BALANCING THE COSTS OF MOBILITY INVESTMENTS IN WORK ZONES

PHASE 1 FINAL REPORT

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16. Abstract
Work zone safety and mobility continue to be critical transportation concerns in Michigan and elsewhere. Previous research has led to the development of a variety of tools, performance measures and decision-making frameworks to analyze work zone safety and mobility. This Phase 1 research sought to provide additional guidance towards assessment of safety and mobility strategies for work zones. The Phase 1 project objectives were as follows: 1.) determine the accuracy of existing methods for estimating delay and diversion; 2.) determine the cost-effectiveness of select strategies that have been implemented; and 3.) provide guidance towards development of work zone decision support tools. The specific tasks included an assessment of the national state-of-the-art and state-of-the-practice, a survey of travelers to gain insight into public perceptions of work zone operations and delay, and collection and analysis of work zone operational, safety, and cost data. The results showed that the median acceptable work zone travel delay reported by Michigan travelers was 10 minutes. Using data collected from several Michigan freeways, work zone travel speeds were found to remain relatively stable up to a flow rate of approximately 1,700 vehicles per hour per lane. Beyond this point, speeds declined (and subsequent delays increased) dramatically. The work zone crash analysis found incremental crash increases when comparing single-lane closures to shoulder closures, double-lane closures to single-lane closures, and lane shifts to double-lane closures. When comparing Michigan safety results to Highway Safety Manual data from California and Missouri, it was found that the effects of work zone length and duration were very similar between Michigan and Missouri, although the California effects were slightly different. Assessment of the costs associated with nighttime versus daytime asphalt resurfacing projects on freeways found some differences in the actual paving costs per lane-mile, but no differences between other related costs. The report also provides guidance for development of a Phase 2 research plan.

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It should also be noted that project team members Peter Savolainen, Timothy Barrette, and Emira Rista changed affiliation to Iowa State University prior to final submission of this report.

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EXECUTIVE SUMMARY

Work zone safety and mobility continue to be critical transportation concerns in Michigan. Previous research has led to the development of a variety of tools, performance measures and decision-making frameworks to analyze work zone safety and mobility. This research study sought to provide additional guidance towards assessment of safety and mobility strategies for work zones in Michigan. The original research plan specified a two-phase study. The initial project phase sought to: 1.) determine the accuracy of existing methods for estimating delay and diversion; 2.) determine the safety effects associated with various work zone characteristics; 3.) determine the cost-effectiveness of select strategies that have been implemented; and 4.) provide guidance towards development of work zone decision support tools. The second phase was to build upon the Phase 1 findings, and include a series of field studies, the findings of which would be used to develop a decision support tool for MDOT. The decision support tool would assist with selection of the optimal work zone mobility treatment(s), based on the characteristics.

Although several important findings were ascertained as a part of the original research work plan, a lack of available detailed work zone condition data inhibited development of the decision support tool. Due to these data shortcomings, it was determined that Phase 2 research would not proceed until the necessary additional data are collected. Further direction towards refinement of the Phase 2 work plan is provided in Appendix B of this report. This includes recommendations for information that should be obtained either prior to or during the Phase 2 research. Specifically, it will be necessary to obtain detailed field data for several work zone locations to allow for examination of how various aspects of the work zone, including the type of mobility treatment, type of work being performed, equipment and worker placement, and other key work zone characteristics, affects safety and mobility.

Ultimately, the collective Phase 1 and Phase 2 research findings will be used to develop the decision support tool for selection of work zone mobility treatments. This tool will utilize site condition data, such as road features, traffic volumes, length of work zone, and type of work, and provide guidance towards selection of potential mobility treatments to minimize delay and traffic safety impacts.

CHAPTER 1
INTRODUCTION

Work zone safety and mobility continue to be critical transportation concerns. Planning and design level decisions by transportation agencies have potentially far-reaching impacts on traveler delay. These decisions also potentially influence work zone safety, an issue that further exacerbates work zone delay when work zone crashes occur. Against this backdrop, the efficient investment of highway funding is becoming increasingly challenging. Fewer dollars are generally available for highway construction projects and those project costs must include work zone impact mitigation strategies that address both mobility and safety impacts. The mitigation strategies used in work zones are generally comprised from a combination of the following categories of alternatives:

- Construction approach (e.g. staging/sequencing of construction, lane/ramp closure alternatives, alternative work schedules, contractor incentives);
- Work zone design (e.g. lane widths, median crossovers, construction of temporary lanes);
- Traffic control operations (e.g. speed limit reductions, truck restrictions, signal timing, signal coordination, and phasing improvements);
- Public information (e.g. public outreach, dynamic message signs, highway advisory radio);
- Incident management and enforcement (e.g. incident management plans, traffic management centers, emergency service patrols, enhanced police enforcement); and
- Travel demand management (e.g. rideshare incentives, transit incentives and improvements).

Furthermore, the mitigation strategies used may vary from one work zone to another based on, for example, the type of pavement being considered. Ultimately, the Michigan Department of Transportation (MDOT) and other road agencies are forced to consider the difficult question of what work zone impact mitigation strategies provide optimal results for the cost of investment. Of particular concern are those work zones that are expected to have "significant" impacts.

The *Work Zone Safety and Mobility Rule*, established in federal regulation *23 CFR 630, Subpart J*, requires that each state "establish a policy for the systematic consideration and management of work zone impacts on all federal aid highway projects across all stages of project planning, development, delivery and operations" [*1*]. In response to this rule, MDOT established the *Work*

Zone Safety and Mobility Policy, which applies to all work zones (i.e., construction, maintenance, utility, etc.) along state trunklines and local roads. The processes, procedures, and guidelines developed as a part of this policy are detailed in the *Work Zone Safety and Mobility Manual* [*1*]. This includes the provision of "significant delay" determined during project scoping as an increase in travel time greater than 10 minutes.

Projects that are expected to exceed this delay threshold mandate the conduct of more extensive planning-level assessments in order to mitigate adverse impacts on mobility and/or safety. Unfortunately, there is currently no explicit guidance provided as to how investment decisions should be prioritized in light of these mobility and safety impacts. Furthermore, as a result of the implementation of this policy, certain types of investments have become more common (e.g., bridge/pavement widening, contract towing, expedited schedules, etc.) and the safety, mobility, and economic impacts of these investments is unclear.

Much of the existing research related to the proposed work has involved the development of analytical frameworks that allow for the assessment of the safety and, particularly, mobility impacts of work zones. Avrenli et al. [*2*] examined the speed-flow relationships of select work zones and compared their results to the *Highway Capacity Manual* methods for freeway sections, noting that *HCM*-style methods offer several advantages, including their relative simplicity. Schroeder et al. [*3*] presented an approach to estimate the impacts of freeway work zones on traffic operations for "significant" work zones as defined by the FHWA. This approach can be used to examine the effects of mitigation strategies such as lane closures, lower speed limits, and capacity reductions while considering traffic diversion on a corridor basis. Much of the analytical work that has examined work zone delay has involved the use of simulation models, Moriarty et al. [*4*] compared a variety of such models, including QUEWZ, QuickZone, and CA4PRS. This study assessed the relative accuracy of these models, as well as the data requirements and user-friendliness of each program.

A difficult aspect of assessing work zone delay is quantifying diversion behavior by motorists. Chen et al. [*5*] developed an optimization model for resurfacing projects on two-lane highways, evaluating alternatives with various lane closure and diversion strategies. In subsequent work [*6*], a process was developed that combined micro-simulation and logistic regression to imitate diversion behavior in work zone areas. A comparison between simulation outputs from VISSIM and field observations suggested that the diversion control module can simulate the queue propagation process effectively. Shelton et al. [*7*] used a multi-resolution modeling technique to calculate user costs and address the impacts of traffic diversion on a system-wide level using simulation models. Schonfeld et al. [*8*] incorporated tradeoffs between work duration and cost and optimized work zone lengths and diversion rates.

Another important consideration in assessing delay is determining practical limits on what constitutes "acceptable" delay to road users. The state of Virginia has developed region-specific tables for allowable work hours, which show when lane closures can be accommodated without creating delays. Ongoing research is aimed at creating work-zone operational performance thresholds to determine acceptable limits for queue lengths and/or delays [*9*].

Given the broad spectrum of methodological issues involved with analyzing work zone impacts, several national guidance documents have been developed in this area. In a recent FHWA report, a decision-making framework was developed to simplify the broader safety and mobility impacts of work zones across the project development stages and provide additional strategies to help manage these impacts during project implementation. The research suggested that agencies should develop an agency-level work zone safety and mobility policy "*intended to support systematic consideration and management of work zone impacts across all stages of project development*" [*10*]. Based upon this policy, it was recommended that:

- Agencies should develop standard procedures which shall include the use of work zone safety and operational data, work zone training, and work zone process reviews;
- Agencies should be encouraged to develop procedures for work zone impacts assessment; and
- Agencies should develop project-level procedures to address the work zone impacts of individual projects and identify which projects may cause a relatively high level of disruption.

In October 2010, a National Cooperative Highway Research Program (NCHRP) national scan of practices was conducted pertaining to work zones [*11*]. The purpose of the scan was to investigate best practices in work zone assessment, data collection and performance measurement, and how these practices were being used to ensure safety and minimize congestion in work zones. The findings from the research resulted in some of the following recommendations to assist agencies in assessing work zone impacts:

- Establish specific and measureable work zone safety and mobility goals and objectives.
- Performance measures used should relate to objective goals for mobility and safety impacts.
- Work zone performance measures must be used rationally and must consider costs, productivity, environmental concerns, and other factors.
- Quality data must be collected in order to engage in effective work zone performance measurement.
- Agencies should strive to improve how work zone safety and mobility data is fully analyzed and utilized to continuously improve agency processes and procedures.

It is often unclear what kind of analytical tool to use in work zone planning and which tools will provide the most value. In further research sponsored by FHWA in 2008, guidance was developed *"to provide the local decision-maker with a broad, fundamental understanding of how analytical tools can be used to support work zone decision making throughout an entire project life cycle"* [*12*]. Work zones incorporate a vast range of work activities, ranging from multi-billion dollar re-build projects to lower-cost bottleneck improvements. Mobility impacts can be an issue for projects on facility types ranging from rural roadways with low volumes to urban freeways with high volumes. The guidance provided in the research included the following:

- Identified a range of work zone impacts to be considered when analyzing work zones, including safety (motorists and workers), mobility, economic considerations, and environmental concerns.
- Presented the context for decision making throughout a typical project life cycle including decisions related to scheduling, application (e.g. construction technique, etc.) and traffic management plans (TMP) and how decisions in the earlier stages of a project will impact and/or constrain decisions in later stages.
- Described the various analytical tools available to support work zone mobility analysis focusing on the classes of tools and the particular trade-offs between the scope of analysis with the desired level of detail for the work zone analysis.
- Provided a work zone analysis process and checklist that provides an effective approach to developing an analytical process to support work zone planning.

The presence of a work zone characteristically results in mobility and safety impacts to road users. Minimizing the adverse impacts associated with work zones has become a higher priority especially since the inception of the *Work Zone Safety and Mobility Rule*. The work zone road user cost is one method used to provide the economic basis for quantifying the adverse impacts that can then be used for effective decision-making to improve work zone mobility and safety. In a 2011 FHWA report [*13*], work zone road user cost concepts and their applications were demonstrated using case studies derived from three real-world construction projects. Key outcomes from this research included the following:

- Step-by-step procedures for deriving the unit costs for monetary components included in the road user cost analysis;
- Lists of the cost sources for each cost component tied to economic indices;
- Input requirements and various tools available for use in work zone road user cost analysis;
- Selecting appropriate project contracting strategies to minimize work zone road user costs and related impacts through early project completion, and
- Approaches for determining the appropriate level of incentives and disincentives.

Further research related to work zone road user costs was conducted in a Texas study that produced practical and meaningful estimates for work zone capacities under a variety of work zone configurations and lane closure scenarios [*14*]. Data collected from 18 work zone locations were used to update the anticipated capacities of various freeway work zone lane closure configurations. Various models used to evaluate traffic conditions in the work zones were evaluated and recommendations were made for their use. Finally, recommendations were included concerning road user cost analysis for freeway construction projects.

An established procedure for analyzing work zone mobility and safety impacts can aid in the planning, decision-making, design, and financial aspects of a construction project. Some of the more recent research regarding mobility and safety in work zones is provided in an FHWA document titled, *Traffic Analysis Toolbox Volume XII: Work Zone Traffic Analysis—Applications and Decisions Framework* [*15*]. The research provided guidance on Work Zone Traffic Analysis (WZTA), including step-by-step procedures to assist in determining the most suitable tools to perform the work zone analysis including the various tool categories ranging from sketch-planning to microsimulation models and the associated pros and cons of each.

Study Objectives

Previous research has led to the development of a variety of tools, performance measures and decision-making frameworks to analyze work zone safety and mobility. The goal of this study is to provide MDOT with important information to guide subsequent work zone planning and implementation strategies. The specific objectives of this Phase 1 research are as follows:

- Determine the accuracy of existing methods for estimating delay and diversion;
- Determine the safety effects associated with various work zone characteristics
- Determine the cost-effectiveness of select strategies that have been implemented; and
- Provide guidance towards development of work zone decision support tools for optimization of mobility and safety.

This report presents results from research conducted between May 2013 and May 2015. This study involved an assessment of the national state-of-the-art and state-of-the-practice, a survey of the traveling public to gain insight into public perceptions of work zone operations and delay, and the collection and analysis of work zone operational, safety, and cost data. Collectively, these efforts are described in the following chapters of this report:

- Chapter 2 – Literature Review
- Chapter 3 – State Agency Survey
- Chapter 4 – Road User Survey
- Chapter 5 – Work Zone Field Evaluations
- Chapter 6 – Analyses of Archived RITIS Data
- Chapter 7 – Analysis of Work Zone Crash Data
- Chapter 8 – Assessment of Project Costs Associated with Nighttime vs. Daytime Resurfacing
- Chapter 9 – Summary and Recommendations for Future Work

CHAPTER 2
LITERATURE REVIEW

Given fiscal constraints, the implementation of highway construction and maintenance programs has become more challenging. Greater emphasis has been placed on spending the limited funding that is available in a manner that is the most efficient and economical. In order to make informed decisions, project costs must include work zone impact mitigation strategies to address mobility and safety impacts within construction projects. This state-of-the-art literature review explores available information related to work zone impact mitigation strategies through the following topic areas:

- Latest State Transportation Agency (STA) Policy
- Tools for Evaluating Work Zone Operations
- Traffic Management Strategies
- Work Schedule/Incentive Strategies
- Innovative Concepts
- Operational and Benefit-Cost Evaluations

State DOT Work Zone Policies

In 2004, the Federal Highway Administration (FHWA) promulgated the *Work Zone Safety and Mobility Rule* to bring greater attention and understanding of impacts of work zones and how to minimize those impacts through traffic management strategies related to design, coordination, scheduling and various other techniques. In order to receive federal highway funding for projects, state Departments of Transportation (DOTs) have developed policies and programs to facilitate implementation of proper work zone practices. From the literature search, some of the most current work zone safety and mobility policy documents developed or updated by DOTs included the following:

- *Colorado DOT - Work Zone Safety and Mobility Rule Procedures Document July 2013* http://www.coloradodot.info/library/traffic/traffic-manuals-guidelines/lane-close-work-zone-safety/work-zone-safety-mobility/WZSM_Procedures.pdf
- *Idaho DOT - Work Zone Safety and Mobility Program – January 2012* https://itd.idaho.gov/highways/docs/Work%20Zone%20Safety%20and%20Mobility%20Program.pdf

- *Montana DT - Work Zone Safety and Mobility Goals and Objectives Procedures Guidelines – September 2007 / Revised March 2009*
  http://www.mdt.mt.gov/other/const/external/manuals_guidelines/workzone_safety_mobility.pdf
- *Nevada DOT* - *Work Zone Safety and Mobility Implementation Guide – January 2008 / Revised March 2012*
  http://www.mdt.mt.gov/other/const/external/manuals_guidelines/workzone_safety_mobility.pdf
- *Virginia DOT – Wok Zone Safety Guidelines for Temporary Traffic Control –January 2012*
  http://www.virginiadot.org/business/resources/wztc/2012_WZPG_Final_Draft.pdf
- *Washington DOT – Design Manual, Chapter 1010 - Wok Zone Safety and Mobility –July 2012*
  http://www.wsdot.wa.gov/publications/manuals/fulltext/m22-01/1010.pdf
- *Wisconsin DOT – Design Manual, Chapter 1010 - Wok Zone Safety and Mobility –July 2012*
  http://www.wsdot.wa.gov/publications/manuals/fulltext/m22-01/1010.pdf

In California, Caltrans investigated innovative strategies to protect construction and maintenance workers in an effort to improve safety. The Safety Innovation Working Group was formed to provide guidance and commitment to improve roadway safety in California with a focus on three areas [*16*]: education and outreach (internal and external); policy and legal options; and equipment (e.g.. warning devices and barriers to keep workers safe). The investigation focused on the current use of work zone technologies during highway/roadside maintenance activities in California and around the nation. A synopsis of the information was compiled, which included multiple resources pertaining to work zone mobility and safety guidance.

Tools for Evaluating Work Zone Operations

Many programs have been developed over the years to assist state DOTs in the evaluation of work zone operations as they pertain to mobility and safety impacts. Some of the most commonly utilized programs include:

- Operational analysis programs – e.g. Highway Capacity Software, CORSIM, FRESIM
- Simulation modeling programs – e.g. Synchro, Trans CAD, VISSIM
- Work zone specific programs – e.g. Queue and User Cost Evaluation of Work Zones (QUEWZ), QuickZone, Work Zone Capacity Analysis Tool (WZCAT), Work Zone Impact and Strategy Estimator (WISE), and Construction Congestion Cost (CO3) software.

While these tools have provided a good means for obtaining information related to highway construction and work zone impacts, new or modified evaluation programs have been developed to address the work zone mobility and safety issues.

Highway work zones frequently cause road congestion and safety concerns to road users. One tool used to address this problem is the Transportation Management Plan (TMP) which can enhance work zone safety and mobility while reducing road user costs. In California, research was performed to enhance the TMP technique. The researchers reviewed TMP reports for the California DOT (Caltrans) projects regarding best practices and the corresponding input from district traffic engineers. Researchers compiled highway project data related to TMP cost estimates for select case studies and incorporated the findings into the Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) software. Based on the CA4PRS analysis, a TMP strategy selection and cost estimate (STELCE) model was developed [*17*]. To validate the model, results were compared between the cost estimates from the STELCE model and those from Caltrans TMP Reports, with the results showing differences of within 5 percent. While the validation proves acceptable for use in California, other DOTs would require adjustments and modifications reflecting their TMP practices before applying a similar model.

In 2007, Caltrans adopted RealCost, a Life-Cycle Cost Analysis (LCCA) software developed by FHWA and used as an analytical technique to evaluate long-term alternative investment options by comparing the values of alternative pavement structures and strategies. Recently, Caltrans created an enhanced version of the RealCost software which has subsequently been adopted as an official LCCA tool for California state highway projects. The improvements incorporated into the RealCost California version software included [*18*]:

- Enhancing the traffic data module with four representative traffic patterns generated through the Caltrans traffic database system
- Adding the cost estimating modules for initial construction and subsequent maintenance and rehabilitation (M&R)
- Adding graphical interfaces to integrate service life, maintenance frequency, and agency costs with given project constraints such as, climate, pavement surface, and design life
- Adding automatic data selection and computerized calculations

Further development of traffic simulation models has incorporated the use of the geographic information system (GIS) in combination with microscopic traffic modeling systems. A recent study demonstrated a basis to combine GIS macro- and microscopic models, specifically TransCAD with TRANSIMS. A framework was applied to integrate a network GIS system with a microscopic traffic modeling system. The integrated system was tested in the Michigan area to evaluate traffic impacts from the I-75/I-96 Ambassador Bridge Gateway Maintenance Project. The research included: grouping of the GIS tools that automate data conversion and processing; visualizing the model results; and comparing the simulation results with field observations. The developed tools allow users to visually compare simulation results with field observations, providing an illustration of changes in traffic pattern caused by work zones [*19*].

Highway construction activities often require that traffic lanes be closed, requiring tradeoffs between construction duration and travel delay. Several states, including Alabama, Florida and Tennessee have developed traffic analysis tools to assist in determining whether or not to close lanes. Recently, a Work Zone Traffic Analysis (WZTA) web-based tool was developed to help determine when traffic volumes are low enough that lanes can be safely closed, as well as to provide delay estimates to quantify the impacts of lane closures and other mobility restrictions [*20*]. In Illinois, WorkZoneQ was developed to automate calculations for queue analysis from traffic information, geometric features, traffic control plans, and value-of-time data. WorkZoneQ is used to estimate the capacity, queue length, delay, users' costs, and congestion duration for work zone locations [*21*].

Traffic Management Strategies

Highway work zone activities present an inherently precarious situation not only for construction workers within a work zone, but for the motoring public traveling in work zones. Various traffic management strategies have been utilized to assist agencies in better management of work zone configurations and operations. Some of the traffic management strategies have included the following practices:

- Road closures (e.g. full road closures, ramp closures, and lane closure restrictions);
- Re-routing (e.g. signed alternate route, movable barrier, split merges, shoulder as lane); and
- Dynamic (e.g. variable speed limits, ramp metering, lane merge systems).

As mobility and safety within work zones continues to be problematic, new strategies have been developed to address and/or mitigate some of the concerns. One strategy area includes providing positive protection guidance. Positive protection refers to the use of various devices including longitudinal barriers, mobile barriers, vehicle arresting systems and end protection systems. Guidance on this topic is available in research from Texas, New Hampshire and Kansas. Kansas developed implementation guidelines for determining when to use a particular positive protection device in a work zone. The guidance provided the following [*22*]:

- Flowchart to assist in determining where work zone positive protection is required to limit, reduce, or eliminate exposure in temporary work zones;
- Reference table describing work zone exposure control measures and corresponding guidance for each measure; and
- Table describing possible positive protection devices currently approved for use.

Another traffic management strategy being investigated involves mitigating the long queues that can accompany conventional lane merge (CLM) designs for work zones and potentially lead to rear-end and sideswipe crashes. Typically, a CLM will guide traffic to an open lane through the work zone. This practice can reduce the available highway capacity approaching a work zone which often creates congestion and delays to motorists. Recent research has investigated innovative ways to improve traffic control strategies leading up to lane closures, which were shown to require less mental activity for drivers, provide higher levels of driver satisfaction, and reduce vehicle operation speed, deceleration, and braking forces. One of these strategies is the Joint Lane Merge (JLM) concept, based on which motorists in both lanes have equal right-of-way and merge using an alternating pattern of lane changes within the transition area. [*23*].

The Virginia Department of Transportation implemented a unique strategy to mitigate congestion in a rural work zone on I-81 by forcing more vehicles to use a detour route. The work zone TMP directed that the right lane of a two lane section of traffic be forced to detour onto a parallel route. Trucks were directed to utilize the left lane and remain on the Interstate via electronic message signs, while signage for the right lane was deliberately limited in order to increase the number of vehicles utilizing the detour. Cars were specifically instructed to use the right lane and detour during peak-volume periods. Results during the construction showed approximately 45 percent of cars on average exited the freeway and nearly 90 percent of trucks remained on I-81 through the work zone [*24*]. A simulation was performed that compared the forced-detour traffic control strategy with traditional work zone strategies. Results from the simulation comparison suggested the forced-detour strategy reduced travel times and queue lengths more than traditional strategies and that this strategy could be utilized at similar locations along rural Interstate corridors.

While highway work zone fatalities have been declining over recent years, 587 fatalities occurred in work zones in the United States during 2011 and work zone safety continues to be a concern of transportation agencies. To this end, research performed in Illinois examined and developed recommendations for minimizing crashes within work zones. The project study analyzed work zone related crashes and corresponding contributing factors, identified the risks associated with various work zone layouts in order to develop recommendations to improve work zone configurations, and evaluated the efficiency of temporary rumble strips in work zones. Results from the study provided guidance for improving the use of temporary rumble strips in work zones [*25*], including recommendations for type, pattern, spacing, and location of the rumble strips.

Work schedule strategies related to work zones have been increasingly utilized over recent years. Construction projects have become more frequent, larger, and more complex due to the aging interstate system which leads to more congestion and travel delay due to work zone related activities. Accelerated work schedules, alternate work schedules, and restricted work hours have been some of the strategies to address this concern. While these strategies have shown to provide relief to the motorists that must travel through these construction sites and have assisted in improving construction scheduling performance, they can also present problems for the construction workers themselves.

As part of the Transportation Research Board's Strategic Highway Research Program, research was conducted to address the concerns of worker related injury to the work schedule strategies being deployed, specifically, how to handle the increased fatigue associated with the work schedule strategies. Some of the work scheduling guidance developed from the study revealed the following strategies [*26*]:

- Day shifts
  - Maintain consistent sleep and wake times throughout the week
  - Maintain similar or identical sleep and wake times on weekend or non-work days
  - Strategic naps (on-the-job) to reduce impact of restricted sleep
- Night Shifts
  - Minimize use of extended shifts (10 – 12 hours) due to reduced individual crew recovery opportunities
  - Consider returning to day schedule (sleeping at least 8 hours/night) on days off
  - Sleep in on the weekend to make up for sleep loss during the week
  - Strategic naps (on-the-job) to reduce impact of shortened sleep periods
- Weekend Closure: 55 hours
  - Consider selective half or full day off after closure to provide recovery opportunity
  - Anchor ("split") sleep schedule (nighttime anchor sleep and daytime nap) for managers to obtain 6 to 8 hours in 2 separate sleep periods
  - Avoid double shifts

Another method for mitigating the impacts of work zones involves utilizing incentive strategies to facilitate the construction project. Various types of incentive strategies have been utilized over the recent years including A+B Bidding, Performance-Based Contracting, Lane/Ramp Rentals and Disincentive/Liquidated Damages strategies. In March 2013, FHWA published a technical memorandum titled *Applying the Work Zone Safety and Mobility Rule to Design-Build Projects* which identified how the key aspects of the FHWA *Work Zone Safety and Mobility Rule*, better known as 'the Rule', could apply to Design-Build (DB) projects. The concept behind 'the Rule', originally developed for Design-Bid-Build (DBB) projects, was *"to bring about greater consideration and understanding of work zone impacts throughout project development; minimization of those impacts where possible through scheduling, coordination, design, and staging decisions; and better management of remaining impacts during construction"* [*27*].

While incentive strategies to reduce construction time have been utilized over the recent years, very little research has been performed to determine if the incentive strategies actually help assist in work zone mobility and safety. One study performed in Missouri evaluated 20 Incentive/ Disincentive (I/D) projects to quantify the impacts of the work zones through road user cost (RUC) calculations based on travel delays, vehicle operating costs, and crash costs. Some of the key findings of this research included the following road user cost savings based on project type, with overall net RUC cost savings of $5.30 for every $1 incentive paid [*28*]:

- Emergency Projects ~ 93%
- Full Closure Projects ~ 86%
- Urban Projects ~ 80%
- Rural Projects ~ 33%
- Non-emergency Projects ~ 33%

Innovative Concepts

The most recent information related to reducing work zone impacts involves the use of technology, enforcement tactics, and transit strategies to assist in mitigating the effects of work zone impacts. Some recent technology to assist in mitigating the effects of work zones involves the use of queue detection systems. Researchers at the University of Minnesota have been utilizing a "low-cost, portable, video-based traffic data collection device to detect and follow the progression of the tail of the queue and trigger an alarm that can be transmitted to warning devices located upstream of the device" [*29*]. Unfortunately, due to funding limitations, this feasibility study was not performed within work zones, but at intersections in order to capture queue data more frequently. The queue detection system was able to provide the following:

- real-time stopped vehicle detection (resulting from queues)
- alarm trigger that can be used by upstream driver warning devices
- length of the queue
- good portability of the system

Reducing the number of crashes in and around work zones has been a priority for DOTs across the nation. It is estimated that as many as 25 percent of fatal crashes in work zones may involve high speeds [*30*]. A fairly new technology for reducing speeds in construction areas involves the use of a public awareness tool in and around the construction areas. Research performed in Arizona utilized a changeable message sign with radar (CMSR) to help reduce speeds. The CMSR device detects speeding vehicles in the work zone and provides real-time feedback to the drivers by displaying the detected speed of the vehicle and a corresponding dollar amount of the potential fine. The findings of this research showed that speeds were consistently reduced in work zones with the CMSR system [*30*] as summarized in Table 1.

Table 1. Speeds in Work Zones with CMSR Systems [*30*]

Speed Over Posted Speed Limit (mph)	Speeding Vehicles without CMSR (percent)	Speeding Vehicles with CMSR (percent)
5 mph	83%	63%
10 mph	51%	31%
15 mph	20%	10%
20 mph	5%	2%
25 mph	0.6%	0.3%

Enforcement tactics have been shown to provide additional mobility and safety benefits in work zones. Research performed in Indiana demonstrated a 41.5 percent reduction in the frequency of crashes attributable to police enforcement [*31*]. Furthermore, all state transportation agencies are required by federal regulations to have a policy in place regarding the use of law enforcement in work zones. Unfortunately, not all state transportation agencies understand how to best implement, manage, and fund enforcement strategies in work zones. Research sponsored by the National Cooperative Highway Research Program (NCHRP) recently developed some guidance to assist states identify appropriate enforcement procedures for use within work zones. Some of the key guidance topics include the following [*32*]:

- Traffic Enforcement Strategies
  - Work Zone Enforcement Techniques (e.g. stationary deployment, circulating or mobile enforcement, automated and semi-automated speed enforcement)
  - Deciding When Enforcement is Needed (e.g. safety benefit versus cost)
  - Work Zone Enforcement Deployment (e.g. arrival, deployment, departure)
- Enforcement Considerations in Planning and Design
  - Establishing Realistic Design Speeds and Speed Limits
  - Considering the Need, Extent, and Type of Enforcement
  - Work Zone Design Features Related to Enforcement (e.g. shoulder closure length, enforcement pullout areas)
  - Speed Management Alternatives, Public Awareness and Motorist Notification of Work Zone Enforcement
- Administrative Considerations
  - Funding Approaches for Work Zone Enforcement
  - Payment Methods for Work Zone Enforcement
  - Officer Work Zone Safety Training

Another strategy to mitigate the impacts that work zones have on mobility and safety involves the use of transit. While most work zone mitigation strategies have concentrated on changing driver habits within the work zone, a potential new strategy would be to change the driving behavior all together, by changing the mode of transportation. Research performed for the Minnesota Department of Transportation involved determining if driver behavior could be altered due to the implementation of a major roadway construction project by providing alternatives to driving. Incentives offered to motorists to change driving modes included:

- Additional trips and park-and-ride facilities to make transit more attractive
- Dedicated bus lanes to reduce travel time
- Free fares to attract travelers to transit

The researchers found that after the construction was completed, less than 15 percent of transit riders changed their behavior within two years and that increasing fares to normal levels did not create a significant incentive to stop using public transit [*33*].

