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Evaluation of MDOT's Methodology for Estimating Work Zone User Delay Times & Costs

Final Report

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16. Abstract Work zones are essential for maintaining and improving transportation infrastructure; however, they often cause significant operational impacts and increased road user costs. The Michigan Department of Transportation (MDOT) currently relies on the Construction Congestion Cost (CO3) tool, an Excel-based work zone analysis framework originally developed in the late 1990s to estimate road users' delay and cost. Although the CO3 tool has historically supported preliminary work zone traffic analysis and user delay estimation, its simplified deterministic assumptions, limited representation of traffic dynamics, and outdated computational processes motivated the need for an enhanced analytical framework. This report presents the development, calibration, validation, and implementation of the Michigan Predictive Analysis of Congestion and its Effects (MiPACE) framework, an integrated work zone traffic analysis and operational evaluation tool developed to improve the representation of traffic behavior under freeway, multilane highway, and flagging work zone conditions. The tool integrates Cell Transmission Model (CTM)-based traffic simulation, calibrated speed-capacity relationships, queue and delay estimation, ramp interaction analysis, detour and diversion modeling, and operational performance evaluation within a unified analytical environment.					
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Executive Summary

Work zones are essential for maintaining and improving transportation infrastructure; however, they often introduce significant operational impacts, including congestion, queue formation, travel delays, speed reductions, diversion behavior, and increased road-user costs. The Michigan Department of Transportation (MDOT) has historically relied on the Construction Congestion Cost (CO3) tool, an Excel-based work zone analysis tool originally developed in the late 1990s to estimate user-delay costs. Although the CO3 tool has been useful for planning-level evaluations, its simplified deterministic assumptions, limited representation of dynamic traffic behavior, outdated computational structure, and restricted ability to evaluate complex operational scenarios highlighted the need for a more advanced and operationally realistic analytical platform.

To address these limitations, this study developed the Michigan Predictive Analysis of Congestion and its Effects (MiPACE), an integrated work zone traffic analysis and operational evaluation framework designed to improve the representation of traffic behavior under freeway, multilane highway, and flagging work zone conditions. The developed framework integrates Cell Transmission Model (CTM)-based traffic simulation, calibrated speed-capacity relationships, multi-regime traffic-flow modeling, queue and delay estimation, ramp interaction analysis, diversion and detour modeling, and operational performance evaluation within a unified analytical environment.

The study was conducted in two major phases. The first phase focused on evaluating existing work zone traffic analysis tools used by state Departments of Transportation (DOTs) and identifying MDOT's user needs for an enhanced analytical framework. Activities included a literature review, user surveys, and focus group discussions with MDOT personnel, comparative assessments of existing tools, and identification of operational limitations associated with current work zone traffic analysis practices. Findings from the first phase guided the second phase's development, which focused on enhancing traffic modeling capabilities through additional work zone traffic data collection and substantial methodological and functional improvements as compared to CO3. Major enhancements included expanded capabilities for data input, traffic operations analysis, ramp and detour analysis, scenario evaluation, and output visualization.

The second phase focused on the development, calibration, validation, and implementation of MiPACE for analyzing freeway, multilane highway, and flagging work zone operations. Major activities included field data collection, model development, calibration, validation, and operational testing. Multiple freeway work zone projects across Michigan were used to support model development and validation under varying operational and congestion conditions. These datasets were integrated to develop Michigan-specific speed-capacity relationships and to validate the performance of the CTM-based simulation methodology. The developed MiPACE framework integrates roadway geometry, traffic demand estimation, CTM simulation, diversion analysis, queue propagation modeling, delay estimation, and automated reporting within a single operational workflow. The framework produces both numerical and graphical outputs, including speed

profiles, queue evolution, congestion heatmaps, travel-time estimates, diversion patterns, and road-user cost analyses to support operational evaluation and transportation decision-making.

The developed MiPACE tool incorporates roadway geometric and operational components derived from the Manual on Uniform Traffic Control Devices (MUTCD), including Advanced Warning Areas (AWA), Transition Areas (TA), Activity Areas (AA), taper sections, buffer spaces, lane-closure configurations, and operational work zone boundaries. These components were integrated into the CTM simulation environment to provide a more realistic representation of traffic progression and work zone operations.

MiPACE utilizes a four-regime flow-density framework representing free-flow, transitional, breakdown, and fully congested traffic conditions observed in freeway work zones. The methodology also incorporates normalization procedures to establish representative traffic-flow relationships for multiple freeway work zone configurations, including lane closures, shoulder closures, crossover operations, lane-shift scenarios, and detour-related operational conditions. For multilane highway facilities, a scalable modeling approach was developed by integrating Highway Capacity Manual (HCM)-based base-condition procedures with calibrated freeway work zone reduction patterns to establish representative operational models for multilane highway work zones.

The framework further integrates ramp merge/diverge logic and dynamic diversion estimation procedures to represent operational impacts associated with freeway ramps, alternative routes, and detour operations during active work zone conditions. Detour-route travel times were estimated using segment-level travel-time and intersection-control-delay analyses based on roadway geometry, intersection configuration, and traffic-control characteristics. Dynamic diversion behavior was estimated by comparing mainline traffic conditions with the operational performance of alternative detour routes throughout the simulation period.

Validation results demonstrated that MiPACE successfully captured observed freeway work zone traffic behavior under varying operational conditions, including severe congestion, ramp interactions, and detour operations. The framework accurately represented the evolution of congestion, queue propagation, travel-time variation, speed reduction, and delay impacts across multiple freeway work-zone corridors. The integration of Google API (Application Programming Interface) datasets, RITIS (Regional Integrated Transportation Information System) observations, and field measurements further improved the reliability and robustness of the calibration and validation procedures.

Overall, this study provides an enhanced and operationally realistic framework for work zone traffic analysis under dynamic traffic conditions. Compared with traditional deterministic methodologies, the developed MiPACE substantially improves the representation of work zone traffic operations and establishes a scalable analytical platform for future work zone analysis, congestion evaluation, operational performance assessment, and transportation decision-support applications for MDOT and other transportation agencies.

List of Abbreviations

AA	Activity Area
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AIC	Akaike Information Criterion
API	Application Programming Interface
ATRI	American Transportation Research Institute
AWA	Advanced Warning Area
AWSC	All-Way Stop-Controlled
BCA	Benefit-Cost Analysis
BIC	Bayesian Information Criterion
BLS	Bureau of Labor Statistics
BQL	Backup Queue Length
CCS	Continuous Count Station
CCTV	Closed-Circuit Television
CFL	Courant–Friedrichs–Lewy
CO3	Construction Congestion Cost
CPI	Consumer Price Index
CTM	Cell Transmission Model
DOT	Department of Transportation
DTW	Dynamic Time Warping
ESRI	Environmental Systems Research Institute
FD	Fundamental Diagram
FFS	Free-Flow Speed
FHWA	Federal Highway Administration
GIS	Geographic Information System
GUI	Graphical User Interface
HCM	Highway Capacity Manual
HERS	Highway Economic Requirements System
HERS-ST	Highway Economic Requirements System – State Version
HQL	Horizontal Queue Length
IRI	International Roughness Index
ITS	Intelligent Transportation System
LCCA	Life Cycle Cost Analysis
LCSI	Lane Closure Severity Index
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MBE	Mean Bias Error

MDOT	Michigan Department of Transportation
MiPACE	Michigan Predictive Analysis of Congestion and its Effects
MoDOT	Missouri Department of Transportation
MOT	Maintenance of Traffic
MUTCD	Manual on Uniform Traffic Control Devices
MVDS	Microwave Vehicle Detection System
NCHRP	National Cooperative Highway Research Program
NSE	Nash–Sutcliffe Efficiency
PA	Passenger Automobile
PCE	Passenger Car Equivalent
PICP	Prediction Interval Coverage Probability
QDR	Queue Discharge Rate
QL	Queue Length
RMSE	Root Mean Square Error
RITIS	Regional Integrated Transportation Information System
RTMS	Remote Traffic Microwave Sensor
RUC	Road User Cost
SAFEZONE	Safety Alerts For Work ZONES
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TA	Transition Area
TDMS	Traffic Data Management System
TRD	Total Ramp Density
TRDF	Texas Research and Development Foundation
TWSC	Two-Way Stop-Controlled
USDOT	United States Department of Transportation
VBA	Visual Basic for Applications
VHD	Vehicle-Hours of Delay
VHT	Vehicle-Hours Traveled
VIF	Variance Inflation Factor
VMT	Vehicle-Miles Traveled
VOC	Vehicle Operating Cost
VOT	Value of Time
WZ	Work Zone
WZTA	Work Zone Traffic Analysis Tool
YOLO	You Only Look Once

Chapter 1: Introduction

1.1 Background and Problem Statement

The Michigan Department of Transportation (MDOT) relies on a macro-enabled Excel spreadsheet, known as the Construction Congestion Cost (CO3) model, developed in the late 1990s, to estimate user delay times and associated costs that the traveling public may experience while navigating through or around construction work zones. Specifically, the CO3 model is designed to provide MDOT with an integrated framework for evaluating the impact of traffic maintenance contract provisions on critical factors, including congestion levels, road-user costs, and overall construction expenditures. According to Carr (1997), this tool consolidates various analytical functions to deliver a comprehensive assessment of work zone impacts.

The CO3 model effectively captures the dynamic nature of construction work zones, which are characterized by fluctuating road capacities. These fluctuations occur as traffic lanes open and close or as work conditions change throughout the construction process. This variability is a fundamental aspect of the model, enabling it to reflect real-world conditions and their implications for traffic flow and congestion. By adopting the methodology established in the Highway Capacity Manual (HCM), the CO3 model employs a sketch-planning approach that uses hourly traffic demand data and capacity analyses to estimate and quantify the impacts of work zones on road users.

Sketch-planning tools, such as the CO3 model, are inherently less detailed and precise compared to more advanced modeling techniques. They adopt a simplified approach, which allows for quick estimations but limits their applicability in later, more detailed project phases. This trade-off in precision makes sketch-planning tools particularly effective during the early stages of a project when less comprehensive data is available. The Transportation Research Board (TRB, 2016) emphasized the appropriateness of such tools for initial planning phases, noting their efficiency and practicality for broad preliminary assessments. Accordingly, MDOT primarily uses the CO3 model to calculate delay costs during the initial phase of construction projects, providing valuable insights for project planning and decision-making (Chan, 2007).

The CO3 model presents both technological and methodological limitations. Because it was developed using legacy Excel macros, long-term compatibility, maintenance, and usability are growing concerns. These limitations are particularly important because CO3 user-delay estimates support key MDOT applications, including life-cycle cost analysis for pavement-type selection and the determination of liquidated damages. Therefore, maintaining a reliable and sustainable method for estimating work-zone user delay and associated costs is important to support continued MDOT planning and decision-making.

In addition to technological limitations, concerns also arise regarding the data and methodologies employed by the CO3 model. While the tool incorporates methodologies from the Highway Capacity Manual (HCM), the field of traffic analysis and user delay estimation has evolved

significantly since the late 1990s. Over time, advancements have been made in both the availability of traffic data and the analytical methods used to estimate user delay costs more accurately. As such, the accuracy of CO3's output requires careful reassessment to determine whether they align with current traffic management standards and practices.

Furthermore, several alternative software tools and methodologies for estimating user delay costs have emerged, potentially offering improved precision, scalability, and user-friendliness. Identifying and evaluating these alternatives is a critical step in ensuring that MDOT adopts a state-of-the-art solution that meets contemporary demands. This evaluation process must also include benchmarking the CO3 model against the latest insights and methodologies presented in the latest edition of the HCM (i.e., the 7th Edition released in 2022). By conducting a thorough review of alternative tools and methodologies, MDOT can ensure that its approach to estimating user delay costs is both accurate and future-proof.

Hourly traffic demand is a key input for analyzing road-user costs and mobility impacts in work zones. It represents the hourly distribution of vehicles traveling in a single direction through the work zone under normal traffic conditions. These hourly variations can either be derived from actual traffic count measurements taken at the work zone site or estimated using hourly distribution factors applied to projected average daily traffic (ADT). These factors account for variations across eight distinct traffic patterns, differentiating among weekdays, weekends, and seasonal traffic. MDOT has developed Michigan-specific hourly distribution factors based on prior research, including findings from the 2018 study *An Evaluation of Michigan's Continuous Count Station (CCS) Distribution* (Oh et al., 2018). These Michigan-specific factors offer a localized perspective that could enhance the accuracy of work-zone delay-time and cost estimates. Also, MDOT maintains other sources of traffic data that can be useful in estimating work zone traffic demand. Therefore, there was a need to evaluate the availability and practicality of incorporating Michigan-specific hourly distribution factors into the model used to estimate user delay costs.

Traffic composition is another important factor to consider when estimating user delay times and traffic performance in work zones. Different vehicle types exhibit varying operational characteristics and performance, particularly under congested and capacity-constrained conditions (Mallela & Sadasivam, 2011a). Road user cost estimation tools such as CO3 should distinguish between passenger cars and heavy vehicles, as recommended in the Federal Highway Administration Traffic Monitoring Guide (FHWA TMG, 2016). However, although CO3 accounts for the truck percentage when estimating user costs, it does not explicitly convert traffic demand and roadway capacity from vehicles per hour to passenger cars per hour. As a result, passenger cars and trucks are not differentiated in the demand–capacity analysis, even though their operational effects may differ. To ensure consistency in demand-capacity analysis and traffic flow representation, heavy vehicles should be converted to equivalent passenger cars using heavy-vehicle adjustment factors (ET) as recommended by HCM.

All models for estimating work-zone user delay time and costs, based on the HCM, treat capacity as an exogenous variable and require it as an input to the model (Edara et al., 2017). While HCM provides general guidelines for work zone capacity estimation, researchers have also developed state-specific models using state-specific datasets. For instance, the CO3 model, as described in its user manual, requires assumed or estimated work zone capacity to be input for analysis. Lyles (1999) evaluated the reasonableness of these input parameters in CO3 by comparing the recommended work zone capacities with observed capacities in Michigan work zones. The findings revealed that the recommended capacities were often exceeded across three lane-closure scenarios.

Furthermore, traffic behavior in work zones is inherently dynamic and nonlinear, characterized by phenomena such as queue formation, shockwave propagation, and congestion spillback. Traditional sketch-planning approaches are unable to capture these complex traffic dynamics, particularly under high-demand conditions or in the presence of bottlenecks such as lane drops and ramp interactions. This limitation highlights the need for advanced modeling approaches that can more accurately represent time-dependent traffic flow.

To ensure accuracy and relevance, the *MDOT Work Zone Safety and Mobility Manual* (2025) incorporates base mainline capacity values depending on the number of open lanes and applies capacity adjustment factors to account for variables such as lane width, work intensity, the presence of heavy vehicles, and entrance ramps. Given these updated guidelines, it was essential to reassess the CO3 model's work zone capacity inputs using the current HCM methodology. Additionally, reviewing research on Michigan-specific work zone capacities across various configurations was critical to ensure the use of accurate, contextually appropriate capacity data when estimating work zone user delay times and costs.

One of the significant challenges faced by MDOT staff in using the CO3 model is the extensive data requirements, which often exceed the information readily available to MDOT regions and other users. For example, critical inputs such as the speed at capacity and volume at capacity are not easily accessible. This issue is not unique to CO3; an assessment of other road user cost estimation tools, such as the QUEWZ (Queue and User Cost Evaluation of Work Zones) model and the TTI (Texas A&M Transportation Institute) lookup table (MicroBENcost), revealed that the lack of readily available input data is a common limitation (Zhu et al., 2009). To address this challenge, it is essential to evaluate CO3's data requirements and, where feasible, simplify them without compromising the accuracy of the model's outputs.

Work zone configurations vary significantly depending on factors such as the type of work being performed and the location. A robust tool is needed to analyze various work zone configurations and provide accurate estimates of queue lengths, delay times, and user delay costs for each type. Input data, such as the facility type and the number of lanes available during and after construction, are crucial for accurately estimating road user costs and should be incorporated into any comprehensive analysis tool (Zhu et al., 2009).

In addition to conventional lane-closure scenarios, modern work zone analysis must account for more complex operational conditions, including multilane highways with access points, freeway segments with ramp interactions, and flagging operations involving alternating one-lane traffic. These scenarios introduce additional complexity in traffic flow behavior and require specialized modeling approaches to accurately estimate delays and user costs. However, many existing tools, including CO3, provide limited support for these configurations.

Another critical factor in estimating work zone user delays and costs is accurately assessing diverted traffic. CO3 requires users to enter the percentage of traffic to be diverted, but the accuracy of these potentially subjective estimates could be improved by incorporating travel demand forecasting models. This reinforced the need to evaluate the adequacy of CO3's current approach and explore whether other tools or methodologies might offer superior capabilities for estimating work-zone user delay times and costs.

Driver responses to congestion, particularly through route diversion, play a critical role in determining traffic conditions in work zones. Diversion behavior is influenced by factors such as travel time differences, route familiarity, and congestion levels, and it evolves dynamically over time. CO3 allows users to specify diversion rates for cars and trucks; however, these rates are user-defined inputs rather than dynamically estimated based on changing traffic conditions or travel-time differences. Therefore, incorporating an internal dynamic diversion model could improve the representation of route-choice behavior during work zone operations.

The outputs generated by a work zone user delay-time and cost-estimation tool like CO3 have broader applications, including providing data for Life Cycle Cost Analysis (LCCA) for pavement type selection. Zhu et al. (2009) incorporated crash costs into road user cost calculations, alongside the value of time (VOT) and vehicle operating cost (VOC). Their method involved a customized formula that considered the proportional change in crash rates in work zones, the length of the work zone, and the average dollar value of crashes. Similarly, Jiang and Adeli (2003) developed a freeway work-zone traffic delay and cost optimization model that included crash costs, using an equation that depends on the number of lane closures and crash rates. Anderson et al. (1992) further categorized crash costs into pavement-related and non-pavement-related categories, emphasizing the importance of including these factors in road-user cost calculations. As such, advancing CO3 and similar tools to better estimate crash costs, traffic diversions, and various work zone configurations is critical for improving accuracy and ensuring the comprehensive application of user delay time and cost data.

1.2 Research Objectives

This study was organized into two phases aimed at improving work-zone traffic analysis and user delay-cost estimation practices for the Michigan Department of Transportation (MDOT). The overall research framework is illustrated in Figure 1-1.

The first phase focused on evaluating existing methodologies and work zone analysis tools, identifying MDOT's operational and analytical needs, and laying the foundation for developing an improved work zone analysis framework. The second phase focused on additional field data collection, model enhancement, tool development, implementation, and validation to support advanced work-zone traffic analysis under diverse operational conditions.

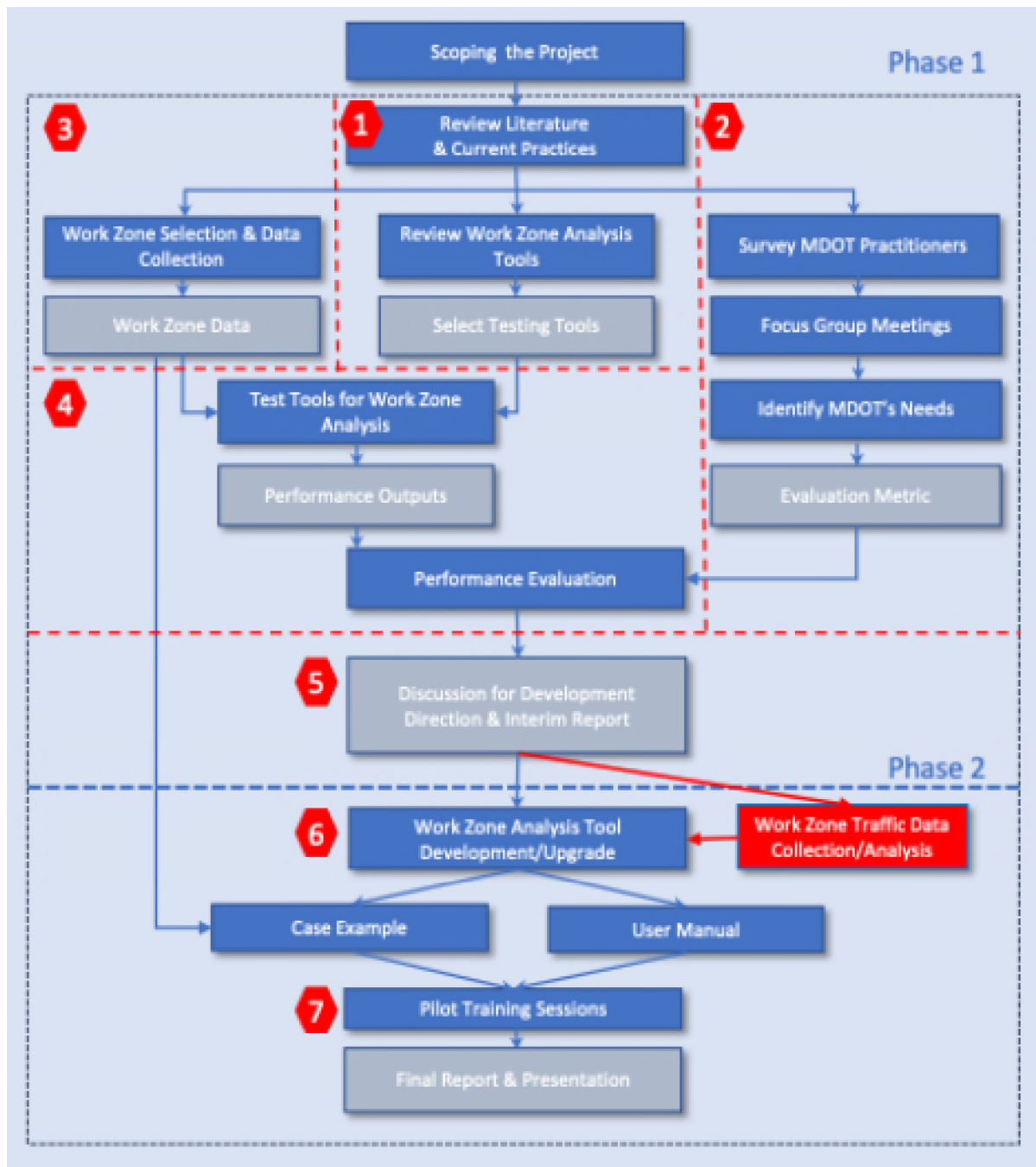


Figure 1-1: Two-Phase Research Process for Work Zone Analysis Tool Development

The first phase of the study included the following objectives:

1. Perform an evaluation and analysis of the current CO3 methodology for estimating work zone user delay times and costs with respect to its future viability, accuracy, and applicability.
2. Review existing literature, methodologies, and work zone analysis tools currently used for estimating delays, queue length, traffic performance, and user costs in work zones.
3. Identify MDOT's needs and challenges related to work zone traffic analysis and operational decision-making through practitioner surveys and focus group discussions.
4. Select representative work zone sites and collect traffic, operational, and geometric data required for evaluating existing tools and identifying modeling limitations.
5. Examine and compare the performance of selected work zone analysis tools under different work zone configurations and traffic conditions.
6. Recommend improved methodologies, modeling approaches, and development directions that better address MDOT's operational and analytical needs.

The second phase of the study focused on the implementation and enhancement of the proposed framework and included the following objectives:

1. Conduct additional work zone traffic data collection and analysis activities to support model development, calibration, and validation under real-world traffic conditions.
2. Develop or update a work zone analysis tool capable of representing freeway, multilane, detour, and flagging work zone operations using advanced traffic modeling approaches.
3. Integrate traffic flow modeling, delay estimation, queue analysis, and diversion analysis within a unified computational framework to improve work zone performance evaluation.
4. Develop case-study applications and support documentation to demonstrate the applicability of the developed framework under different work zone scenarios.
5. Prepare a user manual and conduct pilot training sessions to support the implementation and future application of the developed work zone analysis system by MDOT staff.

1.3 Scope of Study

The scope of this study is the evaluation, enhancement, and implementation of methodologies for estimating work-zone traffic performance, user delay times, and associated impacts under various roadway and operational conditions. The study reviews and assesses existing work zone analysis tools and methodologies used by transportation agencies, particularly the Michigan Department of Transportation (MDOT) CO3 model, with an emphasis on their applicability, limitations, and ability to represent dynamic traffic conditions in work zones.

The research includes collecting and analyzing field traffic data from selected work zone sites across Michigan to support the evaluation, calibration, and validation of the proposed framework. Data sources include field observations, video-based traffic extraction, RITIS data, MVDS (Microwave Vehicle Detection System) / CCS traffic data, and other external traffic information sources. The collected data is used to examine traffic flow characteristics, speed variations, queue formation, delay patterns, and behavior diversion under different work zone configurations.

The study further focuses on developing an integrated modeling framework to represent traffic operations under freeway, multilane, detour, and flagging work-zone conditions. The modeling framework incorporates traffic flow theory, capacity and speed estimation methods, queue and delay analysis, and diversion modeling to capture the spatiotemporal behavior of traffic within work zones. A Cell Transmission Model (CTM)-based approach is adopted to represent dynamic traffic conditions and the propagation of congestion.

In addition, the study includes the development and implementation of a work zone analysis tool that integrates the proposed modeling components into a unified computational framework. The tool is designed to support scenario analysis, operational evaluation, and performance assessment under different work zone conditions. Case studies are conducted to evaluate the applicability and performance of the developed framework and tool using real-world work zone scenarios.

The scope of this study is limited to operational and mobility-related impacts associated with work zones and does not include pavement structural analysis, construction scheduling optimization, or detailed microscopic modeling of driver behavior. The primary focus is on traffic operations, delay estimation, queue analysis, diversion behavior, and the implementation of practical analytical tools to support work zone traffic management and decision-making.

1.4 Organization of the Report

This report is organized into nine chapters that present the evaluation, development, calibration, validation, and implementation of the Michigan Predictive Analysis of Congestion and its Effects (MiPACE) framework for work zone traffic analysis and operational evaluation.

Chapter 1 introduces the research background, problem statement, study objectives, scope of work, and overall organization of the report.

Chapter 2 presents a review of current practices, existing methodologies, and work zone analysis tools used by transportation agencies for estimating traffic performance, queue formation, delay, and road user impacts under work zone conditions. The chapter also identifies major limitations and research gaps associated with current approaches.

Chapter 3 summarizes the survey and focus group activities conducted to identify MDOT's operational needs, user requirements, and challenges associated with existing work zone analysis practices and tools.

Chapter 4 presents the examination and comparative evaluation of selected work zone analysis tools under different work zone scenarios, including freeway lane closures, crossovers, detours, and flagging operations. The chapter also discusses the limitations of existing methodologies and evaluates alternative development approaches for improving work zone analysis capabilities.

Chapter 5 introduces the development of the MiPACE framework, including the integration of geometric input, traffic demand estimation, CTM-based simulation, detour and diversion analysis, road user cost estimation, and visualization modules within a unified analytical environment.

Chapter 6 presents the data collection, processing, and preparation activities conducted to support model development, calibration, and validation. The chapter describes the selected work zone sites, field deployment procedures, traffic data sources, video-based traffic extraction methods, and data quality-control procedures.

Chapter 7 presents the development of the traffic modeling framework implemented within MiPACE, including the Cell Transmission Model (CTM), freeway and multilane work zone models, flagging operation models, and the calibration of Michigan-specific speed and capacity relationships.

Chapter 8 presents the calibration and validation procedures performed for the MiPACE framework using field observations, API data, RITIS datasets, Bluetooth measurements, and MVDS traffic data. The chapter also presents multiple freeway work zone validation case studies and evaluates the framework's operational performance.

Finally, Chapter 9 summarizes the major findings and contributions of the study, presents recommendations for future implementation and enhancement of the framework, and discusses directions for future research and development.

Chapter 2: Current Practices and Literature Review

2.1 Overview of MDOT CO3

CO3 is used by MDOT to estimate work-zone traffic impacts, delay, and associated user costs for maintenance-of-traffic and project decision-making. The CO3 follows a sketch-planning approach based on methodologies derived from earlier editions of the Highway Capacity Manual (HCM). The model estimates work zone impacts by comparing hourly traffic demand with available work zone capacity under different construction and traffic control scenarios. Traffic demand is represented by using historical traffic counts and growth factors, while roadway capacity is defined based on work zone conditions such as lane closures and traffic operations.

The system consists of several integrated worksheets and computational modules, including the Input Sheet, Routes Sheet, Traffic Sheet, Construction Cost Sheet, and Impact Sheet. The Traffic Sheet serves as the primary computational component, estimating traffic performance measures such as queue length, delay, diversion, demand reduction, and user impacts across different work zone scenarios.

The CO3 model incorporates simplified speed-delay and demand-reduction relationships to represent traffic behavior under congested conditions. When traffic demand approaches or exceeds the work zone's capacity, the model estimates the impacts of speed reduction, queue formation, backup delay, and diversion. The model also supports several work zone configurations, including lane closures, detours, ramp closures, and alternating one-lane traffic controlled by flagging.

The output generated by CO3 include total delay, average delay, queue length, diversion impacts, traffic demand reductions, and overall user impacts associated with work zone operations. These outputs are combined with construction-related costs to support the comparison of alternative traffic maintenance strategies and construction approaches.

Although the CO3 model has been widely used by MDOT for preliminary work zone analysis, the methodology relies on simplified assumptions and static traffic relationships that limit its ability to represent dynamic traffic behavior and complex work zone operations. These limitations motivated this study's evaluation of the current methodology and development of an enhanced work zone analysis framework.

2.2 Work Zone Capacity and Speed Models

Work zone capacity estimation plays a critical role in evaluating traffic operations, queue formation, travel delay, and mobility impacts during roadway construction and maintenance activities. Accurate estimation of work zone capacity is essential because even small errors in capacity assumptions can significantly affect predicted queue lengths, congestion duration, diversion behavior, and user delay. Historically, most work zone traffic analysis procedures in the United States have been based on methodologies presented in the Highway Capacity Manual (HCM). However, over time, many state Departments of Transportation (DOTs) recognized that

generalized national assumptions do not always reflect local traffic behavior, geometric conditions, heavy vehicle composition, work intensity, or driver response characteristics. As a result, state agencies gradually adopted different approaches for estimating work zone capacity, ranging from simplified HCM-based lookup tables to simulation-based methodologies and locally calibrated empirical models.

Earlier state DOT work zone practices were largely based on HCM 2000 and HCM 2010 methodologies, commonly referred to as HCM 5th Edition approaches. These methodologies typically assumed a base freeway work zone capacity of approximately 1,600 passenger cars per hour per lane (pcphpl), with adjustment factors applied for work intensity, lane width, heavy vehicles, and ramp effects. Several states continued to use these simplified HCM-based methods via spreadsheets or lookup tables. Texas, for example, developed the Q-DAT tool based primarily on HCM 2010 work zone capacity procedures. Ohio also relied on HCM 2010 methodologies but introduced a local calibration adjustment of approximately -400 pcphpl based on field observations. Missouri used HCM-based approaches as the foundation for its work zone planning tool, incorporating local field adjustments based on work zone location and congestion conditions. Similarly, several eastern states, including Connecticut, Delaware, Maryland, Massachusetts, New Jersey, and the District of Columbia, continued to rely primarily on HCM-based lookup tables and lane-closure severity indices to determine allowable lane-closure schedules and work-zone capacity thresholds.

At the same time, some states moved toward simulation-based approaches to better represent complex traffic behavior and dynamic congestion patterns. States such as Alaska, Colorado, Idaho, and Washington increasingly adopted case-by-case simulation methodologies using tools such as VISSIM or mesoscopic simulation frameworks. These approaches became particularly important for large urban freeway projects, multilane work zones, major detours, and projects involving significant diversion or merge/weave interactions. Illinois also moved beyond traditional HCM methods by developing the WorkZone QPRO tool, based on empirical observations and Cell Transmission Model (CTM)-type traffic-flow concepts. Illinois researchers found that several existing tools, including FRESIM and QUEWZ, either overestimated work zone capacity or underestimated queue length and delay. Consequently, Illinois adopted a more dynamic modeling approach for queue propagation and delay estimation.

The release of the HCM 6th Edition in 2016 marked a major advancement in freeway work-zone capacity estimation methodologies. Unlike earlier HCM procedures that relied primarily on fixed base capacities and generalized adjustment factors, the HCM 6th Edition introduced predictive equations based on nationwide field data collected through NCHRP Project 03-107. The HCM 6 methodology estimates work zone queue discharge rate (QDR) and pre-breakdown capacity as functions of several operational and geometric variables, including lane closure severity index (LCSI), barrier type, area type, lateral clearance, and daytime versus nighttime operations. The methodology also recognizes the distinction between queue-discharge flow and pre-breakdown flow, which earlier methodologies often treated as equivalent.

Despite these improvements, many studies found that the HCM 6th Edition equations still required local calibration. Louisiana validated the HCM 6 work zone capacity model using field data from ten freeway work zone sites and found that the HCM slightly overestimated observed capacity by approximately 6%. Iowa State similarly reported that field-measured pre-breakdown capacities and queue discharge rates were significantly lower than HCM predictions, particularly for complex work zone configurations with narrow lanes, crossovers, and lane shifts. Wisconsin conducted one of the most extensive statewide calibration studies, using 52 work-zone observations across 14 freeway sites, and developed a calibrated HCM 6-based model incorporating Wisconsin-specific coefficients and construction-intensity adjustments.

More recent research has also emphasized that work zone capacity should not always be treated as a deterministic value. Kianfar and Abdoli (2021) demonstrated that traffic breakdown in work zones is stochastic in nature and may occur at different flow levels rather than at a single fixed capacity threshold. Addison et al. (2021) developed a regression-based incident capacity adjustment model using genetic algorithm calibration techniques to dynamically estimate freeway capacity reductions during lane-closure incidents and demonstrated that capacity variation is strongly related to the temporal progression of the incident.

Their work further highlighted the limitations of static capacity assumptions and reinforced the need for probabilistic and dynamic traffic modeling approaches in future work zone analysis frameworks. The HCM 6th and 7th Editions use similar work-zone analysis frameworks for estimating freeway capacity and speed. Table 2-1 summarizes major work zone capacity methodologies and calibration practices used by U.S. state DOTs.

While work zone capacity has historically been the primary focus of freeway work zone analysis, recent studies have shown that speed behavior is equally important in understanding traffic operations under construction conditions. Speed directly affects roadway throughput, queue formation, congestion propagation, travel delay, and safety performance within work zones. Consequently, accurate estimation of work zone speed has become an essential component of modern work zone traffic analysis frameworks.

Earlier work zone analysis methodologies typically relied on simplified or fixed-speed assumptions based on posted speed limits or generalized speed-reduction factors. However, several studies have demonstrated that actual operating speeds within work zones vary significantly with roadway geometry, lane configuration, traffic demand, work activity, heavy-vehicle percentage, barrier type, and driver behavior. As a result, traditional static speed assumptions often fail to accurately represent real-world traffic conditions, particularly under congested or complex work zone scenarios.

Table 2-1: Work Zone Capacity Methodologies and Calibration Practices by State DOTs

State	Primary Methodology	HCM Version Used	Locally Calibrated?	Uses Own Tool / Model?	Key Notes
Texas	HCM-based spreadsheet (Q-DAT)	HCM 5th	No	Yes	Uses HCM-based capacity procedures for lane closure scheduling
Ohio	HCM-based queue tool	HCM 5th	Yes	Yes	Uses approximately –400 pcphpl calibration adjustment
Missouri	HCM-based planning tool	HCM 2000	Yes	Yes	Capacity varies by work zone location and congestion conditions
Illinois	Empirical + CTM-based modeling	No direct HCM method	Yes	Yes	Developed WorkZone Q-pro using field observations and CTM concepts
Wisconsin	Calibrated statewide model	HCM 6th	Yes	Yes	Developed Wisconsin-specific regression model and Excel/VBA tools
Louisiana	HCM validation study	HCM 6th	Yes	No	HCM overestimated field capacity by approximately 6%
Iowa	HCM adjustment-factor study	HCM 6th	Yes	No	Developed adjustment factors for complex work zone geometry
Minnesota	FREEVAL + diversion modeling	HCM-based	Yes	Yes	Developed an iterative diversion-capacity estimation methodology
Arkansas	High-truck-volume calibration	HCM 6th	Yes	No	Focused on heavy vehicle and reduced lane geometry effects
Maryland	Lookup table + HCM equations	HCM 7th	Partial	No	Uses HCM 7 lane closure severity procedures
Florida	Simulation + field calibration	HCM 2000 comparison	Yes	Partial	Developed calibrated analytical models
Alaska	Simulation-based analysis	Case-by-case	Project-specific	Yes	Uses simulation for major projects
Colorado	Simulation-based analysis	Case-by-case	Project-specific	Yes	Uses microsimulation approaches
Idaho	Simulation-based analysis	Case-by-case	Project-specific	Yes	Uses project-specific operational analysis
Washington	Simulation-based analysis	Case-by-case	Project-specific	Yes	Uses dynamic traffic analysis and simulation

The release of the HCM 6th Edition introduced additional speed-related variables into work zone capacity estimation procedures by incorporating the lane closure severity index (LCSI), barrier type, lateral clearance, area type, and daytime versus nighttime conditions. Nevertheless, multiple state-level validation studies later found that HCM-based speed assumptions still require local calibration to accurately represent field conditions. Recent research, therefore, shifted toward developing calibrated freeway work zone free-flow speed (FFS) models using field observations, sensor databases, simulation techniques, and regression-based approaches.

Several states and research agencies developed localized speed calibration models to improve the estimation of work zone operational performance. These studies commonly found that work zone speed behavior is highly sensitive to lane width reduction, lane shifts, crossovers, work intensity, truck percentage, and traffic control strategies. In addition, more recent studies emphasized the importance of integrating speed calibration with dynamic traffic flow modeling, queue propagation analysis, and diversion estimation to improve the accuracy of work zone mobility analysis.

Table 2-2 summarizes major U.S.-based studies related to work zone speed modeling and speed calibration, including the methodologies used, calibration approaches, and major findings from each study.

Table 2-2: Work Zone Speed Modeling and Calibration Practices Across U.S. State DOTs

State	Author(s) / Year	Primary Speed Methodology	HCM Version Used	Locally Calibrated?	Uses Own Speed Model?	Key Notes
Nationwide	Yeom et al. (2015)	Regression- based FFS model	HCM 6th development basis	Yes	Yes	Developed predictive freeway work zone FFS model
Iowa	Dong & Yang (2020)	HCM speed validation	HCM 6th	Yes	Partial	HCM overestimated FFS in complex work zones
Wisconsin	Campbell et al. (2020)	Speed-density calibration	HCM 6th	Yes	Yes	Integrated calibrated speed- density relationships
Oregon	Gambatese & Jin (2021)	Speed variation analysis	HCM-based	Yes	Yes	Speed variability linked to geometry and control
Illinois	Chitturi & Benekahal (2005)	Lane width speed study	No direct HCM	Yes	Yes	Narrow lanes reduced free- flow speed
Pennsylvania & Texas	Porter & Mason (2007)	Work zone speed characterization	HCM comparison	Yes	Partial	Posted speed and WZ type strongly affected speed

State	Author(s) / Year	Primary Speed Methodology	HCM Version Used	Locally Calibrated?	Uses Own Speed Model?	Key Notes
Arkansas	Romano & McKenney (2019)	High truck- volume speed analysis	HCM 6th	Yes	Partial	Heavy vehicles reduced operating speed
Florida	Heaslip et al. (2009)	Speed-flow calibration	HCM 2000 comparison	Yes	Yes	Speed-flow behavior varied by lane closure type
Louisiana	Codjoe et al. (2021)	Speed-at- capacity validation	HCM 6th	Yes	No	Speed at capacity differed across work zones
Maryland	Maryland SHA (2024)	HCM-based lookup procedures	HCM 7th	Partial	No	Uses HCM 7 operational thresholds
Missouri	Bham & Khazraee (2011)	Queue discharge speed analysis	HCM-based	Yes	Partial	Queue conditions reduced operating speed
Minnesota	Kwon & Park (2016)	Diversion-speed relationship modeling	HCM/ FREEVAL	Yes	Yes	Speed used in the diversion estimation process

2.3 Queue and Delay Estimation Methods

Estimating queue length and delay is one of the most critical components of work zone traffic analysis because these measures directly affect mobility, user satisfaction, safety performance, diversion behavior, and maintenance-of-traffic (MOT) decisions. Queue formation in work zones typically occurs when traffic demand exceeds the work zone's capacity, causing congestion to propagate upstream of the bottleneck. Consequently, several methodologies and analytical tools have been developed to estimate queue length, delay, travel-time impacts, and congestion duration under work-zone conditions.

Traditional work zone queue estimation approaches were primarily based on deterministic input-output methods derived from Highway Capacity Manual (HCM) procedures. These methods estimate queue growth using the difference between traffic demand and available work zone capacity over time. Although these methods are computationally efficient and practical for planning-level analysis, they often rely on simplified assumptions regarding traffic flow behavior, queue propagation, and driver response. As a result, they may not accurately capture dynamic congestion conditions, especially in oversaturated or complex work-zone scenarios.

Several state Departments of Transportation (DOTs) developed customized queue- and delay-estimation tools to improve work-zone operational analysis. North Carolina DOT's ARTVAL-WZ tool evaluates delays on arterial roadways by incorporating variables such as mid-segment access points, lost time per signal cycle, and turning vehicle percentages (Schroeder et al., 2015). Delaware DOT validated the Queue Discharge Rate (QDR) methodology, which later became a fundamental component of the HCM 2016 and HCM 2022 freeway work zone analysis procedures. Li et al. (2017) found the QDR methodology to be highly effective for evaluating multilane signalized corridor operations under work zone conditions.

Several studies also identified important limitations associated with spreadsheet-based work zone analysis tools. Jenkins et al. (2015) noted that many state DOT tools, including MDOT's CO3 model, rely primarily on single-segment analysis approaches rather than the multiple-segment methodologies recommended by the HCM. This limitation reduces these tools' ability to accurately represent queue spillback, congestion propagation, merge/diverge interactions, and time-dependent traffic behavior. Consequently, simplified spreadsheet-based methods may underestimate queue lengths and delay under congested conditions.

To improve queue and delay estimation accuracy, several researchers adopted dynamic traffic flow modeling approaches such as the Cell Transmission Model (CTM), mesoscopic simulation, and microscopic simulation. Illinois DOT's WorkZoneQ tool incorporated CTM-based concepts to improve queue propagation and congestion analysis under freeway lane closure conditions. Wisconsin DOT integrated speed-density relationships into calibrated queue estimation models to improve predictions of queue growth, delay duration, and congestion dissipation under different lane closure configurations. Similarly, Minnesota DOT developed an iterative diversion-delay estimation framework that combined FREEVAL simulation with diversion estimation procedures to dynamically estimate freeway delay and diversion behavior on alternative routes.

Queue estimation has also become increasingly dependent on real-time and high-resolution traffic data sources. Modern studies frequently utilize RITIS, Bluetooth travel time data, probe vehicle data, CCTV observations, RTMS sensors, and detector-based speed-flow data to validate queue estimation methodologies and monitor congestion propagation. Wisconsin DOT, for example, used Bluetooth sensors, CCTV footage, Google Maps travel times, and field observations to collect queue data from more than 180 work zone occurrences statewide. Louisiana DOT utilized RTMS devices to collect traffic speed, flow, and queue information at ten freeway work zone sites for validating HCM 6th Edition queue estimation procedures.

In addition to deterministic and simulation-based approaches, recent research increasingly recognizes the stochastic nature of queue formation and traffic breakdown in work zones. Kianfar and Abdoli (2021) demonstrated that traffic breakdown can occur at varying flow levels and that queue formation should not be treated as a deterministic process. Their findings highlighted the importance of incorporating probabilistic traffic behavior into future queue and delay estimation methodologies.

2.4 Review of Existing Work Zone Analysis Tools

Several state DOTs have developed Excel-based tools to analyze the traffic impacts at work zones (Mallela & Sadasivam, 2011b). According to Shrestha et al. (2021), over 80% of the state DOTs are utilizing excel-based tools. An updated overview of these tools is presented in Table 2-3, which lists various work zone-specific analysis tools employed by different state DOTs. While Excel-based tools are advantageous due to their relatively easy development, low cost, and minimal training requirements, they generally provide rough estimates. As these tools rely on a predefined set of assumptions to function, such simplicity often comes at the cost of precision such that underestimation of RUC results in increased costs to the traveling public, while overestimation results lead to overpaying of incentives for early completion of construction projects (Qin & Cutler, 2013). Recognizing the critical need for more accurate output in work zone planning and decision-making, numerous studies have been conducted to enhance these tools. The following discussion explores these efforts in detail, highlighting significant advancements and ongoing challenges in the field.

The evolution of work zone analysis tools across various state Departments of Transportation (DOTs) highlights a trend toward more sophisticated, multifunctional systems that enhance both their accuracy and usability. For instance, recently, the Kansas DOT developed a tool that integrates Microsoft Access and GIS called the KDOT Work Zone Lane Closure Guide for the Wichita metropolitan area (Fitzsimmons et al., 2018). This tool significantly leverages real-time data from traffic management center data available in Kansas DOT such as WICHway and the Intelligent Traffic System (ITS) with the Access database allowing the analyst to identify highways, segment locations, days of the week, and hours of operation for construction activities and the ESRI Dashboard providing a visual representation of traffic data on maps and charts (Hazelton et al., 2022). Also, Florida DOT developed its standalone application called FDOT RUC (Zhu & Ahmad, 2008), which uses Microsoft .NET Framework. They intended to make a tool that would simplify data input requirements while ensuring it produces comparable results by incorporating HCM and AASHTO methodology, the ability to define construction schedules, and consistent data management in a user-friendly, Windows-based environment.

Tennessee DOT, through a study done by Shrestha et al., (Shrestha et al., 2021), developed an excel-based tool called TDOT RUC Calculation Tool. The tool was made to accommodate other DOT processes such as A+B bidding, lane rental cost determination, liquidated damage determination, and early completion incentives calculation. Also, the tool can access internal project-specific data sources and standard external datasets to provide regularly updated data input. Another recent improvement was at the Louisiana DOT where they updated their queue estimation procedure to implement new reduced threshold capacities based on local field observations in Louisiana. This adjustment aimed to enhance the accuracy of queuing estimations, tailoring their tool more closely to state-specific conditions (Codjoe et al., 2021), (Thapa et al., 2021). Washington DOT revisited their QUEWZ tool by a recent study done by Ishimaru et al., (Ishimaru & Hallenbeck, 2019) to review its methodology. Their study proposed both parametric-level and

method-level modifications, such as updating input parameters like costs and speed and adopting the HCM 6th edition. These changes were aimed at enhancing the tool's usefulness for the Washington DOT. The Ohio DOT conducted a study to develop a new Excel-based queue analysis tool and a road user cost tool, named the Lane Closure Queue Analysis Tool (Jenkins & McAvoy, 2015a). This tool was designed to replace the previously used QUEWZ (Schnell et al., 2002). Analysts from ODOT reviewed and revised the new tool to ensure its accuracy and effectiveness. It incorporates the HCM 2010 methodology for calculating freeway capacity and can handle capacity data from short-term work zones with lane closures, integrating valuable features from a range of existing tools. Alabama DOT adapted an Excel-based "Lane Rental Model" originally developed by Oklahoma DOT (Robert Batson et al., 2009). This revised model, enhanced to use the HCM 2000 Hybrid version, included a graphical depiction of the queue profile and more accurate capacity estimation methods. Colorado DOT developed the WorkZone-RUC software, a desktop-based tool that allows for detailed analysis of road user costs associated with various maintenance and rehabilitation strategies. This software generates graphs displaying the queue lengths and user costs for each activity hourly, aiding in comprehensive analysis and planning (Salem & Genaidy, 2008).

For the Web-based tools, the Florida Department of Transportation (FDOT) sought to enhance the planning of work zones on state freeways by commissioning a web-based tool developed by Kittelson. This initiative was driven by the need to streamline the previously complex and time-consuming process of scheduling work zones. The web-based tool simplifies this by requiring minimal user input such as freeway segment, number of lanes closed, barrier type, and timing to provide detailed, hour-by-hour traffic demand forecasts. Also, Oregon DOT replaced its spreadsheet-based package with a web-based tool, Work Zone Traffic Analysis Tool (WZTA), that allows users to access location-specific traffic data, free flow capacity, and vertical and horizontal geometric features of the work zone location and generate delay times and queue length for a user-specified lane closure period.

The detailed discussions of various DOTs' efforts to develop and refine work zone analysis tools illustrate a broader trend toward integrating more comprehensive data analysis features, real-time data capabilities, and user-friendly interfaces into work zone management tools. Despite these efforts, there is a lack of studies evaluating the diverse features and functionalities of the tools used by state DOTs. In this study, features and functionalities of work zone-specific analysis tools employed by different state DOTs for road user cost estimation were reviewed and summarized. Table 2-3 presents the list of work zone analysis tools used in different US states.

