend, and Interactive Map for easy identification and interaction. The intuitive placement of these components guides users through the initial selection process, streamlining the analysis of plow/treatment cycle data. The inclusion of an interactive map at the center of the dashboard allows for dynamic exploration and selection of specific areas of interest. This feature empowers users to focus on precise road segments, facilitating a deeper understanding of cycle times and performance metrics. Incorporating informative metric sections on the right-hand side ensures that users have immediate access to essential data summaries. These sections employ clear and concise visualizations, including bar graphs and detailed segment information, to convey insights at a glance.

Overall, the Cycle Time Dashboard's layout design prioritizes accessibility, usability, and data clarity. This strategic arrangement of components enables users to efficiently extract valuable insights for informed decision-making in winter maintenance planning.

Alpha and Beta Development Stage

The Cycle Time Dashboard was developed to be a tool for users to analyze plow/treatment cycle data during winter maintenance events. This intuitive dashboard provides precise insights into critical metrics, including average cycle times, vehicle performance, and segment-specific information.

Throughout the development and testing phases, meticulous attention was devoted to optimizing user experience and functionality. The interface guides users through a seamless process of selecting sheds, routes, and event dates, ensuring a smooth analysis. The inclusion of an interactive map and detailed metric sections elevates the tool's utility for users.

The dashboard's accuracy and reliability were tested through extensive testing and validation. It excels in providing actionable data to assist in winter maintenance planning, enabling more efficient and effective operations. The Cycle Time Dashboard exemplifies the potential of GIS technology in refining winter maintenance strategies and stands as a valuable asset for users in the field.

6.6 Summary

The goal of this framework is to provide the requirements, steps, and considerations for the development of a plow/treatment cycle tool. AVL and other required data of each agency may be unique; however, this framework should provide adequate information to develop a plow/treatment cycle tool within the agency’s environment, as long as the base requirements are met.

7. Tool Implementation Plan

This section provides information on the implementation of the framework for developing a cycle time visualization tool.

7.1 Recommendation for Implementation

The cycle time visualization tool should be implemented based on the needs of the winter maintenance decision-makers that would benefit most from these data, typically maintenance managers and supervisors. This tool will aid in decision-making either during or after an event. The first determination will be to identify how the tool will be used by these decision-makers. This will help define the desired functionalities and requirements of the tool. For example, if there is no need for the data to be in real-time, this will change the tool requirements.

The second determination is the availability of AVL data as well as other required and optional data. Without any AVL data, the tool cannot be built. If location data are the only available input without the treatment data such as plow up/down or material application rates, the tool will provide a cycle time assuming that the truck is plowing/treating the roadway; however, having data on the treatment being performed will provide a more accurate tool output.

The last determination will be the resources available to develop the tool, which can include personnel with experience and expertise in data processing and tool development and hosting, budget to invest internal hours to the tool development, budget to host and maintain the tool, and/or budget to contract out these efforts. The tool's backend will need to bring in AVL data, spatial join with road attributes, and continually perform a loop function to determine when a cycle is completed (total passes to clear the roadway). This requires persons with experience (internal or external) in the selected tool(s) used to perform these functions and in connecting, storing, and maintaining the data required. Additionally, the tool needs a front-end that allows the users to easily review data. The tool's front-end will require personnel with knowledge and experience in visualization tool/dashboard design and development.

7.2 Steps Needed to Implement

Once it has been determined to implement this tool into the winter maintenance operations, the following are the steps to develop the visualization tool.

Step 1. Identify stakeholders for this task. This will require the proper winter maintenance decision-makers and data analysts.

Step 2. Determine the needs of decision-makers so tool functions and outputs are useful. This will be the goal for the tool, the next two steps will be to review available data to determine if these goals may be met.

Step 3. Review AVL data available. Review the data ingestion process, data latency, and available data fields.

Step 4. Review internal data required for the tool. The tool requires road segments with road width data to properly know when a cycle is completed. Also, for functionality when reviewing the output data, the current routes should be added to the tool.

Step 5. Based on the previous steps, it is important for all users to have the proper expectations of the tool's outputs. If there are limitations in the available data, will the resulting outputs still be valuable to the decision-makers? This step is to determine if an agency should continue with the development of the tool.

Step 6. If an agency moves forward, the next step will be to work with stakeholders on platform and hosting needs for the tool and data.

Step 7. Data Extract, Transform, and Load workflow should be determined. This will use the data reviews in Steps 3 & 4. This may include the need to develop new data tables for equipment datasets and transform existing data.

Step 8. Once data are ready, the development of the algorithm should be done. This will include adding a sorting index to the AVL data, then development of the loop that will continually timestamp as trucks treat/pass through the road segments, pull the proper equipment treatment width, and calculate when the cycle time ratio hits one, representing a complete cycle (treatment of all lanes).