Operational and Benefit-Cost Evaluations

As previously discussed, new mitigation strategies selected for work zones to assist in mobility and safety impacts have been developed related to traffic management strategies, work schedule/incentive strategies, as well as other new concepts. In order to choose the appropriate strategy, however, there must be an understanding of the benefit that is gained from a particular strategy, including whether or not the strategy is cost-effective. Several studies have been performed recently that evaluated some of the strategies used to mitigate the effects that work zones may have on mobility and safety.

One way to determine if a particular mitigation strategy is beneficial is to evaluate the operational effects it has on a highway when deployed. A mitigation strategy evaluation was performed deploying temporary ramp meters at short-term work zones in Missouri. The researchers monitored safety measures related to driver compliance, merging performance, and speed changes for below, at, and above capacity conditions. The operational evaluation for temporary ramp metering in work zones resulted in the following findings [*34*]:

- Temporary ramp meters should only be deployed at work zone locations where there is potential for congestion
- Temporary ramp meters should be turned on only during above-capacity conditions
- Temporary ramp meters for under-capacity conditions could have a major safety issue related to non-compliance
- Temporary ramp meters decreased ramp vehicle platoons
- Temporary ramp meters for work zones revealed a decrease in total delay (24 percent at low truck volumes and 19 percent at high truck volumes)

Another operational evaluation performed on a mitigating strategy was related to the use of Variable Advisory Speed Systems (VASS). The VASS provides drivers approaching a work zone with advanced warning of downstream traffic speeds in order to assist in better decision making. The VASS utilized five sensors and two variable message signs. The study was performed in Utah with the objective of determining the statistical relevance of performance data in order to evaluate the effectiveness of the system on queue mitigation. The findings of the study revealed that [*35*]:

- System was effective on weekends during evening peak hours
- System was ineffective on weekdays during the evening peak hours

It was surmised that weekend drivers were not as familiar with the work zone conditions as weekday commuters and were more likely to honor the speed message presented with the VASS.

Another means to determine if a particular mitigation strategy is favorable is to evaluate the benefits gained from the strategy and compare them to the cost associated with the implemented strategy deployed on the highway. One benefit-cost (B/C) evaluation performed on a mitigation strategy involved the use of a movable barrier in a construction zone located in Utah. This strategy typically offers the benefits of expediting the completion schedule, which in-turn, can have a positive impact on travel time, lower travel distances, less congestion on bypass routes, and reduced impacts on businesses. The Utah Department of Transportation utilized this strategy on a reconstruction project and found the following results [*36*]:

- Safety of the traveling public and the construction workers was enhanced
- Benefits estimated at $1.7 to $2.4 million (based on reduction in travel time due to early project completion and elimination of left-turn crashes at major intersections)
- Estimated B/C ratio ~ 4:1

Another mitigation strategy that was evaluated involved an information technology (IT) tool used to assess construction traffic impacts. The Oregon Department of Transportation (ODOT) evaluated the Work Zone Traffic Analysis (WZTA) tool as part of a program to determine whether the system investment had paid off, and to help decide if the tool should be adopted by ODOT. The WZTA tool provides a GIS database and impact analysis tool for assessing traffic impacts in work zones by allowing users to easily access databases and shorten the time required to evaluate construction sites. The results of the evaluation showed the WZTA tool provided consistent data, allowing for more efficient traffic management during construction, in addition to reducing disruption and delay [*37*].

CHAPTER 3
STATE AGENCY SURVEY

A national state-of-the-practice survey was conducted to collect information from state DOTs as to current strategies, policies, and practices related to work zone operations and safety. The survey was sent to transportation representatives with knowledge and experience in work zone activity in all 50 states. The 25 states that responded to the survey are listed below and will be referenced in this section as follows:

- Arkansas (AR)
- California (CA)
- Delaware (DE)
- Idaho (ID)
- Indiana (IN)
- Iowa (IA)
- Kansas (KS)
- Louisiana (LA)
- Michigan (MI)
- Mississippi (MS)
- Missouri (MO)
- Nebraska (NE)
- Nevada (NV)
- New York (NY)
- North Dakota (ND)
- Ohio (OH)
- Oregon (OR)
- Pennsylvania (PA)
- South Carolina (SC)
- South Dakota (SD)
- Tennessee (TN)
- Texas (TX)
- Virginia (VA)
- Washington (WA)
- West Virginia (WV)

The following is a compilation of the findings from the national state-of-the-practice survey of current strategies, policies and practices related to work zone operations and safety. In some instances the state that provided the information has been identified in parenthesis where appropriate.

1. **Does your state provide guidance as to when and where specific work zone safety and mobility policies, programs, and strategies should be utilized?**

   Responses:

   YES 23

   NO 2

2. **Is your state's work zone safety and mobility policy posted to the FHWA library at: http://www.ops.fhwa.dot.gov/wz/resources/final_rule/state_list.htm?**

   Responses:

YES, and up to date	52% (DE, IN, IA, KS, MI, MO, ND, NV, NY, OH, PA, TN, WV)
YES, but out of date	12% (ID, NE, WA)
NO, not available	36% (AR, CA, LA, MS, OR, SC, SD, TX, VA)

3. **Does your state use guidelines or decision-support tools to make informed investment decisions with respect to work zones?**

   Responses:

YES	64% (AR, ID, IN, MI, MO, NE, NY, ND, OH, OR, PA, SC, TN, VA, WA, WV)
NO	28% (CA, DE, IA, KS, LA, MS, NV)
NOT APPLICABLE	8% (SD, TX)

4. **Which of the following programs does your state currently use to evaluate work zone operations?**

   Responses:

   Figure 1 shows the programs that are most widely used by agencies to evaluate work zone operations are *Highway Capacity Software* (*HCS*) and *Synchro/SimTraffic* (13 states each), followed by *QUEWZ* and *QuickZone* (9 states each), as well as *VISSIM* (8 states) and *CORSIM/FRESIM/NETSIM* (7 states). Other programs that were utilized include *RITIS*, *WZCAT*, *CO3*, *RealCost*, and *TransCAD*.

   In addition to these programs, a number of states have developed or utilize their own decision support tools. This includes the use of *Construction Congestion Cost* (*CO3*) software. Other examples of state-specific programs include:

   - AASHTO Red Book (AR)
   - Detour vs. Runaround Comparison Analysis (IN)

- Work Zone Traffic Analysis (WZTA) Tool (OR)
- Internal program "Lane Closure Decision Support System" (TN)
- Q-DAT Lane Closure Analysis Tool - TTI spreadsheet (TX)
- State Specific Delay Analysis Tool/Spreadsheet (PA)

A number of state DOTs have also developed spreadsheets or tabular summaries that are used to estimate mobility impacts of work zones. These states include Louisiana, Missouri, and Ohio.

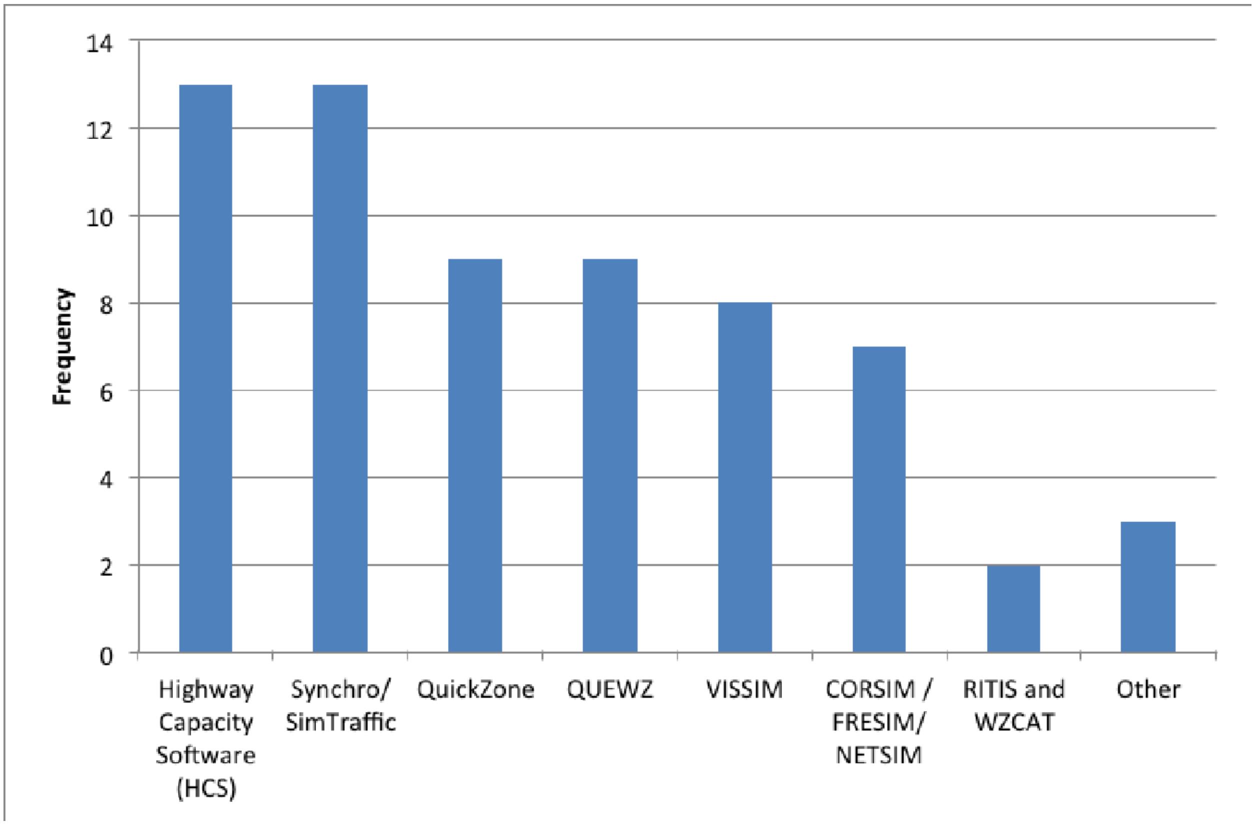

Figure 1. Utilization of Work Zone Evaluation Programs

5. **Has your agency conducted research on public perceptions of work zones and work zone related delay?**

   Responses:

YES	20% (IA, MI, MO, OR, SD)
NO	76% (AR, CA, DE, ID, KS, LA, MS, ND, NE, NV, NY, OH, PA, SC, TN, TX, VA, WA, WV)
NOT APPLICABLE	4% (IN)

6. **Please indicate the frequency with which your agency uses any of the following public awareness tools either before or during work zone activities:**

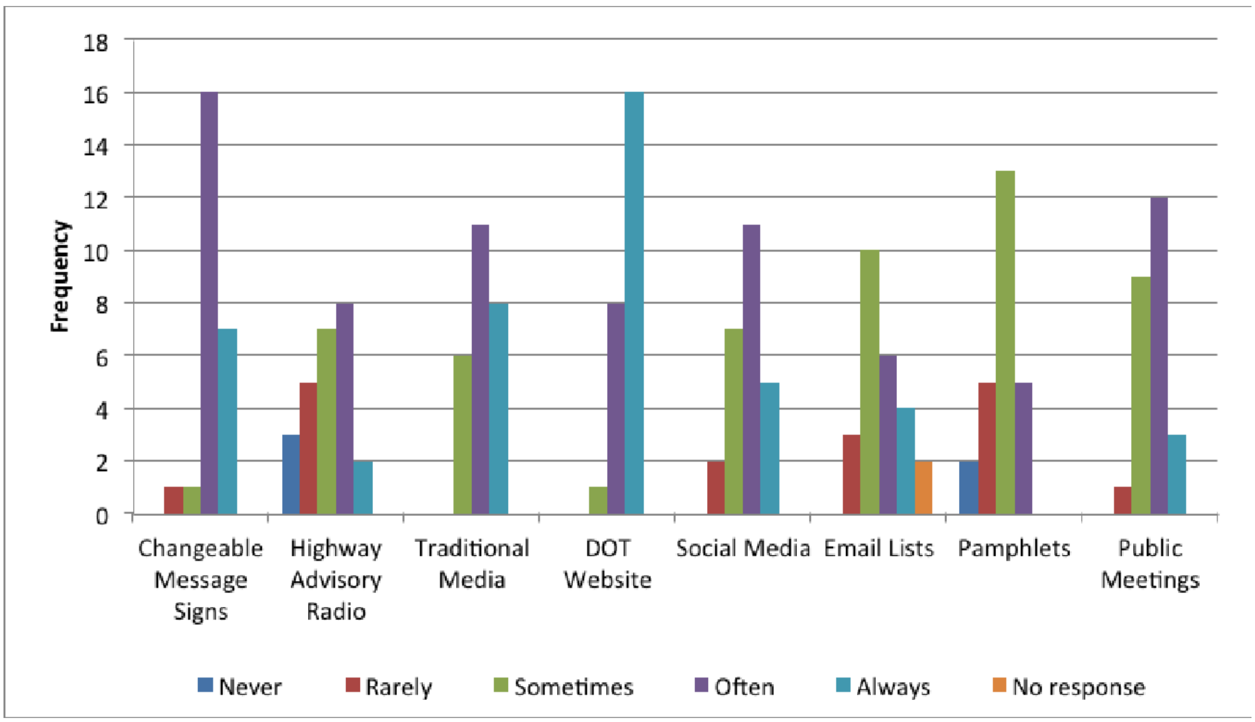

Figure 2. Utilization of Public Awareness Tools

Figure 2 shows those tools with the highest frequency of use by agencies for public awareness activities. The DOT website, changeable message signs (CMS), and traditional media (e.g., newspaper, television, etc.) were the tools that were used with the greatest frequency. Social media outlets, such as Twitter and Facebook, are becoming much more common avenues for media outreach. Some states, such as Michigan and Missisippi, have developed smartphone apps while a number of states have dedicated websites that focus on traffic operations, including work zone activities.

7. **Please indicate the frequency with which your agency utilizes the following traffic maintenance strategies when each strategy is feasible.**

Responses:

Figures 3-6 summarize the frequency of use for various traffic management strategies by state DOTs. The strategies were divided into four categories: closure practices; rerouting practices; dynamic practices; and additional practices.

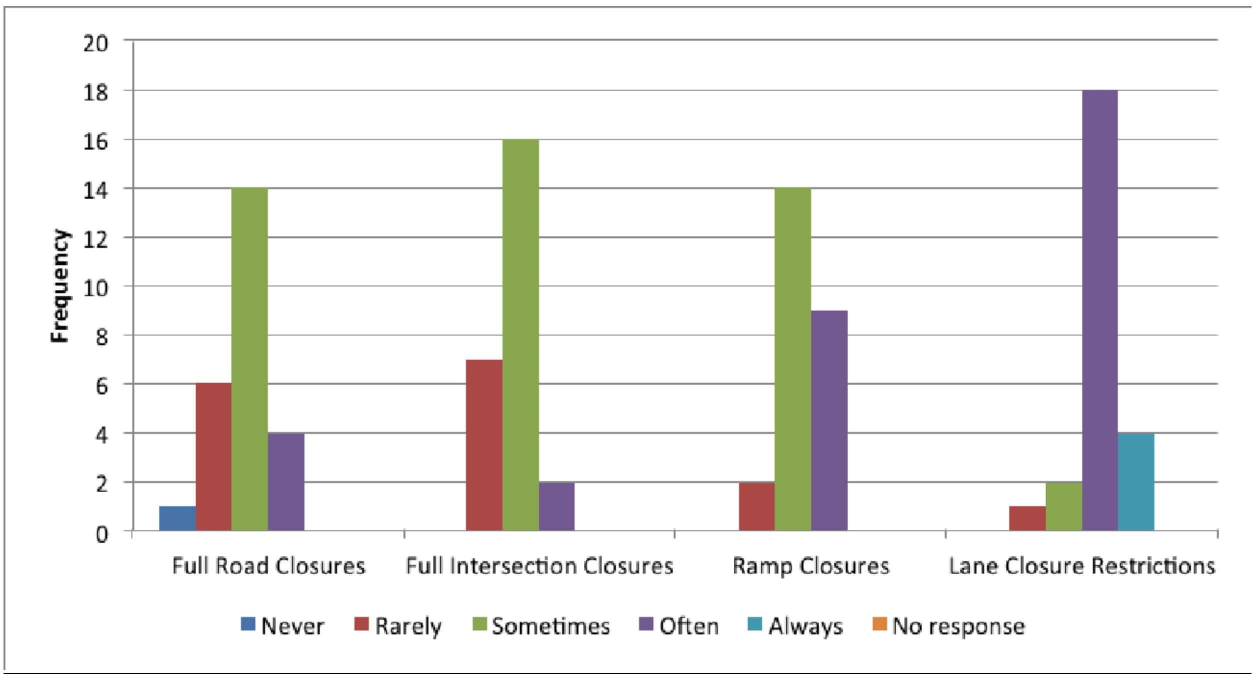

Figure 3. Traffic Management Strategies-Closure Practices

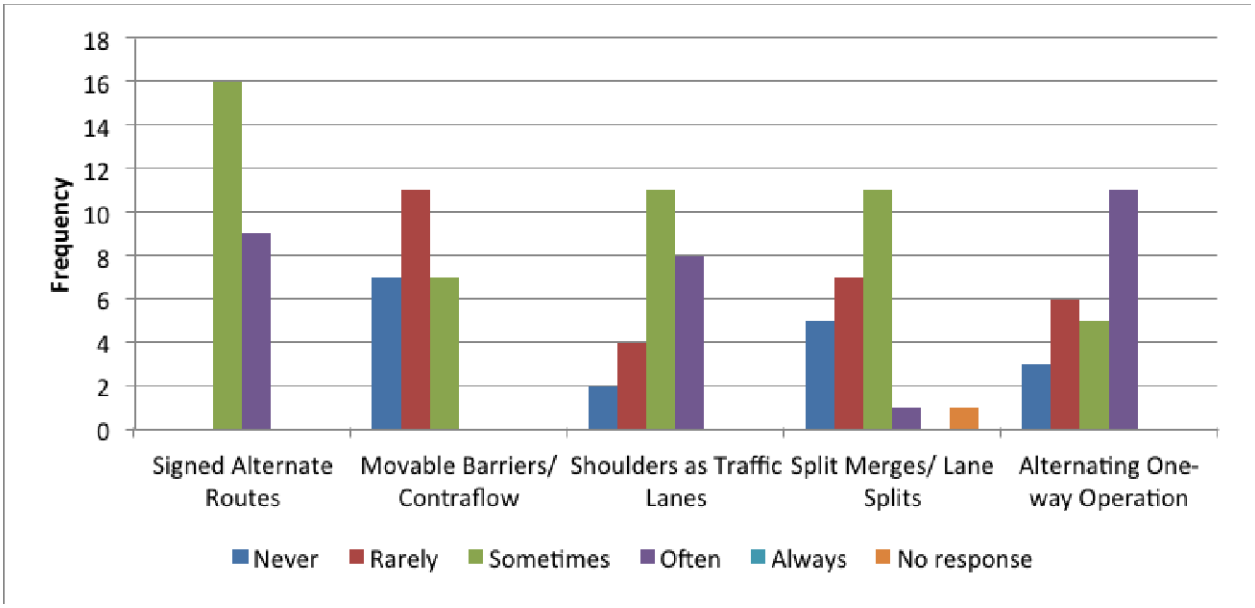

Figure 4. Traffic Management Strategies-Re-Routing Practices

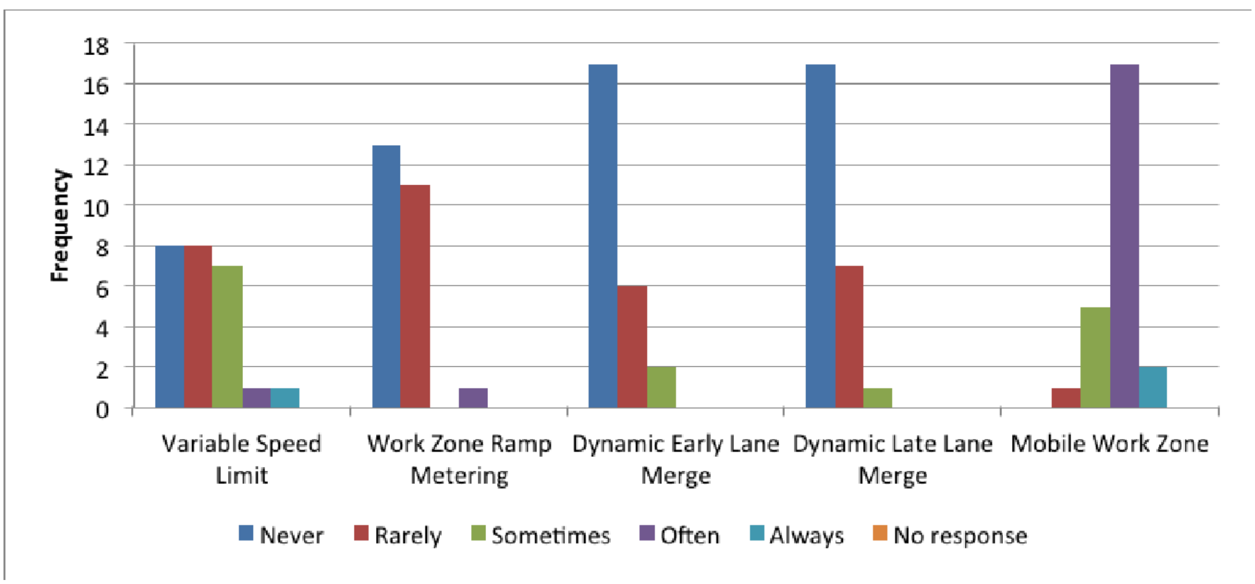

Figure 5. Traffic Management Strategies-Dynamic Practices

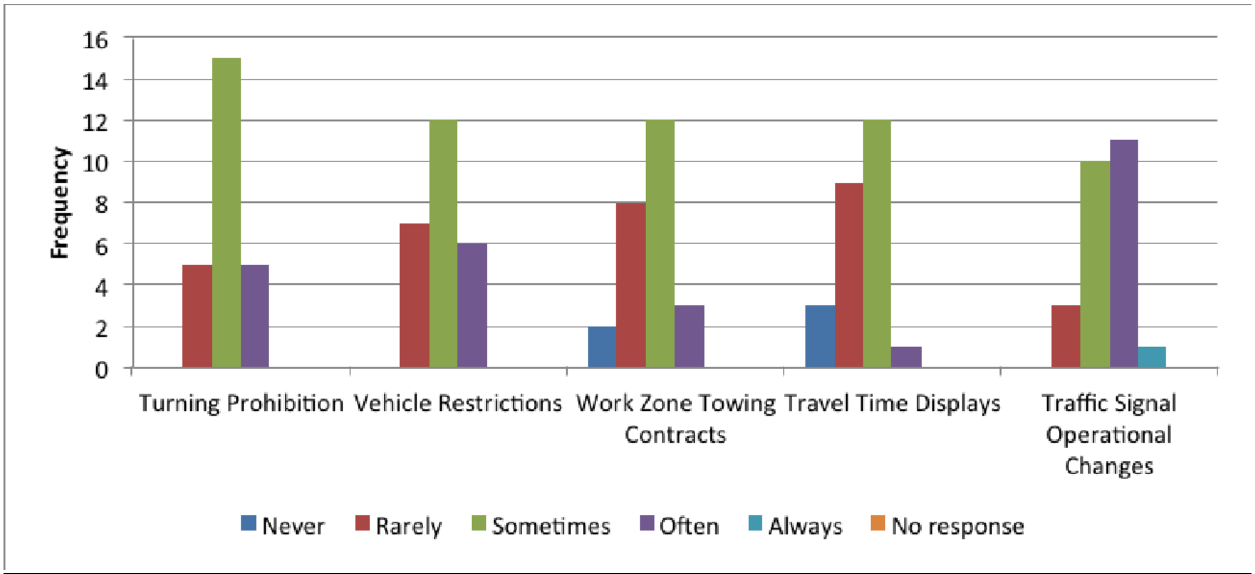

Figure 6. Traffic Management Strategies-Additional Practices

8. **What are your agency's policies or practices with regards to the following work zone characteristics as shown in the accompanying diagram? Please indicate whether they are STANDARDS, GUIDANCE, OPTIONS, etc.**

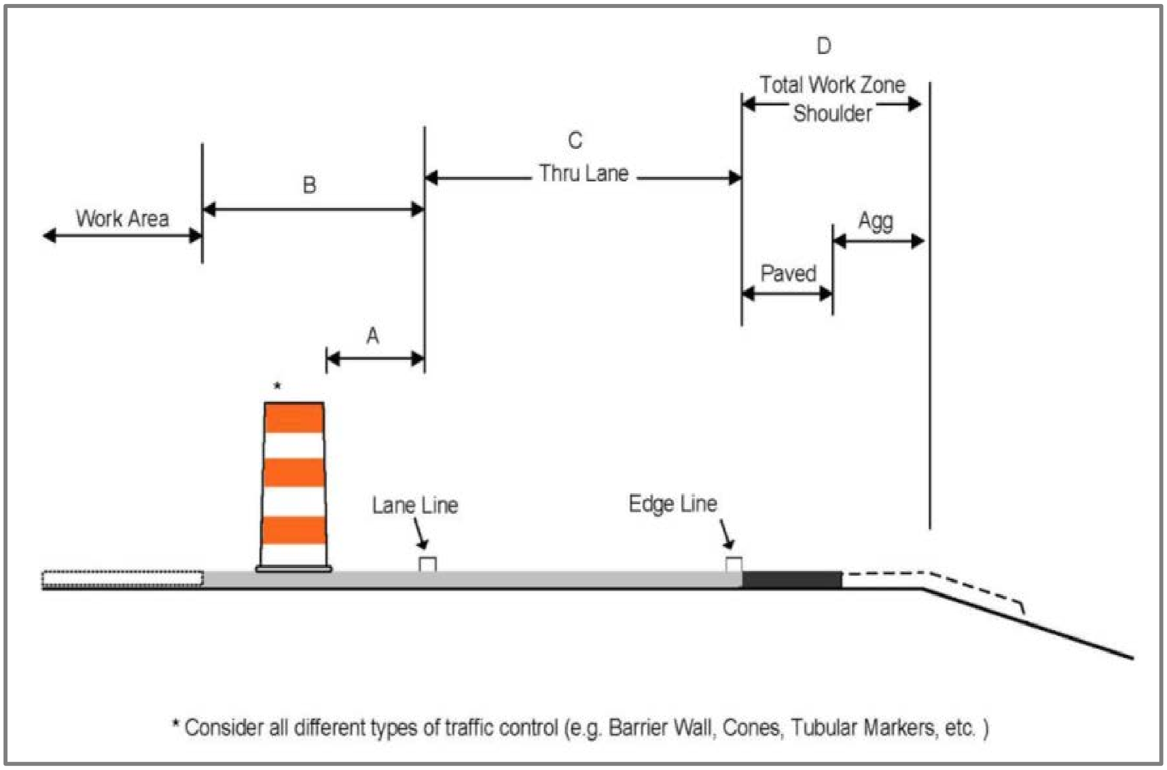

Figure 7. Work Zone Characteristics

Responses:

The responses to this section of the survey varied greatly between the agencies for each of the different aspects of the work zone characteristics. The responses were summarized for each section and the general consensus was as follows:

- Shy Distance – minimum – 0 ft; typical = 2 ft; maximum = 4 ft
- Separation Distance – highly variable, ranging from 0 to 12 ft, with most distances being application-specific
- Lane Width – 10 ft minimum was cited most frequently, with 11 ft generally stated as desirable
- Shoulder Widths – 2 ft minimum was typical; 4 ft in cases where bicylclists were expected on the shoulder; and 5-6 ft widths for cases where median crossovers are provided

9. Please indicate the frequency with which your agency utilizes the following work schedule/incentive strategies when each strategy is feasible. In addition, please indicate which of these strategies have been formally evaluated by your agency.

Responses:

Figure 8 provides a summary of those work schedule/incentive strategies with the highest frequency of use by DOTs. The most frequently used strategies include alternate work schedules/restricted work hours, disincentives/liquidated damages, and accelerated work schedules. Performance-based contracting and A+B bidding were found to be widely used on a case-by-case basis by agencies.

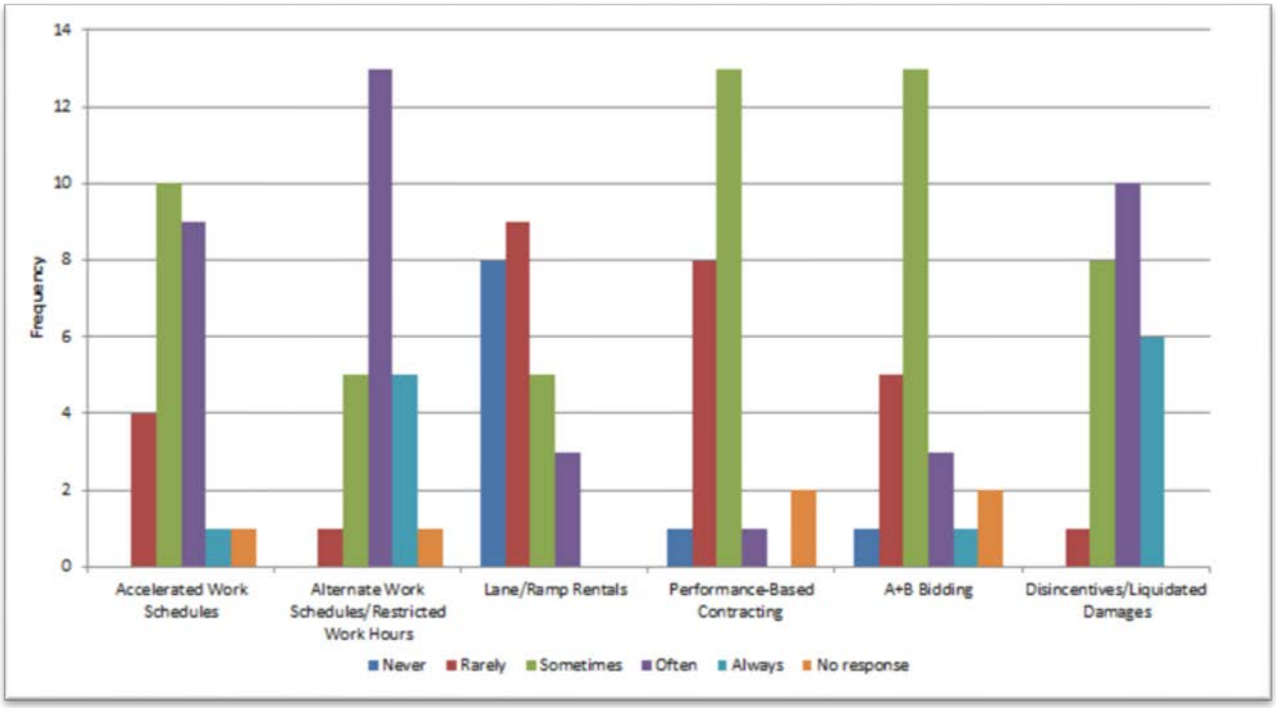

Figure 8. Work Schedule/Incentive Strategies

CHAPTER 4
ROAD USER SURVEY

A key aspect of MDOT's work zone program is the public's perception of acceptable delays due to such highway construction or maintenance activities. Given that highway work zones are often one of the most observable facets of transportation agencies from a public perspective, customer feedback in this area is an extremely important consideration. This is acknowledged in the *Work Zone Safety and Mobility Manual* [*1*], which states:

> "Customer feedback will also be essential for assessing whether the current mobility thresholds (e.g., the 10-minute delay) actually match what the motorist considers tolerable. An important question is whether the customer's perception of what is tolerable generally matches this established threshold of 10 minutes."