Table 2-3: Work Zone Specific Analysis Tools Used by State DOTs

S/N	State	Tool	Year developed
Excel-based tool			
1	Alabama	Lane Rental Model Spreadsheet	1997
2	Arizona	Arizona Work Zone Analysis Tool (AWZA)	
3	California	FHWA RealCost	2003
4	Illinois	Work Zone Q Pro	2013
5	Kentucky	KyUCP (Kentucky user cost program)	
6	Maryland	MD-QuickZone	2000
7	Michigan	CO3	1997
10	Missouri	MoDOT spreadsheet	2008
11	New Jersey	RUC Workbook	2015
12	North Carolina	ARTVAL-WZ, FREEVAL-NC	2013
13	Ohio	Lane Closure Queue Analysis Tool	2015
14	Oklahoma	Lane Rental Model Spreadsheet	
15	Oregon	Work Zone Traffic Analysis Tool	
16	South Dakota	SD-RUC	2011
17	Tennessee	TRCT - TDOT RUC Calculation Tool	2021
18	Texas	RUC Tables	1993
		QDAT Spreadsheet	2005
19	Utah	User Cost Worksheet	
20	Washington	QUEWZ	1998
21	Wisconsin	Freeway work zone capacity analysis tool	
Desktop-based tool			
1	California	CA4PRS	
2	Colorado	WorkZone RUC	
3	Florida	FDOT RUC	2008
4	Maryland	Lane Closure Analysis Program (LCAP)	
5	Oregon	FREEVAL-OR	
6	Pennsylvania	FREEVAL-PA	2020
7	Virginia	HUB-CAP	
Web-based tool			
1	California	Rapid Road Rehabilitation (R3)	
2	Florida	FDOT Work Zone Web Analysis Tool	
3	Oregon	Work Zone Traffic Analysis Tool (WZTA tool)	2019
4	Tennessee	Lane Closure Decision Support System (LCDSS)	
GIS-based tool			
1	Kansas	KDOT Work Zone Lane Closure Guidance Chart	2022
2	New Jersey	Work Zone Interactive Management App (WIMAP-P)	2017
3	New Jersey	Roadway Impact Lane Closure Analysis (RILCA)	

2.5 Limitations of Current Methods and Summary of Findings

The literature review revealed that although existing work zone analysis tools provide practical approaches to estimating traffic impacts during construction activities, many current

methodologies still have important limitations. Most traditional tools were originally developed as spreadsheet-based or sketch-planning applications and therefore rely on simplified assumptions about traffic operations, capacity, speed, queue formation, ramp interactions, and diversion behavior under work-zone conditions.

One of the primary limitations identified is the reliance on generalized or outdated capacity assumptions that may not accurately reflect actual field conditions. Research has shown that work zone capacity is highly sensitive to factors such as roadway geometry, lane configuration, heavy vehicle percentage, work intensity, barrier type, and local driver behavior. For this reason, several state DOTs have recently shifted toward calibrating HCM-based methodologies using locally collected traffic data to improve the reliability of capacity estimation.

The review also showed that many existing tools apply simplified speed assumptions, including fixed speed reductions or generalized speed-flow relationships. However, traffic speeds within work zones vary dynamically with congestion levels, roadway geometry, lane width, traffic composition, and work activity. As a result, simplified speed models may reduce the accuracy of travel-time, queue-propagation, and delay estimates. Another significant issue is the limited ability of many traditional tools to represent dynamic traffic behavior. Several spreadsheet-based methodologies perform single-segment analysis rather than modeling the corridor as multiple interacting segments. Consequently, these tools cannot fully capture shockwave propagation, queue spillback, temporal congestion evolution, or corridor-wide traffic redistribution, particularly for large freeway work zones, multilane facilities, and heavily congested urban corridors.

The literature further highlighted limitations associated with ramp and diversion analysis. Many existing methodologies do not explicitly model the interaction effects of merge, diverge, weave, or ramp, despite the major operational influence ramps can have near lane closures. Similarly, diversion analysis in several tools relies on static or user-defined diversion percentages rather than dynamically estimating route-choice behavior based on congestion conditions and alternative-route performance. In addition, many current methodologies still rely heavily on historical AADT distributions and manually entered parameters and lack integration with modern traffic data sources such as RITIS, Bluetooth data, probe-vehicle data, CCTV observations, and detector-based speed-flow information. This limits their ability to accurately represent real-time or site-specific traffic conditions.

Overall, the literature review demonstrated that different state DOTs use a wide range of work zone analysis tools, including Excel-based, desktop-based, web-based, and GIS-based systems. The findings also revealed a growing trend toward more advanced and multifunctional platforms that improve both analytical accuracy and usability. These identified limitations motivated the development of the enhanced framework presented in this study, which integrates calibrated speed and capacity models, dynamic traffic flow representation, ramp interaction analysis, diversion estimation, and CTM-based simulation within a unified work zone analysis environment.

Chapter 3: Identifying MDOT's Needs for a Work Zone Analysis Tool

3.1 Introduction

This chapter covers an online survey and a focus group meeting designed to identify the Michigan Department of Transportation (MDOT)'s specific needs for work zone traffic analysis and user cost estimation. These methodologies were chosen to ensure a comprehensive understanding of MDOT's needs by leveraging both quantitative and qualitative data. The online survey, administered to MDOT and other stakeholders, including consultants and contractors, provided a structured platform for gathering broad-based feedback efficiently. On the other hand, the focus group meeting enabled in-depth discussions and exploration of nuanced issues that may not have been captured in the survey responses. The survey and focus group meeting were designed to address the following specific objectives:

- Identify MDOT's needs for work zone traffic and cost analysis
- Assess the difficulty and weaknesses of using the current CO3
- Determine desired features and improvements for CO3

3.2 Online Survey

The survey for identifying MDOT's need for work zone traffic and cost analysis practice utilized both an online survey and a focused group discussion. A Qualtrics-based online survey was administered to personnel within the Michigan Department of Transportation and its stakeholders from 9/28/2023 to 10/17/2023. The web-based survey was conducted through four steps: (1) questionnaire design, (2) pilot testing, (3) data collection, and (4) data analysis. This section presents the analysis results from the online survey. For reference purposes, the full online survey is attached in the appendix. The following is a discussion of the survey results.

3.2.1 CO3 tool usefulness

Figure 3-1 presents analysts' ratings of the usefulness of MDOT's CO3 tool, categorized by their levels of experience: Beginners, Advanced, and Experts. Among Beginners, who have used the CO3 tool in fewer than two MDOT projects, responses were evenly distributed across all categories, with 25% rating the tool as 'Not at all,' 'Not so,' 'Somewhat,' or positively ('Moderately' or 'Extremely') useful. Advanced users, with experience in 3-5 projects, showed a stronger neutral trend, with 66% rating the tool as 'Somewhat' useful, while 11% provided negative feedback and 22% gave positive ratings. Experts, who have used the CO3 tool in more than five MDOT projects, had the highest positive feedback, with 50% rating it as 'Moderately' useful and 11% as 'Extremely' useful, although 34% still provided a neutral rating and 6% gave a negative response ('Not at all').

These findings indicate that the perceived usefulness of the CO3 tool increases with experience, as more experienced users tend to rate it positively. However, a significant proportion of users

across all experience levels identified room for improvement, emphasizing the need for enhancements to better address user expectations and project requirements.

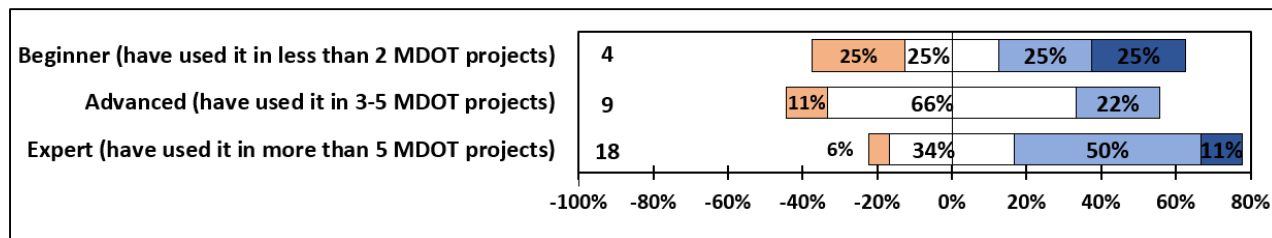


Figure 3-1: Analysts' Rating of Usefulness of MDOT's CO3

3.2.2 CO3 tool ease of use

Figure 3-2 illustrates analysts' ratings of the ease of use of MDOT's CO3 tool, categorized by their experience levels: Beginners, Advanced, and Experts. The results show that Beginners, who have used the CO3 tool in fewer than two MDOT projects, had evenly split opinions, with 50% expressing negative responses ('Not at all' or 'Not so') and the other 50% rating the tool as 'Somewhat' easy to use. Among Advanced users (used in 3-5 projects), the majority (66%) provided a neutral rating of 'Somewhat,' while 11% gave negative ratings and 22% gave positive ratings ('Moderately' or 'Extremely'). Experts, with experience using the CO3 tool in more than five projects, expressed more varied feedback. While 28% rated it as 'Not so' and 6% as 'Not at all,' a substantial portion (50%) rated it as 'Somewhat' and 17% as 'Moderately' or 'Extremely' easy to use.

The analysis indicates that familiarity with the tool does not necessarily result in entirely positive perceptions of its ease of use, as even Experts displayed mixed responses. This highlights the need for potential improvements to the tool's usability to better serve all experience levels.

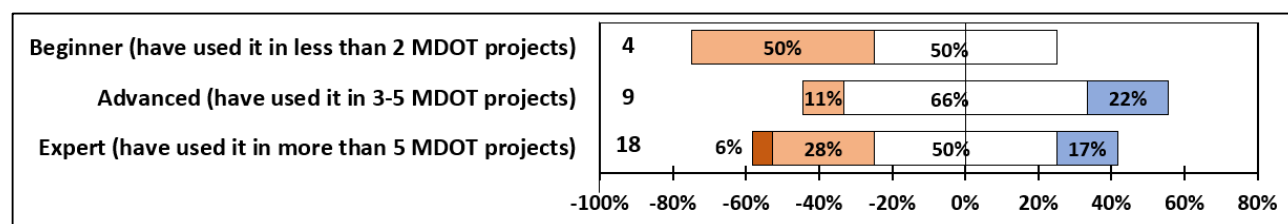


Figure 3-2: Analysts' Rating of Ease of Use of MDOT's CO3

3.2.3 CO3 tool satisfaction

The distribution of satisfaction levels among analysts regarding the MDOT's Excel-based tool, as depicted in the graph in Figure 3-3, indicates a varied perception of the tool's effectiveness. The satisfaction was evaluated based on seven (7) categories, these include, Data Input, Analyzing Various Scenarios, Default Values, Visualization of Results, Instruction or Guidance,

Computational Speed, and Accuracy. The figure shows major concerns on the instruction and guidance, results visualization, tool accuracy and data input.

The accuracy of a work zone analysis tool is fundamentally linked to its methodology. Excel-based tools like CO3, used for high-level analyses such as estimating queue lengths, often struggle with complex network dynamics (Hardy & Wunderlich, 2009). Analysts' feedback reveals diverse opinions on CO3's accuracy, particularly its capacity and diversion analysis methods. Updated Excel-based tools use the in-built HCM methodology with manually entered base capacities (Campbell et al., 2020), while CO3 depends on capacity tables from DOTs. Regarding diversion analysis, CO3 relies on percentage assumptions for traffic diversion, which can lead to skewed results. In contrast, GIS-based tools such as the KDOT Work Zone Lane Closure Guide provide in-depth analyses of both the work zone and diversion routes using real-time data and GIS technology, offering a more comprehensive view (Hazelton et al., 2022).

Regarding various scenario analyses, participants had diverse opinions. They highlighted scenarios such as lane transitions, freeway-to-freeway detours involving lane reductions at ramps and subsequent expansions, variations in Average Daily Traffic (ADT) within work zones, analyses involving signalized detour routes, and dynamic diversion rates. Excel-based tools often simplify analysis, potentially overlooking complex network dynamics. GIS and web-based tools (McCanna, 2010), excel at accounting for these dynamics through spatial data integration, real-time updates, and comprehensive traffic modeling.

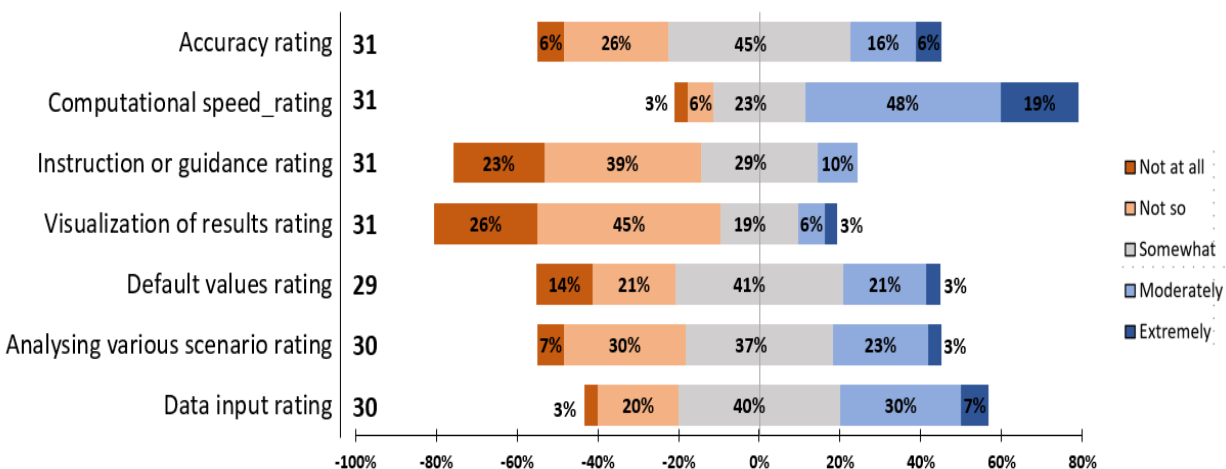


Figure 3-3: Analysts' Satisfaction with MDOT's CO3

An effective data input feature in a work zone analysis tool should ideally require minimal data for analysis and offer an intuitive and simplified method for data incorporation. Based on the ratings for data input, many respondents find the data input functionality of CO3 somewhat or moderately satisfactory. Excel-based tools like CO3 offer manual, straightforward data entry into predefined cells (Carr, 2000; Shrestha et al., 2021), which is simple but time-consuming and prone

to errors (Hardy & Wunderlich, 2009). In contrast, GIS and Web-based tools like the KDOT Work Zone Lane Closure Guide (Fitzsimmons et al., 2018; Hazelton et al., 2022) and the Work Zone Traffic Analysis Tool (WZTA), provide automated data integration from multiple sources, including real-time traffic management systems, with advanced visualization. However, these tools have a steeper learning curve compared to Excel-based tools.

3.2.4 CO3 tool feature and function preferences

Survey participants rated their preference for specific features or functionalities in the current MDOT Excel-based work zone analysis tool. Figure 3-4 shows the results of the preference ratings. Respondents indicated that queue length calculation, delay estimation, detour analysis, and various work zone type analyses were the most preferred features. Conversely, features such as crash cost analysis, life cycle cost analysis (LCCA) for pavement type selection, flagging analysis, and work zone ITS analysis were less preferred by some participants.

For life-cycle cost analysis (for pavement type selection), 23% of respondents did not favor its inclusion in the MDOT tool, considering it would increase complexity. Survey participants prefer using other tools specifically designed for LCCA, like the Kentucky User Cost Program (Rister & Graves, 2002), Rapid Road Rehabilitation (R3) and FHWA RealCost (Smith et al., 2023), which handle LCCA effectively.

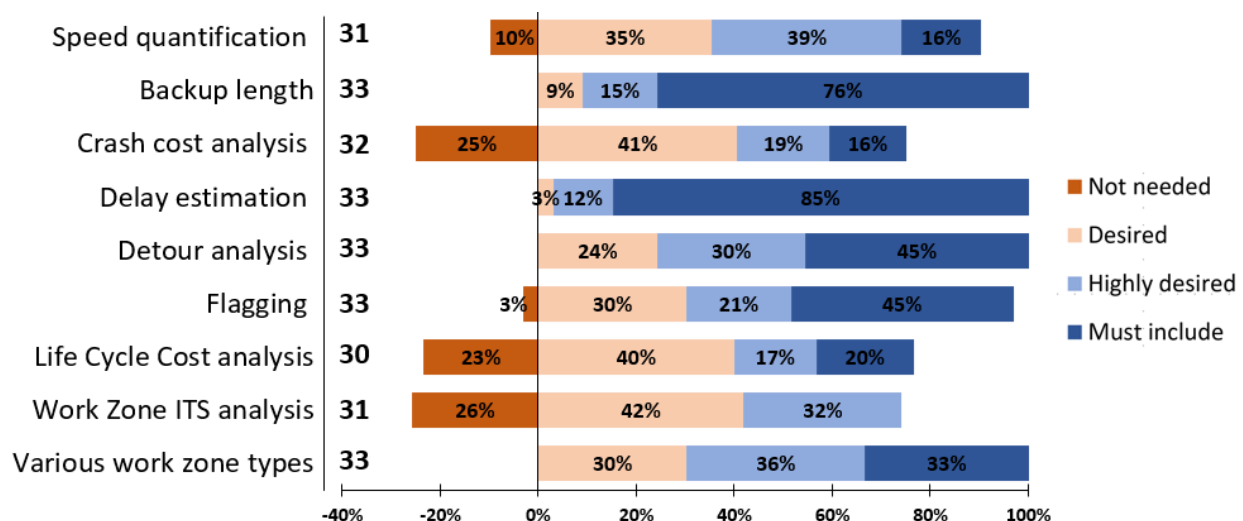


Figure 3-4: Analysts' Feature Preference for the MDOT's CO3

Flagging operations analysis, involving one-lane two-way operations with a flagger, was negatively viewed by only 3% of respondents. The MDOT tool, similar to Illinois DOT Work Zone Q-Pro (Benekohal et al., 2013), includes a separate Excel sheet for flagging operation analysis, aiding in planning and managing traffic flow during such operations. However, most other Excel-based tools do not include this feature, highlighting the importance of dedicated flagging analysis tools for efficient traffic management in complex scenarios.

Crash cost analysis was another area with notable resistance, with 25% of respondents preferring not to include it in the MDOT tool. The complexity and extensive data requirements deter its integration. (Shrestha et al., 2021), found only four states incorporating crash costs in their analysis methods. Most state DOTs, including Michigan DOT, exclude crash cost analysis due to practical limitations, such as the complexity of calculations and lack of comprehensive data. However, the FHWA provides criteria for crash unit cost analysis by injury severity, involving historical crash data and state-specific crash modification factors (Qin & Cutler, 2013).

3.3 Focus Group Meeting

The survey responses shown in the previous section were then supplemented by a focus group discussion conducted on 10/31/2023, which served as a critical way of gathering valuable insights from key personnel involved in work zone management. A total of 15 individuals participated in the focus group meeting. This collective input, representing a diverse range of perspectives, served as the cornerstone of this study's findings and recommendations.

3.3.1 Challenges in CO3 and MDOT's Needs

The focus group discussions revealed several challenges associated with using the CO3 tool for work zone analysis. These challenges, which limit the tool's efficiency and effectiveness, are summarized as follows:

Capacity Analysis

The findings from the focus group meeting highlighted several key areas of capacity analysis where the CO3 tool could be improved to better meet MDOT's needs for work zone traffic and cost analysis. First, CO3 currently lacks built-in capacity-calculation capabilities and instead relies on external input sheets, such as the *MDOT Work Zone Safety and Mobility Manual*. Second, the capacity estimation process does not account for variations in truck percentages or traffic compositions, reducing the accuracy of results. Additionally, there are limitations in accommodating different segments or capacities within a work zone, which further impact its applicability.

To address these challenges, participants suggested incorporating a capacity calculator tailored for both freeway and arterial road scenarios. This addition would preserve the tool's ease of use while significantly enhancing its versatility. Participants also emphasized the importance of integrating real-world capacity examples to improve the tool's practical application. The need for capacity analysis of signalized routes was another key point, as the current reliance on external capacity inputs does not account for delays at intersections, leading to potentially inaccurate results. Additionally, the focus group underscored the need to update the tool to reflect changes introduced in the latest Highway Capacity Manual, as outdated methodologies and calculations diminish the accuracy of the current CO3 version. Finally, there was a strong recommendation to include capacity estimation for flagging operations, recognizing this as a critical area requiring further refinement to comprehensively meet MDOT's operational needs

Queue Analysis

The focus group participants identified a significant gap in the CO3 tool regarding queue analysis, particularly in accounting for lane considerations when calculating queue length. It was noted that the tool reports the total backup length without explicitly accounting for the number of lanes. Analysts must manually divide the backup length by the number of lanes to determine the actual queue per lane. This creates a potential usability challenge, especially for first-time users who may not be aware of this requirement. Participants emphasized that incorporating a feature to automatically account for lane configurations into queue-length computations would enhance the tool's accuracy and user-friendliness, ensuring more reliable and intuitive analysis results.

Detour Route Analysis

Participants in the focus group highlighted key challenges and areas for improvement in the CO3 tool's detour route analysis capabilities. A critical need identified was the ability to evaluate multiple detour routes, particularly in complex scenarios such as freeway-to-freeway transitions. For instance, cases where traffic transitions from three lanes to a single lane on a ramp and then returns to three lanes on the freeway pose difficulties for accurate modeling in CO3. These bottleneck scenarios, which are common at ramps, were noted to be inadequately addressed in the tool, potentially affecting the accuracy of traffic flow predictions. Additionally, the participants stressed the importance of incorporating a guided method for calculating diversion rates. Currently, diversion percentages are based on assumptions that can significantly affect results, especially for metrics like per-minute delays. Small inaccuracies in these assumptions can lead to skewed or distorted analyses, particularly in areas with varying traffic conditions. Enhancing CO3 to address these complexities would improve its utility and reliability in evaluating detour routes.

Instruction or Guidance

The focus group discussion revealed significant concerns regarding the clarity and usability of the CO3 tool, emphasizing the need for improved user instructions and guidance. Participants highlighted the lack of an intuitive user manual, noting that it often fails to provide clear guidance on which values are required in specific fields or how to enter data accurately. They suggested that including detailed examples and descriptions of various analysis scenarios would greatly enhance the manual's effectiveness. Additionally, several participants expressed confusion over the terminologies used in the tool, such as "method travel," "normal travel," "range," and "threshold." These terms were noted to require considerable experience interpreting correctly, creating barriers for less experienced users. Furthermore, the lack of robust error-checking features was a recurring concern. Participants reported that when the tool fails to run, it does not provide clear feedback on the error source, making troubleshooting frustrating and time-consuming. Addressing these issues with a more comprehensive, user-friendly manual, clearer terminology, and enhanced error-checking mechanisms would significantly improve the overall user experience of the CO3 tool.

Data Input

The focus group participants identified several challenges and opportunities for improving data input and integration in the CO3 tool. A key issue was the tool's inability to account for variations in traffic and work zone configurations across a freeway segment. Currently, the tool treats the work zone as a single segment, requiring analysts to manually divide it into separate analyses for cases with varying configurations across different sections of the work zone, a process that risks overestimating user delay and cost. Participants also emphasized the need for more user-friendly input and output interfaces. While traffic volume inputs were straightforward, other data fields were described as unintuitive, with unclear instructions creating confusion.

To address these issues, participants suggested implementing color-coded input fields to improve clarity and usability. For instance, red fields could indicate default values, yellow fields could signal mandatory inputs, and green fields could show modifiable but pre-filled values. They also advocated for the inclusion of default inputs to streamline the analysis process, allowing analysts to quickly proceed without extensive manual adjustments. However, some inputs, such as range cells, were noted as confusing, particularly in scenarios like nighttime closures with lane reductions.

Regarding data integration, participants discussed the difficulty of linking CO3 to Traffic Data Management Systems (TDMS). While exporting data from TDMS was often reduced to a simple copy-paste task, there was interest in incorporating Continuous Count Station (CCS) data to enable more accurate, location-specific analyses. They noted that CCS data includes useful information, such as monthly and daily traffic factors, that could be integrated into AADT data to provide time-of-day distribution. However, concerns were raised about the availability and accessibility of CCS data in suitable formats for seamless integration into CO3. Addressing these gaps through improved data handling, streamlined integration with other systems, and intuitive input mechanisms would significantly enhance the tool's functionality and ease of use.

Results Visualization

The focus group discussion underscored the need for improved visualization of results in the CO3 tool, with an emphasis on clarity and streamlined outputs. Participants noted that while extensive visualization features are not a necessity, a clearer presentation of results would greatly enhance the tool's usability. They emphasized that the current output format lacks clarity, often overwhelming users with a large volume of numbers presented without sufficient organization or context.

A key suggestion was to streamline the output to make it more user-friendly, focusing on presenting essential results concisely and in an interpretable manner. Simplifying the format and grouping related metrics would reduce cognitive load and help analysts quickly extract actionable insights. By addressing these issues, CO3 could better support decision-making processes and reduce the effort required to interpret its output.

Scenario Analysis

The focus group participants identified several areas where the CO3 tool could be enhanced to improve its scenario analysis capabilities. A recurring theme was the need for more robust support for arterial analysis. While CO3 appears to be primarily designed for freeway (uninterrupted flow) scenarios, participants noted that it can be adapted for arterials and ramp work (interrupted flow) with limited guidance. They emphasized that dedicated features or clear instructions for arterial and signalized route analyses would significantly enhance its utility.

Another key suggestion was to enable the comparison of multiple work zone scenarios. Participants appreciated CO3's ease of use for side-by-side comparisons of simple freeway scenarios with varying capacities, but found its capabilities too limited to analyze more complex or diverse work zone configurations. Similarly, the need to analyze multiple segments within a work zone was highlighted, as current functionality does not effectively support segmented evaluations.

Specific feedback was provided regarding flagging operations, where participants pointed to challenges such as determining realistic work zone lengths and resolving input issues, particularly for 24-hour operations. They noted that errors often arise when inputting flagging parameters, requiring iterative adjustments to complete the analysis. Additionally, the lack of clarity around "headway" and "gate time" values on the flagging tab was raised as a concern. Improved guidance on these inputs and default values would help users better understand and utilize these features.

Software Type

Participants expressed a strong preference for maintaining CO3 as an Excel-based tool, citing its ease of use and shareability as key advantages. They noted that the spreadsheet format enables straightforward data sharing and collaboration among users, including consultants and stakeholders. Unlike proprietary software, which may not be universally accessible, the Excel-based tool ensures that data can be easily input and shared without compatibility issues. Participants emphasized that transitioning CO3 to a specialized software platform could complicate its use and limit accessibility, potentially creating barriers for users who lack access to or familiarity with the software. Retaining the spreadsheet format was seen as a practical and inclusive choice for supporting MDOT's work zone traffic and cost analysis needs. These challenges underscore the need for significant enhancements or the development of a new tool to better meet MDOT's work zone analysis needs. Addressing these issues will be crucial to improving the efficiency, accuracy, and user experience of work zone analysis tools.

3.3.2 Development of Evaluation Criteria

To address MDOT's needs for analyzing work zone traffic and costs, an evaluation metric was developed based on findings from the web-based survey and follow-up focus group meetings. The survey gathered insights on the current scope of work zone analysis, difficulties with the CO3 tool,

desired additional features, and experiences with other tools. The focus group meetings provided further clarity on specific needs and priorities for improving work zone analysis practices.

The evaluation metric was designed to enable the comparison of both quantitative and qualitative performance of work zone analysis tools. It integrates criteria derived from MDOT personnel feedback, as shown in Table 3-1.

Table 3-1: Criteria for Tools Evaluation

S/N	Criteria	MDOT Needs	Remarks on CO3
1	Capacity analysis	• Real world Capacity examples • Capacity Calculator • Signalized Routes Capacity Analysis • Highway Capacity Manual • Flagging Operation Capacity Estimation	The tool should include a built-in capacity calculator tailored for freeway and arterial roads as well as flagging operations.
2	Queue analysis	• Lane consideration when computing Queue length	The tool should account for lane configurations when calculating queue lengths and other tool outputs.
3	Detour route analysis	• Multiple Detour Route Analysis • Diversion Rate Calculation	The tool should provide guided methods for calculating diversion rates and/or include diversion sensitivity analysis feature.
4	Instruction or guidance	• User Manual • Confusing terminologies, • Error checking	The user manual should provide detailed examples for various scenarios, and the tool should include robust error-checking features to assist users in troubleshooting.
5	Data input	• User friendly input and output • Color Coding • Default Inputs • Data Integration	The tool should distinguish between input fields and default inputs and consideration should be made for data integration with external data sources.
6	Results visualization	• Result Clarity • Streamlined Outputs	The tool should simplify results visualization by grouping related metrics and presenting key outputs in a concise, user-friendly format, enabling quick and actionable insights for decision-making.
7	Scenario analysis	• Arterial Analysis • Multiple segments Analysis • Signalized routes Analysis • Flagging Analysis	The tool should include robust features for arterial and signalized route analyses, scenario comparison and improved flagging analysis.

3.4 Chapter Summary

This chapter identified MDOT's needs for work zone traffic and cost analysis through an online survey and focus group discussions involving MDOT personnel and stakeholders. The survey assessed the usefulness, ease of use, satisfaction, and desired improvements associated with the CO3 tool, while the focus group provided deeper insights into operational challenges and user expectations.

The online survey results showed that experienced users generally viewed CO3 more favorably than less experienced users; however, significant concerns remained regarding usability, visualization, scenario analysis, and data input requirements. Key weaknesses included limited capacity, queue, and detour analysis capabilities, as well as insufficient guidance for handling complex work zone scenarios. Users identified queue length estimation, delay analysis, and detour analysis as the most valuable features, while crash costs and life-cycle cost analysis for pavement type selection received less support. The survey also highlighted deficiencies in results visualization, scenario evaluation, and capacity estimation, which formed the basis for the focus group discussions.

The focus group discussion further clarified user needs and recommended improvements, including built-in capacity calculators for freeway, arterial, and flagging operations; improved queue analysis with lane-based calculations; support for multiple detour routes and diversion estimation; enhanced error checking; and more intuitive input and output interfaces. Participants also emphasized the importance of better data integration with systems such as TDMS and CCS, streamlined output visualization, and improved support for arterial and signalized-route analyses. While recognizing the limitations of CO3, participants strongly preferred maintaining an Excel-based platform because of its accessibility, transparency, and ease of sharing.

Based on these findings, evaluation criteria were developed to support future assessment and enhancement of work zone analysis tools. The criteria encompass capacity analysis, queue analysis, detour evaluation, user guidance, data input, results visualization, and scenario analysis. Together, these findings identified critical gaps in the current CO3 tool and established the foundation for future improvements and Phase II tool development.

Chapter 4: Examination of Existing Work Zone Analysis Tools

4.1 Introduction

This chapter presents the major findings from the evaluation of existing work zone analysis methodologies and tools conducted throughout the previous chapters. The evaluation was designed to assess the applicability, limitations, and operational performance of current approaches for estimating work zone traffic impacts, including capacity, speed, queue formation, delay, congestion, and diversion effects. The objective was to identify operational gaps in existing practices and establish the basis for developing an enhanced work zone analysis framework tailored to MDOT's needs.

Building upon the literature review presented in Chapter 2, the evaluation process incorporated a review of current state DOT practices, survey and focus group discussions with practitioners, comparative assessment of existing work zone analysis tools, field data collection, and analysis of selected work zone case studies. The assessment focused on key components of work zone traffic analysis, including traffic demand estimation, capacity and speed modeling, queue and delay analysis, diversion estimation, ramp interactions, traffic flow representation, and scenario analysis under different work zone conditions.

This chapter synthesizes findings obtained from these evaluations and identifies areas where existing methodologies may not fully address the operational requirements of modern work zone planning and analysis. These findings provide the foundation for the development of the enhanced work zone analysis framework presented in subsequent chapters.

4.2 Selection of Work Zone Analysis Tools for Examination

4.2.1 Features and Functionalities

This subsection presents a qualitative assessment of the features and functionalities of the selected work zone analysis tools (WZAT), focusing on their features, analysis capabilities and performance measures. The tools were evaluated across several critical aspects to determine their suitability for various work zone scenarios. The criteria considered are illustrated in **Table 4-1** and a detailed discussion follows below:

Capacity Analysis

Capacity analysis is a critical component of work zone evaluation because it determines the maximum traffic flow that can pass through a work zone under specific operating conditions. The evaluated tools showed varying levels of capacity estimation capability. CO3 relies on manually entered capacity values from predefined lookup tables, limiting flexibility and calibration capability. In contrast, more advanced Excel-based tools such as the Ohio DOT Lane Closure Queue Analysis Tool, Illinois DOT Work Zone Q-Pro, and Missouri DOT Spreadsheet integrate HCM-based capacity estimation directly into the tool and incorporate state-specific calibration factors. These approaches improve both flexibility and estimation accuracy.

Table 4-1: Comparison of Tools by Features and Functionalities

S/N	Criteria	CO3	QuickZone	WorkZoneQ-Pro	Freeval-PA	CA4PRS	WZTA	Lane Closure Guide
		Michigan DOT	Maryland DOT	Illinois DOT	PennDOT	California	Oregon DOT	Kansas DOT
		Excel-based	Excel-based	Excel-based	Desktop-based	Desktop-based	Web-based	GIS-based
1	Capacity Analysis							
	In-built Capacity Calculation	-	✓	✓	✓	✓	✓	✓
3	Detour route Analysis							-
	Detour route impact	-	✓	-	-	✓		-
	Diversion sensitivity analysis	O			✓			
5	Data Input							
	Map-based Modeling	-	O	-	✓			✓
	Data Integration	-	-	-	✓		✓	✓
7	Scenario Analysis							
	Multi-Scenario Analysis	O	✓	-	✓	✓	-	-
	Multiple Segment Analysis	-	✓	O	✓	✓	✓	✓
	Lane Closure Scheduling	-	✓	-	✓	✓	✓	✓
	Work Zone ITS Analysis				O			
	Stage/Phase Analysis	-	✓	-		✓		
	Flagging Analysis	✓	✓	✓	-			-

✓ = Function is fully supported; O = Function is partially supported; – = Function is not supported.

Detour Route Analysis

Detour route analysis evaluates the traffic impacts of diverted traffic during work zone operations. Most tools, including CO3, FREEVAL-PA, and CA4PRS, primarily focus on mainline operations and use fixed diversion percentages, which may oversimplify actual diversion behavior. More advanced tools, such as the Arizona Work Zone Analysis Tool (AWZA), include dedicated detour-analysis modules that evaluate detour-route capacity, volume-to-capacity ratios, and diversion sensitivity. These capabilities provide a more comprehensive assessment of traffic conditions on both the mainline and alternative routes.

Data Integration

Data integration significantly improves the efficiency of work zone analysis by reducing manual data input and improving consistency. GIS-based and desktop-based tools such as RILCA, KDOT Lane Closure Guide, WIMAP-P, and FREEVAL-PA integrate directly with statewide traffic databases, sensor systems, crash records, and roadway inventories. In contrast, CO3 primarily relies on manual data entry, increasing analysis time and the potential for user error. The findings indicate that integration with real-time and state-maintained databases can substantially improve work zone analysis capabilities.

Scenario Analysis

Scenario analysis evaluates the ability of tools to assess multiple work zone traffic management strategies and operational conditions. Existing spreadsheet-based tools generally offer limited scenario management capabilities and often require analysts to create separate spreadsheets to compare alternatives. Although CO3 allows limited multi-scenario comparisons through parallel input cells, its scenario management remains less intuitive than that of more advanced desktop- or GIS-based tools. More sophisticated tools support multiple-scenario analysis, stage and phase evaluation, lane-closure scheduling, ITS analysis, and dynamic traffic management strategies, making them better suited to evaluate complex work zone operations.

4.2.2 Comparison of Tool by Output

The output capabilities of work zone analysis tools vary significantly, as shown in Table 4-2. While tools like FREEVAL-PA provide comprehensive outputs, including speed calculations, queue analysis, delay metrics (total, average, and maximum delays), level of service, and user cost, CO3 falls short in several areas. CO3 lacks output for capacity calculations and speed calculations. Additionally, its delay analysis is limited to average delays, omitting critical metrics such as maximum delays, vehicle hours traveled (VHT), and vehicle hours delayed (VHD).

These limitations highlight the need to improve CO3's output capabilities, particularly in incorporating detailed metrics that provide a complete understanding of work zone impacts. Tools like FREEVAL-PA also offer visual outputs, enhancing data interpretation for stakeholders. By adding features such as queue visualization and delay trends, CO3 could become more effective and user-friendly, better meeting the evolving needs of work zone analysis.

Table 4-2: Comparison of Tools by Output

Selected Tools	MDOT CO3	Maryland DOT QuickZone v 2.0	Illinois DOT WorkZoneQ-Pro	PennDOT FREEVAL-PA	McTrans HCS 2024	MoDOT Spreadsheet
	Year	Year	Year	Year	Year	Year
Basis	1999	2005	2020	2020	2024	2021
	Excel-based	Excel-based	Excel-based	Desktop based	Desktop based	Excel-based
1 Capacity Estimation		✓	✓	✓	✓	✓
2 Speed Calculation			✓	✓		
Space Mean Speed				✓		
3 Queue Analysis	✓	✓	✓	✓	✓	✓
4 Delay Analysis	✓	✓	✓	✓	✓	✓
Total Delay	✓	✓	✓	✓		✓
Average Delay	✓					
Maximum Delay		✓				✓
VHT & VHD				✓		
5 Level of Service				✓	✓	
6 User Cost	✓	✓	✓	✓	✓	✓

4.2.3 Selected Tools for Analysis

The selection of tools for this analysis was guided by the need to evaluate a diverse range of work zone analysis methodologies currently used by state Departments of Transportation (DOTs). The selected tools represent different analytical approaches, software platforms, development periods, and Highway Capacity Manual (HCM) methodologies. Table 4-3 summarizes the selected tools, including their development year, tool type, associated HCM version, and inclusion within the quantitative and qualitative analyses conducted in this study.

A total of five tools were selected for detailed quantitative analysis at the selected work zone sites, while the ODOT Capacity Calculator was used specifically for capacity-comparison analyses. For the qualitative evaluation, all selected tools except the ODOT Capacity Calculator were included to assess functionality, usability, data integration capability, and operational flexibility.

The selection process was based on several key criteria. First, tools developed or widely used by different state DOTs were prioritized to ensure representation of diverse regional practices and work zone analysis approaches. Second, the selection included a variety of tool platforms, including Excel-based, desktop-based, GIS-based, and web-based tools, to evaluate the influence of platform type on usability, flexibility, and analysis capability. Third, both older and recently developed tools were included to examine the evolution of work zone analysis methodologies over time. For example, older tools such as CO3 were compared with more recently developed tools such as the MoDOT Spreadsheet and newer HCM-based applications.

Finally, the selection also considered the version of the Highway Capacity Manual implemented in each tool. Some tools rely on earlier HCM methodologies, while others incorporate more recent

HCM 6th Edition procedures. This allowed the study to compare older deterministic approaches with updated methodologies incorporating modern capacity, speed, and queue discharge rate estimation procedures. The inclusion of tools representing different HCM generations also supported the evaluation of how recent methodological updates influence work zone traffic analysis accuracy and operational performance.

Table 4-3: Selected Work Zone Analysis Tools

S/N	Tools	Developed by/for	Year Created	Type	HCM Version	Remark
1	CO3	MDOT	1997	Excel-based tool		Included in Analysis
2	QuickZone v 2.0	Maryland DOT	2005	Excel-based tool	HCM 2000	Included in Analysis
3	Work Zone Q-Pro	Illinois DOT	2020	Excel-based tool		Included in Analysis
4	MoDOT Spreadsheet	MoDOT	2021	Excel-based tool	HCM 2010	Included in Analysis
5	FREEVAL-PA	PennDOT	2020	Desktop based tool	HCM 6 th Ed.	Included in Analysis
6	ODOT Capacity Calc	Oregon DOT	-	Excel-based tool	HCM 7 th Ed.	Included in Capacity Analysis only
7	CA4PRS	California		Desktop-based tool		Not included in Analysis
8	Work Zone Traffic Analysis Tool	Oregon DOT	2019	Web-based tool		Not included in Analysis
9	Lane Closure Guide	Kansas DOT	2022	Web-based tool		Not included in Analysis

4.3 Evaluation of Analysis Tools

4.3.1 Selection of Work Zone Sites for Tool Evaluation

The selection of work zone sites was conducted in two stages corresponding to the major objectives of this study. The first stage focused on selecting work zone sites to evaluate existing work zone analysis tools and methodologies, while the second stage focused on selecting sites for model development, calibration, and validation.

The initial stage of the study focused on evaluating existing work zone analysis tools and methodologies for estimating work zone delay, queue length, diversion, and congestion impacts. A review of MDOT highway construction projects and lane-closure activities from 2018 to 2022 was conducted to identify candidate sites for evaluation. Figure 4-1 illustrates the spatial distribution of construction projects across Michigan in 2022.

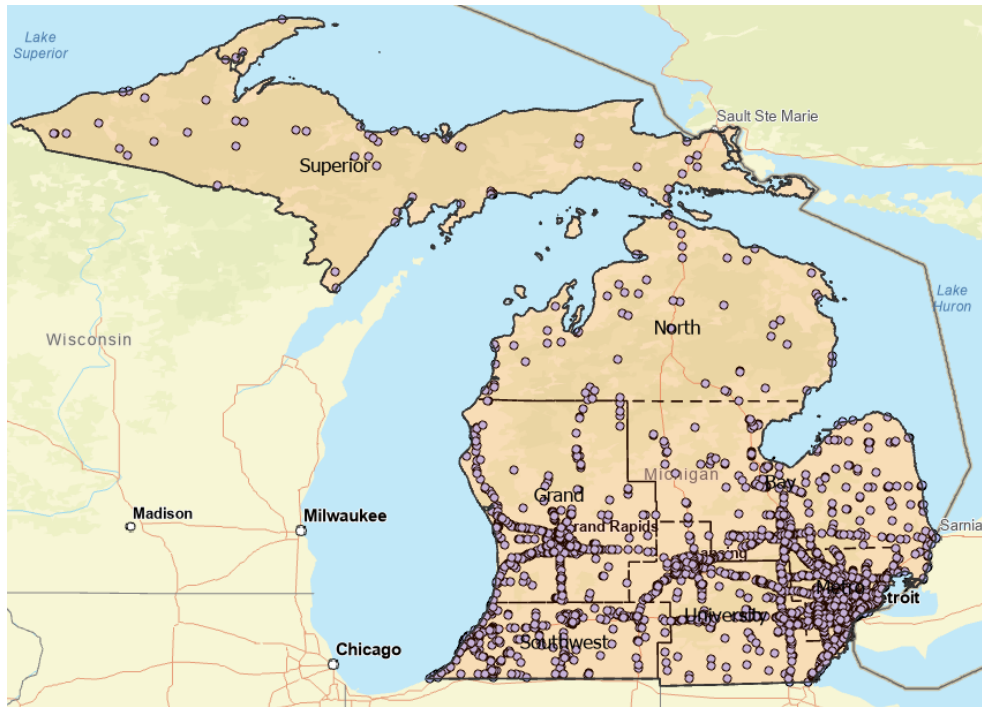


Figure 4-1: Spatial Distribution of Highway Construction Projects (2022)

A total of five work zone sites were selected for the comparative evaluation of work zone analysis tools. The selected sites represented different freeway characteristics, lane-closure configurations, traffic-demand conditions, and operational scenarios to ensure the evaluation captured a broad range of work-zone conditions. Site selection considered several factors, including traffic volume, lane-closure type, work-zone duration, detour conditions, ramp influence, data availability, and observed congestion. Table 4-4 summarizes the details of each selected site and Figure 4-2 shows their distribution among the regions.

Table 4-4: Selected Work Zone Sites for Tool Evaluation

No.	MDOT Region	County	Route	Function Class	Lane Closure category
1	Grand Region	Allegan	US-31	Other Freeway	Single lane closure 2 to 1
2	Metro Region	Wayne	I-275	Interstate	Double lane closure 3 to 1
3	Bay Region	Sanilac	M-90	Minor Arterial	Total closure / bridge rep.
4	Southwest Region	Kalamazoo	I-94	Interstate	Crossover/ Single Lane closure
5	Superior Region	Marquette	US-41	Principal Arterial	Flagging Operation

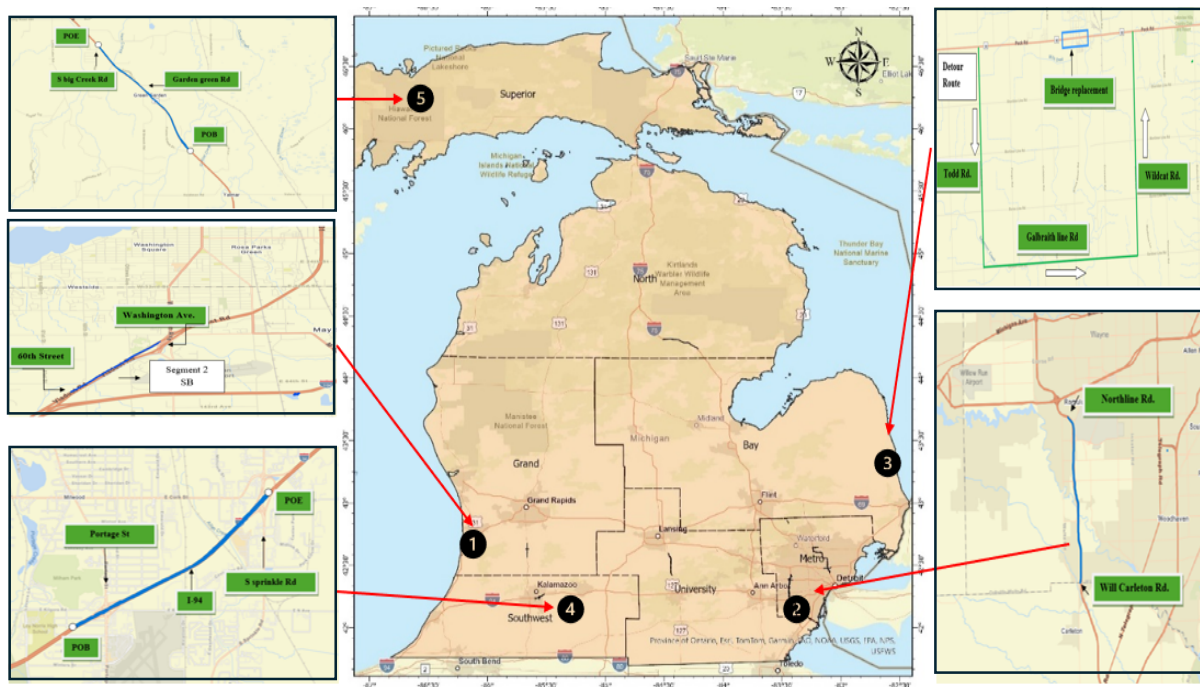


Figure 4-2: Selected Work Zone Sites for Evaluation

4.3.2 Performance Comparison

To compare the performance of the selected work zone analysis tools, the five sites were analyzed individually under varying roadway, traffic, and work zone conditions. Each case study represents a different lane-closure configuration and operational scenario, allowing for a comprehensive comparison of tool performance in estimating capacity, speed, delay, queue length, and congestion impacts. For all case studies, both MDOT demand data and hourly traffic demand obtained from RITIS were used to evaluate the influence of traffic demand source on work zone performance. The following subsections present the detailed analysis for each selected work zone site.

Case 1 – Single Lane Closure on US-31

Project 1 involved a single-lane closure on US-31 southbound between I-196 and Washington Avenue, reducing the freeway from two lanes to one for 2.1 miles. The corridor featured 12-ft lane widths and moderate ramp density, which created noticeable impacts on traffic operations during construction.

The results presented in Table 4-5 showed significant differences among the evaluated work zone analysis tools in their estimates of work zone capacity and operational performance. CO3 used predefined capacity tables adjusted for heavy-vehicle percentages, resulting in lower capacity estimates because geometric and operational characteristics were not explicitly considered. In contrast, FREEVAL-PA produced higher capacity estimates by incorporating detailed roadway geometry, lateral clearance, and operational conditions into the analysis. The MODOT spreadsheet used a simplified methodology that accounted for heavy-vehicle and lane-width effects, while

QPRO provided moderately conservative estimates based on free-flow speed adjustments and work-zone impacts.

