Validating Travel Time Delay Quantification and Measurement Methods for Vermont Work Zones

August 2025

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Validating Travel Time Delay Quantification and measurement methods for Vermont Work Zones

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16. Abstract

Although the *Vermont Standard Specifications for Construction* identify an acceptable delay in work zones of less than 10 minutes per operation and less than 15 minutes cumulatively for a project maintaining one-way traffic, it is recognized that these thresholds have been set without consideration for context, procedures for measuring delay, or methods for mitigating delay. The objectives of this project were to validate the efficacy of various types of travel-time delay measurement methods and quantify the delays incurred across a variety of work zones in Vermont. In terms of mobility performance measures, travel time reliability metrics proved most effective at quantifying work zone mobility across test sites, delivering metrics that were both quantitative and easy to understand. Outcomes from the travel time reliability assessment were used to inform a framework for measuring travel time mobility metrics, setting work zone specific acceptable thresholds of travel time, and assessing work zone performance. Recommended methods for measuring work zone travel time performance and buffer indices to set acceptable travel time thresholds were based on project specific significance levels and traffic volumes. A travel time reliability approach to mobility performance measurement for work zones builds on an expanding body of research and is enabled by technological advances in data collection to support such measures.

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Introduction

The Vermont Agency of Transportation (VTrans) has previously established a *Work Zone Safety and Mobility Policy and Guidance* to address the safety and mobility impacts of Vermont work zones, in compliance with Federal Highway Administration (FHWA) requirements outlined in 23 CFR 630 Subparts J and K. Vermont's existing Policy and Guidance provides tools and procedures to assess and analyze work zone impacts as well as strategies to mitigate these impacts.

Considering advancements in work zone management tools and the availability of new data sources to support proactive monitoring and data-driven performance reviews, FHWA updated its *Work Zone Safety and Mobility Policy* in 2023. The FHWA updates encourage states to include more informed safety and mobility performance measures and routinely review their work zone safety and mobility strategies. As a result, a review of the Vermont *Work Zone Safety and Mobility Policy and Guidance* is in process that will is expected to result an updated version by the end of 2025.

Currently *Vermont Standard Specifications for Construction* identify an acceptable delay incurred from work zones of less than 10 minutes per operation and less than 15 minutes cumulatively for a project maintaining one-way traffic. It is recognized by VTrans that these thresholds have been set without consideration for context, procedures for measuring delay, or methods for mitigating delay. The purpose of this project is to inform the VTrans' standards regarding delay in work zones, evaluate potential tools for monitoring and compliance, and provide recommendations for updates to the current guidance.

Background

The 2006 *Standard Specifications for Construction* introduced the first quantitative maintenance of traffic performance measure in the form of an acceptable delay threshold for Vermont work zones. The standard in Section 104.04(b) dictated that "wherever one-way traffic is being maintained by the Contractor, the traveling public shall not be delayed more than 10 minutes." This threshold was subsequently supplemented in the 2018 Standard Specifications for Construction, where the "traveling public shall not be delayed more than 10 minutes per operation or not more than 15 minutes cumulatively for the Project." The standard also stipulates that two-way traffic will be reinstated during holiday periods, temporary shutdowns, or other periods designated by the Engineer unless the Contractor has approval otherwise.

Though the current delay standards may be effective tools for work zone mobility planning purposes, providing a threshold against which to measure the anticipated impacts of work zone phasing and operations, they remain limited in their application as a performance measure for work zone mobility. Often for projects with significant anticipated mobility impacts, analysis of the planned phasing and operations will evaluate delay, resulting in adjustments to the design to accommodate the acceptable delay and/or translating the acceptable delay thresholds into performance measures that can be monitored in the field. For instance, analysis of the acceptable delay may translate to an equivalent and acceptable queue length that the contractor can measure in situ or may translate to an equivalent and acceptable travel time measured by a probe vehicle between two fixed points within the work zone. Though these methods capture a snapshot of delay experienced in a work zone and enable potential adjustments to maintain compliance, these and other existing methods have a number of limitations in providing a comprehensive performance measure for evaluating the delay experienced by the user. Further, there is a lack of guidance on how the delay is quantified and what the acceptable level of delay might be given the context.

Preliminary work to quantify work zone delay and leverage Smart Work Zone technologies was conducted for construction projects in 2017 (Avery, 2017). The project aimed to investigate the implementation of such technologies through review of Smart Work Zone package applications on interstate projects and quantify the work zone delay across different project types. Based on snap shots of delay between fixed points within work zones, it was found that the average delay in travel time was greatest for paving projects (2.66 minutes), followed by bridge (1.66 minutes) and ledge (0.68 minutes) projects. This work acknowledged the opportunity to utilize radar and Bluetooth technologies to collect traffic data in work zones, the need for flexibility in the application of these technologies to quantify work zone delay, and the opportunity for probe data resources, like the Regional Integrated Transportation Information System (RITIS), to compliment roadside technologies. Further, the project noted the need for consistent methodologies and protocols for evaluating work zone delay and opportunities for future, real-time monitoring, proving foundational for this research effort.

Research Objectives

The research objectives of this project were to:

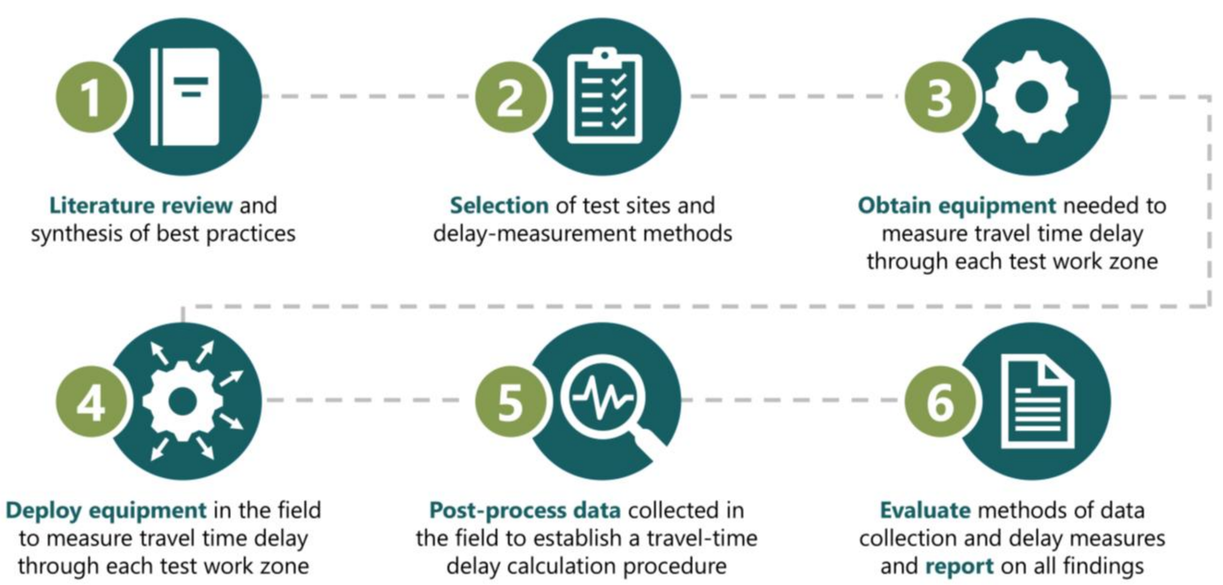
- validate the effectiveness of various types of travel-time delay measurement methods; and,
- quantify the delays incurred across a variety of work zones in Vermont.

These objectives aimed to recommend changes to the current and future VTrans construction specifications and updates to the VTrans *Work Zone Safety and Mobility Guidance* regarding a standard operating procedure for collection of data and measurement of delay to ensure compliance with the specification.

Process Overview

This report summarizes the travel time delay literature review and best practices scan, test site selection, assembly of field measurement equipment, deployment of field measurement equipment, data collection and processing, and the evaluation and identification of appropriate travel-time delay measures and methods of quantification. The process sequence is shown in Figure 1.

Figure 1 Methodology and Tasks



The research validated the effectiveness of various types of travel-time delay measurement methods and quantified delays incurred across a variety of work zones in Vermont. With potential updates to the VTrans Construction Specifications and the VTrans *Work Zone*

Safety and Mobility Guidance, the development of mobility performance measures took into consideration FHWA recommendations, other states' best practices, and Vermont's context. Additionally, the recommended measures consider project significance. Performance measures are most effective when they are specific to project type, and account for scale, context of work zone setup, and appropriate data collection methods. As such, the work zones evaluated cover a range of significance levels, traffic control types, and work zone treatments. The recommendations of the study ultimately informed performance measures and procedures for data collection and delay measurement for compliance with acceptable thresholds.

This report concludes with recommended guidance on implementing a travel time delay metric including a matrix of preferred data collection methods by project significance and traffic volumes, proposed procedure for quantifying the measure, and immediate next steps for advancement towards implementation.

Literature Review and Synthesis of Best Practices

This section documents the literature review and synthesis of guidance and state department of transportation (DOT) best practices for methods, technologies, and tools used to measure and assess travel time delay.

Review Approach

1. Review policy to frame objectives and alignment with federal requirements and state guidance,
2. Assess state DOT practices and scholarly/technical reports to compare work zone mobility performance standards and measurement methods,
3. Define existing Vermont-specific needs and identify suitable mobility performance metrics for data-collection and pilot-test protocols for projects of varying significance.

As directed by FHWA and codified in 23 CFR 630 Subparts J and K, VTrans has established a *Work Zone Safety and Mobility Policy and Guidance* to assess, analyze, and address the impacts of work zones on safety and mobility on Vermont's roadways. A set of mobility related strategies were articulated in the guidance, as follows:

- Establish procedures for identifying potential travel delays associated with work zones and access limitations in planning and design;
- Develop appropriate statewide criteria for context-sensitive maximum acceptable work zone related delays;

- Establish statewide procedures for monitoring on-site/site-related travel delays;
- Establish procedures for mitigating project related travel delays and/or access limitations (VAOT, 2021).

It is clear in the directive that performance measures will be leveraged to manage work zones and clear in the state guidance that setting context-sensitive maximum acceptable delay metrics and establishing methods to measure performance against such criteria are priorities.

Initiatives from the second *Strategic Highway Research Program* (SHRP2) and *Moving Ahead for Progress in the 21st Century Act* (MAP-21) spurred emphasis on performance measurement as a means for managing congestion. A suite of guidance documents, research efforts, and case studies have been developed over time to support establishing appropriate, goal-oriented performance measures. In the interim, significant progress has been made in low-cost technologies enabling performance measurement through improved data collection and data resources.

Work Zone Performance Measures

A key component of work zone safety and mobility planning is the use of performance measures. Performance measures allow agencies to quantitatively monitor the effectiveness of their management strategies and can vary in scale and focus depending on project context and performance review goals.

FHWA guidance, *A Primer on Work Zone Safety and Mobility Performance Measurement*, outlines that work zone performance measures should:

- Relate to the safety and mobility goals and objectives that the agency has established for itself,
- Be consistent with the measures used in impact assessment efforts for work zone planning and design analyses,
- Characterize the different facets of impacts that are occurring,
- Enable the agency to evaluate the effects of alternative strategies for mitigating traffic impacts caused by work zones and be compatible with other performance measures that the agency is using to evaluate its system (Ullman, et.al., 2011).

Three categories of performance measures are used to quantify work zone safety and mobility impacts: exposure, safety, and mobility measures. Exposure measures track how much time, space, or traffic a work zone affects. Safety measures evaluate changes in crash risk compared to baseline conditions. Mobility measures assess how travel conditions, such as traffic flow and delay, are affected.

Mobility Performance Measures

This project was positioned to focus on validating the effectiveness of various mobility performance measures. Typical mobility performance measures include delay, queue, speed, volume to capacity, and level of service. With technology enabling performance measures, there is an expanding body of research and literature that examines metrics of import to the user. Travel time reliability has been a focus of this research and translated to a series of vetted mobility performance measures that more directly relate to the user experience. Various mobility performance measures were summarized below based on available FHWA guidance and practitioner experience.