In an effort to determine the validity of the established delay threshold, as well as providing and quantifying more detailed feedback on work zone-related delays, a state-wide survey of road users was performed. The survey solicited information related to the following topics:

- Maximum acceptable work zone delay based on the type of trip;
- Frequency at which road work information is sought prior to departure;
- Use of road work information to modify route and/or departure time;
- Preferred media for receiving work zone travel information;
- General travel information: primary mode of transportation (including commercial trucks), commute duration, and miles driven per year; and
- General demographic information: home zip code, age, gender, ethnicity, and employment status.

The primary objective of this task was the development of a "Traveler Acceptable Delay Matrix" that relates threshold acceptable values of work zone delay to factors including trip purpose, geographic region, time of day, and various demographic factors.

Survey Methodology

The road user survey was performed by distributing a one-page questionnaire at rest areas and welcome centers state-wide. Surveys were performed within each MDOT region and along each primary freeway route. The one-page questionnaire, shown in Figure 9, was developed by Wayne State University and reviewed by MDOT prior to field implementation. The final version included 17 total questions, which attempted to identify the critical information necessary to achieve the survey objective. Surveyors, typically working in two-person teams, visited rest areas and welcome centers on both weekdays and weekends between 8:00 A.M. and 5:00 PM. A sampling strategy was developed based on recent state-wide vehicle-miles traveled (VMT) data to help ensure a representative number of responses from each geographic region. The survey locations and dates are shown in Table 2 and Figure 10.

Table 2. User Survey Site Locations

Location Name	Region	Day of Week	Date
Belleville	Metro	Friday	September 27, 2013
Howell	University	Friday	September 27, 2013
New Buffalo	Southwest	Friday	October 11, 2013
West Branch	North	Friday	October 11, 2013
Howell	University	Saturday	October 12, 2013
Naubinway	Superior	Saturday	October 12, 2013
Okemos	University	Saturday	October 12, 2013
Clare	Bay	Sunday	October 13, 2013
Portland	Grand	Sunday	October 13, 2013
Clarkston	Metro	Wednesday	October 16, 2013
Chelsea	University	Thursday	October 25, 2013
Battle Creek	Southwest	Friday	November 1, 2013
Clarkston	Metro	Thursday	November 7, 2013
Portland	Grand	Thursday	November 7, 2013
Belleville	Metro	Friday	November 8, 2013
Clarkston	Metro	Friday	November 8, 2013
Portland	Grand	Friday	November 8, 2013
Chelsea	University	Tuesday	November 12, 2013
Clarkston	Metro	Wednesday	November 13, 2013
Clarkston	Metro	Friday	November 15, 2013

MDOT Michigan Department of Transportation

Michigan Work Zone Road User Survey

WAYNE STATE UNIVERSITY

These survey results will provide valuable information to assist the Michigan Department of Transportation (MDOT) in work zone planning activities. Your participation in this effort is greatly appreciated. If you have any questions or comments, please feel free to contact Dr. Peter Savolainen at savolainen@wayne.edu.

1) When you know about the presence of a work zone, do you typically change your departure time, your route, both, or neither for the following trip types?

Trip Type:	Change Departure Time ONLY	Change Route ONLY	Change BOTH	Change NEITHER
Commute or other work-related	□	□	□	□
Shopping or personal business	□	□	□	□
Vacation or recreation	□	□	□	□

2) How frequently do you seek advance information about construction work, such as road closures and delays, for the following types of trips:

Trip Type:	Always	Usually	Rarely	Never
Commute or other work-related	□	□	□	□
Shopping or personal business	□	□	□	□
Vacation or recreation	□	□	□	□

3) Indicate the longest (number of minutes) delay that would be acceptable to you due to a work zone for the following trip types:

Trip Type:	Longest Delay
Commute or work-related (AM)	______ mins
Commute or work-related (PM)	______ mins
Vacation or recreation (leaving home)	______ mins
Vacation or recreation (returning home)	______ mins
Shopping or personal business	______ mins

4) In general, would you prefer:

□ Road be completely closed during a shorter period, or
□ Road be partially closed during a longer period

5) From which of the following sources do you get information about construction work zones, such as road closures and delays? (Please check all that apply.)

□Construction Signs □Radio
□Television □Internet (computer)
□In-vehicle GPS □Smartphone
□Newspaper □Email
□Social Media (e.g., Facebook) □Pamphlets/brochures
□Word of Mouth □Public Meetings
□Other: ____________

6) Which is your MOST preferred source of work zone related travel information? (Please select ONLY one.)

□Construction Signs □Radio
□Television □Internet (computer)
□In-vehicle GPS □Smartphone
□Newspaper □Email
□Social Media (e.g., Facebook) □Pamphlets/brochures
□Word of Mouth □Public Meetings
□Other: ____________

7) How familiar are you with MDOT's "Mi Drive" website?

□ Very Familiar □ Somewhat Familiar □ Not Familiar

8) How often do you use MDOT's "Mi Drive" website?

□ Daily/Weekly □ Monthly □ Every Few Months □ Never

9) Primary Mode of Transportation on a Daily Basis:

□ Personal Automobile □ Motorcycle
□ Semi Truck or Box Truck □ Bus
□ Other □ Do Not Drive

10) Do you drive as a part of your job (not including your commute to work)?

□ Yes, Daily □ Yes, Occasionally □ No □ N/A

11) On average, how long is your commute to work?

□ 10 min or less □ 11-20 min □ 21-30 min □ 31-40 min
□ 41-50 min □ 51-60 min □ over 60 min □ N/A

12) Approximately how many miles do you drive per year?

□ 4,000 or less □ 4,001 to 8,000 □ 8,001 to 12,000
□ 12,001–16,000 □ Over 16,000 □ Do Not Drive

13) Home Zip Code: ____________

14) Age:

□ under 21 □ 21 to 30 □ 31 to 40
□ 41 to 50 □ 51 to 60 □ over 60

15) Gender: □ Male □Female

16) Ethnicity:

□ White □ African American/Black □ Hispanic/Latino
□ Asian □ Mixed race □ Other

17) Employment Status:

□ Employed □ Not Employed □ Student □ Retired

Figure 9. One-Page Questionnaire Road User Survey

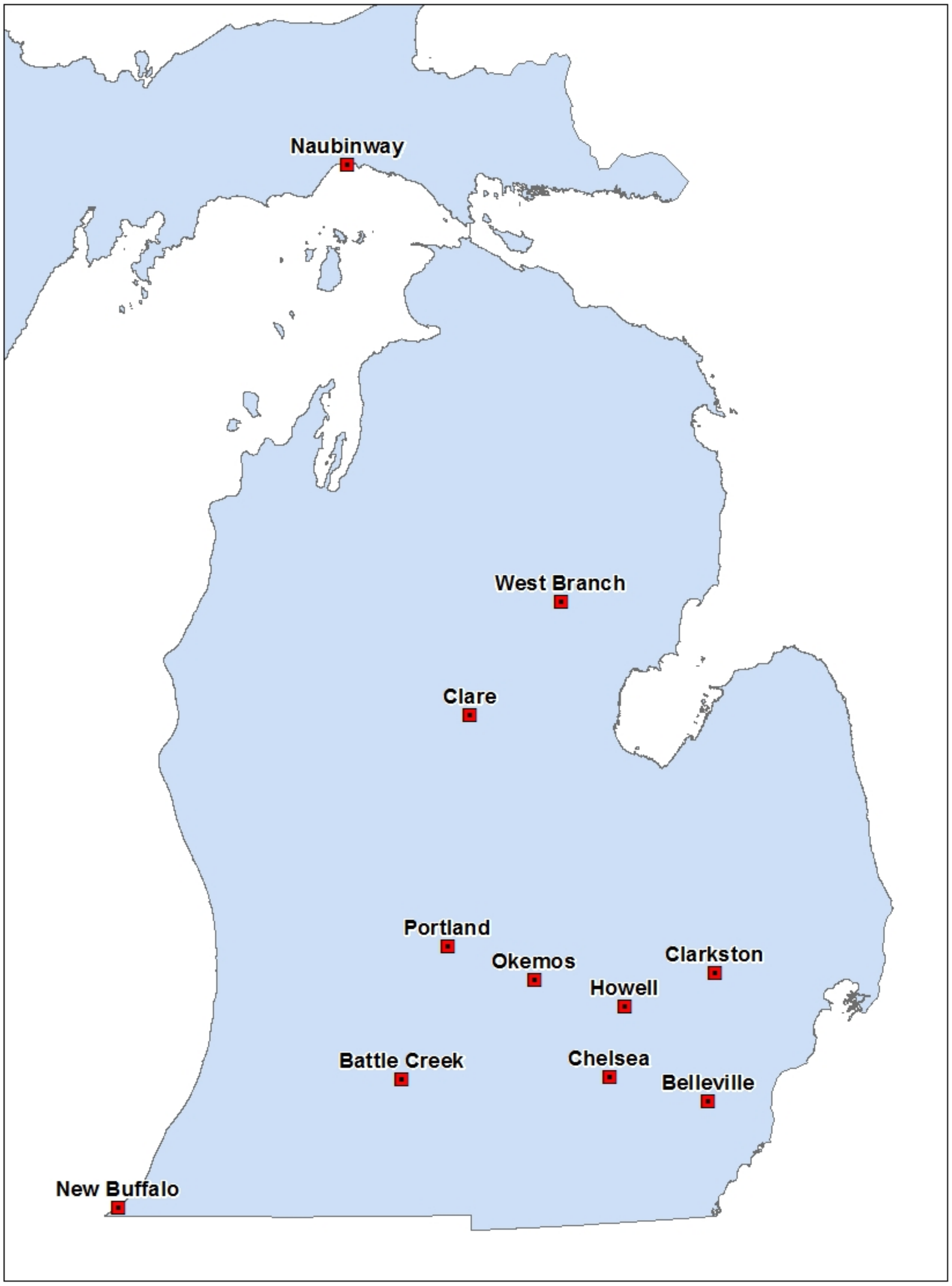

Figure 10. Road User Survey Location Map

Survey Results

In total, 1,265 total survey responses were collected for analysis. Table 3 displays the number of responses by home region, while summarized demographic information is provided in Table 4. It should be noted that additional findings related to the road user survey responses are presented in the Appendix.

Table 3. Survey Responses by Home MDOT Region

MDOT Region	Responses	Percent of Total (%)
Superior	17	1.3
North	74	5.8
Grand	105	8.3
Bay	140	11.1
Southwest	91	7.2
University	192	15.2
Metro	359	24.5
Canada	19	1.5
Out of State	209	16.5
No Response	57	4.5
TOTAL	1,265	100.0

Table 4. Demographic Information on Survey Respondents

Home Zip Code	Number	Percent	Ethnicity	Number	Percent
Michigan	978	77.3%	Caucasian	1119	88.5%
Out of State	230	18.2%	African American	46	3.6%
Other /NA	57	4.5%	Hispanic/Latino	24	1.9%
Age	**Number**	**Percent**	Asian	14	1.1%
16 to 30	101	8.0%	Mixed Race	11	0.9%
31 to 40	110	8.7%	Other	26	2.1%
41 to 50	204	16.1%	NA	25	2.0%
51 to 60	393	31.1%	**Employment Status**	**Number**	**Percent**
over 60	454	35.9%	Employed	883	69.8%
NA	3	0.2%	Not Employed	35	2.8%
Gender	**Number**	**Percent**	Student	22	1.7%
Male	859	68%	Retired	323	25.5%
Female	398	31%	NA	2	0.2%
NA	8	1%	-	-	-

Tables 3 and 4, show that greater than three-quarters of respondents reside within Michigan and nearly one-quarter reside within the Metro Region. Additionally, greater than two-thirds of respondents were over 51 years of age and males outnumbered females by greater than a 2 to 1 margin. The majority of respondents identified themselves as employed, with just over a quarter of the respondents identifying themselves as retired. Table 5 provides the details of the commuting and travel habits of the respondents of the road user survey.

Table 5. Commuting and Travel Habits

Primary Mode of Transportation	**Number**	**Percentage**
Personal Automobile	1084	85.7
Motorcycle	7	0.6
Semi-Truck/ Box Truck	139	11.0
Bus	5	0.4
Other	24	1.9
Do not Drive	4	0.3
No Response	2	0.1
Driving as Part of Job	**Number**	**Percentage**
Daily	500	39.5
Occasionally	190	15.0
No	420	33.2
N/A or No Response	155	12.3
Work Commute Duration	**Number**	**Percentage**
10 min or less	209	22.9
11-20 min	218	23.9
21-30 min	177	19.4
31-40 min	92	10.1
41-50 min	47	5.1
51-60 min	45	4.9
over 60 min	126	13.8
Miles Driven/Year	**Number**	**Percentage**
4,000 or less	55	4.3
4,001-8,000	117	9.3
8,001-12,000	256	20.2
12,001-16,000	255	20.2
over 16,000	561	44.3
N/A or No Response	21	1.7

The overwhelming majority of respondents of the survey drove their personal vehicle as their primary mode of transportation, although 11 percent were commercial truck drivers. Approximately 40 percent of respondents indicated that they drove daily as a part of their job (including commute), with an additional 15 percent indicating occasional work-related driving. Nearly one-half of the respondents indicated one-way daily commute durations of 20 minutes or less, with two-thirds reporting commute durations of 30 minutes or less. Approximately 40 percent of respondents indicated that they drove 8,001-16,000 miles per year, with another 40 percent indicating that they drove over 16,001 miles per year (a similar proportion to those who indicated they drove daily as part of their job).

In addition to obtaining road users attitude in relation to acceptable delay due to highway work zones, it is also interesting to note how road users alter their departure time and/or route in order to mitigate potential work zone delays. These results are reflected in Table 6 and Figure 11.

Table 6. Changes in Departure Time or Route due to Work Zones by Trip Purpose

Change in:	Work Trip		Shopping Trip		Vacation Trip	
	Number	Percent	Number	Percent	Number	Percent
Departure Time Only	266	23.3%	166	14.2%	181	15.3%
Route Only	185	16.2%	303	26.0%	258	21.9%
Both Time and Route	392	34.4%	319	27.3%	389	33.0%
Neither	298	26.1%	379	32.5%	351	29.8%

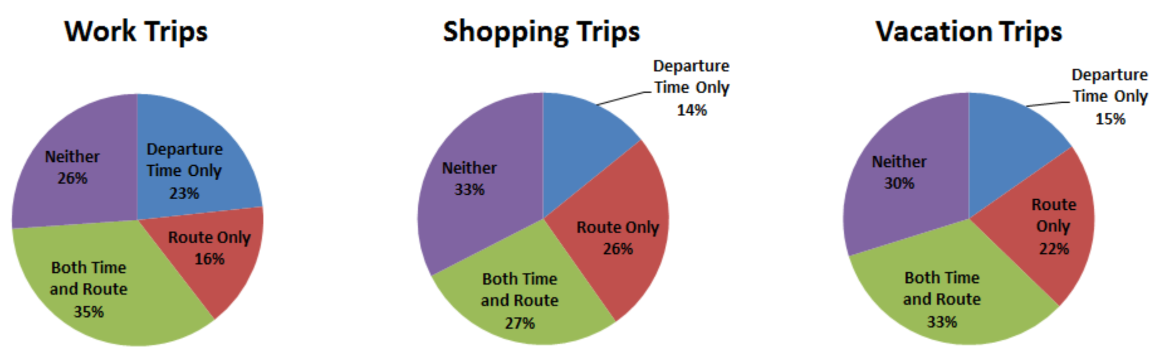

Figure 11. Changes in Departure Time or Route due to Work Zones by Trip Purpose

As would be expected, respondents indicated they were most likely to alter their departure and/or route for work-related trips. This follows logically as road users are changing their normal commute in order to arrive at work on time, whereas shopping or vacation-related trips are generally going to be less sensitive to arriving on or before a pre-scheduled time. Interestingly, respondents in all three cases indicated they would be more likely to change both the time of departure and route then relying simply on a change in one or the other. In fact, this result was most prominently displayed in work trips, which had the greatest percentage of respondents indicating they would change both departure time and route (approximately 35 percent).

In order for road users to determine if altered departure times or routes will be necessary or helpful for a specific trip, they must have some advance knowledge of such work zone-related delays. One way in which this can be accomplished by obtaining advance work zone-related information. Table 7 and Figure 12 show how frequently such information is sought in advance of various types of trips.

Table 7. Frequency of Seeking Advance Work Zone Information by Trip Purpose

Frequency of Seeking Information	Work Trip		Shopping Trip		Vacation Trip	
	Number	Percent	Number	Percent	Number	Percent
Always	177	15.3%	82	6.9%	193	16.1%
Usually	298	25.7%	231	19.6%	333	27.8%
Rarely	384	33.1%	491	41.6%	375	31.4%
Never	300	25.9%	376	31.9%	295	24.7%

Figure 12. Frequency of Seeking Advance Work Zone Information by Trip Purpose

It appears based on the results of the survey that road users about to engage in a shopping-related trip are the least likely to check for advance work zone information. This result is relatively intuitive, as shopping-related trips are typically going to be the least sensitive to incremental differences in arrival times. One notable result relates to respondents checking advance information prior to vacation-related trips, which actually had the greatest proportion of respondents who at least occasionally check such information. This is perhaps related to the long distance and/or unfamiliar nature of such trips where drivers may be unaware of long-term projects which may have a large impact on travel times. While respondents indicated that they were more likely to check for advance information prior to a work-related trip as compared to shopping-related trips, this was slightly less pronounced than for vacation-related trips.

In addition to identifying when road users seek advance work zone information, it is also critical to determine the sources of such information. Table 8 shows the various sources of advance work zone information along with the number and percent of respondents using or preferring that particular information source.

Table 8. Work Zone Information Sources Used and Most Preferred

	Used for Work Zone Information		**Preferred for Work Zone Information**	
Information Source	**Number**	**Percent**	**Number**	**Percent**
Construction signs	949	24.6%	456	36.1%
Radio	713	18.5%	278	22.0%
Television	444	11.5%	118	9.3%
Internet	362	9.4%	127	10.1%
In-Vehicle GPS	306	7.9%	121	9.6%
Smartphone	241	6.3%	86	6.8%
Newspaper	185	4.8%	16	1.3%
Email	59	1.5%	4	0.3%
Social Media	94	2.4%	6	0.5%
Pamphlets	17	0.4%	0	0.0%
Word of Mouth	440	11.4%	37	2.9%
Public Meetings	13	0.3%	0	0.0%
Other	30	0.8%	15	1.2%

Even in today's age of information, with more drivers having immediate access to the internet and smart phone applications than ever before, the most used and preferred source of for advance work zone information remains construction signage. This result shows just how important the impact of effective temporary traffic control, such as portable changeable message signs indicating future detours or closures, is on the general driving population. Respondents indicated that radio is the second most used and preferred source of information, which follows logically as most road users have easy and immediate access to the stations which broadcast such information. Additionally, radio broadcasts which provide advance information relating to work zones often also provide real-time information relating to traffic incidents which is generally important for almost any trip purpose. En-route information sources, such as construction signs, radio, and in-vehicle GPS, comprised greater than two-thirds of the preferred work zone information sources.

It should be noted that digital information is becoming more widely available to road users, with sources including the internet, smartphones, in-vehicle GPS, and social media. These sources can be advantageous as they can provide complex real-time information to road users, perhaps beyond what is generally available via construction signage or radio broadcasts. One way in which this information is distributed in the state of Michigan is via the MiDrive website. Respondents of the survey were asked if they were familiar with the website, as well as how often they use the service to seek information about their upcoming trips. These responses are summarized in Table 9.

Table 9. Responder Familiarity and Use of MDOT's "MiDrive" Website

Familiarity	**Number**	**Percent**
Very familiar	64	5.1
Somewhat familiar	200	15.8
Not familiar	1001	79.1
Use	**Number**	**Percent**
Daily/Weekly	36	2.9
Monthly	44	3.5
Every Few Months	136	10.8
Never / No Response	1049	82.8

As can be seen from Table 9, over three quarters of the respondents indicated that they were unfamiliar with the MiDrive website. However, those who noted that they were at least somewhat familiar are tending to report they use the website at least every few months. This indicates that while many road users may not have access or be familiar with the service, those who have used it are finding the service useful. As internet access becomes more widely available, specifically on a mobile basis via the use of tablets or smartphones, this service may become more widely used in the future.

Another preference among road users which can help road agencies plan certain construction and maintenance activities relates to full or partial closures. Respondents of the survey were asked if they preferred a complete closure for a shorter period of time, versus a partial closure for a longer period of time. The results of this question are provided in Table 10 and Figure 13.

Table 10. Preferences for a Full vs. Partial Road Closure

Scenario	Number	Percent
Road completely closed	511	40.4%
Road partially closed	729	57.6%
No Response	25	2.0%
Total	1265	100.0%

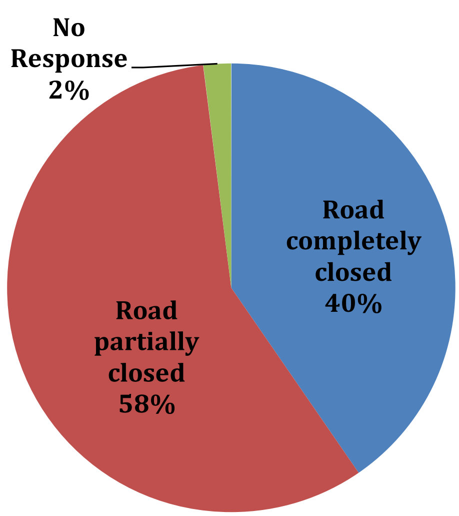

Figure 13. Preferences for a Full vs. Partial Road Closure

Respondents of the survey were relatively mixed on this issue, however; the greater proportion indicated that they would prefer the partial closure scenario versus the complete closure. This suggests that road users more often prefer at least some access via their normal route in most cases, as opposed to the extreme solution of a complete closure even for a shorter duration. One important exception relates to the Metro region, which can be observed in Figure 14. Additional regional breakdowns of the responses are provided in the Appendix.

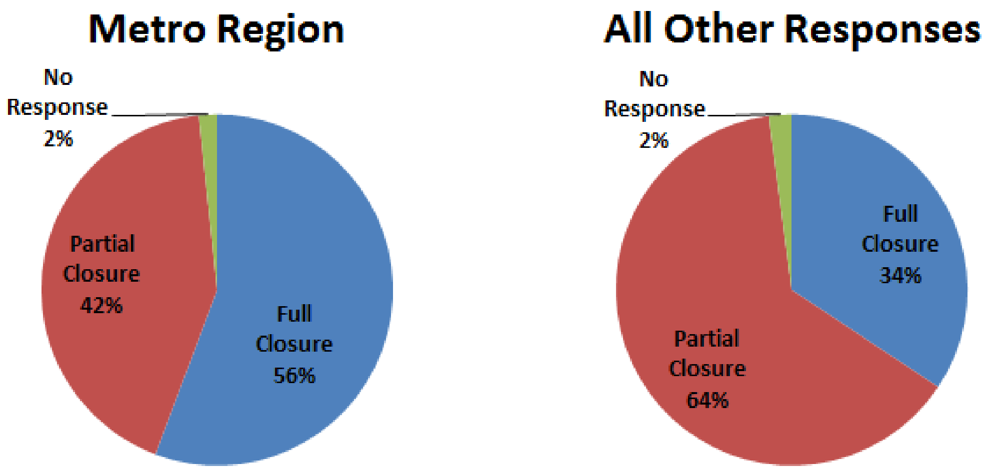

Figure 14. Partial vs. Full Closure - Metro Region vs. Other Responses

While, in general, respondents favored partial closures of longer durations to full closures of shorter durations, the opposite was true for the Metro region. Respondents residing in the Metro region of Michigan actually preferred the full closure scenario over the partial closure. This is perhaps indicative of the differences in the transportation system overall in a metropolitan area, where partial closures may result in significant delays across the available alternative routes. Instead, road users would prefer the roadway be completely closed so that the construction or maintenance activity can be completed as quickly as possible and the system can return to normal operations. Conversely, in more rural settings, partial closures may represent a more viable option that is overall less disruptive to the surrounding traffic system.

Measure of Acceptable Delay

A primary objective of the road user survey was to assess the upper threshold for work zone related delay that is acceptable to road users. Respondents were asked to identify what they felt was an acceptable work zone-related delay duration (in minutes) for the following types of trips:

- A.M. commute or work-related trip,
- P.M. commute or work-related trip,
- Vacation or recreational trip (leaving home),
- Vacation or recreational trip (returning home), and
- Shopping or personal business.

Responses were limited to a maximum delay of 60 minutes in order to limit the effects of respondents indicating excessively large delays (e.g., several hours or more), which would otherwise skew the results. The descriptive statistics for maximum acceptable work zone delay, including mean, median, 85th percentile, and 15th percentile are summarized in Table 11. An additional breakdown of acceptable work zone delay by vehicle type is provided in the Appendix.

Table 11. Maximum Acceptable Work Zone Delay by Trip Purpose

	Maximum Acceptable Work Zone Delay (minutes)			
Trip Type	**15th Percentile**	**Median**	**85th Percentile**	**Mean**
Work Commute AM	5.0	10.0	20.0	13.5
Work Commute PM	5.0	10.0	20.0	14.4
Vacation (leaving home)	5.0	15.0	30.0	19.5
Vacation (returning home)	5.0	15.0	30.0	19.6
Shopping	5.0	10.0	30.0	14.7

Table 11 displays that the lowest mean values for acceptable delay were reported during the AM commuting period, which is likely a reflection of travelers having a tight window to arrive at work on time. The mean acceptable delay was slightly higher during the PM commute, followed by shopping/personal trips. The mean acceptable delay for vacation travel was considerably higher, reflecting a higher tolerance for delay on such trips, which tend to be of a longer duration.

Determination of acceptable threshold values for work zone delay is more effectively estimated based on the percentile values, which reduce the effects of skew from respondents indicating very high delay values. Table 11 shows that 85 percent of respondents agree with an acceptable delay threshold value of 5 minutes, regardless of trip purpose or time of day. Slight differences were observed between trip purposes for the median acceptable delay values, as median delays of 10.0 minutes were reported for commute trips and shopping trips, while a median delay of 15.0 minutes was reported for vacation trips. Only 15 percent of travelers would be agreeable to work zone delays totaling 20 minutes or more during commuting, while this value increases to 30 minutes for vacation and shopping trips.

It is also interesting to observe variability in acceptable delay by the home region of the respondent. Figure 15 shows the median acceptable delay for both the AM and PM commutes by MDOT region. It should be noted that Figure 15 was prepared with data from respondents who indicated their personal vehicle was their primary mode of travel, as those involved with the trucking industry may mischaracterize their daily job tasks as a “commute”.

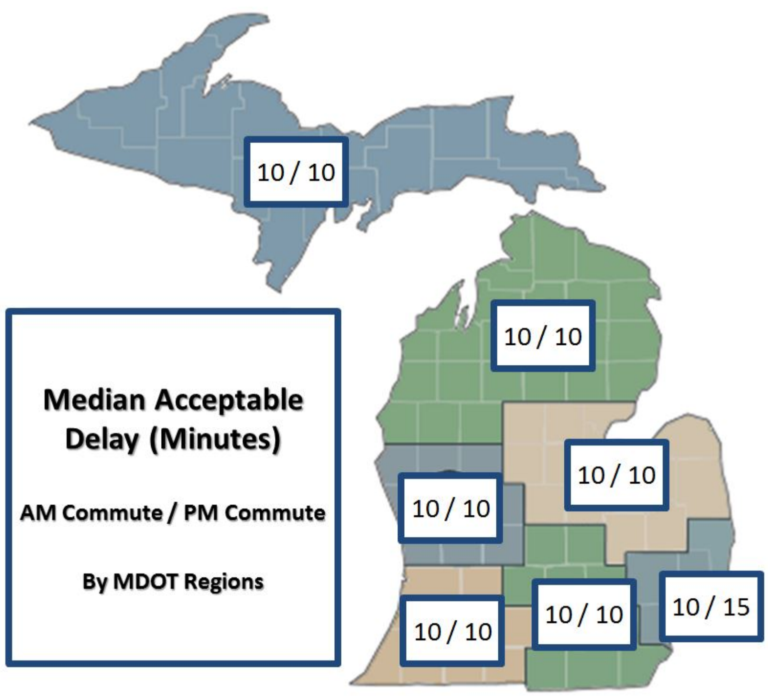

Figure 15. Median Acceptable Delay by MDOT Region for AM/PM Commutes

Figure 15 shows the threshold value for maximum delay is quite consistent across the state. The median acceptable delay value was 10 minutes for the AM commute in every MDOT region.
The 10-minute value also held for the PM commute across the state, except for the Metro region, which showed a 15-minute median acceptable delay. This is likely reflective of the higher volumes in this region, as well as less urgency to arrive on time during the PM vs. AM commute.

CHAPTER 5
WORK ZONE FIELD EVALUATIONS

In addition to examining user perceptions of work zone delay, another of the primary objectives of this study was to assess changes in traffic operations in various work zone environments. Field studies were conducted at work zone locations in the Lower Peninsula of Michigan between August and November of 2013. The purpose of these studies was to collect traffic flow data to determine changes in traffic volume and speed profiles as vehicles entered and exited work zone environments during peak hour traffic periods. A total of 10 work zone locations were visited during this period as shown in Figure 16. These work zones included 8 freeways and 2 non-freeway locations. The subsequent analyses focus on the freeway work zones.