Table 4-5: Results – US-31 Southbound

Case 1	Closure type: Single Lane closure (ID 642165) Demand Source: MDOT Diversion: 0%					
	CO3	Quick Zone	FREEVAL-PA	QPRO	MODOT	RITIS
Work zone capacity (Pc/hr)	1,260*	1,500	1,882	1,632	1,310	NA
Non-WZ FFS (mph)	70	70	68.6	70	70	72.1
WZ-FFS (mph)	55	55	49.7	57.6	55	49.8-54.5**
WZ speed at capacity (mph)	37	NA	NA	48.1	NA	-
Max hourly delay (min)	16.4	3.43	0.52	14.3	1.54	1.4-5.5
Max queue length (miles)	5.43	0	0	4.33	5.12	1.1-3.2
*CO3 Capacity (vph)						
** This range is based on the average work-zone speed.						
Case 2	Closure type: Single Lane closure (ID 642165) Demand Source: RITIS Diversion: 0%					
	CO3	Quick Zone	FREEVAL-PA	QPRO	MODOT	RITIS
Work zone capacity (pc/hr)	1,260	1,500	1,882	1,632	1,310	NA
Non-WZ FFS (mph)	70	70	68.8	70	70	72.14
WZ speed (mph)	55	55	51.4	57.6	55	49.84-54.54**
WZ speed at capacity (mph)	37	NA	NA	48.1	NA	-
Max hourly delay (min)	14.8	4.24	0.34	11.8	1.93	1.43-5.54
Max queue length (miles)	4.13	0	0	2.85	5.33	1.08-3.23
*CO3 Capacity (vph)						
** This range is based on the average work-zone speed.						

Among the evaluated tools, FREEVAL-PA and QPRO explicitly estimated work zone speeds based on traffic conditions. FREEVAL-PA calculated work zone speeds as a function of demand and density, producing speeds that closely matched the observed RITIS speed range, indicating strong capability in representing real-world traffic behavior. QPRO estimated slightly lower speeds using a manual speed-adjustment methodology based on free-flow speed and speed at capacity but still produced reasonable approximations. The comparison between the AADT-based demand scenario (Case 1) and the RITIS-based demand scenario (Case 2) showed that using RITIS demand generally reduced congestion impacts, resulting in lower delays and shorter queue lengths across several tools. The results also indicated that CO3 tended to overestimate both delay and queue length compared to the other methodologies.

Case 2- Double Lane Closure on I-275

The second case study focused on the I-275 Pavement Repair project in the northbound direction between Will Carleton Road and Northline Road. The project involved a double-lane closure that reduced the freeway from three lanes to one over an approximately 8-mile segment. Due to the presence of multiple entrance and exit ramps along the corridor, the work zone experienced complex traffic operations with frequent merging and diverging movements. Crash data analysis indicated a substantial increase in crashes during the construction period compared to conditions before and after the work zone, reflecting the significant operational impacts of the lane closure and traffic congestion.

Table 4-6: Results - I-275 Northbound

Case 1	Closure type: Double Lane closure Demand Source: MDOT Diversion: 0%					
	CO3	QuickZone	FREEVAL-PA	QPRO	MODOT	RITIS
Work zone Capacity	1,260*	1,750	2,160	1,689	1,550	NA
Non-WZ FFS (mph)	70	70	65.58	70	70	72
WZ FFS (mph)	55	55	42.3	57.8	55	49.76-52.34**
WZ speed at capacity (mph)	37	NA	NA	49.7	NA	-
Max hourly delay (min)	147.90	79.95	21.60	121.42	145	6.32-8.39
Max queue length (miles)	24.96	18.29	3.42	16.29	14.87	2.21-5.32
*CO3 Capacity (Vph)						
** This range is based on the average work-zone speed.						
Case 2	Closure type: Double Lane closure Demand Source: RITIS Diversion: 0%					
	CO3	Quick Zone	FREEVAL-PA	QPRO	MODOT	RITIS
Work zone Capacity	1,260*	1,750	2,160	1,689	1,550	NA
Non-WZ FFS (mph)	70	70	65.58	70	70	72
WZ FFS (mph)	55	55	51.54	57.8	55	49.76-52.34**
WZ speed at capacity (mph)	37	NA	NA	48.3	NA	-
Max hourly delay (min)	38.2	19.7	8.2	19.4	35.9	6.32-8.39
Max queue length (miles)	4.4	2.4	1.8	2.1	3.6	2.21-5.32
*CO3 Capacity (Vph)						
** This range is based on the average work-zone speed.						

The I-275 Pavement Repair project was evaluated under two traffic demand scenarios to examine the impacts of demand source on work zone performance. The first scenario used MDOT demand data without diversion, while the second used hourly traffic volumes obtained from RITIS. The

comparison revealed significant differences in estimated delays and queue lengths between the two scenarios, underscoring the importance of accurate traffic demand data for work zone analysis.

FREEVAL-PA demonstrated greater capability in representing dynamic traffic operations for the I-275 Pavement Repair project because it accounts for traffic volume changes at entrance and exit ramps along the corridor. Through map-based segmentation, the tool can model merging and diverging traffic movements more realistically, making it particularly suitable for complex freeway work zones with multiple ramps. In contrast, QuickZone allows users to define detours and network configurations but requires manual demand calculations for each segment, which can increase the potential for input inconsistencies and analysis errors in complex scenarios.

The comparison between Case 1 (MDOT demand data) and Case 2 (RITIS demand data) showed substantial differences in estimated congestion impacts. Case 1 resulted in significantly higher delays and queue lengths across most tools, indicating severe congestion under the MDOT demand assumptions. In comparison, using RITIS demand data in Case 2 resulted in considerably lower delays and shorter queue lengths, demonstrating the importance of accurate traffic demand representation in work zone analysis. The results also showed that CO3 and the MODOT spreadsheet generally overestimated delays compared to the other tools.

Case 3 - Total Closure on M-90

The M-90 Bridge Replacement project involved a total closure of the bridge over the Black River, requiring all traffic to follow a designated 15-mile detour route during construction. The project was located on a minor arterial roadway with a posted speed limit of 45 mph and moderate traffic demand, while the detour route experienced increased traffic volumes throughout the closure period. Crash data also indicated changes in traffic safety conditions on both the main route and detour roads during construction activities.

This case study primarily focuses on evaluating detour operations and traffic impacts associated with total roadway closure conditions. Unlike freeway lane-closure scenarios, this project required traffic redistribution through alternative arterial routes and intersections, making accurate delay estimation more challenging. Although detailed arterial and intersection analysis can typically be performed using tools such as Synchro/SimTraffic, the evaluated work zone analysis tools did not provide direct integration with detailed intersection operational analysis, limiting their ability to fully capture detour-related intersection delays and arterial traffic performance.

Among the evaluated tools, CO3, QuickZone, and the MODOT spreadsheet provided detour analysis capabilities, although with several limitations. As presented in Table 4-7, these tools primarily estimated detour impacts based on additional travel time associated with longer alternative routes rather than detailed intersection-level operational analysis. Consequently, the effects of congestion at intersections and signalized locations along the detour route were not fully represented. Another major challenge in this analysis was the lack of available field data for the detour corridor, which limited the ability to validate tool performance and compare estimated delays with observed field conditions.

Table 4-7: Results - Total Closure on M-90

Closure type: Total Closure (ID 756117)						
Demand Source: MDOT (main route)						
Diversion: 0%						
	CO3	QuickZone	FREEVAL-PA	QPRO	MODOT	RITIS
Work zone Capacity	1,260*	1,500	NA**	1,443	1,470	NA
Non-WZ FFS (mph)	45	45	NA**	45	45	NA
WZ FFS (mph)	45	45	NA**	42.5	45	NA
WZ speed at capacity (mph)	37	NA	NA**	33	45	NA
Max hourly delay (min)	19.5	22.34	NA**	NA***	16.43	NA
Max queue length (miles)	0	0	NA**	NA***	0	NA
*CO3 Capacity (Vph)						
**The tool is applicable for freeways but cannot analyze detours, as it focuses solely on freeway segmentation						
*** No RITIS data available (these segments are not defined as TMC segments)						

Case 4 – Crossover on I-94

This Project focused on the I-94 Reconstruction and Widening project in Kalamazoo, which included a westbound crossover operation and an eastbound single-lane closure over a 2.4-mile segment. The corridor experienced high traffic volumes, multiple ramps, and a relatively high percentage of heavy vehicles, creating complex work-zone traffic conditions.

The westbound direction operated with two lanes open during the daytime, while nighttime operations used a single crossover lane under reduced-speed and reduced-lane-width conditions. The eastbound direction experienced a standard single-lane closure. The results presented in Table 4-8 showed noticeable differences among the evaluated tools in estimating work zone capacity for the crossover configuration. FREEVAL-PA incorporated HCM-based capacity reduction relationships for crossover operations, while QPRO reflected crossover impacts indirectly through reduced free-flow speed adjustments. In contrast, CO3 and Quick Zone generally treated the crossover similarly to a standard single-lane closure. Overall, the analysis demonstrated that crossover operations introduce additional complexity into work zone traffic analysis and can significantly influence estimated operational performance.

Table 4-8: Results - I-94 Reconstruction and Widening

Case 1	I-94 West Bound Closure type: Crossover from (11:00 pm to 6 am) Demand Source: MDOT Diversion: 0%					
	CO3	QuickZone	FREEVAL-PA	QPRO	MoDOT	RITIS
Work Zone Capacity	1,260* 3,330*	1,750	1,814	1,574	1,260	NA
Non-WZ FFS (mph)	70	70	65.85	70	70	76
WZ FFS (mph)	60	60	56.8	52.6	NA	57.5-72.8
WZ speed at capacity (mph)	37	NA	NA	46.8	NA	-
Max hourly delay (min)	26.5	31.3	12.6	NA**	66.1	0.7-4.1
Max queue length (miles)	9.0	12.4	2	NA**	10.1	0-3.1
*CO3 Capacity = 1,260 vph during the median crossover, 3,330 mph within daytime with normal two lanes						
** Queue exceeded the length of the analyzed section; calculations are stopped.						

Case 2	I-94 East Bound Closure type: Single Lane closure (ID 820458) Demand Source: MDOT Diversion: 10%					
	CO3	QuickZone	FREEVAL-PA	QPRO	MoDOT	RITIS
Work Zone Capacity	1,260*	1,750	1,929	1,574	1,260	NA
Non-WZ FFS (mph)	70	70	68.6	70	70	77
WZ FFS (mph)	60	60	57.8	42.5	60	57.5-72.8
WZ speed at capacity (mph)	37	NA	NA	33	NA	-
Max hourly delay (min)	28.4	21.8	8.5	22.6	30.3	0-20.6
Max queue length (miles)	9.2	17.4	0.5	4.1	11.2	0-2.5
*CO3 Capacity (Vph)						

As summarized in Table 4-8, most of the evaluated tools overestimated delays and queue lengths for the I-94 work zone scenarios, particularly in Case 1, likely because traffic diversion effects were not fully accounted for and the assumed traffic demand exceeded actual field conditions. Even in Case 2, which assumed a 10% traffic diversion for the westbound single-lane closure, CO3 and the MODOT spreadsheet continued to overestimate congestion impacts. In contrast, FREEVAL-PA produced the lowest estimates of delay and queue length due to its higher calculated work zone capacity and more detailed operational representation.

Case 5 - Flagging Operation on US-41

Project 5 involves the analysis of a work zone configuration on the US-41 repair and rehabilitation project conducted between Kunde Rd and Big Creek Rd. The project's purpose was to enhance road conditions and safety in Chocolay Township, Marquette County, Michigan, through various construction activities, including hot-mix asphalt overlays and curb-and-gutter replacements. The project timeline spanned from September 2, 2022, to October 28, 2022.

The flagging operation was analyzed only by CO3 and QPRO, as the other tools lack such flagging features. The analysis results are shown in Table 4-9.

Table 4-9: Results – Flagging on US-41

Project 5 Case 1	US-41 North Bound		
	Closure type: Flagging Operation (ID 662495)		
	Length: 3.25 miles		
	Location: S Big Creek Rd to Kunde Rd		
	Time: 9/8/2022 to 10/31/2022 (7 AM to 7 PM)		
	Demand Source: MDOT		
	Diversion: 0%		
	CO3	QPRO	RITIS
Work zone Capacity	786	377	NA
FFF (mph)	55	50	48.0 – 68.3
WZ speed (mph)	45	45	31.1 – 68.1
Max hourly delay (min)	9.8	4.8	1.9
Max queue length (miles)	0	0.2	NA

The flagging operation for the US-41 repair and rehabilitation project was designed to manage one-lane traffic flow effectively, ensuring minimal disruption during peak daytime hours from 7:00 AM to 6:00 PM. To maintain smooth and safe passage under controlled conditions, a 3-second vehicle headway was maintained at the gate. Additionally, a 10-second dead time was allocated during direction changes to safely halt traffic in one direction and allow vehicles in the opposite direction to begin moving. To prevent excessive delays, the gate remained closed to one direction for a maximum of 10 minutes before switching to allow traffic from the other direction.

The analysis incorporated specific input parameters essential for modeling and evaluating the flagging operation. Lane and shoulder widths were set at 11 feet and 8 feet, respectively. A saturation flow rate of 1900 pcphpl was used, reflecting the project's medium work intensity.

CO3 relies on predefined capacity tables and static assumptions to evaluate work zone performance. For the flagging operation, it used the input parameters directly without further adjustments, focusing on providing a simplified and rapid assessment. CO3 is well-suited for preliminary analyses where quick results are needed, but its reliance on generalized values and lack of dynamic adjustments limits its ability to fully capture the impacts of variable traffic conditions and geometric features.

In contrast, WorkZone Q-Pro employs a more dynamic approach by integrating queuing theory into its analysis. It adjusts for specific factors such as vehicle headway and gate closure duration, which are critical for accurately modeling flagging operations. Additionally, Q-Pro offers a more granular representation of traffic flow, enabling it to evaluate the impacts of changing traffic volumes throughout the day. This makes Q-Pro more adaptable for scenarios requiring detailed insights into operational impacts.

4.4 Evaluation of Operational Analysis Methods

4.4.1 Demand Input Analysis

Traffic demand input was identified as one of the most influential factors affecting the results of work zone traffic analysis. The evaluation revealed significant differences among tools in how traffic demand is estimated, distributed, and incorporated into operational analysis. CO3 uses location-specific hourly traffic distributions when available to distribute traffic volume throughout the day. When such data are unavailable, a default hourly traffic distribution may be applied. Although this approach provides general traffic demand estimates, it may not accurately reflect traffic characteristics specific to Michigan conditions.

Other tools use more advanced demand estimation methodologies. INRIX utilizes national AADT datasets at the roadway segment level and converts traffic demand into 15-minute intervals for an average week, providing more detailed temporal traffic patterns. RITIS further expands its demand estimation capabilities by incorporating probe-vehicle data, commercial-vehicle information, observed speeds, penetration rates, the number of lanes, and time-dependent traffic characteristics. These differences demonstrate that modern work zone analysis increasingly relies on high-resolution and dynamic traffic datasets rather than static historical distributions.

The evaluation also indicated that the quality and resolution of traffic demand input significantly affect queue estimation, delay calculation, diversion analysis, and overall operational performance assessment. Consequently, the use of real-world, site-specific traffic demand data was identified as an important requirement to improve the accuracy of work zone traffic analysis.

4.4.2 Capacity Analysis

Capacity analysis was identified as another critical component influencing work zone traffic analysis results. The evaluated tools demonstrated substantial differences in how work zone capacity is estimated and adjusted for operational and geometric conditions. Several methodologies incorporate systematic adjustment procedures to account for factors such as the percentage of heavy vehicles, terrain, lane configuration, barrier type, work zone intensity, and roadway geometry.

The heavy-vehicle percentage was found to be one of the most influential variables for estimating work zone capacity. Tools such as CO3 reduce base capacity values based on truck composition due to the operational impacts of larger vehicle size and reduced acceleration capability. Similarly, FREEVAL-PA, QPRO, and MoDOT integrate HCM-based heavy-vehicle adjustment procedures to improve capacity estimation under varying traffic-composition conditions.

The evaluation also revealed differences in the units and methodologies used among tools. CO3 primarily uses vehicles per hour (vph), whereas most newer tools, such as FREEVAL-PA and QuickZone, use passenger car equivalents per hour (pc/hr). This distinction affects how heavy vehicles and traffic composition are represented within the analysis.

Several tools additionally incorporate terrain and roadway functional classification into capacity estimation procedures. For example, QuickZone applies lower capacity values for steep grades and two-lane facilities compared to level freeway segments. FREEVAL-PA and QPRO further adjust capacity based on lane closures, barrier types, work zone intensity, free-flow speed, and operational control measures such as police enforcement and traffic management treatments.

More advanced methodologies, such as those used by the Oregon Department of Transportation (ODOT), incorporate calibration adjustment factors for driver familiarity and speed adjustment factors for weather conditions using HCM 7th Edition methodologies. Table 4-10 presents detailed factors that are considered by various tools.

Table 4-10: Factors Considered in Work Zone Capacity Analysis by Tool

Factor	CO3	Quick Zone	FREEVAL PA	QPRO	MoDOT Spreadsheet	ODOT Capacity calculator
Lane closure type			✓		✓	✓
Barrier type			✓	✓		
Number of open lanes	✓	✓	✓	✓	✓	✓
Heavy vehicle percentage	✓	✓	✓		✓	
Work zone intensity	✓			✓		
Speed reduction			✓	✓		✓
Geometric features			✓	✓		✓
Free Flow Speed (FFS)			✓	✓		✓
Weather Conditions			✓	✓		✓
Presence of Ramps	✓	✓	✓			✓
Local Traffic Patterns					✓	✓
Type of Construction Activity			✓			

The following Table 4-11 provides a comparative overview of six traffic analysis tools: CO3, QuickZone, FREEVAL, QPRO, MoDOT, and ODOT based on their capacity guidelines, ability to account for percentage truck variation during the analysis period, inclusion of built-in capacity calculators, and capacity variation features in work zone modeling.

Table 4-11: Comparison of Capacity Analysis Methods by Tool

	CO3	Quick Zone	FREEVAL	QPRO	MoDOT	ODOT
Capacity Guideline	MDOT Common input sheet based on the Work zone safety and mobility manual and AASHTO	QuickZone 2.0 incorporates the MDSHA work-zone capacity estimator, offering UMD and HCM (1997 or 2000) estimation methods.	HCM 6 capacity and PENNDOT capacity	HCM 6	Capacity is based on HCM 2010, or it can be input manually	HCM 7, Local Calibration Factor (CAF)
Percentage truck variation with analysis period	No, CO3 does not provide option for traffic composition variation with time	Yes, QuickZone includes truck percentage variation with analysis period as well as weekday and weekend distributions	Yes, FREEVAL provides an option for traffic composition variation with time (calibration)	Yes, Work ZoneQ-Pro provides option for traffic composition variation with time	No, MoDOT does not provide option for traffic composition variation with time	NO ODOT does not provide option for traffic composition variation with time
In-built Capacity calculator	No	Yes	Yes	Yes	Yes	Yes
Work Zone Capacity variation with analysis period	Work Zone capacity can be adjusted over time for a Work Zone	Work-zone capacity can vary over time, but weekly phasing inputs make hourly work-plan modeling time-consuming.	Work Zone capacity can be adjusted over time for a Work Zone	Constant capacity-drop assumptions may not reflect field variability.	Work Zone capacity does not change over time for a Work Zone	ODOT does not provide option for traffic composition variation with time

4.4.3 Queue and Delay Analysis

Queue length and delay estimation are critical components of work-zone traffic analysis because they directly affect congestion assessment, travel-time reliability, and traffic management strategies. The evaluation revealed significant differences among tools in how queues and delays are estimated and represented.

CO3 and the MoDOT Spreadsheet primarily use deterministic input-output queue analysis methods that relate traffic demand to available capacity. In contrast, tools such as QuickZone and FREEVAL-PA apply more systematic deterministic queueing procedures, while Illinois DOT WorkZoneQ-Pro uses a simulation-based Cell Transmission Model (CTM) approach to dynamically representing queue propagation and congestion evolution.

The evaluation also identified differences in assumptions about queue representation. CO3 assumes fixed vehicle spacing regardless of traffic composition, whereas MoDOT adjusts spacing based on truck percentage. FREEVAL-PA and WorkZoneQ-Pro represent physical queues requiring roadway storage space, while CO3 and MoDOT primarily represent vertical queues that focus only on accumulated delay. Additionally, WorkZoneQ-Pro and FREEVAL-PA estimate both moving and stopped queues, providing a more realistic representation of congestion under oversaturated conditions.

Delay estimation methodologies also varied considerably among tools. CO3 estimates speed delay using simplified demand-capacity relationships, while FREEVAL-PA and WorkZoneQ-Pro calculate delay using speed-flow relationships and dynamic traffic simulation. The evaluation showed that queue and delay estimation results are highly sensitive to capacity assumptions, traffic demand inputs, lane-closure configurations, and queue-representation methods.

4.4.4 Speed Analysis

The evaluation showed significant differences among tools in how work zone speeds are estimated and applied within traffic analysis. Among the analyzed tools, only FREEVAL-PA and WorkZoneQ-Pro calculate work zone speeds directly using built-in methodologies. Most other tools, including CO3, rely on user-defined work zone speed inputs rather than internal computing speeds based on traffic and roadway conditions.

In CO3, the work zone speed at capacity is manually entered using values provided in the CO3 manual. This approach requires careful interpretation because the specified speed may represent either the posted work zone speed limit or the actual operating speed under congested conditions. In contrast, FREEVAL-PA applies HCM-based free-flow speed adjustment procedures that account for factors such as lane-closure severity, barrier type, area type, lighting conditions, lane availability, and ramp density to dynamically estimate work-zone free-flow speed.

After estimating the work zone free-flow speed, actual speeds are calculated for each analysis interval based on traffic flow conditions, including volume, density, and lane availability. These calculations continuously update traffic conditions over time and directly affect queue formation, delay estimation, and congestion propagation.

The evaluation also revealed that implementing dynamic speed calculations in spreadsheet-based tools can pose computational challenges, as queue propagation and traffic conditions require iterative calculations across multiple analysis intervals.

4.5 Development Alternatives for Work Zone Analysis Tool

Four development alternatives were evaluated to identify the most suitable approach for improving MDOT's work zone analysis capabilities:

Alternative 1: Adopting an existing, commercially available tool such as FREEVAL-PA or QPRO

Alternative 2: Develop a New Excel-Based Tool

Alternative 3: Transforming the CO3 tool into a standalone software with advanced features and improved usability

Alternative 4: Developing a completely new tool that integrates all stages of work zone analysis

Each of these alternatives is analyzed against nine key criteria in the following subsections:

- **Capacity analysis:** Including real-world examples, flagging operation estimates, and compatibility with the Highway Capacity Manual (HCM).
- **Queue analysis:** Considering lane-specific queue length calculations.
- **Detour route analysis:** Incorporating multiple route and diversion rate assessments.
- **Instruction and guidance:** Emphasizing clear user manuals, intuitive terminology, and error-checking functionality.
- **Data input:** Ensuring user-friendly inputs with default values, color coding, and integration capabilities.
- **Results visualization:** Providing streamlined, clear outputs for easier interpretation.
- **Scenario analysis:** Supporting complex analyses, including arterials, signalized routes, and flagging operations.
- **Development efforts:** Considering the time, resources, and expertise required to implement or adapt the tool to MDOT's specific needs, including software customization and integration with existing systems.
- **Training efforts:** Evaluating the training needs for MDOT staff, ensuring the tool is accessible and user-friendly with adequate support for onboarding, documentation, and ongoing technical assistance.

4.5.1 *Alternative 1: Adopting an Existing Tool*

Adopting an existing tool such as FREEVAL-PA or WorkZoneQ-Pro represents the shortest implementation pathway because these platforms already provide established methodologies for capacity estimation, queue analysis, speed modeling, and delay estimation. The primary effort under this alternative would focus on calibration, customization, and integration with Michigan-specific datasets rather than software development.

Potential enhancements would include incorporating MDOT databases (e.g., CCS, TDMS, AADT sources), calibrating models to Michigan traffic conditions, improving support for flagging operations and complex lane closures, and adapting interfaces to existing MDOT workflows.

Development effort is relatively low because implementation largely depends on configuration and integration activities. However, required modifications may increase costs depending on vendor flexibility and licensing restrictions. Training requirements are expected to be moderate, as users will need to adapt to unfamiliar interfaces and analytical assumptions.

Overall, this alternative provides rapid deployment with limited development burden but reduced flexibility for long-term adaptation.

4.5.2 *Alternative 2: Developing a New Excel-based Tool*

Developing a new Excel-based work zone analysis tool offers a practical approach to improving analytical capabilities while maintaining compatibility with MDOT's existing spreadsheet-based workflows. Rather than modifying the legacy CO3 workbook, this alternative would create a new tool using modern Excel and VBA architecture, with improvements focused on analytical accuracy, usability, modularity, and expanded scenario analysis. The major proposed features are summarized in Table 4-12.

Table 4-12: Suggested Improvements for CO3 while Maintaining its Excel-based Framework

S/N	Criteria	Suggested Improvement for CO3
1	Capacity analysis	Embedded capacity estimation module
2	Queue analysis	Deterministic Queue Analysis based on 15-min volume Accounting for lane-specific configurations to improve queue length and delay estimates. Dynamic vehicle length and spacing based on composition (e.g., 25 ft for cars, 50 ft for trucks).
3	Detour route analysis	Diversion Sensitivity Analysis Detour Route Impact Module and Intersection delay analysis
4	Modular structure	Splitting computational analysis into separate sheets for specific components like speed analysis, capacity modeling, delay calculations, and queue modeling Streamlined functionality to make the tool more organized and user-friendly
5	Input process	Intuitive input sheets with clear prompts and pre-defined dropdown options for critical variables (e.g., lane closure types, diversion rates, truck percentages). Simplified and user-friendly design to reduce input errors and improve efficiency.
6	Results visualization	Adding visual representations of delays, queue lengths, and speed impacts to aid in scenario comparisons and decision-making

Retaining the Excel environment offers an important implementation advantage because MDOT personnel are already familiar with spreadsheet-based applications. A newly developed Excel tool could avoid dependence on legacy macros and outdated functions while providing a more structured and maintainable architecture. It could also incorporate applicable methodologies and useful features from CO3 while allowing new analytical procedures to be integrated more efficiently.

Development under this alternative is estimated at approximately 12 months and would primarily involve building the computational modules, designing the user interface, integrating updated analytical procedures, and organizing the tool into modular components. Training requirements are expected to remain relatively low because users would continue working within a familiar Excel environment, allowing training and implementation to occur progressively as development is completed.

4.5.3 Alternative 3: Transforming the CO3 tool into a Standalone Software Platform

Transforming CO3 into a standalone software platform provides an opportunity to move beyond the computational and interface limitations associated with spreadsheet-based tools while retaining the analytical strengths developed within the existing framework. Unlike incremental Excel improvements, this alternative focuses on developing an independent software environment with enhanced processing capability, improved visualization, and expanded integration with external data sources. The major proposed improvements for this alternative are summarized in Table 4-13.

A major advantage of this alternative is the ability to develop a modern graphical user interface (GUI). The interface could provide real-time visualization of queues, delays, diversion impacts, and operational performance, allowing users to interpret results more efficiently than traditional spreadsheet outputs. Similar to platforms such as HCS or FREEVAL-PA, the software could incorporate interactive graphics, scenario comparison tools, and guided workflows suitable for both technical and non-technical users.

Development efforts for this alternative are estimated at approximately 12–16 months and would involve software design, computational module redevelopment, user interface creation, database integration, and testing. User interface development would occur concurrently with the implementation of the analytical module to improve compatibility between the computation and visualization components. Training requirements are expected to be moderate, with approximately 3–4 additional months needed for onboarding and integration into MDOT workflows.

Overall, transitioning CO3 to standalone software substantially improves scalability, visualization capabilities, and integration potential while preserving the analytical functionality developed in the original tool. However, these improvements require greater development effort, increased implementation cost, and additional training compared with maintaining the Excel-based framework.

Table 4-13: Suggested Improvements for Transforming CO3 into a Standalone Software

S/N	Criteria	Suggested Improvement for CO3
1	Capacity analysis	Embedded capacity estimation module
2	Queue analysis	Deterministic Queue Analysis based on 15-min volume Accounting for lane-specific configurations to improve queue length and delay estimates. Dynamic vehicle length and spacing based on composition (e.g., 25 ft for cars, 50 ft for trucks).
3	Detour route analysis	In-built diversion rate analysis module for evaluating the effects of varying diversion rates on work zone performance Modeling the impact of diversion scenarios on delays, queues, and capacity
4	User Interface	Intuitive interface with graphical capabilities for dynamic visualizations. Real-time visualizations of results, including queue length visualizations for physical and vertical queue analyses User-friendly design inspired by platforms like HCS, ensuring accessibility for technical and non-technical users
5	Integration with Mapping Systems	Integration with MDOT's ESRI-powered AADT data and Traffic Count Database (TDMS). Map-driven interface offering interactive visualization of roadway segments, including ramps, merges, and diverges. Capability for multiple demand input scenarios to model variations in traffic patterns.
6	Results visualization	Visual representation of traffic patterns, queue dynamics, delays, and diversion impact alongside input data.
7	Processing Efficiency	High processing efficiency to handle complex, high-demand scenarios with minimal computational delays.

4.5.4 *Alternative 4: Creating a New Tool for Comprehensive Work Zone Analysis*

Developing a new, comprehensive work zone analysis tool, on the other hand, could address the full lifecycle of highway construction projects, as illustrated in the provided framework (see Figure 4-3). This new tool would integrate multiple functionalities to support decision-making across all stages of work zone planning, implementation, and evaluation. The tool could ensure a robust and holistic approach to work zone management by incorporating advanced features and aligning with modern traffic analysis requirements.

The new tool would start by integrating preliminary traffic analysis to assess the mobility threshold and determine whether a project is significant. Based on this assessment, users could evaluate construction schedules and work zone layouts, while also considering alternative strategies such as staging, pavement techniques, and accelerated bridge construction (AP/ABC) contracting. This would allow users to weigh different scenarios early in the project lifecycle, minimizing delays and optimizing resource allocation.

A core functionality of the tool would be the ability to support detailed work zone traffic analysis, with a focus on mitigation strategies to minimize traffic impacts. This analysis would incorporate TMP (Transportation Management Plan) costs, user costs, and construction costs, enabling a comprehensive life-cycle cost analysis. The integration of cost components enables decision-

makers to evaluate both the short- and long-term implications of various mitigation measures, fostering data-driven decision-making.

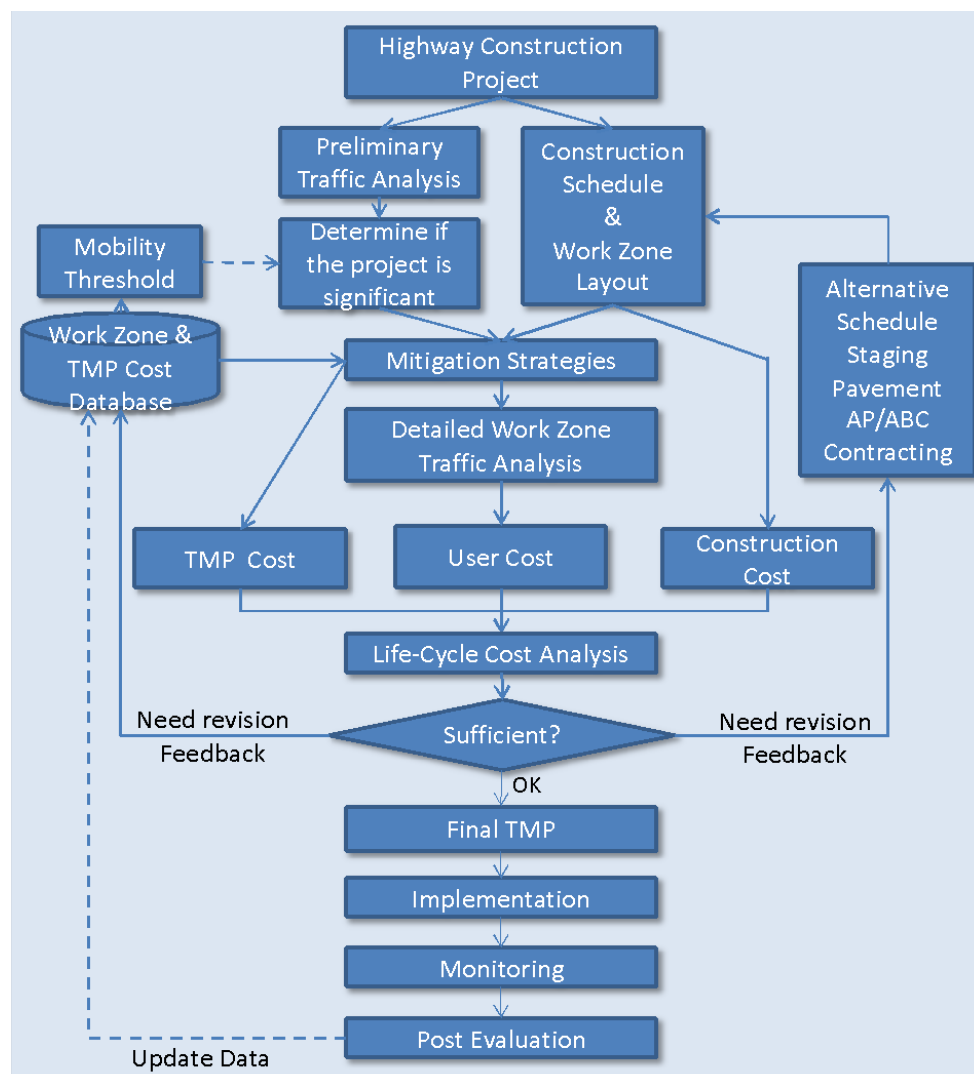


Figure 4-3: Comprehensive Work Zone Analysis Tool

The tool would also feature feedback loops, allowing iterative revisions based on the sufficiency of life-cycle cost analysis results. If revisions are needed, the tool would guide users through refining the TMP, updating cost estimates, and adjusting schedules. Once the analysis is deemed sufficient, the tool will proceed to generate a final TMP ready for implementation. Post-implementation monitoring and evaluation would be integrated, allowing users to update the tool's database with real-world performance data, further improving accuracy for future projects.

Additionally, the tool could include graphical visualizations, such as interactive maps and network diagrams, to represent construction schedules, work zone layouts, and traffic impacts. It could also integrate available MDOT data sources to support cost and mobility analyses and improve

consistency of project inputs. Alternative strategies and multi-scenario analysis would allow users to efficiently compare different schedules, work zone configurations, and mitigation measures.

To address evolving traffic conditions, the tool could simulate the impacts of construction activities on mobility and safety, factoring in ramps, merges, diverges, and other geometric features. The inclusion of multiple demand inputs would enable users to account for peak and off-peak variations, ensuring that the tool's outputs align with real-world conditions.

In conclusion, developing a new, comprehensive work zone analysis tool offers unparalleled flexibility and functionality (e.g., seven criteria in tool evaluation), allowing MDOT to address its unique challenges while meeting modern traffic analysis requirements. While the high development investment and training efforts (estimated at 3 years for software development, tool implementation, and tool training) pose challenges, the long-term benefits of lifecycle integration, advanced analysis capabilities, and scalability make this option a transformative solution for Michigan's work zone management.

4.5.5 SWOT Analysis of Tool Development Options for Work Zone Analysis

SWOT analysis is a critical decision-making tool that helps evaluate the feasibility, risks, and benefits of each alternative, ensuring that the chosen direction aligns with Michigan-specific requirements and MDOT's strategic goals. By identifying the factors affecting each option, this analysis clarifies which approach best improves work zone analysis capabilities while addressing key challenges such as integration, usability, scalability, and cost-effectiveness.

The SWOT analysis presented in Table 4-14 evaluates four potential development alternatives for Michigan's work zone analysis tool: 1) adopting an existing, commercially available tool such as FREEVAL-PA or QPRO, 2) enhancing the current CO3 tool while maintaining its Excel-based framework, 3) transforming the CO3 tool into a standalone software with advanced features and improved usability, and 4) developing a completely new tool that integrate all stages of work zone analysis.

The SWOT analysis underscores the trade-offs among the tool development options in terms of cost, development effort, and long-term functionality. While adopting an existing tool offers immediate implementation, updating or developing CO3 provides opportunities for tailored enhancements and scalability. It also highlights that enhancing CO3 within its Excel-based framework is the most practical and cost-effective solution to improve Michigan's work zone analysis capabilities. This option leverages MDOT staff's existing familiarity with the tool, minimizing training requirements and shortening the implementation timeline compared to more complex alternatives. Additionally, incremental updates can be phased in to address key limitations such as queue modeling and lane-specific analysis, without the high upfront investment required for standalone or entirely new tools. While Excel's inherent constraints must be managed, this approach provides a balanced solution that aligns with MDOT's immediate needs and resource availability, making it the preferred option for improving sustainable work zone analysis.

Table 4-14: SWOT Analysis of Tool Development Options

Category	Adopting an Existing Tool	Developing a New Excel-Based Tool	Transforming CO3 into a Standalone Software	Developing a Comprehensive New Tool
Strengths	- Proven methodologies validated through widespread use.	- Familiarity with CO3 minimizes training needs.	- Enhanced interface with real-time visualizations improves usability.	- Fully tailored to Michigan's work zone analysis needs.
	- Robust features for capacity modeling, delay estimation, and queue dynamics.	- Cost-effective enhancements to address existing limitations.	- Integration with MDOT's ESRI-powered AADT data enables dynamic mapping.	- Supports full life cycle analysis, from planning to post-evaluation.
	- Immediate implementation saves development time.	- Simplified input processes with user-friendly dropdowns and prompts.	- Advanced computational analysis for capacity, queue, and diversion rates.	- Incorporates advanced simulation and multi-scenario analysis.
	- Alignment with HCM 6 standards ensures rigor.	- Modular structure allows independent analyses for speed, capacity, delay, and queue modeling.	- High processing efficiency supports 15-minute interval analysis.	- Integration with real-time data for accurate predictions.
Weaknesses	- Limited customization for Michigan-specific needs.	- Excel's limitations in handling large datasets or dynamic scenarios.	- High development costs compared to maintaining the Excel-based version.	- High development costs and resource requirements.
	- May lack integration with MDOT's TDMS and ESRI-based databases.	- Complexity of modular sheets may confuse users in managing multiple analyses.	- Significant integration efforts are required with MDOT's databases.	- Lengthy timeline for design, testing, and implementation.
	- Vendor dependency may limit future enhancements.	- Minimal graphical capabilities compared to standalone or new tools.	- Transition to standalone software may require significant training for MDOT staff.	- Risk of over-complication if too many features are incorporated at once.
Opportunities	- Collaborate with vendors for customization and regional calibration	- Incremental updates allow for the phased adoption of improvements.	- Opportunity to position CO3 as a leading work zone tool in other agencies.	- Potential to set a benchmark in work zone analysis tailored for Michigan.
	- Expedited implementation ensures quicker benefits realization.	- Flexibility in introducing new features in future updates.	- Incorporates real-time data visualization and advanced modeling.	- Supports long-term MDOT goals for efficient traffic management and mobility improvement.
			- Ability to handle complex scenarios like ramp merges and diverges dynamically.	
Threats	- Misalignment with Michigan-specific workflows and traffic patterns.	- Excel's limitations may restrict the scalability of the tool.	- High upfront investment in development and integration.	- Significant financial and time investments could delay benefits realization.
	- Dependence on external vendors for updates and licensing.	- Complexity in Excel sheets could lead to errors or mismanagement.	- Relying on ESRI or TDMS for integration may pose licensing or data-sharing challenges.	- Risk of feature creep, making the tool overly complex for users.
			- Resistance from users unfamiliar with standalone software.	

4.6 Development Direction: Developing a New Excel-based Tool and Data Collection

Based on the evaluation of existing work zone analysis methodologies and development alternatives, the research team identified Alternative 2: Developing a New Excel-Based Tool as the most suitable direction for MDOT. Rather than modifying or carrying forward the existing CO3 spreadsheet, this alternative uses a new Excel-based framework designed to improve analytical accuracy, usability, modularity, and scenario analysis while remaining compatible with familiar MDOT workflows. The approach provides a practical balance between development effort, implementation cost, organizational compatibility, and long-term maintainability, while minimizing the need for extensive user retraining.

The evaluation of existing methodologies revealed several recurring limitations affecting the accuracy, flexibility, and operational applicability of current work zone analysis tools. These limitations included simplified assumptions about traffic demand, speed estimation, queue formation, diversion behavior, and traffic-flow representation, as well as limited support for dynamic traffic conditions, complex work-zone configurations, and corridor-wide congestion analysis. To improve analytical capability and support MDOT's operational needs, future development efforts should focus on incorporating dynamic traffic modeling approaches, calibrated Michigan-specific parameters, improved scenario analysis, and enhanced visualization capabilities. The major limitations identified and the corresponding future development priorities for the enhanced CO3 framework are summarized in Table 4-15.

To improve the accuracy and reliability of the new Excel-based work zone analysis tool, the WMU team has also proposed a comprehensive work zone data collection effort in 2025. This effort is to support model calibration, validation, and refinement while contributing to the development of a Michigan-specific work zone database.

The data collection effort focused on:

- **Detailed work zone configuration data**, including lane closures, ramp configurations, barrier types, and work zone layouts, to improve scenario representation;
- **Traffic volume and speed data** collected at upstream locations, merge areas, entry points, and within work zones to improve estimation of traffic flow, queue formation, and congestion impacts;
- **Travel time information** from sources such as Google API and probe vehicle datasets to improve delay estimation and predictive capability; and
- **Michigan-specific calibration factors** for work zone speed, capacity, and queue behavior under different facility types and work zone conditions.

These data supported the development of a more calibrated and operationally relevant analysis framework capable of supporting complex work zone planning and traffic management decisions.

Table 4-15: Identified Limitations of Existing Methods and Future Development Priorities

Limitation Area	Existing Method Limitations	Need for Improved Modeling Approach
Traffic Demand	Reliance on static or manually entered demand distributions	Dynamic and site-specific traffic demand integration
Capacity Estimation	Use of generalized or fixed capacity assumptions	Calibrated state-specific capacity models
Speed Estimation	Fixed speed assumptions or simplified speed reductions	Dynamic speed-flow relationships and calibrated speed models
Queue Analysis	Simplified input-output or single-segment queue estimation	Dynamic queue propagation and physical queue modeling
Delay Estimation	Limited representation of congestion evolution	Time-dependent delay estimation with dynamic traffic conditions
Ramp Interaction Analysis	Limited or no representation of merge/diverge and ramp effects	Integrated ramp interaction and crossover analysis
Diversion Analysis	Static diversion percentages	Dynamic diversion and route choice estimation
Traffic Flow Representation	Limited ability to model shockwaves and congestion propagation	Cell Transmission Model (CTM)-based dynamic traffic simulation
Highway Facility Type	Primarily focused on basic freeway lane closures	Support for freeway, multilane, arterial, and detour operations
Work Zone Configurations	Limited support for complex work zone scenarios	Support for lane closures, crossovers, shoulder closures, and flagging operations
Scenario Analysis	Limited multi-scenario and corridor-wide analysis	Flexible scenario-based operational analysis
Computational Capability	Spreadsheet limitations for iterative calculations	CTM-based computational framework for dynamic traffic analysis
Visualization and Outputs	Limited visualization and operational reporting	Enhanced visualization and operational performance outputs

Implementing these improvements would enable the enhanced CO3 framework to transition from a primarily spreadsheet-based analysis tool toward a more dynamic, calibrated, and operationally relevant platform capable of supporting increasingly complex work zone planning and traffic management decisions.

4.7 Chapter Summary

This chapter presented the evaluation and comparative assessment of existing work zone analysis tools and methodologies under different work zone operational scenarios. The evaluation included qualitative and quantitative comparisons of multiple tools with respect to capacity estimation, speed analysis, queue and delay estimation, diversion analysis, scenario flexibility, data integration, and operational applicability.

The results demonstrated substantial differences among the evaluated tools in their ability to represent dynamic traffic behavior and operational conditions within work zones. Tools incorporating simulation-based or HCM-integrated methodologies generally produced more realistic estimates of speed, delay, queue length, and congestion impacts than simplified, deterministic, spreadsheet-based approaches. The evaluation also showed that the representation of traffic demand significantly influences work zone analysis results, particularly under congested freeway conditions.

The case-study analyses further highlighted the importance of accurately representing ramp interactions, diversion behavior, crossover operations, and detour-route conditions within work zone traffic analysis. Several existing tools showed limitations in representing corridor-wide traffic dynamics, queue spillback, and operational variability under complex work zone configurations.

The evaluation also identified several limitations in current methodologies, including simplified capacity assumptions, limited representation of dynamic traffic, insufficient support for multilane and detour operations, and limited integration with modern traffic datasets. These findings reinforced the need for a more flexible and operationally realistic work zone analysis framework that dynamically represents the evolution of congestion, queue propagation, diversion behavior, and traffic-flow interactions under varying work zone conditions.

Overall, the findings in this chapter established the technical and operational foundation for developing the new work zone analysis tool presented in the following chapters.

Chapter 5: Development of New Work Zone Analysis Tool

5.1 Overview of the Work Zone Analysis Tool

The chapter presents the development of a new work zone analysis tool, the Michigan Predictive Analysis of Congestion and its Effects (MiPACE). The tool was developed to support comprehensive work zone traffic analysis and operational evaluation for freeway, multilane highway, and one-lane two-way work zone scenarios. The framework integrates traffic simulation, queue estimation, delay analysis, travel-time estimation, and road user cost evaluation into a unified analytical platform.

The modeling framework integrates several operational components required for comprehensive work zone analysis, including traffic demand estimation, speed and capacity modeling, queue and delay estimation, diversion analysis, ramp interaction representation, and work zone operational control strategies. The framework was developed to support multiple work zone configurations and maintenance-of-traffic (MOT) scenarios, including freeway lane closures, multilane operations, shoulder closures, crossovers, detours, and flagging operations.

Figure 5-1 presents the main user interface of the MiPACE, including the primary workflow components and analysis modules used for work zone evaluation.



Figure 5-1. Main User Interface and Workflow Structure of the MiPACE Framework

Traffic demand within the framework is represented by time-dependent demand profiles derived from CCS data. The framework incorporates calibrated work-zone speed and capacity models developed from field-collected traffic data and operational observations at selected work-zone sites across Michigan. Dynamic traffic conditions are evaluated using discrete time intervals to capture variations in traffic flow, queue formation, and congestion propagation throughout the analysis period.

The roadway network within the CTM framework is divided into multiple homogeneous cells representing roadway segments with consistent geometric and operational characteristics. Each cell is characterized by parameters such as free-flow speed, work zone capacity, critical density, jam density, lane configuration, and traffic demand. The movement of traffic between cells is governed by sending and receiving flow relationships, enabling the model to dynamically simulate traffic evolution throughout the work-zone corridor.

The framework also incorporates operational features required for realistic work zone analysis, including ramp merge/diverge interactions, dynamic queue propagation, physical and moving queue estimation, diversion effects, and lane closure transition effects. In addition, separate operational logic was developed to represent different work zone configurations and traffic control strategies under freeway, multilane, detour, and flagging scenarios.

The tool supports multiple facility types, including freeway facilities, multilane highways, and one-lane two-way operations with flagging control. For freeway and multilane facilities, the framework applies Michigan-calibrated speed and capacity models, integrated with CTM-based traffic simulation, to estimate queue propagation, delay, speed reduction, and travel-time impacts under work-zone conditions. For one-lane two-way operations, the framework incorporates flagging logic and directional traffic control analysis, as illustrated in Figure 5-2.

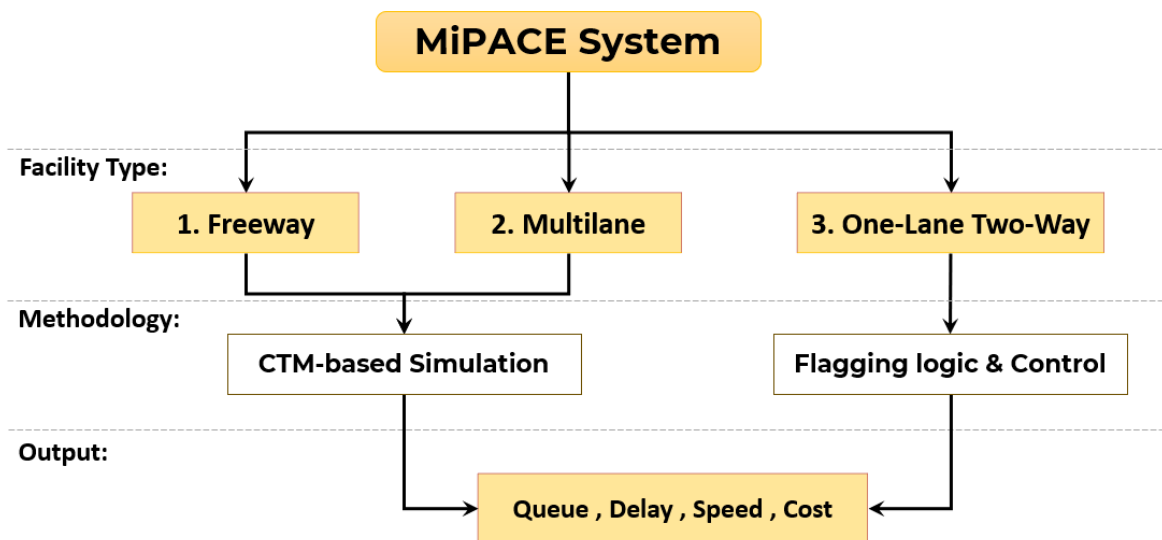


Figure 5-2: MiPACE Facility Classification and Simulation Framework

The tool was designed to provide both numerical and graphical outputs to assist engineers and practitioners in evaluating work zone operational performance. Key outputs include queue length, physical and backup queue propagation, vehicle-hours of delay, travel times, speed profiles, congestion heatmaps, and road user costs. The framework additionally supports optional detour and diversion analysis for projects involving ramp closures or alternative routing strategies.