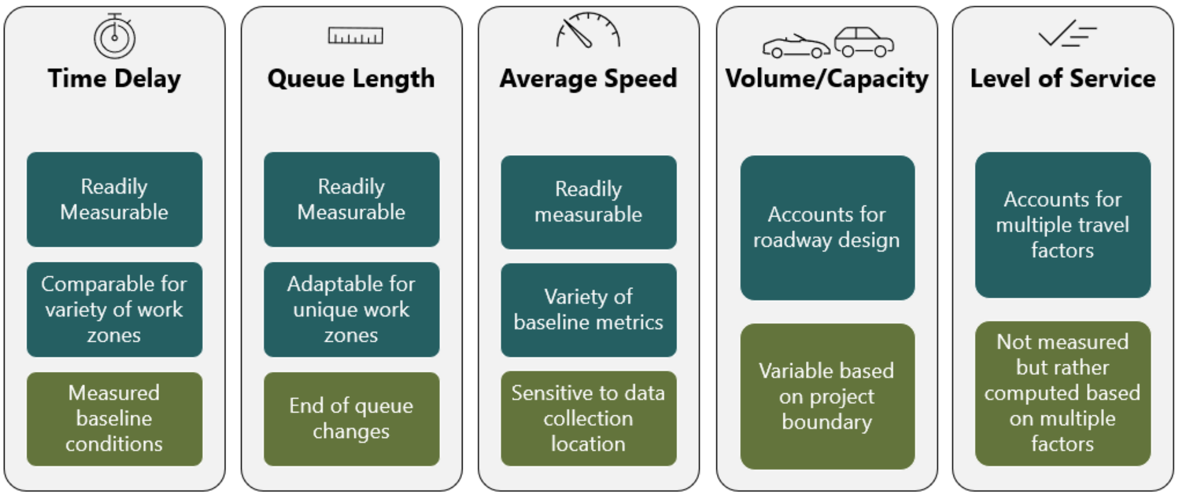


Figure 2. Typical Mobility Performance Measures with Advantages and Limitations

Delay

Delay can be collected continuously through a series of point-based detectors, procured from probe vehicle data from data vendors, or recorded through sampling via pilot cars or field observation. Measuring time delay requires baseline data (pre-work zone) travel times to compare travel times during and is typically presented as additional delay incurred by work zone operations. Potential delay measures include vehicle-hours of delay, average delay per vehicle, maximum per-vehicle delay and percent vehicles experiencing delays greater than an acceptable level.

Queue

Frequency, length, and duration are needed to fully characterize traffic queues in work zones and can be recorded by singular point-based detection, observation or estimated through modeling. Queue length measures are adaptable for unique work zones that have specific impacts incurred as a result of queueing past a specific point, or in locations that are hard to monitor with other data collection setups. Queue length is easily observable and noting queues that extend past a given point is a common field measurement to make and monitor on projects, particularly those with limited anticipated impacts on mobility.

Volume to Capacity and Speed

Capacity reduction reflects how work zone operations constrain vehicle flow relative to typical or design capacity. Speed, which can be readily measured through point-based sensors or probe data, is directly connected to capacity through the speed-flow relationship (Figure 10). Speed reductions incurred by work zone conditions contribute to reduced capacity and overall mobility impacts.

Travel Time Reliability

Travel time reliability measures how much a trip's actual travel time is likely to deviate from its typical or expected travel time. Predictable travel times allow for travelers to plan for the time required to arrive at a desired time. Work zones often reduce the predictability of travel times. Travelers also tend to remember the few bad days they spent in traffic, rather than an average time for travel throughout the year (Figure 3).

Implementing a management strategy based on travel time reliability provides an opportunity to significantly improve performance by putting a focus on reducing the frequency and severity of the worst travel time experiences, an improvement that would not be reported in cumulative travel time averages. Reliability metrics, unlike standard averages, also better reflect public sentiment regarding the Agency's effectiveness due to the focus on mitigating the worst days, which provides an opportunity for the Agency to focus efforts on improvements that align with user experience.

Figure 3 Travel Time Reliability Experience (source: FHWA)

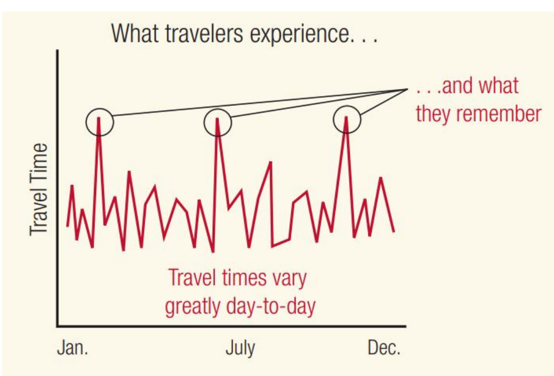
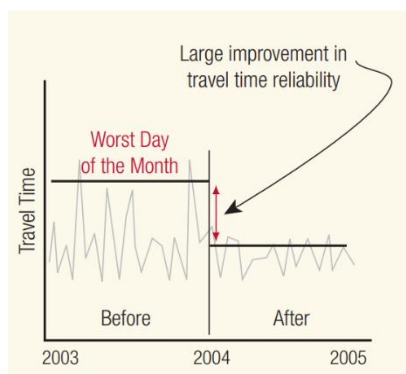


Figure 4 Travel Time Reliability Improvement (source: FHWA)



The FHWA guidance is clear in its direction for state agencies to adopt travel-time reliability measures. They recommend using 90th or 95th percentile travel times along with a buffer index and planning time index. They also reference other less effective measures including standard deviation and coefficient variation, noting these measures are less effective for public communication and give equal weight to early and late arrivals.

Travel time reliability measures are collected for routes or point-to-point travel times. For work zones this is measured as the travel time for a given route that includes a work zone or the travel time between two points just outside of the work zone and is most effective when compared to a benchmark measurement made prior to work zone implementation.

90^{th} or 95^{th} Percentile Travel Time

The 90^{th} or 95^{th} percentile travel time represents a near worst-case scenario travel time that is greater than 90 percent or 95 percent of all other travel times for a trip in a given period. Reported in minutes or seconds for a trip of specific length, travel times are not easily comparable to trips of different length or type. However, additional metrics of reliability, specifically buffer indices or planning time indices, enable the reliability to be expressed in terms that can be compared across varying trip types or settings.

Buffer Time & Buffer Index

The buffer time is the time window that travelers typically allocate to their trips when aiming for a set arrival time, typically with consideration for potential congestion or expected route inconsistencies. The buffer time is the difference between the average, typically experienced travel time for a trip and the 90^{th} or 95^{th} percentile (near worst-case) trip travel time. A traveler would allocate a high buffer window to a trip that has a high chance of experiencing a large delay beyond the typical travel time and would allocate a minimal buffer window to a short trip where they do not expect unusual delay beyond what they typically experience. The buffer index is the buffer time expressed as a percent of the average travel time and allows comparison across trips of diverse types and lengths.

Planning Time & Planning Time Index

The planning time represents the total travel time that should be planned to account for the worst-case scenario. The planning time index is a ratio that represents the magnitude of the worst-case scenario compared to the typical.

Data Collection for Performance Measures

This section outlines common data collection methods for mobility performance measures, based on State DOT practices with a focus on those that are suitable for Vermont's rural context and data availability. These methods include performance measures that are:

- Procured from continuous probe vehicle data,
- Estimated from continuous point-based detector data,

- Collected in periodic special studies (e.g., floating car runs), and/or,
- Evaluated using model techniques including simulations, sketch planning, demand modeling, etc.

Probe Vehicle Data

Probe vehicle data is transmitted from connected vehicles or other onboard, GPS or cellular enabled technologies and aggregated by vendors. The National Performance Management Research Data Set (NPMRDS) offers a data source to state and local transportation agencies for monitoring and reporting transportation system performance measures, as well as for setting and meeting mobility objectives and targets. VTrans has access to the RITIS community and allows access to archived travel time and speed data from probe vehicles. RITIS data has a penetration of approximately 5 to 7% of passing vehicle volumes. It is important to recognize the limitations in a sampling that represents a portion of the traffic and the implications for data quality. With probe data, accuracy of reported metrics tend to increase with larger sample sizes (i.e., higher AADT roadways). Additionally, probe data coverage is a consideration, whether due to sample size limitations or connectivity on cellular networks, Vermont has a way to go to be thoroughly connected when using devices that rely on these technologies.

Point-Based Detector Data

Point-based detectors are deployed at specific locations and capture characteristics from passing vehicles or devices. These detectors support collection metrics, like vehicle presence (e.g., queue detection), volume, speed, or can be used in combination to support point-to-point metrics like travel time. Point-based detectors need to be physically set up, require power, space, connectivity (e.g., cellular coverage), maintenance, and introduce complexity to site management. As a benefit point-based detectors typically have much higher penetration rates relative to probe-based data, capturing information on a larger proportion of passing vehicles.

Table 1 Point-Based Detectors

Point-Based Detectors	Application
Bluetooth Sensors	Portable, inexpensive; limited penetration (80-90%) across all vehicles
Magnetic Sensors	High sensitivity (detects bicycles); requires intrusive installation
Cameras	Provides visual data; requires manual review and interpretation
Radar	Portable, non-intrusive; requires line-of-sight
ALPR (Automated License Plate Readers)	Provides comprehensive data including vehicle classification; expensive and involves sensitive data

Periodic Personnel-Based Collection

Personnel-based monitoring provides snapshot views of work zone operations and performance. These methods are most effective when used to supplement continuous data collection. Common examples include floating car runs and on-site observation like queue lengths and durations. Incident, weather, and work zone operation logs should also be consistently recorded to support interpretation of parallel mobility performance data.

Demand Forecast Modeling

Demand forecasting and traffic simulation tools are useful for estimating projected work zone mobility impacts and informing mitigation strategies. These tools are routinely used to evaluate anticipated delays and accommodations during planning and design phases of project development and can also support ongoing assessment of work zone mobility performance.

State DOT Review

A review of other states' mobility performance practices for work zones was conducted. Table 2 summarizes the work zone mobility performance measures stipulated by other state agencies and the associated acceptable thresholds. Links to where the mobility performance measures are documented for each state are included in the table.

Of the states reviewed that had readily available information on their specifications for work zone mobility performance, twelve states were identified as having some measurable threshold for work zone mobility performance. Along with Vermont, seven states used maximum time delay specification as their primary metric, and two states used time delay as one of several metrics. Other mobility metrics specified included queue length (queue as defined by each state), level of service (LOS), or volume to capacity ratio (V/C).

Of the states that identify delay specifications, four set a threshold to 15 minutes and two at 10 minutes, however Vermont is the only state to set discrete time thresholds for construction operation delay and cumulative delay. Of the nine states reviewed that set delay thresholds to time delays, none provided specific guidance for type of data collection equipment to use, procedures of field setup, or standardization for data analysis. The only exception to this was for New Hampshire. New Hampshire offers guidance for estimating delay time by using "non-intrusive detectors spaced approximately 0.5 miles apart extending beyond limits of work zone congestion…" It should be noted that this recommendation pertains to sensors used to update changeable message signs preceding work zones, not explicitly for mobility performance measurement.

Table 2 State DOT Performance Measure Thresholds

State	Monitoring Method	Threshold	Source
California	Time Delay	Up to 20 min delay (dependent on location and project)	https://dot.ca.gov/programs/construction/construction-manual/section-2-2-traffic
Florida	Queue Length	2 miles maximum (highways with speed > 55 mph)	https://www.fdot.gov/docs/default-source/roadway/ds/13/idx/00600.pdf
Indiana	Queue Length	Queue any length limit to 6 continuous hours Queue any length limit to 12 hours in calendar day Queue > 0.5 miles cannot exceed 4 continuous hours Queue > 1.0 mile cannot exceed 2 continuous hours Queue > 1.5 miles not permitted	https://www.in.gov/indot/files/Safety_WorkZoneSafetyandMobilityPolicy.pdf
Kansas	Time Delay	Max 30 minutes	https://www.ksdot.gov/Assets/wwwksdotorg/bureaus/burConsMain/specprov/2015/805.pdf
Maryland	Queue Length	Queue < 1.0 mile permitted Queue > 2.0 mile not permitted Queue between 1.0 and 1.5 mile limit to 2 hours	https://roads.maryland.gov/mdotsha/pages/Index.aspx?PageId=406
	Time Delay	Max 15 minutes on arterial roads	
	LOS	Dependent on signalized intersection vs. unsignalized intersection and existing LOS	
Michigan	Time Delay	Max 10 minutes	https://www.michigan.gov/mdot/-/media/Project/Websites/MDOT/Business/Work-Zone-Mobility/Work-Zone-Safety-Mobility-Manual.pdf?rev=f5ecc5a301a945a698429b136b25278c&hash=31B68EFBDAD31291EA67A223C81C2A7B
	LOS	Max LOS drop 2 levels LOS no worse than D	
	V/C	V/C < 0.8	
Missouri	Time Delay	Max 15 minutes	https://epg.modot.org/index.php/616.14_Work_Zone_Safety_and_Mobility_Policy
New Hampshire	Time Delay	Max 10 minutes	https://www.nh.gov/dot/org/projectdevelopment/highwaydesign/documents/swzman_05102011.pdf
New Jersey	Time Delay	Max 15 minutes	https://nj.gov/transportation/eng/documents/BDC/pdf/attachmentbdc07t07.pdf
Ohio	Queue Length	Max queue length 1.5 miles	https://www.transportation.ohio.gov/about-us/policies-and-procedures/procedures/123-001-sp
Oregon	Time Delay	Max < 10% of peak travel time	https://www.oregon.gov/odot/ProjectDel/Pages/Mobility-Planning.aspx
Wisconsin	Time Delay	Max 15 minutes	https://wisconsindot.gov/dtsdManuals/traffic-ops/manuals-and-standards/teops/06.pdf

Mobility Metrics and Travel Time Reliability

Work zones are just one facet of the potential disruptions on the system that can affect reliability. There are recurring and non-recurring factors that contribute to congestion and mobility challenges on the roadway network. Recurring factors can include demand patterns (e.g., peak hour demand), existing capacity constraints or bottlenecks (e.g., merge points), or traffic control (e.g., signal phasing and timing). Non-recurring factors can include construction work zones, but also can include traffic incidents, crashes, weather, or special events. As such, there have been studies aimed at quantifying the reliability contributions for different types of congestion. The influence of non-recurring factors on reliability have been explored for traffic incidents or crashes and weather events. Congestion management practices are expanding to incorporate the principles of travel time reliability to non-recurring congestion factors and leveraging low-cost methods to monitor, evaluate, and communicate travel time reliability with the traveling public. This has implications for work zone contributions to travel time reliability on highway facilities.