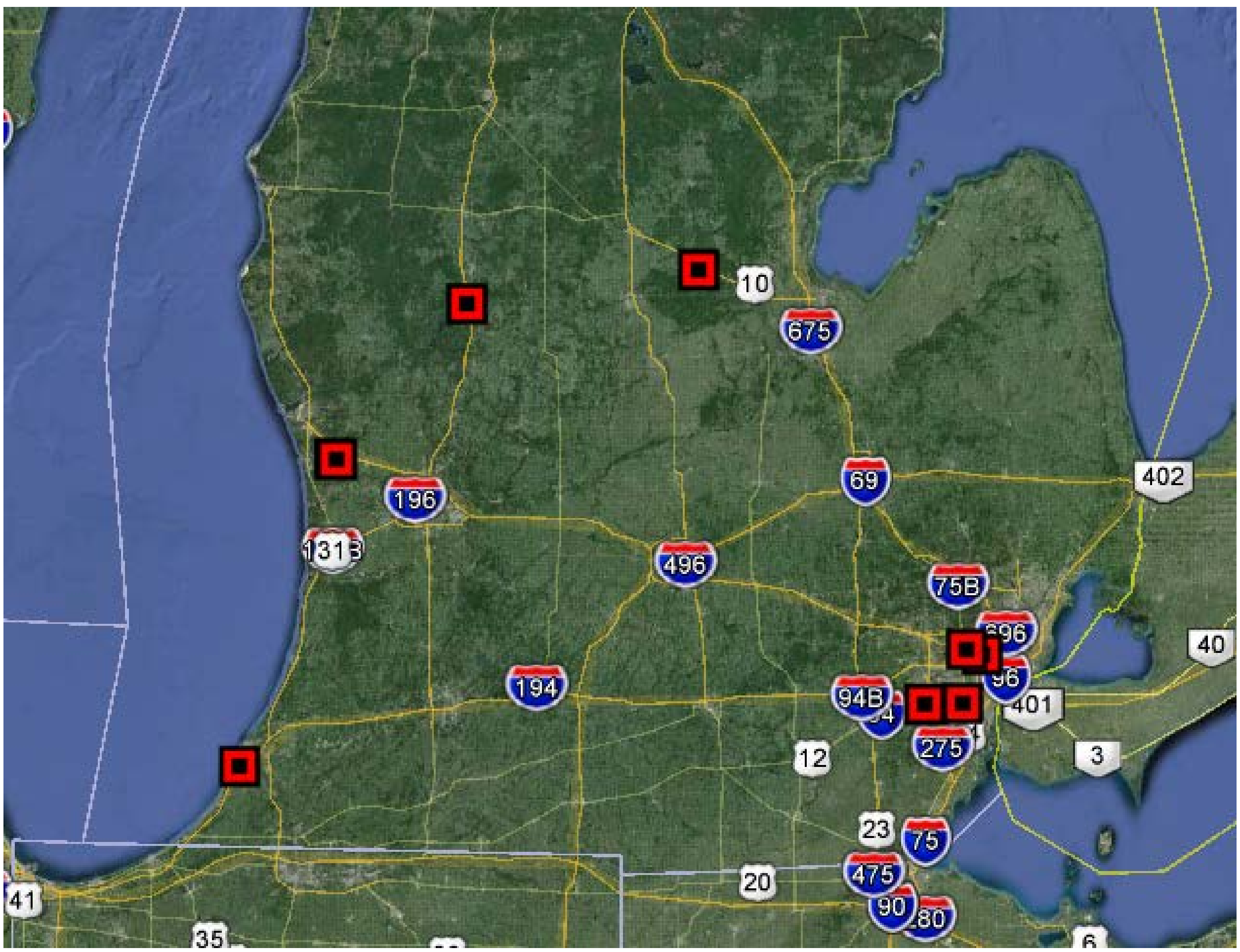

Figure 16. Work Zone Map

Data Collection

These eight freeways resulted in a total of 14 unique work zones (i.e., there was work occurring in both directions at 6 of the 8 sites). Both urban and rural work zones were included in the roadway sample and a variety of work zone conditions were observed across the study locations, including single lane closures with and without crossovers, lane shifts, and shoulder closures as shown in Table 12.

Table 12. Work Zone Summary Table

Date	Roadway	Location Type	Region	Boundaries	Length (EB/WB, NB/SB) (mi)	Number of Total/Open Lanes	Closure Type
8/28/2013	I-94	Freeway	Metro	Monroe to Beech Daly	2.13/2.19	3/2	Lane Closure (EB & WB)
9/17/2013	I-275	Freeway	Metro	Michigan to Ecorse	1.87/1.55	3/2	Lane Closure (NB & SB)
9/24/2013	I-96	Freeway	Grand	Apple Dr to 112th Street	2.74/2.09	2/1	Lane Closure (EB) & Lane Closure/Traffic Shift (WB)
9/26/2013	I-94	Freeway	Southwest	Niles to John Beers Rd	1.65/2.51	3/2	Lane Closure (EB & WB)
10/1/2013	US-131	Freeway	Grand	6 Mile to 13 Mile	0.26/8.57	2/1	Lane Closure (SB) & Traffic Shift (NB)
10/9/2013	US-10	Freeway	Bay	Meridian to Loomis	10.81/10.45	2/1	Lane Closure (EB & WB)
10/16/2013	M-10	Freeway	Metro	6 Mile to 7 Mile	1.14	3/3	Shoulder Closure (NB)
11/7/2013	M-10	Freeway	Metro	6 Mile to 7 Mile	1.14	3/2	Lane Closure (NB)
10/23/2013	M-104	Non-Freeway	Grand	112th to 130th	1.24/2.21	2/1	Total Closure/Detour (EB) & Lane Closure (WB)
11/6/2013	M-102	Non-Freeway	Metro	M-39 to US-24	4.40/3.98	4/2	Lane Closure/Traffic Shift (EB) & Lane Closure (WB)

For the purposes of this study, two types of field data were obtained. Traffic volume data were collected using high-definition video cameras, which were located near the end of each work zone. The cameras were typically targeted to capture traffic exiting the work zone. The cameras were usually placed on overpasses near each end of the work zone or on telescoping aluminum poles fastened to road signs located on the side of the highway or median of a divided highway. When setting up and removing the cameras, the date and time were recorded so that the volume counts could be matched on the basis of time to travel time data that were collected concurrently. The cameras were set up throughout both the AM and PM peak periods, as well as for a short period before and after.

The traffic volume data were linked with travel time information in order to assess the speed-flow relationship at these work zones locations. Travel time runs were conducted, with the first runs generally occurring prior to the peak period and continuing through the peak period until traffic had dissipated. Each run was performed using the floating car method, during which the driver attempted to travel at prevailing traffic speeds, changing lanes when necessary. Between 10 and 20 travel time runs were typically performed at each location during each data collection period.

The travel time was typically computed from the start of the taper to the end of the work zone. For locations where a queue was present upstream of the taper, the travel time was initiated upon joining the back of the queue. The distance corresponding to the travel time was also recorded for each pass. Bi-directional work zones were present at most locations, allowing for data to be recorded for round-trip loops through both work zones.

Work Zone Travel Speeds

The travel time and corresponding traffic volume data were extracted from a manual review of the videos upon returning to the office. The travel time and distance information was utilized to compute the average travel speed for each pass. The traffic volume counts were extracted for the period corresponding to each travel time run, from which the equivalent hourly volume per lane was computed for each pass. Data were ultimately extracted for a total of 284 travel time runs. A scatterplot depicting the average work zone travel speed versus equivalent hourly volume per lane is displayed in Figure 17. These data show a negative correlation between average travel speed and equivalent hourly volume. Substantial drops in speed were observed when traffic volumes increased above approximately 1,700 vehicles per hour per lane. This is an intuitive result as a flow rate of 1,700 vehicles per hour per lane corresponds to Level of Service D per the Highway Capacity Manual.

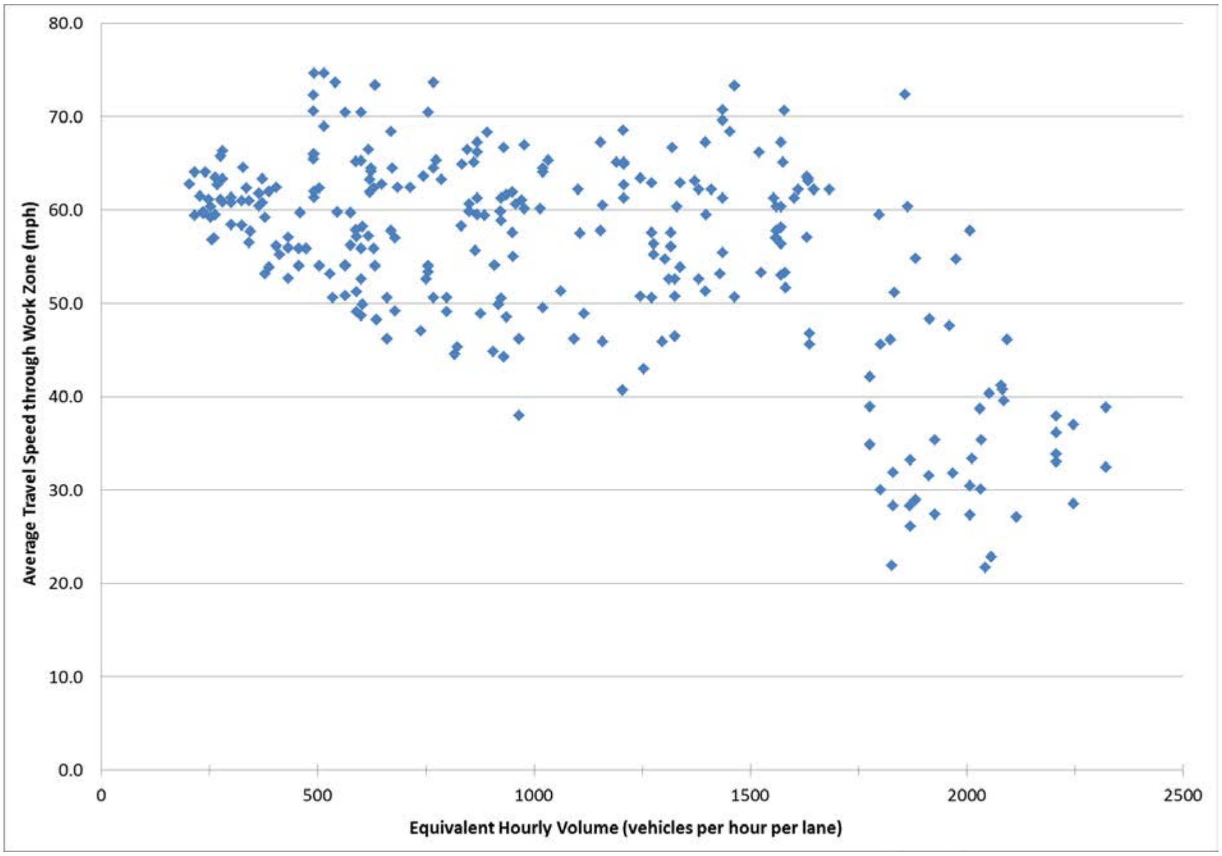

Figure 17. Average Work Zone Travel Speed vs. Equivalent Hourly Volume per Lane

Figure 18 presents these same data, aggregated by work zone location. These data clearly show that traffic flow and work zone mobility are strongly influenced by specific work zone characteristics. Figures 19-21 present data for select sites in further detail. Figure 19 provides details from a work zone on the John Lodge Freeway (M-10) in metro Detroit. These data encompass two studies at this location, one conducted during a shoulder closure and another during a lane closure. Interestingly, speeds are not significantly different between the shoulder and lane closure cases, though greater variability in speeds is observed for the lane closure. Ultimately, the site volume proves to be the strongest determinant of speed. Figure 20 provides an example from I-275, which is also located in the Metro region, demonstrating both congested and uncongested flow regimes in both the northbound and southbound directions. Figure 21 shows an atypical trend for I-96 near Grand Rapids, where the westbound traffic stream is exhibiting markedly lower speeds than eastbound traffic, perhaps due to the unique geometry at this site.

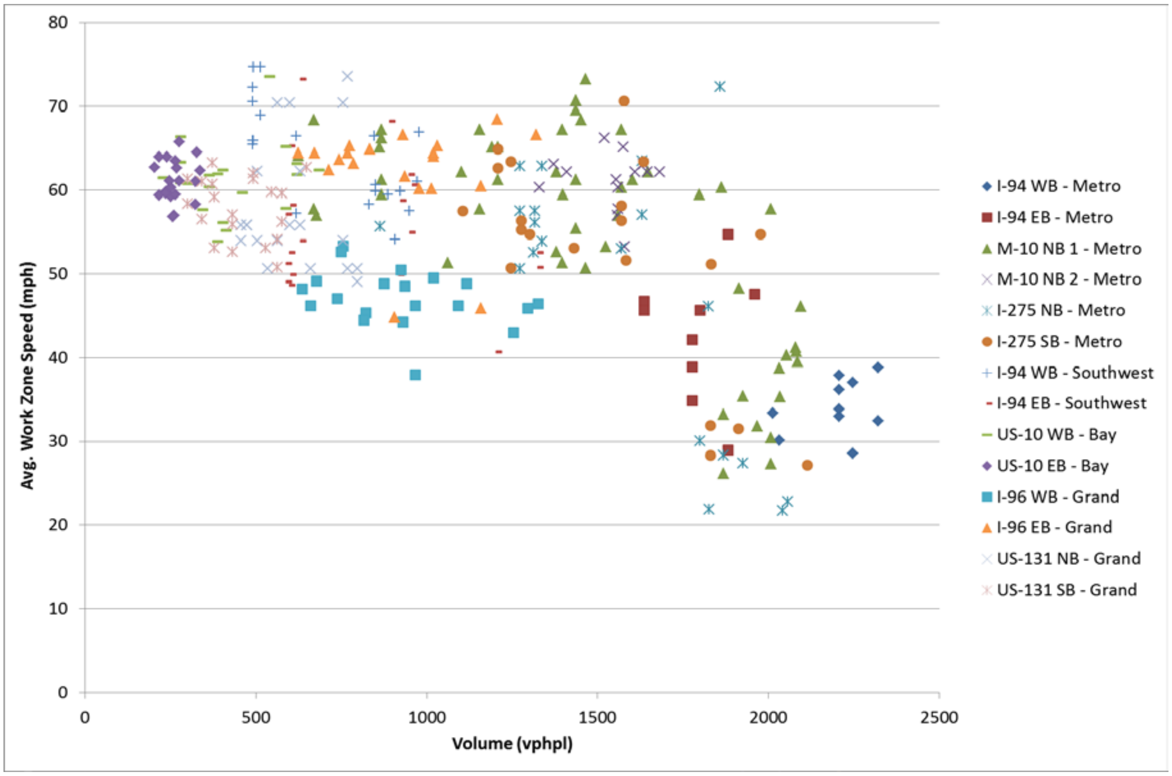

Figure 18. Combined Work Zone Speed-Flow Curve

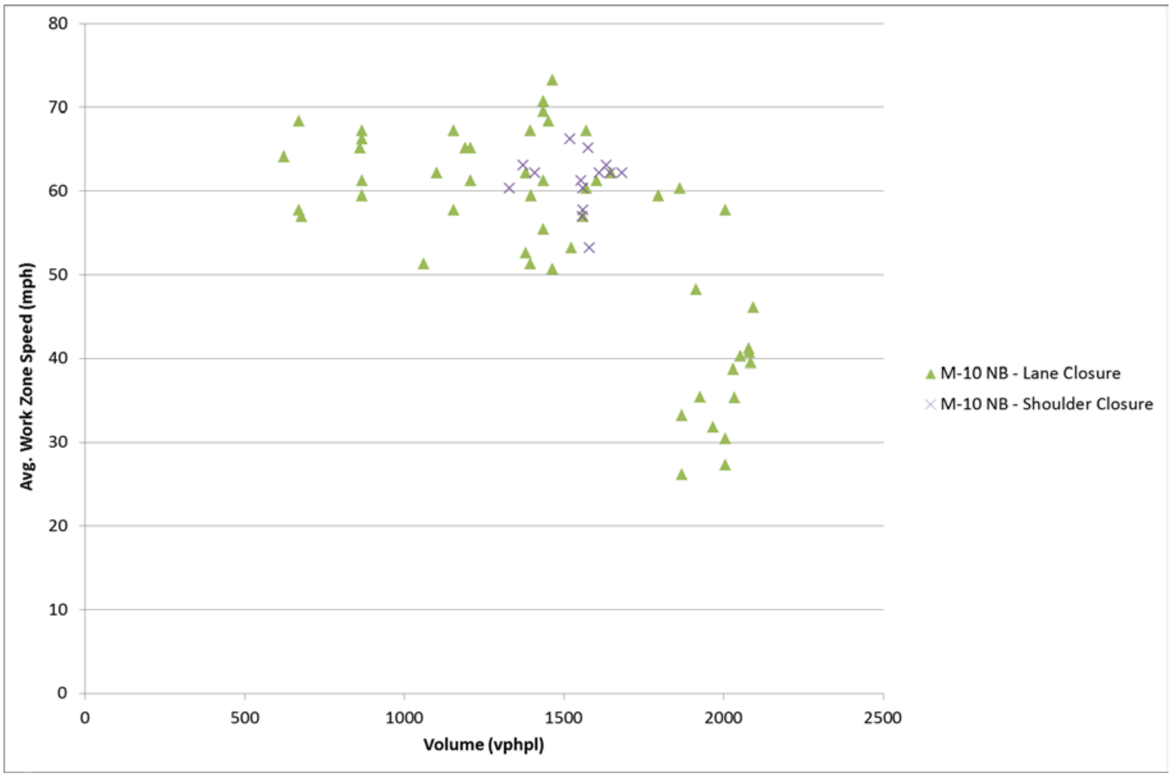

Figure 19. Work Zone on M-10 from 6 Mile Road to 7 Mile Road

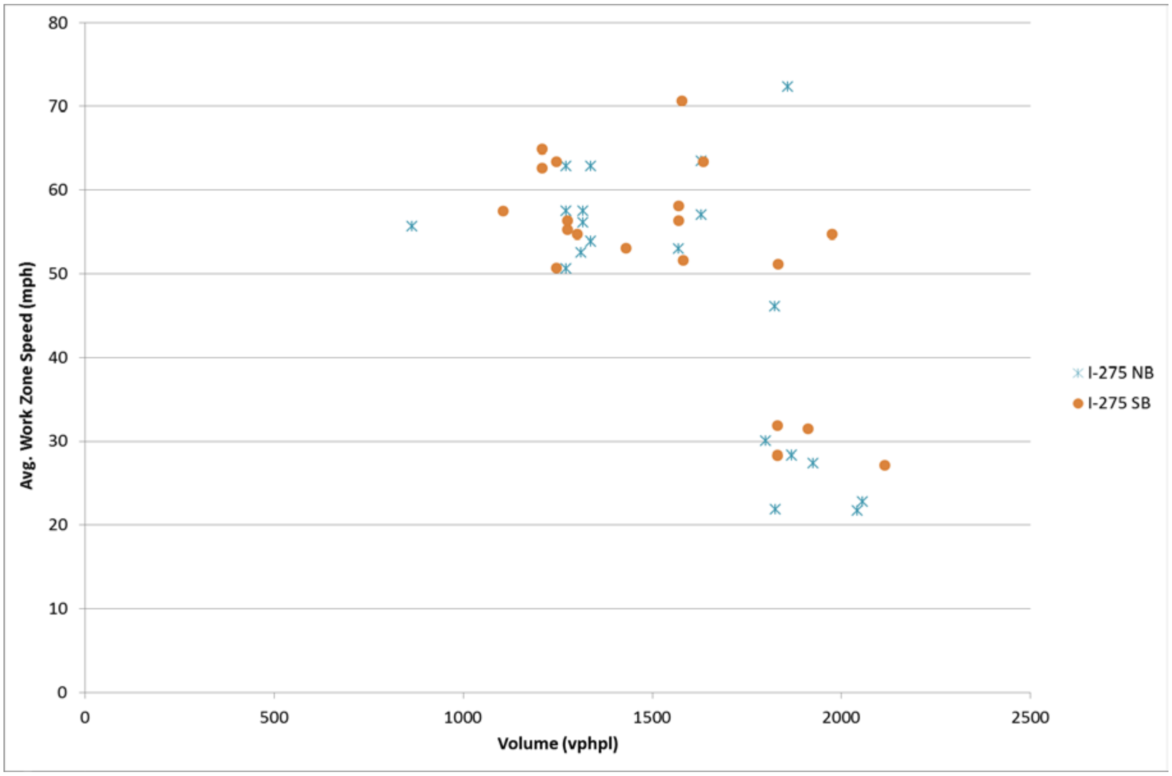

Figure 20. Work Zone on I-275 from Michigan Avenue to Ecorse Road

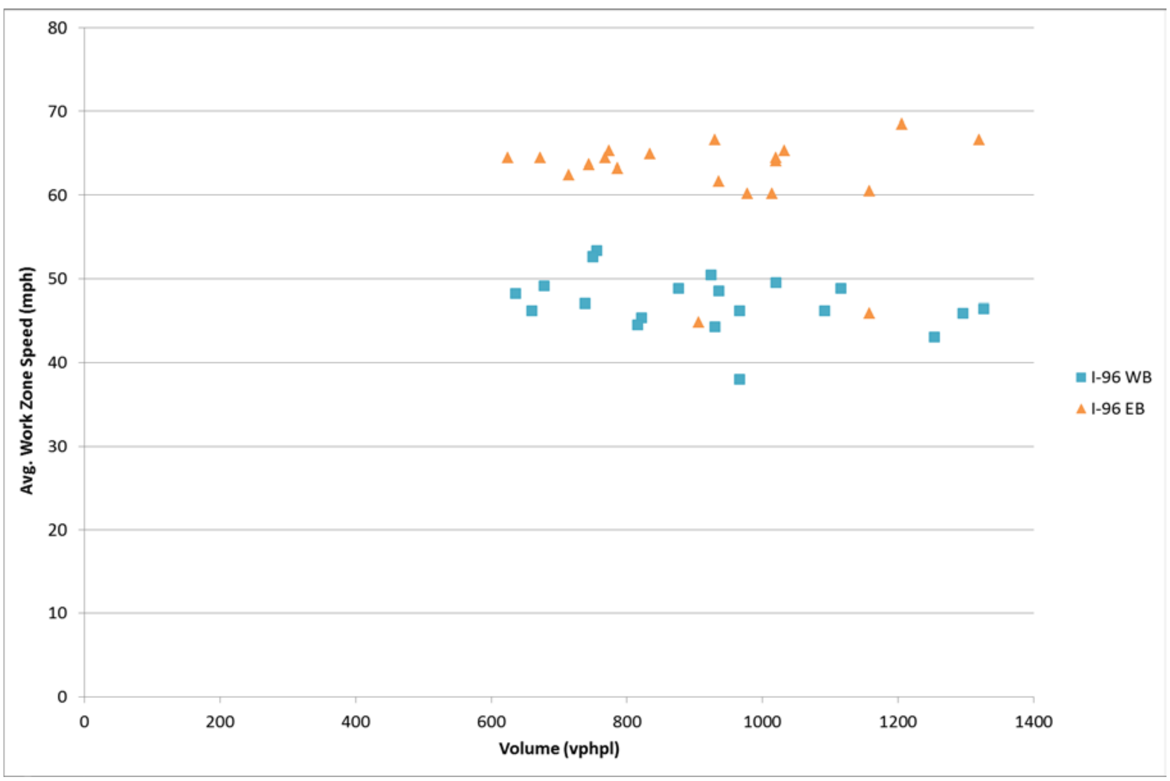

Figure 21. Work Zone on I-96 from Apple Drive to 112th Street

Work Zone Delay

The average travel speeds were converted to work zone delay prior to further analysis. The first step in determining work zone delay was to estimate average travel speeds expected during normal operating conditions. These estimates were obtained using freeway speed prediction models recently developed by the research team for another MDOT research project from data collected at freeway locations in Michigan, Indiana, and Ohio. Separate normal operating speed estimates were generated for cars and trucks as follows:

- Freeway with posted speed limits of 70 mph for cars and 60 mph for trucks:
    - Cars = 73.5 mph
    - Trucks = 62.0 mph
- Freeway with posted speed limits of 55 mph for all vehicles:
    - Cars = 65.6 mph
    - Trucks = 58.4 mph

From there, average travel times for normal operating conditions were computed by dividing the length of each work zone travel time run by the estimated normal average travel speed. The work zone delay was computed for each travel time run based on the difference between the observed work zone travel time and the travel time expected during normal freeway operating conditions with no work zone present. A delay of zero was assigned to cases where the work zone travel time was less than the assumed travel time during normal operating conditions. The average delay values are listed on a site-by-site basis along with other relevant work zone characteristics in Table 13.

Table 13. Work Zone Delay Results by Site

Location	Direction	Location Type	Work Zone Type	Mean Work Zone Length (mi.)	Mean Speed (mph)	Mean Equiv. Hourly Volume per Lane (vphpl)	Mean Delay Cars (min)	Mean Delay Trucks (min)
I-275 Michigan to Ecorse	NB	Suburban	Single Lane Closure	1.87	47.7	1567	1.53	1.27
	SB	Suburban	Single Lane Closure	1.55	52.2	1536	0.88	0.66
I-96/M-104 Apple Dr. to 112th St	WB	Rural	Single Lane Closure w/Crossover	2.09	47.1	928	0.98	0.66
	EB	Rural	Lane Shift	2.74	62.1	930	0.45	0.11
I-94 @ Cleveland	WB	Rural	Single Lane Closure	2.51	64.3	710	0.31	0.06
	EB	Rural	Single Lane Closure	1.65	56.0	821	0.45	0.23
US-10 @ Midland	WB	Rural	Single Lane Closure w/Crossover	10.45	61.3	427	1.74	0.32
	EB	Rural	Single Lane Closure	10.81	61.1	264	1.81	0.27
M-10 6 to 7 Mile	NB	Urban	Single Lane Closure	1.44	54.8	1476	0.58	0.47
M-10 6 to 7 Mile	NB	Urban	Shoulder Closure	1.14	61.2	1542	0.07	0.01
I-94 Monroe to Beech Daly	WB	Suburban	Single Lane Closure	2.19	34.1	2200	2.10	1.77
	EB	Suburban	Single Lane Closure	2.13	42.8	1792	1.35	1.02
US-131 6 to 13 Mile	NB	Rural	Lane Shift	0.45	57.8	615	0.11	0.05
	SB	Rural	Single Lane Closure	8.37	58.0	453	1.87	0.61

To ascertain differences in operations between different types of work zones, a linear regression model was developed for work zone delay. Several factors related to the characteristics of the work zone were entered into the model, including equivalent hourly volume (per lane), work zone length (including queue, where present), presence of a lane closure, presence of a crossover, and the number of lanes available within the work zone. The model results are displayed in Table 14.

Table 14. Linear Regression Results for Freeway Work Zone Delay

Coefficient	Beta	Std. Error	t-statistic	p-value
Constant	-48.275	25.070	-1.926	0.055
Hourly Volume per Lane (vphpl)	0.062	0.007	9.311	<0.001
Work Zone Affected Length (mi.)	14.225	1.266	11.239	<0.001
Lane Closure (0=No, 1=Yes)	-5.286	8.596	-.615	0.539
Crossover (0=No, 1=Yes)	1.744	14.073	.124	0.901
Number of Available Lanes (1, 2 or 3)	-3.554	11.274	-.315	0.753

$R^2 = 0.44$, $F = 42.9$

As expected, the linear regression results show positive correlation between work zone delay and both the equivalent hourly volume per lane and the length of the work zone. Simply put, work zone delay increases with increasing lane volumes and the overall length of the work zone. Interestingly, the work zone configuration (i.e., lane closure, lane closure with crossover, no lane closure) was not found to significantly impact delay. Similarly, work zone delay was also not found to be impacted by the number of lanes available within the work zone (1, 2 or 3). This finding does not suggest that the number of lanes does not impact work zone capacity due to the fact that that the traffic volume data were normalized into hourly lane volumes for modeling purposes. It simply suggests that the additional maneuverability afforded by additional lanes does not impact delay when all other variables (including volume) are held constant. It should be noted that the number of work zones observed was limited as data collection began late in the construction season. Further data collection is recommended to more closely examine these trends.

To account for the relationship between work zone delay and work zone length, the delay values were normalized based on the length of each travel time run, resulting in work zone delay in terms of minutes per mile. These normalized delay estimates for passenger vehicles and trucks are displayed in Figure 22.

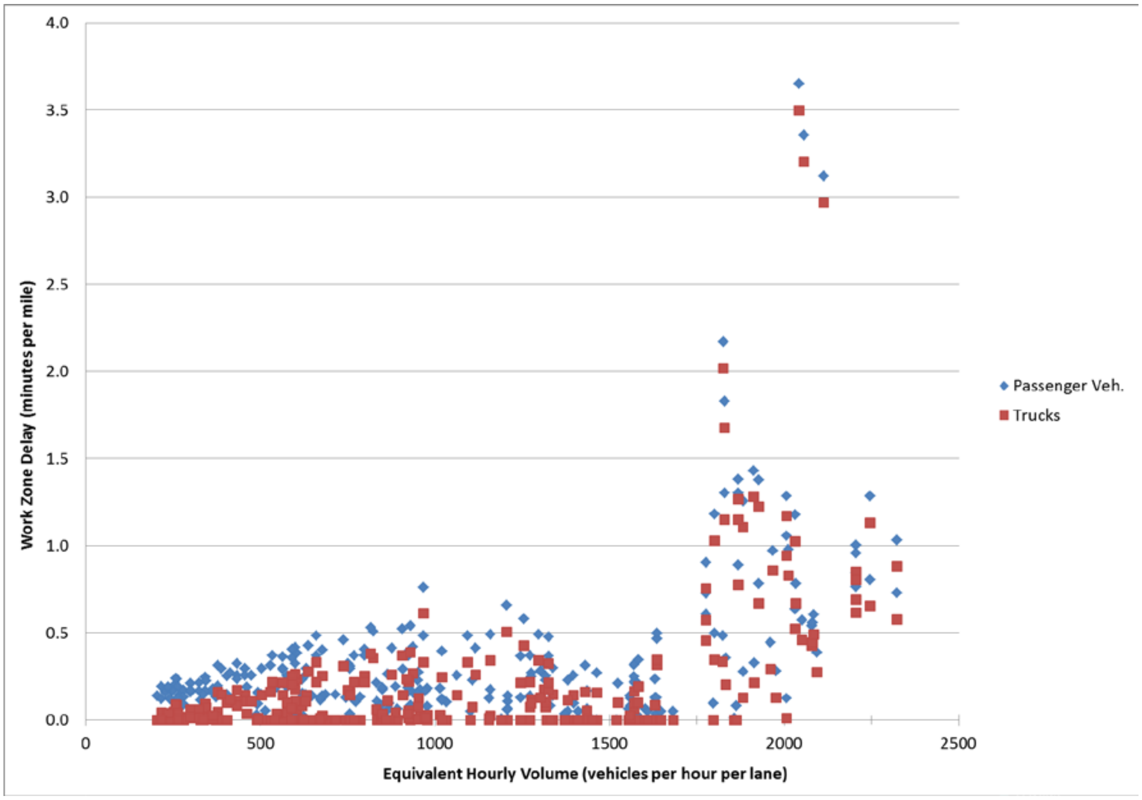

Figure 22. Normalized Work Zone Delay vs. Equivalent Hourly Volume per Lane

As expected, Figure 22 displays results that are similar to those displayed in Figures 17-18, which relate work zone speeds to volumes. A positive correlation between work zone delay and equivalent hourly volume was observed, with considerable increases in delay observed for sites with equivalent hourly traffic volumes between approximately 1,700 vehicles per hour per lane (vphpl) and 2,322 vphpl, which was the maximum volume observed. However, it is interesting to note that within each of these two volume categories (<1,700 vphpl vs. ≥ 1,700 vphpl), a subsequent regression analysis showed no correlation between work zone delay and hourly volume. Consequently, the normalized delay data were split into two discrete categories based on the 1,700 threshold, with the descriptive statistics displayed in Table 15.