The overall workflow of the framework follows a structured sequence: project information input, geometric definition, demand input, optional detour configuration, CTM execution, and output generation. This structure was developed to simplify user interaction while maintaining flexibility for different work zone scenarios and operational conditions.

5.2 Modeling Components

5.2.1 Geometric Input Module

The geometric input module was developed to define the physical and operational characteristics of the roadway and work zone environment within the MiPACE framework. This module serves as the foundation for the CTM-based simulation process by generating the roadway segmentation structure, work zone configuration, lane arrangement, ramp locations, and the spatial traffic analysis framework required for traffic simulation and operational evaluation.

The module allows users to define multiple facility types, including freeway facilities, multilane highways, and one-lane two-way operations. Users can specify roadway characteristics such as the number of lanes, segment lengths, speed limits, work zone configuration, ramp locations, taper lengths, and operational boundaries. The module additionally incorporates the primary work zone components defined in standard traffic-control layouts, including the Advanced Warning Area (AWA), Transition Area (TA), Activity Area (AA), buffer spaces, and taper sections. These components establish the spatial structure required for traffic simulation, queue propagation analysis, and speed-transition modeling within the MiPACE framework. Figure 5-3 presents a typical work zone layout illustrating the operational areas and roadway elements integrated into the geometric modeling process.

For freeway and multilane facilities, the module automatically divides the roadway into CTM cells based on user-defined segment lengths and roadway geometry. The segmentation structure accounts for work zone boundaries, lane reductions, operational bottlenecks, and roadway transition areas. For freeway facilities, the segmentation also incorporates ramp merge and diverge locations, as ramp interactions significantly influence freeway traffic operations and queue propagation. In contrast, multilane highway facilities use an access-point representation rather than ramp modeling because they generally operate without freeway-style ramp systems. This automated segmentation process establishes the spatial framework required for traffic flow propagation, queue formation, density estimation, and speed calculations within the CTM simulation engine.

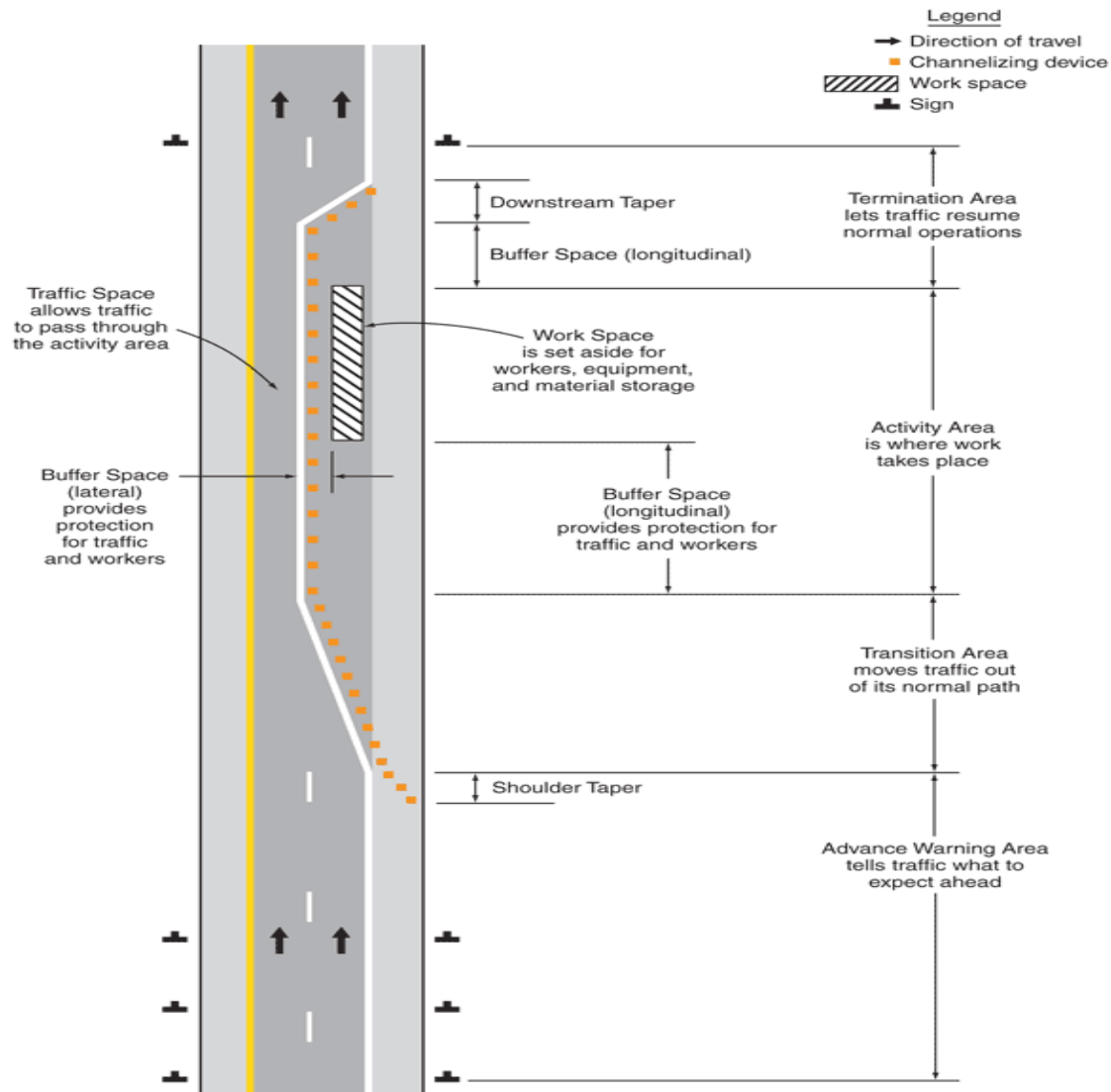


Figure 5-3: Typical Work Zone Layout (adapted from MUTCD).

The geometric input module additionally supports flexible ramp representation and detour integration for freeway facilities. Users can define on-ramp and off-ramp locations, ramp influence areas, and detour-related roadway segments. These geometric components are later integrated into the demand estimation, diversion modeling, and queue propagation procedures within the simulation framework.

Table 5-1 presents the geometric input developed within the MiPACE framework. The module was designed to enable users to define both base roadway conditions and work-zone operational characteristics through a structured input environment.

Table 5-1: Geometric Input Variables for Freeway and Multilane Facilities

Input Variable	Description	Freeway	Multilane	Flagging
Posted Speed Limit	Base roadway speed limit before the work zone	✓	✓	✓
Lane Width	Width of travel lane	✓	✓	✓
Lateral Clearance	Freeway Facilities Measured from the edge of the rightmost lane to the nearest object on the shoulder (Typically refers to right-side lateral clearance) Multilane Highways Measured from the edge of the travel lane to roadside objects on both sides	✓	✓	—
Median Type	Divided or undivided roadway configuration	✓	✓	
Area Type	Urban or rural roadway classification	✓	✓	✓
Total Ramp Density	as the number of ramps per mile, considering ramps within ± 3 miles upstream and downstream of the work zone	✓	—	—
Access Points per Mile	The number of driveways and intersections affecting traffic flow along the segment	—	✓	—
WZ Posted Speed	Posted speed limit within the work zone	✓	✓	✓
Workspace Speed	Speed is maintained through the work activity area	✓	✓	—
WZ Configuration	Lane closure or lane shift configuration	✓	✓	—
WZ Lane Width	Temporary lane width within the work zone	✓	✓	—
Right Shoulder Width	Available right shoulder width	✓	✓	✓
Left Shoulder Width	Available left shoulder width	✓	✓	✓
Barrier Type	Hard or soft barrier separation	✓	✓	—
Detour Route Analysis	Optional detour configuration analysis	✓	✓	—
Grade % at stop bar		—	—	✓
Dead Time (s)		—	—	✓
Allow. Holding Time (s)		—	—	✓

The geometric input module within the MiPACE framework provides a structured interface for defining roadway geometry and work zone operational characteristics, as shown in Figure 5-4.

Reset **Back to Project Info** **Next to Demand Input**

GEOMETRIC INPUT

PROJECT:

A. Base Conditions

*Posted Speed Limit: (mph)	Select Input
*Lane Width: (ft)	Select Input
Lateral Clearance: (ft)	12
*Median Type:	Select Input
*Area Type:	Select Input
Total Ramp Density:	0.00
Access Points/Mile:	0.00

B. Work Zone Conditions

*WZ Posted Speed: (mph)	Select Input
*Work Space Speed: (mph)	Provide Input
*WZ Configuration:	Select Input
*WZ Lane Width: (ft)	Select Input
Right shoulder Width: (ft)	6
Left shoulder Width: (ft)	2
*Barrier Type:	Select Input

C. Detour Analysis

*Detour Route Analysis:	Select Input
-------------------------	--------------

Refresh Tool **Open Output Sheet**

(a) Freeway and Multilane cases

Reset **Back to Project Info** **Next to Demand Input**

GEOMETRIC INPUT

PROJECT:

A. Base Conditions

Posted Speed Limit: (mph)	Select Input
Lane width (ft): (ft)	Select Input
Shoulder width (ft): (ft)	Select Input
Grade (%) at stop bar: %	0%
Area Type:	Select Input

B. Work Zone Conditions

WZ Posted Speed: (mph)	Select Input
WZ Lane Width: (ft)	Select Input

C. Flagging Operation Input

Dead time (s) sec	3
Allowable Holding time min	15

Refresh Tool **Open Output Sheet**

(b) One-Lane Two-Way case

Figure 5-4: Geometric Input Interface within the MiPACE Framework

The geometric input module also incorporates predefined work zone configuration options based on the selected facility type. The supported work zone configurations for freeway and multilane facilities are summarized in **Table 5-2**.

Work Zone Configuration	Freeway	Multilane	Flagging
4 → 2 Lane Closure	✓	—	—
3 → 2 Lane Closure	✓	✓	—
3 → 1 Lane Closure	✓	—	—
2 → 1 Lane Closure	✓	✓	—
Shoulder Closure – 3 Lanes Open	✓	✓	—
Shoulder Closure – 2 Lanes Open	✓	✓	—
Crossover Operation	✓	—	—
Lane Shift Operation	✓	—	—
Two-way - One lane Operation	—	—	✓

Figure 5-5 illustrates the segment layout for lane-closure scenarios, in which the roadway is divided into standard work-zone regions: the Advanced Warning Area (AWA), Transition Area (TA), Activity Area (AA), and Termination Area (TE). The layout varies with the selected lane-closure configuration, while maintaining a consistent structural representation of work-zone segments.

Similarly, Figure 5-6 presents the segment layout for lane-shift configurations, including both 2-lane and 3-lane shift scenarios, in which traffic is redirected within the same number of lanes via lateral shifts rather than lane reductions.

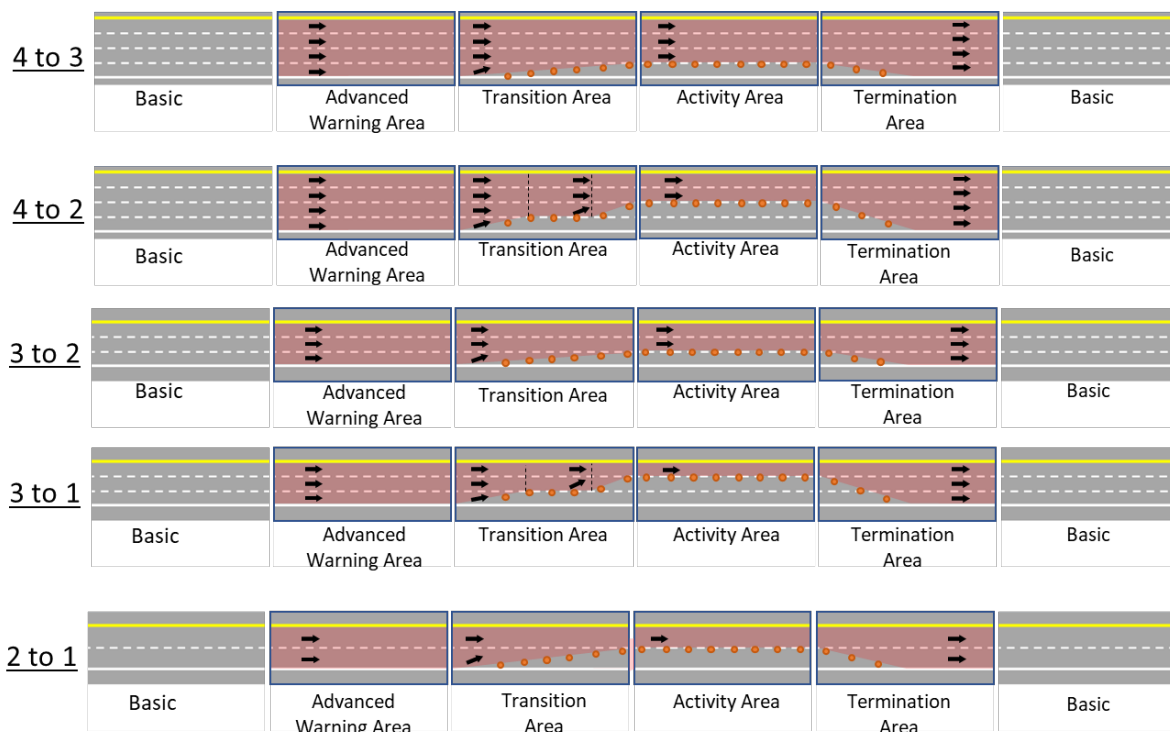


Figure 5-5: Segment Layout for Lane Closure Scenarios

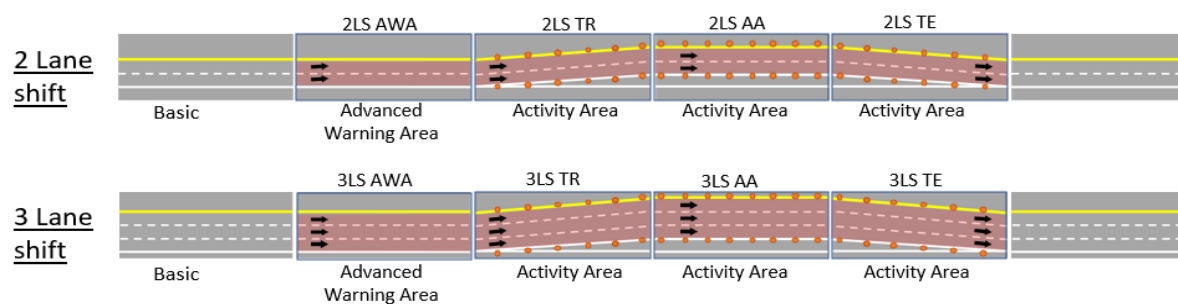


Figure 5-6: Segment Layout for Lane Shift Configurations

Figure 5-7 illustrates the segment layout for crossover scenarios, showing how traffic is redirected across opposing lanes under different configurations

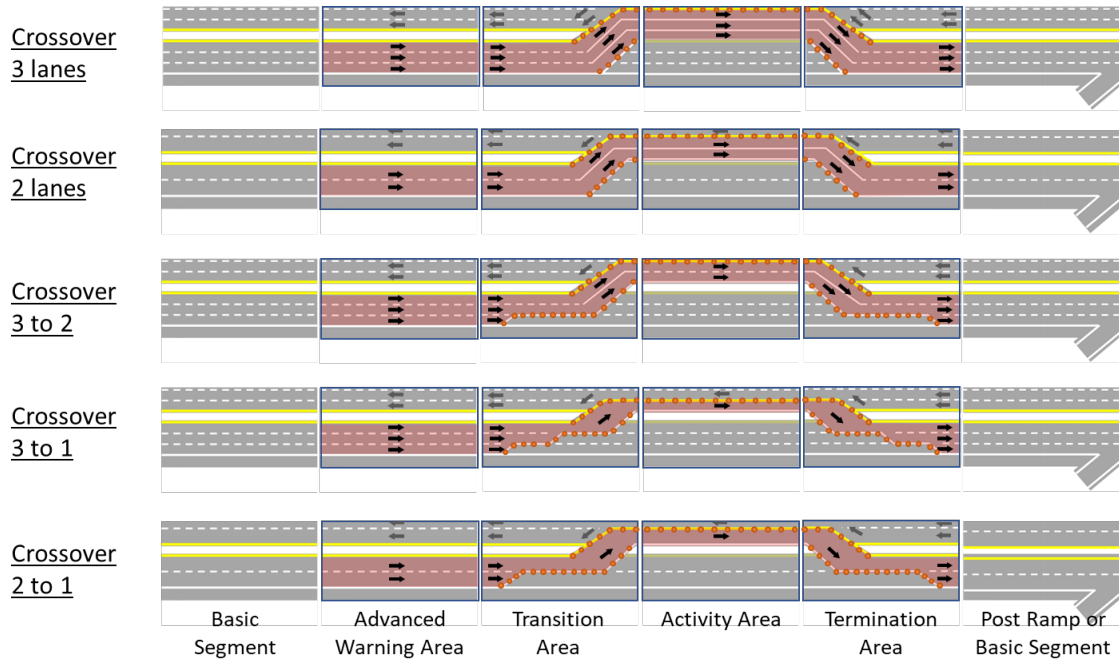


Figure 5-7: Segment Layout for Crossover Scenarios

Figure 5-8 presents the segment layout and segmentation interface developed within the MiPACE framework. The module allows the work zone corridor to be divided into multiple operational segments, including pre-work zone, advanced warning, transition, activity, termination, and post-work zone areas. The framework also supports detailed ramp representation by explicitly incorporating on-ramp and off-ramp segments within the corridor layout. This segmentation structure enables the framework to capture localized variations in traffic flow, lane configuration changes, ramp interactions, and speed transitions throughout the work zone corridor, improving the accuracy of traffic simulation and operational analysis.

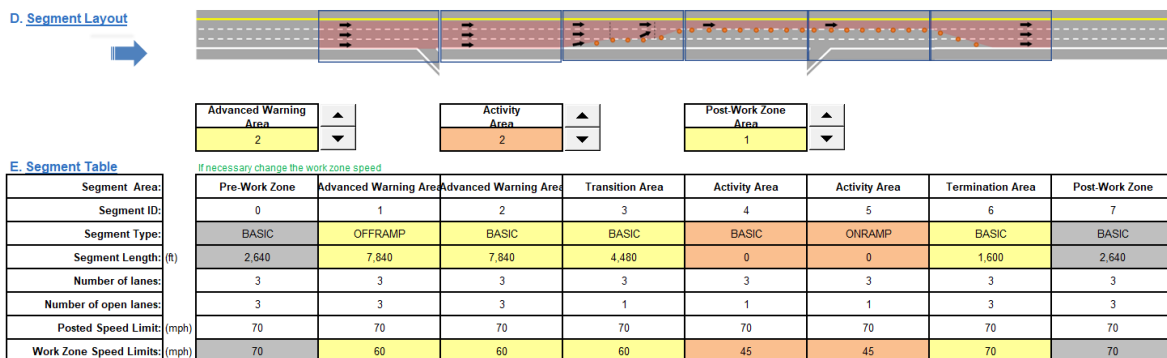


Figure 5-8: Segment Layout and Ramp-Based Segmentation Interface in MiPACE

5.2.2 Demand Input Module

The demand input and traffic data integration module was developed to define the temporal and directional traffic-demand conditions required by MiPACE. This module integrates traffic volume information, directional distribution, heavy-vehicle composition, hourly traffic variation, and demand-reduction adjustments to generate dynamic traffic demand inputs for the CTM-based simulation environment.

The module supports multiple approaches to demand input, depending on the availability of traffic data. Users may use AADT-based demand estimation procedures or directly enter field-collected traffic volumes from traffic sensors, MVDS stations, or video-based traffic counts.

Figure 5-9 illustrates the AADT-based demand input interface developed within the MiPACE framework. In this approach, directional AADT values and truck percentages are entered for the mainline and optional ramp segments, and hourly distribution factors are applied to automatically generate dynamic hourly traffic demand patterns for the simulation.

Input Directional AADT

Segment Area	Pre-Work Zone	Advanced Warning Area	Transition Area	Activity Area
Segment Type:	MAINLINE	-	-	OFFRAMP1
Directional AADT:				
Truck Percentage:				

Optional (for ramps)

Segment Area	Pre-Work Zone	Advanced Warning Area	Transition Area	Activity Area
Segment Type:	MAINLINE	-	-	OFFRAMP1
Directional AADT:				
Truck Percentage:				

One-Lane Two-Way case

Segment Area	Pre-Work Zone	Advanced Warning Area	Transition Area	Activity Area
Segment Type:	MAINLINE	-	-	OFFRAMP1
Directional AADT:				
Truck Percentage:				

(a) Freeway and Multilane case

Analysis Period	Hourly Distribution %	0	1	2	3
12:00:00 AM	1.200%				
1:00:00 AM	0.800%				
2:00:00 AM	0.700%				
3:00:00 AM	0.700%				
4:00:00 AM	1.200%				
5:00:00 AM	2.800%				
6:00:00 AM	4.100%				
7:00:00 AM	5.300%				
8:00:00 AM	5.300%				
9:00:00 AM	5.000%				
10:00:00 AM	5.100%				
11:00:00 AM	5.500%				
12:00:00 PM	5.900%				
1:00:00 PM	6.100%				
2:00:00 PM	6.800%				
3:00:00 PM	7.200%				
4:00:00 PM	7.300%				
5:00:00 PM	7.100%				
6:00:00 PM	5.900%				
7:00:00 PM	4.600%				
8:00:00 PM	3.800%				
9:00:00 PM	3.200%				
10:00:00 PM	2.600%				
11:00:00 PM	2.000%				

(b) One-Lane Two-Way case

Analysis Period	Flag	Hourly Distribution %	Closed Direction	Open Direction
12:00:00 AM	☐	0.500%	0	0
1:00:00 AM	☐	0.300%	0	0
2:00:00 AM	☐	0.200%	0	0
3:00:00 AM	☐	0.300%	0	0
4:00:00 AM	☐	0.500%	0	0
5:00:00 AM	☐	1.400%	0	0
6:00:00 AM	☐	2.600%	0	0
7:00:00 AM	☒	4.700%	0	0
8:00:00 AM	☒	4.600%	0	0
9:00:00 AM	☒	4.700%	0	0
10:00:00 AM	☒	5.200%	0	0
11:00:00 AM	☒	5.900%	0	0
12:00:00 PM	☒	6.700%	0	0
1:00:00 PM	☒	6.800%	0	0
2:00:00 PM	☒	7.300%	0	0
3:00:00 PM	☒	8.300%	0	0
4:00:00 PM	☒	8.800%	0	0
5:00:00 PM	☒	8.400%	0	0
6:00:00 PM	☒	6.600%	0	0
7:00:00 PM	☐	5.300%	0	0
8:00:00 PM	☐	4.600%	0	0
9:00:00 PM	☐	3.300%	0	0
10:00:00 PM	☐	1.800%	0	0
11:00:00 PM	☐	1.100%	0	0

Figure 5-9: AADT-Based Demand Input Interface Using Hourly Distribution Factors

For AADT-based analysis, the tool converts daily traffic demand into hourly and sub-hourly traffic patterns using predefined temporal distribution factors. Figure 5-10 presents an example of the hourly traffic distribution patterns integrated within the MiPACE using the Continuous Count Station (CCS) data obtained from MDOT. These temporal distribution profiles were developed from observed Michigan traffic patterns and are used to transform daily traffic demand into dynamic hourly simulation inputs for the CTM-based traffic analysis procedures.

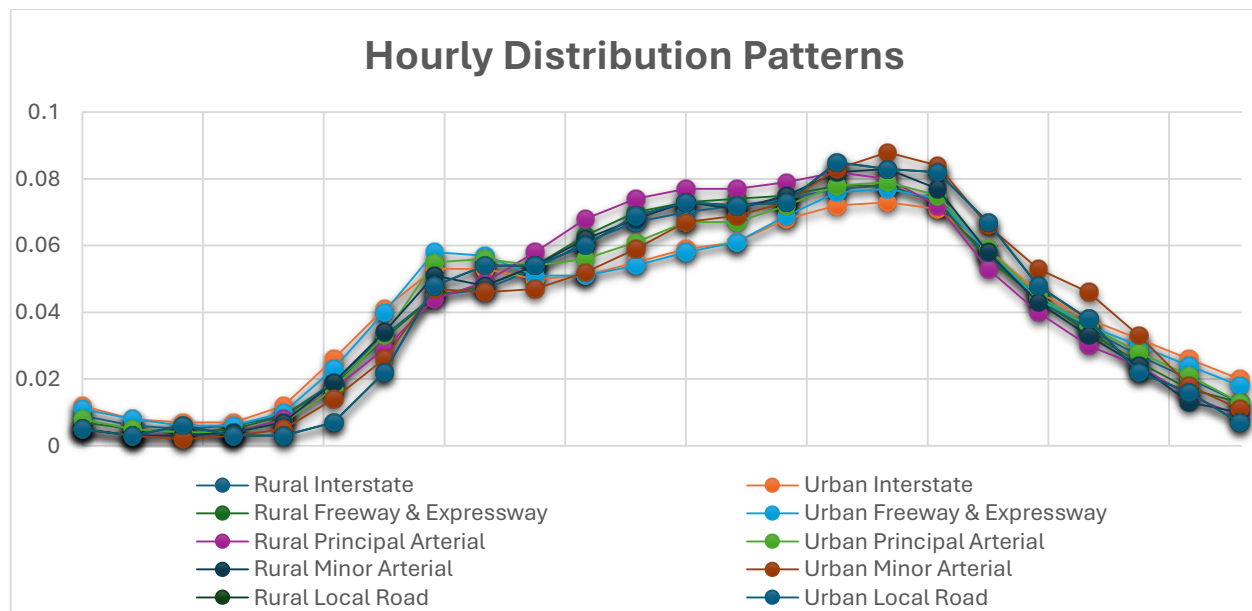


Figure 5-10: MDOT CCS-Based Hourly Traffic Demand Distribution Profiles

Figure 5-11 presents the direct demand input interface used when hourly traffic volumes are available from field data or video-based traffic counts. This approach allows users to directly input time-dependent traffic demand values for both mainline and ramp segments

[D. Demand Table](#)
Units in Veh/hr

➡

Segment Area:		Pre-Work Zone	Advanced Warning Area	Transition Area	Activity Area
Segment Type:	Directional AADT:	MAINLINE	-	-	OFFRAMP1
Truck Percentage:					
Analysis Period	Hourly Distribution %	0	1	2	3
12:00:00 AM	1.200%				
1:00:00 AM	0.500%				
2:00:00 AM	0.700%				
3:00:00 AM	0.700%				
4:00:00 AM	1.200%				
5:00:00 AM	2.800%				
6:00:00 AM	4.100%				
7:00:00 AM	5.300%				
8:00:00 AM	5.300%				
9:00:00 AM	5.000%				
10:00:00 AM	5.100%				
11:00:00 AM	5.500%				
12:00:00 PM	5.900%				
1:00:00 PM	6.100%				
2:00:00 PM	6.900%				
3:00:00 PM	7.200%				
4:00:00 PM	7.300%				
5:00:00 PM	7.100%				
6:00:00 PM	5.800%				
7:00:00 PM	4.800%				
8:00:00 PM	3.800%				
9:00:00 PM	3.200%				
10:00:00 PM	2.800%				
11:00:00 PM	2.000%				

Figure 5-11: Direct Hourly Traffic Demand Input Interface for Mainline and Ramp Segments

The module additionally incorporates terrain-type and heavy-vehicle adjustments to convert traffic demand from vehicles per hour (veh/hr) to passenger-car-equivalent flow rates (pc/hr). This conversion process accounts for the operational effects of heavy vehicles on roadway performance and the propagation of traffic flow under different terrain conditions. The resulting equivalent passenger-car demand values are later integrated into the speed-capacity relationships and CTM simulation procedures.

The module also incorporates optional demand-reduction adjustments to account for reduced traffic demand under work zone conditions. The preferred demand-reduction values are based on the observed field-analysis results presented in Section 6.5.1, where multiple freeway work zone projects were evaluated to quantify traffic demand reduction under different lane-closure configurations and congestion conditions.

5.2.3 Detour and Diversion Module

The MiPACE incorporates an optional detour and diversion module to evaluate traffic redistribution and operational impacts associated with roadway closures, ramp restrictions, and detour-route implementation during work zone operations. This module was developed to estimate detour travel times, diversion behavior, intersection delays, and corridor-level operational impacts resulting from alternative routing conditions in congested work-zone environments.

The detour module allows users to define alternative detour routes using a segment-intersection representation approach. The detour corridor is divided into roadway segments between consecutive intersections, where users specify segment lengths, operating speeds, roadway characteristics, and traffic-control conditions. For each intersection along the detour route, the framework also allows users to define the intersection control type, number of legs, lane configuration, and detour turning movements. These inputs are later integrated into the detour travel-time and delay estimation procedures.

Detour travel time is estimated by combining segment travel times and intersection-control delays. The detour travel-time relationship implemented within the framework is expressed as shown in Equation (1):

$$TT_{detour} = \sum TT_{segment} + \sum Delay_{intersection} \quad (1)$$

Where $TT_{segment}$ = travel time along each detour roadway segment

$Delay_{intersection}$ = estimated control delay associated with each intersection along the detour route.

The estimated mainline travel time generated from the CTM simulation engine is expressed as shown in Equation (2):

$$TT_{main} = \frac{L}{Speed_{avg}} + d_{queue} \quad (2)$$

Where L = roadway segment length,

$Speed_{avg}$ = average operating speed obtained from the CTM simulation,

d_{queue} = queue-related delay estimated during congested work zone conditions.

The diversion component of the framework utilizes the relative difference between mainline and detour travel conditions to estimate diversion behavior during work zone operations. The diversion probability relationship implemented within the framework is expressed as shown in Equation (3):

$$P_{div} = \frac{1}{1 + e^{-(2 - 0.03V_{mainline} - 0.5(TT_{detour} - TT_{main}))}} \quad (3)$$

Where P_{div} = diversion probability,

$V_{mainline}$ = mainline average speed,

TT_{detour} = estimated detour travel time,

TT_{main} represents the estimated mainline travel time.

Figure 5-12 illustrates the operational workflow of the integrated detour and diversion module within the MiPACE framework. The diversion process dynamically compares the estimated mainline travel time generated from the CTM simulation with the calculated detour-route travel time based on segment travel times and intersection delays. Depending on the relative operational performance between the two routes, the framework estimates the diversion probability and updates both freeway demand and detour-route demand conditions for the subsequent simulation interval. This dynamic interaction enables the framework to continuously capture traffic redistribution behavior, diversion impacts, and operational traffic responses under active work zone conditions.

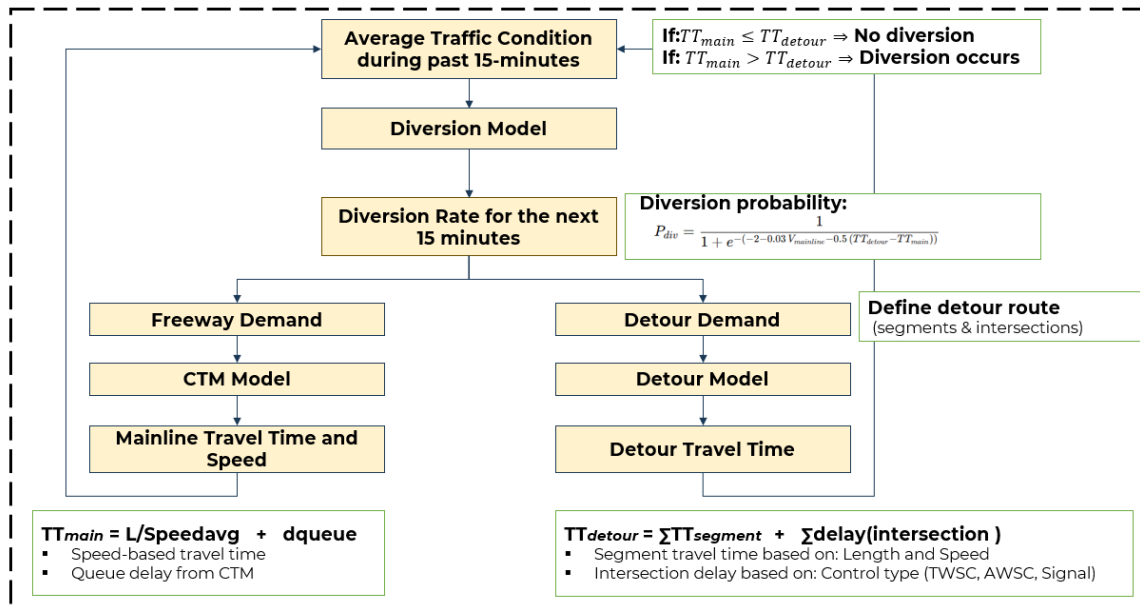


Figure 5-12: Dynamic Detour and Diversion Analysis Workflow in MiPACE

Figure 5-13 presents the detour-route input and intersection-configuration interface developed within the MiPACE framework. The module allows users to define detour route characteristics, segment lengths, roadway classifications, and intersection operational parameters, including control type, number of lanes, and turning movements. The detour and diversion module is fully integrated with the geometric input, demand estimation, and CTM simulation components within the framework, allowing diversion-related traffic demand adjustments to directly influence queue propagation, congestion development, travel time, and delay estimation on both the mainline work zone corridor and the alternative detour route.

Reset **Back to Demand Input**

DETOUR ROUTE INPUT

PROJECT:

A. Detour Input Table

No. Detour Intersections:	2
Existing Detour Street AADT:	
Detour Road Type:	
Detour OFF-Ramp:	No Ramp Available

Legend

Input Cells	
Inactive Cells	
Header/Output Cells	

B. Detour Segments

Detour Segment ID
Length (ft)
Posted Speed (mph)

C. Detour Intersections

Detour Intersection ID
Control Type
No. Leg
Stop-Controlled Approach?
Detour Street Lanes
Cross Street Lanes
Detour Turn Movement

Select Input

Select Input
Interstate
Freeway & Expressway
Principal Arterial
Minor Arterial
Local Road

Segment 0-1 **Segment 1-2** **Segment 2-3**

--	--	--

Intersection 1 **Intersection 2**

--	--

TWSC, AWSC, or Signalized
3-leg or 4-leg intersection
(Yes/No)
No. of lanes on the detour approach
No. of lanes on the intersecting road
left, through, right

Output Sheet

Figure 5-13: Detour Route and Intersection Input Interface within the MiPACE Framework

5.2.4 CTM Simulation Integration

The CTM simulation engine within the MiPACE framework was developed to dynamically integrate roadway geometry, traffic demand, operational work-zone characteristics, and calibrated traffic-flow relationships into a unified traffic simulation environment. The detailed theoretical development of the CTM methodology, including the calibration of the multi-regime flow–density relationships and simulation procedures, is presented later in Chapter 7. Therefore, this section focuses only on the integration and implementation of the CTM simulation module within the overall MiPACE system architecture.

The simulation process begins with the automatic generation of CTM cells by the geometric input module, in which roadway segments are divided according to work zone boundaries, lane configurations, ramps, access points, and operational bottleneck locations. The resulting segmentation structure establishes the spatial framework for traffic propagation, queue formation, density estimation, and speed calculation during the simulation.

Traffic demand conditions obtained from the demand input module are dynamically assigned to the CTM cells throughout the analysis period. The framework continuously updates traffic flow, density, speed, queue length, and delay conditions during each simulation interval using the calibrated CTM relationships developed for freeway and multilane facilities. These dynamic updates enable the framework to model the evolution of congestion, queue spillback, bottleneck formation, and temporal traffic-state transitions under changing work-zone operational conditions.

The integrated simulation environment additionally incorporates operational interactions involving ramps, access points, detours, and diversion behavior. For freeway facilities, ramp merging and diverging effects directly influence traffic propagation and queue formation within adjacent CTM cells. In contrast, multilane facilities incorporate access-point interactions and localized operational effects rather than freeway-ramp-based operational behavior. When detour analysis is activated, the diversion module dynamically updates both the mainline and detour-route traffic demand conditions throughout the simulation.

The framework additionally supports multiple work zone operational configurations, including lane closures, lane shifts, crossover operations, shoulder closures, and full closure scenarios with optional detour implementation. These operational conditions are directly linked to the calibrated speed-capacity relationships and multi-regime flow-density parameters integrated within the simulation engine.

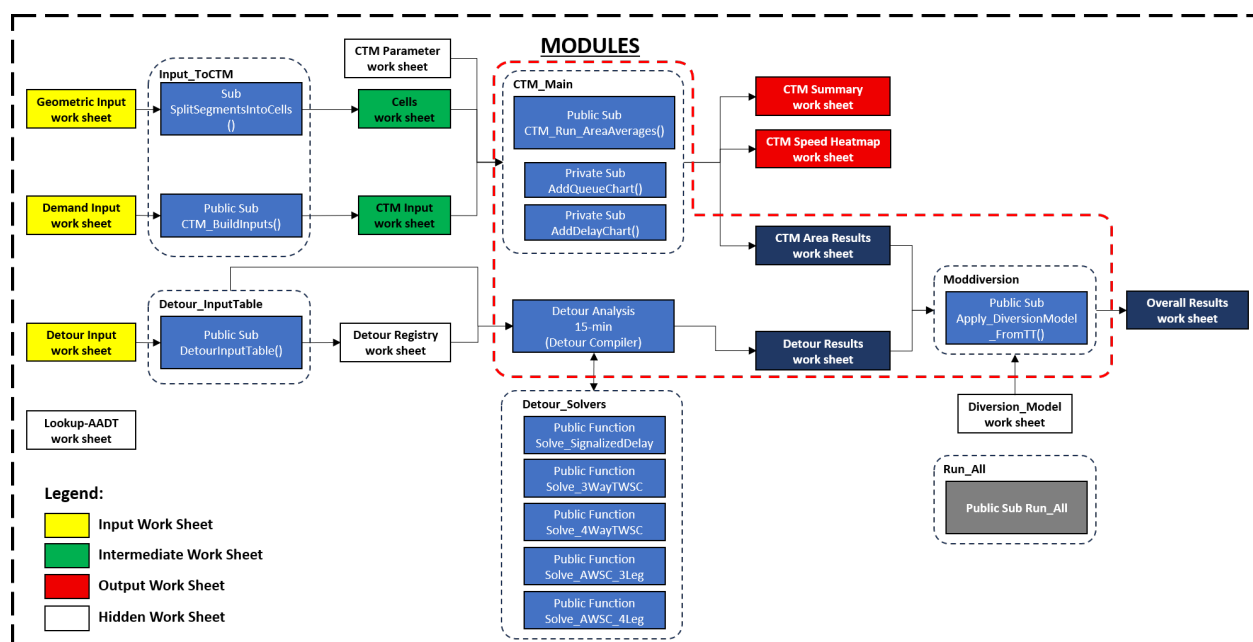


Figure 5-14: System Architecture of the MiPACE CTM Simulation Framework

Figure 5-14 presents the overall architecture for integrating CTM simulations within the MiPACE framework. The figure illustrates the interaction between the geometric input, demand input, detour input, CTM simulation engine, diversion module, and output-reporting components. The

workflow begins with the geometric and demand input worksheets, where roadway segmentation, CTM cells, and traffic demand conditions are generated and transferred into the simulation environment. The simulation engine then executes the CTM operational procedures and produces traffic performance outputs, including speed heatmaps, area-based traffic results, queue estimation, and summary performance measures. When detour analysis is activated, the diversion module dynamically exchanges information between the mainline CTM simulation and the detour-route operational analysis to update traffic demand redistribution and overall corridor performance.

5.3 Road User Cost (RUC)

Road User Cost (RUC) represents the economic impact on roadway users from work-zone operations, congestion, speed reductions, queue formation, and increased travel time. In this study, the MiPACE tool estimates delay-based user costs for passenger vehicles and trucks under work-zone conditions. The RUC module was developed to quantify the operational impacts of work zones in terms of user delay and reduced traffic demand.

The RUC analysis in MiPACE focuses primarily on delay-related costs because delay is the dominant operational effect observed during work-zone congestion. The tool computes passenger-vehicle delay cost, truck delay cost, speed-delay cost, queue-delay cost, and total road-user cost for each analysis interval.

5.3.1 Value of Time (VOT)

The delay-cost calculations were based on the recommended 2025 Michigan-specific Value of Time (VOT) estimates. National VOT values were adjusted using a Michigan wage adjustment factor derived from the ratio of Michigan's median wage to the U.S. median wage.

The adopted values are:

- Passenger Car / Light Truck VOT = 32.89 \$/veh-hr
- Truck VOT = 36.9 \$/veh-hr

The passenger vehicle VOT was derived from USDOT passenger travel-time values, converted to a vehicle-hour basis using occupancy and trip-purpose assumptions, and then adjusted using the Michigan wage factor. The truck VOT was based on a national heavy-truck benchmark value, cross-checked against ATRI freight operating-cost information, and adjusted using the Michigan wage factor. Optional values for light commercial vehicles and buses were documented for potential future MiPACE expansion, but they were not applied in the current two-class MiPACE calculation. The detailed derivation and annual update procedure are provided in Appendix II.

5.3.2 Delay Cost Calculation

The delay-based user cost was estimated based on the total delay incurred during work-zone operations. Passenger vehicle and truck delays were calculated separately using the corresponding Value of Time values.

Passenger vehicle delay cost was estimated as:

$$C_{PV} = D_{PV} \times VOT_{PV}$$

Truck delay cost was estimated as:

$$C_{Truck} = D_{Truck} \times VOT_{Truck}$$

where:

- C_{PV} = passenger vehicle delay cost
- C_{Truck} = truck delay cost
- D_{PV} = passenger vehicle delay (veh-hr)
- D_{Truck} = truck delay (veh-hr)
- VOT_{PV} = passenger vehicle value of time
- VOT_{Truck} = truck value of time

The total road user cost was then computed as:

$$RUC = C_{PV} + C_{Truck}$$

The tool separately tracked speed-related delay and queue-related delay to provide additional insight into the operational causes of user cost generation.

5.3.3 Cost for Reduced Demand

In addition to delay-related user costs, the tool considered the impact of traffic demand reduction due to work-zone conditions. Under congested work-zone operations, some drivers may divert to alternative routes, change travel times, cancel trips, or avoid the corridor entirely. This reduction in traffic demand was incorporated into the Road User Cost (RUC) analysis using the user-equilibrium demand relationship illustrated in Figure 5-15.

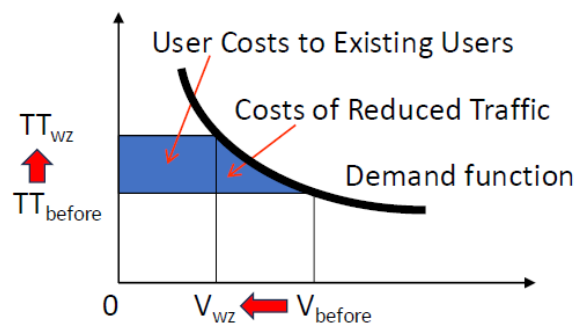


Figure 5-15: Conceptual Illustration of Cost for Reduced Demand

The triangular area represents the user cost associated with reduced demand during work-zone operations. The methodology assumes that traffic demand decreases as travel time increases due

to congestion and reduced roadway capacity. The total user cost was estimated based on the difference between travel time before the work zone and travel time during work-zone conditions, together with the corresponding traffic volumes before and during the work zone.

The blue rectangular area represents the additional delay cost experienced by users who continue traveling through the work zone, while the triangular area represents the loss of user benefit associated with reduced traffic demand.

5.3.4 Review of VOC Approaches and Implementation Limitations

Vehicle operating costs were also reviewed because work zone operations can affect fuel consumption, tire wear, oil consumption, repairs and maintenance, and mileage-related depreciation. FHWA (2012) defines VOC as mileage-dependent running costs associated with vehicle use, excluding fixed costs such as insurance, financing, storage, and time-dependent depreciation. FHWA (2012) further identifies several VOC components in work zone analysis, including speed-change VOC, stopping VOC, queue idling VOC, and detour VOC.

The first VOC approach reviewed for possible implementation was based on FHWA's Highway Economic Requirements System (HERS) example values, which provide vehicle operating cost per vehicle-mile traveled by vehicle class, speed, and pavement roughness. This approach was initially attractive because it used variables that are generally available in the project tool, including vehicle speed, segment length, vehicle class, truck percentage, and pavement roughness. Under this approach, VOC could be estimated by comparing the operating cost under normal-speed conditions with that under work-zone speed conditions, and multiplying the difference by vehicle-miles traveled.

Table 5-3: Example of HERS-based vehicle operating cost

Vehicle type	International Roughness Index (IRI)	Vehicle Speed					
		20 mph	30 mph	40 mph	50 mph	60 mph	70 mph
Small automobiles	50	\$0.366	\$0.305	\$0.284	\$0.291	\$0.320	\$0.365
Small automobiles	95	\$0.383	\$0.322	\$0.302	\$0.311	\$0.341	\$0.390
Small automobiles	170	\$0.417	\$0.357	\$0.339	\$0.351	\$0.387	\$0.442
Combination trucks	50	\$1.220	\$0.989	\$0.884	\$0.888	\$0.990	\$1.175
Combination trucks	95	\$1.258	\$1.029	\$0.929	\$0.940	\$1.050	\$1.244
Combination trucks	170	\$1.341	\$1.119	\$1.030	\$1.055	\$1.184	\$1.401

Note. Adapted from Federal Highway Administration (2019). Appendix A: Highway investment analysis methodology. In Status of the nation's highways, bridges, and transit: Conditions and performance report to Congress. U.S. Department of Transportation.

However, the HERS-based VOC table raised a major interpretation issue for work-zone user-cost analysis. The VOC-speed relationship is not monotonic. As shown in the Table 5-3, vehicle operating costs may be higher at very high speeds and very low speeds, while being lower at moderate speeds. In a work zone cost tool, this can appear as a user benefit rather than a user cost, even though the work zone causes additional delay and operational disruption. This result may be

reasonable from a narrow vehicle-operation perspective, but it is not appropriate for a planning-level tool.

The FHWA Work Zone Road User Costs Concepts and Applications guidance also presents three commonly used U.S. VOC estimation methods: the NCHRP Report 133 method, the Texas Research and Development Foundation (TRDF) method, and the HERS-ST method. The NCHRP Report 133 method estimates work zone VOC emissions based on added costs associated with speed changes, stops, and idling (Curry & Anderson, 1972). However, FHWA (2012) notes that the method is based largely on earlier work by Winfrey and Claffey and that improvements in fuel efficiency, vehicle technology, and tire technology make the accuracy of those relationships questionable for current vehicle standards (FHWA, 2012). In addition, the method requires information on stopping events, speed-change events, and idling time, which are not consistently available from the standard inputs used in this project tool.

The TRDF method was also reviewed because it is one of the VOC methods identified in FHWA work zone user cost guidance. However, the method was developed using older vehicle technology, operating, and economic assumptions from the 1970s and early 1980s, which limit its applicability to current work zone user-cost estimation (Zaniewski et al., 1982).

FHWA's more recent research effort, Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs, was intended to update decades-old VOC equations used in HERS; however, FHWA's 2022 evaluation also noted that additional concerns with specific equations would need further research (Bucci et al., 2022).

A related University of Nevada, Reno VOC calculator documents the FHWA DTFH61-14-C-00044 effort and reports that 4,400 Naturalistic Driving Study trips and approximately 12.5 million seconds of truck data were used to develop driving cycles. The calculator includes models for fuel consumption, tire wear, oil consumption, mileage-related depreciation, and repair and maintenance. However, this implementation did not provide an auditable coefficient table that could be directly incorporated into the project (University of Nevada, Reno, n.d.).

Based on this review, VOC was not included as a monetized component in the final tool. VOC was treated as a reviewed but non-monetized component because the available methods did not satisfy the project requirements for transparency, current validity, ease of implementation, and compatibility with the available input data.

5.4 Output Measures and Visualization

The MiPACE generates both numerical and graphical outputs to support comprehensive evaluation of work zone operational performance. These outputs summarize traffic conditions, congestion evolution, queue propagation, delay impacts, diversion behavior, and economic impacts throughout the analysis period. The generated outputs provide both corridor-level and temporal evaluation of traffic performance under different work zone operational scenarios.

Table 5-4 summarizes the primary numerical and graphical outputs generated within the MiPACE framework.