Other states have guidance to define the acceptable thresholds for mobility metrics and recommended means and methods to measure the metrics in work zones. For some state agencies, like Maryland Department of Transportation, context factors like facility types (e.g., freeways vs. arterials, segments vs. intersections) and number of lanes (i.e., typically and with work zone in place) provide qualifiers for acceptable delay and queue thresholds (MDOT, 2024). Clear guidance is provided on the analysis to conduct during design of the work zone, planning for the projected impact of work zone phasing and configuration ahead of construction. For projected impacts that are compliant with the acceptable thresholds, the analysis is documented, and design and construction can proceed. However, if impacts exceed the thresholds based on analysis, guidance is provided on maintenance of traffic mitigations to consider and reevaluation necessary prior to approval process. Comparison of the anticipated work zone mobility impacts to monitored impacts during the construction phase is stipulated, but the monitoring approach methods are not detailed in guidance.

Although there is generally a lack of guidance from other states on recommended approaches to quantifying mobility measures for compliance during the construction phase, other studies have attempted to quantify mobility metrics across case study work zones. Retroactive case studies of work zone travel time reliability were evaluated for 19 work zones in Wisconsin (Srivastava, 2018). The data gathering included leveraging travel time collected from vehicle probe data from the National Performance Management Research Data Set (NPMRDS) and traffic volume data from the state’s Automatic Traffic Recorder (ATR) system. This work aimed to develop a predictive model of reliability based on work zone attributes. Although methods to quantify reliability through a measure referred to as the work zone impact ratio were employed, which ratioed the travel time reliability for the work zone with the reliability of the baseline scenario, there remained challenges in developing a predictive method to inform the mobility performance measures anticipated for other work zones. Consideration of additional factors may improve the model, but besides a loose, but inconclusive relationship of traffic volume with travel time reliability, did not reveal clear relationships.

Similarly, 15 work zones in Virginia were evaluated using probe data assembled by a private third-party vendor (Edwards, 2012). In this instance, travel time reliability, buffer index, and planning time index were quantified for the work zones to isolate the impacts of this non-recurring congestion on the system. When compared to baseline conditions, 95th percentile travel times were found to be 16% higher with work zones in place and 22% higher with lane closures in place. Buffer indices were found to be 48% higher with work zones in place and 67% with lane closures in place.

Although other states have explored this reliability approach to quantifying performance of work zones, few, if any, have codified the approach to set standards around acceptable reliability thresholds for work zone activities. With expansion of reliable and lower cost data collection, smart work zone packages that leverage this technology and travel time reliability metrics have had an uptick in use. The value of work zone travel time reliability metrics is evident in the guidance that is provided by state agencies to leverage travel time data for real-time messaging to the public.

Project Significance

One factor that should guide the application of data collection methods and performance measures is project significance. FHWA rules for implementing Work Zone Safety and Mobility direct the use of project significance criteria to categorize projects that are likely to have relatively greater effects on traffic conditions in and around their work zones. This classification of projects is intended to help agencies allocate resources more effectively to projects that are likely to have greater impacts and create guidelines for standards of practice relating to safety and mobility impacts of varying scales.

Vermont's current *Work Zone Safety and Mobility Policy* includes criteria for determining significant projects and outlines that the significance category of a project determines the required Work Zone Safety and Mobility documentation. A significant project is defined by FHWA as a project that alone, or in combination with other concurrent projects, is anticipated to cause sustained work zone impacts that are greater than would normally be expected based on State policy or engineering judgment and should be prioritized higher with more resources allocated to mitigate impacts.

Extending this principle, mobility performance measures should also be scaled relative to project significance, ensuring that more impactful projects are monitored for performance commensurate with their expected effects and allocated with appropriate resources for data collection. Mobility performance measures and data collection practices should be recommended relative to project significance.

Data Collection & Post Processing

This chapter documents the work zone travel time data collected in support of the project and results of post-processing the data to develop performance measures. Data was collected at four test sites throughout Vermont between the Fall of 2023 and the Fall of 2024. A detailed description of the data collection process is provided below, including the site selection, the construction of the mobile traffic monitoring platforms (MTMPs), and the deployment of the MTMPs. The post-processing of the collected data included the calculation of:

- Free-Flow Speeds
- Capacity
- Excess Delay
- Average Travel Time
- Control Delay
- Travel Time Reliability
- Buffer Index

Data Collection

Site Selection

Candidate sites for the study were selected through a process that considered potential projects for the construction season in 2023 and 2024. The potential upcoming projects were extracted from VPINS, the VTrans management system for projects, for review with the project's Technical Advisory Committee. The potential projects were categorized by project type and significance level based on the Transportation Management Plan (TMP) Checklist for each project. The TMP Checklist is required for all federal aid highway projects and expected for all other construction activities on Vermont highways. A TMP submittal is included at each project development design phase, providing a framework to evaluate safety and mobility impacts of the project and identify the project significance level based on a set of criteria, as depicted in Table 3.

Table 3. Work Zone Safety and Mobility Guidance Project Significance Criteria

Project Type (Number of Criteria)	Permanent Posted Speed Limit of Facility	Existing AADT	Multi-Project Interaction	Project Location	Non- Automobile Modes	Duration of Project Traffic Impacts	Level of impact to high-volume or critical traffic generators	Network Reliability	Significance	Resulting Requirements
A–Typically high-volume, high-speed roads (meets 1 or more of these criteria)	≥55 mph	>20,000 interstate or >15,000 state highway				2 or more construction seasons			Significant	TMP checklist to determine **required scope** for TO, PI, TTC; consider mitigation
B–Complicated areas due to users, locations generators, or other projects (meets 3 or more of these criteria)		>15,000 interstate or >10,000 state highway	One or more other projects in the vicinity are affected by this project's traffic impacts (or vice versa)	Located within a downtown district or village center that creates additional traffic management challenges	Extensive impact to pedestrian or bicycle facilities with demonstrated demand or transit routes		High Impact	If there is an incident, there is no redundancy in network to ensure mobility	Significant	TMP checklist todetermine **required scope** for TO, PI, TTC; consider mitigation
C–Lower-volume locations with some complications (Meets 2 or more of these criteria)		>10,000 interstate or >5,000 and state highway	One or more other projects in the vicinity are affected by this project's traffic impacts (or vice versa)	Located within a downtown district or village center that creates additional traffic management challenges	Extensive impact to pedestrian or bicycle facilities with demonstrated demand or transit routes		Medium or High Impact	If there is an incident, there is no redundancy in network to ensure mobility	Not Significant	TMP checklist to determine **if any** TO, PI, TTC requirements
D–Simpler work zones on lower-volume roadways			Project is isolated or other projects are not likely to affect traffic or safety of this project	Location presents minimal traffic management challenges					Not Significant	TMP checklist to document **if no** TO, PI, TTC requirements

The aim of the site selection process was to identify a project in each of the four project significance categories to evaluate, providing a realistic range of project types, mobility impacts, and contexts appropriate to the range of work zones experienced on Vermont's roadways. Once the options were narrowed based on significance category and construction schedule, the viable sites were assessed for site suitability. Ideal project selections for the development of methodology had few, if any, sinks or sources of trips along the corridor and width within the right-of-way to stage equipment. The list of candidates for each of the site significance categories was narrowed based on desktop review of the corridor and site suitability criteria. Final selections were made based on site accessibility, work zone timing, and responsiveness of the resident engineer for coordination purposes. It is noteworthy that identifying a project from each of the four categories proved challenging across the two construction seasons. It may be a matter of the active projects available during the research study, but it is noted that there is a wider ongoing discussion of whether differentiating between four distinct categories has utility for the range of projects on Vermont's roadways or refining the categories may allow for some consolidation of significance levels to simplify the process.

From the list of candidate project sites, the projects selected were detailed in Table 4 below. The project significance level, project number, location, project description, and work zone configuration were described.

Table 4. Candidate Project Selections

Significance Level	Project Number	Location	Project Description	Work Zone
A	IM 091-1(70)	Westminster	Replace deck and bearings on BR21 N&S on I-91 in Westminster, over TH1 ("VT121")	Divided interstate highway crossover with lane reduction referencing MUTCD Typical Application TA-39.
B	NH 028-1(31)	Colchester	Improvements to the US2 and US7 intersection and the US2 and I-89 Exit 17 interchange; includes off-alignment bridge replacement and corresponding roadway improvements.	Mixed traffic control for shoulder and lane reductions and lane closures. This project utilizes a phased approach to maintenance of traffic and includes some night work.
C	STP 2941(1)	St. Albans	Resurfacing/rehabilitation of VT 104 in St. Albans, beginning at MM 0.00 in St. Albans and extending easterly 7.856 miles to the intersection of VT 105.	Lane closures, flaggers, UTOs, temporary markings, and mobile operations referencing MUTCD Typical Applications TA-6, TA-10, TA-17, and TA-27. Primarily night work.
D	STP 0161(32)	Hubbardton	Removal of ledge along VT30 in Hubbardton, beginning 3.00 miles north of the Castleton-Hubbardton town line extending north 0.13 miles; includes clearing, rock removal, scaling, and installation of rockfall catchment fence.	One-way alternating with temporary signal referencing MUTCD Typical Application TA-12.

Each project satisfies a significance level from the *Work Zone Safety and Mobility Policy and Guidance* and collectively they represent a range of typical temporary traffic control types with various levels of impact on the capacity of the highway facilities.

The work plan called for the deployment of traffic flow (speed and volume) and travel time sensors at 4 locations surrounding each work zone (Figure 5), both with and without the work zone in place. It is important to note that with the Bluetooth travel time sensors, pairs of the devices are required to measure the travel time between each pair. For instance, a Bluetooth sensor at trailer location 1 and 4 would measure travel time through the entire work zone, between trailers 1 and 4. An additional Bluetooth device at trailer location 2 would enable measurement of travel time upstream of the work zone, between trailers 1 and 2, as well as travel times within and downstream of the work zone, between trailers 2 and 4.

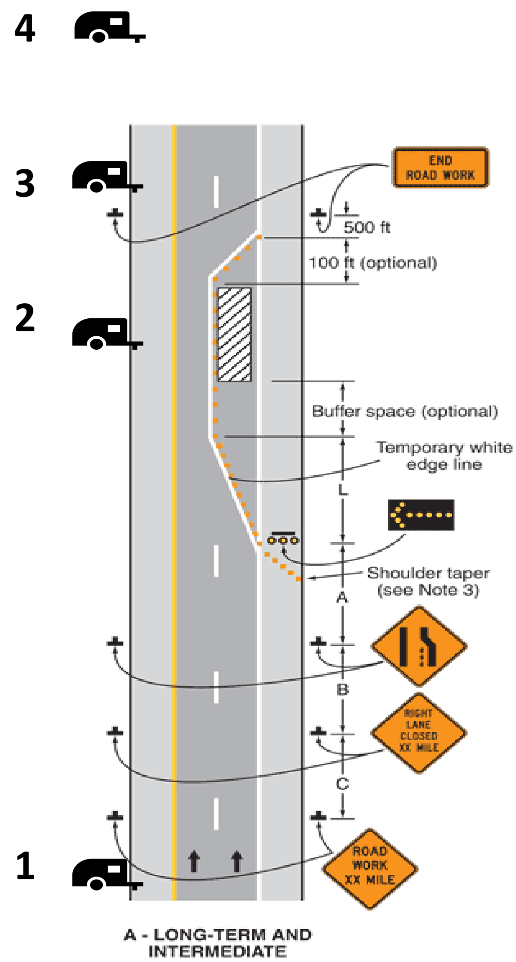


Figure 5 Schematic trailer placement for data collection

This data collection was supplemented with travel time data from two additional sources. The first was a separate set of travel time sensors deployed at the Level B site for its Smart Work Zone requirements. The second was travel time data from probe vehicles accessed through the Agency's participation in the RITIS community which began in 2023 and allows access to archived travel time data from probe vehicles.