Table 15. Work Zone Speed and Delay by Volume Category

	Hourly Volume (vphpl)		Speed (mph)		Average Delay – Cars (min/mile)		Average Delay - Trucks (min/mile)	
Volume Category	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Volume < 1,700 vphpl	868	1682	58.9	74.7	0.20	0.76	0.08	0.61
Volume ≥ 1,700 vphpl	1984	2322	38.0	72.4	0.98	3.65	0.85	3.50

Table 15 shows that for locations with traffic volumes exceeding 1,700 vphpl, the average delay for cars is 0.20 minutes per mile, which is five times greater than locations with traffic volumes less than 1,700 vphpl. This effect is even greater for trucks, as the average delay is 10 times greater for trucks at locations with traffic volumes greater than 1,700 vphpl. Additional investigation into the effects of specific work zone configurations/closure types on work zone delay should be performed, particularly for sites with hourly volumes exceeding 1,700 vphpl. In particular, several sites with volumes exceeding 2,200 vphpl should be included to establish the maximum work zone capacity.

Maximum Work Zone Lengths to Achieve Acceptable Delays

The traveler surveys performed as a part of this research provided evidence that the median acceptable delay during the daily commute is approximately 10 minutes. As work zone delay is a function of work zone length, it was important to estimate the approximate work zone length that would result in expected delays of 10 minutes of delay per vehicle. The acceptable work zone length threshold was determined by extrapolating the normalized work zone delays to 10 minutes.

For locations with volumes less than 1,700, the mean delay of 0.20 minutes per mile would require a 50 mile work zone to accumulate 10 minutes of delay. In practical terms, this is an unrealistic work zone length and it may be concluded that such low volumes will generally not produce unacceptable delays. Even when using the maximum observed delay, the maximum acceptable work zone exceeds 13 miles, which still exceeds the typical length of work zone in Michigan. However, for such lengthy work zones, exit/entrance ramps and other features will be introduced that may increase interference and subsequently increase delays. Thus, although these preliminary results would suggest that delays for work zones with traffic volumes lower than 1,700 vphpl will likely not exceed 10 minutes, further research is needed to determine impacts associated with interchanges and other roadway features, particularly for longer work zones where volumes are less than 1,700 vphpl.

However, for work zones with traffic volumes exceeding 1,700 vphpl, a work zone length of slightly greater than 10 miles is expected to produce passenger vehicle delays of 10 minutes, on average. The maximum acceptable work zone lengths in the higher volume category are approximately 10 to 15 percent greater for trucks. When considering the maximum observed delay, the maximum acceptable work zone length decreases to slightly greater than 2.7 miles. These values are within the range of typical work zone lengths observed on Michigan freeways. Thus, it can be reasonably concluded that work zones with traffic volumes greater than 1,700 vphpl may exceed acceptable delays if the work zone exceeds approximately 2.7 miles in length. It is recommended that additional field data be collected for a diverse set of higher volume work zone locations to provide a better understanding of the conditions that may potentially affect work zone delay.

Economic Cost of Work Zone Delays

Delays experienced by motorists when traveling through work zones may be equated to an economic cost. It is first necessary to determine average hourly value-of-time estimates for typical users of the Michigan highway network. MDOT provides separate value-of-time unit estimates for passenger vehicles and commercial trucks for use with the Construction Congestion Cost (CO3) estimation software [*38*]. The MDOT value-of-time unit estimates are based on the FHWA publication *Life-Cycle Cost Analysis in Pavement Design* [*39*] and are currently displayed in 2012 dollars. It was necessary to index these values to current conditions using a ratio of the August 2014 Consumer Price Index (CPI) to the 2013 annual CPI, as follows: 237.852 / 232.957 = 1.0210 [*40*]. These values are displayed in Table 16.

Table 16. Value-of-Time Unit Costs by Vehicle Type and Year

	User Costs (dollars per hour per vehicle)	
Vehicle Type	2013	August 2014*
Passenger Vehicle	$17.70	$18.07
Truck	$31.22	$31.88

*Assumes increase of 2.10 percent from 2013 based on CPI.

An economic analysis was performed considering passenger vehicles and heavy vehicles separately across a range of work zone durations and lengths. An average affected daily traffic volume of 40,000 vehicles per day with 10 percent trucks was assumed for all cases. The typical posted speed limit at the site was assumed to be 70 mph for cars and 60 mph for trucks. For practical purposes, it was assumed that 30 percent of the volume was traveling through the work zone during the peak periods, while the remaining 70 percent was traveling during off-peak periods. For purposes of this example, it was assumed that unit delays corresponding to the ≥1,700 vphpl category would apply to peak period volumes, while unit delays corresponding to the <1,700 vphpl category would apply to off-peak volumes. Based on those assumptions, the corresponding mean and maximum unit delay values displayed in Table 15 were utilized to calculate average delay per vehicle and total daily user delay costs separately for passenger vehicles and heavy trucks for each scenario with the results provided in Table 17.

Table 17. Estimated Work Zone Delay Costs for ADT = 40,000 vpd

Work Zone Length	Mean Truck Delay (min/veh)	Mean Truck Delay Cost per Day ($)	Max Truck Delay (min/veh)	Max Truck Delay Cost per Day ($)
3 miles	0.93	$1,977	4.43	$9,415
5 miles	1.56	$3,316	7.39	$15,706
10 miles	3.11	$6,610	14.78	$31,412
15 miles	4.66	$9,904	22.15	$47,076
Work Zone Length	Mean Passenger Vehicle Delay (min/veh)	Mean Passenger Veh. Delay Cost per Day ($)	Max Passenger Vehicle Delay (min/veh)	Max Passenger Veh. Delay Cost per Day ($)
3 miles	1.30	$14,095	4.88	$52,909
5 miles	2.17	$23,527	8.14	$88,254
10 miles	4.34	$47,054	16.27	$176,399
15 miles	6.51	$70,581	24.41	$264,653

Assumptions: ADT = 40,000 vpd (10% trucks); 30% peak period traffic; 70% off-peak period traffic; value-of-time unit cost assumptions: truck = $31.88 per vehicle-hour; passenger veh. = $18.07 per vehicle-hour;

Considering a maximum acceptable delay of 10 minutes per vehicle, it can be observed from Table 17 that under average conditions, work zones of up to 15 miles are not expected to experience unacceptable delays. However, it is possible under the maximum delay situation that a 10 mile long work zone will exceed 10 minutes of delay per vehicle for both passenger vehicles and commercial trucks.

CHAPTER 6
ANALYSES OF ARCHIVED RITIS DATA

To supplement travel time data that were collected in the field, this study also involved an examination of historical travel time data, which were available from the Regional Integration Transportation Information System (RITIS) maintained by the University of Maryland. The RITIS system includes a data archive, which includes Michigan-specific data that can be downloaded in raw format. The data archive allowed for travel time and speed data to be downloaded for small segments of freeways, which could then be compiled into larger sections that included entire work zones. The average speed over all of the segments included in each work zone could then be examined for any specified time period.

Comparison of RITIS and Field-Collected Data

The RITIS data is ultimately useful for several purposes. For the purposes of this project, the RITIS data were first compared to field data collected by Wayne State University during the field studies of work zone operations. As noted previously, these field data were collected via travel time runs through the work zones during peak periods. The comparison of RITIS to field data was important to ascertain whether RITIS could be used on a large-scale basis to assess work zone operations.

In order to utilize the RITIS data, the segments for which data were available had to be matched to the same segments that were observed during the field studies. One limitation that arose initially was due to the fact that the roadway segments as defined in RITIS typically break at freeway exits and do not necessarily coincide with work zone start or end points. Consequently, travel time and speed data were obtained between the segments that included the start and end points of the work zone.

Figure 23 provides one example comparison, which is between field observed (best fit polynomial regression of field-observed speed values) and RITIS speed data for southbound US-131 from 15 Mile Rd to Jefferson. Visual examination shows the RITIS data to very closely match the field observed speed data.

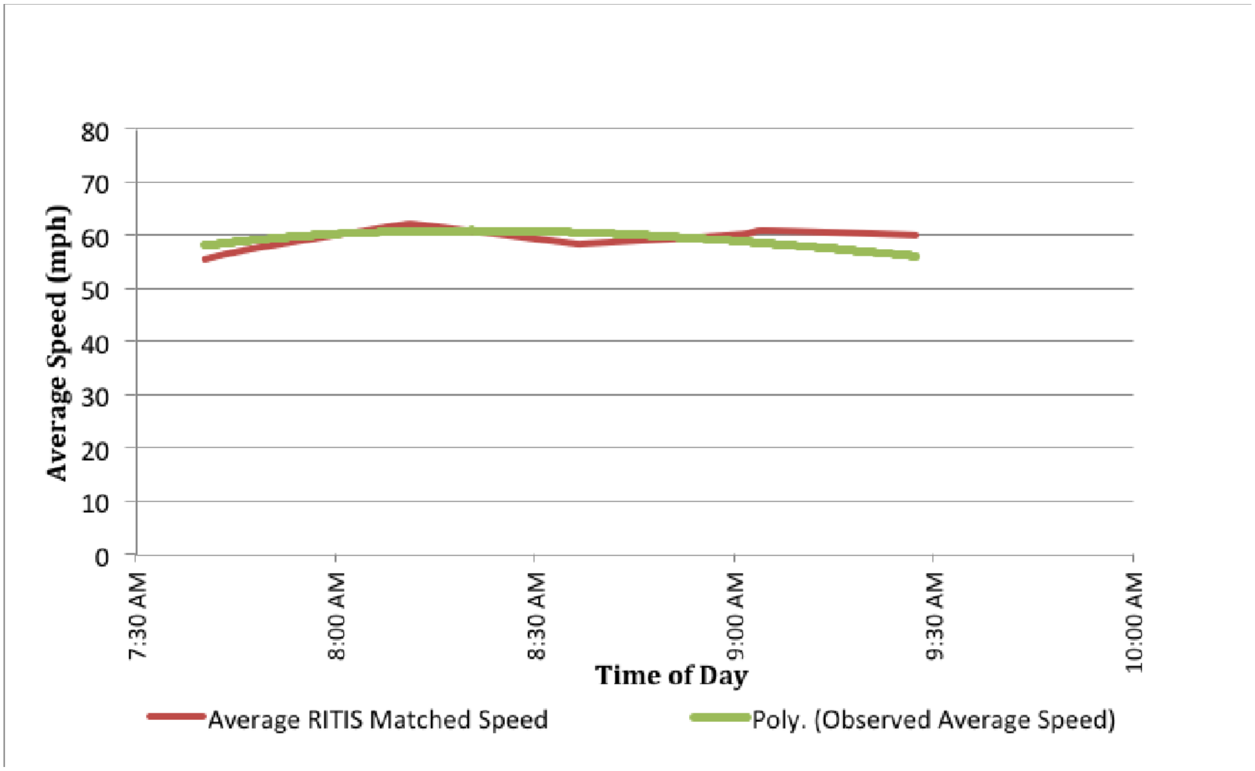

Figure 23a. AM Peak Period

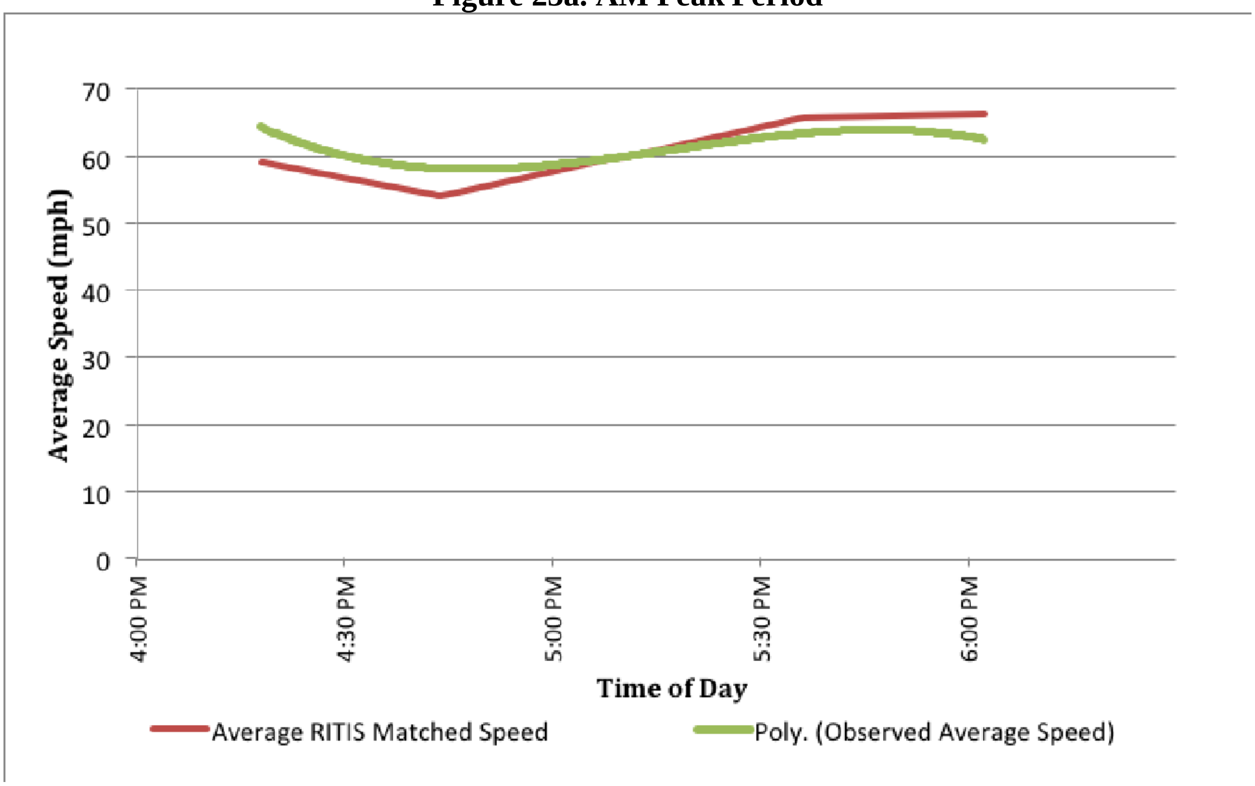

Figure 23b. PM Peak Period

Figure 23. Comparison of RITIS vs. Observed Speed, SB US-131 (15 Mile to Jefferson)

There is generally some degree of variability between the RITIS data, which are collected from probe vehicles, and the field data collected by the WSU vehicles. This is to be expected as the WSU data represent a series of individual runs while the RITIS data are aggregated over five-minute intervals. The RITIS data also include an overrepresentation of slower moving trucks, though sometimes the field-observed are higher and other times they are lower. However, the general trends (in terms of direction and relatively magnitude) in travel speeds are generally similar. Figures 24 and 25 provide additional examples comparing the WSU field-observed and RITIS archival data.

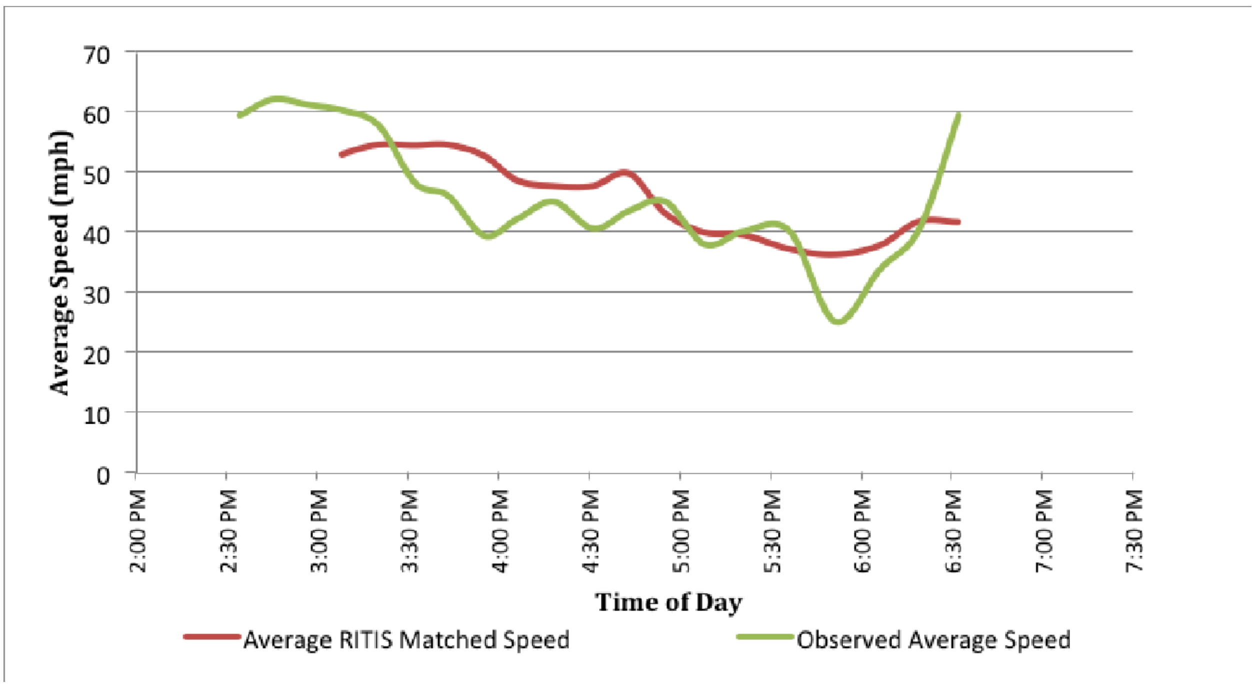

Figure 24. Comparison of RITIS vs. Observed Speed, NB M-10 (Linwood to Greenfield)

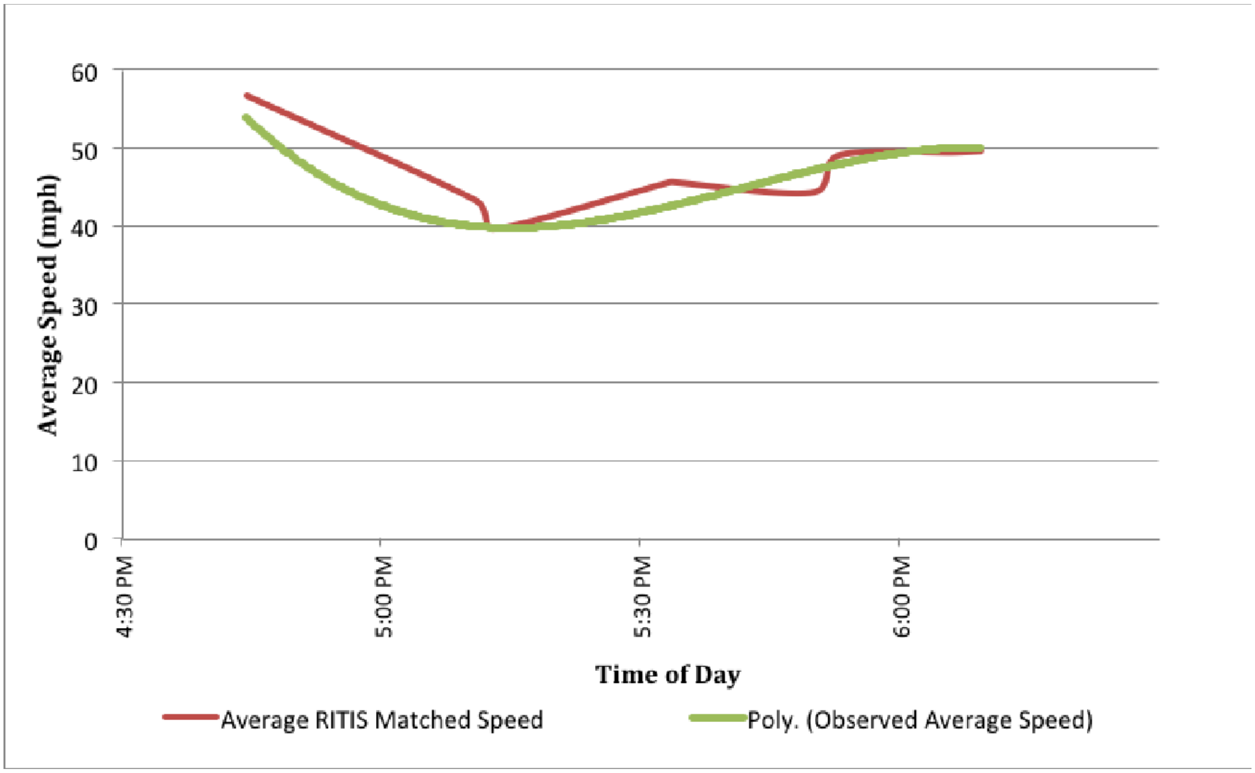

Figure 25a. Eastbound Direction

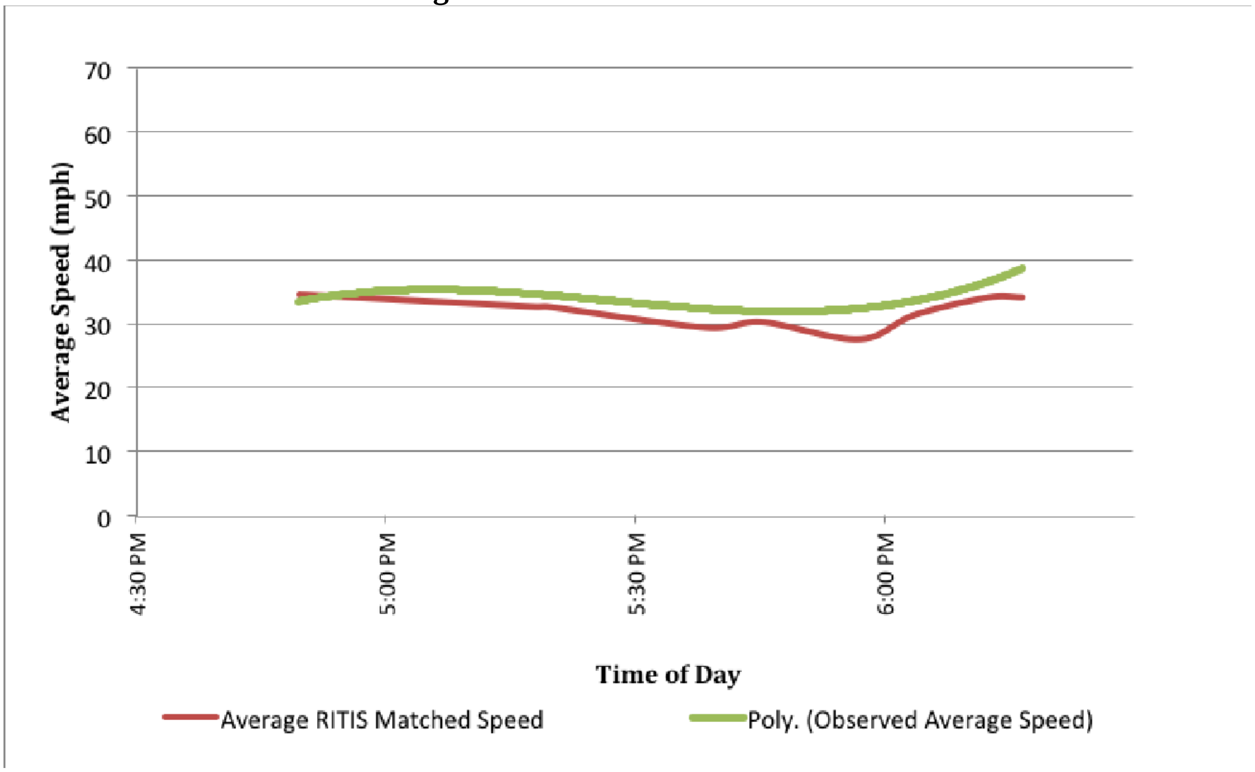

Figure 25b. Westbound Direction

Figure 25. Comparison of RITIS vs. Observed Speed, I-94 (Monroe to Beech Daly)

Comparison of RITIS Data for Work Zone and “Typical” Conditions

Given the consistency between the speed trends, an additional value of the RITIS data is that it can be utilized to compare travel speeds when work zones are in place to travel speeds under “typical” conditions when a work zone is not in place. In order to conduct such a comparison, travel time and speed data are aggregated for the work zone period and then compared to similar data for the same section when the work zone was not in place.

Average travel speeds were determined for each of the work zones examined as part of the field studies described previously. However, these speeds were calculated for the entire construction period (instead of just the days on which field data were collected). Specifically, data were obtained for each day in 2013 when a work zone was in place and these data were compared to the same data from 2012, excluding the winter months (December through March). Data were only collected for Monday through Thursday to capture typical weekday travel patterns.

Figures 26-28 provide examples comparisons of the speed profiles for the work zone and typical conditions. In nearly all instances, the speeds while work zones were in place exhibited significant differences from typical operations. Figure 26 shows a lower volume site, US-10 between Loomis Rd and Meridian Rd. While speeds are similar during off-peak periods, between the AM and PM peak, speeds are typically from 2 to 5 mph lower when the work zone is in place. However, magnitudes of this difference would ultimately have little impact on work zone mobility and road user costs as discussed in Chapter 5.

Larger differences are observed at the higher volume sites. For example, Figure 27 shows that I-275 from Ford Rd to Eureka Rd shows differences as large as 15 mph. This site exhibits significant delay during the AM and, particularly, during the higher-volume PM peak period. Figure 28 illustrates trends along I-94 from Middlebelt Rd to Pelham Rd. In contrast to the other sites, this location shows much larger delay during the AM peak in the eastbound direction and the PM peak in the westbound direction. This is reflective of the fact that this commuter route largely serves traffic entering the city (in the eastbound direction) during the AM peak and exiting the city during the PM peak.