Table 5-4: MiPACE Output Measures and Visualization Components	
Numerical Outputs	
Speed Performance	Free-Flow Speed (FFS)
	Average Work Zone Speed
	Minimum Speed
	Maximum Speed
	Approach Speed
	Corridor Travel Speed
Delay and Congestion Performance	Vehicle-Hours Traveled (VHT)
	Vehicle-Hours of Delay (VHD)
	Vehicle-Miles Traveled (VMT)
	Total Delay
	Speed Delay
	Backup Queue Delay
	Queue Length
	Queue Occurrence Time
	Congestion Duration
Road User Cost (RUC)	Travel Time
	Diversion Demand
	Passenger Vehicle Delay Cost
	Truck Delay Cost
	Total Road User Cost (RUC)
	Speed-Delay Cost
Traffic Visualization Outputs	
Queue Length Profile	Delay Profile
Speed Heatmap	Diversion Profile

Overall, the MiPACE framework was developed as an integrated, operationally flexible platform for work-zone traffic analysis, congestion evaluation, delay estimation, diversion assessment, and road-user cost analysis. The framework combines geometric representation, traffic demand integration, CTM-based simulation, detour and diversion modeling, and automated reporting within a unified analytical environment that supports multiple roadway facilities and work-zone operational scenarios.

The integrated workflow and module interaction structure implemented within MiPACE allow the framework to dynamically represent changing traffic conditions, queue propagation, congestion evolution, and operational impacts throughout the analysis period. The inclusion of both numerical and graphical outputs further enhances the framework's ability to support operational evaluation, interpretation of traffic performance, and decision-making under complex work zone conditions.

5.5 Chapter Summary

This chapter presented the development of the Michigan Predictive Analysis of Congestion and its Effects (MiPACE) framework for work zone traffic analysis and operational evaluation. The chapter described the main components of the framework, including geometric input, traffic demand estimation, detour and diversion analysis, CTM-based simulation, road user cost estimation, and output visualization.

The framework was developed to support different roadway facility types and work zone configurations, including freeway, multilane highway, crossover, shoulder closure, detour, and flagging operations. The chapter also introduced the segmentation structure used to represent traffic conditions throughout the work zone corridor, including ramp interactions and changes in roadway geometry and operational conditions.

Different traffic-demand input approaches were incorporated into the framework, including AADT-based demand estimation and direct hourly traffic-demand input from field observations. In addition, the framework integrated detour and diversion analysis procedures to evaluate traffic redistribution and alternative route operations during construction activities.

The chapter presented the implementation of the CTM simulation environment used to model traffic flow propagation, congestion development, queue formation, travel time, and delay under work zone conditions. Output modules were also developed to provide both numerical and graphical summaries of traffic performance and road user impacts.

Overall, this chapter established the operational and computational structure of the MiPACE framework, which serves as the foundation for the calibration, validation, and performance evaluation procedures presented in the following chapters.

Chapter 6: Data Collection for Traffic Model Development

Field data collection and processing activities were conducted to establish an empirical foundation for the work zone traffic analysis framework and to support model development, parameter calibration, and validation. The collected data was used not only to document observed field conditions but also to evaluate traffic operations under different work zone scenarios. The principal traffic measures of interest included speed, traffic volume, travel time, and queue formation at selected locations within and around active Michigan work zones.

The second stage of the study focused on selecting work zone sites to support the development, calibration, and validation of the enhanced work zone analysis framework. A total of 17 work zone projects were selected across multiple MDOT regions to represent a broad range of freeway corridors, lane-closure configurations, traffic demand conditions, and operational characteristics. The selected projects included single-lane closures, double-lane closures, crossovers, shoulder closures, and detour operations to ensure that various work zone traffic scenarios were represented in the analysis.

Because work zone operations vary significantly depending on facility type, lane-closure configuration, traffic demand, truck percentage, ramp influence, detour availability, and field visibility, no single data source was sufficient to represent all required operational conditions. Therefore, this study adopted a multi-source data framework. The research team deployed video cameras and Bluetooth sensors at selected field sites, while additional traffic data were obtained from MDOT-provided sources, including API-based speed records, RITIS datasets, SAFEZONE project data, and MVDS detector data. Manual traffic counts were also prepared from selected video periods to provide a direct reference for validating automated video-derived traffic volumes.

6.1 Selection of Work Zone Sites for Data Collection

The site selection process began by reviewing and categorizing highway construction projects based on lane-closure type, roadway geometry, traffic demand conditions, truck percentages, regional distribution, and the availability of traffic data sources. Emphasis was placed on selecting projects with sufficiently high traffic demand and operational complexity to generate observable congestion, queue formation, travel-time variability, and operational impacts suitable for framework development, calibration, and validation. The selected projects represented a wide range of work zone conditions, including single-lane closures, double-lane closures, crossovers, shoulder closures, and detour operations across multiple freeway corridors in Michigan.

Because work zone traffic operations vary significantly depending on facility type, ramp influence, traffic demand, detour availability, and closure configuration, this study adopted a multi-source data framework. Data was obtained from three primary sources: (1) sites with detailed field data collection conducted by the research team, (2) Safe Zone project datasets, and (3) MVDS detector-based monitoring locations. The research team deployed video cameras and Bluetooth sensors at selected field sites to collect traffic speed, volume, travel time, and queue data. Additional traffic

information was obtained from API speed data, RITIS datasets, Safe Zone records, and MVDS detector data to support framework development, calibration, and validation activities.

The geographical distribution of the selected work zone sites used in this study is illustrated in Figure 6-1, and the selected projects and their operational characteristics are summarized in Table 6-1.

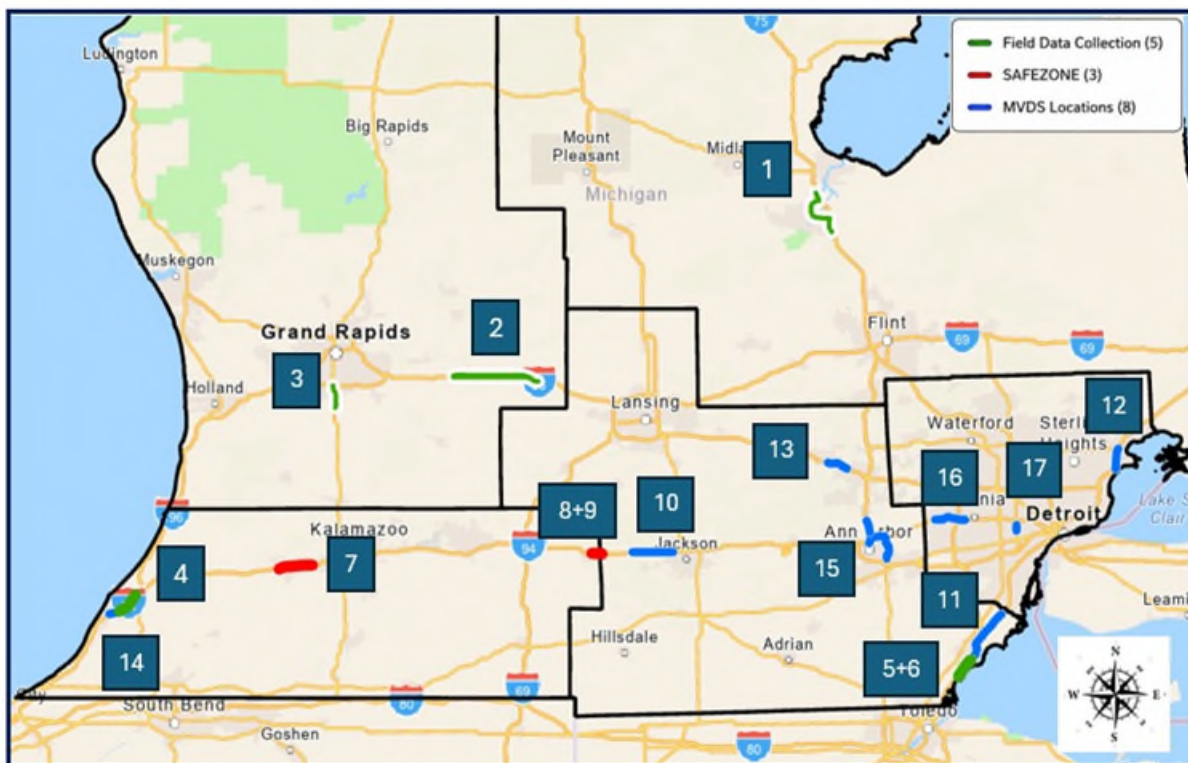


Figure 6-1: Geographical distribution for selected work zone sites

Table 6-1: Selected Work Zone Sites Used for Tool Development

	S/N	Region	Route/Dir.	County	Type of Lane Closure	AADT	Trucks (%)
Field Data Collection	1	Bay	I-75/I-675 NB	Saginaw	Full closure (4 to 2) Detour route	48,168	14
	2	Grand	I-96 WB	Ionia	Single lane closure with movable barrier	39,725	11
	3	Grand	US-131 SB	Kent	Crossover (2 lanes)	54,024	14
	4	Southwest	I-94 WB	Berrien	Single lane closure at Location 2 / Crossover (3 to 2) at Location 3	65,527	28
	5	University	I-75 SB	Monroe	Single lane closure (weekday)	61,215	34
	6	University	I-75 SB	Monroe	Double lane closure (weekend)	61,215	34
Safe Zone Data	7	Southwest	I-94 EB	Van Buren	Single lane closure	46,275	36
	8	Southwest	I-94 EB	Calhoun	Single lane closure	30,232	20
	9	Southwest	I-94 WB	Calhoun	Single lane closure	30,232	20
MVDS Data	10	University	I-94 EB	Jackson	Single lane closure (2 to 1)	36,373	23
	11	University	I-75 NB	Monroe	Shoulder closure (3 lanes)	61,215	34
	12	Metro	M-39 Service Dr NB	Wayne	Single lane closure (3 to 2)	139,054	3
	13	University	I-96 EB	Livingston	Single lane closure (3 to 2)	75,100	11
	14	Southwest	I-94 EB	Berrien	Single lane closure (3 to 2)	65,527	28
	15	University	US-23 SB	Washtenaw	Shoulder closure (3 lanes)	74,315	11
	16	Metro	I-96 NB	Livonia	Double lane closure (4 to 2)	129,733	7
	17	Metro	I-94 NB	Wayne	Shoulder closure (3 lanes)	118,538	3

6.2 Field Data Collection

The field data served three primary functions in the study. First, the data provided direct observations of work-zone operating conditions, including queue development and speed reduction near lane closures, crossovers, detours, and ramp influence areas. Second, the data supported calibration of model inputs and relationships, including speed profiles, capacity-related flow conditions, and travel-time patterns. Third, the data provided independent validation to test whether the final model could reproduce observed work-zone conditions with reasonable accuracy.

The collection strategy was therefore designed around the model's needs. Video cameras were placed where local speed, volume, and queue-development information could be observed. Bluetooth sensors were placed upstream, intermediate, downstream, and at detour points to estimate travel times and route usage. API, RITIS, and MVDS data were then used to extend the field observations beyond the camera view and to validate that the extracted speed and volume trends were consistent with independent traffic data sources.

6.2.1 Data Sources and Contributions

A distinction is made between data physically collected by the research team and data obtained from MDOT-supported or MDOT-provided sources. This distinction is important because the video and Bluetooth components required field planning, equipment placement, sensor mounting, calibration, and retrieval, whereas Google API, RITIS, and MVDS data were obtained from established data systems and processed for analysis.

Table 6-2: Data sources and contributions to model development and validation

Data Source	Traffic Measures	The need for this data
Video Data	Speed, volume, vehicle classification, queue observation, merging behavior	Primary field source for extracting location-specific speed and traffic volume
Bluetooth Data	Travel time, average speed, matched devices, timestamps	Estimating travel time and average speed between sensor locations
Google API Speed Data	Time-stamped roadway speed observations	Validation of video-based speed trends and development of reference speed profiles
RITIS Speed Data	Speed, congestion trends, queue behavior, and corridor performance	Validation of congestion patterns and corridor-level traffic conditions
MVDS Detector Data	Speed, volume, occupancy, lane data, vehicle classification	Supplementary detector-based source for traffic and occupancy analysis

6.2.2 Field Data Collection Framework

A comprehensive field data collection framework was developed to capture traffic operations and driver behavior throughout the work-zone corridor. The framework combined video cameras and Bluetooth sensors to monitor traffic conditions at key points within the work zone, including upstream approach areas, transition zones, active work areas, and downstream recovery sections.

The deployment strategy was designed to evaluate traffic speed, travel time, queue development, merging behavior, and work-zone delay under real traffic conditions. Figure 6-2 illustrates the typical field setup for traffic sensor deployment adopted in this study for sensor placement and traffic monitoring within the work-zone environment.

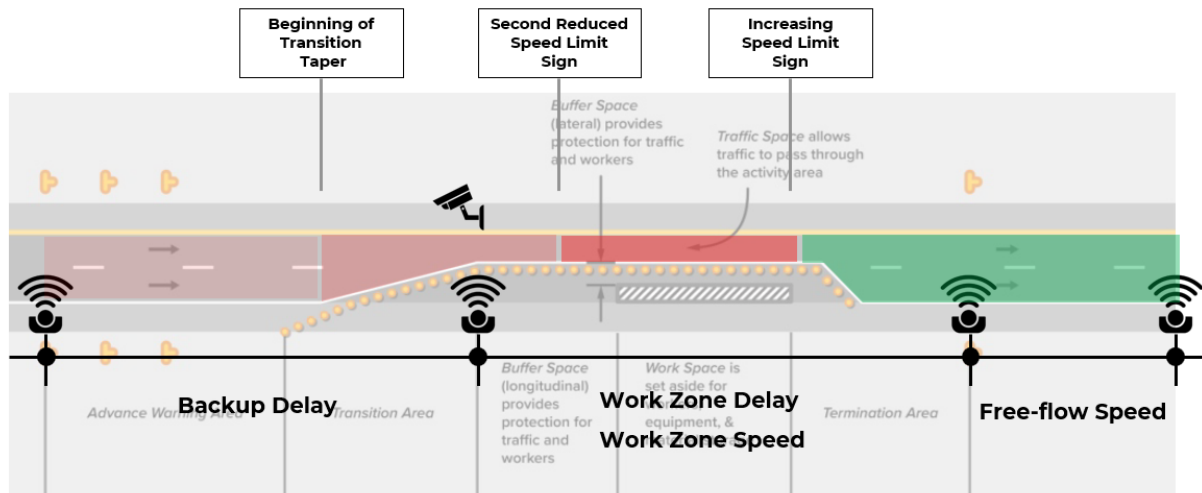


Figure 6-2: Typical Setup of Traffic Sensor Deployment

The general layout of the work-zone monitoring system, including the locations of Bluetooth sensors and video cameras relative to major work-zone elements such as:

- First reduced speed limit sign
- Beginning of transition taper
- Second reduced speed limit sign
- Work-space area
- Increasing speed limit sign
- Termination area

Each segment was associated with specific traffic performance measures. The upstream segments were primarily used to evaluate queue formation and backup delay, while the work-zone segment was used to estimate work-zone speed and operational delay. Downstream sensor locations were used to measure traffic recovery conditions and free-flow speed after vehicles exited the work zone.

Bluetooth sensors were strategically positioned at key corridor points to estimate average travel time and speed between sensor pairs using matched anonymized device records. Video cameras were installed at locations with clear roadway visibility to support traffic volume extraction, vehicle speed estimation, queue observation, and analysis of merging behavior.

6.2.3 Equipment Installation

Following the development of the deployment framework and the identification of monitoring segments, field equipment was installed at selected work-zone locations to support continuous traffic data collection under active roadway conditions. The installation process considered sensor functionality, traffic operations, roadway geometry, camera field of view, Bluetooth detection coverage, available mounting infrastructure, and field safety constraints.

Video cameras and Bluetooth sensors were installed at locations that maximized data quality while maintaining safe and stable deployment conditions. Existing roadside infrastructure, including lighting poles, signposts, overhead gantry supports, and emergency-route signs, was utilized whenever feasible to reduce installation time and improve equipment stability. In locations where suitable infrastructure was unavailable, temporary mounting poles and portable supports were used.

For video-based traffic monitoring, camera placement and viewing angle were critical to achieving accurate traffic extraction results. Cameras were positioned at elevated locations with oblique viewing angles to maximize roadway coverage and minimize perspective distortion. The selected camera angle was required to satisfy several technical conditions, including:

- Adequate longitudinal roadway visibility for vehicle trajectory tracking
- Clearly visible lane boundaries and counting reference lines
- Sufficient vehicle tracking distance for speed estimation
- Limited vehicle occlusion during congested conditions
- Reduced interference from glare, shadow, sunlight reflection, and nighttime lighting effects
- Stable perspective geometry suitable for perspective correction and spatial calibration



Figure 6-3 Field sensor installation for video camera data collection

Camera calibration was performed using known roadway reference dimensions, including lane width, pavement markings, shoulder width, barrier spacing, and work-zone taper lengths. These reference points were used during video processing to convert image coordinates into real-world distances for estimating speed and trajectory.

Figure 6-4 presents examples of video camera installation configurations used for traffic volume extraction, speed estimation, queue monitoring, and traffic behavior analysis.

Bluetooth sensor installation focused on maintaining reliable detection zones and sufficient spacing between sensor pairs for travel-time estimation. Sensors were deployed at strategically selected upstream, transition, work-zone, and downstream locations to capture matched anonymized device records throughout the corridor. The sensor spacing was selected to ensure measurable travel-time differences while minimizing signal overlap between adjacent sensors.

The deployment configuration supported the estimation of:

- Average segment travel time
- Corridor travel speed
- Vehicle progression through the work-zone system
- Traffic recovery downstream of the work zone

Special attention was given to maintaining equipment stability during long-duration deployment periods. Mounting systems were checked for vibration resistance, sensor orientation stability, power reliability, and environmental exposure to ensure consistent data collection quality throughout the monitoring period. Figure 6-4 presents examples of Bluetooth sensor installation configurations used for travel time and speed data collection.



Figure 6-4 Examples of field sensor installation for Bluetooth data collection

6.2.4 Field Data Collection Sites

Field data collection was conducted at multiple active work-zone locations across several MDOT regions to capture a wide range of traffic and operational conditions for model calibration and validation. The selected field deployment sites included:

Site 1: Grand Region: I-96 WB, Ionia County

The Grand Region I-96 WB data collection was conducted from August 25 to August 27, 2025. The deployment included five locations, each equipped with a combination of video cameras and Bluetooth sensors. This site was designed to capture both mainline work-zone impacts and detour-route usage along Grand River Avenue.

The sensor deployment layout for the I-96 WB work zone in Ionia County is illustrated in Figure 6-5 showing the spatial arrangement of Bluetooth sensors and video camera locations throughout the monitored corridor.

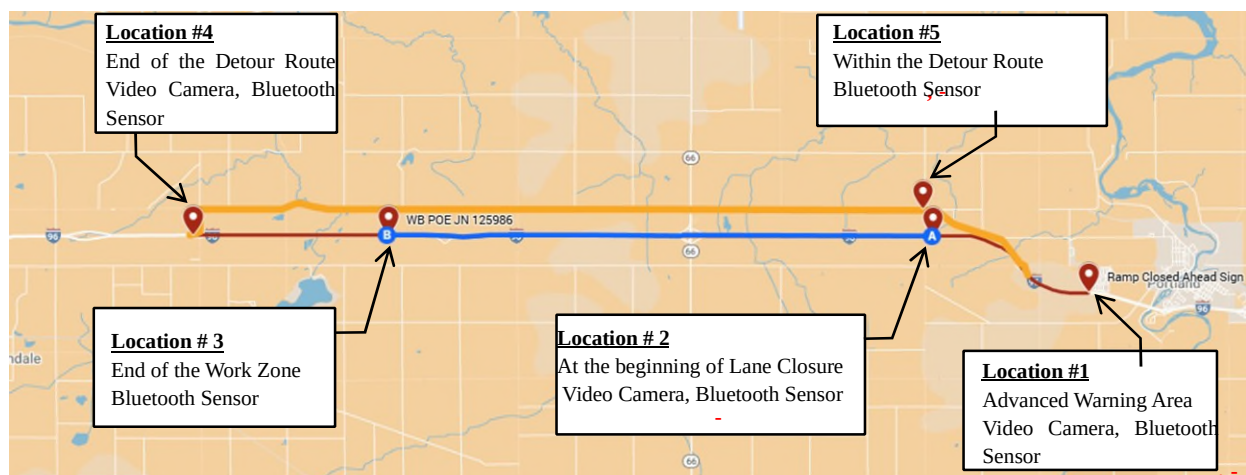


Figure 6-5 Sensor locations, I-96 WB, Ionia County

Representative field camera views from the I-96 WB work zone under congested traffic conditions are presented in Figure 6-6.

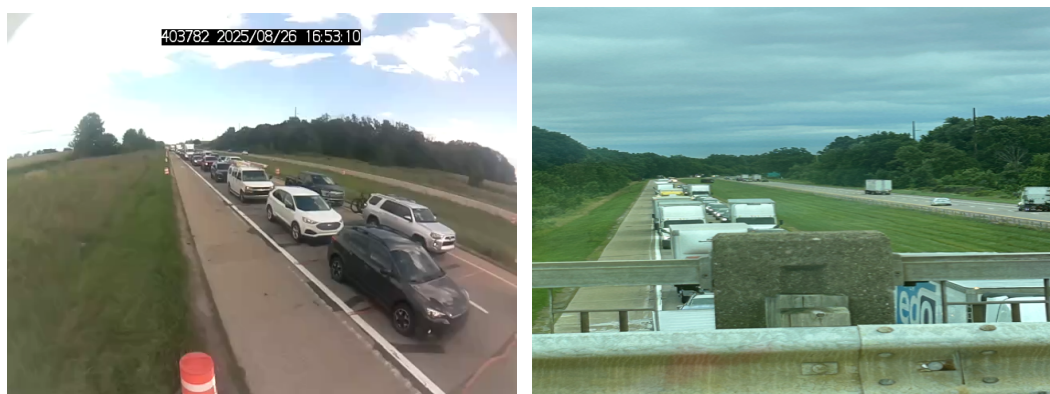


Figure 6-6 Field Observations of Queue Formation on I-96 WB

Site 2: Grand Region: US-131 SB, Kent County

The US-131 SB field deployment was conducted from August 18 to August 20, 2025, following a linear upstream-to-downstream monitoring configuration. Three monitoring locations were established at the advance warning area, the beginning of the lane closure, and the downstream end of the work zone, using Bluetooth sensors and video cameras to capture traffic volume, travel time, and queue development. The deployment layout and sensor locations are illustrated in Figure 6-7 . Representative field-camera views collected during the deployment are shown in Figure 6-8.



Figure 6-7 Sensor Locations, US-131, Kent County

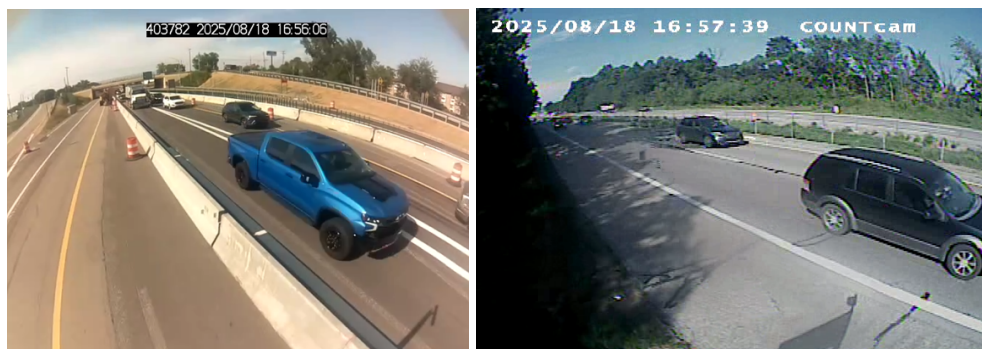


Figure 6-8 field camera views: US-131 SB

Site 3: Bay Region: I-75 NB, Saginaw County

The Bay Region I-75 NB field deployment was conducted from September 4 to September 6, 2025, for a four-lane closure at I-75 to a two-lane detour condition at I-675. The deployment included six monitoring locations equipped with Bluetooth sensors and video cameras to capture traffic approaching the work zone, diverting through I-675, traveling along the detour route, and reconnecting to I-75 downstream of the work zone. Sensor installation locations and deployment configuration are illustrated in Figure 6-9.

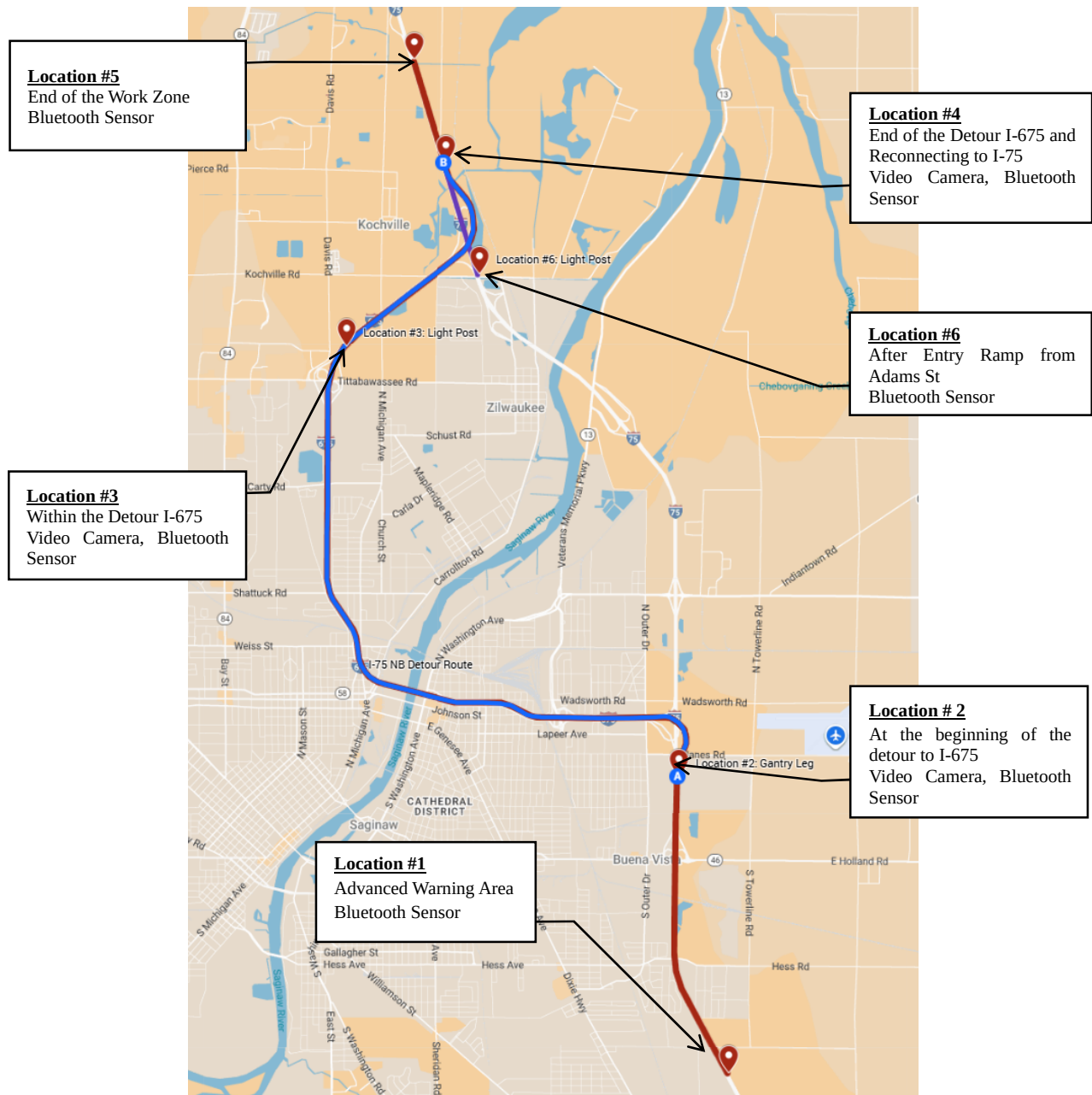


Figure 6-9 Sensor Locations, I-75 NB, Saginaw County



Figure 6-10 Field camera views: I-75 NB

Site 4: University Region: I-75, Monroe County

The University Region I-75 deployment, as shown in Figure 6-11 represented a three-lane-to-one-lane work-zone configuration. The field plan included five locations with Bluetooth sensors and selected camera devices. Sensors were placed at the advanced warning area, the beginning of the lane closure, downstream of the closure, after the ramp-merge area, and at the end of the work zone.

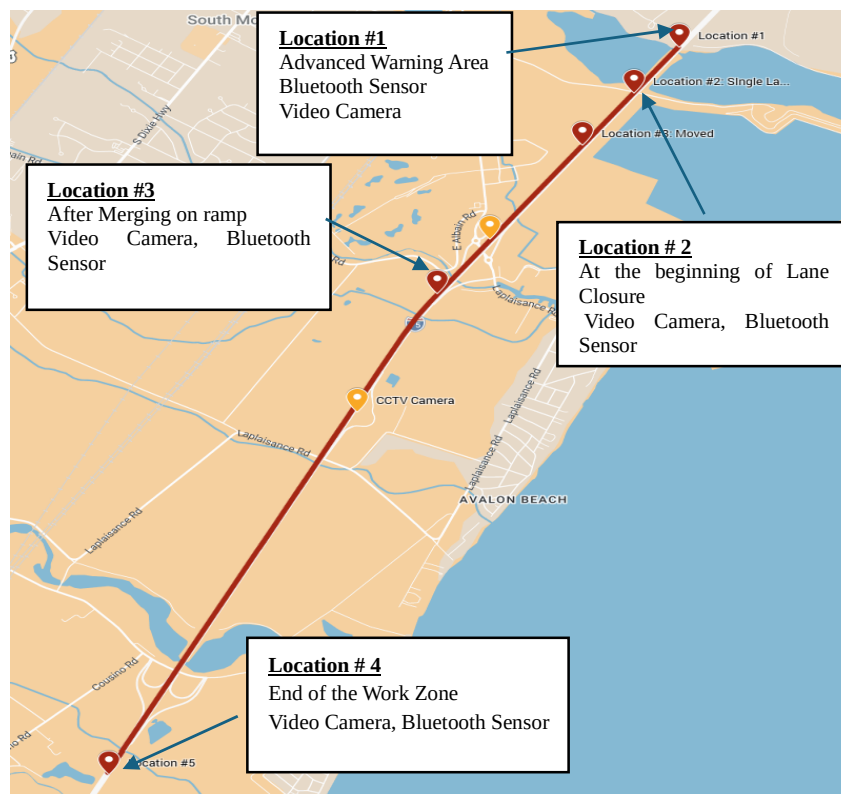


Figure 6-11 Sensor Locations, I-75, Monroe County



Figure 6-12 Representative field camera views: I-75 (Congestion)

Site 5: Southwest Region: I-94, Berrien County

The Southwest Region I-94 work zone was a reconstruction with a three-lane-to-two-lane configuration. The deployment in Figure 6-13 included four locations covering the advanced-warning area, the single-lane closure start, the crossover starts, and the end of the work zone.

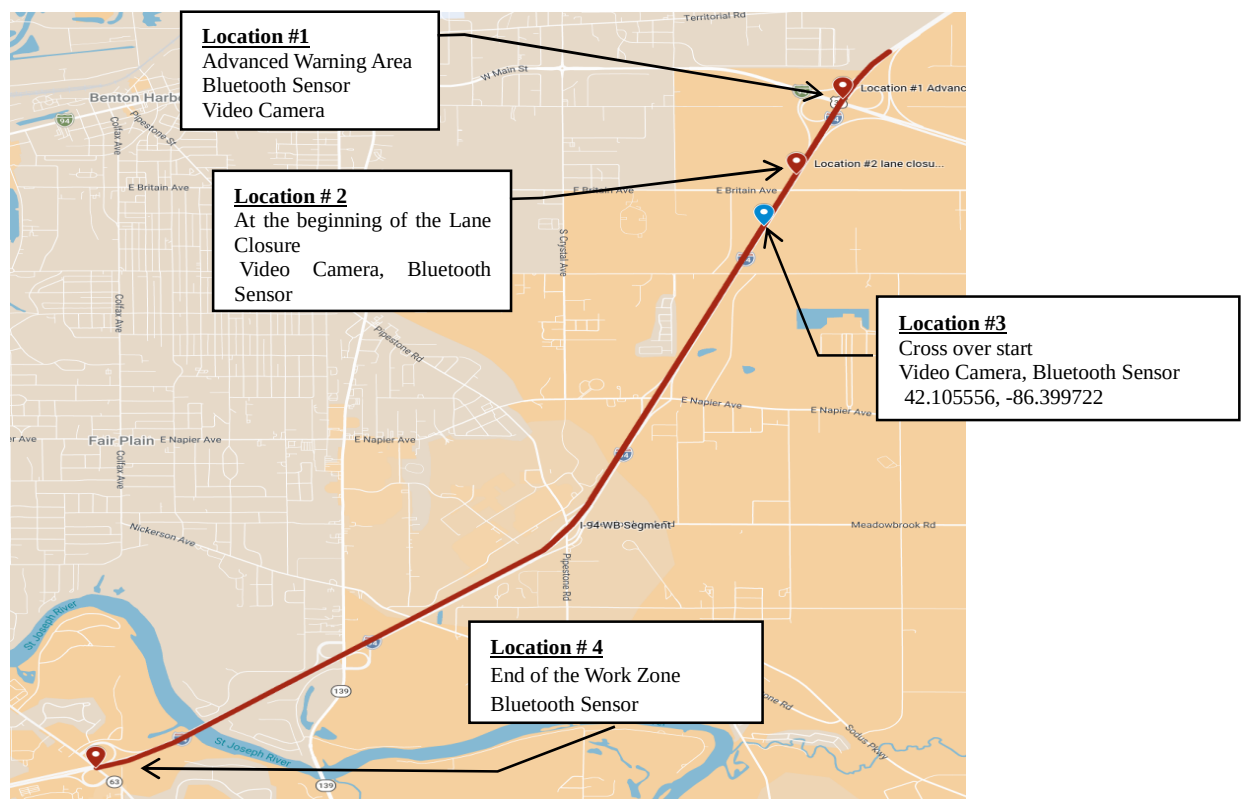


Figure 6-13 Sensor Locations, I-94, Berrien County

This deployment was designed to capture traffic conditions through a major lane-reduction and crossover configuration. Location 1 identified vehicles entering the work-zone influence area. Location 2 captured traffic entering the restricted lane-closure section. Location 3 represented the

crossover transition, and Location 4 measured traffic exiting the work-zone segment. Representative field camera views from these locations are shown in Figure 6-14.



Figure 6-14 Representative field camera views: I-94

6.3 Data Processing and Preparation

After field collection and data acquisition, all raw datasets were processed into a consistent analysis-ready structure. The data sources differed in format, spatial coverage, temporal resolution, and reliability. Therefore, a structured workflow was required to clean the raw observations, align records by time and location, aggregate the data into common intervals, validate speed and volume estimates, and produce final datasets for model development, calibration, and validation.

6.3.1 Video-Based Data Extraction Methodology

Video-based processing was used to extract speed and volume from field-recorded traffic videos. Figure 6-15 summarizes the video-based extraction workflow used in this study. The extracted outputs were then cleaned, aggregated, and validated before being used in the final analysis dataset.

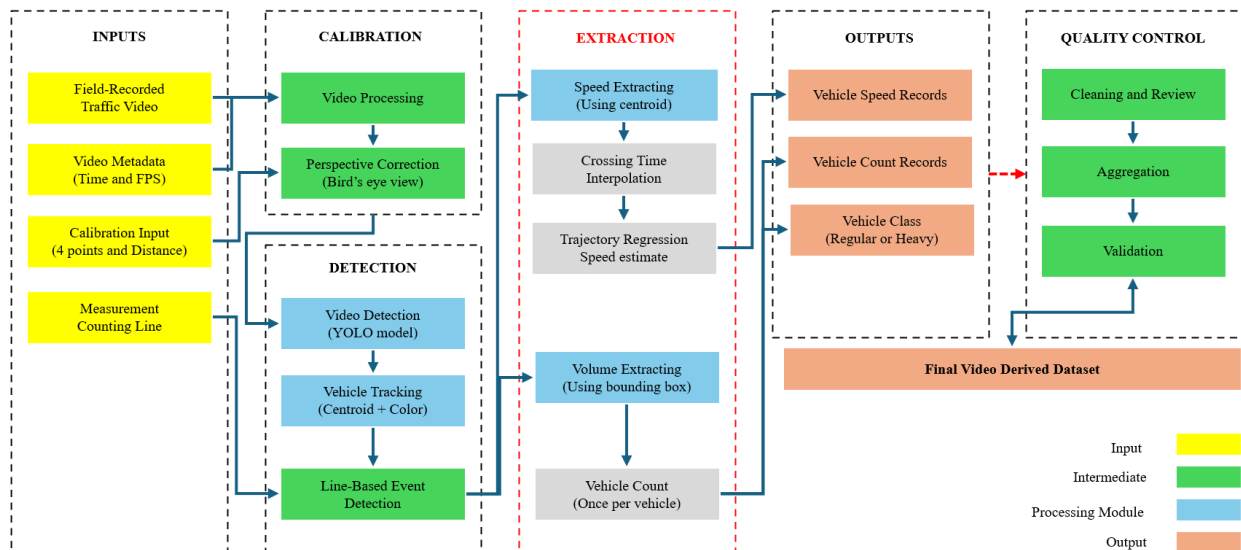


Figure 6-15 Flow Chart of Video-based Data Extraction

6.3.2 Speed Data Extraction

Vehicle speed extraction was performed using field-recorded traffic videos collected at multiple study locations. The methodology combined perspective correction, video calibration, vehicle detection, tracking, and line-crossing analysis to estimate vehicle speeds accurately.

Raw traffic videos contain perspective distortion because roadway distances appear differently depending on the vehicle position relative to the camera. To reduce this effect, four reference points were selected in the original camera view and transformed into a rectangular bird's-eye-view image, as illustrated in Figure 6-16.

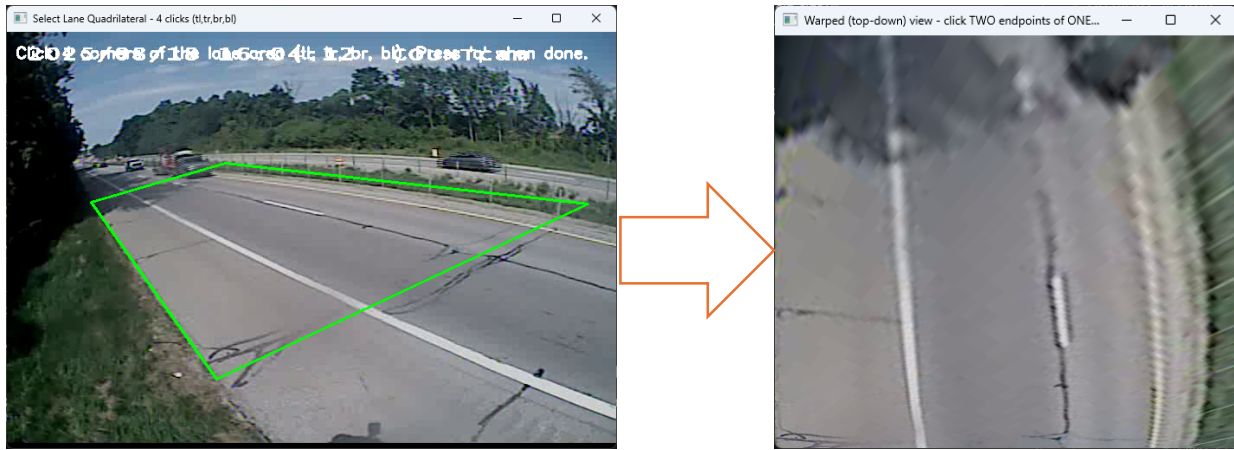


Figure 6-16 Example of perspective correction and bird's-eye-view transformation used for video calibration

Following the transformation, video calibration was performed using known roadway reference distances. The pixel distance between two selected calibration points was computed using:

$$D_{pixel} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

The distance-per-pixel conversion factor was then calculated as:

$$\text{feet per pixel} = \frac{D_{real}}{D_{pixel}}$$

where D_{real} represents the known real-world roadway distance.

Vehicles were detected using a You Only Look Once (YOLO) object-detection model and tracked across consecutive video frames using centroid location, bounding-box overlap, and visual similarity. Vehicle speed was estimated as each tracked vehicle crossed a predefined measurement line. To improve stability and reduce frame-level noise, the speed calculation used a short time window around the crossing event rather than relying on only two consecutive frames. Vehicle centroid movements were analyzed over a short time window around the line-crossing event using linear regression to estimate vehicle motion in both spatial directions. The resulting movement

was converted into real-world speed using the video calibration factor obtained from the perspective-corrected roadway view. Vehicle size information from the detected bounding boxes as shown in Figure 6-17 was also used to classify vehicles as regular or heavy vehicles. The final output included vehicle ID, timestamp, frame number, estimated speed, calibration information, and vehicle classification category.



Figure 6-17 Example of annotated video output showing line crossing and speed estimation

6.3.3 Traffic Volume Extraction

Traffic volume extraction was performed using a calibrated virtual counting line defined within the corrected video frame. The counting line was positioned perpendicular to the primary traffic movement direction at locations with clear vehicle visibility and minimal occlusion. The placement of the counting line was selected to ensure accurate vehicle detection and consistent traffic counting under both free-flow and congested conditions.

Vehicle detection and tracking were conducted continuously throughout the video sequence using the same tracking framework applied for speed extraction. A vehicle count event was generated when the tracked vehicle bounding box intersected the predefined counting line. The detection logic evaluated whether any edge of the bounding box crossed the line or whether the counting line entered the detected vehicle region during frame-to-frame movement.

To prevent duplicate observations, each tracked vehicle was assigned a unique track identifier and was counted only once during the first valid line-crossing event. After the crossing event was recorded, the vehicle track was marked as completed for counting purposes, preventing repeated counts while the vehicle remained near the counting location across multiple frames.

Traffic volume data were aggregated over selected analysis intervals to estimate directional traffic flow and hourly traffic demand. The methodology supported both short-duration interval analysis and expanded hourly volume estimation for traffic operations evaluation.

Each counted vehicle was also assigned an accurate timestamp using the video start time, frame number, and video frame rate. The timestamping procedure allowed every traffic count observation to be linked to a specific date, time, and frame position within the original video sequence. This information supported synchronization with Bluetooth travel-time data, queue observations, congestion periods, and other traffic datasets used in the study.

The final traffic volume dataset included vehicle track ID, counting timestamp, frame number, counting location, analysis interval, and traffic count records for subsequent calibration and validation analyses.

6.3.4 Limitations

The limitations of the video-based speed and volume extraction process were identified during the initial video screening, calibration trials, and review of annotated output videos. The video-based method assumes that the camera remains fixed after calibration. Camera shaking, vibration, or movement can shift the calibrated roadway area, measurement line, and perspective-correction points, which can affect both speed and volume estimates. The accuracy of speed extraction also depends on the correct selection of the four perspective-correction points, the two calibration points, and the known field distance. Errors in these inputs directly affect the distance-per-pixel conversion and therefore the final speed estimates.

Video quality and environmental conditions also affect detection and tracking. Low resolution, compression artifacts, motion blur, unclear vehicle boundaries, rain, fog, wet pavement, reflections, glare, and shadows can lead to missed detections, false detections, unstable tracks, or incorrect vehicle classification. Low-light and evening conditions were a major concern because vehicle shapes and colors have become less visible, and headlights or reflections can interfere with detection. For this reason, the automated video extraction emphasized daytime periods where vehicle detection and tracking were more reliable.

Occlusion was another important limitation. During congested conditions, large vehicles or closely spaced vehicles can block smaller vehicles, causing missed counts or incorrect track assignment. Similarly, vehicles moving between sunlit and shaded areas may appear visually different across frames, increasing the risk of tracking errors when color similarity is used as part of the tracking process. Because of these limitations, annotated video outputs and extracted data were reviewed, and manual counting was used as the reference for volume validation wherever available.

The need for validation led to the development of a multi-source processing approach. Video-derived speed was compared with independent API, RITIS, Bluetooth, and MVDS speed sources. Automated video volume was compared with manual counts and supplemented with detector-based volume where available. This cross-source validation reduced reliance on any single data source and improved the reliability of the final analysis dataset.

6.4 Data Cleaning and Quality Control

Data cleaning was performed separately for each source before integration. For speed datasets, timestamp and speed fields were identified, records were sorted chronologically, duplicate or incomplete records were removed, and abnormal speed observations were screened. A rolling Hampel filter was used to reduce isolated spikes or unrealistic observations while preserving the overall temporal traffic pattern.

Bluetooth data required additional processing because observations were based on anonymized device fingerprints. Duplicate detections were reduced, repeated observations at the same sensor were grouped into visit-level records, and common fingerprints between upstream and downstream sensors were matched. Travel time between a sensor pair was calculated as the difference between upstream and downstream visit times. Records with unrealistic or inconsistent travel times were removed before computing the average segment speed.

For video data, quality control included review of the annotated output video, inspection of line-crossing events, and comparison of automated vehicle counts with manual counts. Manual review was especially important because automated processing can be affected by camera movement, occlusion, shadows, glare, or temporary tracking failure.

6.4.1 Temporal Aggregation and Data Alignment

After cleaning, all datasets were aggregated into common time intervals so that observations from different sources could be compared directly. Five-minute intervals were primarily used for detailed validation of video speed, video volume, manual count, API, RITIS, Bluetooth, and MVDS data. Fifteen-minute intervals were used when a more stable representation was needed for broader modeling and calibration activities.

The aggregation rule depended on the traffic measure. Vehicle volume and vehicle-class counts were summed within each interval. Speed, travel time, and occupancy were averaged within the interval. Each aggregated record included the date, day of the week, interval timestamp, source, location, sample size, average speed, sum of volumes, average travel time, occupancy, vehicle-class totals, and quality-control flags, when applicable. This interval-based structure allowed the project team to align the data by work zone, location, date, and time period.

6.4.2 Manual Volume Validation and Correction

Automated video volume outputs were validated using manual vehicle counts where available. Manual counting was conducted by reviewing selected video periods and recording passenger-car and heavy-vehicle passages using the manual counter workflow. When manual counts were available for a time interval, they were treated as the primary reference for volume validation. Automated video counts were compared against the manual counts to identify undercounting, overcounting, or tracking-related errors.

For intervals without manual counts, corrected video volumes were developed using the observed relationship between manual counts and raw video counts. Correction factors were based on local ratio or bias adjustments derived from periods where both manual and automated counts were available. When short gaps occurred, smoothing or interpolation was used only when operationally reasonable and when adjacent intervals supported the adjustment. This process produced a more reliable volume dataset than using automated video counts alone.

6.5 Findings

The field data collection and processing activities provided important insights into traffic behavior under active freeway work zone conditions. The collected datasets captured operational changes associated with lane closures, speed reduction, congestion formation, queue propagation, and traffic redistribution across multiple freeway corridors in Michigan. The analysis also demonstrated the importance of integrating multiple traffic data sources to accurately capture temporal traffic variation and dynamic work-zone operational behavior.

The field observations indicated that freeway work zones significantly affect both traffic demand and operating speeds. These impacts varied depending on the lane-closure configuration, congestion severity, traffic demand, nearby ramp activity, and the availability of alternative routes. The following subsections summarize the major findings on demand and speed reduction observed during the field data analysis.

6.5.1 Demand Reduction

The field data analysis demonstrated that active freeway work zone operations resulted in measurable reductions in observed traffic demand compared with corresponding non-work-zone conditions. These reductions were primarily attributable to traffic diversion, traveler behavioral responses, schedule adjustments, route avoidance, and congestion-related traffic redistribution during work zone operations. The demand-reduction analysis was conducted using MVDS traffic datasets by comparing observed traffic volumes during active work zone periods with corresponding non-work-zone traffic conditions from the previous week at the same locations and time periods.

Figure 6-18 - Figure 6-21 present examples of observed weekly traffic demand patterns comparing non-work-zone (non-WZ) and active work-zone (WZ) conditions at multiple freeway locations. The results show that traffic demand under work zone conditions was consistently lower than the corresponding non-work-zone demand patterns, particularly during peak traffic periods and severe lane-closure operations.