Step 9. Development of dashboard or Graphical User Interface (GUI). This will allow users to query the cycle time for a specific route or selection of road segments.

Step 10. Validate and test that the dashboard and insights are correct and useful.

Step 11. Develop user references for navigating the tool, such as How-To guides, Frequently Asked Questions memos, and/or walkthrough videos.

Step 12. Utilize and maintain tools.

These are the basic steps for implementing this tool. More details on the development are provided in Section 6 of this report.

7.3 Suggested Time Frame for Implementation

Implementation can start immediately. The time frame for the tool development will depend on the resource availability. Ideally, planning and development of the tool should be conducted during the off season with the end goal of starting up a tool prior to the beginning of the winter season.

7.4 Expected Benefits

The benefits of this tool are:

- A better understanding of the cycle time needs for road segments.
- Reliable information to disseminate on situational awareness. Increase awareness to the public of conditions to increase their safety.
- Resource allocation.

- Best practices for readiness and disaster-level snow and ice events. Decision-making tool for emergency closures and reopening.
- Data for optimized routes.
- Better recommendations for MDSS.

See the user stories presented in Section 4 for more insights into the benefits of implementing a plow cycle tool.

7.5 Potential Risks and Obstacles

The potential risks to implement are:

- Lack of proper data attributes available through the AVL to provide an accurate representation of the treatment of the roadway. Not all agencies have the same sensors or equipment integrated into their AVL system.
- Lack of proper resources available to develop and maintain the tool.

7.6 Strategies to Mitigate Potential Risks and Obstacles

To mitigate the risks above, the team should work through the first four steps listed above and determine the available data and resources. Step 5 is to reassess if the tool should be developed. This step will provide insight into the data available and the effort to develop a tool to meet the user's needs. The agency can discuss resources available to develop in-house or with an external team. If moving forward, it would be ideal to set milestones to keep the project on track and determine if more resources are required.

7.7 Primary and Secondary Users

The primary users of the visualization tool will be the winter maintenance managers and supervisors. They can monitor the performance of their fleet in terms of cycle times. Other users may include emergency response teams and incident management centers to get an understanding of the event's impact.

7.8 Implementation Costs

The costs for this tool include the capital cost to clean data, build the algorithm, and develop the dashboard; the cost to access the AVL's API (if not included in the current contract with the vendor); the cost to host the tool; the cost to store the data; and the cost to maintain the tool. These costs will vary based on an agency's available resources and skill set to develop or the cost to contract out to a third party.

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Appendix A – Survey Responses

Available separately; contact the Clear Roads administrative contact (see https://clearroads.org/contact-us/) for access.

Appendix B – Sample AVL Data

Massachusetts DOT Sample AVL Data (GeoTab AVL Solution)

Variable	**Sample Data**
Vehicle	05926
Display Name	Flaherty
Driver	*empty*
Driver Status	*empty*
Last Record	3/3/2019 20:15
GPS Fix	F
Reason	Ignition On
Direction	N
Speed	0
Latitude	42.223125
Longitude	-71.183365
Landmark	Canton
Street	121 Providence Hwy
City	Westwood
State / Province	MA
Unique ID	*empty*
Solid Material	*empty*
Solid Rate	*empty*
Solid Spread	*empty*
Prewet Rate	*empty*
Prewet Spread	*empty*
Anti-ice Rate	*empty*
Anti-ice Spread	*empty*
Road Temperature	*empty*
Air Temperature	*empty*
Spinner Setting	*empty*
Spread Width	*empty*
Gate Setting	*empty*
Blast	*empty*
Pause	*empty*

Variable	Sample Data
Mode	*empty*
IN 0	GPS Antenna Connected
IN 1	*empty*
IN 2	*empty*
IN 3	*empty*
IN 4	*empty*
IN 5	*empty*
IN 6	*empty*
IN 7	*empty*
IN 8	*empty*
IN 9	*empty*
IN 10	*empty*
IN 11	*empty*
IN 12	*empty*
IN 13	*empty*
IN 14	*empty*
IN 15	*empty*

Colorado DOT Sample AVL Data (GeoTab AVL Solution)

Variable	Sample Data
DateTime	2022-10-31T12:00:14.000Z
Vehicle ID	b75341A
Device ID	b21C
Speed	81
Latitude	35.9456253
Longitude	-78.5441818

Ohio DOT Sample AVL Data

Variable	Sample Data
ID	8372095
DeviceId	96
MsgId	00409DC0A_20141115151815
MsgType	1
UnitId	00409DC0A