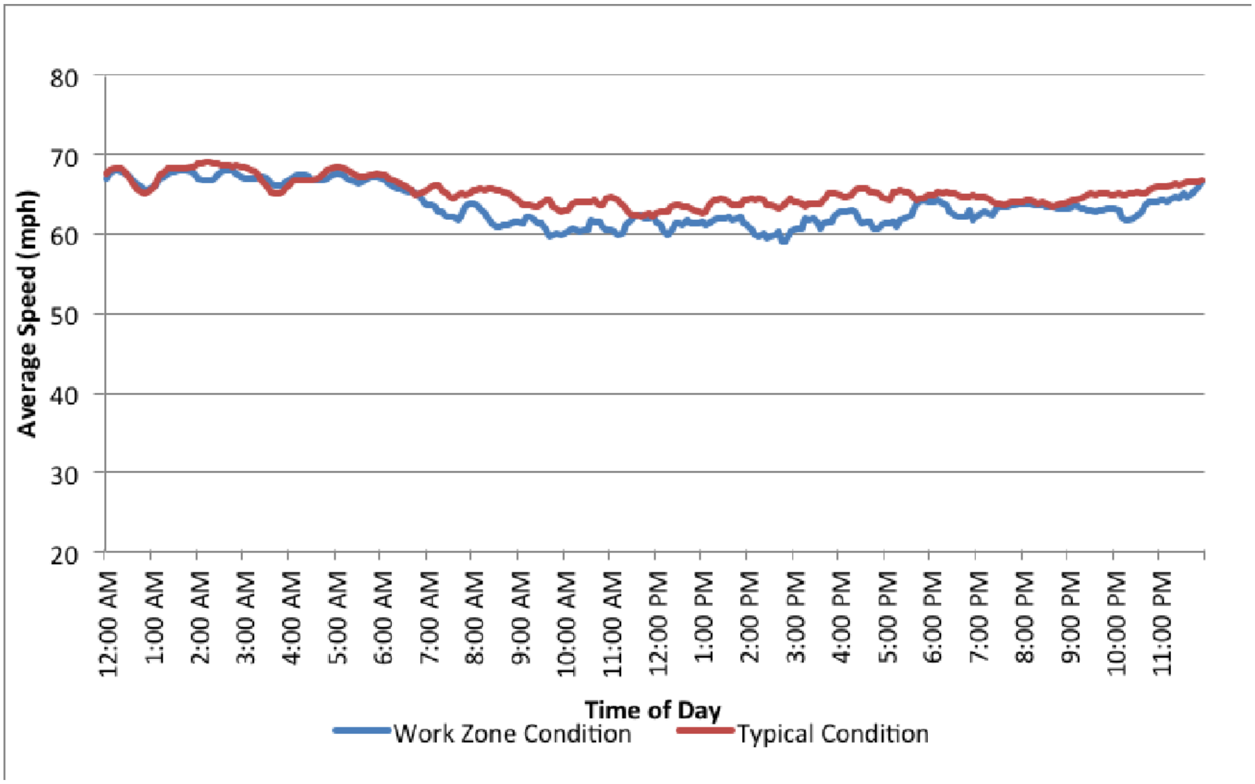

Figure 26a. Eastbound Direction

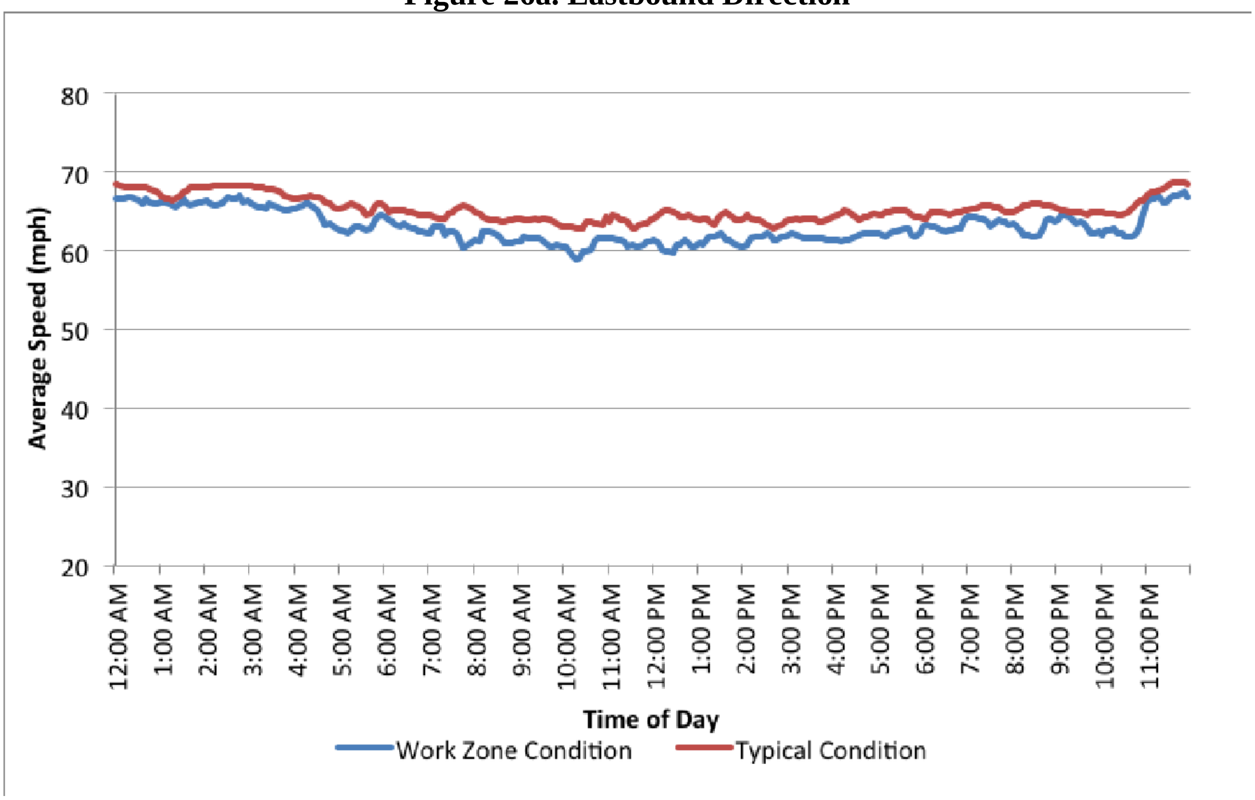

Figure 26b. Westbound Direction

Figure 26. Average Speed, US-10 From Loomis Rd to Meridian Rd

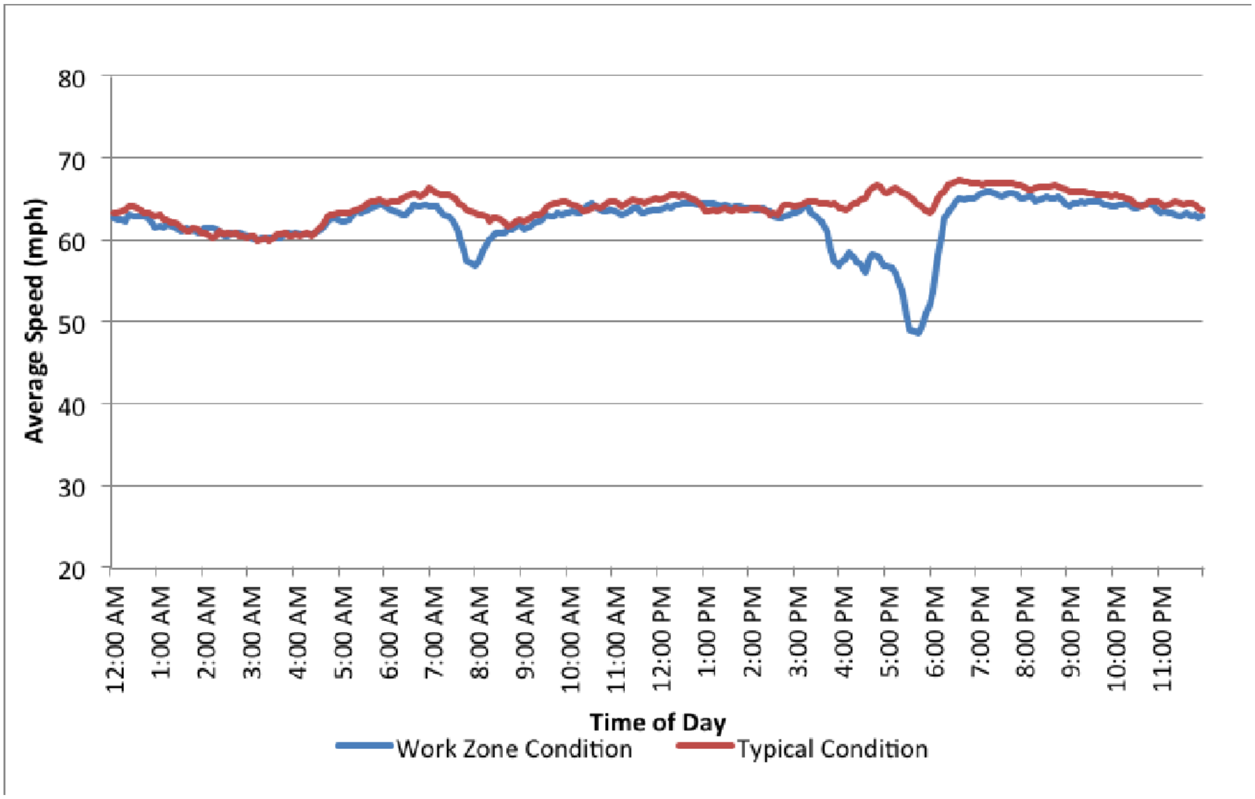

Figure 27a: Northbound Direction

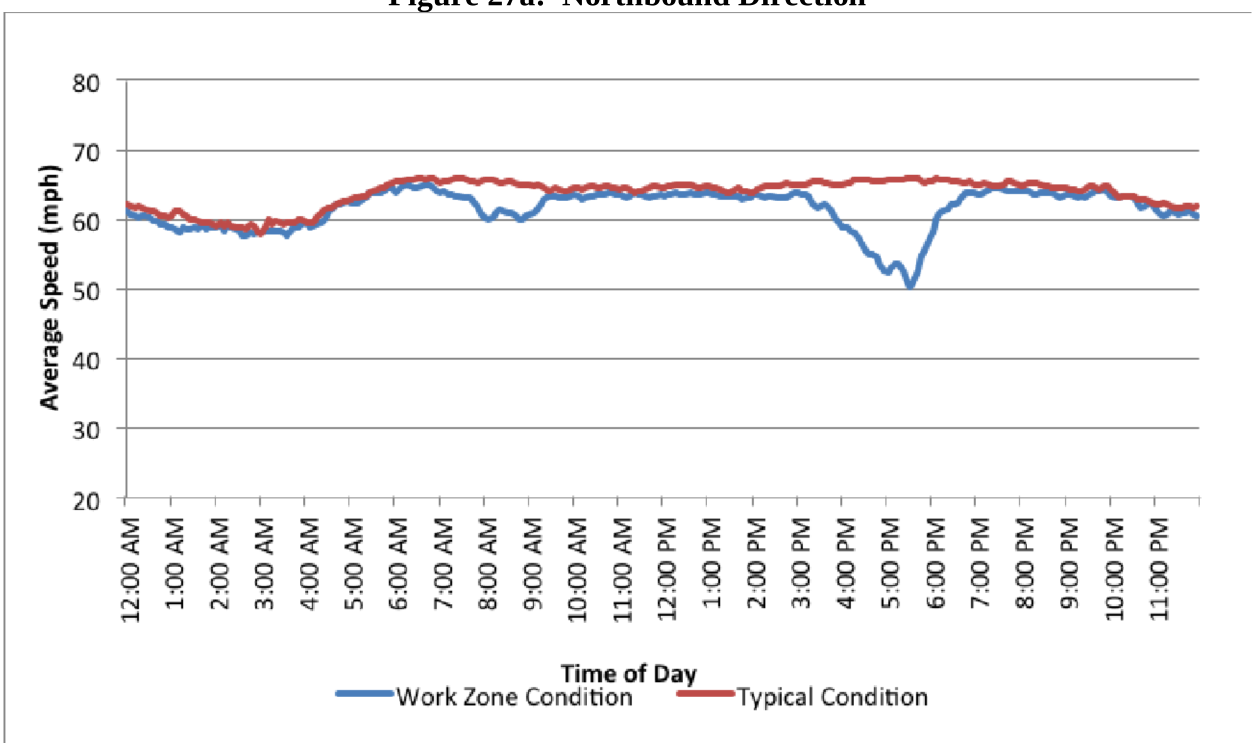

Figure 27b. Southbound Direction

Figure 27. Average Speed, I-275 from Ford Rd to Eureka Rd

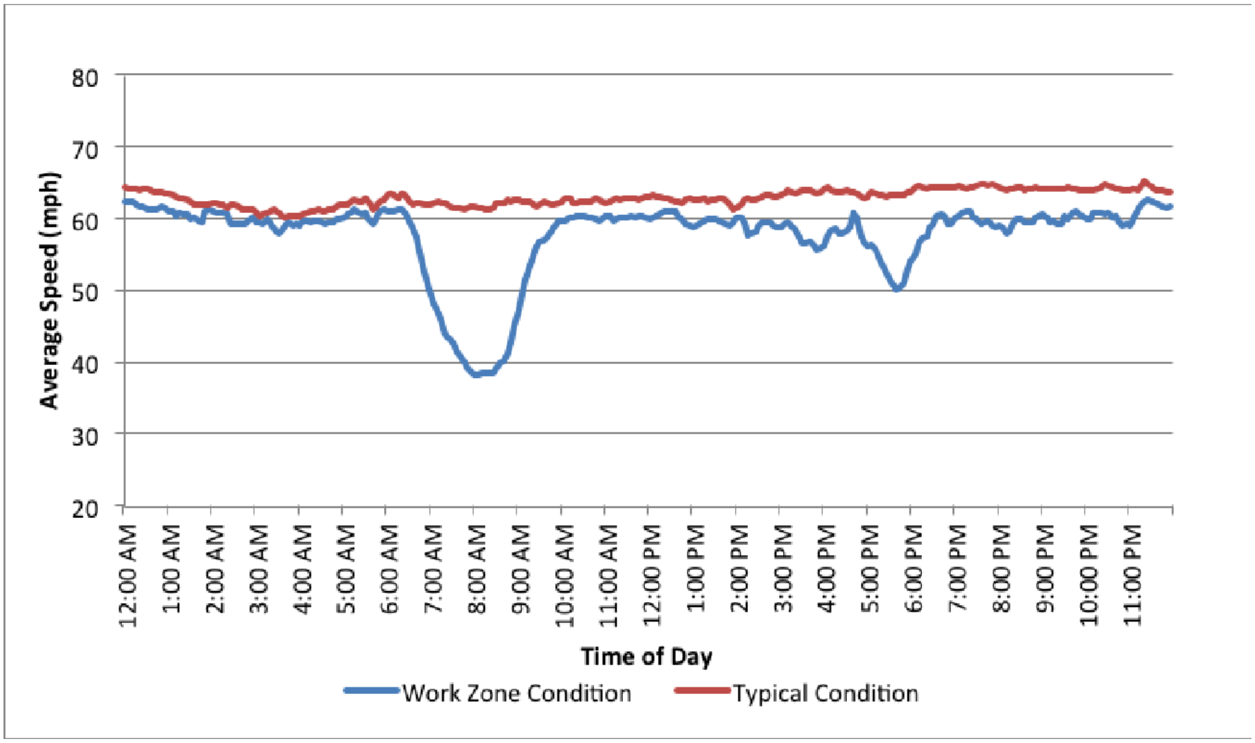

Figure 28a. Eastbound Direction

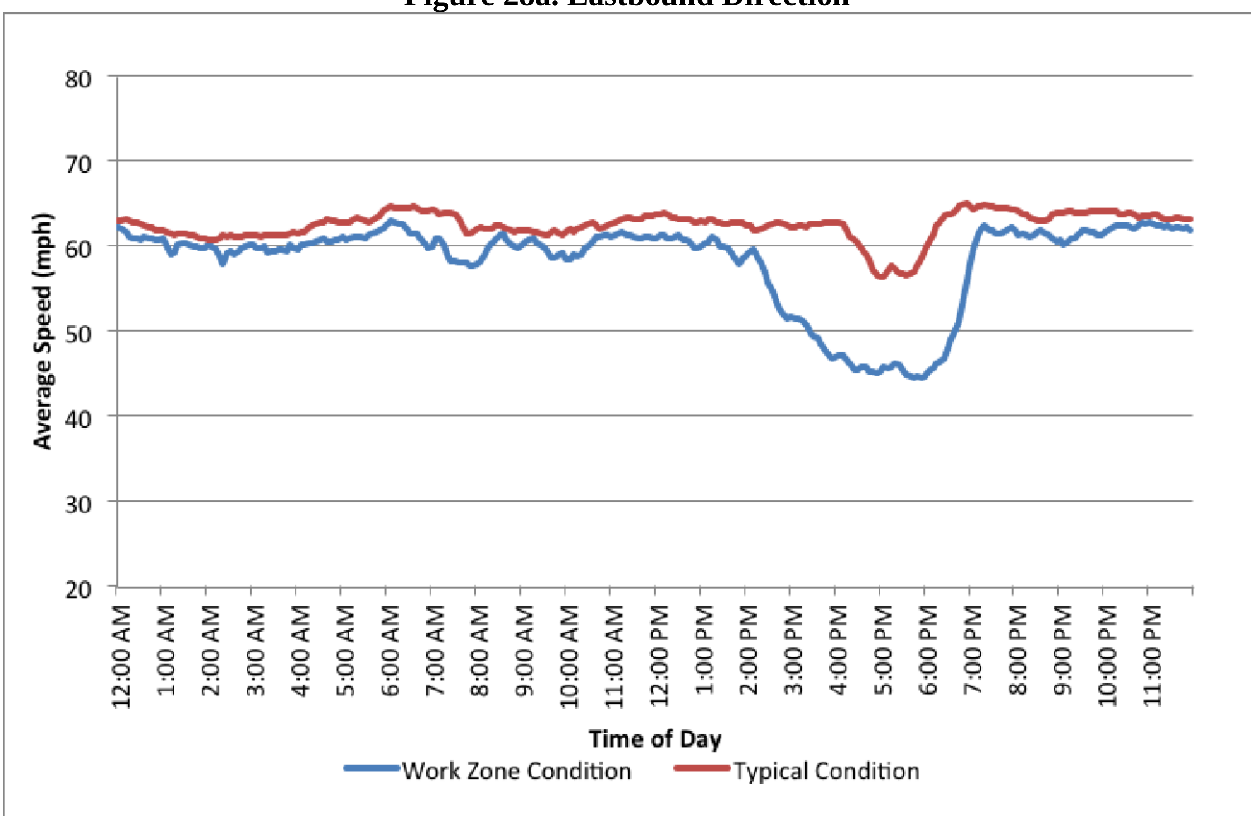

Figure 28b. Westbound Direction

Figure 28. Average Speed, I-94 from Middlebelt Rd to Pelham Rd

Ultimately, exploration of the RITIS data shows that the system is capable of documenting consistent trends in speeds and, as a result, delays as they relate to the presence of a work zone environment. In order to fully exploit the data, it would be very useful to obtain additional information on traffic volumes. This represents a promising avenue for further research.

Using RITIS Data to Examine Traffic Crashes

A final use of the RITIS data that was investigated as a part of this study was to examine travel speeds when a crash occurs. While it is well understood that traffic crashes have significant impacts on traveler delay due to disruptions in traffic flow, there has been less research focused on the mobility impacts of work zone crashes on delay.

Figures 29 and 30 provide a sample illustrating mobility impacts of crashes and how they vary between normal operating conditions. Figure 29 illustrates such data for typical conditions while Figure 30 provides similar data for when a work zone is in place. These data are drawn from a segment of northbound I-275, between Warren Road and Plymouth Road.

In Figure 29, a speed profile is provided for the typical (i.e., non-work zone) scenario over the period from April 22 to June 15, 2011. Speed data are provided separately for May 3, 2011, the date on which a crash occurred. This crash occurred at 8:10 AM on May 3rd and Figure 29 shows that while traffic speeds are generally lower during the peak periods, speeds were significantly lower during the period immediately following the crash. It is interesting to note that speeds also dropped in the opposite (southbound) direction at the time of the crash, which is consistent with prior work that has related this to drivers in the opposite direction being distracted by the post-crash clearing process.

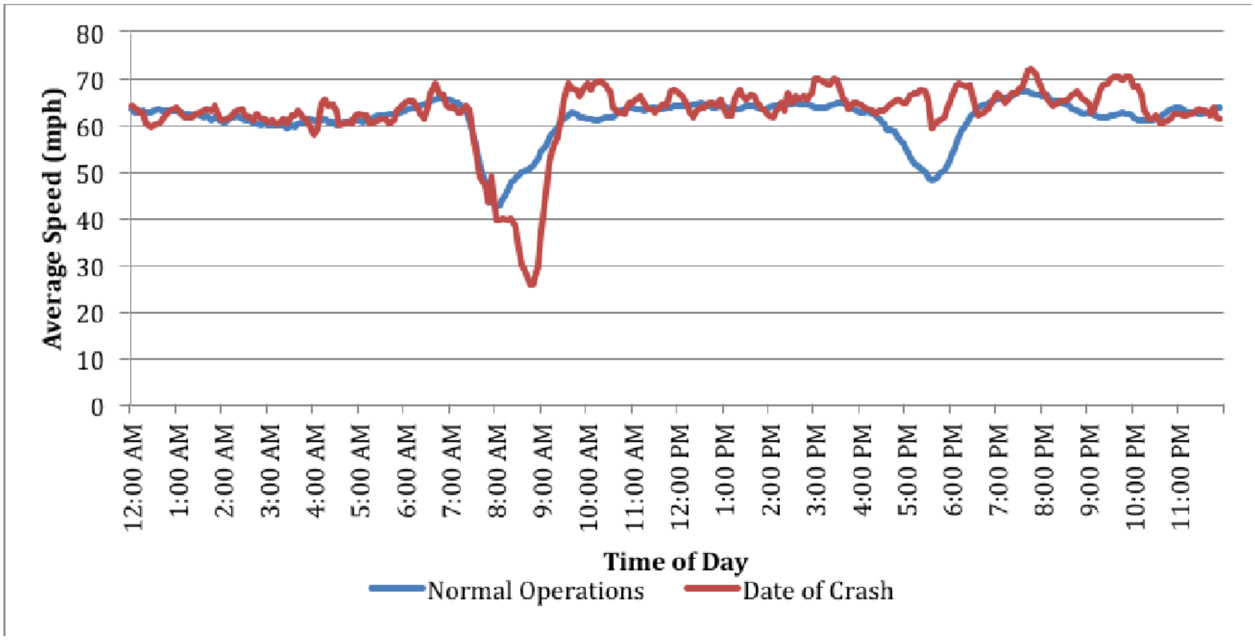

Figure 29a. Northbound (Crash) Direction

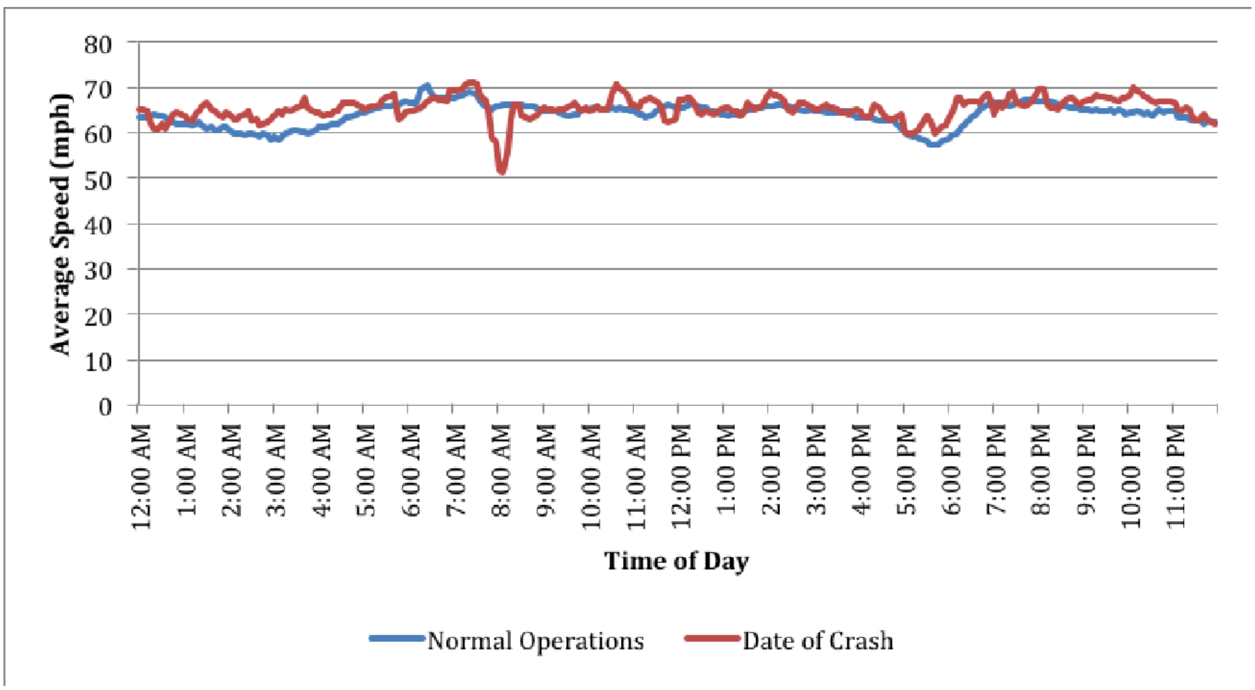

Figure 29a. Southbound (Opposite) Direction

Figure 29. Mobility Impacts of Traffic Crash During Typical Operations: I-275 from Warren Rd to Plymouth Rd

Figure 30 presents similar data for the same location when a work zone was in place. In general, the travel speeds are somewhat slower under the work zone conditions, with longer periods of sustained slower moving traffic during the peak periods in comparison to the normal operating conditions (as compared to Figure 29).

The work zone was in place at this location from April 22 to June 15 of 2012 and a crash was found to have occurred on April 23, 2012, at 5 PM. At this time, speeds declined sharply and were restored to pre-crash conditions by 6:30 PM. The opposite (i.e., southbound) direction also shows a slight decrease in in travel speeds from the time the crash occurred in the northbound direction. Interestingly, the most notable reductions from the prevailing work zone travel speeds occurred from roughly 7 AM to 1 PM, although it is unclear what factors may have contributed to these reduced speeds (no crashes were reported for this time period).

These figures illustrate how traffic operations may be impacted by the occurrence of a crash, as well as how these effects may be amplified when that crash occurs in a work zone. The effects are somewhat masked due to the erratic nature of travel speeds in work zones. It should also be noted that the RITIS speed profiles tend to vary widely when looking at only a single day of crash data. Given the random and rare nature of traffic crashes, further investigation of this issue would require extensive screening of work zone, RITIS, and police-reported crash databases.

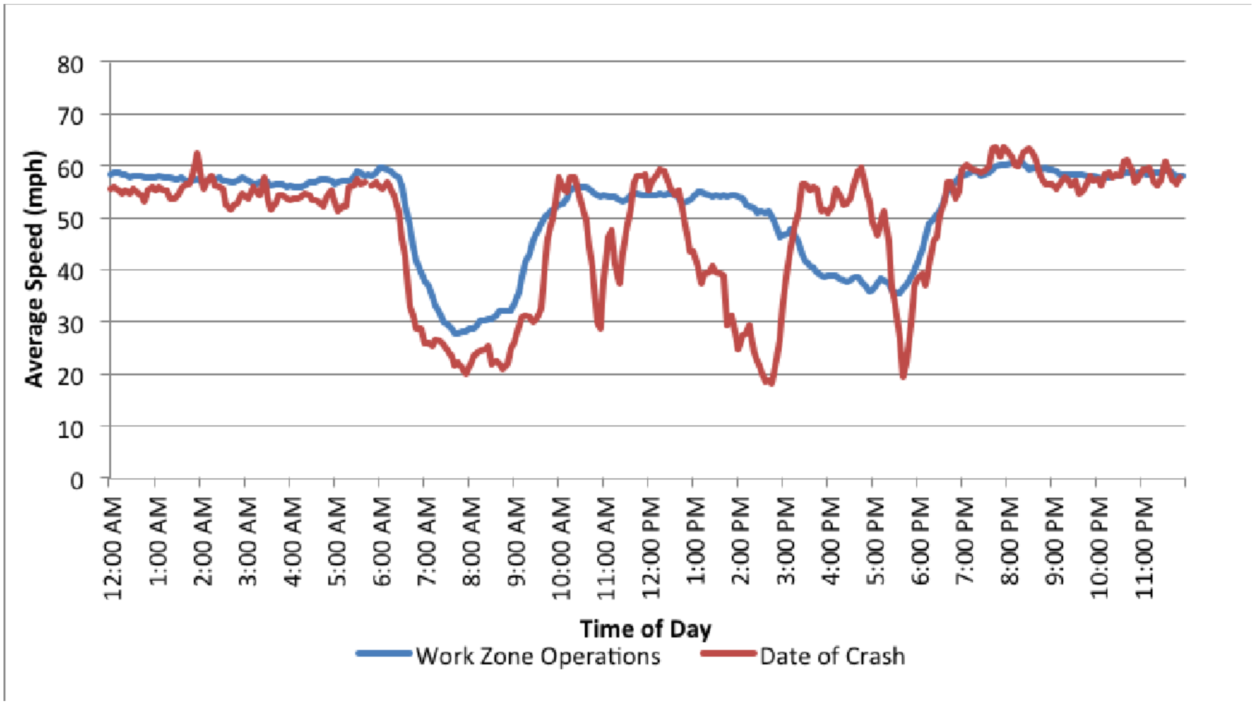

Figure 30. Northbound (Crash) Direction

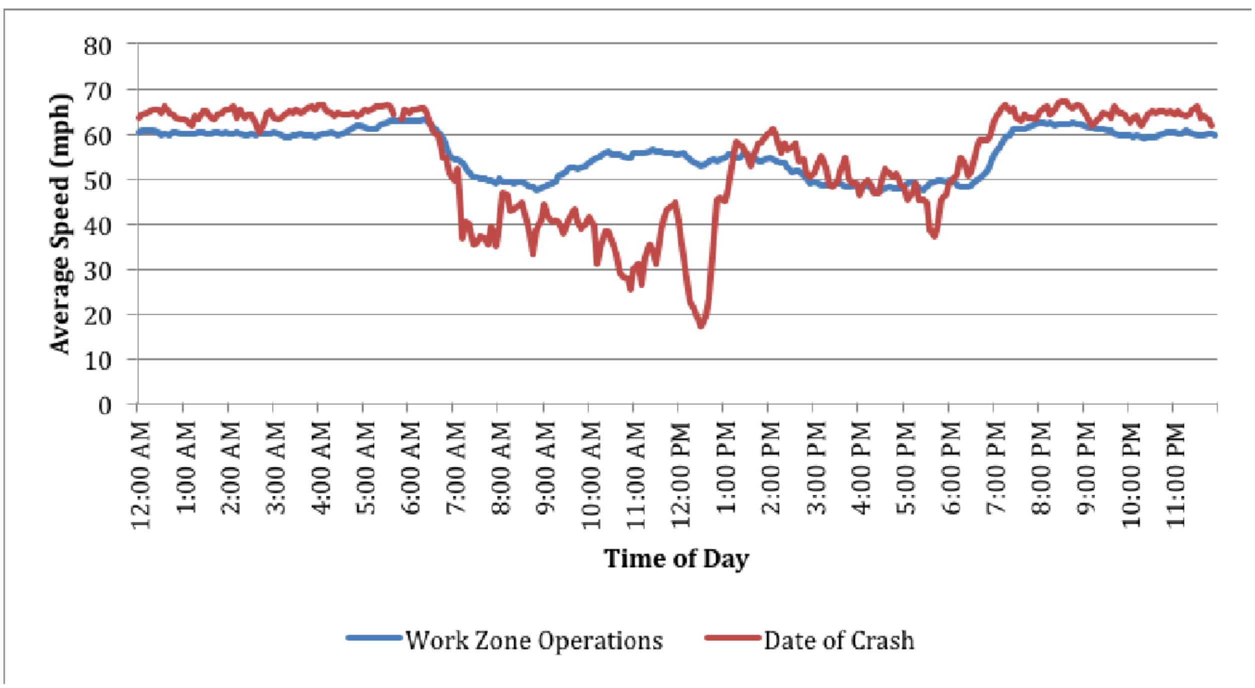

Figure 30b. Southbound (Opposite) Direction

Figure 30. Mobility Impacts of Traffic Crash During Work Zone Operations: I-275 from Warren Rd to Plymouth Rd

CHAPTER 7
ANALYSIS OF WORK ZONE CRASH DATA

Assessing the potential impacts of work zone temporary traffic control strategies on traffic safety (i.e., crashes, injuries, and fatalities) continues to be a primary emphasis of work zone research. In 2010, the *Highway Safety Manual* (*HSM*) was published, providing a framework for road agencies to estimate the safety performance of various road facility types [*41*]. The first edition of the HSM provides methods for estimating the effects of work zones on limited access facilities.

For this project, Michigan-specific data were collected for work zones that included either a shoulder closure, lane closure, or lane shift. Data were collected from 2008 through 2013 in order to develop analytical methods that can be used by the Michigan Department of Transportation (MDOT) to estimate the expected number of crashes for various work zone environments. This chapter details the extant research literature in this area and presents the resulting predictive models that were developed for use by MDOT.

Summary of Work Zone Safety Research

A recent paper summarized most of the work in this area dating back to 1978 [*42*]. Much of the work in this area has involved estimating the change in crash risk that under work zone operations as compared to "normal" (i.e., non-work zone) traffic operations. This research has shown work zone crash risk to increase from 20 to 30 percent as compared to normal operations [*43*].

The crash risk for a given work zone is obviously dependent upon a number of factors, some of which are related to the work activity and others that are related to site-specific factors, such as traffic volumes and roadway geometry. Recent work has aimed to discern how crash risk varies with respect to these factors. For example, *NCHRP Report 627* [*43*] showed that when work activity was occurring and travel lanes were temporary closed, the crash risk for individual motorists increased by 66 percent during daytime conditions and 61 percent at night (both values as compared to similar works for non-work zone conditions).

As road agencies are faced with a myriad of potential alternatives in developing temporary traffic control strategies for a specific work zone, the ability to estimate the impacts of these alternatives on the frequency or rate of traffic crashes is an important criterion. To this end, the *Highway Safety Manual* (*HSM*) provides a series of crash modification functions (CMFs) that can be used to estimate the increase in crash risk posed by work zone operations [*41*].

These CMFs provide an estimate of the increase in crashes that would occur within a given work zone based upon work zone length and project duration. The following equations illustrate the increase in crashes that would be expected to occur as the length of the work zone (in miles) increases or as the project duration (in days) increases:

$$CMF = 1.0 + \frac{(\%\ increase\ in\ length\ in\ miles\ \times 0.67)}{100}$$

$$CMF = 1.0 + \frac{(\%\ increase\ in\ duration\ from\ 16\ days\ \times 1.11)}{100}$$

To use these CMFs, an initial baseline estimate of the number of crashes at a given location is required (e.g., the number of crashes that would occur at the work zone location in the absence of a work zone during the same analysis period). This baseline estimate is then multiplied by these CMFs to estimate the total number of crashes that would occur while the work zone is in place. For example, a 10-percent increase in work zone length would result in a 6.7-percent in crashes (1.0+ (10% x 0.67)/100). Similarly, a 10-percent increase in project duration would result in an 11-percent increase in crashes (1.0 + (10% x 1.11)/100).

The CMFs from the *HSM* were based upon data from 36 work zones in California [*44*]. Recently, data from the state of Missouri was used to develop similar CMFs as part of a project conducted through the Smart Work Zone Deployment Initiative [*45*]. This research, which was based on data from 162 work zones in Missouri, showed similar effects. The magnitude of these effects was slightly less pronounced than the California study. Crashes increased by 0.58 percent for every one-percent increase in work zone length and by 1.01 percent for every one-percent increase in work duration.

The research literature includes a several additional studies that have involved the development of CMFs, as well as safety performance functions (SPFs), which can be used to estimate the number of work zone crashes as a function of characteristics such as AADT, work zone length, and project duration.

A 1996 Indiana study showed crash rates in work zones were significantly higher than the same roadways under non-work zone conditions [*46*]. Similar models were developed as part of a 2000 study that related crashes to project duration, type of work, AADT and work zone length [*47*]. Separate models were calibrated for the work zone area, as well as the approaches immediately upstream of the work zone.