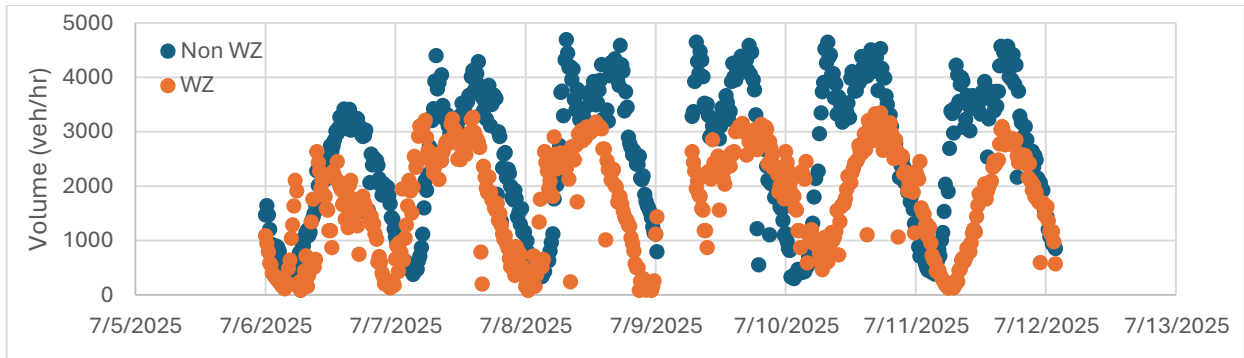


Figure 6-18: Demand Pattern/location 12 (M-39 Service Drive/Wayne)

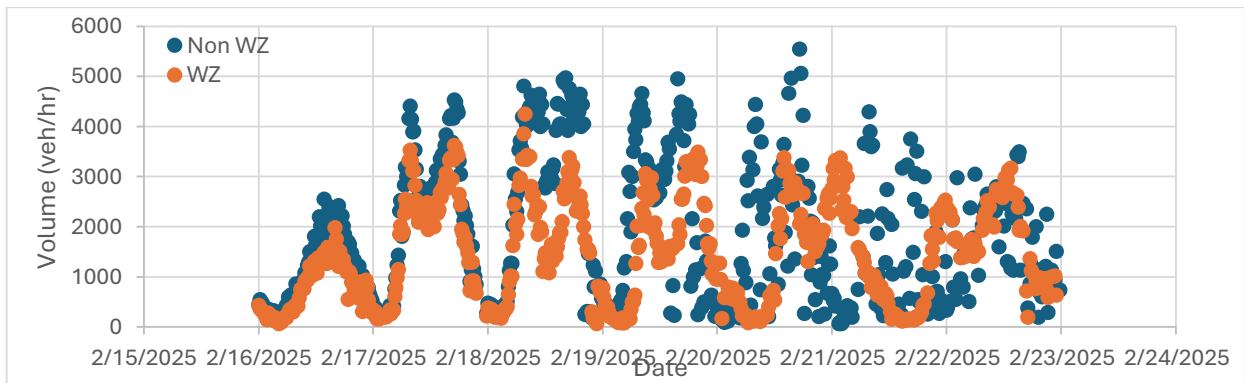


Figure 6-19: Demand Pattern/location 14 (I-94/Berrien)

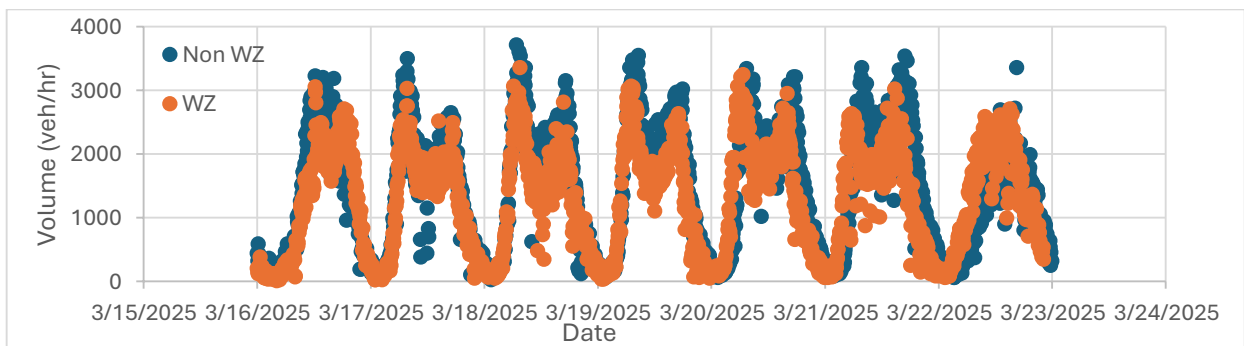


Figure 6-20: Demand Pattern/location 13 (I-96/Livingston)

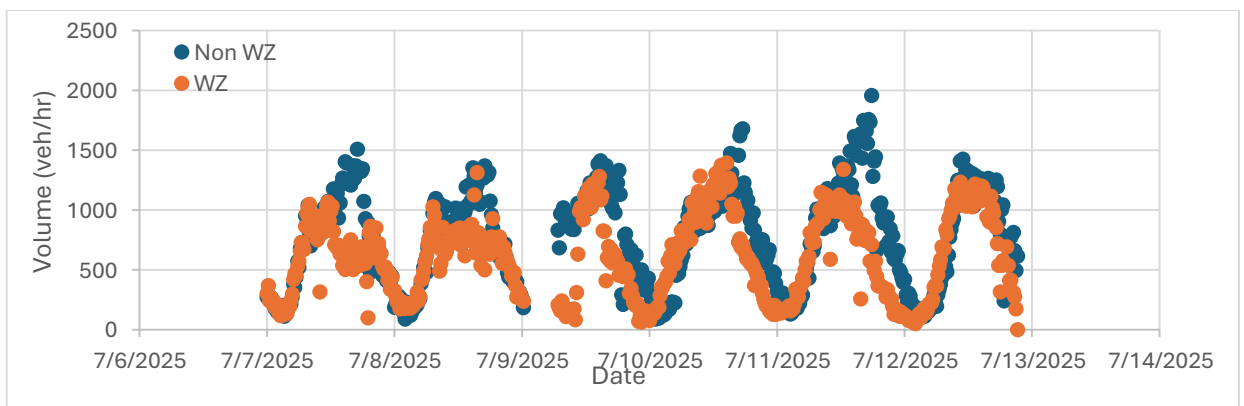


Figure 6-21: Demand Pattern/location 10 (I-94/Jackson)

The observed demand-reduction behavior varies depending on the lane-closure configuration and congestion severity. In general, 3→2 lane closures produced larger traffic-demand reductions than 2→1 lane closures because of the greater operational impact and increased congestion severity associated with the reduced roadway capacity. The analysis also showed that demand reduction was more pronounced during AM and PM peak periods than under daily average conditions.

Table 6-3 summarizes the observed average, worst-case, and best-case demand-reduction conditions identified during the field analysis process. The results indicated that average total daily demand reductions were approximately 11% for 3→2 lane closures and approximately 8% for 2→1 lane closures. Peak-period reductions were generally higher, with observed AM peak reductions reaching approximately 16% under 3→2 lane-closure conditions

Table 6-3: Observed Traffic Demand Reduction under Freeway Work Zone Conditions

Lane Closure Type	Total Daily Demand Reduction	AM Peak Reduction	PM Peak Reduction
3 → 2	Average Reduction	11%	16%
	Worst-Case Reduction	29%	34%
	Best-Case Reduction	1%	0%
2 → 1	Average Reduction	8%	15%
	Worst-Case Reduction	10%	11%
	Best-Case Reduction	0%	6%
4 → 2*	5%	6%	8%
Shoulder Closure (2 lanes) *	4%	6%	5%
Shoulder Closure (3 lanes) *	3%	3%	3%

*The results were based on one observed location for each configuration.

The field observations additionally demonstrated that demand reduction is highly location-dependent and influenced by surrounding network conditions, route availability, regional travel behavior, and congestion severity. Consequently, the study recommends using actual observed traffic demand whenever field data are available. However, when observed demand data are unavailable, appropriate demand-reduction assumptions should be applied in work-zone operational analysis to better represent traffic redistribution behavior under congested work-zone conditions.

6.5.2 Speed Reduction

The field data analysis also demonstrated substantial reductions in operating speed under active freeway work-zone conditions. Observed speed reductions were associated with lane closures, congestion buildup, queue propagation, ramp interactions, crossover operations, and work-zone geometric constraints. The speed-reduction analysis was conducted by comparing observed work-zone speeds with corresponding non-work-zone speeds at the same freeway locations, using API and field-observed traffic datasets.

Figure 6-22 - Figure 6-24 present examples of observed speed patterns under different freeway work zone configurations. The results indicate that freeway work zones consistently reduced operating speeds under both uncongested and congested conditions. Even under relatively stable traffic conditions, work-zone free-flow speeds were typically reduced by 15–20 mph compared with corresponding non-work-zone conditions.

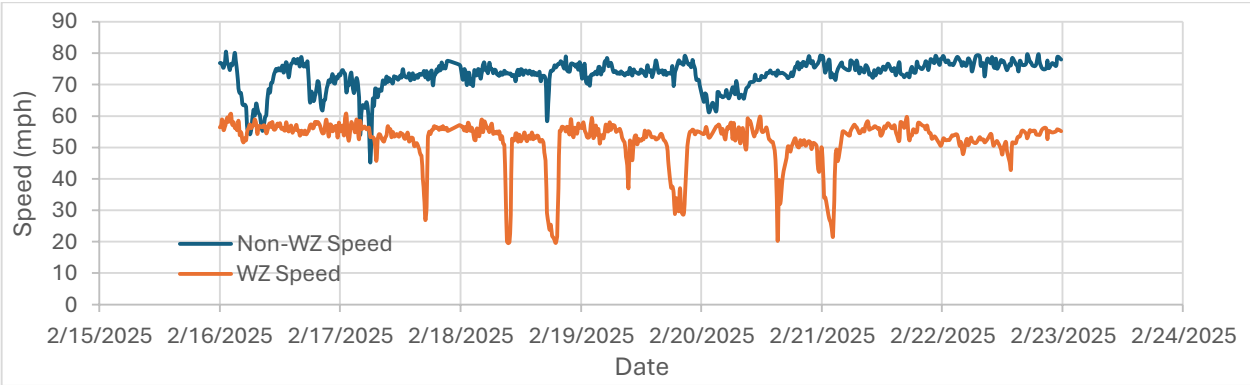


Figure 6-22: Speed Pattern/location 16 (I-96/Livonia)

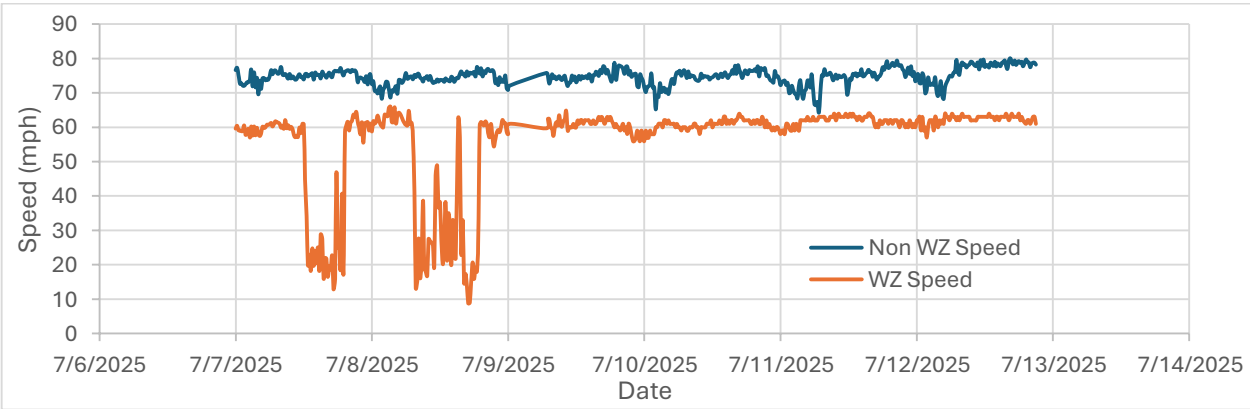


Figure 6-23: Speed Pattern/location 10 (I-94/Jackson)

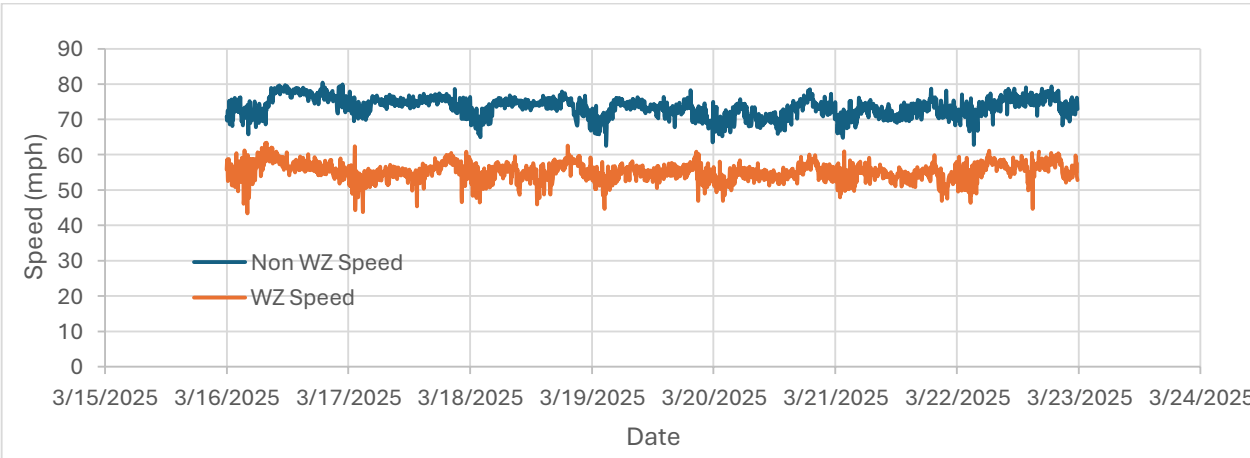


Figure 6-24: Speed Pattern/location 13 (I-96/Livingston)

The analysis additionally demonstrated that severe congestion and queue formation produced substantial operational speed degradation. Under highly congested conditions, observed operating speeds dropped to approximately 10–20 mph at severe bottleneck locations, particularly near lane reductions, merge areas, and queue spillback regions. These conditions resulted in substantial speed reductions relative to corresponding non-work-zone traffic conditions.

The observed field conditions also demonstrated that traffic speed becomes substantially less stable within work zones. Compared with non-work-zone traffic conditions, work-zone traffic exhibited greater speed fluctuations, increased temporal variability, and more unstable operational behavior throughout the analysis period. This variability was particularly evident under severe congestion conditions and work zone configurations involving major lane reductions.

Table 6-4 summarizes the observed speed-reduction conditions for the evaluated freeway work-zone configurations. The observed speed-reduction behavior obtained from the field analysis was subsequently used during the calibration of the freeway work zone speed models and multi-regime flow-density relationships developed within the MiPACE framework. These observations provided the operational basis for calibrating realistic work-zone free-flow speed conditions and congestion-related speed transitions across varying freeway work-zone operational scenarios.

Table 6-4: Observed Speed Reduction under Freeway Work Zone Conditions

Lane Closure Type	Performance Measure	Non-WZ Condition	Work Zone Condition	Speed Reduction
4 → 2	Free-Flow Speed (FFS)	78 mph	56 mph	28%
	Average Operating Speed	75 mph	55 mph	27%
	Typical Congestion Speed	60–65 mph	35–45 mph	38%
	Highest Observed Speed	82 mph	61 mph	28%
	Lowest Observed Speed	45 mph	20 mph	44%
3 → 2	Free-Flow Speed (FFS)	78 mph	60 mph	23%
	Average Operating Speed	76 mph	58 mph	24%
	Typical Congestion Speed	72 mph	55 mph	22%
	Highest Observed Speed	80 mph	62 mph	23%
	Lowest Observed Speed	65 mph	45 mph	30%
2 → 1	Free-Flow Speed (FFS)	76–78 mph	58–60 mph	24%
	Average Operating Speed	73–75 mph	58–60 mph	22%
	Typical Congestion Speed	65–70 mph	30–40 mph	45%
	Highest Observed Speed	80 mph	62 mph	22%
	Lowest Observed Speed	60 mph	10 mph	80%

6.6 Chapter Summary

This chapter presented the data collection, processing, and preparation activities conducted to support the development, calibration, and validation of the MiPACE framework. Multiple work zone sites across Michigan were selected to represent different lane-closure configurations, traffic demand conditions, and operational characteristics under freeway work zone conditions.

The chapter described the multi-source data framework adopted in this study, which integrated field-collected video and Bluetooth data with MDOT-provided datasets, including API speed data, RITIS observations, Safe Zone project data, and MVDS detector data. The field deployment procedures, sensor installation methods, and traffic monitoring framework were also presented for the selected work zone corridors.

In addition, the chapter introduced video-based speed and traffic volume extraction methodologies, including perspective correction, vehicle tracking, traffic counting, and data validation procedures. Data cleaning, temporal aggregation, quality control, and manual validation were performed to prepare consistent, analysis-ready datasets for model development and calibration.

The field observations demonstrated that active freeway work zones significantly affect both traffic demand and operating speed. The analysis showed measurable reductions in demand and speed, congestion development, and queue formation under different work zone configurations. These findings provided important operational insights and established the empirical foundation required for calibrating and validating the developed traffic models that are described in the subsequent chapters.

Chapter 7: Development of Work Zone Traffic Models

7.1 Modeling Approach Overview

The modeling framework developed in this study was designed to improve the representation of traffic operations under work-zone conditions by integrating dynamic traffic flow analysis, calibrated operational models, and scenario-based evaluation into a unified computational environment. The framework was developed based on findings from the evaluation of existing methodologies, field data collection, and operational requirements identified through practitioner surveys and focus group discussions.

The MiPACE uses a Cell Transmission Model (CTM)-based traffic simulation approach to model the spatiotemporal behavior of traffic flow in freeway and multilane work zones. The CTM methodology was selected for its ability to represent dynamic traffic phenomena, including queue propagation, shockwave propagation, congestion formation, bottleneck behavior, and traffic dissipation, under varying operational conditions. Compared with traditional deterministic or spreadsheet-based approaches, the CTM framework offers greater flexibility and a more realistic representation of traffic conditions across time and space.

The roadway network within the CTM framework is divided into multiple homogeneous cells representing roadway segments with consistent geometric and operational characteristics. Each cell is characterized by parameters such as free-flow speed, work zone capacity, critical density, jam density, lane configuration, and traffic demand. The movement of traffic between cells is governed by sending and receiving flow relationships, enabling the model to dynamically simulate traffic evolution throughout the work-zone corridor.

The framework also incorporates operational features required for realistic work zone analysis, including ramp merge/diverge interactions, dynamic queue propagation, physical and moving queue estimation, diversion effects, and lane closure transition effects. In addition, separate operational logic was developed to represent different work zone configurations and traffic control strategies under freeway, multilane, detour, and flagging scenarios.

7.2 Cell Transmission Model (CTM)

The Cell Transmission Model (CTM) was adopted in this study as the primary traffic flow modeling framework to represent dynamic traffic operations under work-zone conditions.

The CTM, originally developed by Daganzo (1994, 1995), is a macroscopic traffic flow model based on the conservation of vehicles and the fundamental relationship between flow, density, and speed. Within the proposed framework, the roadway corridor is discretized into homogeneous cells with fixed spatial and temporal resolutions, enabling dynamic updates to traffic conditions over time. The implemented CTM framework incorporates work zone-specific operational characteristics, including lane closures, shoulder closures, crossovers, ramp interactions, detour operations, and dynamic diversion behavior. The model captures essential traffic phenomena such

as queue formation, shockwave propagation, congestion spillback, and congestion dissipation, providing a more realistic representation of traffic behavior compared with traditional deterministic or spreadsheet-based methods. In addition, the framework integrates calibrated work zone speed and capacity relationships, multi-regime fundamental diagrams, merge/diverge logic, and dynamic queue propagation within a unified simulation environment.

7.2.1 Spatial and Temporal Discretization

The Cell Transmission Model (CTM) implemented in this study is based on a discrete space–time representation of traffic flow, where the roadway is divided into a sequence of finite spatial units (cells), and traffic states are updated at fixed time intervals. This discretization framework allows the model to capture the dynamic evolution of traffic conditions, including congestion formation, queue propagation, and shockwave behavior, while maintaining computational efficiency and numerical stability.

The roadway is partitioned into homogeneous cells, each with a fixed spatial length of $\Delta x = 0.1$ mile, and the simulation progresses using a constant time step of $\Delta t = 4$ seconds. Within each cell, traffic conditions are assumed to be uniform at each time step and are represented by key state variables such as the number of vehicles, flow, and density. The model advances from time step j to $j + 1$, updating traffic conditions based on the interaction between adjacent cells and any additional inflows or outflows.

As illustrated in Figure 7-1, CTM tracks traffic movement between neighboring cells over consecutive time steps. For a given cell i , the traffic state at the time j is defined by the number of vehicles N_i^j and the flow q_i^j exiting the cell. The evolution of traffic conditions is governed by the principle of vehicle conservation, where the number of vehicles in a cell at the next time step is determined by the balance between inflows and outflows.

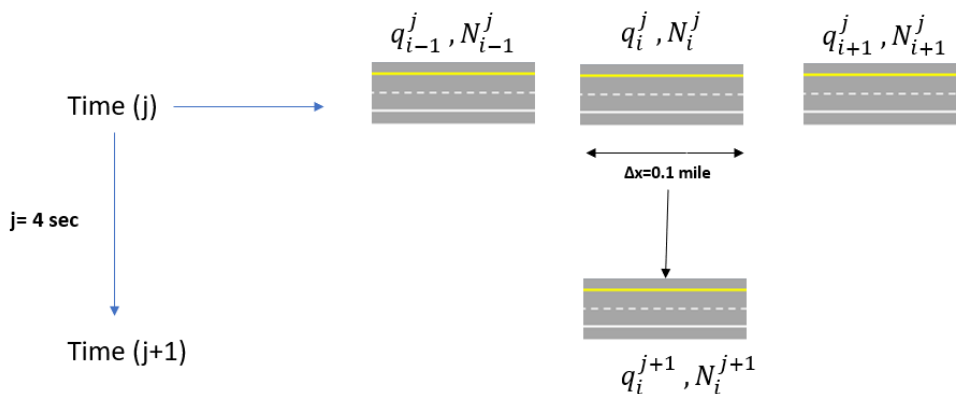


Figure 7-1: CTM Cell-Based Flow Representation

The conservation equation is expressed as shown in Equation (4):

$$N_i^{j+1} = N_i^j + q_{i-1}^j + p \cdot r_i^j - q_i^j - p \cdot s_i^j \quad (4)$$

Where:

- q_{i-1}^j represents the flow entering from the upstream cell,
- q_i^j is the flow exiting to the downstream cell,
- r_i^j is the on-ramp inflow,
- s_i^j is the off-ramp outflow, and
- p is a ramp adjustment factor.

This formulation ensures that the change in the number of vehicles within a cell is governed by the difference between total inflow and total outflow, allowing the model to capture both mainline traffic propagation and ramp interactions.

The discretization scheme follows the classical CTM formulation introduced by Daganzo (1994), ensuring consistency with kinematic wave theory. To guarantee numerical stability, the model satisfies the Courant–Friedrichs–Lewy (CFL) condition, which requires that the distance traveled by vehicles within one time step does not exceed the cell length. Using the model parameters, the condition is satisfied, confirming that the simulation remains stable under the selected discretization.

7.2.2 Ramp Interaction Logic (Merge and Diverge Rules)

The CTM framework in MiPACE incorporates ramp interactions by explicitly modeling on-ramp (merge) and off-ramp (diverge) nodes. These interactions introduce additional inflow and outflow terms into the system and play a critical role in capturing localized congestion, capacity constraints, and traffic redistribution within the corridor.

At ramp locations, traffic flow is governed by node-based rules, in which multiple streams interact under downstream capacity constraints.

On-Ramp (Merge) Logic

At on-ramp locations, traffic from the mainline and the on-ramp merge into a single downstream cell. The available downstream capacity must be shared between these competing flows.

As shown in **Figure 7-2**, a portion of the downstream capacity is allocated to the on-ramp flow, while the remaining capacity is reserved for the mainline. For example, the model may allocate approximately 20% of capacity to the on-ramp and 80% to the mainline, depending on demand and priority rules.

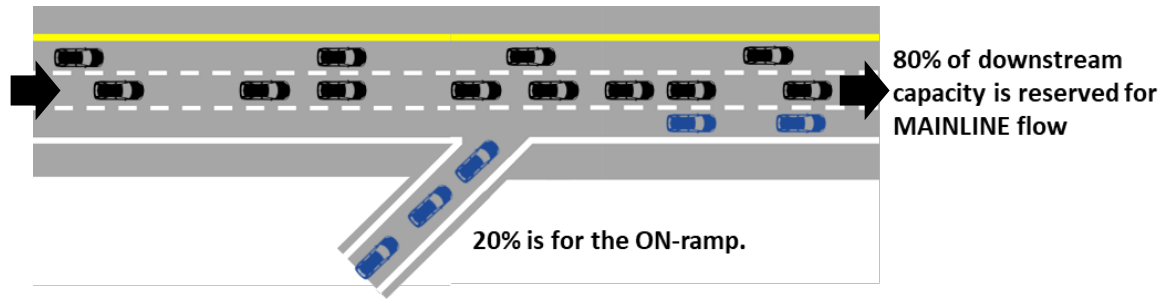


Figure 7-2: On-Ramp Merge Behavior Showing Capacity Allocation between Mainline and Ramp Flow

The merge behavior is governed by the following conditions:

- If the total demand from both streams does not exceed downstream capacity:

$$m_{send} + r_{send} \leq R_{cap} \quad (5)$$

then:

$$m_{flow} = m_{send}, r_{flow} = r_{send} \quad (6)$$

- Otherwise, when capacity is constrained, the available capacity is distributed between the mainline and ramp flows based on a priority factor, ensuring that both streams are proportionally accommodated.

The total flow entering the downstream cell is in Equation **Error! Reference source not found.**):

$$F_i = m_{flow} + r_{flow} \quad (7)$$

where:

m_{send} = mainline sending flow

r_{send} = ramp sending flow

R_{cap} = downstream receiving capacity

m_{flow} = mainline flow entering the downstream cell

r_{flow} = ramp flow entering the downstream cell

F_i = total flow entering downstream cell

Off-Ramp (Diverge) Logic

At off-ramp locations, a portion of the mainline traffic exits the system, reducing the downstream flow.

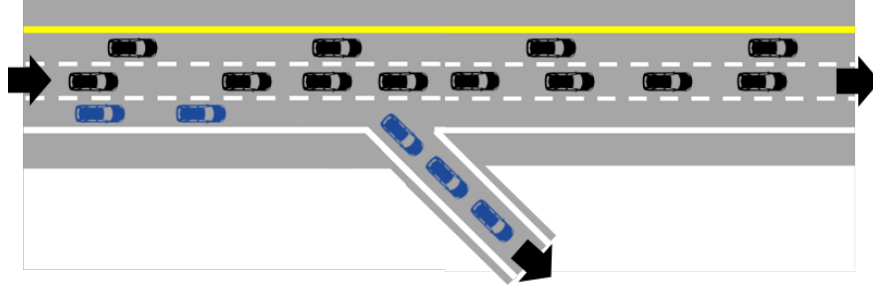


Figure 7-3: Off-Ramp Diverge Behavior Showing Flow Separation from Mainline Traffic

As illustrated in Figure 7-3, vehicles diverge from the mainline toward the off-ramp, creating a split between continuing and exiting traffic. This process is modeled by subtracting the off-ramp flow from the upstream sending flow (see Equation (7)):

$$S_{rem}(i) = S_i - O_{real}(i) \quad (7)$$

where:

S_i is the sending flow from the upstream cell

$O_{real}(i)$ is the actual off-ramp flow

This formulation ensures that the remaining flow continues downstream while accounting for traffic leaving the system.

7.2.3 Integration with CTM Conservation Equation

The presence of ramp flows modifies the standard CTM conservation equation. The updated formulation includes both on-ramp inflow and off-ramp outflow (See Equation (8)):

$$N_i(t + 1) = N_i(t) + F_{i-1} + U_{real}(i) - O_{real}(i) - F_i \quad (8)$$

where:

$U_{real}(i)$ represents the on-ramp inflow

$O_{real}(i)$ represents off-ramp outflow

This extended formulation allows the CTM model to capture realistic traffic dynamics, including:

- Increased density due to merging
- Reduced downstream flow due to divergence
- Localized congestion near ramp areas

7.2.4 CTM Logic: Fundamental Diagram and Flow Functions

Several previous studies demonstrated that traffic behavior near congestion breakdown cannot be adequately represented using traditional single-regime or triangular Fundamental diagram formulations. Kerner (2002) showed that freeway traffic exhibits multiple traffic phases and hysteresis behavior under congested conditions, while Laval and Leclercq (2011) demonstrated that traffic transitions near breakdown conditions are nonlinear and highly dynamic. Similarly, Avrenli, Benekohal, and Ramezani (2011) developed three- and four-regime work-zone speed-flow curves using field data collected from freeway work zones and showed that work-zone traffic conditions comprise multiple operational states, including free-flow, transition, breakdown, and congested regimes. Based on these findings, the proposed framework in this study adopts a four-regime FD structure consisting of:

1. Region 1 – Free-Flow Region,
2. Region 2 – Transitional Region,
3. Region 3 – Breakdown Region,
4. Region 4 – Fully Congested Region.

As shown in Figure 7-4, the model explicitly represents the Free-Flow Limit Point, Capacity Point, Breakdown Point, and Jam Point to characterize transitions among traffic states. The sending function is primarily governed by uncongested traffic conditions, whereas the receiving function reflects downstream congestion and roadway storage limitations under congestion. This formulation enables the CTM framework to dynamically capture traffic state transitions, congestion evolution, queue propagation, shockwave propagation, and post-breakdown traffic behavior under work-zone conditions.

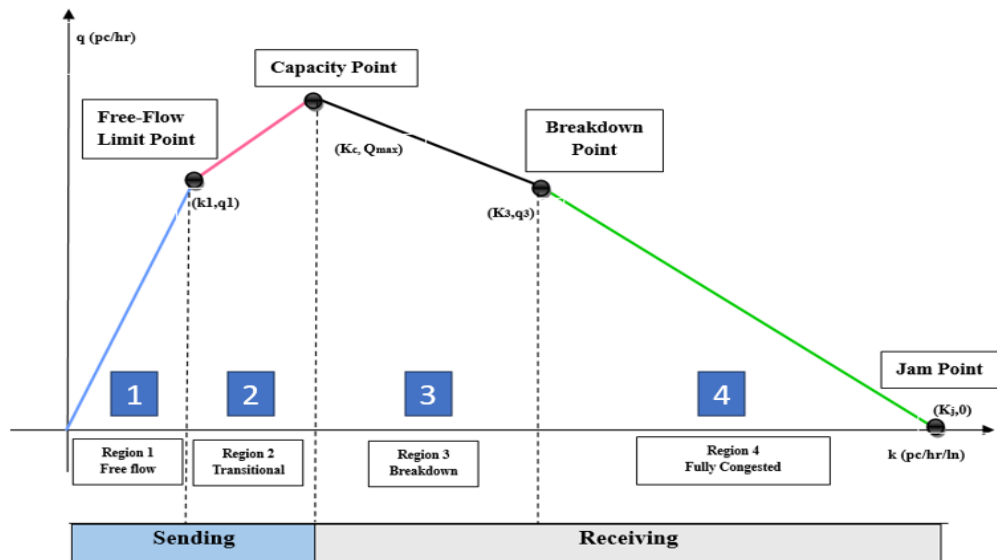


Figure 7-4: Four-Regime Fundamental Diagram Showing Traffic States and Sending/Receiving Behavior

The flow–density relationship is defined using four linear segments corresponding to distinct traffic states. In Region 1 (free flow), traffic operates under uncongested conditions, and flow increases linearly with density according to:

$$q(k) = \frac{q_1}{k_1} \cdot k$$

In Region 2 (transitional/near-capacity), traffic approaches maximum throughput, and flow continues to increase at a reduced rate:

$$q(k) = q_1 + \frac{Q_{max} - q_1}{k_c - k_1} (k - k_1)$$

In Region 3 (breakdown/post-capacity), flow decreases as density increases, representing the onset of congestion:

$$q(k) = Q_{max} + \frac{q_3 - Q_{max}}{k_3 - k_c} (k - k_c)$$

Finally, in Region 4 (fully congested), traffic is oversaturated, and flow decreases toward zero as density approaches the jam conditions:

$$q(k) = q_3 + \frac{0 - q_3}{k_j - k_3} (k - k_3)$$

Based on this formulation, the CTM defines two governing functions for traffic propagation. The sending function represents the maximum flow that can leave a cell and is determined by the upstream demand conditions:

$$\text{Sending} = \min(q_A(k), q_B(k))$$

where $q_A(k)$ corresponds to the free-flow branch and $q_B(k)$ represents the capacity-limited branch. The receiving function represents the maximum flow that can be accepted by the downstream cell and is governed by congestion conditions:

$$\text{Receiving} = \min(q_C(k), q_D(k))$$

where $q_C(k)$ and $q_D(k)$ correspond to the post-capacity and fully congested branches, respectively.

This formulation enables the CTM to dynamically capture transitions among traffic states, including free-flow, near-capacity, breakdown, and fully congested conditions. As a result, the model can accurately represent key traffic phenomena such as capacity drop, congestion propagation, and shockwave movement, which are critical for analyzing work zone impacts.

7.3 Traffic Model Development

The MiPACE modeling framework was developed to provide a unified, transferable traffic analysis environment capable of representing multiple work zone configurations under dynamic traffic conditions. The framework integrates Cell Transmission Model (CTM)-based traffic simulation, multi-regime traffic-flow representation, calibrated work-zone operational parameters, and scenario-specific traffic behavior within a consistent analytical framework. The overall framework supports freeway, multilane, and one-lane two-way operations using separate operational logic and traffic control methodologies depending on facility type and work zone configuration.

7.3.1 Capacity and Speed Modeling

This section presents the development and calibration of the freeway work zone speed and capacity models implemented in MiPACE. The modeling framework was developed using the Highway Capacity Manual (HCM 7th Edition) work zone methodology as the baseline reference and subsequently calibrated using observed freeway work zone traffic data collected from Michigan work zone projects. The objective of the calibration process was to evaluate the applicability of the generalized HCM relationships under Michigan work-zone conditions and to develop locally calibrated equations to better represent actual freeway work-zone operational behavior.

The HCM 7th Edition methodology estimates work zone free-flow speed and work zone capacity using adjustment factors associated with lane-closure severity, barrier type, area type, lighting condition, lateral clearance, and ramp density. The HCM 7th Edition work zone free-flow speed model is expressed as shown in Equation (9):

$$FFS_{HCM7} = 9.95 + 33.49f_{Sr} + 0.53SL_{wz} - 5.6LCSI - 3.84f_{Br} - 1.71f_{DN} - 8.7TRD \quad (9)$$

Similarly, the HCM 7th Edition work zone capacity model is expressed as shown in Equation (10):

$$QDR_{HCM7} = 2093 - 154LCSI - 194f_{Br} - 179f_{AT} + 9f_{LAT} - 59f_{DN} \quad (10)$$

where:

- $LCSI$ = lane closure severity index, $LCSI = \frac{1}{OR \times N_o}$, OR = open-lane ratio, N_o = number of open lanes
- f_{Br} = barrier type factor, (0= hard/concrete barrier, 1= soft barrier/cones),
- f_{AT} = area type factor (0= urban, 1= rural),
- f_{LAT} = lateral clearance factor (0–12 ft),
- f_{DN} = lighting condition factor (0= daylight, 1= nighttime),
- f_{Sr} = speed ratio (non-work-zone speed limit ÷ work-zone speed limit),
- SL_{wz} = work zone speed limit (mph),
- TRD = total ramp density (ramps/mi within ± 3 mi of the center of work zone).

Using observed freeway work-zone traffic data, locally calibrated Michigan-specific speed and capacity equations were subsequently developed to better represent actual freeway work-zone operational behavior. Regression analysis was performed on observed traffic flow, speed, and queue discharge rate data collected from selected freeway work zone projects. The resulting Michigan-calibrated free-flow speed model is expressed as shown in Equation (11):

$$FFS_{MI} = 8.93 + 33.49f_{Sr} + 0.44SL_{wz} - 2.40LCSI - 1.60f_{Br} - 1.50f_{DN} - 5.42TRD \quad (11)$$

Similarly, the Michigan-calibrated work zone capacity model is expressed as shown in Equation (12):

$$Capacity_{MI} = 1960 - 132LCSI - 178f_{Br} - 179f_{AT} + 8.6f_{LAT} - 59f_{DN} \quad (12)$$

Because of the limited number of observed shoulder-closure work zone datasets available during calibration, the development of fully calibrated regression-based capacity relationships for these scenarios was deemed not statistically reliable. Therefore, fixed representative capacity values were adopted for the shoulder-closure configurations within the MiPACE framework. Based on the observed traffic behavior and calibration results, the capacity values were set to 2,165 pc/h/ln for shoulder-closure scenarios with three lanes open and to 2,035 pc/h/ln for those with two lanes open.

To simplify the calibration and statistical analysis processes, a symbolic notation system was developed to classify freeway work zone operational conditions by area type, barrier condition, lighting condition, lateral clearance, lane configuration, and total ramp density. The notation structure included the number of open lanes (NO), the number of closed lanes (NC), and the total ramp density (TRD) to represent the operational severity of each work zone scenario. Table 7-1 summarizes the symbolic notation used for the freeway work-zone calibration cases.

Table 7-1: Scenario Definition for Work Zone Calibration Cases

Scenario Code	Definition
NO/NC	Number of open lanes/Number of closed lanes
S/H	Barrier type: S = soft barrier, H = hard barrier
U/R	Area type: U = urban, R = rural
LC	Lateral clearance from traveled lane to barrier (ft)
D/N	Work time: D = daylight, N = nighttime
TRD	Total ramp density (ramps/mi)

For example, the scenario code U-S-D-LC4-NO1-NC1-TRD0.45 represents a freeway work zone located in an urban area (U), with a soft barrier separation (S), daytime operation (D), 4-ft lateral clearance (LC4), one open lane (NO1), one closed lane (NC1), and a total ramp density of 0.45 ramps/mi.

Table 7-2 shows the comparison between the observed queue discharge rates and the estimated values obtained using the HCM 7th Edition and Michigan-calibrated models for each work zone scenario.

Table 7-2: Comparison Between HCM 7th Edition and Michigan-Calibrated Capacity

Location	Symbol	HCM7 Pc/hr/ln	MI model Pc/hr/ln	Field Pc/hr/ln	Field vs HCM7 %	Field vs MI %
I-96	U-S-D-LC4-NO1-NC1-TRD0.45	1642	1551	1588	3.4%	-2.3%
US-131	U-H-D-LC0-NO2-NC0-TRD0	1643	1537	1568	4.8%	-2.0%
I-94	U-S-D-LC3-NO2-NC1-TRD0	1826	1708	1708	6.9%	0.0%
I-75	U-S-D-LC6-NO2-NC2-TRD0.30	1814	1701	1732	4.7%	-1.8%
I-75	U-S-D-LC5-NO2-NC1-TRD0.68	1844	1725	1692	8.9%	1.9%
I-75	U-S-D-LC5-NO1-NC2-TRD0.40	1651	1624	1621	1.8%	0.2%
I-94	U-S-D-LC2-NO1-NC1-TRD0.64	1624	1534	1523	6.7%	0.8%
I-94	U-S-D-LC3-NO1-NC1-TRD0.65	1633	1543	1512	8.0%	2.1%
I-94	U-S-D-LC3-NO1-NC1-TRD0.65	1633	1543	1587	2.9%	-2.8%
I-94	U-S-D-LC2-NO1-NC1-TRD0.24	1624	1534	1535	5.8%	-0.1%
I-75	U-S-D-LC0-NO3-NC0-TRD0.55	1863	2165	2163	-13.9%	0.1%
M-39	U-S-D-LC0-NO2-NC1-TRD0.38	1799	1682	1672	7.6%	0.6%
I-96	U-S-D-LC3-NO2-NC1-TRD0.34	1826	1708	1681	8.6%	1.6%
I-94	U-S-D-LC0-NO2-NC1-TRD0.50	1799	1682	1682	6.9%	0.0%
US-23	U-S-D-LC0-NO3-NC0-TRD0.64	1837	2035	2035	-9.7%	0.0%

Table 7-3 summarizes the statistical performance measures used to evaluate the Michigan-calibrated work zone capacity model implemented in MiPACE. The results indicate strong model performance and high predictive capability across the freeway work zone calibration dataset. The goodness-of-fit measures demonstrate that the calibrated model successfully captured the

variability observed in the field capacity data, while the low prediction-error metrics indicate high estimation accuracy and limited bias. In addition, the regression diagnostics and validation measures confirmed the statistical significance, robustness, and generalizability of the developed capacity model. Overall, the statistical evaluation demonstrates that the Michigan-calibrated capacity equation (Equation (12)) provides a better representation of freeway work zone operational behavior than the generalized HCM-based relationship.

Table 7-3: Statistical Performance Measures Used for Capacity Model Evaluation

Goodness-of-Fit Performance Measures				
(R ²)	Adjusted (R ²)	Correlation Coefficient (R)	RMSE (pc/h/ln)	Relative RMSE (%)
0.89	0.87	0.94	2.8	4.5
Error and Prediction Accuracy Measures				
MAE (pc/h/ln)	MAPE (%)	Mean Bias Error (MBE)	Maximum Absolute Error (pc/h/ln)	Nash–Sutcliffe Efficiency (NSE)
2.1	3.8	0.00057	6.5	0.87
Statistical Significance and Regression Diagnostics				
AIC	BIC	p-value	Durbin–Watson Statistic	Variance Inflation Factor (VIF)
118.4	124.2	<0.01	1.96	<2.0
Validation and Uncertainty Assessment Measures				
Cross-Validation Accuracy	Prediction Interval Coverage Probability (PICP)		Residual Standard Deviation	
91%	94%		Low	

The observed freeway work-zone free-flow speed data were compared with both the original HCM 7th Edition speed model and the Michigan-calibrated speed model to evaluate the prediction accuracy and applicability of the developed equations under Michigan work-zone conditions. Table 7-4 summarizes the comparison between observed work-zone speeds and estimated values obtained using the HCM and Michigan-calibrated speed equations for each freeway work-zone scenario. The comparison results indicate that the generalized HCM speed model consistently underestimated the observed free-flow speeds in work zones across several freeway configurations. In contrast, the Michigan-calibrated speed model produced estimates that more closely matched the observed field measurements and substantially reduced the prediction error across most scenarios.

Table 7-4: Comparison Between HCM 7th Edition and Michigan-Calibrated Speed

Location	Symbol	HCM7 Pc/hr/ln	MI model Pc/hr/ln	Field Pc/hr/ln	Field vs HCM7 %	Field vs MI %
I-96	U-S-D-LC4-NO1-NC1-TRD0.45	61.78	57.13	60.09	-7.53	-2.74
US-131	U-H-D-LC0-NO2-NC0-TRD0	67.80	69.59	65.72	+2.64	-3.07
I-94	U-S-D-LC3-NO2-NC1-TRD0	64.30	65.92	64.05	-0.57	-0.34
I-75	U-S-D-LC6-NO2-NC2-TRD0.30	63.64	61.27	63.06	-3.73	-0.91
I-75	U-S-D-LC5-NO2-NC1-TRD0.68	60.77	56.32	58.56	-7.32	-3.64
I-75	U-S-D-LC5-NO1-NC2-TRD0.40	59.36	58.83	61.10	-0.89	+2.93
I-94	U-S-D-LC2-NO1-NC1-TRD0.64	59.21	53.86	56.87	-9.04	-3.95
I-94	U-S-D-LC3-NO1-NC1-TRD0.65	59.80	53.77	56.78	-10.08	-5.05
I-94	U-S-D-LC3-NO1-NC1-TRD0.65	59.65	53.77	56.78	-9.86	-4.82
I-94	U-S-D-LC2-NO1-NC1-TRD0.24	63.54	59.25	61.62	-6.75	-3.02
I-75	U-S-D-LC0-NO3-NC0-TRD0.55	69.50	66.62	69.52	-4.15	+0.03
M-39	U-S-D-LC0-NO2-NC1-TRD0.38	62.90	58.96	61.74	-6.26	-1.84
I-96	U-S-D-LC3-NO2-NC1-TRD0.34	62.10	60.91	63.34	-1.91	+2.00
I-94	U-S-D-LC0-NO2-NC1-TRD0.50	63.60	58.83	61.10	-7.50	-3.93
US-23	U-S-D-LC0-NO2-NC0-TRD0.64	69.70	64.54	67.90	-7.40	-2.58

Table 7-5: Statistical Performance Measures Used for Capacity Model Evaluation

Goodness-of-Fit Performance Measures				
(R ²)	Adjusted (R ²)	Correlation Coefficient (R)	RMSE (mph)	Relative RMSE (%)
0.86	0.84	0.93	1.90	3.0
Error and Prediction Accuracy Measures				
MAE (mph)	MAPE (%)	Mean Bias Error (MBE)	Maximum Absolute Error (mph)	Nash–Sutcliffe Efficiency (NSE)
1.69	2.73	-1.29	3.02	0.86
Statistical Significance and Regression Diagnostics				
AIC	BIC	p-value	Durbin–Watson Statistic	Variance Inflation Factor (VIF)
96.3	102.1	<0.01	1.94	<2.0
Validation and Uncertainty Assessment Measures				
Cross-Validation Accuracy	Prediction Interval Coverage Probability (PICP)		Residual Standard Deviation	
93%	95%		Low	

The statistical evaluation results in Table 7-5 demonstrate that the Michigan-calibrated speed model provides substantially improved prediction accuracy compared with the generalized HCM relationship. The calibrated model achieved lower RMSE, MAE, and MAPE values while maintaining strong goodness-of-fit and high predictive capability across the freeway work zone calibration dataset.

7.3.2 Freeway Model Development

The freeway model development process was based on the freeway work-zone projects presented in Section 6.2. These projects represented a wide range of freeway work zone configurations, including 2→1, 3→2, 3→1, and 4→2 lane closures; lane-shift operations; crossover configurations; and shoulder closures. The selected projects included field-collected traffic data from WMU studies, MDOT project datasets, and MVDS traffic observations. The purpose of using multiple projects was to capture traffic flow behavior under different work-zone operational and geometric conditions and to develop representative traffic flow relationships for each work-zone configuration.

The development of freeway traffic flow models began with an analysis of flow-density relationships observed in the Advanced Warning Area (AWA), which was selected as the primary reference condition because it consistently exhibited the full range of traffic-state transitions across multiple freeway work zone projects. As illustrated in Figure 7-5, the AWA flow-density relationship captured all four traffic regions defined in the proposed framework.

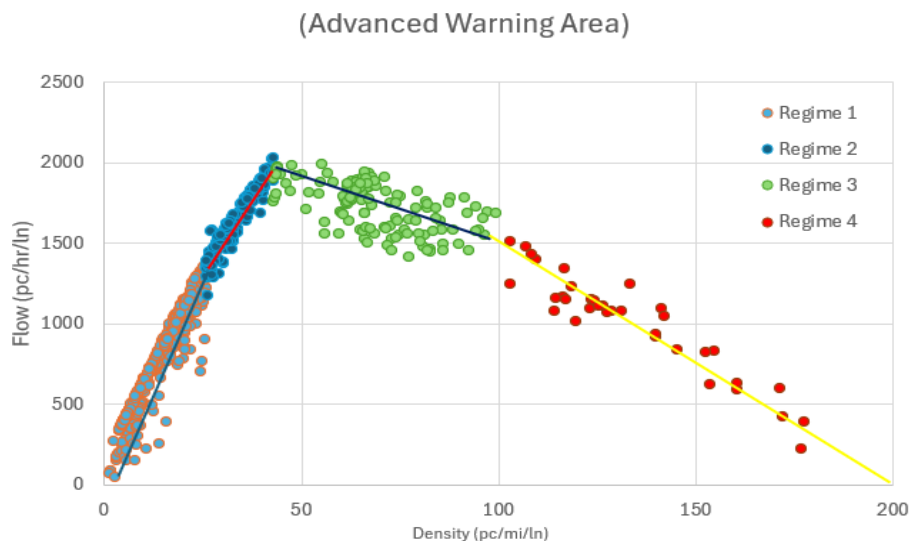


Figure 7-5: Flow-Density Relationship in AWA

Emphasis was placed on determining the jam-density parameter, which represents the maximum traffic density at which near-zero traffic flow occurs under fully congested conditions. Based on

the observed freeway work-zone data, the jam density used in this study was approximately 200 pc/mi/ln. Considering heavy-vehicle percentages ranging between 10% and 30%, the corresponding jam-density range is approximately 154–182 veh/mi/ln. This range is generally consistent with previously reported freeway work zone jam-density values summarized in Table 7-6.

Table 7-6: Reported Jam-Density Ranges for U.S. Freeway Work Zone Studies

State	Jam Density Findings
Texas	Typical jam-density range inferred from trailer speed–density data: 110–170 veh/mi/ln (I-35 Austin)
Missouri	Multiple work zones on I-70 & I-44 showed densities in the 130–180 veh/mi/ln range under heavy queue.
Nebraska	Rural freeway WZ queues with higher spacing; inferred jam density 110–150 veh/mi/ln.
Iowa	Observed densities on I-80 & I-35 WZ corridors fell in 120–160 veh/mi/ln range.
Kansas	Urban freeway work zones with high saturation; density measured 140–180 veh/mi/ln.
South Dakota	Lower jam density due to high truck %, lane shifts → 110–140 veh/mi/ln.
Illinois	Observed jam-density values 130–170 veh/mi/ln, Chicago interstates.
Minnesota (FHWA data incorporated)	Queue-density measurements 140–160 veh/mi/ln.