Constructing the Mobile Traffic Monitoring Platforms

In order to collect all of the data needed for the planned implementation of this research at candidate work zones, the team needed to deploy 4 traffic flow sensors and 3 Bluetooth travel-time sensors at remote locations with limited roadside space. This required the use of small, lightweight trailers to transport the equipment, and portable power sources to maintain data collection where a hardwired power source was not available. The 2 trailers made available by the state of Vermont were equipped with traffic flow sensors, portable batteries, and solar panels so they could be relatively self-sufficient. However, their size and wheelbase made them difficult to fit in tight roadside locations. Therefore, the team selected the smallest, lightest trailers they could find for the creation of mobile traffic monitoring platforms (MTMPs) to be used for the collection of data at 2 additional locations – see Figure 6.

Figure 6 Trailers used to construct MTMPs

The team then obtained the following equipment:

- (3) BlueTOAD Spectra Bluetooth travel-time sensors, including:
- (6) 12V 60Ah batteries
- (3) 90W solar panel rechargers
- (2) WaveTronix SmartSensor HD traffic flow monitors, including:
- (4) 12V 95Ah batteries
- (2) 12V battery chargers
- (2) waterproof UL listed electrical boxes

Figure 7 Completed MTMP and Primary Components

Battery storage capacity was doubled so that a full set of batteries could be charging while the other set was being used in the field. With galvanized angle iron and stainless steel hardware, the electrical boxes were attached to the trailer for storage and protection of batteries, and the sensors were attached to the trailers and wired into the electrical boxes for power. A completed MTMP is shown in Figure 7, with the traffic flow sensor at the top, the travel-time sensor below it on the same vertical angle iron, and the batteries housed in the electrical box on the trailer. Where sun exposure allowed for solar recharging, a solar panel unit was added and wired into the batteries inside the electrical box. The solar panel rechargers allowed 1-5 more days of data collection before batteries discharged and needed replacement.

Deploying the MTMPs and State Trailers

The research team visited each site before deploying equipment, in order to coordinate specific locations on the right of way where trailers could be staged. This step was particularly challenging at the Level D site, where only one side of the highway could be used to stage the MTMPs and space between the edge of the active travel lane and a nearby creek was limited (Figure 7).

Deployment was successful at 3 of the 4 planned locations, where the 2 MTMPs and the 2 state trailers during construction allowed for collection of traffic flow and travel time data. At the Level C and D locations, the MTMPs and state trailers were deployed for a period of 2 weeks before construction and 2 weeks during construction with the work zone in place. The Level A project was not completed on time, so the team was unable to collect data without the work zone in place. Therefore, the team used data collected at nearby RWIS stations before the work zone had been implemented to provide traffic flow and travel time without the work zone in place. At the Level B location, the work zone was too complex to deploy the MTMPs effectively for traffic flow data collection, and a rich set of travel time data was already available through the Smart Work Zone deployment that was part of the construction package. Therefore, at this site, the team relied solely on travel time data to assess delay.

Batteries were exchanged every 2-5 days based on sun exposure and temperature, and at each exchange, traffic flow data was downloaded on site (Figure 8).

Through the deployment, there were several notable lessons learned that have value to the research study and inform the recommendations for future application of the approaches evaluated. Data collection encountered challenges, including:

- Site limitations – Placement of data collection equipment in locations that did not interfere with work zone operations while remaining safely located in the highway right of way can be a challenge. Retroactively locating equipment for the study required close coordination and collaboration from the resident engineer and contractor. Opportunities to discuss site limitations and understand equipment placement sooner in the project development process will help to alleviate this challenge in future applications.

- Poor network connectivity – Some data collection devices require connectivity, typically via cellular network or direct internet connection. This was encountered with the state trailers as well as the Bluetooth devices. Although there are means and methods to archive data locally on equipment and upload information periodically, the preference is generally to have devices connected so information is available in near real-time. Poor network connectivity, including poor cellular coverage, in many parts of the state will be a consideration in planning for work zone data collection and may affect the selection of methods.
- Data collection intervals – The interval at which data are collected and/or aggregated to often can be set as a user preference for these types of devices. The data collection intervals were set to a default interval on state trailers, which was inconsistent with the selected intervals for data collection on the MTMPs. These settings should be considered and set appropriately to maintain consistent temporal intervals for data reconciliation in post processing.
- Equipment malfunctions – There is always some risk associated with collecting data directly in the field, especially with equipment that is left unaccompanied for longer periods of time. Equipment malfunctions can and do occur and should be considered in the proposed data collection methodology. Loss of data and information is one of the more minor consequences associated with this risk. During data collection, other issues that led to equipment malfunctions occurred, like an instance of solar panel theft that led to batteries draining faster than anticipated.

Plans for data collection should account for potential issues, like those identified above and others, in order to capture the appropriate and relevant data to perform analyses. Redundancy in data collection and methods to alert data managers to issues early can help alleviate issues and prevent some of the risk inherent to these activities. This will be especially relevant should the methods proposed here be employed to determine compliance with acceptable delay standards for work zones.

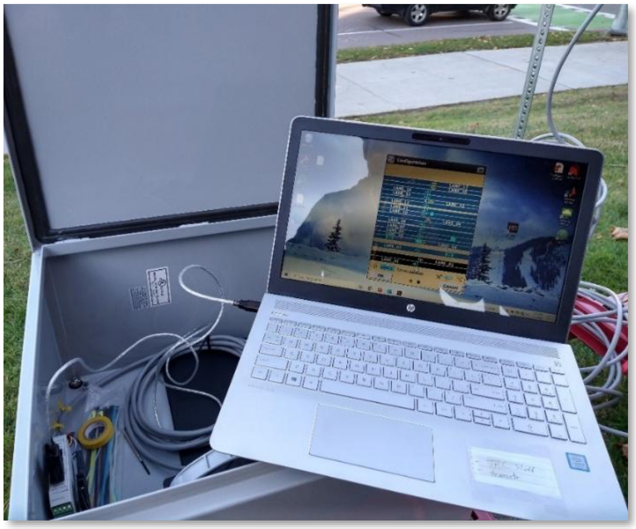


Figure 8 On-site downloading of speed-flow data

Figure 9 Challenges to staging the MTMPs

Post-Processing

Once the data collection had been completed for the four candidate project sites, the team began post-processing the data to calculate travel-time, capacity, and delay using the methods selected in Task 2. These calculations included:

- Free-Flow Speeds
- Capacity
- Excess Delay
- Average Travel Time
- Control Delay
- Travel Time Reliability
- Buffer Index
- Travel Time Threshold

Free-Flow Speeds

Free-flow speeds correspond to the average speeds during traffic flows below the breakpoint (BP), where speeds begin to reduce due to the effects of congestion (Figure 10).

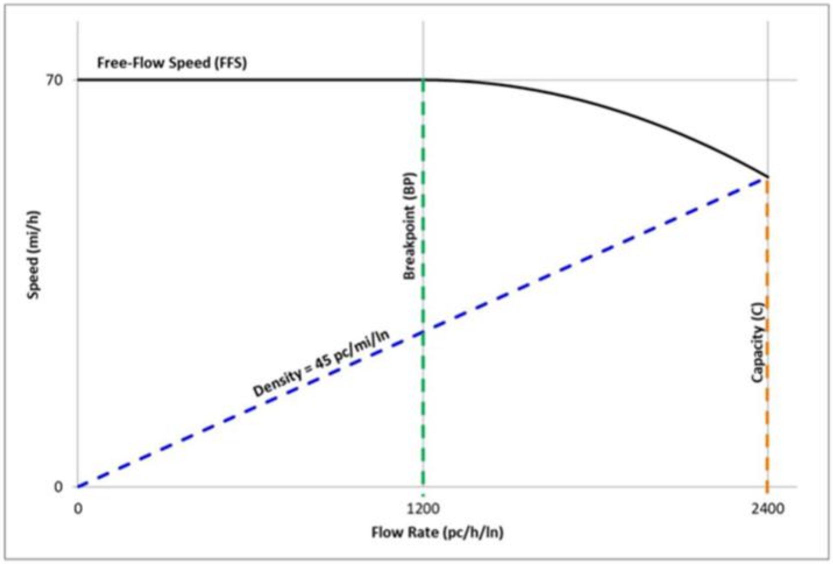


Figure 10 Free-flow speeds on the speed-flow curve

Free-flow speeds were calculated from the speed-flow data collected at each candidate site, both before the work zone was in place, and during work zone operations. Table 5 provides the results of these calculations for each deployment.

Table 5 Free-flow speeds (mph) calculated at each MTMP deployment

Significance Level	Site	Location	Posted Speed Limit (mph)	before / after	during	loss
D	**Hubbardton VT-30**	Far North of the WZ	50	57.6	57.6	0%
D	**Hubbardton VT-30**	Within the WZ	50	47.9	33.0	31%
D	**Hubbardton VT-30**	Just South of the WZ	50	53.6	32.0	40%
D	**Hubbardton VT-30**	Far South of the WZ*	50	--	--	--
A	**Westminster I-91**	Far North of the WZ	65	71.0	71.0	0%
A	**Westminster I-91**	Just North of the WZ	65	71.0	71.0	0%
A	**Westminster I-91**	Within the WZ	65	77.2	62.2	19%
A	**Westminster I-91**	Far South of the WZ	65	77.2	77.2	0%
C	**St Albans VT-104**	Far North of the WZ*	40	--	--	--
C	**St Albans VT-104**	Just North and Within WZ	40	44.6	42.3	5%
C	**St Albans VT-104**	Just South and Within WZ	40	41.6	40.4	3%
C	**St Albans VT-104**	Far South of the WZ*	40	--	--	--
	*Connectivity issues prevented the state trailers from obtaining speed-flow data in certain locations with poor service					

At the Westminster I-91 site, it was not possible to collect speed-flow data before or after, since the work zone was in place during this entire research project. Therefore, the free-flow speeds for the “before/after” condition for that site were estimated from speed-flow data from RWIS stations on the same freeway a few miles away. Note that only the speed-flow data within the work zone, or immediately upstream/downstream of it showed effects on vehicle speeds. The Hubbardton site had considerable reductions in free flow speeds due to the use of temporary traffic signals and flaggers to stop traffic to facilitate two-way use of a single travel lane. Also notable was the reduction of free-flow speed at the Westminster I-91 site, which included a speed limit reduction through the work zone area with a lane reduction from two to one in each direction of travel.

Capacity

Plotting the entire speed-flow curves allowed the team to estimate a capacity reduction due to the work zone that resulted in speed reductions across a variety of flow rates. Capacity took into consideration all of the data collected in order to estimate the capacity reduction experienced with the work zone. Plotting the speed-flow curves during and before/after the work zone was in-place illustrates this reduction (Figure 11 through Figure 15).