As a part of *NCHRP Project 17-30,* data from California, North Carolina, Ohio, and Washington were used to estimate a series of negative binomial models for work zone crashes by severity level [*48*]. Based on the results of these models, separate CMFs were estimated for daytime and nighttime conditions.

A recent New Jersey study examined the effects of work zone length on crash frequency while accounting for potential errors in length measurement due to deviations from the construction schedule [*49*]. Results showed that crashes were influenced by work zone length, traffic volumes, speed limit, lighting condition, and the number of operational and/or closed lanes.

A 2014 Indiana study compared the results of random effects and random parameter negative binomial models, with results demonstrating similar accuracy between the two methods [*50*]. Significant variables included work zone length, traffic volume, and various roadway (e.g., shoulder widths) and work zone (e.g., lane shift, lane split, etc.) features. Crashes were also found to vary by time-of-year and region.

Michigan Work Zone Data

In order to develop similar predictive models for Michigan work zones, data were obtained from three primary sources:

1. Lane closure reports maintained by MDOT;
2. Annual average daily traffic estimates from the MDOT sufficiency file; and
3. Traffic crashes from the Michigan State Police crash database.

For the purposes of this analysis, the lane closure reports were used to identify those closures that were of at least 0.4 miles in length and at least 3 days in duration. These thresholds were established to ensure: (a) the work zone was sufficiently long such that crash data could be accurately assigned to the associated road segment; and (b) the duration was large enough such that some baseline crash frequency could be established.

When identifying boundaries for the work zones, these limits were established at the nearest upstream/downstream overpass or entrance/exit ramp. Consequently, these limits generally extend outside of the work zone and include portions of the freeway segments that were immediately upstream and downstream of the actual work zone area. Similarly, the closure dates were as noted in the MDOT lane closure database. Some closures were intermittent and it is possible that temporary traffic control was not in place during the entirety of the analysis period.

In addition to collecting data for the work zone period, traffic crash and volume data were also obtained for the same period during the prior year. These data serve as a “baseline” condition, allowing for a comparison of how crash rates change when a work zones is in place.

Table 18 provides summary statistics for the work zone crash database while Table 19 provides similar data for the pre-work zone period. The variables that are included in both data sets are as follows:

- Average annual daily traffic
- Length of analysis segment
- Duration of analysis period
- Total, property damage only (PDO), and injury crashes

Table 18. Summary Statistics for Work Zone Data (N = 790)

Variable	Minimum	Maximum	Mean	Std. Deviation
Annual Average Daily Traffic	2342.00	98813.03	38117.19	21741.34
Length of Work Zone Segment	0.44	41.65	5.00	5.54
Duration of Analysis Period	3.00	389.00	28.78	46.20
Shoulder Closure	0.00	1.00	0.15	0.36
Single-Lane Closure	0.00	1.00	0.56	0.50
Multi-Lane Closure	0.00	1.00	0.25	0.43
Lane Shift	0.00	1.00	0.04	0.19
Total Crashes	0.00	242.00	5.06	12.95
Property Damage Only Crashes	0.00	167.00	4.08	9.85
Injury Crashes	0.00	75.00	0.98	3.43
Work Zone Related Crashes	0.00	42.00	1.95	5.05

Table 19. Summary Statistics for Control (Pre-Work Zone) Data (N = 790)

Variable	Minimum	Maximum	Mean	Std. Deviation
Annual Average Daily Traffic	2354.00	98267.76	38640.13	22249.15
Length of Control Segment	0.44	41.65	5.00	5.54
Duration of Analysis Period	3.00	389.00	28.78	46.20
Total Crashes	0.00	143.00	4.74	11.86
Property Damage Only Crashes	0.00	95.00	3.73	9.00
Injury Crashes	0.00	48.00	1.01	3.10

In addition to these general site characteristics, data were also obtained from the MDOT lane closure file as to the type of closure that was in place at a given site. These include shoulder, single-lane, and multi-lane closures, as well as lane shifts (e.g., redirecting one or more travel lanes onto the shoulder).

The length, duration, and AADT data were comparable to those from prior studies, including the California study that was the basis for the HSM methods [*44*] and the Missouri study [*45*].

Traffic volumes were relatively stable over the two analysis periods. The segment lengths and durations of the analysis periods were identical due to the case-control nature of the study design. When examining crash data at the aggregate level, total and PDO crashes were higher when the work zones were in place while injury crashes were slightly lower.

Statistical Methods

Once the datasets were assembled, a series of statistical analyses were conducted to ascertain how these crash trends related to the work zone and other site characteristics. The safety performance of Michigan work zones was examined by estimating a series of negative binomial regression models. The negative binomial is a generalized form of the Poisson model. In the Poisson regression model, the probability of work zone i experiencing y_i crashes during a specific period is given by:

$$P(y_i) = \frac{EXP(-\lambda_i)\lambda_i^{y_i}}{y_i!},$$

where $P(y_i)$ is probability of work zone i experiencing y_i crashes during the period and λ_i is the Poisson parameter for work zone i, which is equal to the segment's expected number of crashes, $E[y_i]$. Poisson regression models are estimated by specifying the Poisson parameter λ_i (the expected number of work zone crashes) as a function of explanatory variables, the most common functional form being λ_i = EXP(βX_i), where X_i is a vector of explanatory variables and β is a vector of estimable parameters.

The negative binomial model is derived by rewriting the Poisson parameter for each work zone i as λ_i = EXP($\beta X_i + \varepsilon_i$), where EXP($\varepsilon_i$) is a gamma-distributed error term with mean 1 and variance α. The addition of this term allows the variance to differ from the mean as $VAR[y_i] = E[y_i] + \alpha E[y_i]^2$. The α term is also known as the over-dispersion parameter, which is reflective of the additional variation in crash counts beyond the Poisson model (where α is assumed to equal zero).

In order to interpret the practical impact of the variables affecting crash risk, elasticities are calculated. Elasticities represent the average percent change in crash frequency associated with an increase in one of the independent variables. For continuous variables, the elasticity is calculated as follows:

$$E_{x_{ij}}^{\lambda_i} = \frac{\partial \lambda_i}{\partial x_{ij}} \frac{x_{ij}}{\lambda_i},$$

where E represents the elasticity; λ_i is the expected crash frequency for work zone i; and x_{ij} is the jth explanatory variable related to work zone i.

For the purposes of this study, continuous variables (e.g., AADT, work zone length, project duration) were included in the equation in log-form (i.e., taking the natural log of these variables). Consequently, the parameter estimates represent the percent increase in crashes associated with a one-percent increase in the specific variable.

Alternately, for binary indicator variables (i.e., closure type), the pseudo-elasticity can be calculated using the following formula:

$$E_{x_{ij}}^{\lambda_i} = \frac{EXP(\beta_j)-1}{EXP(\beta_j)},$$

where β_j is the parameter estimate for variable j. The pseudo-elasticity represents the percent change in crashes when x_{ij} is changed from zero to one (e.g., the change in crashes related to a specific closure type).

Results

For the purposes of this study, three levels of analyses were conducted:

1. First, separate regression models were estimated for the work zone and the pre-work zone control data. These models allow for a comparison of general trends in total crashes between the two data sets.
2. Secondly, joint models were estimated that included all crash data for both time periods. Under this modeling framework, the effects of traffic volume (AADT), segment length, and duration were constrained to be equal. This allowed for estimation of average

differences in crash frequencies at locations where one of the four closure types were in place. Separate models were estimated for property damage only (PDO) crashes and injury crashes.

3. Lastly, a work zone specific model was estimated for two purposes: (a) to examine differences in safety performance when considering only those crashes that are indicated to be work zone related by the investigating officer; and (b) to assess the sensitivity of crashes to project duration and segment length, allowing for a comparison with similar data from California and Missouri.

Regression Models for Work Zone and Pre-Work Zone Conditions

First, basic models were estimated for both the work zone and pre-work zone datasets using only the duration of the analysis period, annual average daily traffic (AADT), and segment length as predictors. These models take the following general form:

$$\lambda_i = EXP(\beta_0) AADT_i^{\beta_1} Length_i^{\beta_2} Duration_i^{\beta_3},$$

where:

- λ_i is the expected number of crashes on segment *i*;
- $AADT_i$ is the estimated annual average daily traffic for segment *i* in vehicles per day;
- $Length_i$ is the length of segment *i* in miles;
- $Duration_i$ is the duration of the analysis period for segment *i* in days; and
- β_0, β_1, β_2, β_3 are estimable parameters.

Tables 20 and 21 present the model results for the work zone period and pre-work zone period, respectively. For each model, the parameter estimate (β) is provided that corresponds to each variable, along with the standard error, the lower and upper 95 percent confidence limits, and the associated p-value. The confidence limits are provided to illustrate that the effects of duration, traffic volume, and segment length are not significantly different between the two datasets.

Table 20. Model Results for Work Zone Period

Variable	***Β***	**se(*β*)**	**Lower Limit**	**Upper Limit**	**P-value**
Intercept	-14.537	0.5795	-15.673	-13.401	<0.001
Duration	0.908	0.0236	0.862	0.954	<0.001
AADT	1.138	0.0504	1.039	1.237	<0.001
Length	0.824	0.036	0.753	0.894	<0.001
α	0.227	0.0308	0.174	0.297	<0.001

This point is noteworthy as it suggest that a simpler, joint model can be estimated in order to examine how crash frequency changes on a segment by segment basis based on the type of traffic control strategy that is utilized.

Table 21. Model Results for Pre-Work Zone Period

Variable	***β***	**se(*β*)**	**Lower Limit**	**Upper Limit**	**P-value**
Intercept	-12.882	0.5278	-13.916	-11.847	<0.001
Duration	0.884	0.0217	0.841	0.926	<0.001
AADT	1.007	0.0461	0.916	1.097	<0.001
Length	0.784	0.0328	0.720	0.848	<0.001
α	0.183	0.0255	0.139	0.240	<0.001

Joint Models to Assess Impacts of Traffic Control Strategies

These joint models expand upon the general form presented previously, adding four additional terms to distinguish the effects of various closure types:

$$\lambda_i = EXP(\beta_0 + \beta_1 Sh + \beta_2 OneLane_i + \beta_3 Multi_i + \beta_4 Shift_i) AADT_i^{\beta_5} Length_i^{\beta_6} Duration_i^{\beta_7},$$

where:

- λ_i is the expected number of PDO or injury crashes on segment *i*;
- Sh_i is is a binary (0/1) indicator variable for the presence of a shoulder closure;
- $OneLane_i$ is a binary (0/1) indicator variable for the presence of a single-lane closure;
- $Multi_i$ is a binary (0/1) indicator variable for the presence of a multi-lane closure;

- *Shift*$_i$ is is a binary (0/1) indicator variable for the presence of a lane shift;
- *AADT*$_i$ is the estimated annual average daily traffic for segment *i* in vehicles per day;
- *Length*$_i$ is the length of segment *i* in miles;
- *Duration*$_i$ is the duration of the analysis period for segment *i* in days; and
- β_0, β_1, β_2, β_3, β_4, β_5, β_6,are estimable parameters.

Tables 22 and 23 present the final models for PDO crashes and injury crashes, respectively. These results show the duration/time of the analysis period, traffic volume (AADT), and segment length to have effects that were nearly elastic (i.e., a one-percent increase in any of these variables results in an increase of approximately one percent in crashes). The coefficients for duration and segment length are slightly less than one, which indicates that crashes increase more rapidly at low values of segment length and duration, and increase less rapidly in longer work zones or for longer work durations. In contrast, injury crashes tended to increase more rapidly at sites with higher volumes. Injury crashes increased by 1.347 percent for every one-percent increase in AADT.

Table 22. Model Results for PDO Crashes

Variable	***β***	**se(*β*)**	**P-value**
Intercept	-13.747	0.4084	<0.001
Duration	0.895	0.0169	<0.001
AADT	1.044	0.0354	<0.001
Length	0.828	0.0253	<0.001
Shoulder Closure	-0.012	0.0738	0.870
Single-lane Closure	0.178	0.0514	0.001
Multi-lane Closure	0.172	0.0704	0.015
Lane Shift	0.534	0.1101	<0.001
α	0.174	0.0199	<0.001

Turning to the primary variables of interest, the number of PDO crashes was not significantly different when a shoulder closure was in effect versus normal traffic conditions. This seems to imply that driver behavior remains relatively unaltered under such a setting, and is not an unexpected result as the work is taking place outside of the normal travel lanes. Conversely, PDO crashes increased when a single- or multi-lane closure was in effect, although there was little difference between the effects of single- and multi-lane closures. It is interesting to note, from Table 23, that injury crash rates were not higher for shoulder, single-lane or multi-lane closures as compared to normal (non-work zone) conditions at the locations. However, both PDO and injury crashes increased at a significantly greater rate when a lane shift was in place compared to non-work zone conditions.

Table 23. Model Results for Injury Crashes

Variable	β	se(β)	P-value
Intercept	-18.176	0.7622	<0.001
Duration	0.895	0.0293	<0.001
AADT	1.347	0.0662	<0.001
Length	0.776	0.044	<0.001
Shoulder Closure	0.022	0.1222	0.855
Single-lane Closure	0.016	0.089	0.859
Multi-lane Closure	-0.04	0.1256	0.749
Lane Shift	0.413	0.186	0.026
α	0.332	0.0525	<0.001

Table 24 presents a summary of the results from the PDO and injury crash models presented previously. Both PDO and injury crashes increased by 0.9 percent for every one-percent increase in duration. The increase in PDO and injury crashes was elastic with respect to traffic volumes, indicating that crashes increase directly in proportion to AADT. The effect of length was slightly inelastic, with both PDO and injury crashes increasing by 0.8 percent for every one-percent increase in work zone length. These trends are generally consistent with prior research as to general (i.e., non-work zone) crash trends on Michigan freeways [*51*]. It is important to note that the AADT estimates used in the development of these work zone models reflect annual averages. Subsequent research is warranted, which considers actual volumes under work zone conditions to capture potential impacts due to diverted traffic for example.

Segments where shoulder closures were in place experienced only marginally different crash rates between the construction and pre-construction periods for both PDO and injury crashes. Conversely, segments where a lane closure occurred (either single- or multi-lane) experienced approximately 19 percent greater PDO crashes during the construction period as compared to pre-construction, although injury crashes were only marginally impacted. The most pronounced construction related crash increases occurred where lane shifts were present. In these cases, crashes increased by 70.6 percent for PDO crashes and 51.1 percent for injury crashes when the work zone was in place compared to the pre-construction periods.

The findings related to lane shifts should be viewed with caution due to the limited sample size and lack of specific details regarding the work zone temporary traffic control plans. Nevertheless, the results of this preliminary safety analysis suggest that lane shifts may have a greater impact on crash rates than standard lane closures. This result is not completely unexpected, as lane shifts are more variable, both geometrically and from a human performance standpoint, compared to standard lane closures. Lane shifts typically include movement of traffic onto the shoulder or a temporary lane (or shoulder extension), which creates several potential issues. First, the quality of the lane-to-shoulder (or lane-to-temporary lane) transition may impact the ability for drivers to negotiate the lane shift, causing a loss of control. This may be further exacerbated by the presence of shoulder rumble strips, although filling in the rumble strips should reduce any issues. Secondly, the presence of milled or otherwise removed pavement markings may affect lane-keeping behavior, thereby increasing the risk of lane-departure collisions. Finally, the loss of usable shoulder area greatly reduces the shy line, thereby positioning vehicles closer to the pavement edge and any barriers that may be present, further increasing the risk of lane-departure collisions. The reduced length of shifting tapers compared to merging tapers may also negatively impact human performance. Furthermore, because the capacity is not reduced to the level of a standard lane closure, lane shifts create the potential for higher speeds while approaching the work zone and within the transition area. Additional research, preferably using a case-control design, is needed to assess the impacts of the specific features unique to lane shifts, including the types of devices utilized, that may be contributing to the comparably greater increase in crash rates during the construction period for lane shifts compared to standard lane closures.

Table 24. Elasticities/Percent Change in Crash Frequency

Variable	Pct. Increase in PDO Crashes	Pct. Increase in Injury Crashes
Duration	0.9*	0.9*
AADT	1.0*	1.3*
Length	0.8*	0.8*
Shoulder Closure	-1.2	2.2
Single-lane Closure	19.5*	1.6
Multi-lane Closure	18.8*	-3.9
Lane Shift	70.6*	51.1*

*indicates increases that are statistically significant at 95-percent confidence level

Model for Police-Reported Work Zone Related Crashes

As a last step in the work zone safety analysis, another regression model was estimated in order to examine only those crashes that were flagged as work zone related by the investigating officer as per the police crash report form. This helps to address the fact that approximately half of the crashes occurring during the indicated closure period were not coded as work zone related. While some of these crashes are likely to be work zone related, given that such a large percentage may be non-work zone related, these data may mask important trends in the data.

Table 25 presents a model that compares the safety performance of the four work zone closure methods. It should be noted that the lane shift strategy variable has been excluded as the comparison case (the parameter estimates for the three other strategies reflect the relative difference from the lane shift case). Consistent with the prior model results, lane shifts produced the largest increase in crashes (note the negative signs for each of the other traffic control strategies). Compared to lane shifts, multi-lane closures experienced 27 percent fewer crashes, single-lane closures experienced 47 percent fewer crashes, and shoulder closures experienced 89 percent fewer crashes. (Each of these reductions represents the calculated elasticity for the stated variables, akin to those values displayed in Table 24.) These results are also illustrated graphically in Figure 31, which relates crashes to directional AADT by closure type. As a limited sample of work zones and crash data was utilized – particularly where lane shifts were present - a more detailed investigation is required before any decisions or modification to current policies and practices can be made.

Table 25. Model Results for Police-Reported Work Zone Related Crashes

Variable	*β*	se(*β*)	P-value
Intercept	-11.643	0.6642	<0.001
Duration	1.003	0.0306	<0.001
AADT	0.849	0.0578	<0.001
Length	0.578	0.0418	<0.001
Shoulder Closure	-2.105	0.1685	<0.001
Single-lane Closure	-0.643	0.1067	<0.001
Multi-lane Closure	-0.316	0.1266	0.013
α	0.111		

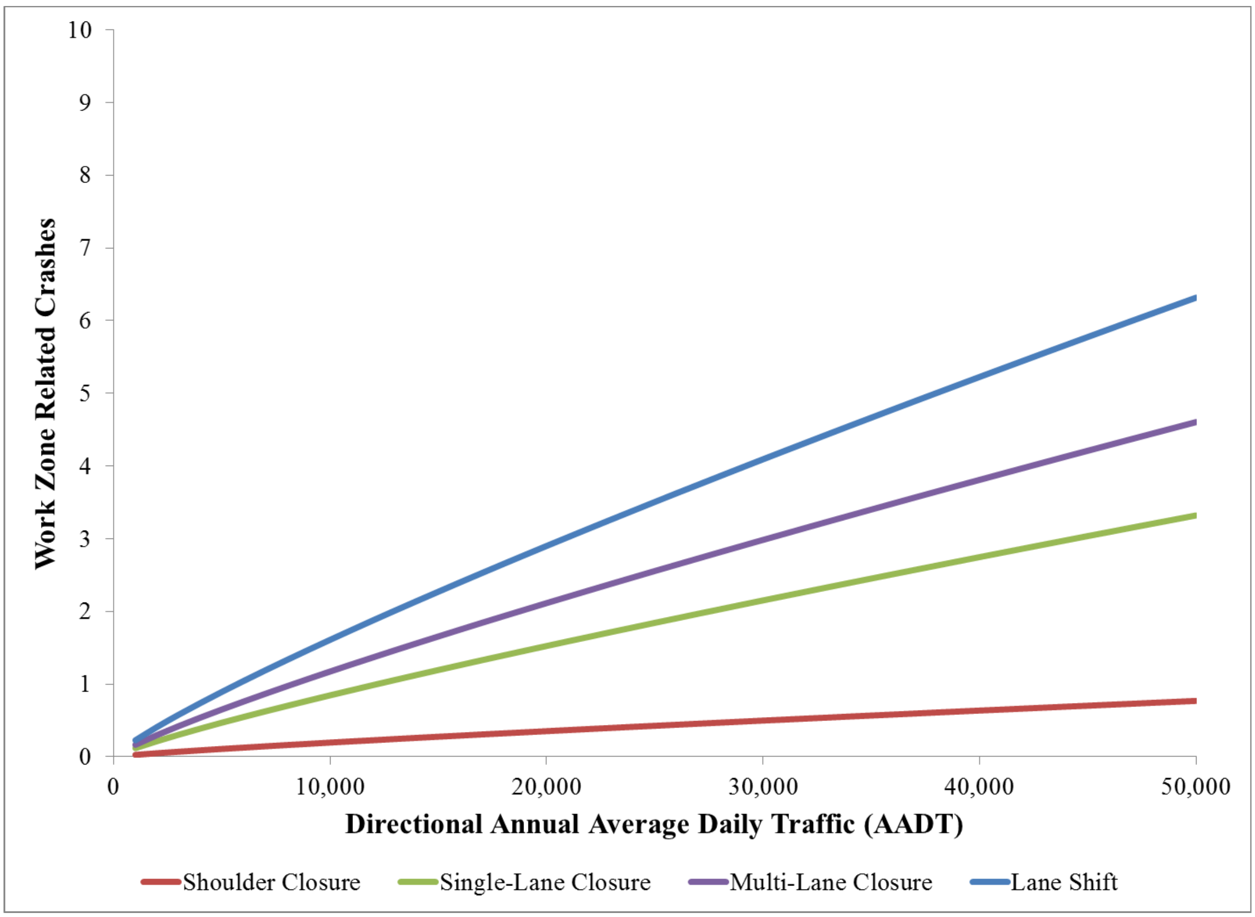

Figure 31. Model Results for Work Zone Related Crashes by AADT (Directional) and Work Zone Closure Method

It is important to note some differences between these results and those presented previously. When considering only crashes coded as work zone related, there is now a much larger difference between the single- and multi-lane closures (with the multi-lane closures experiencing more crashes). These results suggest more pronounced effects, though additional research is warranted to investigate the reason for these differences. The following are a few of the factors that could not be examined as a part of this study and should be included in future analyses: 1.) whether work activity was ongoing at the time of a closure; 2.) specific elements that were included in the temporary traffic control plan; and 3.) geometric characteristics associated with the affected road segments.

Lastly, the results of the model for work zone related crashes were examined with respect to the work zone length and project duration variables. These are the variables that are used to adjust the baseline crash rates for work zones as per the Highway Safety Manual [*41*] based on data from California [*44*]. Subsequent research from Missouri found similar impacts [*45*]. The results are shown in Table 26. It is interesting to note that the Michigan results were found to be very much in line with prior research. In fact, the effects of length and duration are nearly identical between Michigan and Missouri, slightly below the effects found in higher volume work zones from California. These results suggest that the safety impacts of work zones tend to be quite consistent across geographic locations and driver population groups. It is also interesting to note that the California and Missouri datasets established minimum project durations of 15-16 days, which is significantly larger than the 3-day threshold used in Michigan. This suggests that the duration effects tend to be consistent, even when considering shorter-term (i.e., 4 to 15 days) work zones. Ultimately, these results provide important information for use by MDOT in subsequent work zone planning activities.

Table 26. Comparison of Duration and Length Effects between CA, MO, and MI

Variable	California	Missouri	Michigan
Work Zone Length	0.67	0.58	0.58
Project Duration	1.11	1.01	1.00

CHAPTER 8
ASSESSMENT OF PROJECT COSTS ASSOCIATED WITH NIGHTTIME VS. DAYTIME RESURFACING

A variety of work zone mobility treatments are utilized by MDOT and other transportation agencies to help reduce work zone delay. Such treatments include: median crossovers, lane shifts, split merges, and nighttime work, among other treatments. Although mobility treatments may result in delay reductions, such enhancements may also involve increased agency costs that may potentially negate any road user benefits. A primary task of this project is to assess the relationship between work zone mobility treatments and roadway project costs.

As project costs vary widely based on a variety of factors, isolation of the marginal differences associated with the specific work zone mobility treatment presents numerous challenges, particularly limiting the cost related biases from external sources. To help facilitate the isolation of the project costs associated with the specific mobility treatment, a preliminary assessment was performed to investigate the differences between daytime and nighttime costs for a sample of statewide projects involving asphalt resurfacing on freeways. As the nature of the actual work being performed, pay items, and quantities are similar when comparing nighttime versus daytime lane closures for resurfacing, the likelihood of external bias affecting the project costs is reduced. The method presented here should be expanded as a part of subsequent work to include other mobility treatments and other related factors.

Project Selection

Requiring road work to be performed at night is a popular method for reducing delays associated with lane closures, particularly for asphalt resurfacing work on freeways and other maintenance and rehabilitation work that does not involve around-the-clock closures. The projects used in this preliminary cost assessment were selected from freeway projects throughout Michigan that included asphalt resurfacing within the project and involved closure or one or more traffic lanes. To provide further uniformity, projects were limited to those that were at least 3 days in duration and at least 1.5 miles in roadway length. In general, projects were identified through a review of the work descriptions provided within the MDOT lane closure assessment (LCAR) database, which included projects occurring between 2008 and 2013.

After a sample of suitable statewide projects were identified, the Job ID number was utilized to obtain the current project voucher summaries from MDOT's website, which include all pay items included within the project. In some cases, such as for projects involving both road work and bridge work, the Job ID number included several individual projects. For example, guardrail installation was often combined with roadway resurfacing projects under the same Job ID number. For these cases, it was necessary to obtain data for projects included in the job in order to obtain all costs relevant to this analysis, particularly those related to traffic control, as such items may be included within any or all of the individual projects.

The final sample of freeway projects involving roadway resurfacing and subsequent lane closures included projects from throughout Michigan. Metro Region projects were specifically excluded from this preliminary cost assessment due to difficulties in identifying comparable daytime asphalt resurfacing projects. A total of 16 projects were ultimately selected for use within this preliminary analysis, 10 of which were projects in which the resurfacing was performed exclusively at night, while the remaining six were projects in which either all or a majority of the resurfacing work was performed during daylight periods. The list of selected projects is shown in Table 27.

Table 27. Selected Freeway Resurfacing Projects for Nighttime vs. Daytime Cost Analysis

Work Period	Region	Hwy	County	MDOT Job ID	Year	Roadway Mileage	Lane Miles Resurfaced
Day	Southwest	I196	Van Buren	118835	2013	9.5	38.0
Day	North	I75	Emmet	90217	2009	1.7	6.8
Day	North	I75	Cheboygan	107727	2010	2.1	4.3
Day	North	I75	Crawford	110603	2011	9.0	18.0
Day	Superior	I75	Mackinac	118802	2013	7.4	29.7
Day	University	US23	Washtenaw	113145	2012	4.9	19.5
Night	Grand	I96	Kent	102905	2009	13.7	54.8
Night	Grand	M6	Kent	102983	2009	5.0	20.0
Night	Grand	US31	Muskegon	105717	2010	6.3	25.2
Night	Southwest	I94	Kalamazoo	100091	2008	6.8	27.2
Night	Southwest	US131	Allegan	103163	2009	7.4	14.8
Night	Southwest	US131	Allegan	106648	2010	7.4	14.8
Night	Southwest	I94	Kalamazoo	110571	2011	8.3	16.6
Night	Southwest	US131	Allegan	115596	2013	7.5	30.0
Night	University	I94	Jackson	100021	2008	4.5	18.2
Night	University	I96	Ingham	103319	2009	9.0	36.1

Identification of Project Cost Components

The pay item summary data for the selected freeway resurfacing projects were assembled into a single database for further assessment. As some projects included additional work unrelated to the resurfacing (e.g., guardrail installation, etc.), it was necessary to further categorize project pay items based on relevancy to roadway resurfacing work. Categorization also helped address the lack of uniformity with pay items between projects and alleviated issues associated with bid imbalances between projects. The following general categories were utilized:

- Cold milling hot mix asphalt (HMA) surface,
- HMA paving (e.g., 3e, 4E, and 5E asphalt grades),
- Other related HMA costs (e.g., HMA approach, quality initiatives and adjustments, etc.),
- Work zone traffic control (e.g., drums, barricades, signs, etc.), and
- Other project pay items (e.g. mobilization, guardrail installation, etc).

Relevant MDOT pay item codes were included within each of the three categories as shown in Table 28. All other costs were considered superfluous to this analysis. Note that the pay item codes listed in Table 28 include only those pay items for the projects listed in Table 27 and is not intended to be a completely comprehensive list of all related MDOT pay items.

Table 28. Categorization of MDOT Pay Items Related to Asphalt Resurfacing Work

Cold Milling HMA Surface	Hot Mix Asphalt Paving	Other HMA Paving Related Items	Work Zone Traffic Control
5010002, 5020003	5010045, 5010052, 5010056, 5010059, 5020032, 5020045, 5020049, 5020050, 5020051, 5020052, 5020055, 5020056, 5020057, 5020058, 5020059, 5020060, 5027031	5010000, 5010007, 5010061, 5010703, 5017051, 5017060, 5020061, 5020515, 5040005, 5040010, 5047060	8120005, 8120006, 8120016, 8120017, 8120018, 8120020, 8120021, 8120022, 8120023, 8120030, 8120031, 8120035, 8120036, 8120042, 8120043, 8120044, 8120050, 8120077, 8120080, 8120081, 8120085, 8120086, 8120090, 8120091, 8120100, 8120101, 8120102, 8120103, 8120105, 8120110, 8120111, 8120130, 8120131, 8120135, 8120136, 8120140, 8120141, 8120142, 8120153, 8120160, 8120170, 8120180, 8120200, 8120210, 8120211, 8120220, 8120221, 8120230, 8120240, 8120241, 8120250, 8120251, 8120310, 8120320, 8120330, 8120331, 8120340, 8120341, 8120350, 8120351, 8120352, 8120353, 8127001, 8127010, 8127050, 8127051, 8127060

Table 29. Categorized Freeway Project Costs

Work Period	Job ID	Cold Milling HMA	HMA Paving	Work Zone Traffic Control	Other HMA Related Costs	TOTAL PAVING RELATED	Mobilization and Other Items	PROJECT TOTAL
Day	118835	$156,145	$1,352,181	$51,194	$217,347	$1,776,867	$173,102	$1,949,969
Day	90217	$73,768	$256,876	$41,456	$0	$372,100	$77,592	$449,692
Day	107727	$12,002	$147,762	$9,500	$7,093	$176,357	$15,787	$192,144
Day	110603	$11,118	$490,292	$29,321	$8,560	$539,291	$50,138	$589,429
Day	118802	$69,488	$1,742,625	$42,152	$59,376	$1,913,641	$397,795	$2,311,436
Day	113145	$267,373	$1,107,697	$135,234	$220,009	$1,730,313	$577,431	$2,307,744
Night	102905	$472,169	$3,410,032	$256,618	$0	$4,138,819	$394,075	$4,532,894
Night	102983	$78,849	$1,706,360	$74,575	$0	$1,859,784	$101,985	$1,961,769
Night	105717	$133,677	$1,596,081	$61,543	$37,300	$1,828,601	$194,967	$2,023,568
Night	100091	$228,223	$1,657,000	$46,343	$396,213	$2,327,779	$125,573	$2,453,352
Night	103163	$46,270	$1,165,142	$37,890	$174,782	$1,424,084	$67,900	$1,491,984
Night	106648	$76,791	$936,556	$20,864	$141,417	$1,175,628	$107,021	$1,282,649
Night	110571	$38,474	$978,585	$39,003	$68,694	$1,124,756	$86,551	$1,211,307
Night	115596	$91,722	$1,850,010	$59,912	$280,506	$2,282,150	$405,668	$2,687,818
Night	100021	$141,594	$922,503	$56,879	$0	$1,120,976	$495,177	$1,616,153
Night	103319	$313,015	$2,869,070	$124,877	$73,760	$3,380,722	$734,642	$4,115,364

Analysis

Upon sorting and categorizing the relevant pay items, the categorized project costs were then normalized based on the project lane-mileage. T-tests were utilized to test for differences between the costs per lane-mile for nighttime versus daytime projects within each of the categories.