As shown in Table 7-6, previous freeway work zone studies conducted across multiple U.S. states reported jam-density values generally ranging from approximately 110 to 180 veh/mi/ln, depending on roadway geometry, lane configuration, truck percentage, congestion severity, and operational characteristics.

The development process began by generating flow-density relationships for each individual freeway work zone project using observed traffic flow, speed, and density data. Separate flow-density curves were developed for each work zone scenario to capture the operational characteristics of different lane-closure configurations and traffic-control conditions. As illustrated in Figure 7-6 The selected freeway work zone configurations, including 4→2, 3→1, 3→2, and 2→1 lane closures, exhibited traffic conditions across all four traffic regimes defined in the proposed framework. These projects experienced sufficient congestion to capture the full traffic evolution, including free-flow conditions, transitional behavior, breakdown conditions, and fully congested states. Consequently, the resulting flow-density relationships allowed the identification and calibration of all four FD regions within the CTM framework.

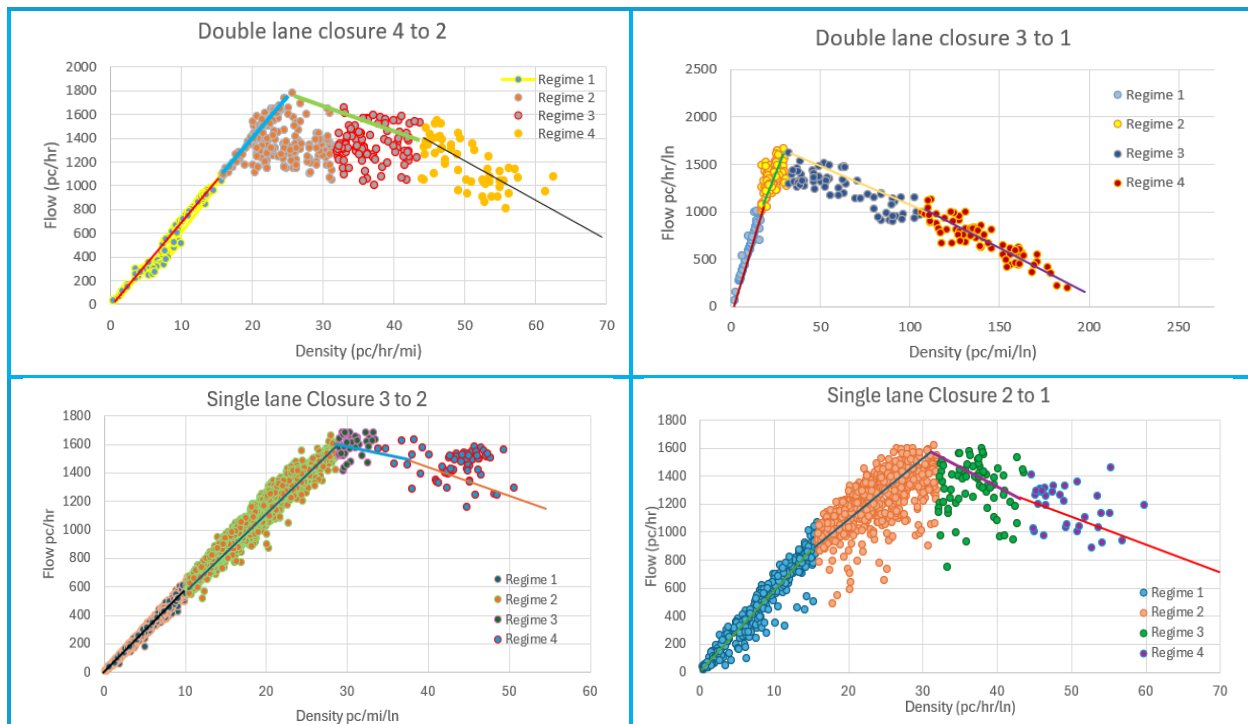


Figure 7-6: Flow-Density Relationships for Congested Freeway Work Zone Configurations

In contrast, some work zone configurations, particularly shoulder-closure scenarios, did not experience severe congestion or traffic breakdown during the observation period. As illustrated in Figure 7-7, the shoulder-closure cases primarily remained within the free-flow and transitional traffic regions and did not fully reach the breakdown and fully congested regimes. Therefore, the corresponding flow-density relationships for these scenarios captured only partial traffic-state transitions. Nevertheless, these observations were incorporated into the framework to preserve the operational characteristics of shoulder-closure conditions and maintain consistency within the normalized modeling structure.

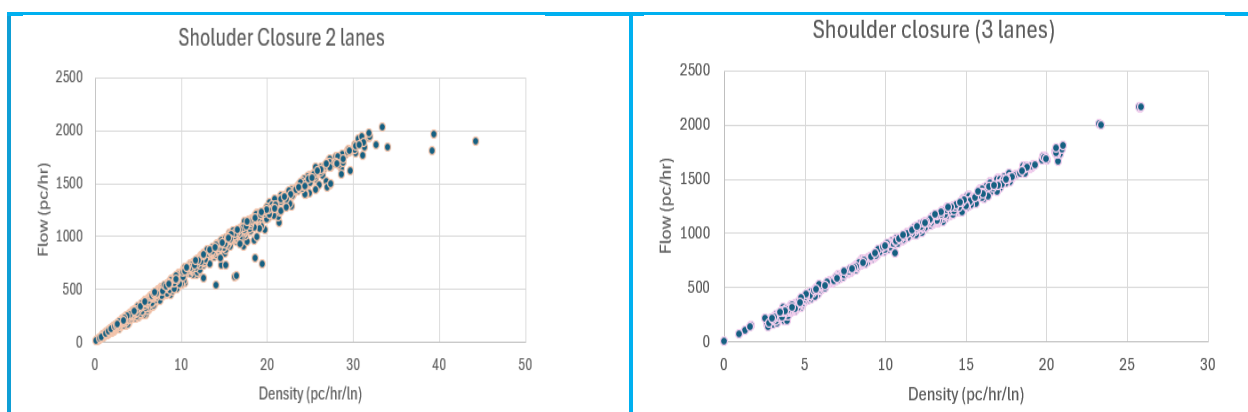


Figure 7-7: Shoulder Closure Traffic Conditions within the Proposed FD Framework

To establish a consistent analytical framework, all traffic flow models were classified according to the four-regime fundamental diagram (FD) structure adopted in this study, comprising the free-flow, transitional, breakdown, and fully congested regions. For each project, the primary traffic flow control points were identified from observed flow-density relationships, including the free-flow limit point, capacity point, breakdown point, and jam-density point. These control points were subsequently used to define the piecewise-linear, multi-regime FD relationships for each work-zone configuration.

The CTM parameters for each traffic regime were then calculated using linear flow-density relationships. The regime equations were represented using piecewise-linear relationships, where the slope and intercept values define the operational behavior of each traffic state. Using these relationships, the primary CTM traffic-flow parameters were calculated for each work-zone configuration, including free-flow speed, work-zone capacity, critical density, breakdown density, jam density, backward-wave speed, and regime-specific slope coefficients. Because the resulting flow-density relationships varied in magnitude and operational range across projects, a normalization process was performed to transform all project-specific models into a unified analytical framework. As illustrated in Figure 7-8, the original flow-density relationships were shifted and normalized relative to common reference conditions to reduce variability while preserving the overall operational behavior associated with each work zone type. This normalization process established a consistent relationship between traffic flow and density across different work zone scenarios while preserving the relative characteristics of each lane-closure configuration.

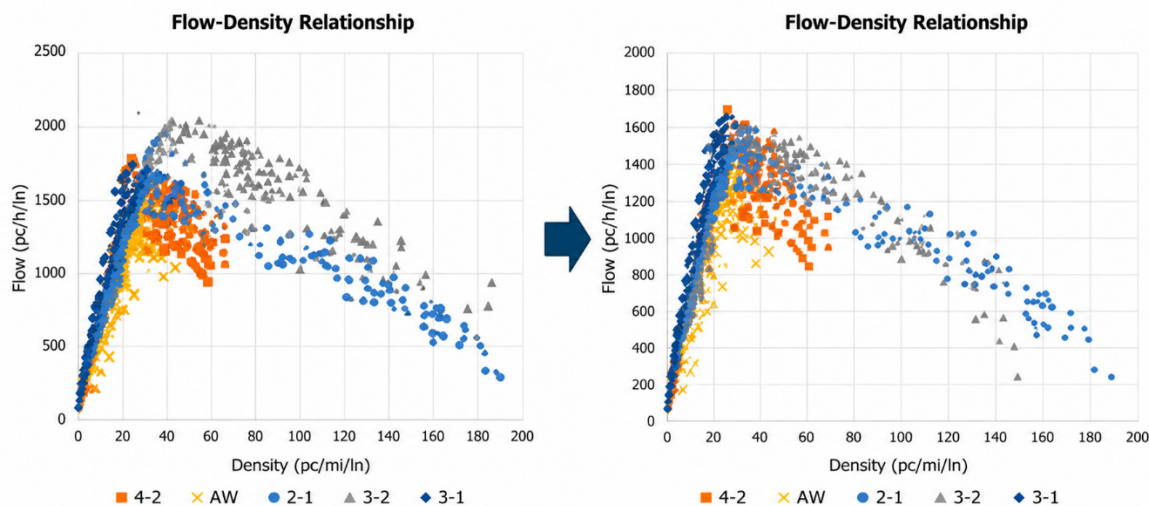


Figure 7-8: Normalized Multi-Regime Flow-Density Relationships

Following normalization, representative FD curves were developed for the major freeway work-zone scenarios, including 2→1, 3→2, 3→1, and 4→2 lane closures; crossover operations; lane-shift scenarios; shoulder closures; advanced warning areas; and non-work-zone conditions. As

illustrated in Figure 7-9, the normalized traffic flow models provided a unified framework for representing different freeway work zone configurations within the same CTM structure.

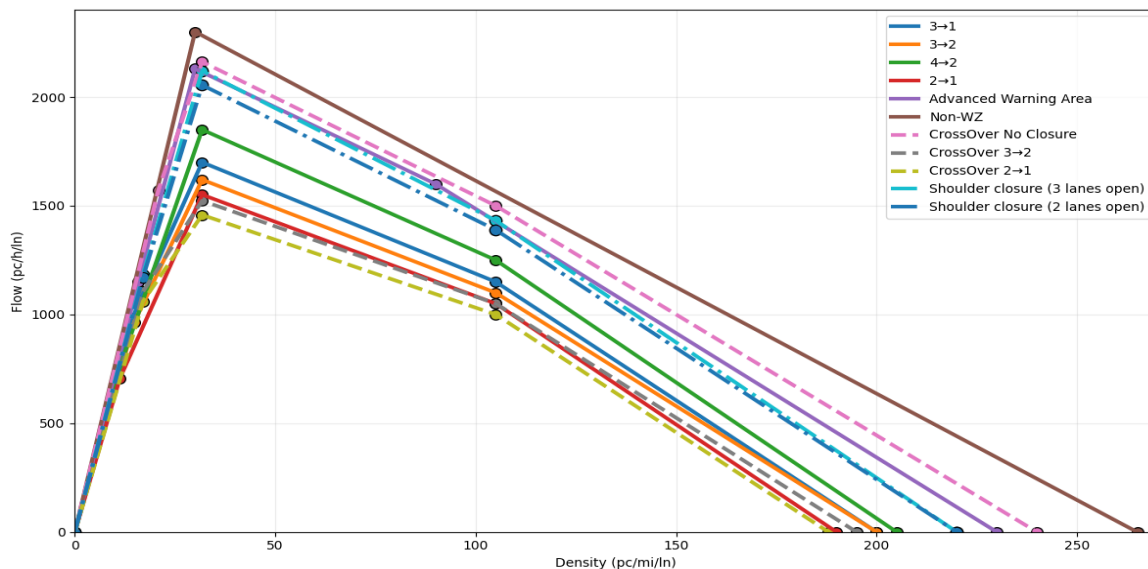


Figure 7-9: Normalized CTM Flow-Density Relationships for Major Freeway Work Zone Configurations

An important advantage of the normalization methodology is that it enables the framework to generate representative traffic-flow models for freeway work-zone configurations where direct field data may not be available. By applying the same normalized parameter structure and modeling approach, additional work zone scenarios can be generated consistently while preserving realistic traffic flow behavior and operational characteristics.

The resulting CTM parameters and normalized FD relationships were integrated directly into the MiPACE simulation framework to support dynamic freeway traffic analysis.

7.3.3 Multilane Highway Model Development

Unlike freeway work zones, the Highway Capacity Manual (HCM) does not provide direct work zone operational models specifically developed for multilane highway facilities under lane-closure conditions. Therefore, the multilane highway modeling framework developed in this study was established by combining HCM base-condition procedures with calibrated work-zone reduction patterns derived from the freeway work-zone analysis framework.

The development process began by estimating the base-conditioned traffic characteristics for multilane highways using standard HCM procedures. Under non-work-zone conditions, the free-flow speed (FFS) was estimated as a function of the base free-flow speed and geometric adjustment factors associated with lane width, lateral clearance, median type, and access density. Similarly, the base-conditioning capacity was estimated as a function of free-flow speed using the HCM multilane highway methodology. These calculations established the reference non-work-zone operating conditions for each multilane facility scenario.

Because no direct HCM work-zone speed-flow models currently exist for multilane highway work zones, the freeway work-zone reduction patterns developed in this study were subsequently applied to the multilane base-condition traffic relationships. The reduction patterns were derived from calibrated freeway multi-regime fundamental diagrams and used to adjust the base-condition multilane traffic characteristics across different work zone configurations. This approach enabled the development of representative multilane work-zone flow-density relationships while maintaining consistency with the freeway calibration framework.

As illustrated in Figure 7-10, separate normalized flow-density relationships were developed for different multilane work zone scenarios and free-flow speed categories. The resulting curves represent both non-work-zone and work-zone operating conditions, including shoulder-closure and lane-reduction scenarios. Compared with the corresponding non-work-zone relationships, the work-zone models exhibit reduced work-zone capacity, lower operational efficiency, and reduced jam-density conditions due to lane restrictions and work-zone operational impacts.

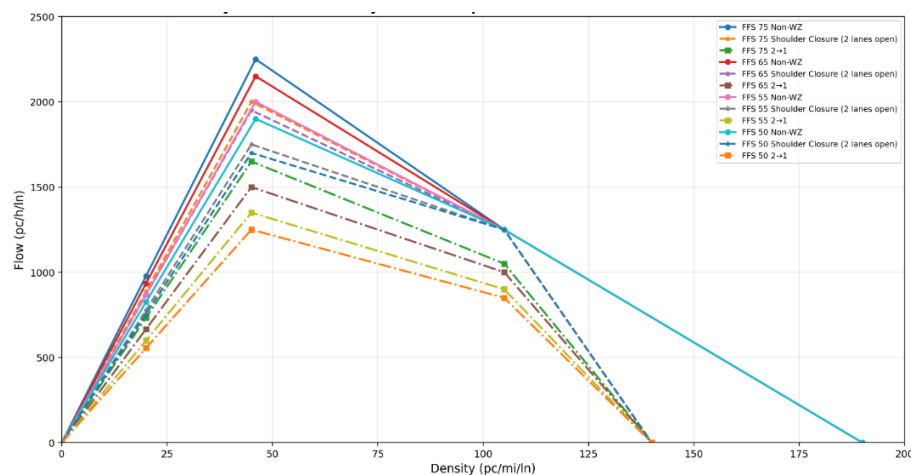


Figure 7-10: Calibrated Multilane Work Zone Flow-Density Relationships

The multilane work zone models were developed using the same multi-regime FD structure adopted for the freeway framework. The resulting relationships were then used to calculate the primary CTM parameters required for simulation, including free-flow speed, work-zone capacity, critical density, jam density, breakdown density, and backward-wave speed. These parameters were subsequently integrated into the MiPACE simulation framework to support dynamic multilane work-zone traffic analysis under varying operational and traffic-demand conditions.

This approach provides a scalable methodology for representing multilane highway work zone operations despite the absence of direct HCM work zone models for multilane facilities. By integrating HCM base-condition procedures with calibrated freeway-reduction patterns and multi-regime CTM relationships, the framework enables a realistic representation of multilane work-zone traffic behavior, congestion evolution, queue propagation, and operational impacts within a consistent analytical environment.

7.3.4 Flagging Operation Model Development

One-Lane Two-Way Work Zones

A common traffic control strategy for one-lane two-way work zones involves alternating directional movements under the control of flaggers or temporary signals. Vehicles from one approach are released while opposing traffic remains stopped. After the active direction completes traversal of the work zone and a clearance interval elapses, right-of-way is transferred to the opposing direction. This process repeats continuously throughout operation.

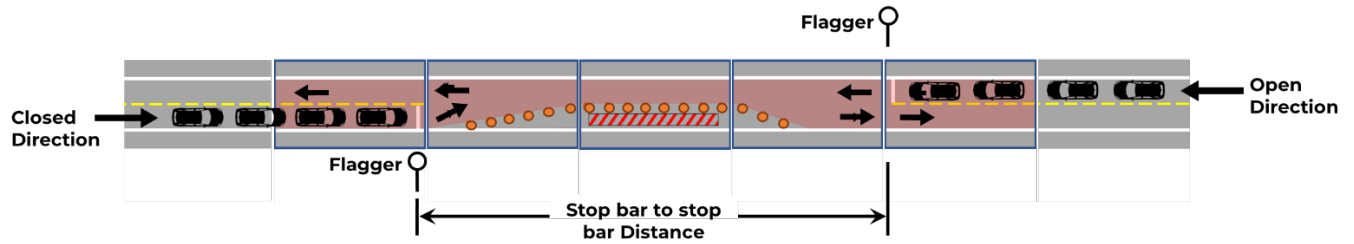


Figure 7-11: Typical one-lane two-way flagging operation

Flagging Variables

To mathematically represent these operations, several variables governing directional service, transition periods, queue growth, and cycle timing are first defined. These variables form the basis for simulating queue evolution and optimizing flagging performance.

i. Dead Time (T_d)

Dead Time (sec) represents the transition interval between terminating service for one direction and releasing traffic from the opposing direction. This interval accounts for the time required to safely transfer right-of-way between opposing traffic streams and avoid conflicting vehicle movements within the work zone.

ii. Holding Time (H_i)

Holding Time, also referred to as Gate Closed Time (sec), is the duration vehicles in one direction remain stopped while opposing traffic receives service. Holding time contributes directly to queue accumulation and delay. To maintain acceptable operating conditions, users specify a **Maximum Allowable Holding Time (H_{max})** as an input parameter. This constraint limits the maximum duration a direction may remain stopped before service must be transferred to the opposing movement.

For direction i , the Holding Time as shown in Equation (13):

$$H_i = G_j + T_{clear,j} + 2T_d \quad (13)$$
$$H_i \leq H_{max}$$

where:

H_i = holding time for direction i (sec)

G_j = green time for opposing direction j (sec)

$T_{clear,j}$ = clearance time for opposing direction (sec)

iii. Clearance Time (T_{clear})

Clearance Time (sec) is defined as the total time required for the final vehicle in a released platoon to completely vacate the work zone after the gate closes. Unlike conventional travel time formulations, clearance time incorporates:

1. Vehicle traversal time through the work zone
2. Initial acceleration time required after release from a stopped condition
3. Additional merging time required for queued vehicles to enter and stabilize within the active one-lane section

Thus, for direction i , Clearance Time is given by Equation (14):

$$\text{Clearance Time } (T_{clear,i}) = \frac{\text{Stop bar to stop bar distance}}{\text{work zone operating speed}} + T_{acc} + T_{merge} \quad (14)$$

where:

T_{acc} = acceleration time from stopped condition (sec)

T_{merge} = additional time required for vehicles to merge into the operating single lane (sec) for closed direction

iv. Green Time (G_i)

Green Time (sec) is the duration during which vehicles from a given direction are permitted to enter the work zone. Separate green times are determined for each direction because directional demand, queue length, and service requirements differ.

G_c = green time for closed direction (sec)

G_o = green time for open direction (sec)

Unlike fixed-time flagging operations, green times are not predefined inputs. Instead, they are dynamically determined through the optimization framework described in the next section to satisfy three objectives:

1. Ensure complete queue dissipation within a cycle ($Q_{res} = 0$)
2. Minimize total control delay
3. Minimize maximum queue length while satisfying operational constraints

Flagging Cycle Structure

The flagging operation was modeled as a repeating sequence of alternating directional service periods, clearance intervals, and transition phases. Unlike conventional deterministic approaches that estimate delay using aggregate capacities or average gate times, the proposed framework explicitly simulates queue formation and dissipation throughout successive cycles. This approach was adopted because queue dynamics in one-lane two-way work zones are highly dependent on previous operating conditions; queues unresolved in one cycle may propagate into subsequent cycles, and congestion generated within one analysis period may persist into the next. Consequently, assuming independent cycles or resetting queues between hours may underestimate delays and oversaturation effects. The cycle-based simulation therefore enables more realistic representation of directional interaction, queue evolution, and operational constraints under varying traffic demands.

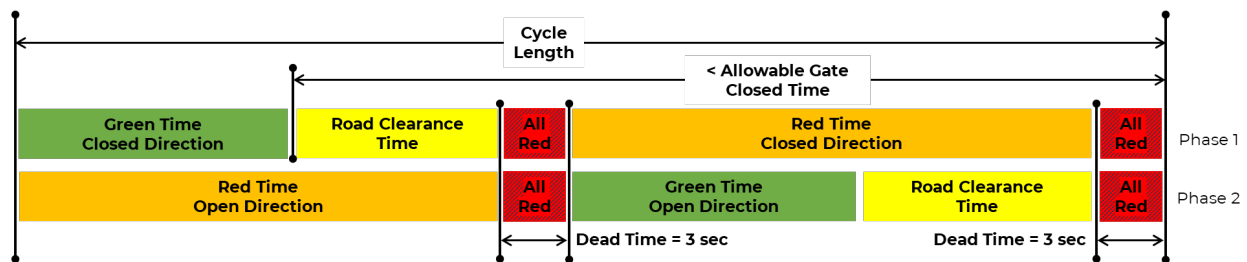


Figure 7-12. Conceptual representation of cycle-by-cycle flagging operations

Figure 7-12 illustrates the conceptual structure of the cycle-by-cycle flagging operation adopted in the model. The proposed framework accounts for the following mechanisms:

- **Alternating directional service:** Only one direction receives service at a time while the opposing direction remains stopped.
- **Directional holding periods:** Holding time for one direction depends on the green duration, clearance interval, and transition periods of the opposing direction.
- **Queue accumulation:** Vehicles arriving during holding periods accumulate and contribute to maximum queue formation.
- **Queue dissipation during service:** Queues discharge during green intervals according to directional discharge capacity.
- **Residual queue propagation:** Queues not fully dissipated within a cycle are transferred to subsequent cycles.
- **Cycle-by-cycle recursive simulation:** Operating conditions are updated continuously across cycles rather than assuming independent cycles.
- **Hourly queue carryover:** Residual queues at the end of an analysis hour become initial conditions for the following hour.

- **Cycle clock continuity:** Incomplete cycles extending beyond hourly boundaries continue into the subsequent analysis period rather than resetting.
- **Oversaturation control:** Maximum allowable holding time constraints limit excessive delays and infeasible queue growth.

Green Time Optimization

The determination of directional green times is critical in one-lane two-way flagging operations because insufficient service periods may leave residual queues unresolved, whereas excessive green durations increase holding times and user delay for the opposing direction. Therefore, the proposed model formulates flagging control as a constrained multi-objective optimization problem that identifies cycle lengths and directional green times capable of:

- (1) ensuring complete queue dissipation within each cycle,
- (2) minimizing total delay, and
- (3) minimizing maximum queue length while satisfying operational constraints.

The optimization process evaluates candidate cycle lengths iteratively and retains only feasible solutions satisfying queue clearance and cycle consistency requirements. Among feasible solutions, the cycle with the minimum weighted objective value is selected as the optimal flagging strategy.

i. Decision Variables

The optimization evaluates candidate cycle lengths: $C = G_c + G_o + T_{clear,c} + T_{clear,o} + 2T_d$

Candidate cycles are generated incrementally beginning from the minimum feasible cycle:

$$C = C_{min}, C_{min} + 2, \dots, C_{min} + 300$$

where:

C_{min} = minimum cycle satisfying queue clearance requirements

The 2-second increment permits progressive evaluation of alternative timing plans while limiting computational burden.

ii. Queue Dissipation Requirement

Before evaluating delay and queue performance, each candidate cycle must satisfy complete queue dissipation.

Maximum queue before service:	$Q_{max,i} = Q_{0,i} + \lambda_i H_i$
Residual queue after green:	$Q_{res,i} = Q_{max,i} - (\mu_i - \lambda_i) G_i$
where:	
$Q_{0,i}$ = initial queue	
λ_i = arrival rate	
μ_i = discharge rate	

Candidate cycles are feasible only if:

$$Q_{res,c} \leq 0$$

$$Q_{res,o} \leq 0$$

This ensures all queued vehicles dissipate within the cycle and preventing repeated stopping of the same vehicles across successive cycles. This queue clearance condition establishes the minimum feasible green and cycle time durations:

$$G_c \geq G_{c,min}$$

$$G_o \geq G_{o,min}$$

Although complete queue dissipation is desirable, varying traffic demand and operational constraints may result in residual queues that propagate between cycles and persist across hourly boundaries. Consequently, the proposed framework maintains queue continuity and incorporates hourly green time optimization to prevent progressive oversaturation. The conceptual relationship among queue dissipation, residual queue propagation, hourly carryover, and optimization is illustrated in Figure 7-13.

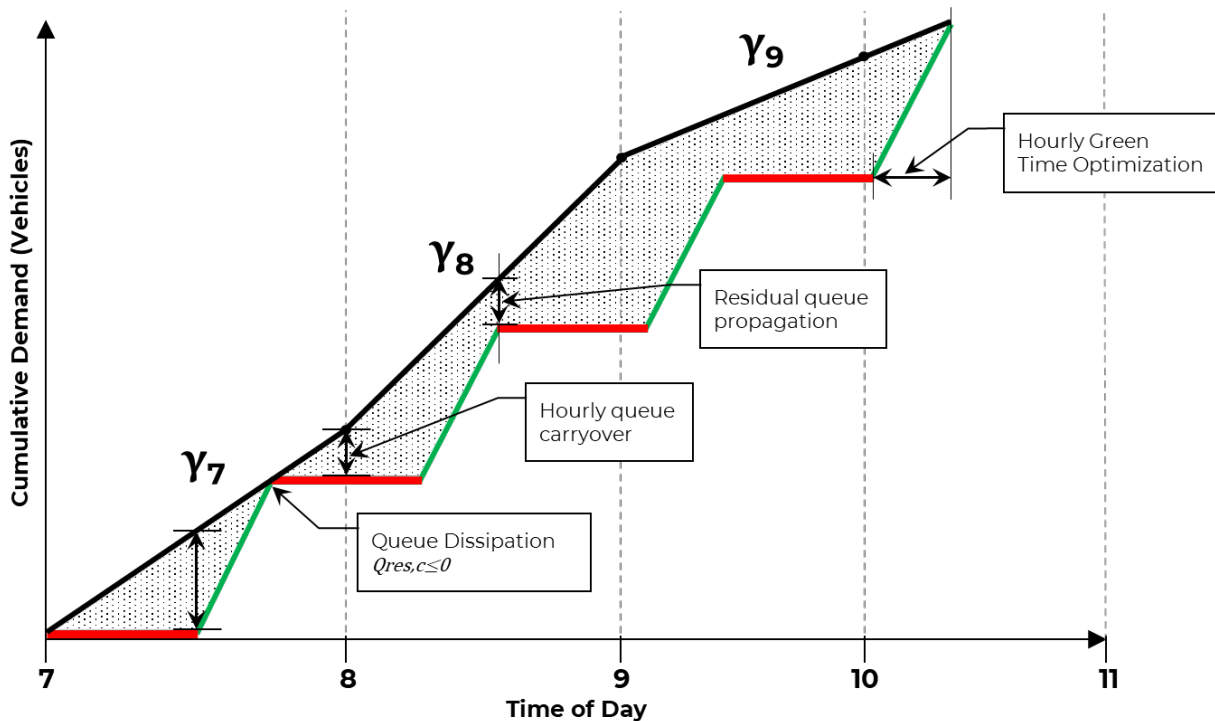


Figure 7-13. Conceptual representation of queue evolution in cycle-based flagging operations

iii. Objective Function

The optimization minimizes two competing performance measures:

1. Total Delay (TD)
2. Maximum Queue (MQ)

Reference values are obtained using the minimum feasible cycle:

$$TD_{ref} = TD(C_{min})$$

$$MQ_{ref} = MQ(C_{min})$$

The normalized weighted objective function is given as shown in Equation (15):

$$Obj(C) = w_1 \frac{TD(C)}{TD_{ref}} + w_2 \frac{MQ(C)}{MQ_{ref}} \quad (15)$$

$$C^* = \arg \min Obj(C)$$

where:

$$\left. \begin{array}{l} w_1 + w_2 = 1 \\ w_1 = 0.70 \\ w_2 = 0.30 \end{array} \right\} \text{Weights adopted}$$

Greater weight was assigned to delay minimization to prioritize user mobility while maintaining queue control.

iv. Optimization Constraints

The optimization is subject to operational feasibility constraints:

$$\begin{array}{ll} C \geq C_{min} & \text{Minimum feasible cycle} \\ \left. \begin{array}{l} G_c \geq G_{c,min} \\ G_o \geq G_{o,min} \end{array} \right\} & \text{Minimum green requirements} \\ \left. \begin{array}{l} Q_{res,c} \leq 0 \\ Q_{res,o} \leq 0 \end{array} \right\} & \text{Queue clearance requirement} \\ C = G_c + G_o + \Delta & \text{Cycle consistency:} \end{array}$$

$$H_i \leq H_{max} \quad \text{Maximum allowable holding}$$

where:

$$H_{max} = \text{user-defined maximum allowable holding time}$$

This constraint prevents excessive waiting periods and limits oversaturated conditions associated with persistent residual queues.

7.4 Chapter Summary

This chapter presented the development of the traffic modeling framework used in the MiPACE system to represent freeway, multilane highway, and flagging work zone operations under dynamic traffic conditions. The chapter introduced the Cell Transmission Model (CTM) framework adopted in this study and described the spatial and temporal discretization procedures, ramp interaction logic, and multi-regime traffic-flow representation integrated into the simulation environment.

The freeway modeling process used observed work-zone traffic data from multiple Michigan freeway corridors to develop calibrated multi-regime flow-density relationships for various work-zone configurations, including lane closures, shoulder closures, lane shifts, and crossover operations. The resulting normalized traffic-flow relationships and CTM parameters provided a consistent framework for representing traffic behavior under varying operational conditions.

The chapter also presented the development of multilane highway and one-lane two-way flagging operation models. For multilane facilities, calibrated freeway-reduction patterns were integrated with HCM base-condition procedures to establish representative multilane work-zone operational models. For flagging operations, a cycle-based traffic control model was developed to represent alternating directional traffic flow, queue formation, and operational delays under one-lane two-way control conditions.

In addition, Michigan-calibrated work zone speed and capacity models were developed and compared with the HCM 7th Edition methodologies. The calibration results demonstrated that the Michigan-specific models improved agreement with observed freeway work-zone traffic conditions and provided more realistic representations of speed and capacity under Michigan work-zone operations.

Overall, this chapter established the theoretical and operational foundation of the MiPACE traffic simulation framework and provided the calibrated traffic-flow relationships and operational models required for the calibration and validation procedures presented in the following chapter.

Chapter 8: Model Calibration and Validation

This chapter presents the calibration and validation procedures performed for the MiPACE work zone traffic analysis tool. The objective of the calibration process was to adjust the model parameters and operational relationships to accurately represent observed freeway work zone traffic behavior under Michigan conditions. Following calibration, the framework was validated using independent traffic datasets to evaluate its predictive capability and operational reliability under different work zone scenarios.

The calibration and validation process focused primarily on evaluating the accuracy of the developed procedures for estimating speed, capacity, queue, and delay within the CTM-based simulation framework. Multiple traffic datasets and observational sources were integrated to support model calibration, parameter estimation, and operational validation. These datasets included traffic speed observations, travel-time measurements, queue conditions, traffic volumes, and congestion patterns collected during actual freeway work-zone operations.

To improve the reliability and robustness of the calibration process, the framework incorporated multiple independent traffic data sources, including RITIS data, API-based traffic observations, and Bluetooth travel-time measurements. The integration of multiple data sources allowed cross-validation of traffic conditions and improved the representation of dynamic traffic behavior under varying work zone operational conditions.

8.1 Model Calibration

8.1.1 Data for Model Calibration

The calibration and validation of the MiPACE framework required integrating multiple traffic data sources that could represent real-world freeway work-zone traffic conditions. Because work zone traffic operations exhibit substantial temporal and spatial variability, multiple independent datasets were used to capture traffic flow behavior, congestion evolution, speed variation, queue propagation, and travel-time conditions under different work zone scenarios.

The selected datasets were used to calibrate and validate the CTM parameters, multi-regime fundamental diagrams, speed-capacity relationships, queue estimation procedures, and diversion behavior implemented within the MiPACE framework. The primary calibration datasets included:

- RITIS traffic data,
- API-based traffic observations,
- Bluetooth travel-time data.

These data sources were selected because they provide complementary operational information and collectively improve the reliability of the calibration process.

The calibration process required preparing and comparing multiple traffic datasets to determine the most reliable data source for representing freeway work-zone speed behavior across different

operational conditions. Because the calibration framework relied heavily on accurate speed estimation and temporal traffic evolution, traffic speed profiles from multiple corridors were evaluated using API data, RITIS observations, and Bluetooth measurements.

The first stage of the data preparation process involved generating corridor-level speed signatures for the selected freeway work zone projects. As illustrated in Figure 8-1, temporal speed profiles were developed for multiple freeway corridors, including I-94, US-131, I-75 Monroe, and I-75 Saginaw. The API dataset was initially treated as the reference dataset because it consistently provided continuous temporal coverage and stable speed observations across the selected corridors. The comparison also allowed the identification of congestion periods, speed breakdown conditions, and temporal traffic variations during work zone operations.

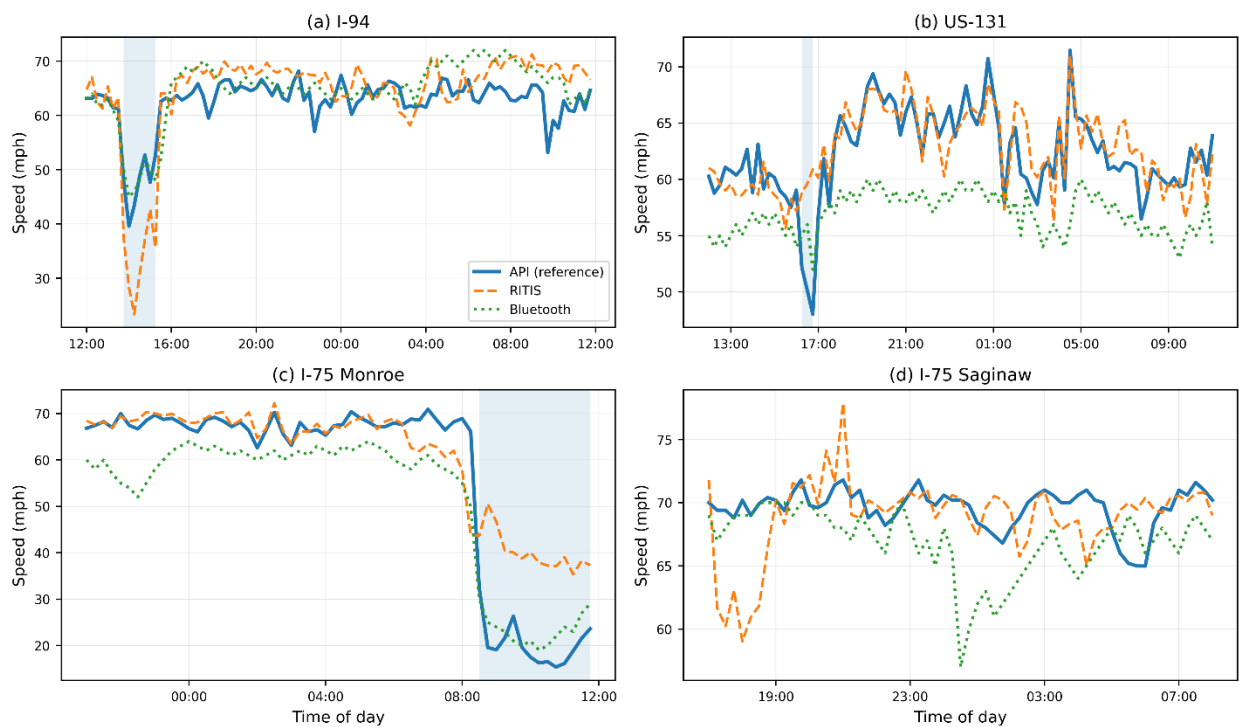


Figure 8-1: Corridor-scale Speed Signatures using API as Reference Dataset

To evaluate the consistency between the different data sources, multiple statistical comparison procedures were performed. Figure 8-2 presents the agreement scatter matrices comparing RITIS and Bluetooth observations against the API reference dataset. The results showed that the API and RITIS datasets generally exhibited stronger agreement across several corridors, whereas Bluetooth data showed greater variability under certain operational conditions. Additional agreement evaluation was performed using Bland–Altman analysis, as illustrated in Figure 8-3 to assess systematic bias and variability across datasets. The Bland–Altman plots demonstrated that API data generally maintained lower bias and more stable agreement patterns across multiple corridors.

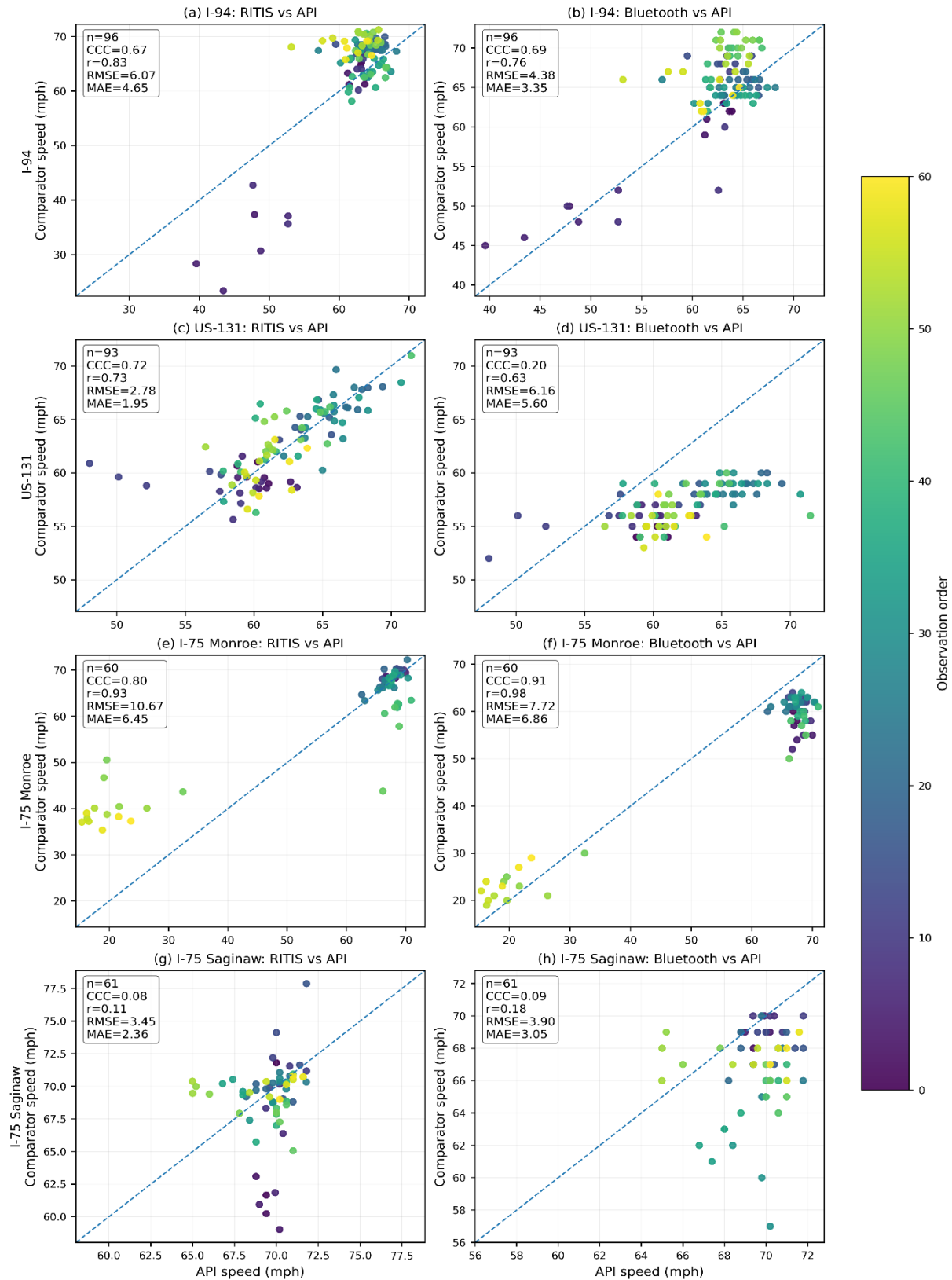


Figure 8-2: Agreement scatter matrix across corridors

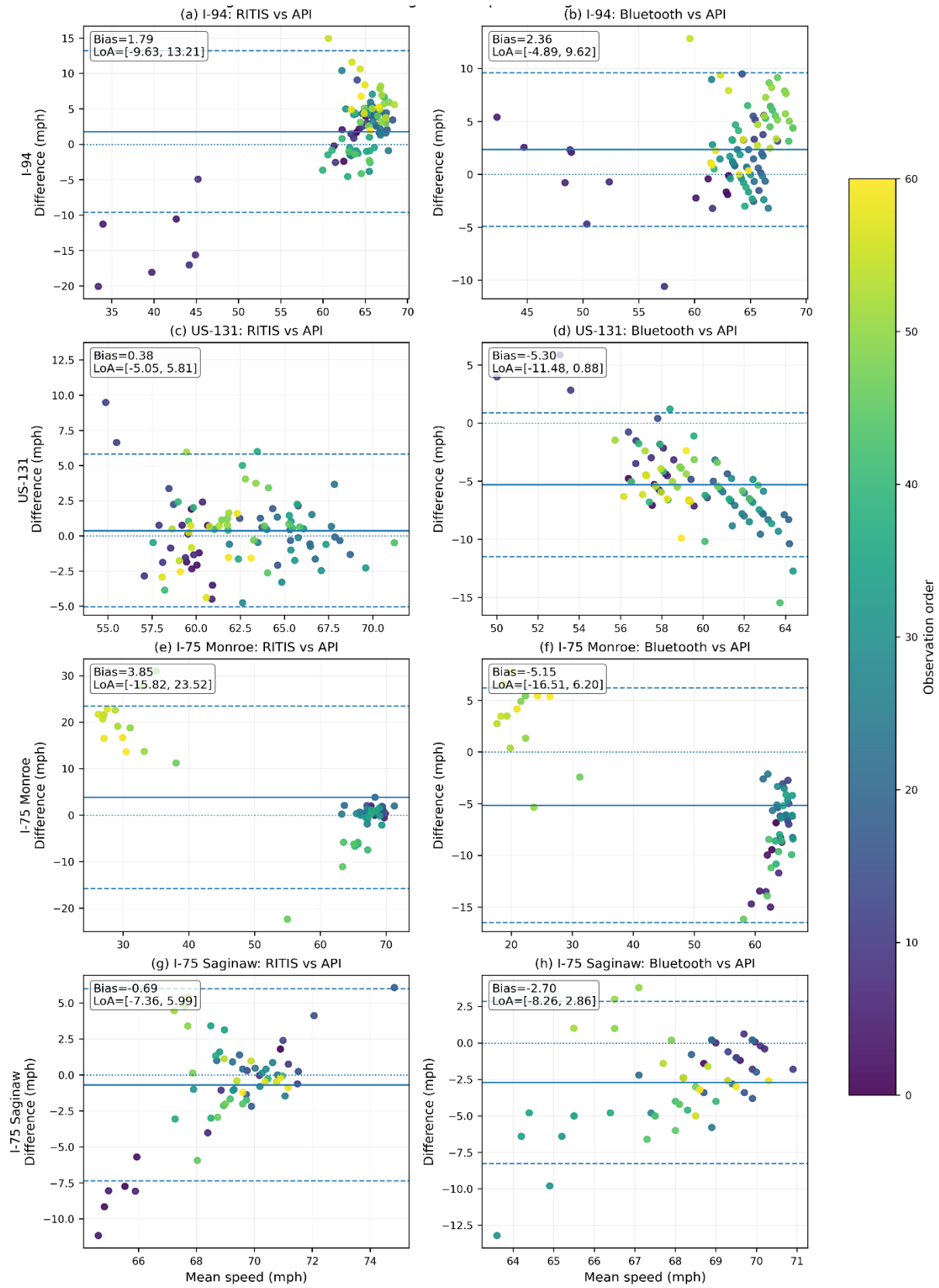


Figure 8-3: Bland-Altman agreement plots using API as reference

To further evaluate the relative performance of the datasets, cross-location validation and Dynamic Time Warping (DTW) analyses were conducted. Figure 8-4 summarizes the overall validation performance across the different corridors using multiple statistical indicators, including MAE, RMSE, bias, concordance correlation coefficient (CCC), correlation coefficient, and DTW distance.

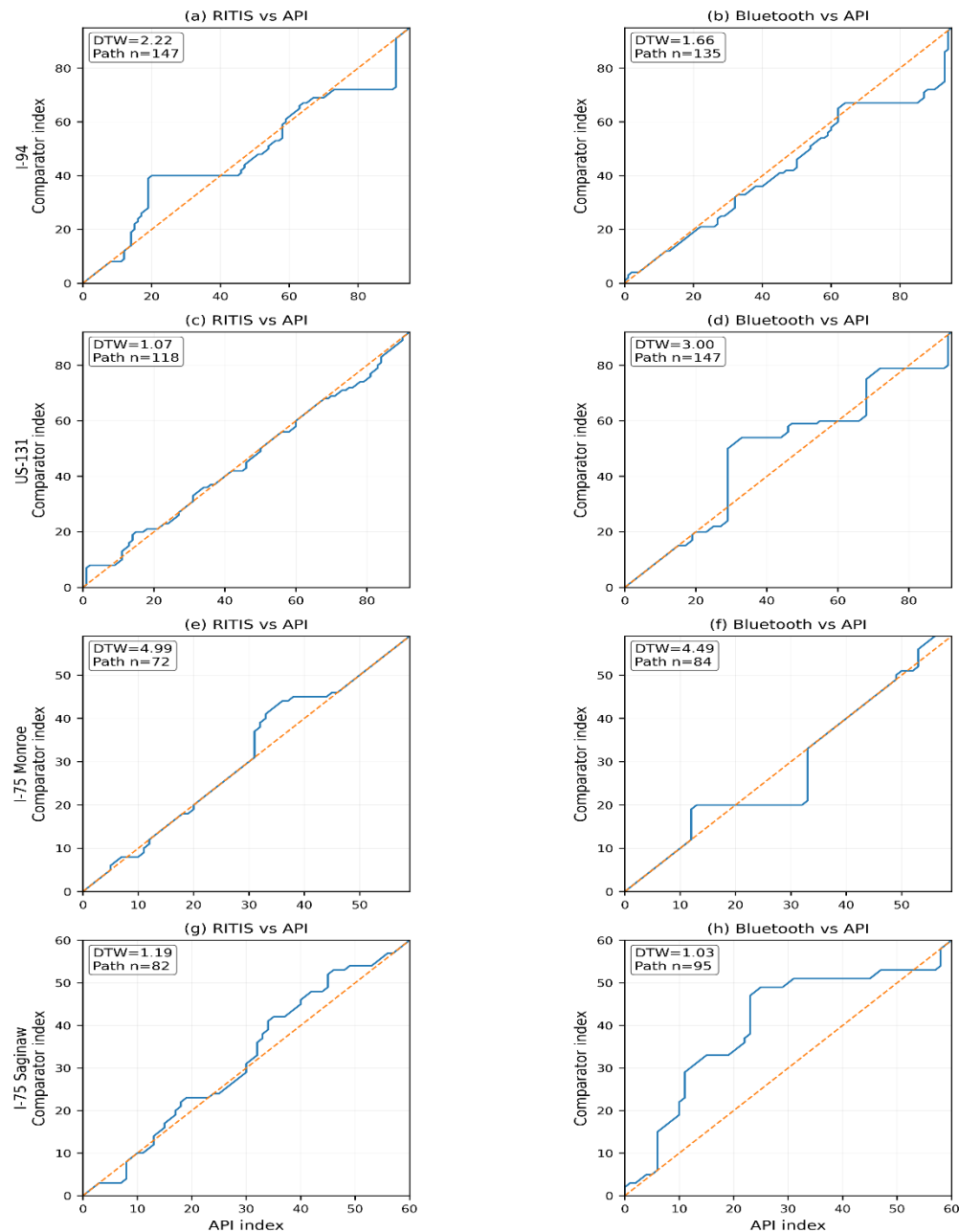


Figure 8-4: DTW wrapping path diagnostics

Based on the overall ranking and comparative analysis results, the API dataset demonstrated the most stable and consistent performance in representing freeway work-zone speed behavior and

temporal traffic evolution. Therefore, API-based speed observations were selected as the primary data source for calibrating the speed-related components of the MiPACE framework, including free-flow speed estimation, speed-flow relationships, and dynamic speed propagation within the CTM simulation environment.