Variable	Sample Data
Date	11/15/2014
Altitude	0
Heading	0
OperatorID	*empty*
MeterialCode	*empty*
GranularRate	0
GranularLaneSetting	0
GranularStormTotal	0
GranularStormDistance	0
PreWetRate	0
PreWetStormTotal	0
PreWetStormDistance	0
AntiIceRate	0
AntiIceStormTotal	0
AntiIceStormDistance	0
AntiIceLaneSetting	0
SpreaderStatusFlags	*empty*
SpreaderBlastTime	0
SpreaderGateHeight	0
RoadTemp	0
FrontPlowPosition	0
HoistPosition	0
RightWingPosition	0
LeftWingPosition	0
ScraperPosition	0
LowOil	0
HotOil	0
FilterStatus	0
LowLiquid	0
LowAntiIceLiquid	0
PlowFLoat	0
PanicButton	0
UserDefinedEvents	0
EthernetMACAddress	*empty*
RecordTime	2/18/2022 13:24
ReceivedTime	2/18/2022 13:24
Descript	Firmware Update Command
StatDay	1/2/2019 0:00
CreatedOn	1/9/2019 1:16
CreatedBy	dd555ef5-525d-4095-a942-5136bce42526
UpdatedOn	1/9/2019 1:16
UpdatedBy	dd555ef5-525d-4095-a942-5136bce42526

Variable	Sample Data
AttachmentFile	https://odotrouteopt.blob.core.windows.net/dailystatupload/ ODOT GPS-AVL Daily Report 01-02-2019.pdf
CountyId	17
GarageId	221
AssetId	T4-865
Model	Dell Edge Gateway 3001
ModelNumber	3001
MAC	0023A7E2FE4C
IPAddr	166.254.122.187
Port	80
IsActive	TRUE
LastGPSID	841892634
LastSpreaderSummaryID	579086764
LastBedScaleID	*empty*
LastTempID	*empty*
LastPlowID	*empty*
LastPicID	32098226
TruckName	T4-865
InventoryBarcode	372507
LastInventoryStatus	*empty*
isCamera	FALSE
BenchTest	TRUE
FieldTest	FALSE
LastGPIOID	*empty*
LastSecondarySpreaderSummaryId	*empty*
FieldGPS	TRUE
FieldGPSon	9/20/2018 20:02
FieldHyd	TRUE
FieldHydon	9/20/2018 20:02
FieldPic	TRUE
FieldPicon	2/16/2021 9:35
LastNon00GPSID	841892634
CamPass	A2F928889FD34465A9F0ED1C5DDBED
CamPassUpdated	TRUE
configadded	TRUE
InMaintenance	TRUE
InMaintenanceOn	3/23/2020 16:25
LastPicHB	35689321
LastHydHB	579086150
LastSprayerSummaryId	*empty*
LowDataMode	FALSE
LowDataDeviceOnlineCheckInterval	*empty*

Variable	Sample Data
IMEI	1.4751E+13
Phone	16143816082
ICCID	8.9148E+19
CamConfig	TRUE
CameraOverlaySet	TRUE
StaticEth	192.168.2.15
SpreaderId	Epoke
SpreaderType	SH-4900ES gram
kmCounter	0
DrySpreadAlert	TRUE
LiquidSpreadAlert	TRUE
PreWetSpreadAlert	FALSE
PlowInput1	FALSE
PlowInput2	FALSE
SymmertryAngleDry	30
SymmetryLiquid	0
DryDosage	20
LiquidDosage	40
PrewetDosage	0
MaxDryDosage	FALSE
CumDryMat	548
CumLiquidMat	32725
CumPreWetMat	0
SpreadingDryWidth	2
SpreadingLiquidWidth	2
DryMaterial	0
LiquidMaterial	0
AirTemp	20.5
Latitude	0.968107
Longitude	0.15903
AlarmStatus	0
PPLM	142
SpreaderStatus	Stand-By
GranularMode	Open Loop
Units	English
VehicleSpeed	38
DistanceTotal	15678.95
GranularMaterialName	SALT
GranularMaterialSetting	0
SpinnerLaneCompensationSetting	*empty*
GranularMaterialTotal	0
SpinnerDialSetting	0