As can be observed in Table 30, the mean HMA paving costs for daytime and nighttime operations were statistically different from one another. The mean HMA paving cost for daytime work was $41,779 per lane-mile, while the mean nighttime paving cost was nearly 60 percent greater at $66,474 per lane mile. It is also worth noting that the mean unit costs for the HMA paving pay items were $59.08/ton and $66.60/ton for daytime and nighttime operations, respectively, which were not statistically different from each other. Table 30 also shows that no significant differences were observed between the daytime and nighttime costs for cold milling HMA, work zone traffic control, other HMA related costs, and all other items.

Table 30. Categorized Freeway Project Costs per Lane-Mile

Work Period	Job ID	Cold Milling HMA	HMA Paving	Work Zone Traffic Control	Other HMA Related Costs	Mobilization and Other Items
Day	118835	$4,109	$35,584	$1,347	$5,720	$4,555
Day	90217	$10,825	$37,694	$6,083	$0	$11,386
Day	107727	$2,820	$34,717	$2,232	$1,667	$3,709
Day	110603	$618	$27,238	$1,629	$476	$2,785
Day	118802	$2,340	$58,692	$1,420	$2,000	$13,398
Day	113145	$13,697	$56,747	$6,928	$11,271	$29,582
DAYTIME AVG.		$5,735	$41,779*	$3,273	$3,522	$10,902
Night	102905	$8,616	$62,227	$4,683	$0	$7,191
Night	102983	$3,935	$85,148	$3,721	$0	$5,089
Night	105717	$5,313	$63,437	$2,446	$1,483	$7,749
Night	100091	$8,391	$60,919	$1,704	$14,567	$4,617
Night	103163	$3,126	$78,726	$2,560	$11,810	$4,588
Night	106648	$5,189	$63,281	$1,410	$9,555	$7,231
Night	110571	$2,321	$59,022	$2,352	$4,143	$5,220
Night	115596	$3,057	$61,667	$1,997	$9,350	$13,522
Night	100021	$7,797	$50,799	$3,132	$0	$27,267
Night	103319	$8,676	$79,520	$3,461	$2,044	$20,361
NIGHTTIME AVG.		$5,642	$66,474*	$2,747	$5,295	$10,284

*Statistically significant difference between daytime and nighttime costs

Comparison to User Delay Costs

Nighttime resurfacing resulted in an incremental difference of nearly $25,000 per lane mile compared to daytime resurfacing. Considering a 4-lane freeway, this equates to $100,000 per mile of resurfacing. Based on the user delay costs shown in Table 17, a three-mile long work zone will result in expected daily user delay costs of $1,977 and $14,095 for trucks and passenger vehicles, respectively, for a total expected delay cost of $16,072 per day. The daily user costs may be compared to the additional project costs to estimate the time-of-return for the particular mobility treatment.

CHAPTER 9
CONCLUSIONS AND RECOMMENDATIONS

Summary and Conclusions

This report summarizes the activities involved in *Balancing the Costs of Mobility Investments in Work Zones* (OR13-004). These tasks included the conduct of a state-of-the-art literature review and a national state-of-the-practice survey, which were focused on examining the safety and mobility impacts of work zones. The state-of-the-practice survey included a review of specific countermeasures, treatments, and strategies that have been used for work zone temporary traffic control by various state DOTs. The project also involved the implementation of a survey of Michigan road users to ascertain public perceptions of work zone related delay, as well as the collection and analysis of traffic operations data from both field studies and additional data that were available through the Regional Integrated Transportation Information System (RITIS). An assessment of work zone traffic crash data was also performed, in addition to preliminary methodological development for determining the agency cost impacts associated with mobility enhancements. The principal findings from these activities are summarized as follows:

1. Road User Survey – A road user survey was implemented at rest areas in each of the seven MDOT regions. This survey provided public opinion data with respect to work zone related delay from a sample of 1,265 respondents. The primary questions of interest dealt with what respondents felt was a maximum acceptable level of delay (in minutes), as well as whether respondents favored shorter closures of an entire roadway or longer closures of a portion of that roadway.
    - Acceptable Delay – MDOT currently considers a threshold of 10 minutes for acceptable delay. This threshold is well supported by the survey data, which showed a consistent median value of 10 minutes at the statewide level for both the AM and PM commute. This trend held statewide, as well as within each of the MDOT regions. Respondents indicated a 10-minute delay threshold for shopping business trips and a higher delay threshold (median value of 15 minutes) for vacation travel.
    - Closure Preferences – Respondents were generally split as to whether they preferred a longer-term partial road closure (59 percent of those responding) or a shorter-term

full closure (41%). Interestingly, the MDOT Metro region showed the opposite, with 57 percent favoring a total closure.

2. Field Data Collection – Field data were collected from work zones in various geographic regions of Michigan. Traffic volume and speed data were collected through a series of in-vehicle travel time runs, as well as through the review of video data for each work zone. These data were used to estimate the delay experienced by motorists encountering work zones. Delay was principally affected by traffic volume and work zone length.
    - Traffic Volumes – Travel speeds remained relatively stable up to a flow rate of approximately 1,700 vphpl. Beyond this point, speeds declined (and delays increased) dramatically. As only a limited number of work zones had flow rates above 1,000 vphpl, further data are necessary to better understand traffic dynamics at higher volumes.
    - Mobility Impacts – The majority of these work zones involved a single lane closure. There were limited instances of shoulder closures, lane shifts, and median crossovers. While some general trends emerged (e.g., delays were higher for lane closures vs. shoulder closures, specific geometric configurations had significant impacts on delay), further data is required in order to develop reliable estimates for the impacts of select strategies, particularly at high volumes.
    - Road User Costs – The field delay data were utilized to obtain estimates of daily road user costs associated with the work zone length. Considering a maximum acceptable delay of 10 minutes per vehicle, lane closures shorter than 5 miles are not likely expected to produce unacceptable delays.
3. Use of RITIS Data – Information was obtained from the RITIS to supplement the results of the field studies that were conducted. These data were used for several purposes.
    - RITIS data were compared to data from the work zone field studies for the same time periods. The RITIS data exhibited similar trends to the field data, though there were some differences on a location-by-location basis.
    - Further historical data were collected from the RITIS for the entire time period during which the study work zones were in place during 2013. Comparison data were collected for the same roadway locations and date range during the prior year (2012). Consistent reductions were observed at both high-volume and low-volume locations.

Lower-volume sites showed differences of 2 to 5 mph on average, while the higher-volume sites showed speed reductions of 15 mph or more.

- The RITIS data were also utilized to examine traffic flow after the occurrence of work zone-involved crashes. However, the inherent variability of single-day speed profiles limits the ability to extrapolate beyond the sample data collected thus far.

4. Work Zone Crashes – Regression models were developed to examine crash risk in Michigan work zones, including a comparison with prior year (i.e., non-work zone) data. Data were obtained from a variety of sources that included: MDOT lane closure reports; annual average daily traffic estimates from the MDOT sufficiency file; and traffic crashes from the Michigan State Police crash database. Several levels of analyses were conducted for this study, which included: comparison of work zone vs. pre work zone crash occurrence; comparison of crash occurrence between the following four closure types: shoulder closure, single lane closure, multi lane closure, lane shift; an assessment of officer-coded work zone crashes; and comparison of the Michigan specific results with similar Highway Safety Manual data from California and Missouri.
   - Property damage only (PDO) crash rates were not significantly different when a shoulder closure was in effect versus normal traffic conditions, although PDO crashes increased when a single- or multi-lane closure was in place, and increased further when a lane shift was in place, although a small sample of lane shift data were available. Further analyses are recommended to understand specific factors that affect work zone crash risk.
   - Considering only work zone coded crashes (as noted on the UD-10 crash report form), incremental crash increases were observed when comparing single-lane closures to shoulder closures, double-lane closures to single-lane closures, and lane shifts to double-lane closures.
   - The effects of work zone length and duration were found to be very similar between Michigan and Missouri, and slightly below the effects found in higher volume work zones from California.
5. Mobility Treatment Costs – A preliminary assessment of nighttime freeway resurfacing work was performed to determine a methodology for identifying the project costs associated with the various mobility treatments. Pay items and cost data were obtained

for a sample of 16 hot-mix asphalt resurfacing projects on freeways statewide. Project pay items were separated into general categories that included: cold milling of HMA, HMA paving, other related HMA costs, work zone traffic control, and other pay items. These data were then normalized based on the project lane miles.

- The mean HMA paving cost for daytime work was $41,779 per lane-mile, while the mean nighttime paving cost was nearly 60 percent greater at $66,474 per lane mile.
- No significant differences were observed between the daytime and nighttime costs for cold milling HMA, work zone traffic control, other HMA related costs, or all other items.

Recommendations for Future Research

Although several important findings were ascertained as a part of the original research work plan, a lack of available detailed work zone condition data inhibited development of the decision support tool. Due to these data shortcomings, it was determined that Phase 2 research would not proceed until the necessary additional data are collected. Further direction towards refinement of the Phase 2 work plan is provided in Appendix B of this report. This includes recommendations for information that should be obtained either prior to or during the Phase 2 research. Specifically, it will be necessary to obtain detailed field data for several work zone locations to allow for examination of how various aspects of the work zone, including the type of mobility treatment, type of work being performed, equipment and worker placement, and other key work zone characteristics, affects safety and mobility. Ultimately, the collective Phase 1 and Phase 2 research findings will be used to develop the decision support tool for selection of work zone mobility treatments. This tool will utilize site condition data, such as road features, traffic volumes, length of work zone, and type of work, and provide guidance towards selection of potential mobility treatments to minimize delay and traffic safety impacts.

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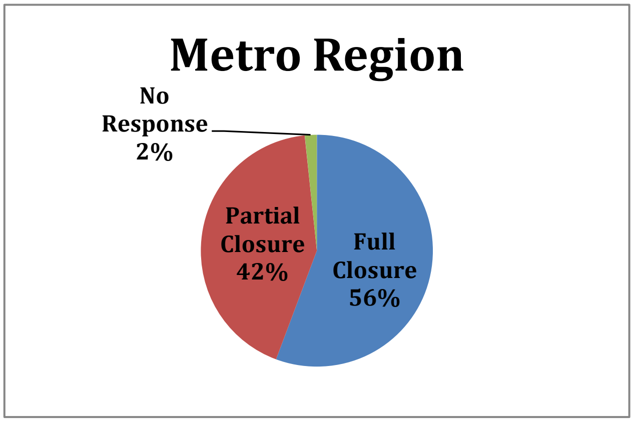
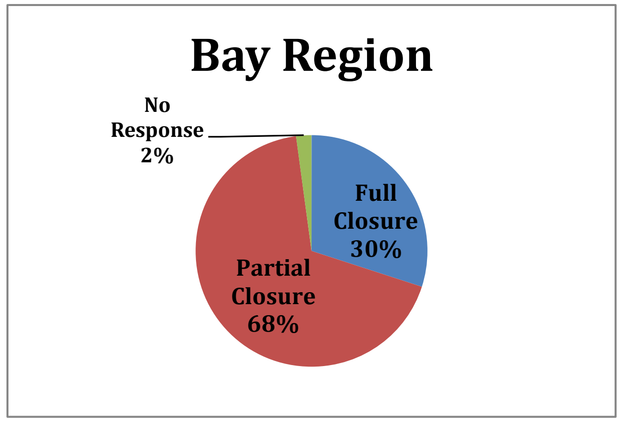
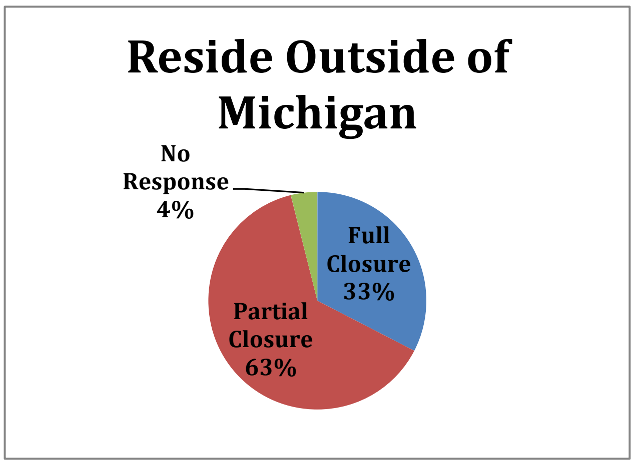
APPENDIX A

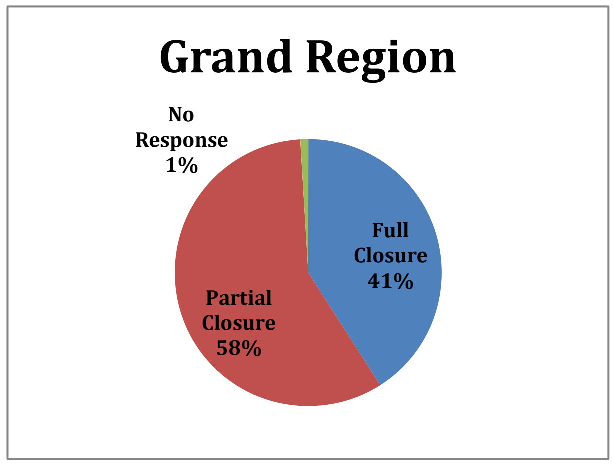
ADDITIONAL ROAD USER SURVEY RESULTS

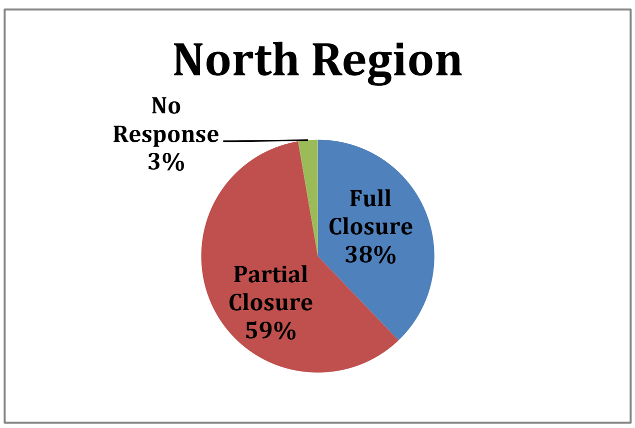
In general, would you prefer the *road be completely closed during a shorter period* or *the road be partially closed during a longer period*?

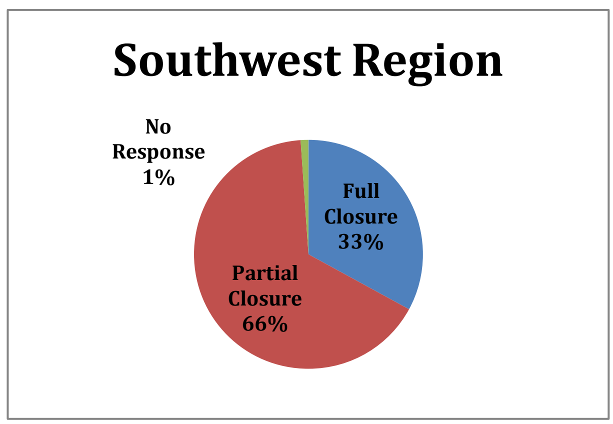


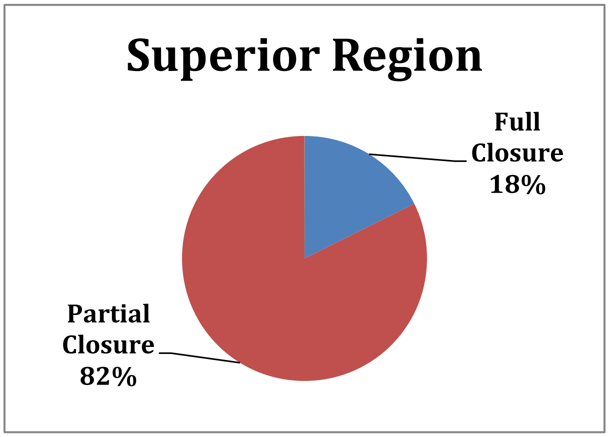


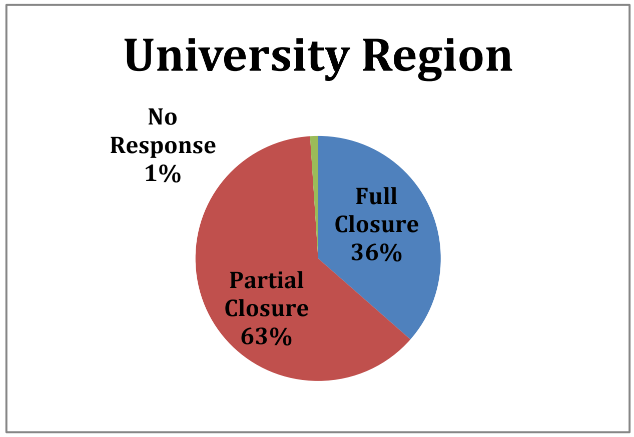


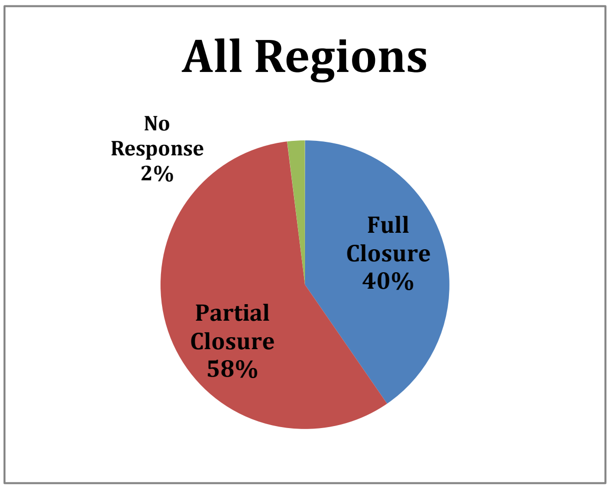







Superior Region
Full Closure 18%
Partial Closure 82%


University Region
No Response 1%
Full Closure 36%
Partial Closure 63%


All Regions
No Response 2%
Full Closure 40%
Partial Closure 58%

Indicate the longest (in number of minutes) delay that would be acceptable to you due to a work zone for commute or work-related trips, for vacation-related trips, and for shopping or personal business trips.

All Vehicles (N=1265) - Acceptable Delay in Minutes				
Trip Type	**Mean**	**Median**	**85th Percentile**	**15th Percentile**
Work / Commute AM	13.487	10.0	20.0	5.0
Work / Commute PM	14.416	10.0	20.0	5.0
Vacation (leaving home)	19.538	15.0	30.0	5.0
Vacation (returning home)	19.647	15.0	30.0	5.0
Shopping	14.716	10.0	30.0	5.0

Personal Vehicles (N=1091) - Acceptable Delay in Minutes				
Trip Type	**Mean**	**Median**	**85th Percentile**	**15th Percentile**
Work Commute AM	12.746	10.0	20.0	5.0
Work Commute PM	13.652	10.0	20.0	5.0
Vacation (leaving home)	19.372	15.0	30.0	5.0
Vacation (returning home)	19.270	15.0	30.0	5.0
Shopping	14.198	10.0	20.0	5.0

Truck/Bus (N=144) - Acceptable Delay in Minutes				
Trip Type	**Mean**	**Median**	**85th Percentile**	**15th Percentile**
Work / Commute AM	18.372	15.0	30.0	10.0
Work / Commute PM	19.570	15.0	30.0	10.0
Vacation (leaving home)	20.174	15.0	30.0	5.0
Vacation (returning home)	21.904	15.0	30.5	5.0
Shopping	18.673	15.0	30.0	5.0

APPENDIX B
SUGGESTED NEXT STEPS

INTRODUCTION

Although several important findings were ascertained as a part of the original research work plan, many questions related to the Phase 2 objectives could not be fully addressed. Specifically, the work zone site condition data necessary for development of a decision support tool was not available during the Phase 1 research. Consequently, the information presented in this appendix will provide direction towards development of a potential Phase 2 work plan, including specific information that should be obtained by MDOT either prior to or during the Phase 2 research. The Phase 2 work plan should involve a detailed empirical analysis based upon a series of field studies and build upon the information gained and lessons learned during the Phase 1 research. These field studies will allow for an examination of how various aspects of the work zone, including the type of mobility treatment, type of work being performed, equipment and worker placement, and other key work zone characteristics, affect safety and mobility. Ultimately, the collective research findings will be used to develop a decision support tool to provide MDOT with guidance toward selection of work zone mobility treatments.

The primary objective of the Phase 2 work plan is to develop a decision support tool that will provide MDOT with guidance toward selection of work zone mobility treatments that will optimize mobility and safety for a given scenario. In a basic sense, this decision support tool would take information pertaining to the specific work zone site and provide recommendations as to the appropriate work zone mobility treatment(s) based on the cost-effectiveness of the treatment.

To the extent possible, the decision support tool should be developed based on empirical data obtained from Michigan work zones. Thus, a well-founded study design is necessary to accomplish this objective. The tasks identified below present guidance related to site selection, data collection, relevant cost, and crash/economic analyses.

TASK 1: DETERMINE POTENTIAL SITE CONDITIONS AND MOBILITY TREATMENTS

Prior to the start of the Phase 2 research, it will be necessary for MDOT to determine the types of site conditions and mobility treatments that warrant inclusion within the decision support tool. Initially, MDOT should consider prioritizing the desired types of mobility treatments and site conditions that will be input parameters for the decision support tool. To ensure an adequate number of locations for each desired condition, it is recommended that the Phase 2 research evaluation and analysis be constrained to longer, higher volume work zones involving typical work (i.e., HMA resurfacing, PCC repair) and utilizing common mobility treatments.

One potential condition that should be limited during subsequent research is hourly traffic volumes. The Phase 1 research study showed only minor impacts to vehicular delay associated with freeway lane closures at volumes below 1,700 vehicles per hour per lane. Travel speeds remained relatively stable up to a flow rate of approximately 1,700 vphpl. Beyond this point, speeds declined (and delays increased) dramatically. Furthermore, even for locations with greater than 1,700 vphpl, it was estimated that work zone delays would not exceed 10 minutes for work zones of less than five miles. Thus, consideration should be given towards including relatively long work zones that experience relatively high hourly volumes during portions of the day. Specifically, it is appropriate to exclude freeway work zones that do not experience volumes greater than 1,000 vphpl within a typical day. Free-flow speeds will typically prevail for all freeway conditions below this limit, and consequently, work zone mobility treatments will not have a significant impact. While this will contribute to oversampling of work zone locations in urban or suburban areas, such higher volume locations possess the greatest mobility needs.

Furthermore, shoulder closures have comparatively less impact on overall roadway capacity and subsequent road user delays. Thus, it may be appropriate to eliminate shoulder closures from consideration during subsequent research. It may also be beneficial to exclude less common mobility treatments, such as temporary bridges (a significant data deficiency for Phase 1), as it may be difficult to collect adequate data given the limited implementation.

It may also be desirable to limit the decision tool to include freeways only, given difficulties with capturing important characteristics of non-freeways such as diverted and detoured traffic. Although MDOT may benefit from a decision tool that considers non-freeways, the site conditions and applicable mobility treatments are substantially different than those for freeways. To that end, MDOT may wish to consider potential decision tools for non-freeway work zones separately after successful creation of a freeway-specific decision tool.

TASK 2: SELECT STUDY SITES

From there it will be necessary for MDOT to identify work zone locations that include the specific conditions identified in the previous task. These should be new projects that are initiated during the upcoming construction season(s). It will initially be necessary for MDOT to obtain work zone transportation management plans (where available), traffic control plans, and/or other details in order to accurately identify the duration and limits of each candidate project, in addition to the layout, configuration, duration, and limits of each specific mobility treatment.

During the project identification process, preference should be given to projects that include staging of multiple treatments at a single site, as this will help control the variability between sites. Preference should also be given to include longer sites (length and/or duration) to ensure that a sufficient amount of crash data will ultimately be available. Higher volume locations should also be given preference, specifically locations with greater than 1,700 vphpl, in an attempt to identify work zones with excessive user delay. Specifically, it is recommended that work zones less than 5 miles in length and with volumes that do not exceed 1,000 vphpl be excluded from the subsequent analysis. To assist with site selection, it may be helpful to estimate work zone delay based on MDOT's Construction Congestion Cost (CO3) software.

The precise number of projects should be determined and in accordance with standard statistical sampling procedures. It is recommended that a minimum of five work zones should be selected for each primary mobility treatment warranting investigation. Additional work zones should also be identified as back-up locations in the event that any of the primary locations are inaccessible. While these sites should be drawn from various regions of the state, it is acknowledged that an overrepresentation of locations in certain regions (i.e., Metro) may be necessary to fully investigate certain treatments and to include higher volume locations.

TASK 3: FIELD DATA COLLECTION

The Phase 1 study helped identify the data necessary to accomplish the objectives identified for a Phase 2 research study, along with viable methods used to obtain such data. After selection of study sites, it will be necessary to gather site inventory data both prior to the work zone and while the work zone is in place.

Pre-Work Zone Data

Prior to implementation of the work zone, it will be necessary to obtain accurate hourly volume counts. Historical counts taken from the prior three years may be utilized to fulfill this requirement, where available. It will also be necessary to collect segment speed and/or travel time data for each location. Lane and shoulder widths should also be measured.

Work Zone Data

A primary finding of the Phase 1 research study was the necessity of detailed field data to verify the actual work zone conditions. In order to obtain the necessary field data, project-level assessments will be required at the selected work zone locations. The necessary work zone related data include inventory data (e.g., work zone limits, mobility treatment information, work being performed, worker and equipment information, access point locations), in addition to operational data (e.g., hourly volumes, speeds, etc.). Regular site visits may be required to obtain the necessary data.

TASK 4: OBTAIN AGENCY COSTS

Agency costs are the costs associated with the particular mobility treatment that are incurred by MDOT. As project costs vary widely based on a variety of factors, careful consideration must be given towards isolation of the marginal differences associated with the specific work zone mobility treatment. The initial research presented a preliminary methodology to investigate the differences between agency costs for mobility treatments and provides the basis for subsequent investigation of the agency related costs associated with each mobility treatment. While the preliminary cost assessment showed differences between paving costs for daytime versus nighttime operations, additional research is needed to assess the differences in project costs associated with other common mobility treatments. The costs should be categorized to isolate the pay items associated with the work zone mobility treatment from other pay items.

TASK 5: ESTIMATE WORK ZONE DELAY COSTS

Delays experienced by motorists when traveling through work zones represent an economic cost. Delay may be equated as the difference in travel time between normal operating conditions and work zone conditions. Work zone delay calculations must consider equivalent days of the week, times of day, and changes in traffic volume after implementation of the work zone.

Assuming that incremental delay improvements can be ascertaining for a given mobility treatment, road user benefits may be calculated based on the CO3-based estimation procedure described in the main body of this report. The travel time and hourly volume data collected at each of the study sites during the pre-work zone and work zone conditions may be utilized to calculated the average delay per vehicle and total work zone delay associated with each work zone mobility treatment. MDOT provides value-of-time unit estimates for passenger vehicles and commercial trucks as a part of the CO3 estimation software. These unit costs (in 2014 dollars) are displayed for passenger vehicles and heavy trucks in Table 16 of this report.

TASK 6: ANALYZE CRASHES

In addition to affecting agency costs and user delay costs, work zone mobility strategies may also have substantive impacts on traffic safety. The initial research included a preliminary development of safety performance functions for work zone related crashes in Michigan. The preliminary results indicated that PDO crashes increase when a single- or multi-lane closure or lane shift was in place. However the models were based on a limited sample of work zones and crash data, particularly where lane shifts were present. Furthermore, data for other mobility treatments, including crossovers, were not included in the models. Thus, a primary task during subsequent research will be to further refined the safety performance functions developed during the initial research and attempt to develop crash modification factors (CMF) related to specific mobility treatments. The research should also seek to resolve several issues that were identified during the preliminary analysis, including difficulties with identifying crashes that were actually associated with the work zone, determining the actual work zone configuration at the time of the crash, determining the specific location of the crash with respect to the work zone traffic control.

Although it will not likely be possible to collect the necessary data for all work zone sites included in the safety analysis, at the very least it will be necessary to obtain inspector daily reports and/or other records that would depict the work zone configuration, work period, work location, and nature of the work. In addition to collecting data for the work zone period, traffic crash and volume data must also be obtained for the same period and same boundary locations during prior year(s). These data will serve as a "baseline" condition, allowing for a comparison of how crash rates change when the particular work zone mobility treatment is in place. The safety analysis should also include assessment of the appropriate location for the upstream boundary of the work zone for safety analyses.

TASK 7: PERFORM ECONOMIC ANALYSIS

Although certain mobility treatments may result in delay and/or crash reductions, such enhancements may also involve increased agency costs that may potentially negate any user benefits. Future research should specifically assess whether the net road user benefits provided by the mobility strategy outweigh the additional agency costs for the particular strategy. To that end, a benefit/cost analysis should be performed, considering agency costs, delay benefits (or disbenefits), and safety benefits (or disbenefits). The subsequent results may then be utilized toward development of the work zone mobility decision support tool. Additionally, other cost-effective mobility strategies that have been implemented elsewhere (or on a very limited basis in Michigan) may also provide promising options for further implementation in Michigan and should be considered within the decision support tool, to the extent possible. Such strategies may include: dynamic lane merge systems (which have been selectively implemented in Michigan); speed management systems; utilization of intelligent transportation systems, and use of performance/incentive-based contracting.

TASK 8: DEVELOP DECISION SUPPORT TOOL

The principal objective of the Phase 2 research will be to develop an interactive, user-friendly decision support tool that can be used by MDOT to determine the cost-effectiveness of various work zone mitigation strategies aimed at keeping delay below acceptable thresholds. The inputs for this decision support tool will include the following, as well as other key decision criteria as determined in consultation with MDOT:

- Road features
- Traffic volumes
- Type of work being conducted
- Length of work zone
- Anticipated duration of work activity
- Potential mobility treatments

From these inputs, guidance will be given as to the appropriate mobility treatment(s). Where data are available, estimates of the impacts of the selected strategies on mobility, safety, and economic costs may also be provided to further assist with decision making. By comparing the output from alternative strategies that are under consideration, the user will be able to make an informed decision regarding mobility treatment selection.