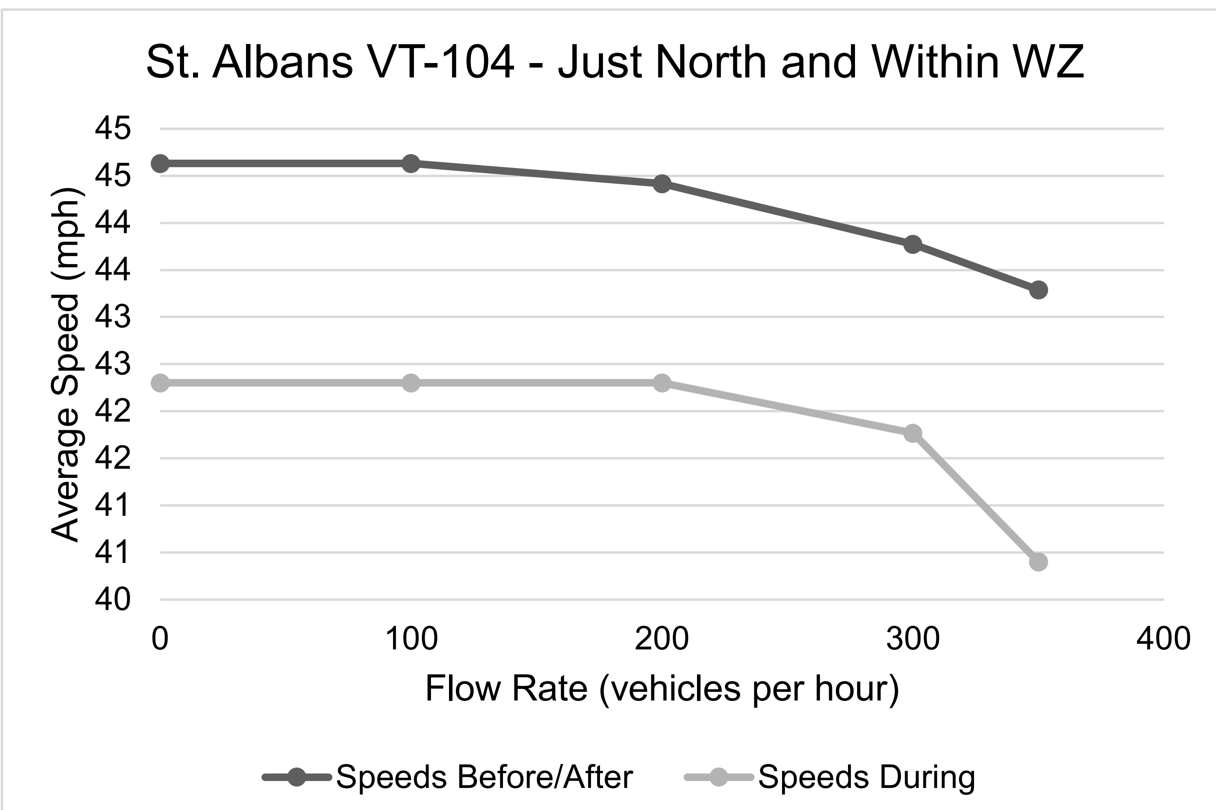


Figure 11 Speed-flow curves

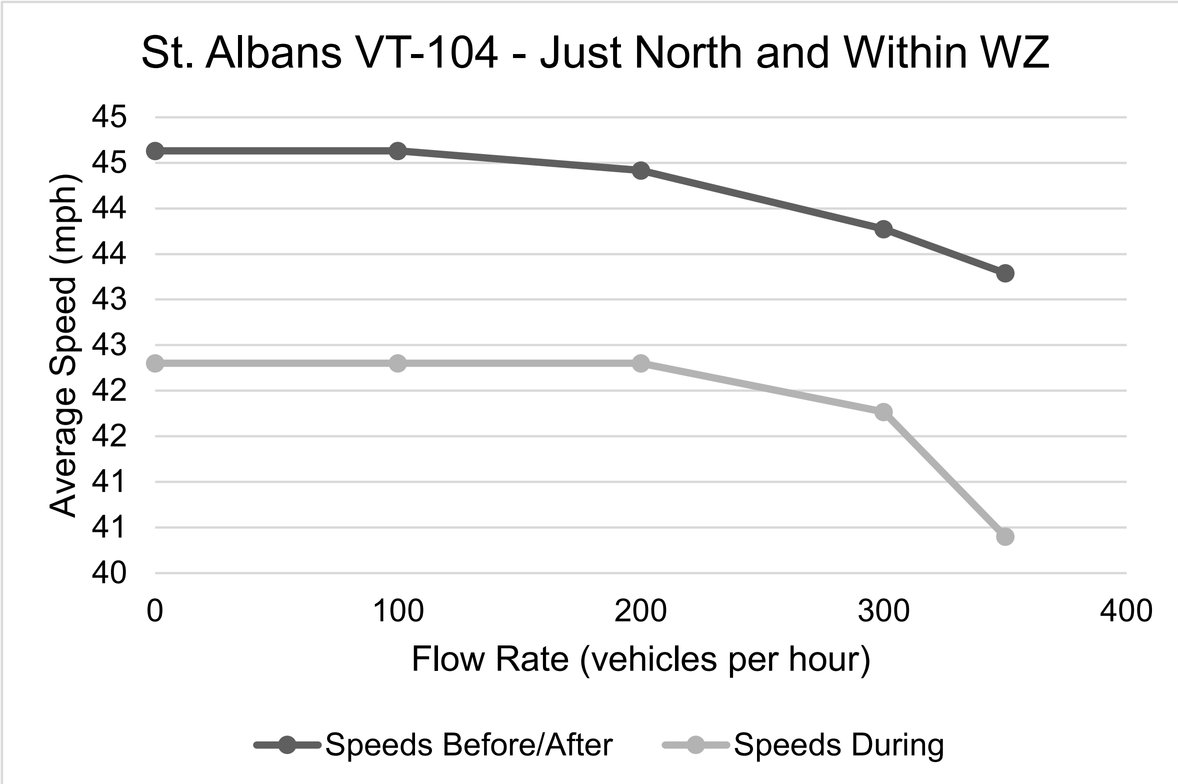


Figure 12 Speed-flow curves

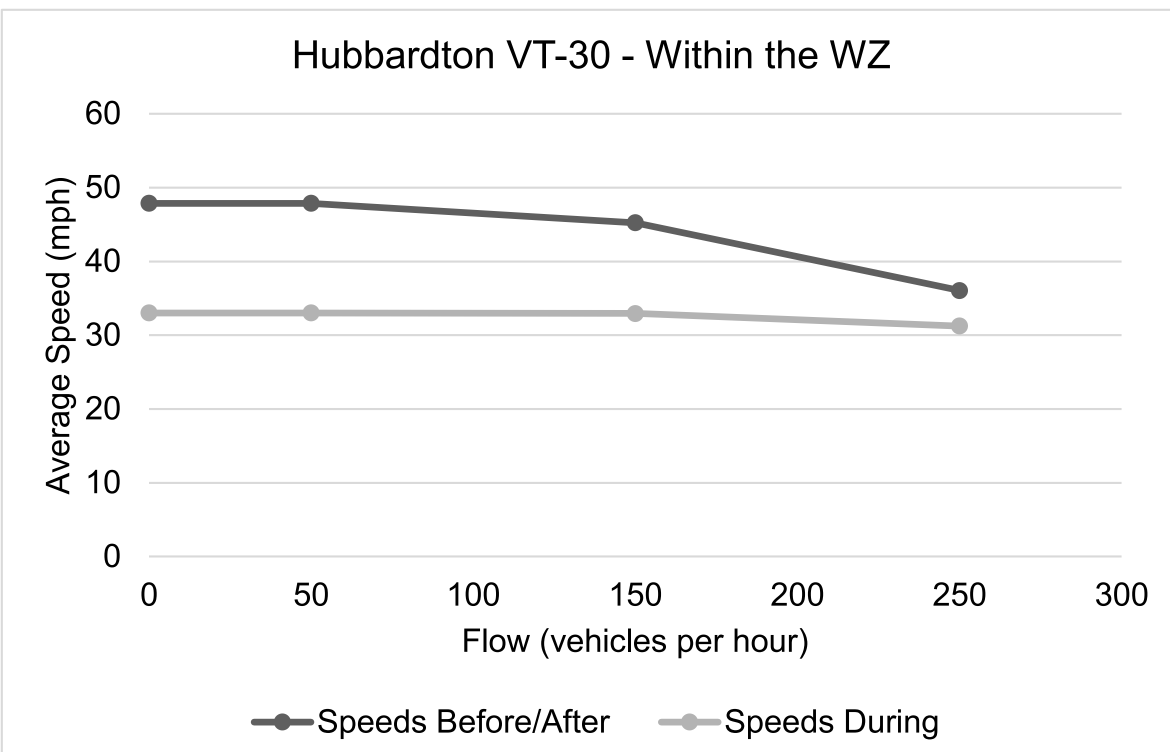


Figure 13 Speed-flow curves

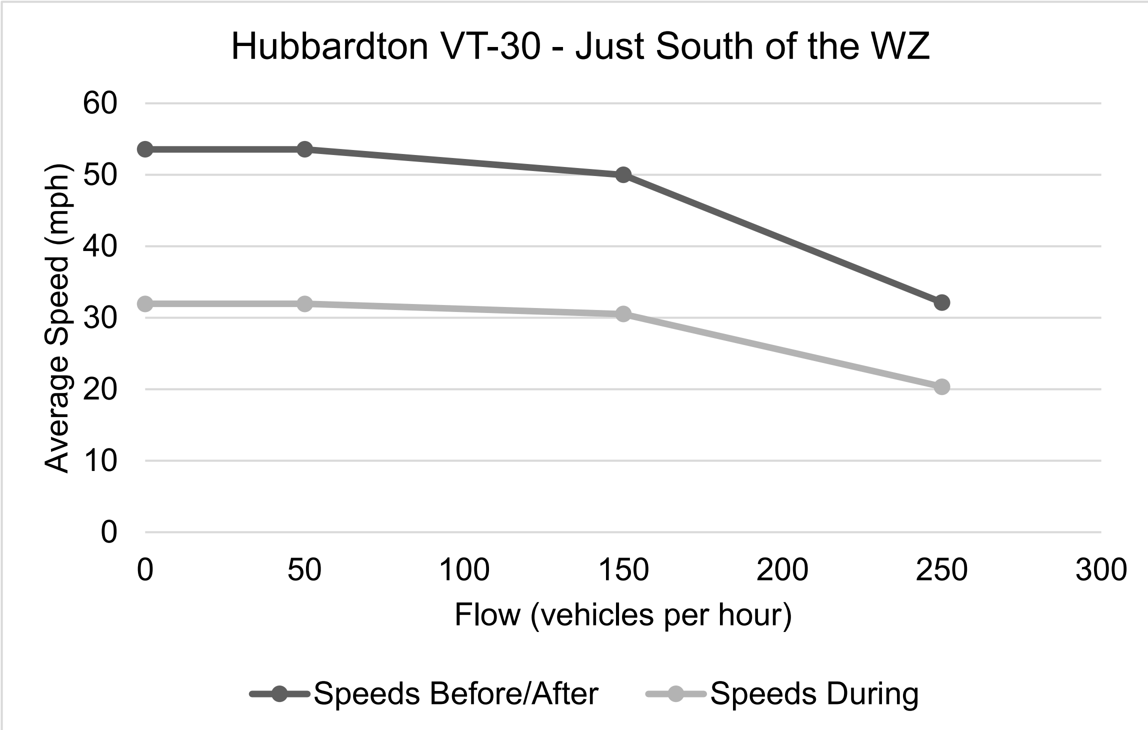


Figure 14 Speed-flow curves

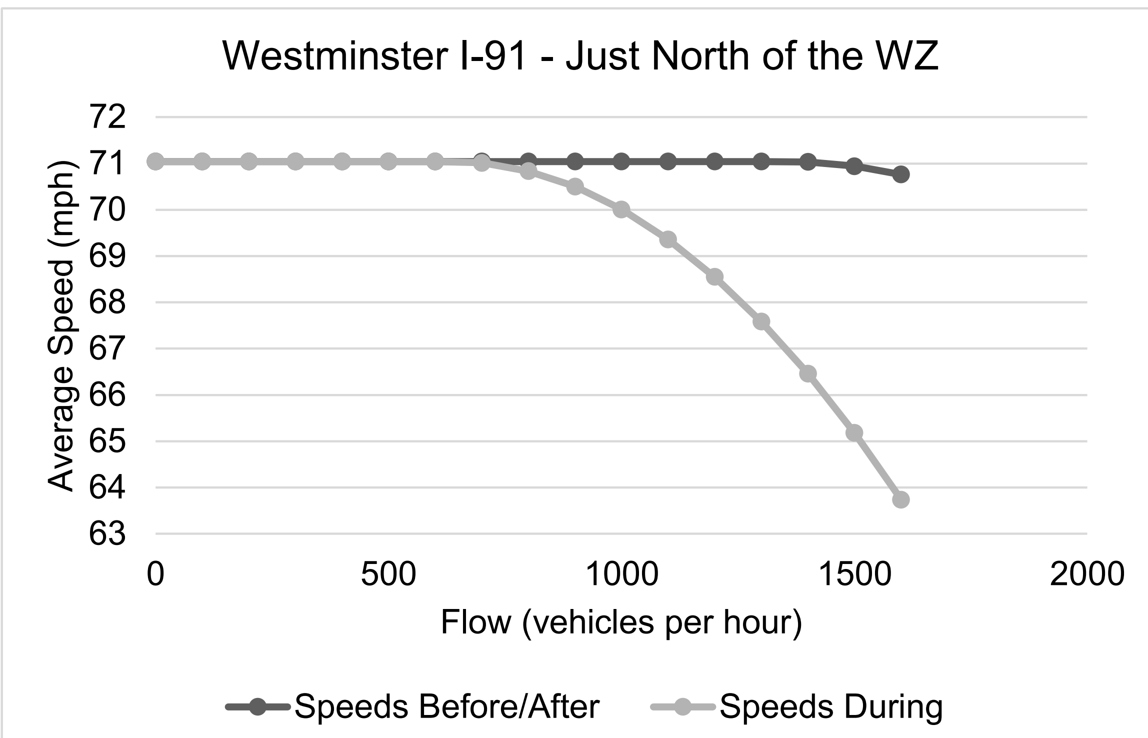


Figure 15 Speed-flow curves

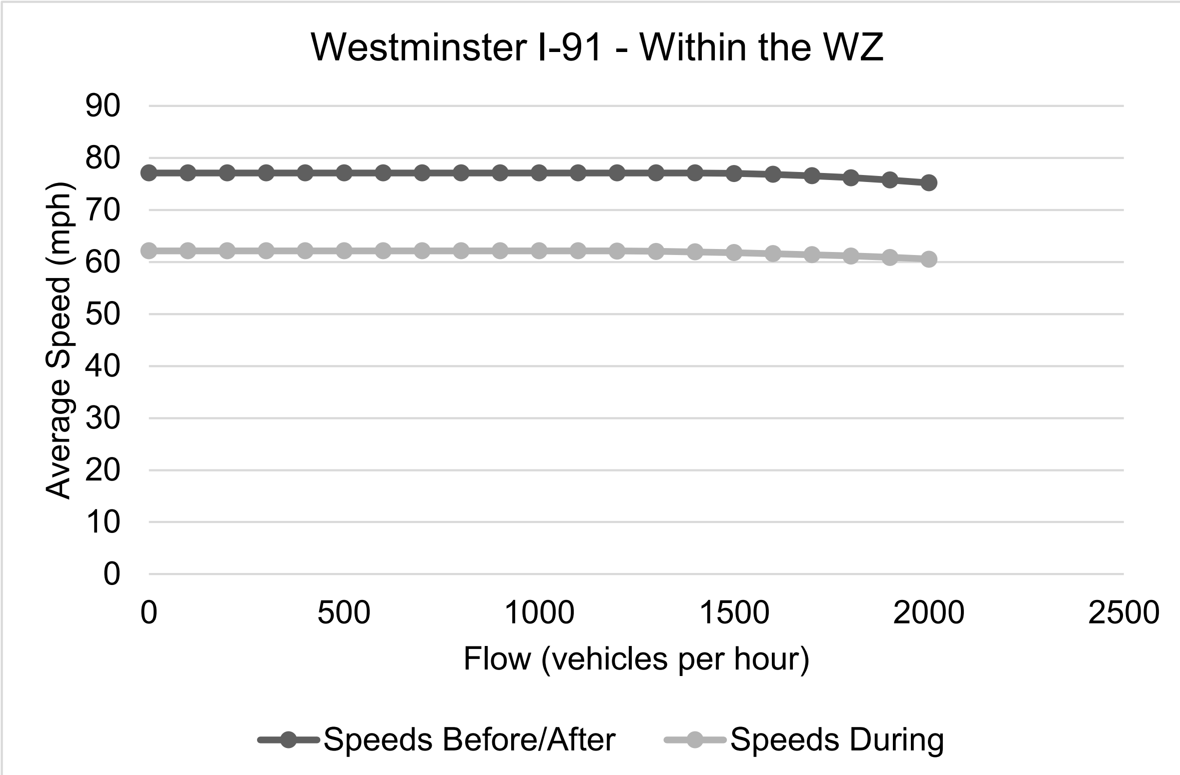


Figure 16 Speed-flow curves during and before/after the work zones

Capacities before/after and during the work zone implementations are provided in Table 6.

Table 6 Capacities (vehicles/hour) calculated at each MTMP deployment

Significance Level	Site	Location	before / after	during	loss
D	Hubbardton VT-30	Far North of the WZ	697	697	0%
D	Hubbardton VT-30	Within the WZ	409	311	24%
D	Hubbardton VT-30	Just South of the WZ	330	300	9%
D	Hubbardton VT-30	Far South of the WZ*	--	--	--
A	Westminster I-91	Far North of the WZ	2336	2336	0%
A	Westminster I-91	Just North of the WZ	3800	2870	24%
A	Westminster I-91	Within the WZ	3800	1728	55%
A	Westminster I-91	Far South of the WZ	3135	3135	0%
C	St Albans VT-104	Far North of the WZ*	--	--	--
C	St Albans VT-104	Just North and Within WZ	1050	651	38%
C	St Albans VT-104	Just South and Within WZ	590	367	38%
C	St Albans VT-104	Far South of the WZ*	--	--	--
*Connectivity issues prevented the state trailers from obtaining speed-flow data in certain locations with poor service					

Capacity losses within the work zones varied from 9% to 55%. The largest capacity reduction was within the Westminster I-91 work zone. This reduction is due to the combined effect of a reduction in free-flow speed through the work zone, a restriction on the number of through lanes available, and a loss of shoulder space for maneuvering. Interestingly, the reduction that occurred within the Hubbardton VT-30 work zone was less (24%), even though free-flow speeds were reduced and a temporary signal was in place.

Excess Delay

Using the speed-flow curves in Figure 11 through Figure 15, excess delay was calculated. Excess delay is the delay to drivers incurred by the capacity loss imposed by the work zone. This calculation of excess delay (ed) consisted of finding the average delay imposed by the reduced speeds at each volume *i*, weighted by the volume:

$$ed = (\sum_i (\frac{L}{s_{2i}} - \frac{L}{s_{1i}}) * vol_i) \,/ \sum_i vol_i$$

The results of these calculations are provided in Table 7.

Table 7 Excess delay (seconds) calculated at each MTMP deployment

Significance Level	Site	Location	Excess Delay (sec.)
D	**Hubbardton VT-30**	Far North of the WZ	0.00
D	**Hubbardton VT-30**	Within the WZ	5.6
D	**Hubbardton VT-30**	Just South of the WZ	62.4
D	**Hubbardton VT-30**	Far South of the WZ*	--
A	**Westminster I-91**	Far North of the WZ	0.00
A	**Westminster I-91**	Just North of the WZ	0.5
A	**Westminster I-91**	Within the WZ	2.8
A	**Westminster I-91**	Far South of the WZ	0.00
C	**St Albans VT-104**	Far North of the WZ*	--
C	**St Albans VT-104**	Just North and Within WZ	13.8
C	**St Albans VT-104**	Just South and Within WZ	13.4
C	**St Albans VT-104**	Far South of the WZ*	-

Average Travel Time and Total Delay

Travel time data was collected by creating pairs of travel-time sensors in the Iteris user interface, then matching the MAC addresses picked up by each device and measuring the time elapsed between matches. All travel times were averaged through a period of at least 2 weeks representing conditions before/after the work zone was implemented and during the work zone operation. A summary of these travel times, and the length of road segment represented by each, is provided in Table 8.

Table 8 Average travel times and total delay at each test site

Significance Level	Description		length (mi.)	travel time (s) before / after	travel time (s) during	total delay (s)
From Bluetooth sensors' travel-time data						
D	**Hubbardton VT-30**	NB	2.40	166.0	238.1	72.1
D	**Hubbardton VT-30**	SB	2.40	168.5	238.6	70.1
A	**Westminster I-91**	Long NB	3.40	172.4*	192.5	20.1
A	**Westminster I-91**	Short NB	2.20	109.0*	123.8	14.8
C	**St Albans VT 104**	NB	1.60	87.3	96.1	8.8
C	**St Albans VT 104**	SB	1.60	82.1	88.9	6.8
From Smart Work Zone data						
B	**Colchester I-89 Exit 17**	I-89N to I-89N	0.52	38	40	2.0
B	**Colchester I-89 Exit 17**	I-89N to US-2W	0.89	94	119	25.0
B	**Colchester I-89 Exit 17**	I-89N to US-7N	0.65	140	155	15.0
B	**Colchester I-89 Exit 17**	I-89S to I-89S	0.51	36	39	3.0
B	**Colchester I-89 Exit 17**	US-2E to I-89S	0.44	39	53	14.0
B	**Colchester I-89 Exit 17**	US-2/7N to US-7N	0.45	31	38	7.0
B	**Colchester I-89 Exit 17**	US-7S to I-89S	0.75	101	114	13.0
B	**Colchester I-89 Exit 17**	US-7S to US-2/7S	0.45	39	48	9.0
From RITIS probe vehicle data						
B	**Colchester I-89 Exit 17**	I-89N to I-89N	0.76	41.2	43.8	2.7
B	**Colchester I-89 Exit 17**	I-89N to US-2W	1.24	102.4	115.4	13.0
B	**Colchester I-89 Exit 17**	I-89N to US-7N	1.47	139.7	147.4	7.7
B	**Colchester I-89 Exit 17**	I-89S to I-89S	0.98	51.6	53.2	1.7
B	**Colchester I-89 Exit 17**	US-2E to I-89S	1.01	67.2	72.3	5.1
B	**Colchester I-89 Exit 17**	US-2/7N to US-7N	1.11	106.8	113.6	6.8
B	**Colchester I-89 Exit 17**	US-7S to I-89S	1.91	161.4	167.2	5.8
B	**Colchester I-89 Exit 17**	US-7S to US-2/7S	1.47	131.3	139.1	7.8
*Travel times inferred from free-flow speeds far north of the WZ						