Although API data were selected as the primary calibration source for speed modeling, RITIS data provided valuable corridor-level operational information related to congestion duration, queue formation, travel-time variability, and delay evolution. Consequently, RITIS observations were primarily used for validating delay performance, queue propagation behavior, and congestion evolution within the MiPACE simulation framework.

8.1.2 Model Calibration Methodology

The calibration methodology adopted in this study was developed to adjust the operational parameters and traffic-flow relationships within the MiPACE framework to accurately represent observed freeway work zone traffic behavior under Michigan conditions. The calibration process focused primarily on improving the representation of traffic speed, queue discharge rate, flow-density relationships, congestion evolution, and queue propagation within the CTM-based simulation framework.

The calibration activities utilized freeway work zone projects together with integrated traffic datasets, including API data, RITIS observations, Bluetooth measurements, MVDS data, and field-collected traffic observations. Traffic datasets were first preprocessed and synchronized using consistent temporal intervals and corridor segmentation. Abnormal observations and incomplete records were removed prior to calibration.

The calibration process began by applying the HCM 7th Edition work-zone speed and capacity equations to establish baseline operational estimates for each freeway work-zone scenario. These estimates were then compared with the observed field measurements. Regression-based calibration procedures were subsequently performed to develop Michigan-specific speed and capacity relationships that better reflect observed traffic conditions.

The calibration process also incorporated the multi-regime fundamental diagram (FD) framework developed in Section 7.3. Flow-density relationships were generated for each freeway work zone scenario, and the major traffic-state control points, including the free-flow limit point, capacity point, breakdown point, and jam-density point, were identified. Using these control points, the CTM parameters, including free-flow speed, work zone capacity, critical density, breakdown density, jam density, backward-wave speed, and regime-specific slope coefficients, were calibrated for each work zone configuration.

An additional normalization process was performed to reduce variability across projects and establish representative traffic-flow relationships for different work-zone scenarios. The resulting calibrated parameters were then iteratively adjusted within the CTM simulation framework to improve agreement between simulated and observed traffic conditions.

8.2 Model Validation with Field Data

Following the calibration process, the MiPACE was validated using observed field data from selected Michigan freeway work zone projects. The validation process focused specifically on freeway work-zone scenarios because the field datasets collected during this study were primarily associated with freeway facilities and lane-closure operations.

The objective of the validation process was to evaluate the ability of the developed CTM-based framework to accurately represent real-world freeway work zone traffic behavior under varying operational and congestion conditions. For each freeway case study, the simulated traffic performance outputs generated by MiPACE were compared against observed field conditions using both quantitative statistical measures and visual traffic performance evaluation. The validation process also evaluated the framework's ability to capture queue spillback, congestion duration, dynamic traffic evolution, and spatiotemporal traffic behavior under actual freeway work-zone operations.

8.2.1 I-75 Monroe Freeway Work Zone Validation

The first validation case study focused on the I-75 Monroe freeway work zone project, which experienced significant congestion and queue propagation during weekend lane-closure operations. The corridor provided a suitable validation environment due to the high traffic demand and severe congestion observed during active work zone periods.

Figure 8-5 presents the observed work zone operational conditions obtained from the RITIS Work Zone Performance Report for the I-75 Monroe corridor. The figure illustrates the observed evolution of congestion, queue formation, physical queue development, and backup queue propagation during the operation of the freeway work zone. The RITIS Work Zone Performance Report feature was used to obtain observed corridor-level traffic performance and queue-related operational information for validation.

To validate the MiPACE framework, the simulated traffic performance outputs were compared against observed API and RITIS measurements. **Table 8-1** summarizes the comparison between the simulated and observed traffic performance measures, including average approach speed, average work zone speed, maximum and minimum speed, average travel time, total daily vehicle-hours of delay (VHD), and maximum queue length.

The validation results demonstrated strong agreement between the simulated and observed freeway work zone traffic conditions. The average approach speed differed by approximately 1.0%, while the average speed through the work zone differed by approximately 4.0%. Similarly, the estimated travel time through the work zone differed by approximately 4.2% from the observed API measurements. The predicted maximum queue length exhibited an approximately 10% deviation relative to the queue conditions observed in the RITIS data.

The comparison of total daily vehicle hours of delay (VHD) showed greater variation between simulated and observed conditions because the RITIS delay estimation methodology relies on

INRIX-estimated traffic volumes, which are generally lower than actual freeway traffic demand and may therefore underestimate total corridor delay.

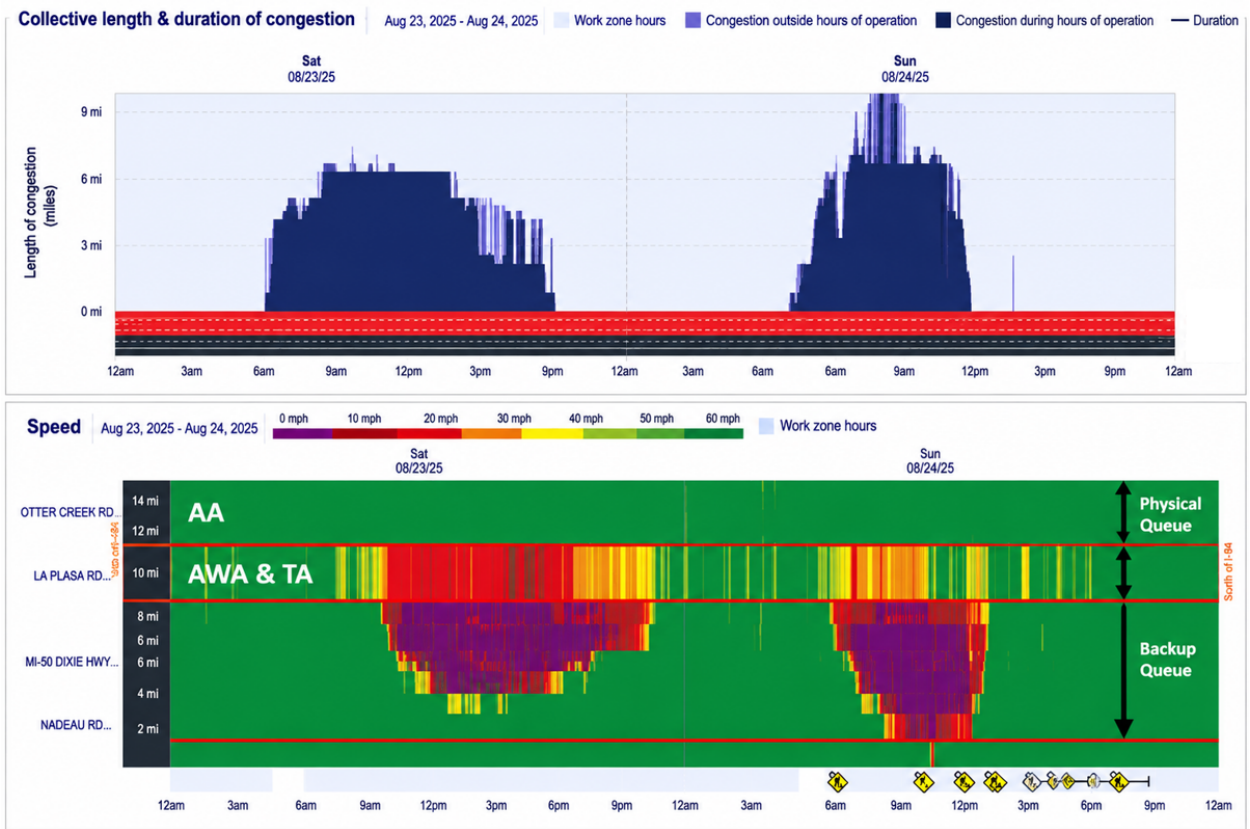


Figure 8-5: RITIS-Based Congestion Evolution for the I-75 Monroe Work Zone

Table 8-1: Model Validation: I-75 Monroe Corridor

Work Zone Info	Corridor length	4.82 miles		
	Direction	I-75 Monroe SB		
	Dates analyzed	August 23 - 24, 2025 (Weekend)		
Performance Index		MiPACE	Google API	Error (%)
Speed Performance	Avg. speed approaching WZ (mph)	51.2	50.7	1.0%
	Avg. speed through WZ (mph)	54.2	52.1	4.0%
	Max speed through WZ (mph)	67.9	67.3	0.9%
	Min speed through WZ (mp)	23.1	22.9	0.9%
	Avg. travel time through WZ (min)	13.7	14.3	4.2%
Delay Performance	Total daily vehicle hours of delay (VHD) *	6,034	5,214*	15.7%
	Max Queue Length (mile)	9.9	9	10.0%

* VHD is calculated based on delay relative to free-flow conditions; RITIS uses INRIX estimated volumes, which are typically lower than actual traffic, leading to potential underestimation of delay.

8.2.2 I-94 Albion Freeway Work Zone Validation

The second validation case study focused on the I-94 Albion freeway work zone project, which featured active ramp interactions and no detour operations. Compared with the I-75 Monroe case study, the corridor experienced moderate congestion, with localized queue formation influenced by nearby ramp activity and work-zone operational conditions.

Figure 8-6 presents the observed work zone operational conditions obtained from the RITIS Work Zone Performance Report for the I-94 Albion corridor, including congestion evolution, queue formation, physical queue development, and backup queue propagation during the work zone operation.

The MiPACE simulation outputs were compared against observed API and RITIS measurements for multiple traffic performance indicators, including speed, travel time, queue length, and vehicle-hours of delay (VHD). Table 8-2 summarizes the comparison between the simulated and observed corridor performance measures.

The validation results demonstrated reasonable agreement between the simulated and observed traffic conditions. The average approach speed and average work zone speed differed by approximately 5.7% and 6.0%, respectively, while the predicted maximum queue length differed by approximately 4.8% from the observed RITIS conditions. Larger variation was observed in total daily vehicle-hours of delay (VHD), primarily because RITIS delay estimation relies on INRIX-estimated traffic volumes, which may underestimate actual freeway traffic demand.

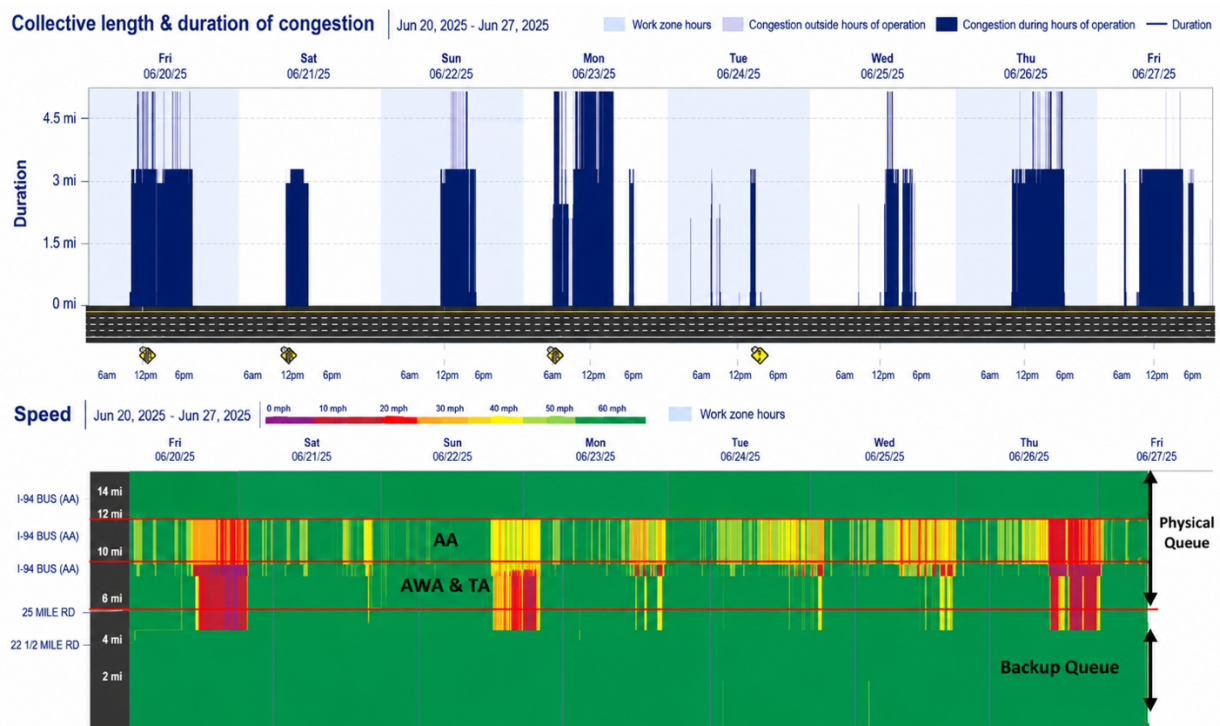


Figure 8-6: RITIS-Based Congestion Evolution for the I-94 Albion Work Zone

Table 8-2: Model Validation: I-94 Albion Corridor

Work Zone Info	Corridor length	2.94 miles		
	Direction	I-94 Albion		
	Dates analyzed	June 20-27, 2025		
Performance Index		MiPACE	Google API	Error (%)
Speed Performance	Avg. speed approaching WZ (mph)	43.2	45.8	5.7%
	Avg. speed through WZ (mph)	52	55.3	6.0%
	Max speed through WZ (mph)	58.2	62.4	6.7%
	Min speed through WZ (mp)	16.2	19.3	16.1%
	Avg. travel time through WZ (min)	2.3	2	15.0%
Delay Performance	Total daily vehicle hours of delay (VHD) *	1249.3	975.4*	28.1%
	Max Queue Length (mile)	5.9	6.2	4.8%

* VHD is calculated based on delay relative to free-flow conditions; RITIS uses INRIX estimated volumes, which are typically lower than actual traffic, leading to potential underestimation of delay.

8.2.3 I-96 Ionia Freeway Work Zone Validation

The third validation case study focused on the I-96 Ionia freeway work zone project, which represented a scenario involving both ramp interactions and detour operations. Compared with the previous validation cases, the Ionia corridor exhibited more complex operational behavior because of the combined influence of freeway lane restrictions, nearby ramps, and diversion activity associated with the detour configuration.

Figure 8-7 presents the observed work zone operational conditions obtained from the RITIS Work Zone Performance Report for the I-96 Ionia corridor. The figure illustrates the observed evolution of congestion, queue formation, physical queue development, and backup queue propagation during the freeway work zone operation. The observed traffic conditions further demonstrated the operational effects of ramp interactions and diversion-related traffic redistribution within the corridor.

The MiPACE simulation outputs were compared against observed API and RITIS measurements for multiple traffic performance indicators, including speed, travel time, queue length, and vehicle-hours of delay (VHD). Table 8-3 summarizes the comparison between the simulated and observed corridor performance measures.

The validation results demonstrated good agreement between the simulated and observed traffic conditions. The average approach speed and average speed through the work zone differed by approximately 3.9% and 4.7%, respectively, while the estimated travel time through the work zone differed by approximately 4.0% from the observed API measurements. The predicted maximum queue length deviated by less than approximately 1% from the queue conditions observed in RITIS data.

Collective length & duration of congestion & Speed | Aug 20, 2025 – Aug 21, 2025

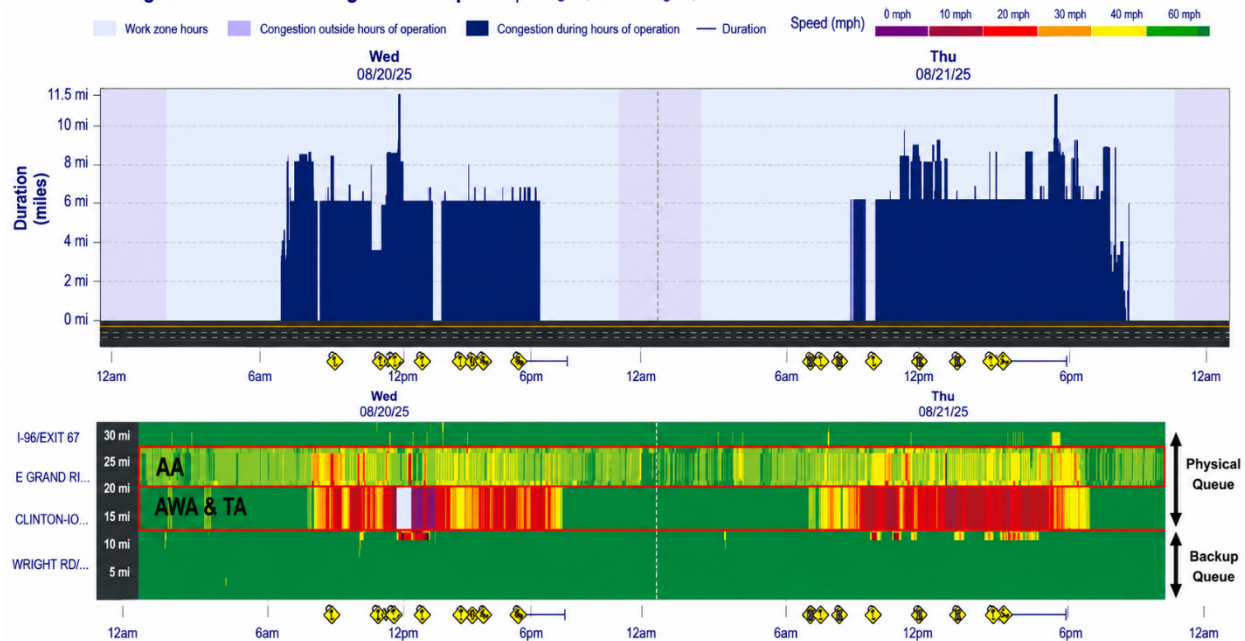


Figure 8-7: RITIS-Based Congestion Evolution for the I-96 Ionia Work Zone

Table 8-3: Model Validation: I-96 Ionia Corridor

Work Zone Info	Corridor length	20.3 miles		
	Direction	I-96 Westbound		
	Dates analyzed	Aug 25–26, 2025		
Performance Index		MiPACE	Google API	Error (%)
Speed Performance	Avg. speed approaching WZ (mph)	63.71	66.28	3.9%
	Avg. speed through WZ (mph)	56.35	59.1	4.7%
	Max speed through WZ (mph)	65.782	69.15	4.9%
	Min speed through WZ (mp)	45.05	41.56	8.4%
	Avg. travel time through WZ (min)	20.22	19.45	4.0%
Delay Performance	Total daily vehicle hours of delay (VHD) *	901.3	1213	25.7%
	Max Queue Length (mile)	11.41	11.5	0.8%

* VHD is calculated based on delay relative to free-flow conditions; RITIS uses INRIX estimated volumes, which are typically lower than actual traffic, leading to potential underestimation of delay.

8.3 Key Findings

The calibration and validation results demonstrated that the MiPACE framework successfully represented freeway work zone traffic behavior under varying operational and congestion conditions. The integration of Michigan-calibrated speed and capacity relationships, multi-regime fundamental diagrams, and CTM-based traffic simulation improved the representation of congestion evolution, queue propagation, travel-time variation, and overall operational performance within freeway work zone environments.

The validation case studies showed that the framework captured major traffic dynamics associated with freeway work zone operations, including congestion formation, queue spillback, speed reduction, delay evolution, and temporal traffic-state transitions. The multi-regime FD structure improved the representation of traffic breakdown and oversaturated traffic conditions within the simulation framework.

The results additionally demonstrated the importance of incorporating ramp interactions and diversion behavior within the freeway work zone analysis. Corridors with active ramps and detour operations exhibited more complex traffic behavior and queue propagation patterns, and integrating ramp merge/diverge logic and diversion estimation improved the realism of the simulated traffic conditions.

The comparison of multiple traffic data sets indicated that API observations provided a stable representation of freeway work-zone speed behavior and temporal traffic evolution, while RITIS data were particularly valuable for evaluating congestion evolution, queue propagation, and delay performance.

Chapter 9: Conclusions and Recommendations

9.1 Summary of Findings

This study evaluated existing work zone traffic analysis methodologies and developed an enhanced work zone analysis tool, MiPACE, that represents dynamic traffic operations under freeway, multilane, detour, and flagging work zone conditions. The research was motivated by the operational and methodological limitations associated with MDOT's existing CO3 tool, including simplified traffic assumptions, limited representation of congestion propagation, limited support for dynamic diversion behavior, and insufficient integration with modern traffic datasets and operational modeling approaches.

The first phase of the study focused on evaluating current work zone analysis methodologies and tools used by transportation agencies across the United States. The evaluation included a literature review, user survey, and focus group discussions with MDOT personnel, comparative tool analysis, and field observations. The findings demonstrated that many existing tools rely on simplified deterministic approaches that cannot accurately represent dynamic traffic conditions, queue spillback, congestion evolution, ramp interactions, and diversion behavior under complex work zone operations. The evaluation also identified several operational needs within MDOT, including improved capacity estimation, enhanced queue and delay analysis, improved visualization capabilities, support for multiple work-zone scenarios, and integration with modern traffic data sources.

The second phase of the study focused on field data collection, model development, calibration, validation, and implementation of the proposed MiPACE framework. Multiple freeway work zone projects across Michigan were used to develop and validate the framework under varying operational and congestion conditions. The integrated datasets included field observations, video-based traffic data extraction, Bluetooth measurements, API datasets, RITIS data, and MVDS observations.

A major contribution of this study was the development of a CTM-based work zone traffic simulation tool capable of dynamically representing congestion formation, queue propagation, shockwave movement, travel-time variation, and operational traffic-state transitions. Unlike traditional spreadsheet-based approaches, the proposed framework integrates dynamic traffic-flow representation, calibrated multi-regime flow-density relationships, diversion analysis, ramp-interaction logic, and operational traffic-control scenarios within a unified analytical environment. The framework additionally supports freeway, multilane, detour, crossover, shoulder-closure, and one-lane two-way operational conditions.

The freeway work zone model development process demonstrated that traffic behavior under work zone conditions is highly dynamic and cannot be accurately represented using traditional single-regime or deterministic traffic relationships. The developed four-regime flow-density framework successfully captured free-flow, transitional, breakdown, and fully congested traffic conditions

observed within freeway work zones. The normalization methodology also enabled the development of representative traffic-flow models for multiple freeway work-zone configurations while preserving the operational characteristics of each lane-closure scenario.

The calibration results demonstrated that the Michigan-calibrated work zone speed and capacity relationships substantially improved agreement with observed freeway work zone traffic conditions. The developed calibrated models reduced prediction error for both work zone capacity and speed and provided an improved operational representation of freeway traffic behavior under Michigan work zone conditions.

The validation case studies further demonstrated that the MiPACE successfully mimicked observed freeway work-zone traffic behavior across various operational scenarios, including severe congestion, ramp interactions, and detour operations. The framework accurately predicted the evolution of congestion, queue propagation, speed variations, travel-time impacts, and delay conditions across the evaluated corridors.

The developed MiPACE framework additionally demonstrated strong flexibility in integrating multiple modeling components within a unified simulation environment. The framework successfully integrated geometric representation, traffic demand estimation, CTM simulation, detour and diversion analysis, queue estimation, delay analysis, speed-capacity modeling, and reporting procedures within a single operational workflow. The inclusion of both numerical and graphical outputs further improved the framework's applicability to operational evaluation and decision-making under work-zone conditions.

9.2 Contributions of the Study

This study contributes to the field of work zone traffic analysis by developing an integrated and operationally realistic framework for representing dynamic traffic behavior under freeway and multilane work zone conditions. One of the study's primary contributions is the development of the MiPACE that integrates CTM-based traffic simulation, calibrated operational relationships, detour and diversion analysis, and multi-regime traffic-flow modeling into a unified analytical environment based on MDOT's needs. The MiPACE provides enhanced capability for evaluating congestion conditions, queue propagation, travel delay, diversion impacts, and road user costs under different work zone operational scenarios.

Another major contribution is the development of Michigan-calibrated freeway work zone speed and capacity models, based on observed freeway work zone traffic data and operational measurements. These calibrated models improve the representation of freeway work zone traffic behavior under Michigan conditions and provide an operationally realistic alternative to generalized traffic relationships.

9.3 Limitations in MiPACE

MiPACE was developed to support corridor-level work zone traffic analysis for freeways, multilane highways, and one-lane two-way flagging operations. While the framework is capable of analyzing work zones with simple detour routes, its application is primarily intended for sketch-planning and corridor-level analyses. As a result, MiPACE has limited capability for evaluating complex network-wide traffic impacts involving multiple diversion routes, route-choice behavior, and dynamic traffic redistribution across an extensive transportation network. For such applications, more comprehensive traffic analysis tools, such as mesoscopic or microscopic traffic simulation models, may be more appropriate.

The traffic models incorporated into MiPACE were developed and calibrated using traffic data collected from multiple freeway work zones throughout Michigan. Although the framework includes Michigan-specific freeway work zone traffic models, the operational models for multilane highway work zones and flagging operations were derived primarily from freeway-based observations and adjustment procedures due to limited availability of field data. Consequently, future research should focus on collecting additional traffic data from multilane highway and flagging work zones to further calibrate and validate these models. Such efforts will improve the accuracy, reliability, and applicability of MiPACE across a broader range of work zone configurations and operating conditions.

MiPACE estimates delays at intersections along detour routes using simplified intersection analysis procedures suitable for planning-level evaluations. While this approach provides reasonable estimates for work zone traffic analysis, it does not explicitly model detailed intersection operations, signal timing optimization, or vehicle interactions. Therefore, when more detailed operational assessments are required, users should consider supplementing MiPACE analyses with specialized intersection analysis tools such as Synchro or PTV Vistro.

9.4 Implementation Plan

The research team has developed the Michigan Predictive Analysis of Congestion and its Effects (MiPACE) tool and an accompanying user guide that includes detailed instructions and case-study examples. As MiPACE is intended to serve as MDOT's primary work zone traffic analysis tool, replacing the existing CO3 tool, successful implementation will require a structured deployment and training effort.

To facilitate the transition from CO3 to MiPACE, additional training sessions are recommended for MDOT engineers, consultants, and other practitioners involved in work zone planning and analysis. These training sessions should focus on data preparation, model setup, interpretation of results, and application of MiPACE to various work zone scenarios. Such training will help ensure consistent and effective use of the tool across MDOT projects.

It is also recommended that MiPACE, together with its user guide, training materials, and software updates, be maintained on an MDOT-hosted website to provide users with convenient access to

the latest resources. As traffic conditions, work zone practices, and economic parameters evolve over time, periodic updates to key model components, such as value-of-time (VOT) estimates, capacity and speed models, and other core traffic models, will be necessary. Maintaining these updates through a centralized web platform will help ensure that MiPACE remains accurate, reliable, and consistent with current state-of-practice methodologies.

9.5 Recommendations for Future Research

9.5.1 Improvement of Work Zone Traffic Models in MiPACE

Work zone operational analysis should, whenever practical, incorporate calibrated speed-capacity relationships to accurately represent local traffic behavior and congestion characteristics. The calibration results from this study demonstrated that Michigan-specific operational models provide better agreement with observed freeway work zone traffic conditions than generalized capacity assumptions. However, the calibration effort was based on a limited number of work zone sites and traffic datasets.

One of the highest priorities for future research is the development of dedicated operational models for multilane highway work zones using field-observed traffic data. As discussed previously, the current multilane highway work zone relationships implemented in MiPACE were derived by combining calibrated freeway work zone reduction patterns with Highway Capacity Manual (HCM)-based procedures. While this approach provides a reasonable planning-level approximation, the collection and analysis of field data from multilane highway work zones would enable the development of Michigan-specific operational models that more accurately reflect actual traffic conditions. Such efforts would improve the realism, accuracy, and reliability of multilane highway work zone analyses performed using MiPACE.

In addition, although the freeway work zone models incorporated in MiPACE were developed and calibrated using field data collected from several Michigan work zones, further refinement is recommended using a larger and more diverse dataset. Expanding the calibration database to include additional work zones with varying traffic demands, geometric characteristics, lane-closure configurations, traffic compositions, and congestion levels would improve the robustness and transferability of the models. These efforts would enhance the accuracy of speed, capacity, queue, and delay estimates and further strengthen the reliability of MiPACE for evaluating freeway work zone operations across a wider range of conditions.

To support continuous improvement, MDOT should consider establishing an ongoing work zone traffic data collection and model calibration program. Periodic updates to the underlying operational models would help ensure that MiPACE remains consistent with evolving traffic patterns, roadway characteristics, and work zone practices, while maintaining its effectiveness as MDOT's primary work zone traffic analysis tool.

9.5.2 Integration of Work Zone Safety Performance in MiPACE

While MiPACE currently focuses on estimating mobility-related impacts such as delay, queue length, travel time, and road user costs, future enhancements should consider integrating work zone safety performance analysis into the framework. Safety is a critical component of work zone management, and transportation agencies increasingly seek decision-support tools that can evaluate both mobility and safety impacts when assessing alternative work zone strategies.

One area for future research is the incorporation of work zone safety performance measures within the MiPACE framework. Such measures could include crash frequency, crash severity, surrogate safety indicators, and exposure-based performance metrics that provide a more comprehensive assessment of work zone impacts. The inclusion of safety-related measures would enable practitioners to evaluate the tradeoffs between mobility and safety when selecting work zone traffic management strategies.

Future studies should also focus on developing crash prediction models specifically for work zone conditions. These models could be developed using historical crash data, roadway characteristics, traffic volumes, work zone configurations, and operational conditions observed in Michigan work zones. Integrating crash prediction methodologies into MiPACE would allow users to estimate the potential safety implications of alternative work zone designs and traffic control plans during the planning and design stages.

In addition, research should investigate the safety impacts of various work zone traffic control strategies, including lane closures, crossover operations, detour routes, flagging operations, dynamic lane merge systems, variable speed limits, and other traffic management techniques. Quantifying the safety benefits and risks associated with these strategies would support more informed decision-making and help agencies identify treatments that improve both mobility and safety performance.

Ultimately, the integration of mobility and safety performance measures within a unified decision-support framework would significantly enhance the value of MiPACE. Such a framework would enable transportation agencies to evaluate work zone alternatives using a more comprehensive set of performance criteria, supporting balanced decisions that consider operational efficiency, user costs, and roadway safety simultaneously.

9.5.3 Comprehensive Work Zone Cost Analysis with MiPACE

While MiPACE focuses primarily on estimating road user impacts such as delays, work zones also involve other important costs, including construction costs and traffic management costs. Construction costs may vary depending on the selected construction and scheduling strategy associated with the traffic management scheme, such as weekend construction, nighttime construction, accelerated construction methods, or the use of specialized materials for activities such as pavement curing. These decisions can significantly influence overall project costs.

In addition, traffic management strategies often require supplemental investments in temporary traffic control devices, traveler information systems, advanced merge systems, speed control systems, enforcement activities, and other operational measures. These strategies may increase project costs, while they can also reduce congestion, travel delays, and road user costs.

Because construction costs, traffic management costs, and road user costs are closely interrelated, evaluating only one cost component may not provide a complete assessment of work zone impacts. Future research should therefore investigate the integration of these cost components within a comprehensive decision-support framework that enables MDOT to evaluate tradeoffs among construction efficiency, traffic operations, user impacts, and overall project costs while the user costs are estimated by MiPACE.

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APPENDICES

Online Survey Questionnaire

Introduction

1. What is your role or profession in relation to work zone management or transportation planning?
 - ☐ MDOT Staff
 - ☐ Consultant/ Contractors to MDOT
 - ☐ Other_____

2. Have you used CO3 in the past?
 - ☐ Yes.
 - ☐ No. (Go to **Q13**)

3. Please indicate your level of experience with CO3?
 - ☐ Beginner (*just started using it*)
 - ☐ Intermediate (*have used it in 1-2 MDOT projects*)
 - ☐ Advanced (*have used it in 3-5 MDOT projects*)
 - ☐ Expert (*have used it in more than 5 MDOT projects*)

4. How would you rate the overall usefulness of the CO3 tool for work zone analysis?
 - ☐ Extremely useful
 - ☐ Moderately useful
 - ☐ Somewhat useful
 - ☐ Not so useful
 - ☐ Not at all useful

5. How would you rate the ease of use of the CO3 tool for work zone analysis?
 - ☐ Extremely easy
 - ☐ Moderately easy
 - ☐ Somewhat easy
 - ☐ Not so easy
 - ☐ Not at all easy

Features, challenges and improvement for CO3

6. For the following features and functionalities of the current version of CO3, please rate your overall satisfaction in assessing work zone road user cost (5=extremely satisfied, 1=Not at all satisfied).

	1	2	3	4	5
Data input	☐	☐	☐	☐	☐
Analyzing various scenarios	☐	☐	☐	☐	☐
Default values	☐	☐	☐	☐	☐
Visualization of results	☐	☐	☐	☐	☐
Instructions or guidance	☐	☐	☐	☐	☐
Computational Speed	☐	☐	☐	☐	☐
Accuracy of results	☐	☐	☐	☐	☐

7. Please describe specific features or functionalities that you would like to add to the current CO3?

8. Have you encountered any challenges while assessing configurations for road user costs? If your answer is YES, please specify the difficulties you have faced.

9. Please list analysis tools (e.g. Synchro) that you would like to interface with CO3?

- ☐ Yes, specify _____
☐ No, not at this time.

10. Have you used the COFlag?

- ☐ Yes. Continue
☐ No. Go to **Q13**.

11. How well, do you think, the **COFlag.xls** program aligns with your organization's needs and requirements for managing flagging operations?

- ☐ Extremely well
☐ Moderately well
☐ Somewhat well
☐ Not so well
☐ Not well at all

12. Would you prefer if the functionalities of the **COFlag.xls** program for flagging operations were integrated directly into the CO3 spreadsheet?

- ☐ Yes, it would be very beneficial.
- ☐ No, I prefer to use them separately.
- ☐ Either way is fine.

13. What type of work zone cost analysis tools have you used in the past? (Select all applicable)

- ☐ CO3
- ☐ QUEWZ
- ☐ RealCost
- ☐ Quick ZONE
- ☐ CA4PRS
- ☐ Others. Please specify _____

14. At which stage do you use the Work Zone User Delay Cost? Select all applicable.

	Must include	Highly desired	Desired	Not need
Speed quantification	☐	☐	☐	☐
Delay estimation	☐	☐	☐	☐
Backup length	☐	☐	☐	☐
Detour analysis	☐	☐	☐	☐
Life cycle cost analysis	☐	☐	☐	☐
Various work zone types	☐	☐	☐	☐
Work zone ITS analysis	☐	☐	☐	☐
Crash cost analysis	☐	☐	☐	☐
Flagging operation	☐	☐	☐	☐
Other. Please specify	☐	☐	☐	☐

15. How familiar are you with developing the maintenance of traffic (MOT) plan during highway construction?

- ☐ Extremely familiar
- ☐ Moderately familiar
- ☐ Somewhat familiar
- ☐ Not so familiar
- ☐ Not at all familiar

16. Please provide any comments helpful in developing a tool for work zone road user cost analysis.

17. If you do not mind being contacted for further details, would you provide your contact information.

Name: _____

Title: _____

Affiliation: _____

Email: _____

Phone: _____

Procedure for Developing and Updating Michigan-Specific Value of Time Estimates

This appendix presents a recommended procedure for developing, documenting, and annually updating Michigan-specific Value of Time (VOT) estimates for use in the MiPACE user cost framework. The procedure is intended to provide a transparent and reproducible method for converting national VOT benchmarks into Michigan-calibrated unit values for passenger cars and trucks, while maintaining consistency with federal benefit-cost analysis guidance and current MDOT practice.

The procedure includes four major elements:

- 1. Establishing national VOT benchmark values.
- 2. Adjusting national values to Michigan economic conditions.
- 3. Validating freight-related values using trucking cost data.
- 4. Establishing an annual update and documentation process.

The current MiPACE model actively uses two VOT inputs:

- CarUserCostPerHr
- TruckUserCostPerHr

Additional values, such as light commercial vehicles or buses, may be retained for future model expansion but are not required for the current two-class MiPACE implementation.

2 Deriving Michigan Unit s by Vehicle Type

2.1 Establish National Baseline Values

The first step is to establish national VOT benchmark values using the most recent applicable **USDOT Benefit–Cost Analysis (BCA) Guidance**. These values should be treated as the national reference point before applying Michigan-specific adjustments.

For the working 2025 MiPACE update, the following national reference values were used as baseline inputs:

Travel Category	Vehicle Class	National Reference Value (in 2024 USD)
Personal travel	Passenger cars and light trucks	\$20.10/person-hour
Business travel	Passenger cars and light trucks	\$34.60/person-hour

Travel Category	Vehicle Class	National Reference Value (in 2024 USD)
Truck driver time	Trucks	\$37.20/person-hour

These values are expressed on a **person-hour** basis in 2024 USD. These can be inflated to 2025 USD using CPI ($\approx +6\%$). For use in MiPACE, the values must be converted to **vehicle-hour** units using vehicle occupancy assumptions and trip-purpose shares.

For **passenger vehicles**, the general conversion is:

$$\begin{aligned}
 VOT_{national,veh} &= (Share_{personal} \times VOT_{personal} \times Occ_{personal}) \\
 &+ (Share_{business} \times VOT_{business} \times Occ_{business})
 \end{aligned}$$

where:

- $VOT_{national,veh}$ = national passenger-vehicle VOT, \$/vehicle-hour
- $Share_{personal}$ = share of passenger vehicle travel associated with personal purposes
- $Share_{business}$ = share of passenger vehicle travel associated with business purposes
- $VOT_{personal}$ = value of personal travel time, \$/person-hour
- $VOT_{business}$ = value of business travel time, \$/person-hour
- $Occ_{personal}, Occ_{business}$ = vehicle occupancy factors

For planning-level MiPACE implementation, the personal and business VOT values should be taken from USDOT BCA Guidance Table A-2. For the 2026 BCA Guidance, these values are \$20.10/person-hour for personal travel and \$34.60/person-hour for business travel, expressed in 2024 dollars. The default trip-purpose shares are based on the USDOT local surface-mode distribution of 88.2 percent personal travel and 11.8 percent business travel. Vehicle occupancy factors should be based on local or corridor-specific data where available. If such data are not available, USDOT Table A-3 values may be used. For the current implementation, which applies one passenger-car VOT value, the “all travel” occupancy rate of 1.52 persons per passenger vehicle is recommended.

For **heavy trucks**, the general conversion is:

$$VOT_{national,truck} = VOT_{truck} \times Occ_{truck}$$

where:

- $VOT_{national,truck}$ = national truck-vehicle VOT, \$/vehicle-hour

- VOT_{truck} = value of truck travel time, \$/person-hour
- $Occ_{truck} = 1$, truck occupancy factor

Therefore, the resulting national vehicle-hour values were as follows:

Vehicle Type	Working National VOT, 2024 \$/vehicle-hour	
Passenger car / light truck (personal component)	\$26.95	=88.2%×\$20.10×1.52
Passenger car / light truck (business component)	\$6.21	=11.8%×\$34.60×1.52
Heavy truck / semitruck	\$37.2	=\$37.20×1.0

These values represent working national benchmarks for calibration and comparison. Final values should be verified against the USDOT guidance applicable to the selected price year.

$$\text{National passenger-vehicle VOT, 2024} = \$26.95 + \$6.21 = \$33.15 / \text{vehicle-hour}$$

$$\text{National truck VOT, 2024} = \$37.20 / \text{vehicle-hour}$$

Convert National Values to 2025 Dollars

Because the USDOT baseline values are expressed in 2024 dollars, convert them to 2025 dollars before using them in MiPACE. Using the CPI-U annual-average ratio shown in the calculation slide:

$$2025/2024 \text{ price-year factor} = 321.943 / 313.689 = 1.0263$$

This corresponds to an approximately 2.63% price-year adjustment.

$$\text{National passenger-vehicle VOT, 2025} = \$33.15 \times 1.0263 = \$34.03 / \text{vehicle-hour}$$

$$\text{National truck VOT, 2025} = \$37.20 \times 1.0263 = \$38.18 / \text{vehicle-hour}$$

2.2 Adjust National Values to Michigan Economic Conditions

After establishing national vehicle-hour benchmarks, Michigan-specific values are developed by applying a wage-based adjustment factor. The adjustment factor compares Michigan's median hourly wage with the national median hourly wage.

$$AdjFactor_{MI} = \frac{Wage_{MI,median}}{Wage_{US,median}}$$

where:

- $AdjFactor_{MI}$ = Michigan economic adjustment factor
- $Wage_{MI,median}$ = Michigan median hourly wage
- $Wage_{US,median}$ = U.S. median hourly wage

Using **May 2024 BLS Occupational Employment and Wage Statistics** as an illustrative basis:

$$\begin{aligned} Wage_{MI,median} &\approx \$23.69/hr \\ Wage_{US,median} &\approx \$24.51/hr \\ AdjFactor_{MI} &= \frac{23.69}{24.51} \approx 0.9665 \end{aligned}$$

The Michigan-adjusted VOT is then calculated as:

$$VOT_{MI} = VOT_{national} \times AdjFactor_{MI}$$

The resulting working Michigan values are shown below.

Vehicle Type	National VOT, 2025 \$/veh-hr	Michigan Adjustment	Proposed Michigan VOT, 2025 \$/veh-hr
Passenger car / light truck (personal component)	34.03	× 0.9665	32.889
Heavy truck / semitruck	38.18	× 0.9665	36.901

Thus, the recommended 2025 Michigan-specific VOT inputs are:

$$\begin{aligned} CarUserCostPerHr &= 32.89\$ \\ TruckUserCostPerHr &= 36.9\$ \end{aligned}$$

A separate light commercial / service vehicle VOT is not calculated in the current two-class MiPACE implementation. If MiPACE is expanded to include additional vehicle classes in the future, light commercial vehicles should be assigned a separately derived VOT value.

2.3 Cross-Check Truck VOT Using ATRI Operating Cost Data

Truck-related VOT values should be cross-checked using freight operating cost data, particularly from the **American Transportation Research Institute (ATRI)**. ATRI publishes annual operational cost data for the trucking industry, including cost components such as driver wages, benefits, fuel, maintenance, insurance, and equipment costs.

If ATRI regional data are available, a regional adjustment factor may be applied:

$$AdjFactor_{ATRI} = \frac{ATRI_{region}}{ATRI_{national}}$$

The Michigan truck VOT can then be calculated as:

$$VOT_{truck,MI} = VOT_{truck,national} \times AdjFactor_{wage} \times AdjFactor_{ATRI}$$

where:

- $VOT_{truck,MI}$ = Michigan-adjusted truck VOT
- $VOT_{truck,national}$ = national truck VOT benchmark
- $AdjFactor_{wage}$ = Michigan-to-U.S. wage adjustment factor
- $AdjFactor_{ATRI}$ = regional trucking cost adjustment factor

For the current MiPACE VOT update, ATRI is used only as a freight cost reasonableness check and is not applied as a separate multiplier in the final TruckUserCostPerHr value. If MiPACE is expanded to include vehicle operating costs or freight-specific cost adjustments, ATRI data may be used to support those future components.

2.4 Document Values in the MiPACE Parameter Structure

The final Michigan-specific values should be documented in the MiPACE input or parameter structure. At minimum, the current MiPACE model should include the following values:

MiPACE Parameter	Description	Proposed 2025 Value	Unit
CarUserCostPerHr	Passenger cars and light trucks	32.89	\$/vehicle-hour
TruckUserCostPerHr	Trucks, including heavy trucks and semitrucks	36.90	\$/vehicle-hour

3 Annual Update Procedure for VOT Values

A systematic annual update process is recommended to maintain consistency with national practice and to ensure that MiPACE reflects current economic conditions.

3.1 Identify Annual Data Sources

The following data sources should be reviewed during each annual update cycle.

Data Type	Recommended Source	Update Frequency	Use in MiPACE
State and national median hourly wage	BLS Occupational Employment and Wage Statistics	Annual	Passenger and service-vehicle VOT adjustment
Truck operating cost	ATRI Operational Costs of Trucking	Annual	Freight VOT validation and truck adjustment
Price inflation	CPI-U or applicable price index	Monthly / Annual	Price-year conversion
USDOT VOT baseline	USDOT BCA Guidance	Periodic	National benchmark and methodology confirmation

Where current USDOT VOT guidance is available for the desired price year, those values should be used directly. If the available national baseline is expressed in an earlier price year, the value should be adjusted to the current year using an appropriate inflation index.

3.2 Compute the Michigan-to-U.S. Wage Adjustment Ratio

Each year, the Michigan-to-U.S. wage adjustment factor should be recalculated as:

$$AdjFactor_{MI,t} = \frac{Wage_{MI,t}}{Wage_{US,t}}$$

where:

- t = update year
- $Wage_{MI,t}$ = Michigan median hourly wage in year t
- $Wage_{US,t}$ = U.S. median hourly wage in year t

This ratio should be applied to national vehicle-hour VOT values to produce Michigan-specific VOT estimates.

3.3 Apply Price-Year Adjustment

If a VOT value is carried forward from a prior year, a price-year adjustment should be applied:

$$VOT_{current} = VOT_{previous} \times \frac{Index_{current}}{Index_{previous}}$$

where:

- $Index_{current}$ = current-year price or wage index

- $Index_{previous}$ = previous-year price or wage index

For time-related values, wage or compensation indices are preferred where available. CPI should be used primarily for price-year conversion when a more specific wage or compensation index is not available.

3.4 Update MiPACE Values

The annual update can be implemented manually or automated through the MiPACE parameter sheet. The following relationships summarize the recommended update logic:

$$VOT_{car,MI,t} = VOT_{car,national,t} \times AdjFactor_{MI,t}$$

$$VOT_{truck,MI,t} = VOT_{truck,national,t} \times AdjFactor_{MI,t}$$

If an automated Excel/VBA implementation is used, the updated values may be written directly to the MiPACE input cells:

$$VOT_{car} = VOT_{national_car} * AdjFactor_MI$$

$$VOT_{truck} = VOT_{national_truck} * AdjFactor_MI * ATRI_ratio$$

If price-year conversion is required, a CPI or wage-index ratio should be included before writing the values to the model.

3.5 Quality Control and Reporting

Each annual update cycle should include the following quality-control steps:

1. Document all data sources used for the update.
2. Record the national baseline values and price year.
3. Record the Michigan and U.S. wage values used to compute the adjustment factor.
4. Report year-over-year percentage changes in VOT values.
5. Conduct optional sensitivity checks using ± 10 percent wage or cost variation.
6. Store the results in a MiPACE documentation or audit worksheet, such as VOT_Audit.

A recommended audit table is shown below.

Update Year	National Car VOT	MI Wage Factor	MI Car VOT	National Truck VOT	MI Truck VOT	Data Sources
2025	34.03	0.9665	32.89	38.18	36.90	USDOT, BLS, ATRI

3.6 Multi-Year Methodology Review

In addition to the annual numerical update, a broader methodological review should be conducted approximately every three years. The review should evaluate whether the MiPACE VOT structure remains aligned with:

- current USDOT BCA guidance,
- FHWA work zone road user cost guidance,
- national or regional freight cost data,
- updated vehicle occupancy assumptions, and
- any changes to MiPACE vehicle classification logic.

This review should also determine whether additional vehicle categories, such as light commercial vehicles or buses, should be incorporated into future MiPACE versions.

4. Illustrative Annual Update Example: 2025 to 2026

Assume the following changes from 2025 to 2026:

- Michigan median wage increases by **3 percent**.
- U.S. median wage increases by **4 percent**.
- CPI or applicable price index increases by **2 percent**.

The updated Michigan wage adjustment factor is:

$$\begin{aligned} AdjFactor_{MI,2026} &= \frac{1.03}{1.04} \times 0.9665 \\ AdjFactor_{MI,2026} &= 0.957 \end{aligned}$$

If the national passenger car benchmark is carried forward and adjusted by 2 percent inflation:

$$VOT_{car,national,2026} = 34.03 \times 1.02 = 34.71$$

The 2026 Michigan passenger car VOT is then estimated as:

$$\begin{aligned} VOT_{car,2026} &= 34.71 \times 0.957 \\ VOT_{car,2026} &= 33.22 \end{aligned}$$

Thus, the updated 2026 Michigan passenger car VOT would be approximately:

$$\boxed{33.22 \text{ \$/vehicle-hour}}$$

This example is provided for illustration only. Final annual values should be calculated using the actual annual BLS wage values, ATRI data, and applicable price-year adjustment factors.