Variable	Sample Data
PrewetSetting	0
PrewetTotal	0
DirectSetting	0
DirectTotal	0
DirectLaneSwitches	0
Ambienttemperature	*empty*
ErrorStatus	0
OpperationGateSetting	*empty*
PrewetLoopOperation	*empty*
PrewetMaterialName	PWT
Time	19:17:27
SpinnerDialPosition	0
PrewetLiquidRateSetting	0
PrewetVolumeTotal	0
DirectLiquidSetting	0
DirectLiquidTotal	0
DirectLiquidLanes	*empty*
RoadTemperature	0
SpreaderInformation	1
DriverID	*empty*
VehicleID	T3 621
GateSetting	0
PrewetLiquidMode	Manual
PrewetLiquidName	BRINE
DirectLiquidMode	*empty*
UnloadFunction	*empty*
GranularRateIndex	0
PrewetRateIndex	0
DirectRateIndex	*empty*
CommandTypeId	3
Command	*empty*
Uri	https://odotrouteopt.blob.core.windows.net/gateway-updates/gateway-update-manager_2.1.0.0_amd64.snap
ActiveDatetime	1/8/2020 5:18
FirmwareVersion	2.1.0.0
HashKey	https://odotrouteopt.blob.core.windows.net/gateway-updates/gateway-update-manager_2.1.0.0_amd64.snap.sha512
ModifiedBy	dd555ef5-525d-4095-a942-5136bce42526
ModifiedOn	1/8/2020 5:24
GatewayManagementId	10
CompletedDate	1/8/2020 5:50

Variable	Sample Data
AttemptedDate	6/30/2020 19:32
CurLocation	POINT (-80.94228 41.7664)
CardinalHeading	N
SpeedMPH	0.04143
SpeedkMPH	0.067173408
StartGPSId	854344025
StartLocation	POINT (-80.81089 40.76952)
StartRecordTime	9/6/2022 6:10
EndGPSId	854344033
EndLocation	POINT (-80.81088 40.76954)
EndRecordTime	9/6/2022 6:10
MetersTraveled	2
AverageSpeed	0
DistrictId	4
Route	US-30
LogPointId	1900996
UserID	cb6966ed-6c03-4166-b00b-614bb367fff3
TimeViewed	12/12/2018 10:21
GroundSpeedMPH	0
BatteryVoltage	5.458823529
AirTemperature	349.5
PumpPressure	0
LoadPressure	0
AutoModeFlag	TRUE
ClosedLoopAuger	FALSE
CLosedLoopPrewet	FALSE
Paused	FALSE
Blasting	FALSE
SpreaderMode	1
AugerRate	0
Auger2Rate	0
AntiIceRateAverage	0
MilesTraveledSinceLastDataPoint	0
MilesBlastedSinceLastDataPoint	0
ProductDumpedSinceLastDataPoint	0
ProductBlastedSinceLastDataPoint	0
PreWetLiquidOutpuSinceLastDataPoint	0
PreWetSystemMode	0
SystemTankOilLevel	255
AntiIceLiquidOutputSinceLastDataPoint	0

Variable	Sample Data
TotalProductDumped	0
SystemOilTemperature	-1
TotalLiquidDumped	7102803
ProductName	*empty*
RollDirection	right
RollDegree	0
PitchDirection	down
PitchDegree	45
RequiredHydRate	0
DayWeek	FRI
Speed	56.3
SpreadRate	0
SpreadAlert	FALSE
SpinnerRate	450
AugerConstant	88
MphCalLo	*empty*
MphCalHi	*empty*
AugerMin	*empty*
AugerDrag	*empty*
AugerJam	*empty*
FT1	*empty*
FT2	*empty*
FT3	*empty*
FT4	*empty*
FT5	*empty*
FT6	*empty*
FT7	*empty*
FT8	*empty*
FT9	*empty*
FT10	*empty*
FT11	*empty*
FT12	*empty*
FT13	*empty*
FT14	*empty*
FT15	*empty*
PresHiZero	*empty*
WetPumpRatio	*empty*
WetSlippage	*empty*
WetMaxGPT	*empty*
FluidType	*empty*
PicName	907-20191214310077.jpg

Variable	Sample Data
MediaLocation	https://freezepoint.blob.core.windows.net/camera-images/907-20191214310077.jpg
PicNotes	Headed N on SR-93 at 2mph [SLM: 5.52]
GPSLocationID	201453537
SizeBytes	267874
SpreaderBlast	FALSE
EpokeRawSpreaderID	*empty*
FA5100EXRawSpreaderID	*empty*
FA5100RawSpreaderId	*empty*
FA6100RawSpreaderId	*empty*
PWRawSpreaderId	3972060
Spreading	FALSE
CertifiedPowerRawSpreaderId	*empty*
HeartBeatRawSpreaderId	*empty*
MuncieRawSpreaderId	*empty*
LiquidRate	0
Name	VideoPullCount
Code	VP
datestamp	1/21/2019 21:04
StatTypeId	1
Value	1
FileLocation	*empty*
GatewayFileUploaded	FALSE
TransferComplete	FALSE
VideoStartTime	8/10/2022 10:00
VideoEndTime	8/10/2022 10:30
RequestExpiration	8/12/2022 0:00

CLEAR ROADS

research for winter highway maintenance

Lead state:
Minnesota Department of Transportation
Research Services
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St. Paul, MN 55155