The right most column shows the total delay, or the difference in average travel times that resulted from the implementation of the work zone at each site. Total delay varied from over 70 seconds at the Hubbardton VT-30 site to only about 2 seconds at the Colchester I-89 Exit 17 site for traffic traversing the work zone along I-89N or I-89S.

Control Delay

Control delay is measured by taking the difference between the total delay and the excess delay. For these calculations, the maximum values of the excess and total delay for each of the sites was used. The results of this calculation are shown in Table 9.

Table 9 Control delay at each MTMP deployment

Significance Level	Site	Maximum Total Delay (sec.)	Maximum Excess Delay (sec.)	Control Delay (sec.)
D	**Hubbardton VT-30**	72.1	62.4	9.7
A	**Westminster I-91**	20.1	2.8	17.3
C	**St Albans VT-104**	8.8	13.8	**-5.0**

The negative value for the St. Albans VT-104 site indicates that the work zone did not have the effect on travel times that was expected from the capacity reduction. This phenomenon is likely the result of the use of night work for this site. With most of the travel times occurring during the day, when the work zone had been returned to a non-work state, the impact of delays experienced overnight on the average travel times measured by the sensors was muted. This occurrence highlights the diminished impact that a work zone occurring only at nighttime has on delay.

The control delay represents the average delay that occurred beyond what was expected due to the capacity loss incurred by the work zone implementation. Overall, the St. Albans VT-104 site performed best, whereas the Westminster I-91 site performed worst, allowing an extra 17.3 seconds of delay per vehicle through the work zone, above the expected delay of only 2.8 seconds, which results primarily from a reduction in free-flow speed from 77.2 mph to 62.2 mph.

Travel Time Reliability

Travel time reliability is typically experienced more acutely by drivers than average delay. Therefore, in addition to quantifying average delay, travel time reliability was quantified for all work zone travel times in Table 8. There are multiple methods to represent travel time reliability. The travel time reliability represented as the 90th percentile of the travel-time distribution provides a measure of the near worst-case scenario travel time for a trip by indicating the travel time that is higher than 90% of travel times experienced for that trip. In other words, a metric that represents on time arrival 9 times out of every 10 trips. Reliability as both standard deviation and as 90th percentile were calculated for each travel time to observe how reliability changes with the work zone implementations. Table 10 contains a summary of the standard deviation and 90th percentile reliability metrics for each of the travel time distributions obtained.

Table 10 Travel time reliability, as standard deviation and 90th percentile

Significance	Description		travel-time reliability, as standard deviation (sec)			travel-time reliability, as 90th percentile (sec)		
			before / after	during	loss	before / after	during	loss
From Bluetooth sensors' travel-time data								
D	**Hubbardton VT-30**	NB	15.6	37.5	140%	175.8	312.0	77%
D	**Hubbardton VT-30**	SB	28.1	32.5	16%	182.0	319.0	75%
A	**Westminster I-91**	Long NB	6.9	7.5	9%	181.2	217.0	20%
A	**Westminster I-91**	Short NB	3.7	4.0	8%	113.7	141.0	24%
C	**St Albans VT 104**	NB	22.6	42.0	86%	105.3	129.9	23%
C	**St Albans VT 104**	SB	3.6	36.4	911%	87.7	97.0	11%
From Smart Work Zone data								
B	**Colchester I-89 Exit 17**	I-89N to I-89N	4	11	175%	43.1	54.1	25%
B	**Colchester I-89 Exit 17**	I-89N to US-2W	17	72	324%	115.8	211.2	82%
B	**Colchester I-89 Exit 17**	I-89N to US-7N	32	51	59%	181.0	220.3	22%
B	**Colchester I-89 Exit 17**	I-89S to I-89S	2	4	100%	38.6	44.1	14%
B	**Colchester I-89 Exit 17**	US-2E to I-89S	3	21	600%	42.8	79.9	86%
B	**Colchester I-89 Exit 17**	US-2/7N to US-7N	9	15	67%	42.5	57.2	35%
B	**Colchester I-89 Exit 17**	US-7S to I-89S	30	59	97%	139.4	189.5	36%
B	**Colchester I-89 Exit 17**	US-7S to US-2/7S	16	21	31%	59.5	74.9	26%
From RITIS probe vehicle data								
B	**Colchester I-89 Exit 17**	I-89N to I-89N	2.8	6.1	116%	44.7	51.6	15%
B	**Colchester I-89 Exit 17**	I-89N to US-2W	7.8	15.1	92%	112.5	134.8	20%
B	**Colchester I-89 Exit 17**	I-89N to US-7N	14.0	17.3	24%	157.6	169.5	8%
B	**Colchester I-89 Exit 17**	I-89S to I-89S	2.4	3.7	52%	54.7	57.9	6%
B	**Colchester I-89 Exit 17**	US-2E to I-89S	3.4	5.4	59%	71.6	79.3	11%
B	**Colchester I-89 Exit 17**	US-2/7N to US-7N	18.8	23.1	23%	130.8	143.1	9%
B	**Colchester I-89 Exit 17**	US-7S to I-89S	16.1	22.7	41%	182.0	196.2	8%
B	**Colchester I-89 Exit 17**	US-7S to US-2/7S	14.1	19.2	36%	149.3	163.7	10%

Note how the use of the 90th percentile as a measure of travel time reliability filters out some of the outliers in the data that have an effect on the standard deviation. Therefore, the change in reliability measured by the 90th percentile of the travel time distributions is lower than what is shown by the change in standard deviation. Outlier travel times at the high end indicate travelers who may have stopped somewhere between the two sensors, perhaps simply pulling off onto the shoulder, or making a stop at a service station. These outliers should not be factored into the reliability measurement, so this omission is helpful. The 90th percentile provides a more reasonable number to work with, and a good target upon which to base a maximum acceptable threshold.

Loss of travel-time reliability varied from 6% along I-89 southbound at the Colchester I-89 Exit 17 site, to around 80% at other sites.

Buffer Index & Acceptable Thresholds

Although travel time reliability serves as a useful performance measure, it remains difficult to relate the travel time reliability metrics to the end user. When it comes to mobility, the traveler wants to be able to plan for how long the trip will take. To account for the travel time reliability, a buffer index provides a measure of the additional time needed to account for travel time variability above and beyond the typical travel time. The buffer index measure is represented as a decimal percentage and can be applied to the travel time to calculate the buffer time needed for the trip. For instance, a buffer index of 0.20 for a trip that has a typical travel time of 5 minutes would have a buffer time of 1 minute. Calculated with the 90th percentile reliability, this means that the user should allot 6 minutes of total travel time for the trip for an on time arrival 90% of the time. Calculated across the range of sites, the buffer index for the daily data interval was estimated to be 0.03 to 0.43.

For each of the directions or origin destination pairs for each site, the daily buffer index was calculated. This quantification of the buffer index as a measure to account for reliability provides a metric that is more specific to the context and can be compared across work zones. Applying the buffer index, a threshold for each direction or origin-destination pair for each site can be calculated. This threshold provides indication of the acceptable travel time based on the site's travel time, reliability, and buffer index. A variation on the planning time metric, the travel time threshold is relatable to the traveling public.

Table 11. Daily Buffer Index and Acceptable Travel Time Threshold

Significance	Description		average travel time (s)			travel-time reliability, as 90th percentile (sec)			Daily Buffer Indices	Acceptable Daily Threshold (s)
			before / after	during	total delay	before / after	during	loss		
From Bluetooth sensors' travel-time data										
D	**Hubbardton VT-30**	NB	166	238.1	72.1	175.8	312	77%	0.43	252.2
D	**Hubbardton VT-30**	SB	168.5	238.6	70.1	182	319	75%	0.42	257.7
A	**Westminster I-91**	Long NB	172.4	192.5	20.1	181.2	217	20%	0.12	202.3
A	**Westminster I-91**	Short NB	109	121.5	12.5	113.7	141	24%	0.11	126.7
C	**St Albans VT 104**	NB	87.3	96.1	8.8	105.3	129.9	23%	0.10	115.9
C	**St Albans VT 104**	SB	82.1	88.9	6.8	87.7	97	11%	0.08	95.0
From Smart Work Zone data										
B	**Colchester I-89 Exit 17**	I-89N to I-89N	38	40	2	43.1	54.1	25%	0.05	45.4
B	**Colchester I-89 Exit 17**	I-89N to US-2W	94	119	25	115.8	211.2	82%	0.27	146.6
B	**Colchester I-89 Exit 17**	I-89N to US-7N	140	155	15	181	220.3	22%	0.11	200.4
B	**Colchester I-89 Exit 17**	I-89S to I-89S	36	39	3	38.6	44.1	14%	0.08	41.8
B	**Colchester I-89 Exit 17**	US-2E to I-89S	39	53	14	42.8	79.9	86%	0.36	58.2
B	**Colchester I-89 Exit 17**	US-2/7N to US-7N	31	38	7	42.5	57.2	35%	0.23	52.1
B	**Colchester I-89 Exit 17**	US-7S to I-89S	101	114	13	139.4	189.5	36%	0.13	157.3
B	**Colchester I-89 Exit 17**	US-7S to US-2/7S	39	48	9	59.5	74.9	26%	0.23	73.2
From RITIS probe vehicle data										
B	**Colchester I-89 Exit 17**	I-89N to I-89N	41.2	43.8	2.7	44.7	51.6	15%	0.07	47.6
B	**Colchester I-89 Exit 17**	I-89N to US-2W	102.4	115.4	13	112.5	134.8	20%	0.13	126.8
B	**Colchester I-89 Exit 17**	I-89N to US-7N	139.7	147.4	7.7	157.6	169.5	8%	0.06	166.3
B	**Colchester I-89 Exit 17**	I-89S to I-89S	51.6	53.2	1.7	54.7	57.9	6%	0.03	56.5
B	**Colchester I-89 Exit 17**	US-2E to I-89S	67.2	72.3	5.1	71.6	79.3	11%	0.08	77.0
B	**Colchester I-89 Exit 17**	US-2/7N to US-7N	106.8	113.6	6.8	130.8	143.1	9%	0.06	139.1
B	**Colchester I-89 Exit 17**	US-7S to I-89S	161.4	167.2	5.8	182	196.2	8%	0.04	188.5
B	**Colchester I-89 Exit 17**	US-7S to US-2/7S	131.3	139.1	7.8	149.3	163.7	10%	0.06	158.2

Examining a sample of travel time against the acceptable daily threshold established for the Westminster (Significance Level A) site provides an example of the metrics applied to a work zone. The average travel time for a two-week period with the work zone in place and the variability of average daily travel time are depicted in Figure 17. In addition, the daily threshold established for the site, accounting for the travel time, reliability, and buffer index, is also depicted. In instances where you have a steady stream of travel time information being collected through the work zone, a clear picture of exceedances above this acceptable daily threshold could be monitored. Metrics like number of exceedances and/or duration of exceedance would prove useful.

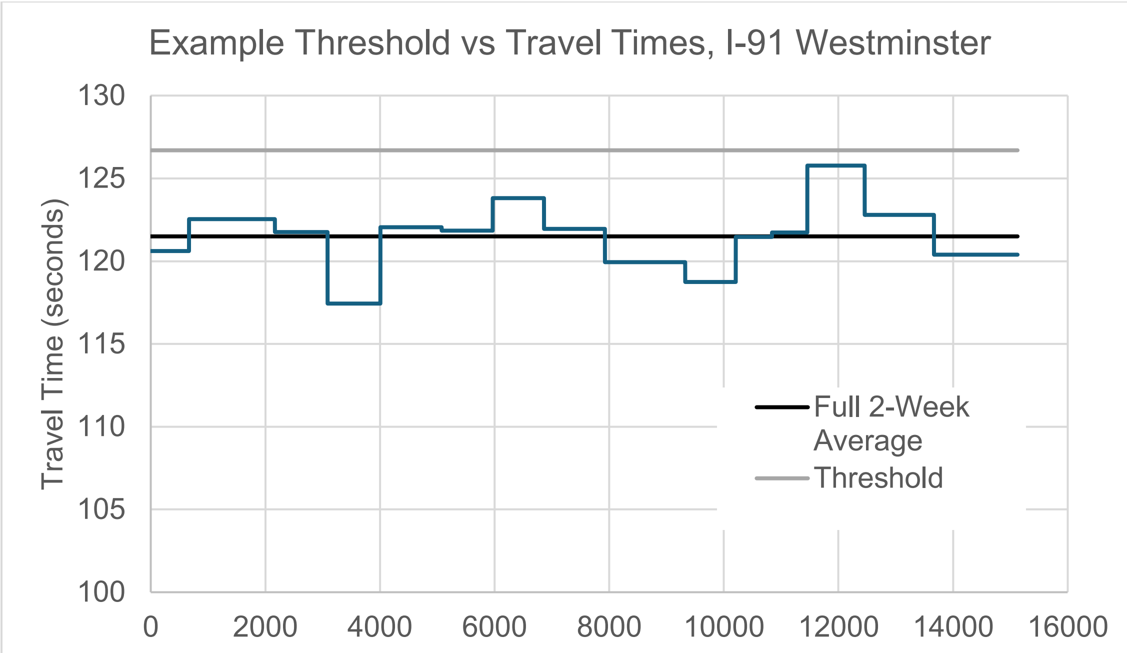


Figure 17. Westminster Daily Travel Time Threshold Example

Examining the travel time for the Westminster site at a different time scale provides another example of the metrics applied to a work zone and demonstrates the influence of the selected time interval on the application. The average travel time for a two-week period with the work zone in place and the variability of average hourly travel times are depicted in Figure 18. In addition, an hourly travel time threshold established for the site is also depicted, based on the hourly travel time, reliability, and buffer index. Again, in instances where a steady stream of travel time information is provided, a clear picture of exceedances above the acceptable threshold established for hourly travel times could be monitored and metrics like number of exceedances or duration of exceedance would prove useful.

It is important to note that the threshold established in this case requires adjustment to be appropriate for data parsed at hourly intervals with buffer indices and hourly thresholds that reflect the hourly interval. Hourly buffer indices were estimated to range from 0.07 to 0.87 across the sites with associated acceptable hourly thresholds shown in Table 12. Depending on traffic volumes and penetration rates of the data collection methodology, the appropriate interval at which the data are parsed and evaluated may need to be on a case-by-case basis.

Table 12. Hourly Buffer Index and Acceptable Hourly Threshold

Significance	Description		Hourly Buffer Indices	Acceptable Hourly Threshold (s)
	From Bluetooth sensors' travel-time data			
D	**Hubbardton VT-30**	NB	0.87	328.5
D	**Hubbardton VT-30**	SB	0.83	333.4
A	**Westminster I-91**	Long NB	0.23	223.5
A	**Westminster I-91**	Short NB	0.23	139.8
C	**St Albans VT 104**	NB	0.20	126.5
C	**St Albans VT 104**	SB	0.17	102.2
	From Smart Work Zone data			
B	**Colchester I-89 Exit 17**	I-89N to I-89N	0.11	47.6
B	**Colchester I-89 Exit 17**	I-89N to US-2W	0.53	177.4
B	**Colchester I-89 Exit 17**	I-89N to US-7N	0.21	219.8
B	**Colchester I-89 Exit 17**	I-89S to I-89S	0.17	45.0
B	**Colchester I-89 Exit 17**	US-2E to I-89S	0.72	73.5
B	**Colchester I-89 Exit 17**	US-2/7N to US-7N	0.45	61.7
B	**Colchester I-89 Exit 17**	US-7S to I-89S	0.26	175.3
B	**Colchester I-89 Exit 17**	US-7S to US-2/7S	0.46	87.0
	From RITIS probe vehicle data			
B	**Colchester I-89 Exit 17**	I-89N to I-89N	0.13	50.6
B	**Colchester I-89 Exit 17**	I-89N to US-2W	0.25	141.1
B	**Colchester I-89 Exit 17**	I-89N to US-7N	0.11	175.0
B	**Colchester I-89 Exit 17**	I-89S to I-89S	0.07	58.3
B	**Colchester I-89 Exit 17**	US-2E to I-89S	0.15	82.5
B	**Colchester I-89 Exit 17**	US-2/7N to US-7N	0.13	147.5
B	**Colchester I-89 Exit 17**	US-7S to I-89S	0.07	195.1
B	**Colchester I-89 Exit 17**	US-7S to US-2/7S	0.12	167.0

In the case of the hourly example, there are five exceedances of the hourly threshold in a two-week period for the site. Each of these exceedances occur in the middle of the night with extremely low volumes of traffic. For instance, the first exceedance occurs at 1:00 AM and only four travel times were recorded, with two of the four going very slowly through the work zone resulting in an exceedance of the hourly threshold. This outcome is noteworthy in that although the hourly data may be appropriate for this location on the interstate with relatively high volumes of traffic, when volumes are low the influence of just one or two operators may skew the outcomes. As such, it will be important to select an appropriate time interval for monitoring assessments that are sensitive to anticipated traffic volumes and to monitor the volume sampled along with travel time delay metrics.

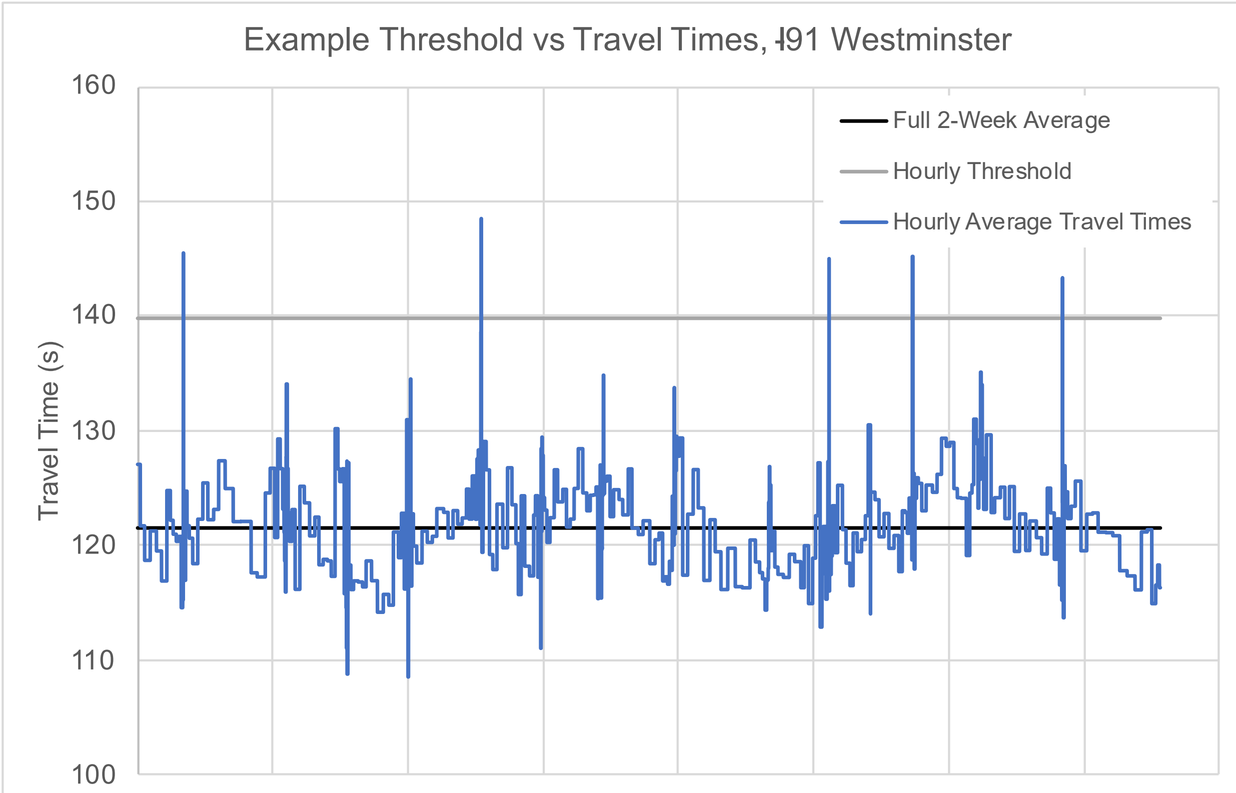


Figure 18. Westminster Hourly Travel Time Threshold Example

Conclusions and Recommendations

The components of travel time reliability have emerged as key performance measures and metrics of mobility. These metrics can be applied specifically to the case of work zones as demonstrated through the methodology development and study sites above. These metrics provide an end user relatable, context-sensitive solution to work zone travel time delay. The one size fits all metrics of work zone delay that have been held as the standard for maintaining one-way traffic and mobility during construction have provided acceptable thresholds for work zone planning and design purposes, but not translated into measurable, real-time, and relatable metrics for work zones during the construction phase. Following review of the outcomes for each of the study sites and assessment of the effectiveness of the travel time delay measures at quantifying delay incurred across a multitude of work zone contexts, a set of recommended approaches to benchmark acceptable work zone delay and measure work zone delay for compliance have been assembled.

Proposed Delay Metric and Application

In terms of mobility performance measures, travel time reliability metrics proved most effective at quantifying work zone mobility across test sites, delivering metrics that were both quantitative and easy to understand. A travel time reliability approach to mobility performance measurement for work zones builds on an expanding body of research and is enabled by technological advances in data collection to support such measures.

This approach entails establishing an acceptable travel time threshold for a work zone, providing a relatable metric for work zone performance that is rooted in the typical travel time, travel time reliability, and context appropriate buffer index for Vermont's work zones. This acceptable threshold can then serve to quantify number and duration of exceedances for a work zone. This approach has the potential to enable proactive management by providing near real-time feedback and alerting resident engineers and contractors to work zone performance issues.

There were a number of lessons learned through the data collection process, as discussed in previous sections. These lessons informed preliminary recommendations for context sensitive data collection methodologies to support measuring travel time reliability in work zones in Vermont. Table 13 presents the suggested data collection method for each project significance level at different anticipated traffic levels – measured as annual average daily traffic (AADT). Data coverage in Vermont's rural context, anticipated data penetration of Bluetooth pairs (i.e., two MTMPs deployed in series) and RITIS probe data, and the level of effort, resources, and maintenance required for deploying each data collection method were considered.

Table 13 Recommended Data Collection Methods

Recommended Data Collection Methods					
	AADT				
Level	**<5000**	**>5000**	**>10000**	**>15000**	**>20000**
A	RITIS	RITIS	RITIS	RITIS	RITIS
B	BT Pairs	RITIS	RITIS	RITIS	RITIS
C	Other	BT Pairs	BT Pairs	RITIS	RITIS
D	Other	Other	BT Pairs	RITIS	RITIS

The range of buffer indices observed across the study sites helped to inform a framework for acceptable, context sensitive buffer indices to consider in establishing the acceptable travel time thresholds for any given Vermont work zone. The buffer index is indicative of the percent of additional time above and beyond the typical travel time that is deemed acceptable for the work zone, developed in consideration of on time arrival 9 out of 10 times.

Within the framework, any given Vermont work zone would allow for a range from 10% to 40% above and beyond typical daily travel times for the facility, as proposed in Table 14. Any given Vermont work zone would allow for a range from 20% to 80% above and beyond typical hourly travel times for the facility, as proposed in Table 15. The appropriate daily or hourly buffer index is adjusted to context based on the work zone level of significance and anticipated traffic volumes. For example, the acceptable travel time threshold for a Significance Level D project with low anticipated traffic volumes would allow for 40% above the typical daily travel time for that facility whereas a Significance Level B project with over 5,000 vehicles per day would allow for 15% above and beyond typical daily travel time. To establish the acceptable travel time threshold for a work zone, the 90th percentile travel time for the facility is captured prior to the work zone being in place and the appropriate daily or hourly buffer index is applied by multiplying [1+BI].

Table 14 Daily Buffer Indices (BI)

Buffer Indices (BI)					
	AADT				
Level	<5000	>5000	>10000	>15000	>20000
A	0.10	0.10	0.10	0.10	0.10
B	0.15	0.15	0.10	0.10	0.10
C	0.20	0.15	0.15	0.10	0.10
D	0.40	0.35	0.30	0.25	0.25

Table 15. Hourly Buffer Indices (BI)

Buffer Indices (BI)					
	AADT				
Level	<5000	>5000	>10000	>15000	>20000
A	0.20	0.20	0.20	0.20	0.20
B	0.30	0.30	0.20	0.20	0.20
C	0.40	0.30	0.30	0.20	0.20
D	0.80	0.70	0.60	0.50	0.50

It is important to recognize that this framework for buffer indices was established based on only a small subset of work zones with specific project types, maintenance of traffic approaches, capacity reductions, etc. Additionally, the daily and hourly data intervals are demonstrated with the above examples but should be investigated further. As such, this framework should be tested across a broader range of work zones to refine the appropriate indices for establishing acceptable travel time thresholds.

Implementation Guide

The following process outlines the proposed procedures for establishing, collecting, and monitoring travel time reliability measures for work zones in Vermont.

1. Consult Table 13 to determine the appropriate data collection method.
    a. **RITIS:** Check RITIS data coverage for suitability. Use RITIS data if it is available, the defined segments align with project limits and anticipated work zone traffic influence area, and the data quality and resolution are sufficient to support baseline and continuous travel time monitoring.
    b. **Bluetooth pair:** Deploy Bluetooth devices in series with at least one device upstream, one device within, and one device downstream of work zone operations. Depending on work zone configuration, project length, project duration, and anticipated influence area, consider strategic spacing of devices to capture travel times along segments of the work zone.
    c. **Other:** Use an agreed upon measurement approach that is suitable for the work zone. Depending on the project work zone and anticipated mobility impacts, a proxy performance measure or periodic personnel-based data collection may be appropriate.
2. Perform data collection and reporting.
    a. Measure travel times through the corridor before the work zone is in place. At least two weeks of data collection prior to establishing work zone should be considered.
    b. Calculate the baseline 90th percentile travel time reliability.
    c. Calculate the acceptable threshold by multiplying the 90th percentile by [1 + BI] using Table 14 for daily intervals or Table 15 for hourly intervals.
    d. Measure average travel times continuously during work zone implementation and compare to the threshold.
    e. If the average travel time exceeds the threshold, calculate the amount of time elapsed before the average travel time goes back down below the threshold.
3. Supplemental monitoring

a. Incident, weather, and work zone operation logs should be consistently recorded to support interpretation of mobility performance data.

Key Considerations

There are a few key considerations to account for in standardizing the approach to a travel time reliability performance measure for work zones.

There are some sites where there are limitations on the placement of roadside data collection equipment. Although in this process, with cooperation from resident engineers and contractors on each project, acceptable locations for equipment were sited, this can pose a barrier to the necessary data collection to establish benchmarks and monitor for compliance. Early consideration of the type of data collection appropriate to the site and context will be crucial (i.e., TMP Checklist consideration). Additionally, data collection methods should be incorporated into traffic control plans early in their development to allocate appropriate resources. Related, different devices have different criteria for mounting location and height, which is particularly relevant when considering the temporary nature of these mobile deployments. The MTMPs were specifically designed to mount the devices at their appropriate height. Specific device standards for deployment should be consulted.

Poor network connectivity or cellular data coverage can have implications for data collection. Many of the devices, including the Bluetooth devices and state trailers employed in this study, prefer to be connected directly to the network to provide near real-time data streams and data archiving. Additionally, not all locations and roadways are covered in the RITIS data resources. Thus, coverage for a site, whether from RITIS resources or network connectivity, should be considered early in the process. Connectivity can prove to be a major obstacle for many projects across Vermont.

As encountered in data collection for this study, the temporal data aggregation for measures of mobility and exposure should be decided upon and consistent. Although hourly aggregation is likely sufficient, data are available at shorter increments like 1-, 5-, and 15-minute intervals. Aggregation at 15-minute intervals may provide an appropriate level of disaggregation to identify peak periods that exceed the acceptable threshold while balancing the higher resolution data archiving and storage considerations.

The length of travel time segments is another key consideration for evaluating these measures. For data collection methodology leveraging RITIS, the segmentation of the travel time corridors may be fixed or customized. For roadside Bluetooth device data collection, the siting of devices should be considered carefully to develop reasonable segmentation while balancing the feasibility of equipment placement. Ideally, the segments represent upstream, within work zone, and downstream effects of the work zone in both directions. As such, analysis conducted ahead of the project should be consulted to identify the work zone limits, limits of anticipated work zone influence, and potential spacing between devices. This way, upstream and downstream effects of the work zone are captured in the travel time evaluation. For long work zones, multiple segments or pairs may be reasonable to be able to isolate issues within the work zone. States, like New Hampshire, stipulate a half mile spacing for travel time data collection equipment, while others, like Texas, provide guidance that indicates spacing of devices is project specific.

Given the varied data penetration rates between roadside travel time measurements using Bluetooth technology and probe data from RITIS, it may be advisable to collect volume and speed data as a standard practice in most work zones. This is especially pertinent for those work zones where RITIS data is leveraged to evaluate the travel time reliability metrics. It is generally understood that the RITIS data provides a sample of approximately 5 to 7% of the traffic stream through its assembly of various data vendor devices. Having on the ground exposure data to help validate the data gathered from RITIS and extrapolate the travel time experience based on volume will provide a means for aggregating the impact of any travel time delay or threshold exceedance.

Next Steps

A more appropriate and context sensitive approach to evaluating acceptable delay in work zones was developed based on advances in the field of travel time reliability, the suite of metrics associated with reliability, and the technology enabling measurement of such metrics. With this recommended approach, each project will establish the acceptable travel time threshold for each work zone based on its travel time reliability without the work zone in place and its associated acceptable buffer index according to the significance level and traffic volume for the facility.

Recognizing the limited sample of study sites that informed the proposed framework for quantifying delay through Vermont’s work zones, it is recommended that the methodology be field tested across a greater number of work zones. Data from RITIS can be leveraged to conduct these evaluations by stepping through the procedure for a selection of work zones that have been implemented over the past 2 to 3 years. Data extracted from a two-week period prior to the work zone being in place should be processed to set the threshold by evaluating the travel time reliability for the site and applying the appropriate buffer index for the project characteristics. Data from the active construction period should then be processed and compared against the threshold, recording the number of exceedances and duration of exceedances. Once compiled, these results should be reviewed against the recommended framework to make any adjustments to the proposed approach.

Based on the directive from FHWA to identify mobility performance measures for work zones, it is anticipated that the proposed framework will be tested alongside another mobility performance metric for work zones over the upcoming construction seasons to evaluate the utility of each metric and further refine the methodology to implement. The implementation of these metrics and lessons learned from the process will inform future updates to the *Vermont Work Zone Safety and Mobility Policy and Guidance* and *Vermont Standard Specifications for Construction*.

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